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STRUCTURE AND PETROCHEMISTRY OF THE REYKJADALUR CENTRAL VOLCANO

AND THE SURROUNDING AREAS, MIDWEST ICELAND.

By

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Graduate Society, Durham.

Thesis submitted for the degree of Doctor of Philosophy at the
University of Durham.





Til Sifjar

ABSTRACT

The main geological feature of the research area is a Tertiary flood basalt pile, about 2.7 km thick, within which are three Tertiary central volcanoes. The "basement" consists of faulted and tilted basalts, probably about 12-13 m.y. old. These basalts were overlain by the Hredavatn sedimentary horizon, 7 m.y. ago, followed by lavas of the Hallarmuli central volcano which was active from 6.7 to 6.0 m.y. ago. The time sequence of the volcanism was of acid ignimbrites, then intermediate flows, and finally thin tholeiite flows. The volcano did not evolve the structural or geothermal characteristics usually associated with central volcanoes.

The Reykjadalur central volcano became active about 5.8 m.y. ago and is situated on a series of thick tholeiite flows which overlie unconformably the Hallarmuli central volcano. Voluminous acidic and some intermediate rocks formed first and were succeeded by thin tholeiite flows. A collapse caldera, 10 km in diameter, then formed and was filled with volcanics. After the formation of the caldera, a basic to acid cone sheet swarm, about 20 km in diameter and concentric to the caldera, intruded the country rocks. About 4.3-4.4 m.y. ago, soon before the volcano became extinct, a massive icecap covered the volcano and its environs; the Holtavörðuheidi sedimentary horizon covered the area east and southeast of the volcano at this time.

The Laugardalur central volcano consists of a caldera and its volcanic filling; it may be parasitic to the Reykjadalur central volcano. Later, 3.4 m.y. ago, acid tephra was erupted from the Litla Baula vent and the Baula acid intrusion was emplaced at this time.

Volcanic activity was renewed about 2 m.y. ago, represented by the Snjofjöll series and a few more recent volcanics.

The Tertiary basalts are tholeiitic. The rocks from the central volcanoes show a trimodal volume distribution, with basalts and rhyolites more abundant than rocks of intermediate compositions. Three distinct breaks occur in the chemical properties : between the olivine tholeiites and the quartz tholeiites; between the quartz tholeiites and the basaltic icelandites; and within the dacites.

The basalts were derived from the Upper Mantle, olivine tholeiites being produced by a greater degree of partial melting and/or at greater depths than the quartz tholeiites. On volume and time relations and on geochemical grounds, the acid and intermediate volcanics are considered to be derived by two-stage melting of the Icelandic lower crust. The acid magmas were generated first, followed by intermediate magmas from partially melting the residuum at a higher temperature. Although this process is fuelled by basaltic intrusions within the lower crust, the late appearance of basalts in the central volcanoes is attributed to the density-depth relations between the crust and the rising magma.

ACKNOWLEDGEMENTS

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Geological map of the research area is folded in a pocket at the back of the thesis

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CHAPTER 1:

INTRODUCTION

Scope of Study

The area described in this thesis is located in western Iceland, in the upper part of Bergarfjörður and across the mountain range into the southern part of the Dalir area (Fig. 2.1). The area involved is about 30x30 km but it has not been mapped completely and gaps occur in the mapping, as can be seen on the Geological Map (folded at the back of the thesis).

The work was originally suggested by Dr. Kristjan Saemundsson of the National Energy Authority, Department of Natural Heat, Iceland, as part of a much bigger project which has been in progress for several years, involving the mapping of the entire western flank of the western volcanic zone (called the Reykjanes-Langjökull zone in this study).

The main aim of the study, for the National Energy Authority, was to establish the stratigraphy (and age) and the structural-tectonic features of the area. It was hoped that the study would supply some new explanations of the puzzling Borgarnes-anticline and the highly abnormal geology of the Snaefellsnes peninsula. It was also hoped that the study would give clues to understanding the origin and perhaps the distribution of the vigorous geothermal activity in the south-eastern part of the area (especially in Reykholtssdalur), which is of great economic value.

Along with the stratigraphical work a large number of samples were collected to establish the geochemical features of the Tertiary rocks. It was important to compare the geochemistry of the older rocks of the research area with the geochemistry of Tertiary rocks from other areas already studied and with the geochemistry of the more



recent volcanics in the research area and the surrounding areas. It was hoped that detailed stratigraphical and structural studies of the central volcanoes in the area, along with chemical analyses of the intermediate and acid rocks, would reveal some new evidence on the origin of these rocks.

Previous Work

The geology of the area was relatively unknown until the present investigation. During the last century and at the beginning of this century a few Scandinavian and German geologists travelled through the area, without taking notice of anything but the prominent Mt. Baula and the lignite beds in the area west of Hredavatn.

Thoroddsen (1906) travelled around Borgarfjörður and examined the lignite beds, and he mentioned many other geological phenomena most of which are more related to the Quaternary geology of the area than to the Tertiary basement. Thoroddsen (1901) also published the first useful geological map of Iceland.

Bardarson (1923) studied in detail the postglacial deposits (mainly marine deposits) in the Borgarfjörður area and described them in his classical paper on sea-level changes in western Iceland.

The next contribution to the knowledge of the geology of the area was made by German and Dutch geologists in the 1950's. Schwarzbach (1956) described the area around the Grabrok lava field and Pflug (1959) studied the lignites of Hredavatn and Holtavörduheidi. Rutten and van Bemmelen (1955) studied the geology of the Baula complex.

Tr. Einarsson (1957, 1962) was the first scientist to study the Tertiary lava pile, for which was established the first palaeomagnetic map (1957), but without relating his results to the geomagnetic time scale which was established later.

Piper (1971) repeated this palaeomagnetic study and obtained a similar pattern, but he related the geomagnetic pattern to the

magnetic anomalies of the ocean floor.

Recently Saemundsson and Noll (1974) have mapped the area around the Husafell central volcano, towards the active volcanic zone.

Since 1971, K. Saemundsson together with groups of Icelandic undergraduate students have conducted geological mapping in the eastern and south-eastern parts of the Borgarfjörður area.

CHAPTER 2:

GEOLOGICAL SETTING OF THE RESEARCH AREA

Iceland is the biggest landmass astride the Mid-Atlantic Ridge, consisting entirely of volcanic rocks with a small portion of intercalated sediments, also of volcanic origin. The oldest rocks, which are exposed in the extreme east and northwest of the island, are from 12 to 16 m.y. old (Moorbath et al., 1968) and they dip towards the active volcanic zones. The Recent volcanism is limited to two volcanic zones (rifting zones; Fig. 2.1). The eastern volcanic zone terminates towards the south at the Vestmannaeyjar islands and to the north it is offset westward by the Tjörnes Fracture Zone (Saemundsson, 1974). The western volcanic zone (the Reykjanes-Langjökull zone) is the continuation of the Reykjanes ridge and fades out north of Langjökull, but was formerly continuous from Langjökull glacier to the Skagi peninsula, where it possibly joined the Kolbeinsey ridge. The northern part became extinct about 3-4 m.y. ago according to Saemundsson (1974), but rocks of considerably younger age (about 0.7 m.y.) have been reported from the Skagi peninsula (Everts et al., 1972). A small area of active volcanism stretches from WNW to ESE along the Snaefellsnes peninsula, but it cannot be classified as a rifting zone.

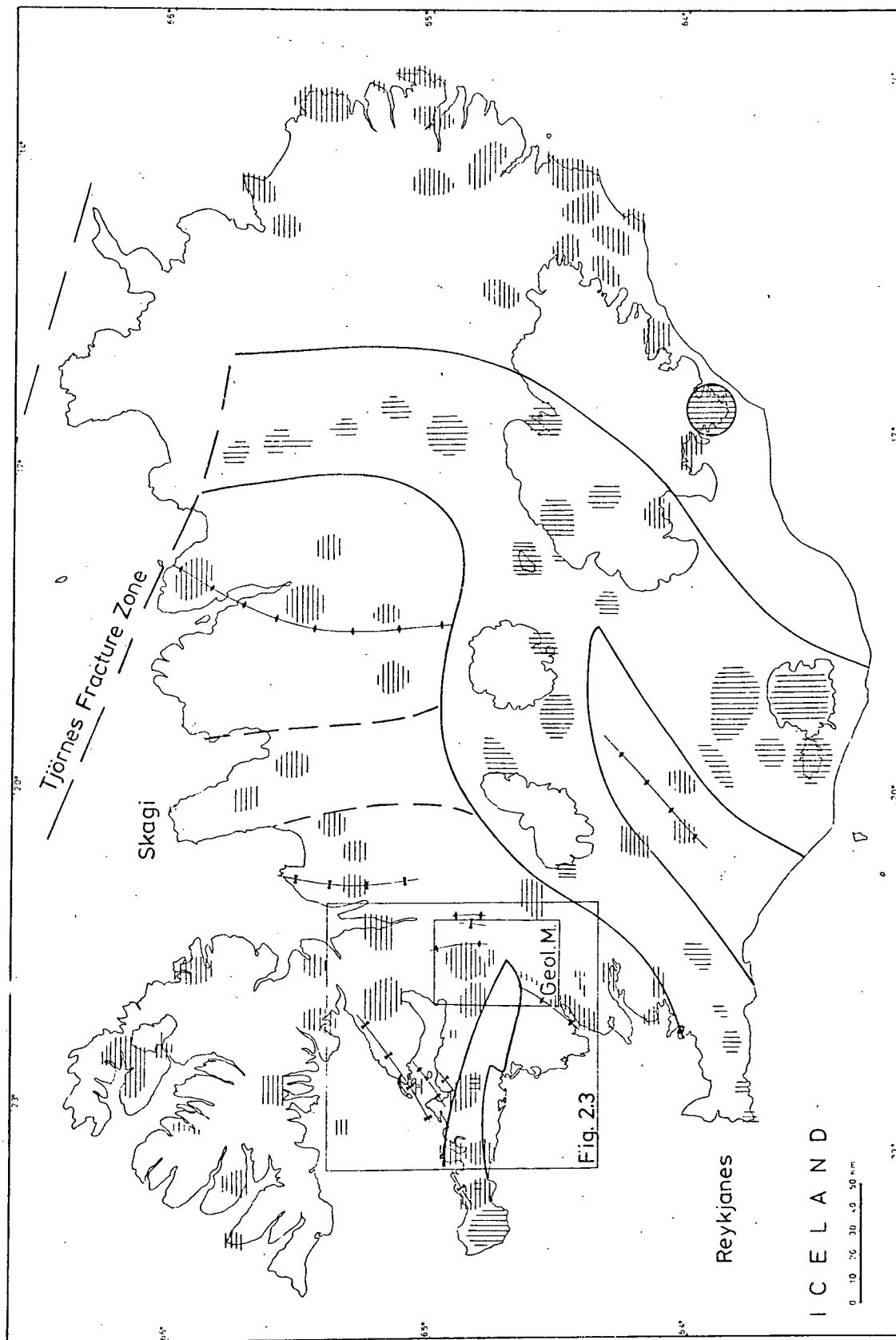
The volcanic zones consist of en echelon fault and fissure swarms with a central volcano sitting in the centre of each swarm (Saemundsson, 1974). The fault swarms are inclined at a small angle to the trend of the volcanic zone.

The volcanism is restricted to three principal types of volcanoes:-

1. fissures which produce the bulk of the basalts in Iceland;
2. lava shields which intercalate with the flows produced by the fissures; and

Fig. 2.1 Simplified geological map of Iceland showing the known central volcanoes and main tectonic features. Vertical stripes : active or dormant central volcanoes; horizontal stripes : extinct central volcanoes. The active volcanic zones are bordered by heavy lines and anticlines and synclines are shown by conventional symbols. Areas covered by Fig. 2.3 and the Geological Map are indicated.

Sources : Sigurdsson (1967), Hald et al., (1971), K. Saemundsson, pers. comm., Th Einarsson, pers. comm., and the author's own observations.



3. central volcanoes which produce all the intermediate and acid rocks.

At present about 57 extinct central volcanoes of Tertiary and Quaternary age are known, and 21 others which are either active or presumably dormant along with four on the Reykjanes peninsula which have no differentiates exposed at the surface but are represented by high temperature areas. In all, 83 volcanoes occur (Fig. 2.1)

The synclinal structure of the active volcanic zones may be due to loading and subsequent sagging of the lava flows, which were erupted inside it (Walker, 1960).

The geology of western Iceland is more complicated than this simple model described above. The main anomaly is the presence of the Borgarnes anticline (Fig. 2.2), which breaks the inward dipping trend of the Tertiary lava flows. This anticline stretches from the coast south of Borgarnes village, north-eastwards as far as Langavatn and Vikravatn where it disappears beneath the Hredavatn sedimentary horizon. The main part of the research area is on the eastern flank of the Borgarnes anticline. The flows on the western flank dip north-westwards, as far as the Setberg area (Sigurdsson, 1970a), where the dip changes across the axis of the so called Snaefellsnes syncline.

In the northern part of the research area the dips are towards the northeast. This dip changes again in the extreme north, near the southern coast of Hvammsfjörður, where the rocks dip towards the south and southeast. This change in the dip direction is caused by an unconformity running along the southern coast of Hvammsfjörður, with the rocks dipping south and underlying the rocks having north-easterly dips. The dip and strike relations suggest a large block of basalt pile of similar age, extending from Haukadalur in the east to Alftafjörður in the west.

There are numerous central volcanoes in western Iceland (Fig. 2.3). Three of them are included in this study; Hallarmuli, Reykjadalur and

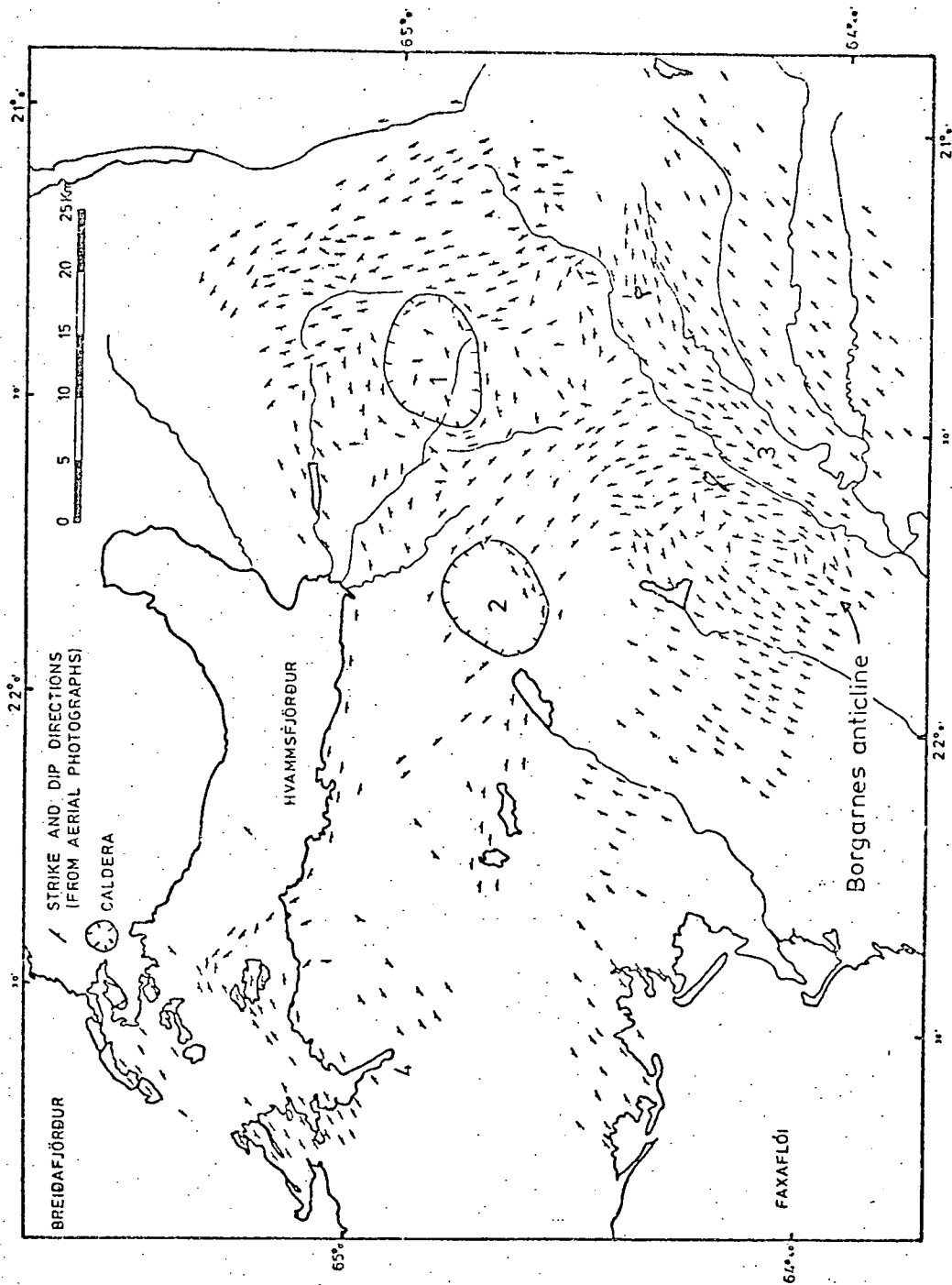


Fig. 2.2 Strike and dip directions (compiled from aerial photographs) in western Iceland.

- I : Reykjadalur central volcano;
- II : Laugardalur central volcano
- III : Hallarmuli central volcano

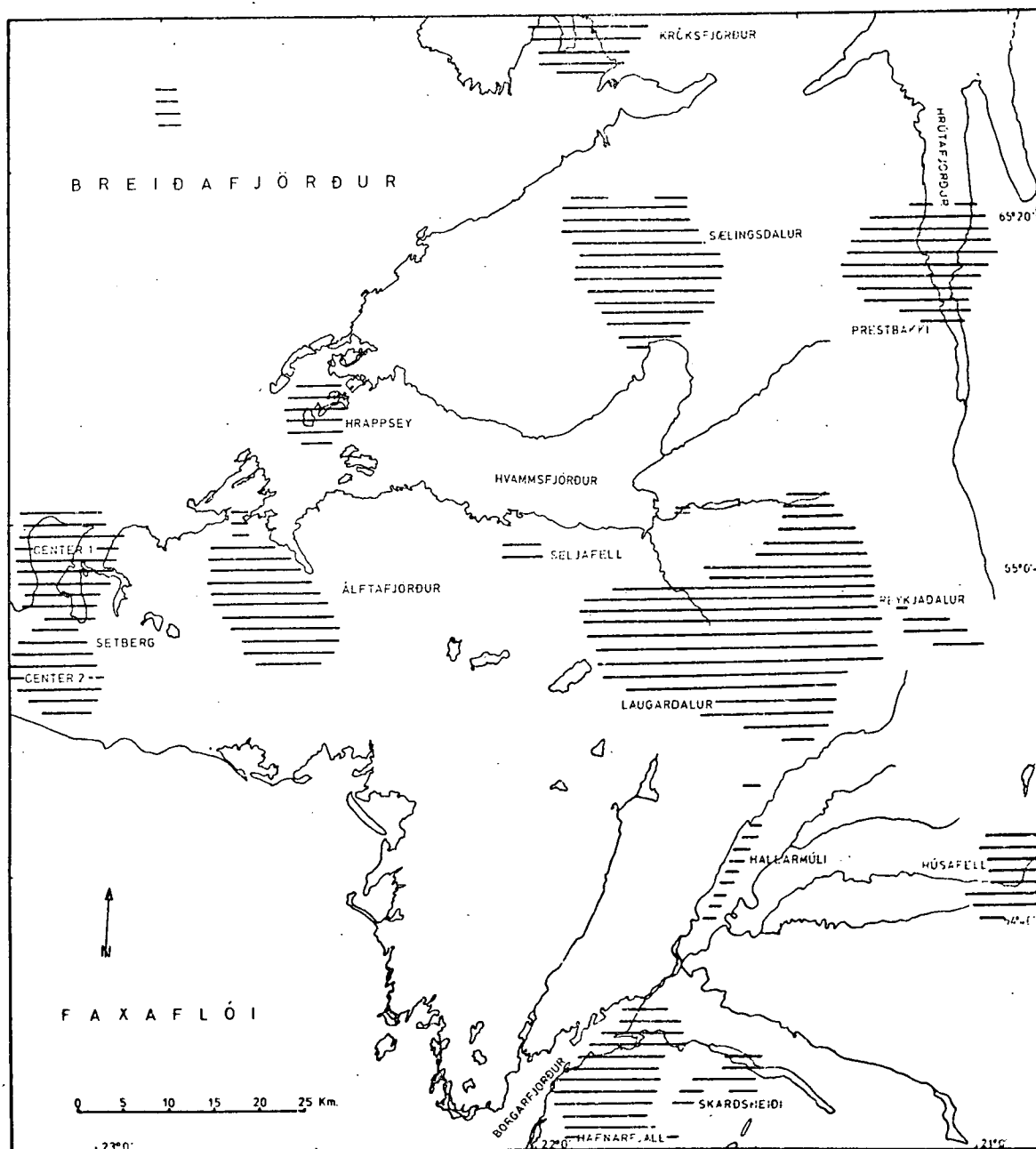


Fig. 2.3 Central volcanoes in western Iceland. The horizontal lines show the known distribution of intermediate and acid rocks.

Sources : Sigurdsson (1970a), Saemundsson and Noll (1974), Hald et al., (1971) and the author's observations.

and Laugardalur. The former two were mapped carefully and part of the third was mapped roughly to establish its connection with the rest of the area. Very little is known about the other central volcanoes in western Iceland, except for the two Setberg complexes (Sigurdsson, 1970a) and the Husafell volcano (Saemundsson and Noll, 1974); mapping of the Hafnarfjall volcano is in progress (H. Franzson, pers. comm.).

The central volcanoes have great stratigraphical significance, because they pin-point the location of an active volcanic zone at a given time.

The topography of the area is complex and can be divided roughly into three main groups:-

(1) the high mountain range north of Nordurardalur and Thverarhlid, which extends westwards along Snaefellsnes;

(2) the Holtavörduheidi-Borgafjadardalur peneplain in the eastern part of the area, about 300-400 m.a.s.l.;

(3) the Myrar-Stafholtstungur peneplain in the south-western part of the area, about 20-100 m.a.s.l. Group 1 coincides with the central volcanoes and its height must be attributed to a high effusion rate at the time of their formation. Group 2 roughly corresponds to the areas overlying the Holtavörduheidi sedimentary horizon, which marks a major change in the setting of volcanism in the area. Group 3 corresponds roughly to the rocks underlying the Holtavörduheidi sedimentary horizon, which in turn seems to coincide with a low effusion rate.

G. Palmason (pers. comm.) has recently made an accurate gravity map of Iceland and has kindly allowed the author access to the part concerning this research area (Fig. 2.4). The research area is on the western slopes of the central Iceland gravity bowl (Tr. Einarsson, 1954), and on the slopes are a few peaks which coincide with the central

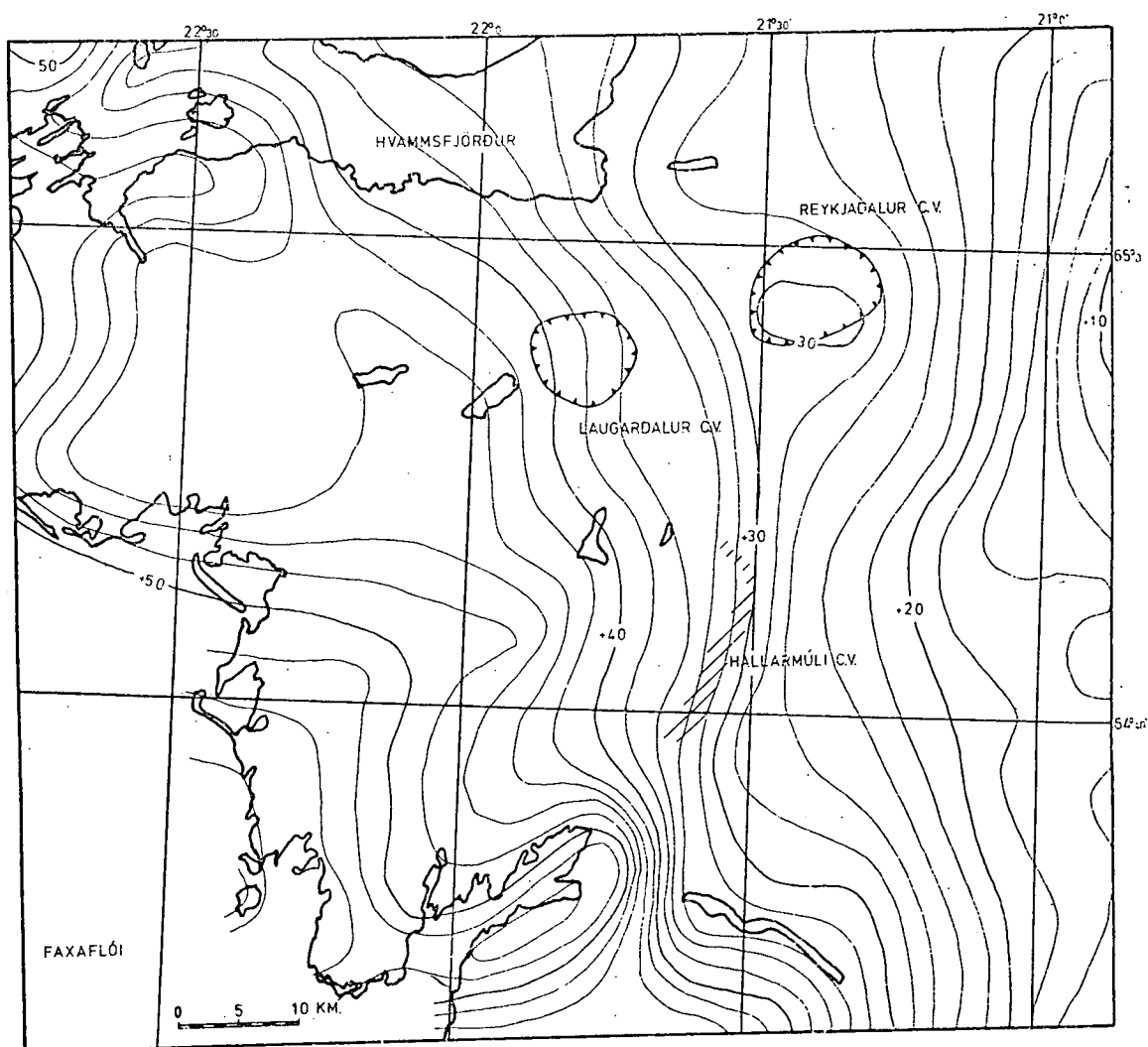


Fig. 2.4 An unpublished gravity map (preliminary) of western Iceland (kindly made available by Dr. Gudmundur Palmason). Two-milligal isopachs are shown along with the location of the three central volcanoes in the research area.

volcanoes (except Hallarmuli), suggesting high density material within the volcanoes, in contrast with the surrounding areas.

Th. Sigurgeirsson (pers. comm.) has conducted an aeromagnetic survey over the Borgarfjordur-Dalir area and has also kindly allowed the author access to the part concerning this research area (Fig. 2.5). Again, anomalous features are detected over the central volcanoes, either positive or negative (except for Hallarmuli).



Fig. 2.5 An unpublished aeromagnetic map of western Iceland (kindly made available by Dr. Thorbjörn Sigurgeirsson).
 (1) Reykjadalur
 (2) Laugardalur
 (3) Hallarmuli

CHAPTER 3:

THE PLATEAU BASALT PILE (VIKRAVATN-HVITARSIDA)

Introduction

The mapped section lies across the eastern flank of the Borgarnes-anticline (Saemundsson, 1967; Th. Einarsson, 1968) and the lava flows dip from 1° to 12° towards the southeast (Fig. 2.2). The area was mapped by the author in the summer of 1971 and the data presented as a B.S. dissertation of the University of Iceland (Johannesson, 1972). The following summer the whole profile was re-checked and extended towards the north; the Vikravatn-Grjothals area was revised completely, especially a graben west of Hredavatn. The geology is shown on the Geological Map (folded at the back of the thesis). The southeasternmost part of this map is partly based on a survey done by undergraduate students from the University of Iceland (Albertsson et al., 1971; Gudbergsson et al., 1971). The following description is a brief summary of Johannesson (1972) with some revisions and new interpretations.

In the region, all the lava flows are basaltic except those belonging to the Hallarmuli central volcano (described in Chapter 4). The basaltic pile is divided into 12 series using Walker's (1959) field classification. The classification is based on appearance, grainsize, phenocryst content and amygdales, but not on chemical composition of the lava flows. However, the typical field tholeiite turns out to be quartz normative tholeiite and the typical field olivine basalt turns out to be olivine normative tholeiite. Thus the field term "tholeiite" corresponds roughly to the petrochemical term "quartz tholeiite" and the field term "olivine basalt" to the petrochemical term "olivine tholeiite". Also common in the field are lavas which show characteristics of both the tholeiite type and the olivine basalt type.

It is probably meaningless to draw conclusions about the chemistry of such lavas from the field characteristics alone.

In addition to Walker's (1959) classification, the writer has adopted the term "compound lava flow" (Walker, 1971) for very coarse-grained, olivine-rich lava flows which show flow unit structure and have no intercalated clastic beds. These flows are thought to have their origin in shield volcanoes which more appropriately should be called lava shields (Walker, 1971).

During the initial field work (1972) the magnetic polarity of every flow was determined in the field using a portable fluxgate magnetometer. In the summer of 1973 all the lava flows of the entire section were drilled by N. D. Watkins and L. Kristjansson and the magnetic properties and polarity measured in the laboratory at the University of Rhode Island. The two sets of results are nearly identical except for the bottom series. A correlation of the section with the palaeomagnetic time scale is shown in Fig. 3.11. I. McDougall has made K-Ar datings on a number of samples from the section (Table 3.1). The palaeomagnetism and K-Ar data is to be published in the near future (McDougall et al., 1975).

The lava pile will be described from bottom to top. The profiles and their locations are shown on Figs. 3.1 and 3.2. The magnetic polarity, as determined in the laboratory, is also shown and the K-Ar datings are listed in Table 13.1.

Normal faulting made correlations between the various profiles often very difficult but most of the correlations were double checked. The regional description ends with a group of plagioclase-phyric flows which date from the Mammoth event of the Gauss epoch and which are of the same age as the oldest glacial horizon discovered in Iceland so far (McDougall and Wensink, 1966). The lava pile which follows

Fig. 3.1

A map showing the locations of the profiles of the representative section (Fig. 3.2) through the Tertiary lava pile in the Borgarfjörður area.

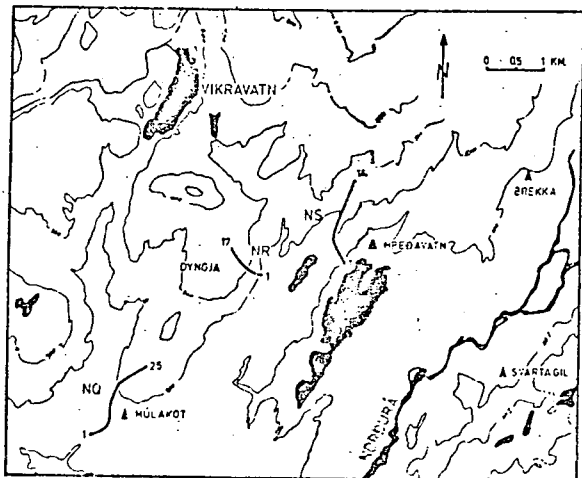
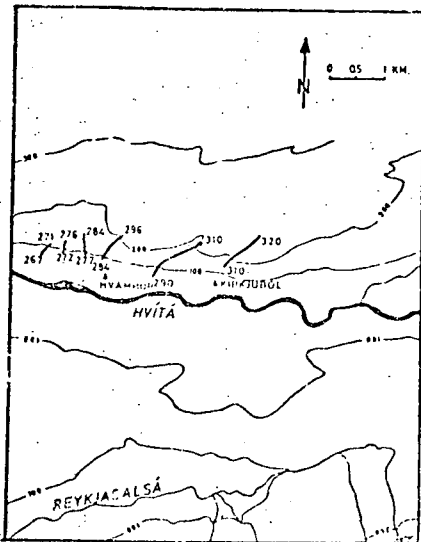
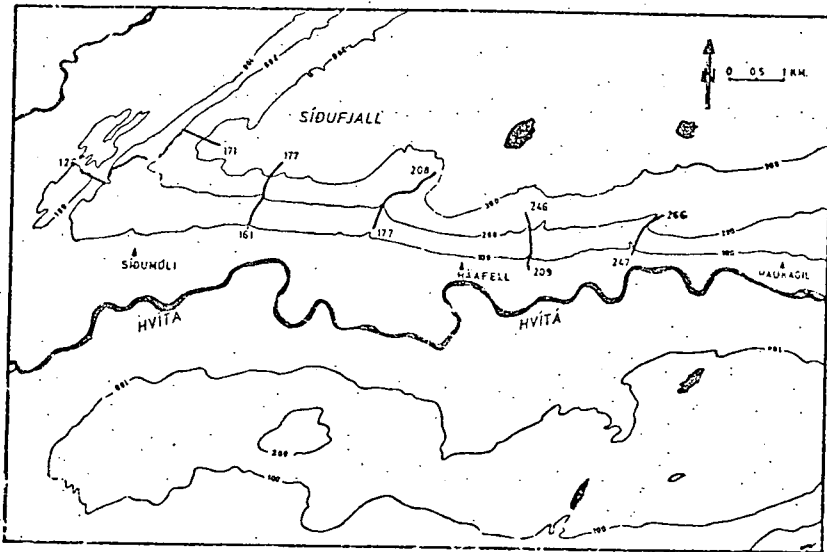
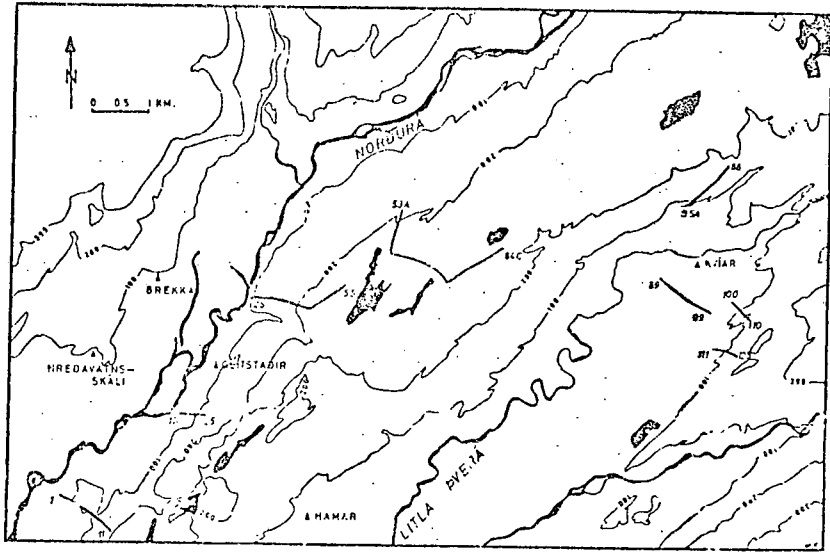
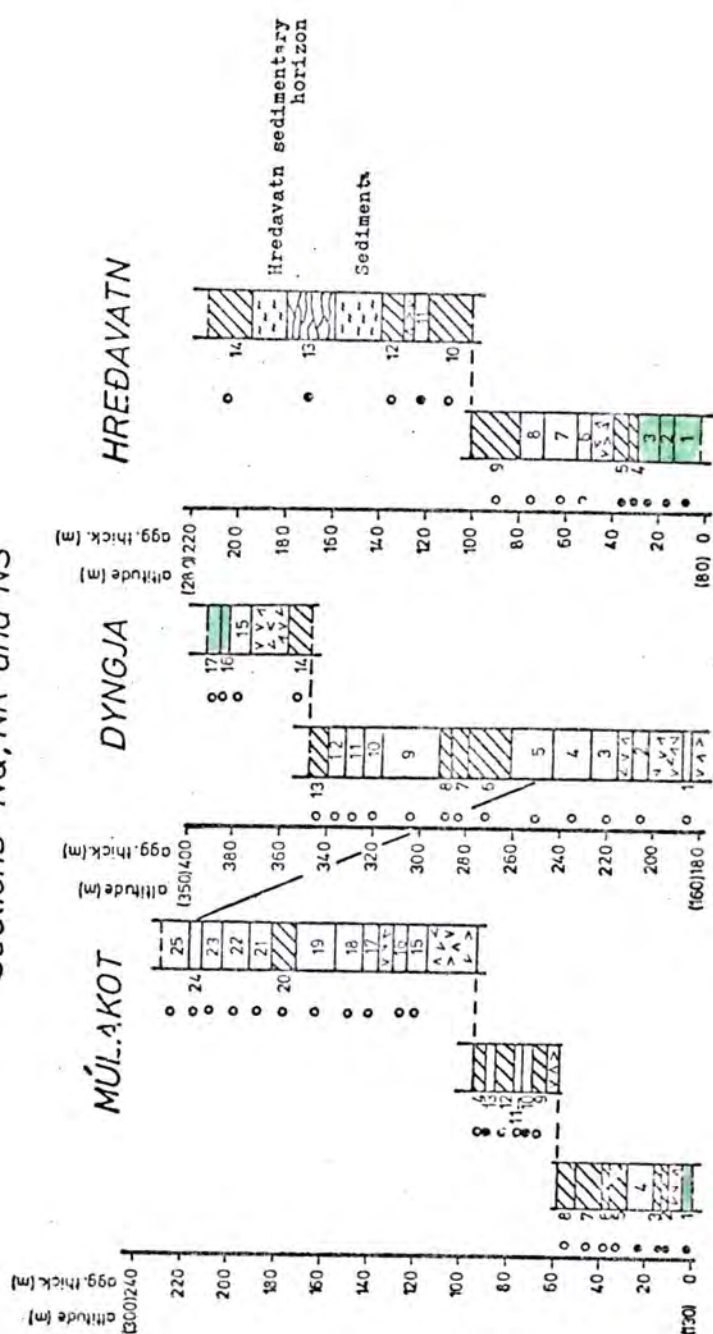


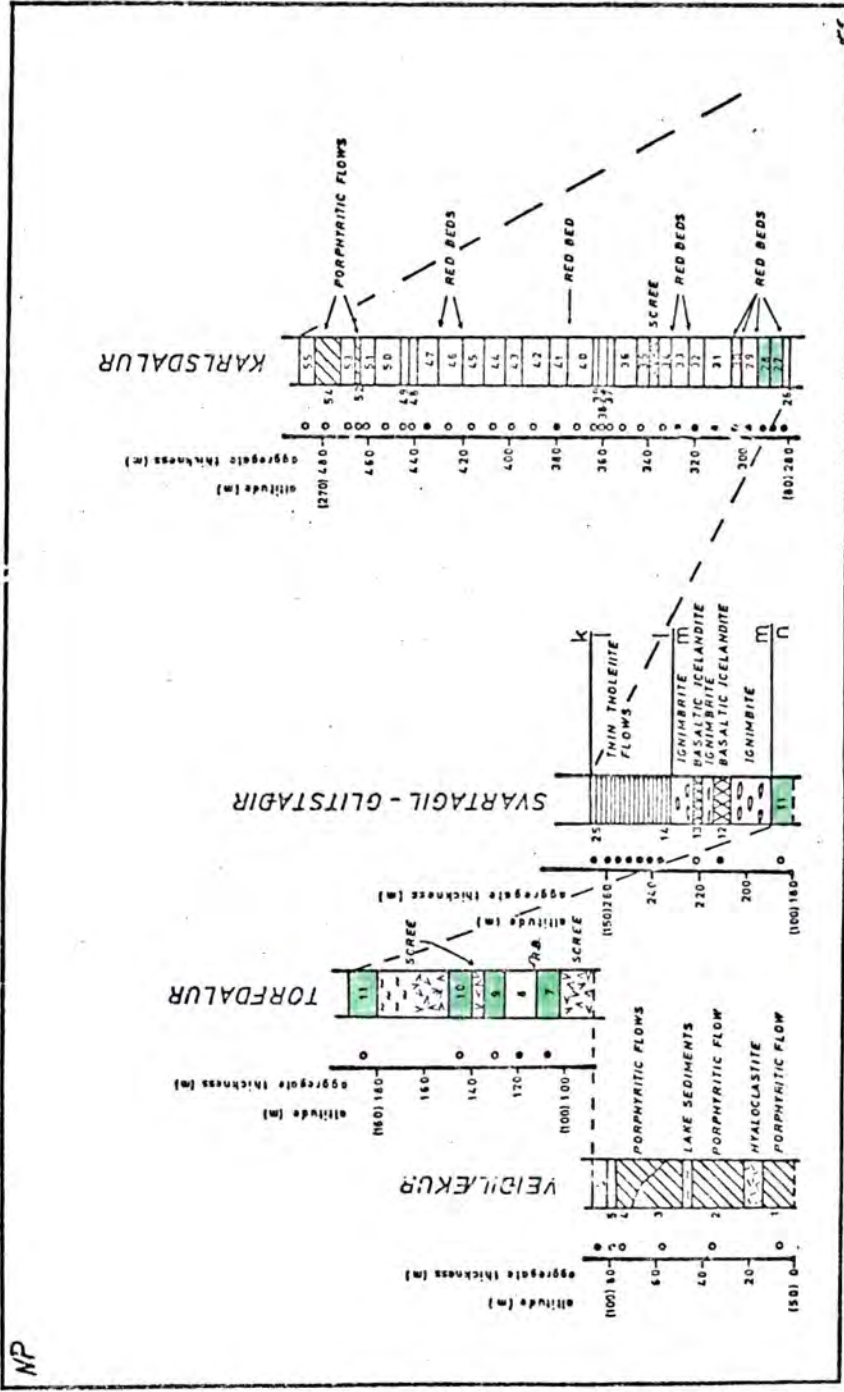
Fig. 3.2 A representative section through the lava pile in the Borgarfjörður area, from Nordurardalur to Hvitarsída.

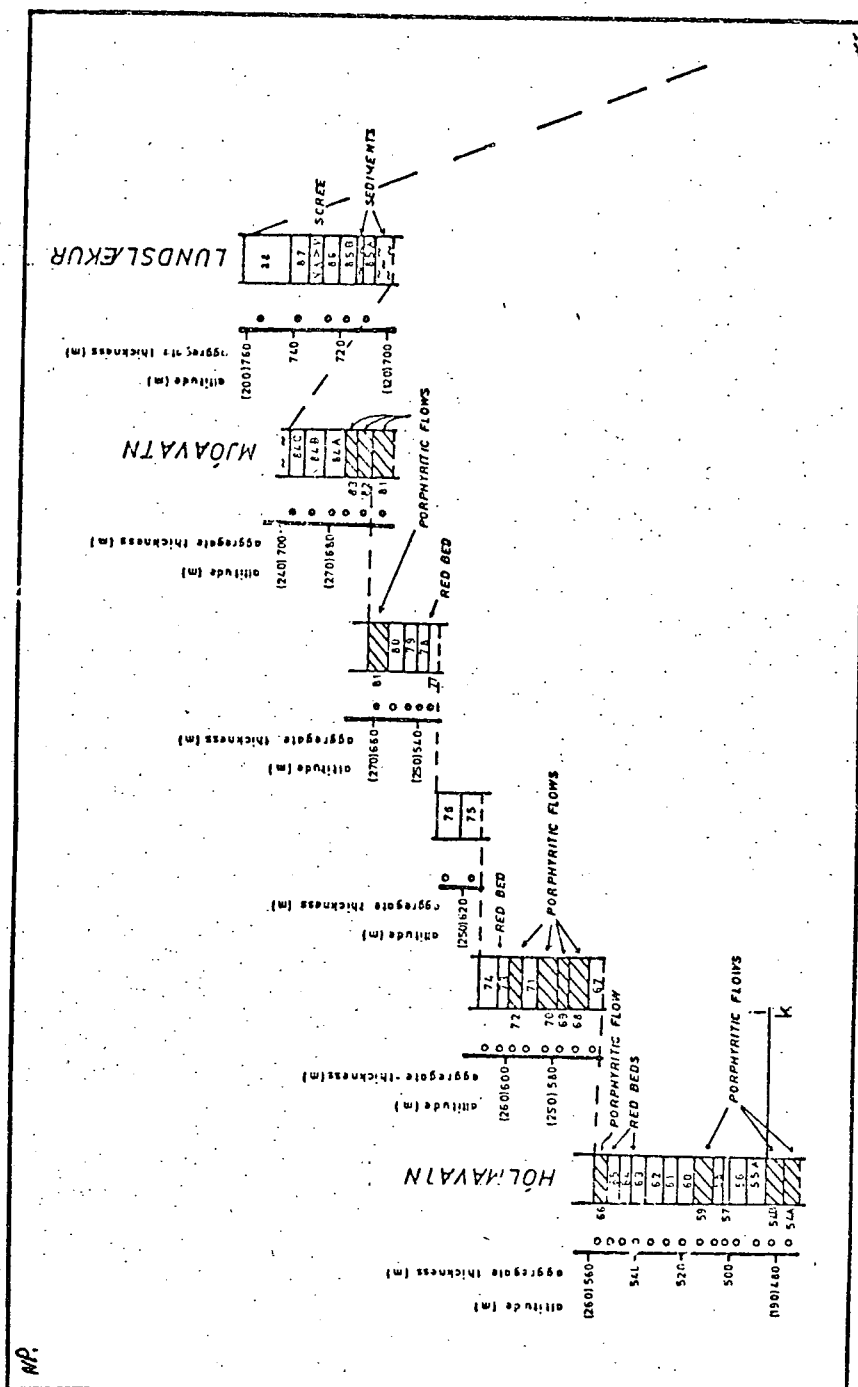
-  Tholeiite flow
-  Olivine basalt flow
-  Porphyritic flow
-  Compound lava flow (lava shield)
-  Thin tholeiite flow
-  Intermediate flow
-  Ignimbrites
-  Sedimentary bed
-  Scree (i.e. no outcrops)
-  Glacial horizon (incl. tillite)

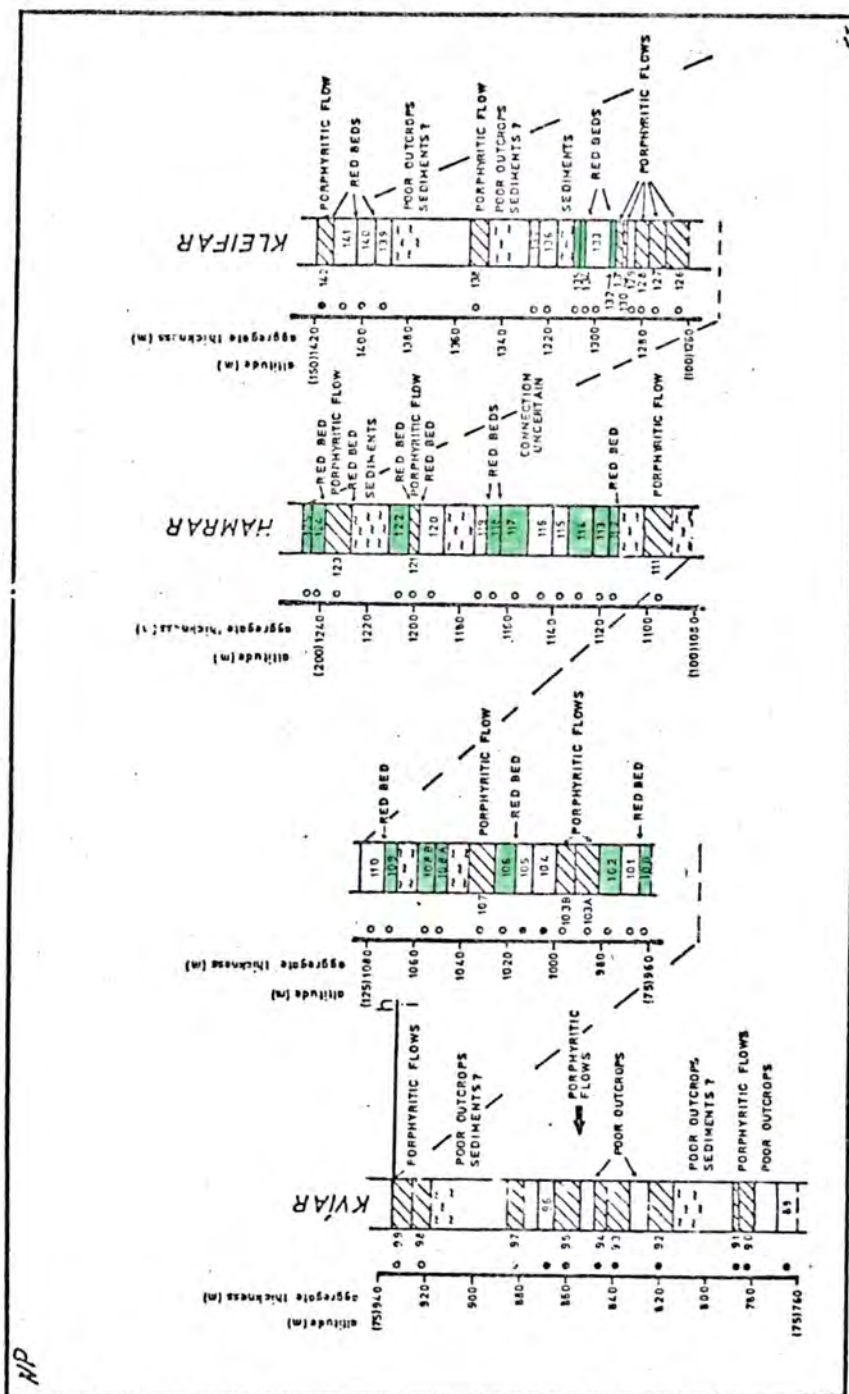
Open circle : reverse magnetized flow.
Solid circle: normally magnetized flow.

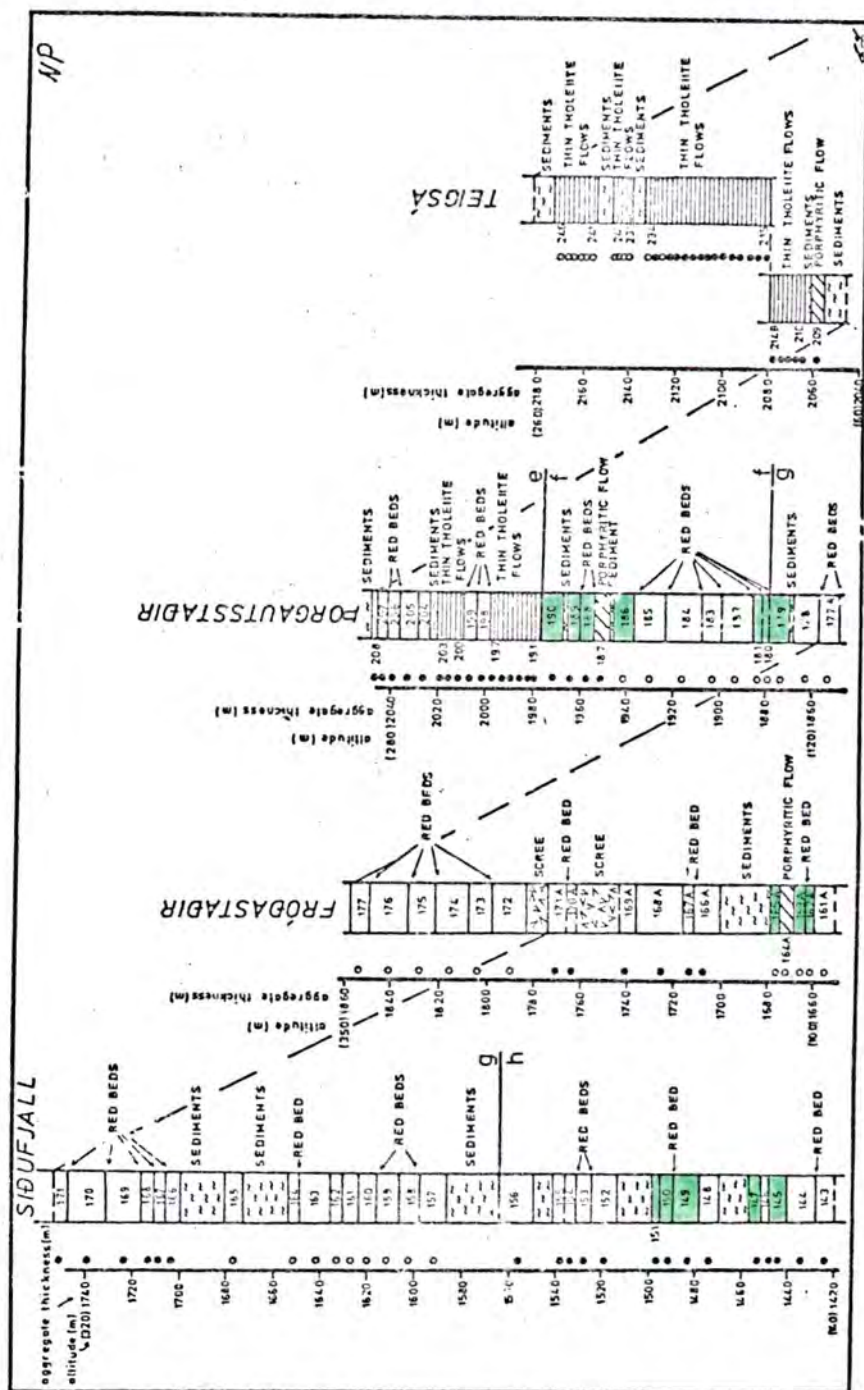
Sections NQ, NR and NS

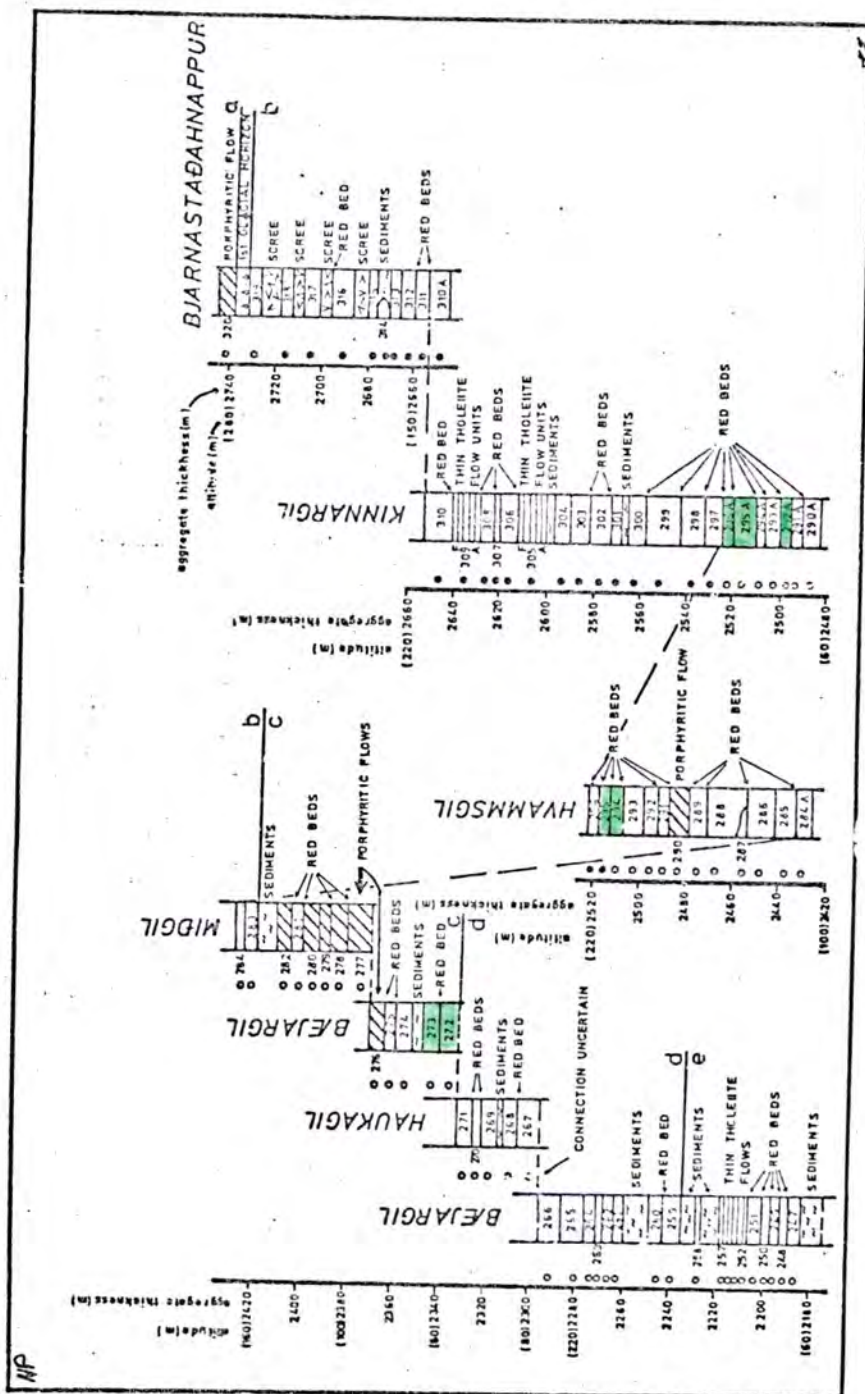












stratigraphically on top of the described section has been mapped by Saemundsson and Noll (1974).

Stratigraphy

- (1) Hredavatn series (flows up to no. 11 in section NP in Fig. 3.2).

All rocks which lie stratigraphically below the Hallarmuli central volcano are grouped under this heading even though they include many different rock types. The mapping of the area turned out to be extremely difficult because of extensive normal faulting and rather poor exposures. There still exist more uncertainties about the geological structure of the Hredavatn series, than anywhere else in the area discussed in this thesis. The normal faults form a mosaic pattern of predominantly NW-SE and NE-SW faults (Fig. 10.1). West of Hredavatn, a pronounced graben structure is present which is bounded on its south by a very large fault (the Dyngja-fault, Fig. 10.5), the throw of which has not yet been established. A correlation could not be made across this fault in spite of several attempts. The tectonics of this area will be dealt with in more detail in Chapter 11. Underlying the Hredavatn series is a thick lava pile of at least 600 m which has not been mapped in detail (Fig. 3.2) and which will not therefore be described. The thickness of the Hredavatn series is about 250 m. The very characteristic of the series is the influence of water during the formation of most of its units.

The Hredavatn series starts with a 20-30 m thick, compound lava flow (Fig. 3.3). It consists of numerous flow units which have black-weathering surface. The rock is coarsegrained and extremely rich in olivine. This unit is only found inside the graben west of Hredavatn. The best exposures are on Litli Thrimill and Hestabrekkur.

Overlying the compound lava flow is a 10-15 m thick, very



Fig. 3.3 Litli Thrimill, a compound lava flow (a) showing a flow unit structure. The overlying Hredavatn sedimentary bed (c) is exposed right of the normal fault (b) followed by two-tiered porphyritic (d) and tholeiite (e) flows.



Fig. 3.4 Hestabrekkur north of Hredavatn. The Hredavatn sedimentary bed (a) followed by the lower part of a two-tiered porphyritic lava flow (b). The compound lava (c) flow is exposed left of the stream, left of a normal fault (d) with a downthrow to the right.

persistent, plant-bearing sedimentary horizon, which has been referred to in the literature as the Hredavatn beds. It has been described by many geologists in the past (latest summary by Schwarzbach, 1956). These sediments can be traced, at least, from Vikravatn-Fossadalur eastward through the graben, across the Nordurardalur valley, and as far south as Stafholtskastali. In Hestabrekkur, northwest of the Hredavatn farm (Fig. 3.4), the lower part of the layer consists of a 3 m thick, dark brown siltstone with thin bands of lignites. The upper part consists of scoria and of plagioclase-phyric hyaloclastite which is an aqueous facies of the overlying basalts. A diatomite with some plant fossils occurs in the same sedimentary horizon in Brekkua and Veidilaekur. Lignite is quite common and is thickest in Surtarbrandsgil (about 50 cm thick). At Stafholtskastali, the beds consist of plant-bearing siltstone and sandstone, at least 10 m thick, overlain by ignimbrite from the Hallarmuli central volcano. In many places the porphyritic flows, which lie on top of the sediments, have flowed into water and formed pillows and hyaloclastites. The sediments are water-transported gravel, mud, and laminated silt sediments deposited in a lake. The field relationships indicate that sediments accumulated in a depression, probably a tectonic graben, partly filled by the lake.

Overlying the sedimentary horizon is a unit of plagioclase-phyric flows showing very regular columnar jointing. The thickness varies from 100 m in Hallarmuli (Fig. 3.5) to 15 m in the area west of Nordurardalur valley (Fig. 3.4). Its thickness south of Hallarmuli is uncertain because of poor outcrops in a boggy lowland, but it is considerable. In Hallarmuli are four flows but only one west of Nordurardalur valley. In the area around Veidilaekur, two of the porphyritic flows are below the Hredavatn beds. The flows are very plagioclase-phyric and the phenocrysts can reach 1-2 cm in size.



Fig. 3.5 Hallarmuli seen from Grabrok. The porphyritic unit of the Hredavatn series is overlain by one two-tiered tholeiite flow (b) followed by the olivine basalt unit (c) which forms the top of the series. The main succession of intermediate flows (d) and acidic ignimbrites (e) follows on top of the Hredavatn series and a sill (f) is intruded in the ignimbrite. The Grabrok lava field is in the foreground.

Interbedded with the porphyritic flows are plagioclase-phyric hyaloclastites which have been formed at the same time as the flows. The hyaloclastites are most often 3-4 m thick but south of Hallarmuli their thickness reaches at least 10-20 m.

The porphyritic flows do not overlie the sediments everywhere but instead, a two-tiered tholeiite flow covers them - probably the same flow which covers the porphyritic flows. This tholeiite flow is 20-50 m thick and is easily traced from Svartagil across the Nordurardalur valley as far west as lake Vikravatn. The problem of two-tiered columnar jointing has been discussed by Saemundsson (1970). He believes that the lava flows ponded in valleys and depressions where they developed columnar jointing. The peculiar division of flows into lower colonnades and upper chilled entablatures is explained by water flooding the lavas while their interiors were still molten.

The topmost unit of the Hredavatn series consists of olivine basalt flows and is about 100 m thick in the Hallarmuli area (Fig. 3.5), but only 30 m west of Hraunsnefsöxl. South of Hallarmuli, the thickness of this unit decreases rapidly (see Chapter 4). The number of flows is greatest in the Hallarmuli area. South of Hallarmuli, this unit is represented by a compound lava flow (Fig. 4.2). This unit of olivine basalt flows, thus forms a topographic high in the Hallarmuli area, where at that time the Hallarmuli central volcano was starting its activity.

(2) Hallarmuli central volcano (flows no. 12 to 13; described in Chapter 4).

(3) Kolvidarholt series (flows no. 14-25)

This series is up to 45 m thick, and consists of thin tholeiite flows. It is found in Hallarmuli, Kolvidarholt and at the base of Hraunsnefsöxl. It is thickest on Kolvidarholt, northeast of Svartagil,

but gets thinner in both directions from there. The thick-layered Grjothals series rests unconformably on top of the Kolvidarholt series in the area northeast of Svartagil but conformably at Hyaunsnefsöxl. The number of flows varies from 5 to 15 and they are vesicular and with hardly any intercalated clastic beds. The flows have black-weathering surface but are fine-grained and no zeolites are present; they thus show tholeiitic affinities. This series is perhaps the flank succession of the Hallarmuli central volcano.

(4) Grjothals thick-layered series (flows no. 27-57b).

This series is part of the Reykjadalur thick-layered series (see Chapter 5) which can be traced, at least, from Hallarmuli in the south to Budardalur in the north and from Sanddalur in the east to Langavatnsdalur in the west. The part described in this chapter is on Grjothals and Hraunsnefsöxl (Fig. 3.6). It is about 180 metres thick and numbers about 30 flows. The thickness of the series decreases towards the west and northwest. West of Sata the series is within 140 m thick and becomes even thinner further west.

Most of the flows are typical, thick tholeiite flows but two units of porphyritic flows are present. The lower unit is found over a wide area, from Grjothals to Saturdalur north of Vikravatn. It is also probably found north of the Reykjadalur central volcano (see Chapter 5). In Hraunsnefsöxl (Fig. 3.6) the unit is 20-30 metres thick and consists of 4-5 flows. They are plagioclase and/or pyroxene phyric and gabbro xenoliths are abundant in places. The further north, the more compound becomes the nature of the unit. In Bjarnadalur and Vesturardalur the unit consists of olivine rich compound lava. The upper part is rather poor in olivine phenocrysts but the lower half has up to 50% of olivine phenocrysts.

The upper porphyritic unit is 10-20 m thick (1-2 plagioclase phyric flows) and forms the top of the series west of Holmavatn, and



Fig. 3.6 Hraunsnefsöxl in Nordurardalur, exposing the thick tholeiite flows of the Grjóthals (Reykjadalur) thick-layered series, with two thin units of porphyritic flows (a) and at the top is an intermediate flow (b) from the Reykjadalur central volcano. The lower slopes are formed of Recent landslip (c).



Fig. 3.7 Sidufjall seen from Thverarhlid. The Sidufjall series (a) separated from the Sleggjlaekur series (b) by a 20 m thick sedimentary bed (c).

north along Grjóthals. It is also present at the top of Hraunsnefsöxl.

Sediments are rather rare in this series, apart from the thin red beds which are common. One sedimentary horizon accompanies the lower porphyritic unit. It is formed of bedded sandstone and conglomerate with rounded pebbles and boulders. Another sediment is found on Skalafell, southeast of Glitstadir, but its place in the stratigraphy is not certain because of faulting. It consists of bedded sandstone, siltstone and clay.

(5) Grjóthals thin-layered series (flows no. 57-99).

This series is part of the Reykjadalur thin-layered series which extends at least from Karlsdalur in the south to Haukadalur in the north and from Holtavörduheidi in the east to Langavatnsdalur in the west. The main part of the series will be described in Chapter 5. The part described in this chapter is on Grjóthals and Thverarhlid. The series is about 470 m thick, but the thickness increases considerably towards the north. The number of flows is about 50, and most of them are thin and vesicular, although this feature changes along the strike. In the southern part, the lavas tend to be thicker and with fewer vesicles but further north one goes, the thinner and more vesicular the flows.

The bottom half of the series is a mixture of rather thin tholeiitic and plagioclase-phyric flows. The number of flows is uncertain because of faulting, but is about 35. Followed northwards, this part inter-fingers with thin, vesicular, olivine basalt flows, especially west of Raudabergsvatn. Sediments are very rare in this part, except for a few thin red beds, which indicates a rather high effusion rate.

Between Lundur and Fiskivatn is a unit of thick tholeiite flows. It is 20-60 m thick and consists of 2-7 flows. The thickness of the unit decreases rapidly towards the south, and is not found on the

western side of Nordurardalur. Underlying this unit are two sediment layers, each 5-10 m thick and consist of bedded tuff and sandstone.

The topmost lava unit consists of extremely plagioclase-phyric flows (up to 50-60% phenocrysts). The thickness of the unit varies from 25 to 150 metres. It is thickest south of the Kviar farm, where it appears to be about 150 m, but it is very poorly exposed. Only 9-10 flows are exposed (total about 80 m) and it must be assumed that the rest of the unit consists of sediments rather than lava flows. Only about 10-15 metres of bedded sandstone are exposed on a river bank northeast of the Kviar farm. When the unit is followed along strike to the north and northeast, just across the river Litla Thvera, the thickness decreases to 30 m and 3-5 flows. On the mountain peak, just northeast of Litla baula, is a 60-70 m thick porphyritic unit which is most likely the same unit. It seems likely that the thickness distribution is caused by the topographical difference between the crater(s) and the lowlands south and southeast of the Reykjadalur central volcanic region. The flows were erupted somewhere north of Mt. Baula, probably near the caldera rim and flowed south and south-eastwards and down the slopes of the central volcanic region (where the unit is thinnest). When they reached the lowlands they tended to become thicker because of ponding. The sediment distribution can be explained similarly because on the assumed slopes of the central volcanic region, few sediments have been found, but in the lowlands the sediments are both thick and abundant.

(6) Sleggjulaekur series (flows no. 100-156).

This series is about 520 m thick and has been traced from the inner part of Thverarhlid to Sidufjall (Fig. 3.7 ; Johannesson, 1972) and Kroppsmuli (Gudbergsson et. al., 1971). It is also in the lowlands west of Reykholtisdalur and Hvitarsida (incl. Veggjahals).

The number of flows is about 60 and they are of all types. The bottom part of the series consists mainly of olivine basalt flows and few tholeiite and porphyritic flows. In the middle of the series is a unit of plagioclase-phyric flows, about 5-7, which can be traced from Thverarhlid and Kleifar south along the Veggjahals. The upper half of the series consists mainly of tholeiitic flows intercalated with few olivine basalt and porphyritic flows.

Because of faulting this series is not as well established as the others. The number of normal faults is enormous and they make correlation in some cases extremely difficult. Some of the irregularities of the series must be explained by the lavas flowing in a landscape marked by tectonic faulting and erosion. Most of these faults are NW-SE to E-W and were already active in Tertiary times. The problems of the faults will be discussed in Chapter 10. In this tectonic environment, sediments were laid down. Sediments are more common in this series than in any other series in the Borgarfjörður area. Thin red beds are common but thicker sediments form up to 20% of the series and in some places even as much as 30%. Because of the sediments the outcrops in this series are poorer than expected. Most of these sediments have been described in detail by Johannesson (1972). Most consist of sandstone and conglomerate but in a few cases of finer material. The topmost of the sediments is found in Kleifar and in the gorge of the Kjarra river and stretches further north, through Svarthamar and into Thverarhlid and Holtavörduheidi, (Chapter 6). It varies both in thickness and type. In the area from Kleifar to Svarthamar (Figs. 3.8-3.10) it consists of sandstone and coarse conglomerate with rounded boulders which range in size from a few cm to 1-2 m. North of Svarthamar the layer becomes finer, of sandstone and siltstone. All the other sediments in the



Fig. 3.8 Svarthamar in Thverarhlid: a 25 m thick outcrop of Tertiary conglomerate (see Fig. 3.9).



Fig. 3.9 A poorly sorted conglomerate in Svarthamar in Thverarhlid (see Fig. 3.8).

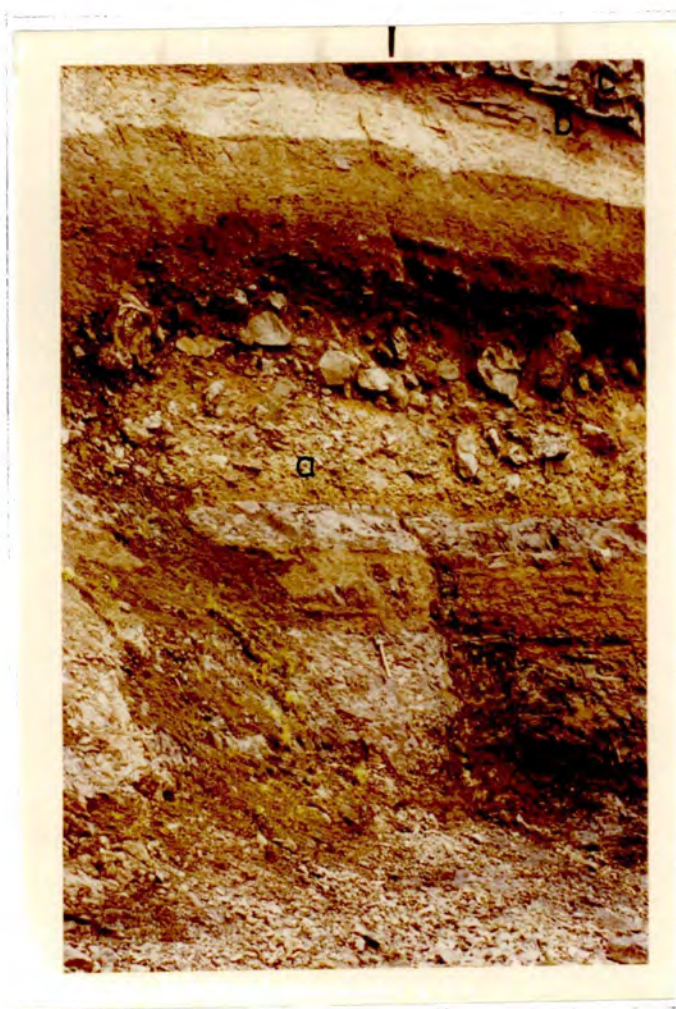


Fig. 3.10 The same sedimentary bed as in Svarthamar. It consists mainly of sandstone and siltstone, but in the centre of the bed is a lenticular body of conglomerate (a) and the top of the bed (b) has been baked by the overlying flow (c).

series are more restricted in their distribution and most of them cannot be traced over long distances and often end up against fault escarpment. The thickness of the series as a whole decreases towards the north but accurate measurements for the northern part are not available. On the other hand, the thickness of the sediments increases towards the north.

(7) Sidufjall series (flows no. 157-179).

A 20 m thick sedimentary layer overlies the Sleggjulae kur. It can be traced from Sidufjall (Fig. 3.7), through Kjarrardalur and to the Thverarhlid area. In Sidufjall the main part consists of bedded sandstone and siltstone with rhyolitic ash and lignites near the top. In Thverarhlid both basic hyaloclastites and acid ignimbrites are present. This sediment was first described by Einarsson (1957). Pflug (1959) conducted pollen analysis study of it.

The Sidufjall series is about 310-320 m thick and is found on Sidufjall and Hurdarbaksfell, and further south in Kroppsmuli and Flokadalur (Gudbergsson et. al., 1971). The series consists of about 30 flows nearly all of which are typical tholeiite flows and usually thick. In Kroppsmuli the series is about 340 m thick. Red beds are common and two thick sediments were found. Near the top of the series is a 5 m thick layer of tuff and clay sediments. The other is in the lower part of the series. It is about 40-45 m thick with one lava flow in the middle of it, and consists mainly of brown siltstone and sandstone, and fine to coarse conglomerate with angular and rounded boulders. This layer has been traced from Sidufjall through Kjarrardalur and Thverarhlid and into the Holtavörduheidi area (Chapter 6).

(8) Thorgautsstadir series (flows no. 180-190).

This series is about 100 m thick in Hvitarsida. It is also found on Skaneyjarbunga and Kroppsmuli (Gudbergsson et. al., 1971)

where it is about 140 m thick. In Hvitarsida the series is found in Thorgautsstadagil and consists of 13 flows, most of which are olivine basalt flows with few tholeiite and plagioclase-phyric flows. Red beds are common. One layer of 1-2 m thick sandstone and fine conglomerate is present in Thorgautsstadagil but the same layer is about 14 m thick on Skaneyjarbunga.

(9) Haafell series (flows no. 191-258).

This series is about 210 m thick in Hvitarsida and has been traced over an area from Kjarrardalur to Flokadalur. The thickness south of Reykholtisdalur is uncertain because of poor outcrops and faulting. It consists of thin, very vesicular tholeiite flows which are very characteristic and easy to recognise. They are usually very thin, 2-3 m on average compared with 5-15 m for ordinary tholeiite flows. Usually 1/3-1/2 of the thickness is scoria. 2-3 olivine basalt flows and plag/px-phyric flows are present in the middle part of the series. The number of flows is about 70 but it is nearly impossible to give an accurate number for the series because many lava flows pinch out and new ones come in. Red beds are rare in the series which points to a high effusion rate. There are four sedimentary horizons and the thicknesses range from 5 to 10 m. They consist of clay-rich material to sandstone with small rounded pebbles. In the highest bed (in Husagil inside Samstadir) are a few plant fossils.

The series may have its origin in the area around the Skardsheidi central volcano (Saemundsson, per. com.) and possible having the same relationships with the volcano as the Reykjadalur thin-layered series with the Reykjadalur central volcano (see Chapter 5). The thinness of the flows may thus be attributed to topographical circumstances, i.e. flowing down the flanks of the central volcanic region.

(10) Haukagil series (flows no. 259-271).

The thickness of this series is uncertain in Hvitarsida because of a gap in the middle part caused by poor exposures. If the thickness is calculated from the strike and dip a figure of 140 m is obtained, where of 1/3 is not exposed. It has been mapped in Raudsgil (Albertsson et. al., 1971) where the thickness is about 180 m and the author has mapped the same series on Steindorstadaöxl and found a similar thickness. This series consists of typical tholeiite flows both in Hvidarsida, Raudsgil and Steindorstadaöxl. The number of flows in Raudsgil and Steindorstadaöxl is about 30 but in Hvitarsida only 14 flows are exposed. Thin red beds intercalate most of the flows. In Husagil (inside Samstadir) are two thick sediment layers. The lower one, which is at the bottom of the series, is 15-20 m thick and consists predominantly of brown sandstone and fine, bedded conglomerate. The upper one is about 10 m thick and consists of grey to yellow tuff and clay sediments as well as coarse rhyolitic ash (ignimbrite ?) with pieces of black basaltic pumice. This ash is probably from one of the central volcanoes in the Skardsheidi region. In Haukagil is a 2 m thick conglomerate with angular to rounded boulders and a yellowish tuff and clay matrix.

(11) Midgil series (flows no. 272-283).

It is about 70 m thick and made of 10-11 flows. Six of the flows are plagioclase phyric and the rest are tholeiitic or olivine basaltic. This series is also found on Signyjarstadahals, and Raudsgil and Steindorstadaöxl (Albertsson et. al., 1971), where it is nearly 80 m thick. Some of the flows are extremely plagioclase phyric (up to 50%) with a few pyroxene phenocrysts as well. Thin red beds intercalate the flows but near the bottom of the series is one fine conglomerate, 2-3 m thick.

(12) Kinnargil series (flows 283-319).

A 10-15 m thick sedimentary horizon overlies the Midgil series. The main part consists of brown siltstone and sandstone but the uppermost part consists of fine conglomerate with rounded pebbles.

The Kinnargil series is about 300 m thick in Hvitarsida. It is also found in Raudsgil and Steindorstadaöxl where it is somewhat thicker (Albertsson et al., 1971; Saemundsson and Noll, 1974). This series consists mainly of tholeiite flows with a few olivine basalt and plagioclase phyric flows, in all nearly 40 flows. Thin red bed intercalate nearly all the flows, but in the upper half of the series are 3-4 thicker sediments (each 1 to 4 m thick), mainly of bedded conglomerate.

On top of the Kinnargil series follows a glacial horizon and group of plagioclase phyric lava flows, which together provide a useful marker horizon. A magnetic reversal from normal to reverse also occurs at this stratigraphic boundary. The interpretation is that the reversed flows represent the Mammoth event of the Gauss epoch and that the glacial horizon marks the onset of the Quaternary glaciations which follow at regular intervals higher up in the succession (Saemundsson and Noll, 1974).

Age Relations

The palaeomagnetic scale for the Borgarfjörður area (Fig. 3.11) and the K-Ar datings (Table 13.1) give an absolute age for the various stratigraphic series. McDougall et al. (1975) have dealt in detail with the correlation between this scale and the ocean-floor scale. The upper part of the section fits remarkably well with the revised time scale for the ocean floor (Cox, 1969; Talwani et al., 1971) although the bottom 1000 m of the section cannot be correlated as easily, because of unconformities and a possible hiatus. The Gauss and

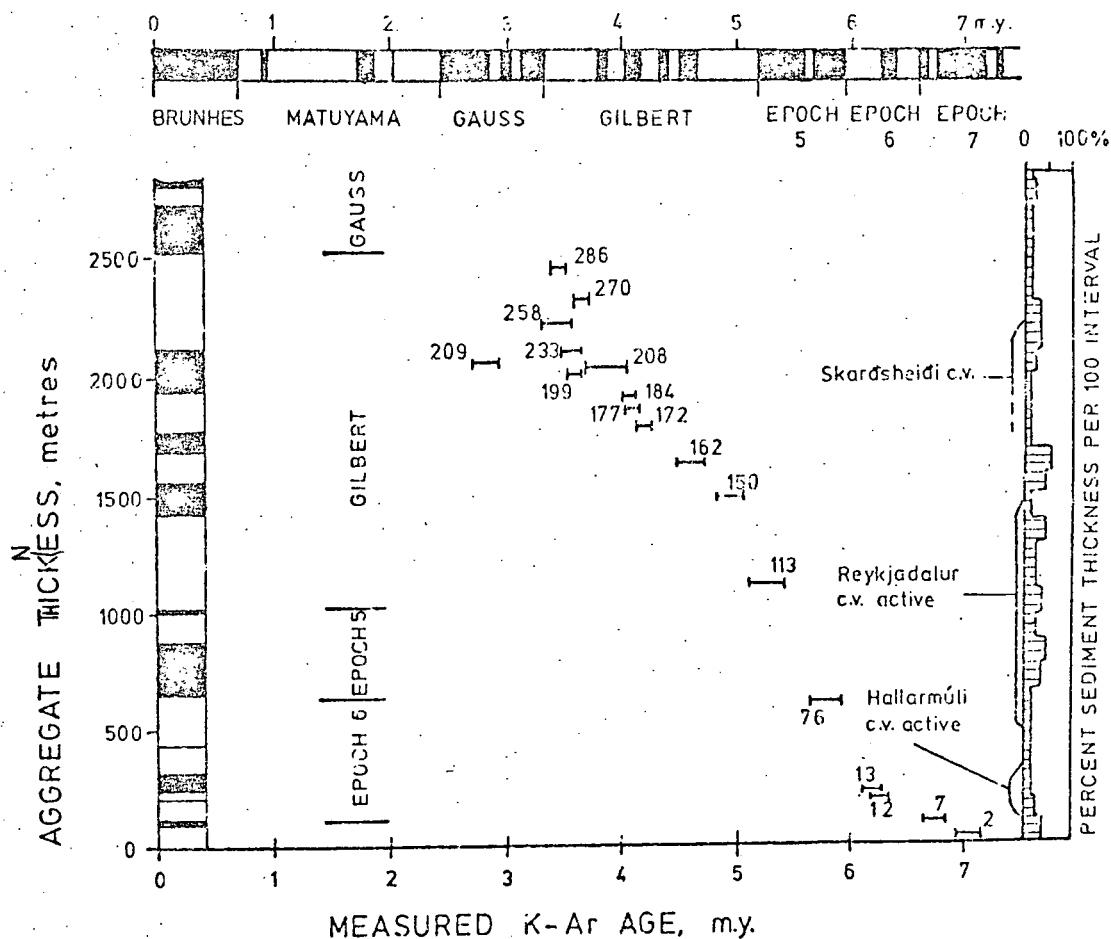


Fig. 3.11 The K-Ar ages, with precision limits indicated, plotted against the aggregate stratigraphic thickness above the base of the sequence. Polarity log for the sequence is given adjacent to the thickness axis (black, normal polarity and white, reversed polarity). Upper part of the diagram shows the polarity time scale after Talwani *et al.* (1971). The proportion of sediment present per 100 m of section is shown on the right. Modified after McDougall *et al.*, 1975.

Sample number	Calculated age in (m.y.)	Mean age in (m.y.)
NP286	3.49 ± 0.07	3.46 ± 0.07
	3.44 ± 0.06	
NP270	3.64 ± 0.06	3.66 ± 0.06
	3.68 ± 0.05	
NP258	3.36 ± 0.07	3.45 ± 0.13
	3.54 ± 0.06	
NP233	3.52 ± 0.02	3.56 ± 0.08
	3.60 ± 0.07	
NP209	2.77 ± 0.11	2.82 ± 0.11
	2.88 ± 0.11	
NP208	4.12 ± 0.11	3.89 ± 0.20
	3.80 ± 0.08	
	3.74 ± 0.07	
NP199	3.64 ± 0.07	3.60 ± 0.07
	3.56 ± 0.06	
NP184	4.05 ± 0.06	4.08 ± 0.06
	4.12 ± 0.05	
NP177	4.12 ± 0.06	4.10 ± 0.06
	4.09 ± 0.05	
NP172	4.19 ± 0.06	4.20 ± 0.06
	4.22 ± 0.05	
NP162	4.67 ± 0.09	4.60 ± 0.10
	4.53 ± 0.06	
NP150	5.03 ± 0.08	4.94 ± 0.13
	4.85 ± 0.06	
NP113	5.45 ± 0.09	5.26 ± 0.16
	5.16 ± 0.09	
	5.18 ± 0.09	
NP76	5.62 ± 0.09	5.78 ± 0.15
	5.92 ± 0.07	
	5.79 ± 0.07	
NP13	6.18 ± 0.09	6.20 ± 0.09
	6.22 ± 0.07	
NP12	6.20 ± 0.10	6.25 ± 0.10
	6.30 ± 0.07	
NP7	6.75 ± 0.11	6.74 ± 0.11
	6.73 ± 0.08	
NP2	7.11 ± 0.12	7.05 ± 0.12
	7.00 ± 0.09	

Table 3.1 K-Ar ages of some lava flows from the Borgarfjörður area. The sample numbers refer to flows in Fig. 3.2. (From I. McDougall et al. 1975)

Gilbert geomagnetic epochs are easily recognized and Epoch 5 as well, but the latter is shorter than expected, probably because of a lower effusion rate and a possible unconformity. The magnetic stratigraphy is more complicated below Epoch 5, due to numerous short magnetic events. The lower boundary of Epoch 6 (Opdyke, 1972) is probably at the bottom of profile NS and the thick normal event, exposed in the Kolvidarholt series and the bottom part of the Grjóthals thick-layered series, is probably anomaly 4, on the revised time scale (Talwani et al., 1971).

The main stratigraphical features of the 2.7 km thick section are shown in Fig. 3.12. The Hredavatn sedimentary horizon rests unconformably on top of faulted and tilted basalts. These basalts may be considerably older than the rocks overlying them. A basalt flow from the core of the Borgarnes anticline has been dated by Moorbath et al. (1968) and an age of 13.2 ± 2.0 m.y. was obtained. The strike and dip relations indicate that the rock underlying the Hredavatn sedimentary horizon may be of similar age, or slightly younger. Thus there is a gap of about 6 m.y. between the sediments and the underlying basalts. Two more unconformities occur in the lava pile; one between the Kolvidarholt-series and the Grjóthals thick-layered series, and the other between the Grjóthals thin-layered series and the rocks overlying the sedimentary rich part of the pile.

The proportion of sediments in the whole section is about 15% of the total thickness. Detrital beds (sedimentary and proclastic) constitute about 6% of a 4.5 km thick section in the Reydarfjördur area in eastern Iceland (Walker, 1959), which is considerably less than in the Borgarfjördur area.

The effusion rate can be established by using the palaeomagnetic data and the K-Ar-datings. It is on average about 730 m/m.y., but variations occur (see McDougall et al., 1975); for example, the effusion rate near the bottom of the section is much lower than elsewhere.

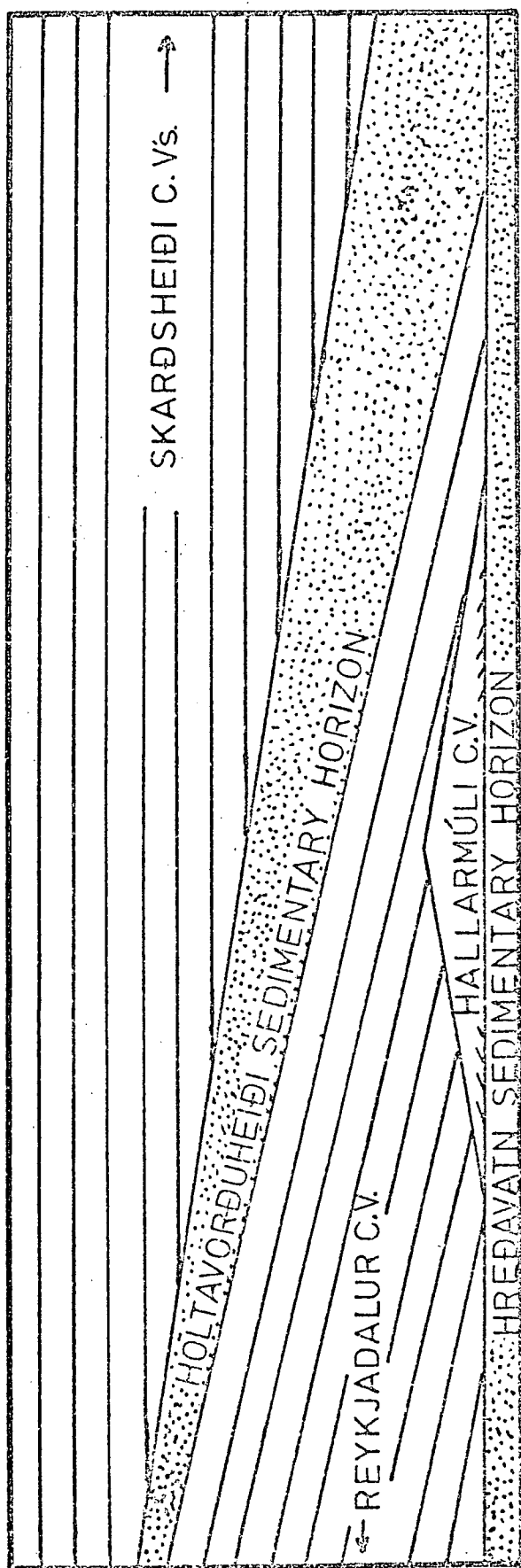


Fig. 3.12 A simplified stratigraphic section of the Borgarfjörður area. The stippled areas represent pile rich in sediments and the three main unconformities are shown

CHAPTER 4:

THE HALLARMULI CENTRAL VOLCANO

The Hallarmuli central volcano lies on the eastern flank of the Borgarnes anticline. The regional lava pile dips from 2° to 10° towards the east and southeast. It is rather difficult to pin-point the centre itself because no structural or geophysical anomalies (Figs. 2.4 and 2.5), usually associated with central volcanoes have been found or observed. The flows which belong to the volcano have similar strike and dip to the flows of the plateau basalt around. The fieldwork suggests that the main central activity took place in the area between Svartagil and Höll (Fig. 3.5) and probably down-dip in the lava pile.

The Grjóthals ridge and the Hallarmuli are dissected by a number of NE-SW to N-S running faults. The downthrow is usually on their western side (see Chapter 10), but there are exceptions. One prominent fault, with an opposite throw, runs from Glitstadir south along Hallarmuli and reaches the boggy lowlands about 0.5 km east of Höll. It is also likely that this fault extends further south along the eastern side of the low ridge Veggjahals from Höll to Stafholt. No rocks related to the Hallarmuli central volcano have been found east of the fault, except for one flow of basaltic icelandite and one flow of rhyolite about 0.5 km south of the Hamraendar farm (Fig. 4.1).

The earliest rock unit associated with the volcano is an ignimbrite layer at Stafholtskastali and a very thin ignimbritic layer on top of the porphyritic unit northeast of Veidilaekur. The ignimbrite at Stafholtskastali overlies the Hredavatn beds. It is up to 10 m thick yellow to red-brown in colour, and contains a few small xenoliths of mainly basic material; it is overlain by



Fig. 4.1 Rhyolite and basaltic icelandite flows
(the three small hummocks left of the farm),
about 500 m south of Hamraendar in
Stafholtstungur.

tholeiite flows. The same ignimbrite is probably exposed in a poor outcrop about 1 km northeast of Veidilaekur. On top of this ignimbrite layer is the topmost unit of the Hredavatn series. It is thickest in the Hallarmuli area and thins towards the SW. At Stafholtskasatali it has disappeared altogether. A few thin ignimbrite layers intercalate the upper part of this unit (Fig. 4.2).

On top of the Hredavatn series lies the main acid succession of the Hallarmuli volcano which thickness varies from 10 to 100 m. It is thickest on Hallarmuli, up to 100 m, but becomes gradually thinner towards the north and south (Fig. 4.3). The volcanic sequence consists of alternating ignimbrite layers and intermediate lava flows with a few intercalated plant-bearing mudstone and conglomerate beds.

On Hallarmuli the lower half of the sequence consists of four ignimbrite layers intercalated with occasional intermediate lava flows but the upper half consists of intermediate lava flows only, which are best exposed south of Torfdalur (Fig. 4.4). Each individual flow is of fairly limited extent, from a few tens of metres up to 500 m. Some of the flows have followed river courses, which were cut into the ignimbrite layers (Fig. 4.5).

Each ignimbrite layer on Hallarmuli can be divided roughly into 5 units. The bottom part consists of fine ash which is rather unconsolidated and contains few and small xenoliths (usually about 0.5-1 m thick). Due to hydrothermal alteration the ash has partly been converted to clay (montmorillonite). Then there is, in most cases, a rather sharp change to a coarser ignimbrite containing big pieces of pumice and xenoliths, but still rather unconsolidated. The centre of each layer is firmly

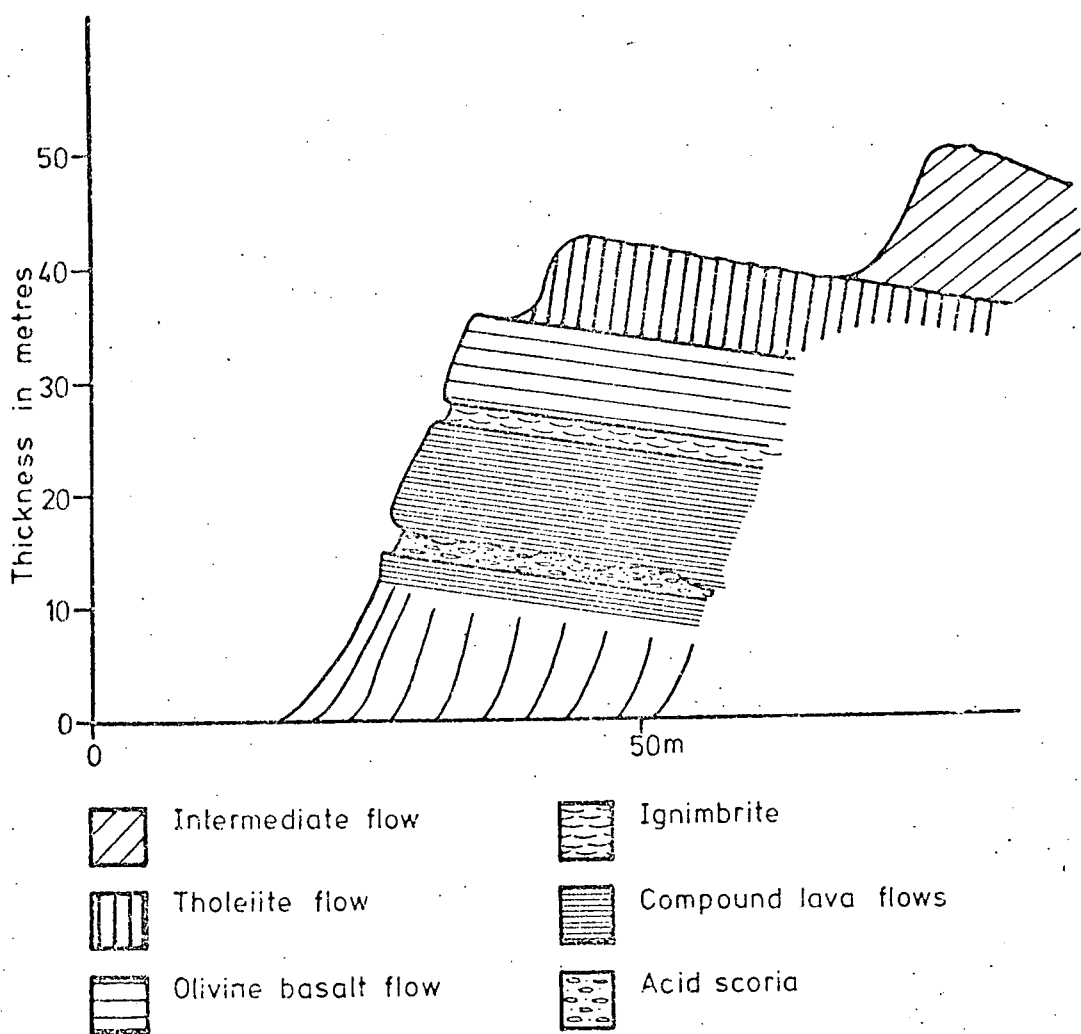


Fig. 4.2 Section through the topmost part of the Hredavatn series, about 250 m north of Varmaland.

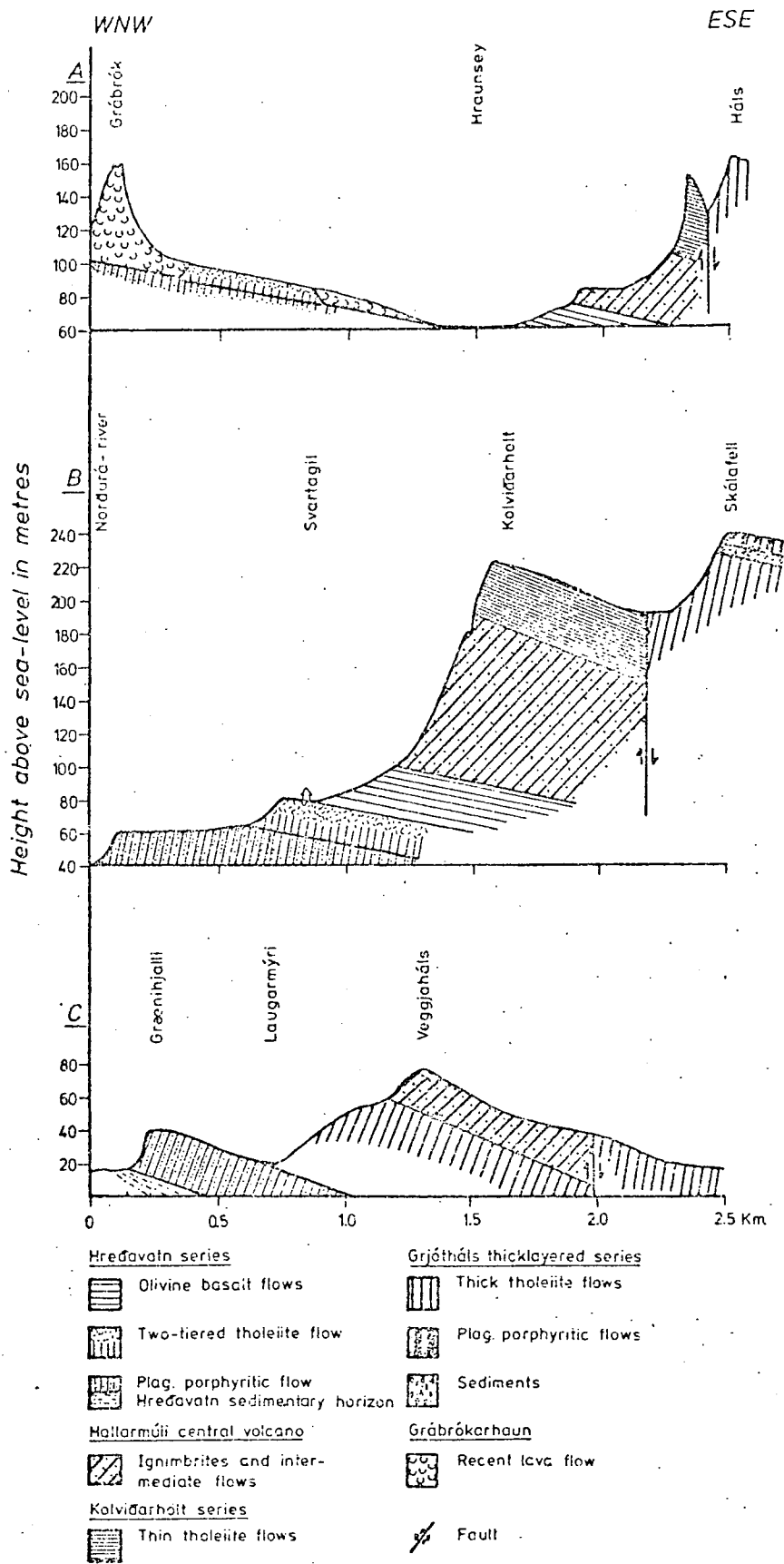


Fig. 4.3 Sections through the lava pile in the Hallarmuli area. A : Græbrók-Hraunsey;
B : Svartagil;
C : Varmaland.

consolidated and often welded; the pieces of pumice are flattened and xenoliths are abundant. Then there is again a gradual continuum to an unconsolidated ignimbrite and at the top is a fine grained ash. This subdivision is only valid for the Hallarmuli area itself. West of Nordurardalur and south of Hallarmuli the fine ash at the bottom and top is missing and the ignimbrites have not welded centre.

The fine ash at the bottom is probably an airfall deposit formed at the beginning of an eruption. The main part of the ignimbrite is then formed during the main outburst as an ash flow or a "nuee ardente" deposit. The ash at the top either settled from the dust left in the air after the ash flow had come to a rest or it formed as an airfall tuff after the eruption changed its character to more Plinian type activity. This subdivision indicates a proximity to the eruptive vent(s).

Most of the xenoliths are angular and reach up to 3-5 cm in size, but usually they are much smaller. They are of all types from basalt to rhyolite and pitchstone. No plutonic xenoliths have been found except for a rather coarse-grained rhyolite, which is probably from a shallow intrusive body. The xenoliths are less abundant in the two lowest ignimbrite layers (1. and 2. layer) but most abundant in the fourth layer.

The first and third layers are the main ignimbrite layers and both of them have welded centres.

The first ignimbrite layer (Fig. 4.4) is reddish in colour and has maximum thickness of 15 m. At its base, just north of Hóll, are vertical moulds after tree trunks. The layer is thickest near Torfdalur and thins towards the north and is not present west of Hraunsnefsúxl. It has been found in one outcrop south

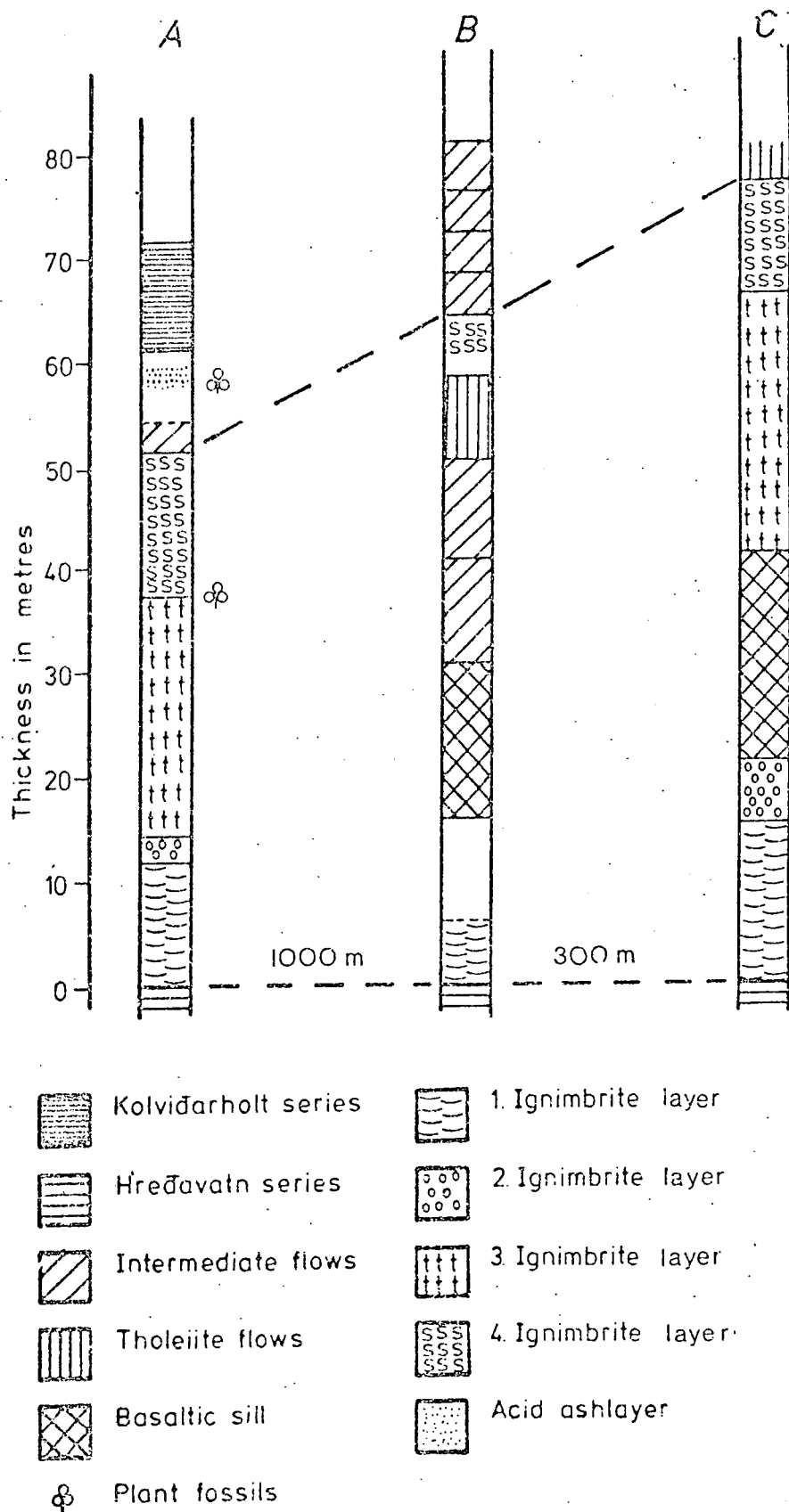


Fig. 4.4 Three sections through the main acid succession of the Hallarmuli central volcano.

A : Svartagil;

B : central part of Torfdalur;

C : southern slope of Torfdalur.



Fig. 4.5 Icelandite lava flow, showing platy flow-structure parallel to walls of a river course.

of Hallarmuli, approx. 1 km northwest of Hjardarholt, where it is less than 10 m thick. In many places, especially in the southern part of Hallarmuli, this layer is overlain by about 10 m thickness of cross-bedded sediment with pebbles and boulders of all types with a tuffaceous matrix. Occasionally an intermediate flow separates layers 1 and 2.

The second layer is yellow-green in colour, 2.5-5 m thick, and finer in grain than the three others, and probably entirely formed of airfall tuff. It is often difficult to distinguish between layers 2 and 3.

The third layer is also yellow-green in colour but about 20-25 m thick (Fig. 4.4). It is thickest in Torfdalur and thins towards the south and has not been found south of Höll. It is also considerably thinner west of Nordurardalur (7-10 m) and appears to have been re-sedimented. In Fossadalur the layer is accompanied by plant-bearing lake deposits. In the Hallarmuli area thin sediment (0.5-1 m) with silicified tree trunks and an occasional intermediate lava flow separate layers 3 and 4.

The fourth layer is red-brown in colour and 5-15 m thick. It is thickest near Svartagil and thins to the north and to the south.

The bulk of the intermediate flows overlie the fourth ignimbrite layer. They vary in number from 1 to 7 and can vary in thickness from 2 to 25 m but occasional tholeiite flow occurs also among the intermediate flows (Fig. 4.4). This group of intermediate flows is thickest in the area from Torfdalur to Varmaland and no flows occur west of Hraunsnefsöxl or south of Stafholtkastali.

Most of the flows are basaltic icelandites and icelandites, but dacite flows were also identified. Only one rhyolite flow has

been found so far, in a particularly poor exposure about 0.5 km south of the Hamraendar farm (Fig. 4.1). This rhyolite flow occurs east of the fault running along the eastern side of Veggjahals, probably stratigraphically slightly higher than the intermediate flows described above.

The youngest differentiated rocks in the Hallarmuli area is a one metre thick rhyolitic ash layer accompanied by silicified tree trunks on Kolvidarholt. Conformably on top of the differentiated rocks of the Hallarmuli central volcano lies the Kolvidarholt series (see Chapter 3) which may represent a flank succession of the volcano.

After central activity ceased, the volcano was buried by flood basalt flows and subsequently cut by dykes, some of which intruded the ignimbrites and formed sills (Fig. 3.5). All the sills are basaltic except for one of icelandite.

The Hallarmuli central volcano is highly abnormal compared to other mapped central volcanoes in Iceland (Walker, 1963; Sigurdsson, 1966; Fridleifsson, 1973; see also Chapter 5). One of the main differences is the absence of intrusive sheets, cone sheets, or laccoliths and the associated alteration aureoles which usually accompany mature central volcanoes. The only intrusives are a few dykes, most if not all of which were intruded after the volcano became extinct, and the evidence for a shallow rhyolitic intrusion(s).

The analcime zeolite zone is slightly higher in the Hallarmuli area than the surrounding areas.

During the fieldwork no evidence of a caldera or circularity in structure was found either, which is common among central volcanoes.

As mentioned earlier, no gravity or magnetic anomalies or other irregularities (Figs. 2.4 and 2.5) have been detected over the volcano and the surrounding areas.

The age of the lowest ignimbrite (1 km northeast of Veidilaekur) is about 6.7 m.y. (Fig. 3.2) and the topmost ignimbrites are about 6.2 m.y. No K-Ar datings are available for the rocks from the final stages of the volcano but combining the available K-Ar dates and the palaeomagnetism, a minimum age of 6.0 m.y. is obtained for the Kolvidarholt series. The life span of the Hallarmuli central volcano, as we know it today, was thus of the order of 600,000 to 750,000 years. This is in an agreement with the estimated average life span of central volcanoes in western Iceland of 0.5-1.0 m.y. (Saemundsson and Noll, 1974; Piper, 1971).

The thickness of the pile, from the first differentiates until the end of activity related to the volcano (including the topmost unit of the Hredavatn series and the whole of the Kolvidarholt series), is about 200-250 m, which gives an effusion rate of 35 m/100,000 years thus contrasting with 73 m/100,000 years for the lava pile in the Borgarfjörður area as a whole (McDougall et al., 1975). The effusion rate in a central volcanic area is usually much higher than for the basalt pile around it. These figures thus suggest abnormal conditions in the area during the volcano's life-time. Perhaps the main difference from other central volcanoes is that the Hallarmuli central volcano appears to represent a period of low extrusion rate compared to the succession above it.

The Hallarmuli central volcano is the oldest in the Borgarfjörður area but according to the stratigraphy in Nordurardalur the activity of the Reykjadalur central volcano started less than 200,000 years later.

CHAPTER 5:

THE REYKJADALUR CENTRAL VOLCANO

Introduction

The Reykjadalur central volcano lies in the heart of the mountain range between Borgarfjörður and Dalir. Except for Mr. Baula (Rutten and van Bemmelen, 1955) the area has not been described before. Mapping was carried out in the summers of 1972, 1973 and 1974. Because of the enormous size of the area involved, parts of it could not be mapped in detail. The main difficulties encountered were poor exposure, and intense faulting in the eastern and southeastern parts of the area. The centre itself is represented by a caldera, approximately 10 km in diameter, which is best exposed in the Reykjadalur valley (after which the volcano is named). The flanks of the volcano extend, on average, about 10 km outwards from the caldera rim, but sometimes they extend for up to 13 km. The actual diameter of the volcano thus ranges from 25 to 30 km.

The extrusive rocks of the area can be divided into four main groups or series:-

1. The Reykjadalur thick-layered series
2. The Main Phase of differentiated extrusives
3. The Reykjadalur thin-layered series
4. The caldera filling and the final differentiated extrusives.

The intrusives related to the volcano can also be subdivided into three groups (dykes belonging to the plateau basalt are described in Chapter 9):-

1. Intermediate and rhyolitic dykes, which are feeders to the Main Phase of differentiated extrusives.

2. Basaltic to rhyolitic cone sheets and sills, which are feeders to the thin-layered series and to the final differentiated extrusives.
3. Rhyolite cone sheets and other intrusive bodies from the final stages of central volcanic activity in the area.

Stratigraphy

(1) Reykjadalur thick-layered series

The series froms the base of the volcano and also part of the "cone" itself. The flows dip about 2° - 5° towards the volcano from the north, the south and the west (it is not exposed on the eastern side). The dip changes abruptly about 2-3 km outside the caldera rim, where it was found to dip 5° - 25° outwards, forming a circular structure on the volcano's western side (Fig. 5.1). The dips of the slopes of the cone would be increased if corrections are made for the regional dip. The thicknesses of the tholeiite flows measured on the slopes indicate that they were extruded on a flat topography rather than on a steep slope. The main cause of the observed dip may be uplift resulting from later intrusive activity, perhaps of acid intrusions at shallow depths. The regional dip curves around the volcano (Fig. 5.2) and this may be caused by sagging of the floor of the volcano due to the load of later volcanics similar to the Breiddalur central volcano in eastern Iceland (Walker, 1963).

A section through the series in the Grjóthals area (the Grjóthals thick-layered series) has been described in Chapter 4. The series rests unconformably on top of the Kolvidarholt series and the Hallarmuli central volcano, in the southern part of the region. There it consists mainly of thick tholeiite flows, with two units of porphyritic flows; the lower unit also occurs north of the Reykjadalur volcano.



Fig. 5.1 Unconformity (a) between the Reykjadalur thick-layered series (b) and the overlying Reykjadalur thin-layered series (c). A lava flow from the Main Phase of differentiated extrusives is exposed on the right of the photograph (d). Note the circular, outward-dipping structure of the thick-layered series.

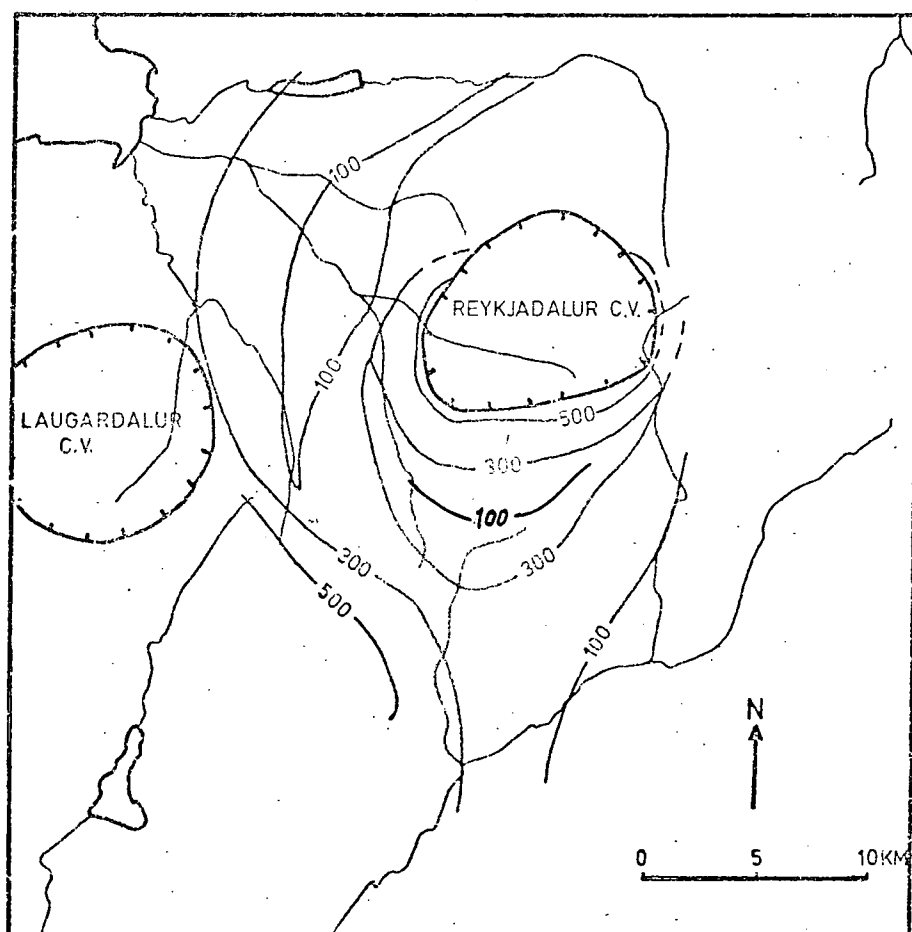


Fig. 5.2 The present elevation (in metres) of the top of the Reykjadalur thick-layered series.

The stratigraphically lowest rocks, which were examined north of the volcano, are exposed in the gorge of the Haukadalur river north of Harrastadir. Poorly exposed tholeiite flows are overlain by an olivine-rich compound lava flow which can be traced for at least 10 km towards the north. This flow is succeeded by an icelandite flow, which is the oldest salic rock in the area around the Reykjadalur volcano. It is not clear whether this particular flow has its origin within the central volcano, but it is thought likely. The icelandite flow is overlain by a 50-75 m thick unit of thick tholeiite flows succeeded by a porphyritic unit, the same as on the southern side of the volcano. This unit can reach up to 50 m in thickness but is usually about 25 m. In Haukadalur and Hördudalur the unit consists of a typical compound lava flow, but elsewhere consists of olivine basalt flows and plagioclase-phyric flows. The topmost part of the series consists of about 150 m of thick tholeiite flows which are interleaved by a few intermediate flows in Sökkolfsdalur and Sudurardalur. Thin red clastic beds intercalate with most of these flows.

The stratigraphic thickness of this series, from the icelandite flow in the gorge of the Haukadalur river upwards, is about 250-300 m and the thickness on Hraunsnefsöxl, in Nordurardalur, is about 200 m. It is thus likely that the compound lava flow and icelandite flow in the gorge of Haukadalsá river correspond in time to the compound lava flow underlying the Hredavatn beds and to the differentiated rocks of the Hallarmuli central volcano.

(2) The Main Phase of differentiated extrusives

This series which lies conformably on top of the preceding series, includes most of the intermediate and acid extrusives of the Reykjadalur central volcano. Its total thickness varies from 10 to 200 m. Very few basalt flows intercalate with the acid rocks, although there

is a 50-75 m thick unit of thin tholeiite flows in Vesturardalur. The series consists both of lava flows and pyroclastic material (ash and unwelded ignimbrites) but due to later intrusive activity, the stratigraphy south and southeast of the caldera rim is difficult to assess; some of the ignimbrites and the ash have been replaced by basic cone sheets and sills (Fig. 5.3). The earliest rocks belonging to this series are a few rhyolite flows and a huge acidic ignimbrite layer(s) whose thickness could not be established due to the difficulties described above. It certainly runs into tens of metres. This layer may consist of more than one eruptive phase. It is greenish in colour and often considerably altered, and small xenoliths are common within it. The ignimbrite may have had its origin near the top of the volcano (which later collapsed) flowing down the eastern and southeastern slopes of the volcano, but its full extent is not known because it disappears down-dip. The layer is thickest at the head of Austurardalur and in Mjoidalur. The activity spread soon to other areas, from Vesturardalur to Haukadalur. Most of the lava flows have their origin in vents and dykes outside the cone of the volcano. Seven of these vents have been identified (see Geol. Map); the best exposed vents occur in Vilfildalur (Fig. 5.4). Each eruption started with a **explosive** phase (Plinian phase) forming a 2-10 m thick bedded tephra layer (Fig. 5.5), which contains numerous basaltic xenoliths of up to 0.5 m in diameter. After the initial explosive phase a highly viscous rhyolitic magma was extruded and, due to its high **viscosity**, a small dome-shaped body was formed over the vent (Fig. 5.4). Some of the intermediate and acid flows have their origin on the slopes of the cone, and perhaps near the original summit. Their volume is, however, small compared with those erupted away from the cone. It is difficult to estimate the volume relations between the intermediate and rhyolitic rocks but roughly estimated, the rhyolitic rocks make up

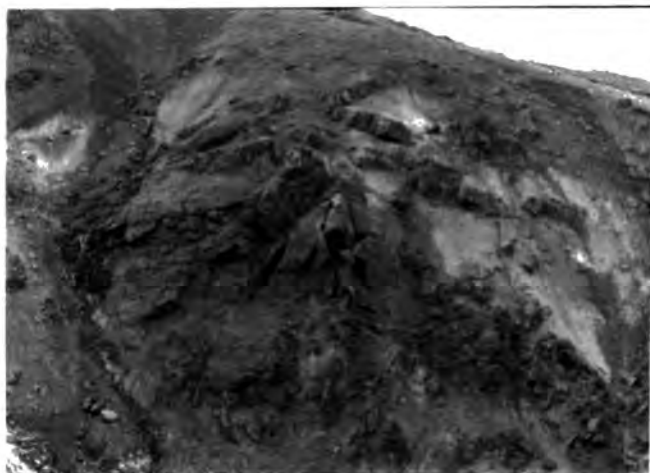


Fig. 5.3 Basic sheets and sills emplaced in unwelded ignimbrite of the Main Phase of differentiated extrusives in Mjoidalur.

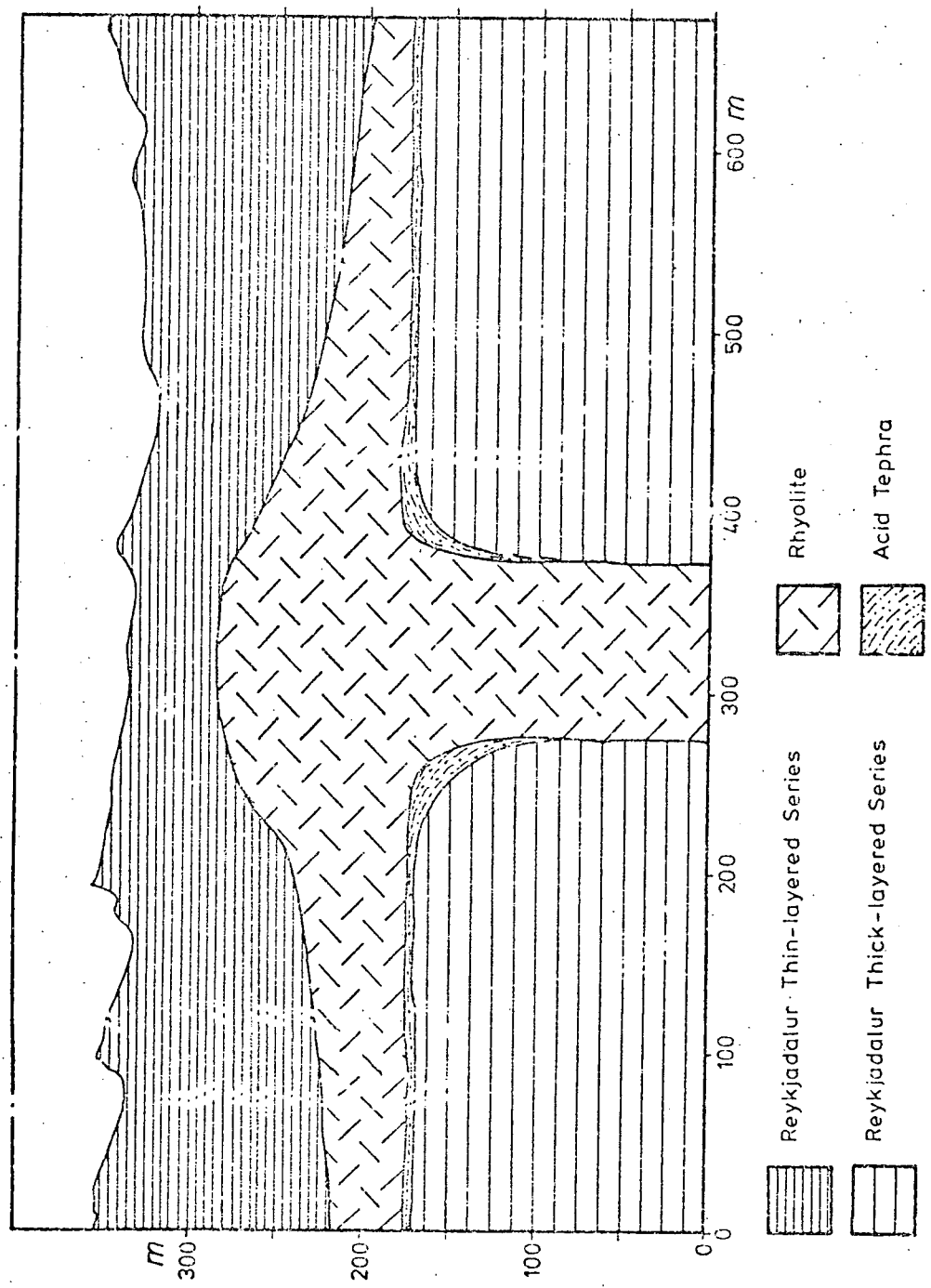


Fig. 5.4 A schematic section of a rhyolitic eruptive vent in Vilfilisdalur

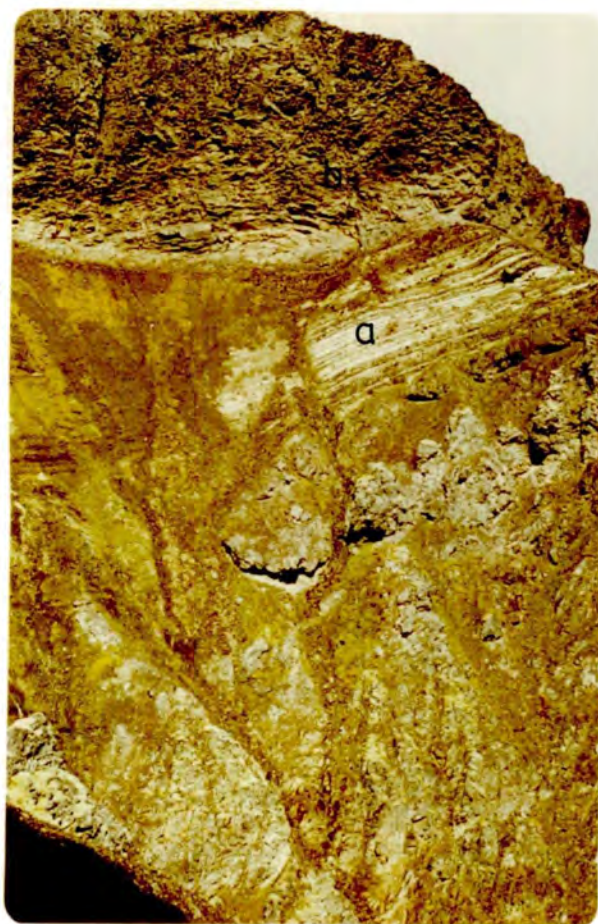


Fig. 5.5 Bedded rhyolitic tephra (a) underlying a rhyolite lava flow (b) of the same eruption; belonging to the Main Phase of differentiated extrusives in Vilfildalur.



Fig. 5.6 The upper tillite in the Reykjadalur thin-layered series. The tillite (a) rests on a polished surface of lava flow (b). Pillow lava (c) overlies the tillite. Svarthamar north of Jörva-Thverdalur.

about two-thirds of the whole series.

(3) Reykjadalur thin-layered series

This is the most spectacular series in the whole research area and consists of numerous thin vesicular flows, most of which show tholeiitic characteristics. On the outskirts of the area these thin tholeiite flows interfinger with thin, vesicular olivine basalt flows. The flows are usually not thicker than 2-4 m. Three plagioclase-phyric units occur in the upper part of the series, and a few intermediate and rhyolite flows interleaf with the series north of the caldera. The total thickness of the series is not known; its minimum thickness is about 600 m but it may be as thick as 1000 m. The thickness is greatest near the volcano, pointing to close relationships between the central volcano and the series.

The series rests unconformably on top of the preceding series in the immediate vicinity of the volcano (Fig. 5.1) but it is conformably on top of the underlying series further away (6-7 km from the caldera rim). Flows belonging to the series dip about 5° outwards, close to the caldera rim, but level off about 2 km outside the rim and still further away they tend to follow the regional dip.

The structure of the series is irregular and complicated by contemporaneous faulting, accompanied by a few small unconformities which may be caused by shifting of activity from one part of the area to another, and by erosion.

The porphyritic units, which vary from 15 to 75 m in thickness, have a high plagioclase content. The phenocrysts can reach 2-3 cm in size, but are usually less than 0.5 cm. The porphyritic flows are usually two or three times thicker than the thinner tholeiite flows. Most of the porphyritic flows seem to have their origin near the centre of the central volcanic region, from whence they flowed outwards and down the slopes of the volcano, especially towards the

south and southeast. The lowest porphyritic unit includes, in a few places on the northern side of the volcano, pillow lavas and hyaloclastites which indicate the presence of water at the time of extrusion.

Sediments are rare in this series. The thin red beds of clastic material, which are so common in the Tertiary lava pile, are missing altogether and the few sediments present are cross-bedded stream deposits, rarely exceeding 5 m in thickness. They are more common on the volcano's southern and eastern slopes, and, as mentioned in Chapter 3, the upper part of this series, in Thverarhlid, contains a great amount of sediments.

The formation of the series was interrupted at least twice by erosional forces, probably glaciations. The earliest evidence for a possible glaciation is indicated by a conglomerate in Saurstadagil (eastern slope at 580 m a.s.l.) and in Slettidalur (350 m a.s.l.). The conglomerate is about 10-15 m thick. It consists of boulders which are up to 1-2 m in diameter, angular to rounded, with a tuffaceous matrix. The basement on which it rests is not exposed and the layer is confined to the immediate neighbourhood of the caldera. The origin of the layer is not certain but two explanations may be considered : either a mud flow (lahar), or a tillite. The author favours the latter explanation because of the relatively great extent of the conglomerate layer. About 100-200 m higher up in the series is a major break, accompanied by an unconformity close to the caldera rim. This break is certainly due to a major glaciation as borne out by the polished surface of the underlying flow and the following tillite (Fig. 5.6). Near the volcano the glacier carved out shallow valleys, which were later filled by pillow lavas and hyaloclastites, often accompanied by siltstone and sandstone. These rocks can be traced across the caldera rim where they interfinger with the topmost unit of the caldera filling.

The thickness of the horizon is usually about 10-30 m on the northern slopes but it thickens towards the east, and merges with the Holtavörduheidi sedimentary horizon (Chapter 6). This horizon of tillite, pillow lavas and hyaloclastites is considered to be formed under glacial conditions, either as a result of an extensive Tertiary ice sheet or of a big mountain glacier covering the volcano and the surrounding areas. The Holtavörduheidi horizon (Chapter 6) is underlain by a tillite, suggesting a massive glaciation, but the lack of tillites in the Thverarhlid area and further south indicates that the glaciated area was confined to the volcano and its nearest surroundings. The sediments of the Holtavörduheidi horizon could therefore be ascribed to an outwash-plain from the glaciers on the highlands around the volcano.

The hyaloclastite/pillow lava horizon is overlain by a further 100-200 m of thin tholeiite flows which, however, are missing in the area south of Snjofjöll, probably due to erosion before the Snjofjöll series was formed.

Walker (1963) described unusually thin tholeiite flows on the flanks of the Breiddalur central volcano. He suggested that they are thin because they flowed down the slopes of the volcano. This explanation may be valid for the thin flows around the Reykjadalur central volcano and the Kolvidarholt series. It is more difficult to accept for the thin tholeiite flows of the Haafell series, (Chapter 3) because no unusual tilt is observed in that area. However, these flows may be derived from another central volcano (Skardsheidi) about 30 km further south (McDougall et al., 1975).

(4) The caldera filling

Some time during the formation of the thin-layered series a collapse caldera, about 10 km in diameter, was formed. Volcanic activity went on during and after the collapse, forming a great variety of volcanic rocks and eventually filling the caldera completely. Many

of these rocks are loose in character and later cone sheets easily penetrated them, causing a great deal of disturbance. The extrusives, and the accompanying sediments inside the caldera, have been divided into 8 main units. Fig. 5.7 shows two schematic sections across the caldera.

1. As the floor of the caldera subsided, screes (talus-breccias) were formed on the slopes of the caldera escarpment (Fig. 5.8). These breccias show a great variation in character, partly due to the great variety of contained rocks and partly due to gravitational and fluvial sorting. The breccias are usually coarsest nearest to the caldera rim and they dip inwards, becoming finer and often laminated near the centre of the caldera; lenticular bodies of coarse breccias occur interbedded with the finer material. It is often difficult to distinguish between genuine talus-breccias and highly altered and brecciated lava flows.

2. One or more rhyolite flows from the early stages of the caldera occur on the lower slopes of the Reykjadalur valley. The exposed thickness of the rhyolite is about 150-200 m, but as it has been replaced partly by later cone sheets the original thickness is uncertain. The rhyolite is one of the earliest volcanics inside the caldera, and it may have been erupted during the subsidence of the caldera floor.

3. Basaltic pillow lavas, hyaloclastites and two-tiered jointed flows (Fig. 5.9) intercalate with the breccias of unit (1), at the head of Reykjadalur, but because of poor outcrops little is known about the extent and thickness of this unit. Normal faulting in this part of the caldera made fieldwork difficult (Fig. 10.1). Some of the hyaloclastites show evidence of having been redeposited under aqueous conditions.

4. A 25 m thick tuffaceous sediment with leaf impressions occurs in Kalfagil in Reykjadalur. It has not been found elsewhere.

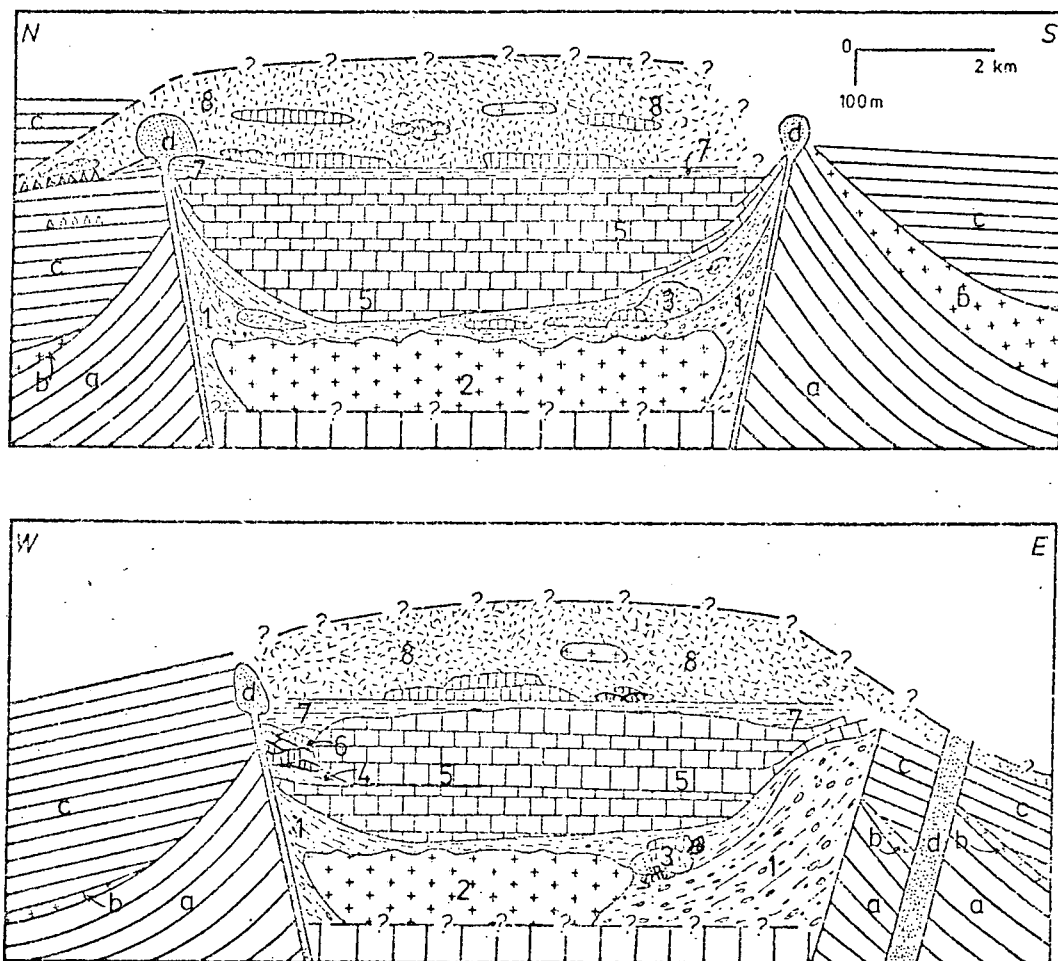


Fig. 5.7 Two schematic sections across the Reykjadalur caldera. The units of the caldera filling are numbered as in the text (1 to 8); the Reykjadalur thick-layered series (a), Main Phase of differentiated extrusives (b), Reykjadalur thin-layered series (c), and intermediate and acid cone sheets and plugs (d).



Fig. 5.8 Talus-breccias (scree) dipping into the Reykjadalur caldera in Sanddalur.



Fig. 5.9 Two-tiered, columnar jointed basalt flow in the Reykjadalur caldera filling (unit 3) at the head of Reykjadalur. The flow overlies and is overlain by redeposited hyaloclastites.

5. A unit about 200 m thick of basaltic subaerial lava flows (Fig. 5.10) overlies the previous units. The number of flows in the unit is about 12-15 and each is about 10-25 m thick. They do not normally have a rubbly top but, instead, a plane surface. This is due to the flows ponding inside the caldera and solidifying as a lava pool. As a result, many of the flows are coarse-grained and some have microgabbroic textures. Some of the flows have their origin outside the caldera, and flowed down the slopes into the caldera. The lower part of the unit has suffered severe alteration in the central parts of the caldera.

6. A unit of basic-intermediate lava flows, less than 75 m thick, overlies unit (4) in Kalfagil in Reykjadalur. The bottom part of the unit consists of pillow lava but this gradually changes to sausage-like bodies separated by brecciated parts of the same flow, caused by rapid chilling by water.

7. Units (5) and (6) are covered by a sedimentary bed, which has been found in many places inside the caldera and also outside the caldera rim, near Lambahnukur, indicating that no subsidence occurred after the bed was laid down. The thickness of this unit is about 10 to 25 m and although it consists mainly of siltstone, sandstone and clay occur in places. Ignimbritic material is common in the western part of the caldera but it does not form a continuous layer. Plant fossils are abundant east of Kalfagil. These include leaf impressions, a great number of pine needles, and some pine cones.

8. A unit of miscellaneous volcanic rocks (Fig. 5.10) overlies the sedimentary bed. The present exposed thickness is about 200-250 m but the upper part may be missing. This unit has been traced across the northern and eastern caldera rim, where it merges with the Holtavörduheidi sedimentary horizon and with the tillite/hyaloclastites of the thin-layered series. The lower part of the unit consists of



Fig. 5.10 The Reykjadalur caldera filling in Geldingadalur. Units exposed: a, talus-breccias (unit 1); b, sub-aerial lava flows (unit 5); c, sedimentary bed (unit 7); and d, hyaloclastites and pillow lavas (unit 8).



Fig. 5.11 Intermediate lava flows showing pillow-like structures caused by rapid cooling in the presence of water. On the eastern slopes of Gamalhnukar.

irregularly columnar jointed lava flows, and the upper part consists of hyaloclastites and pillow lavas. Some of the hyaloclastites have been re-deposited. Thin sedimentary beds and rhyolitic ash intercalate with the lava flows and the hyaloclastites. The flows are basaltic to intermediate in composition and they usually display pillow-like features (Fig. 5.11). The Gamalhnukar hyaloclastite is the thickest layer of this unit, about 150 m thick. Small lenticular basaltic intrusive bodies are common in the hyaloclastites and they may be cogenetic with the hyaloclastites, formed as offshoots from the magma vent. The structure and composition of this unit raises the interesting question as to whether it was formed under subaqueous or glacial conditions. The caldera had been filled at the time of formation of the sediments underlying unit (8), leaving little or no space for a deep lake. It is thus unlikely that unit (8) was formed under subaqueous conditions. Deep water would be needed to form some of the thicker layers of this unit. It is more likely that the unit was formed subglacially. This is supported by the occurrence of tillite underlying the corresponding pillow lavas and hyaloclastites outside the caldera. The volcano was thus covered by an ice cap where subglacial eruptions occurred.

Intrusive Activity Related to the Reykjadalur Central Volcano

Intense intrusive activity took place during the latter half of the volcano's life-span. No large intrusive bodies are exposed at the present erosion level, except for Mt. Baula. The intrusives are mainly dykes and cone sheets which form a circular, inclined, funnel-like structure around the volcano. The intrusives can be divided into 3 groups.

(1) Intermediate and acid dykes cut the thick-layered series south of the caldera rim (especially in Austurardalur). These dykes are feeders to the Main Phase of differentiated rocks. They have a NE-SW trend and have suffered severe hydrothermal alteration. It is

difficult to reconstruct some of these dykes because they have been extensively penetrated by later cone sheets. The dykes rarely exceed 10 m in thickness.

(2) Basic to acid cone sheets form a circular, inclined swarm around the volcano. The swarm is slightly elongated from NE to SW (Fig. 5.12). These sheets may be feeders to the Reykjadalur thin-layered series, and to the final differentiated extrusives. The sheets tend to follow the trend of the caldera rim, but towards the southwest their strike tends to change to NE-SW, which is the same trend as for the dyke swarm in that area (see Chapter 9). An individual sheet does not cover more than a few degrees of an arc.

Most of the sheets are basic and their thickness ranges from 0.25 to 4 m. The majority are about 0.75-1 m thick. It is difficult to assess the age relationships between the various sheets but the fine-grained are usually older than the coarse-grained sheets. This may be due to an increase in geothermal gradient as the intrusive activity progressed. Some of the youngest sheets consist of gabbro or granophyre.

A few basic plugs occur near the outer margin of the cone sheet swarm (Fig. 5.12). Kirkjufell in Haukadalur, which is the biggest of these plugs (about 100 m high) consists of coarse-grained and vesicular basalt, indicating a shallow depth of intrusion.

Granitic and especially gabbroic xenoliths are commonly enclosed in the sheets. Many of the sheets are plagioclase and/or clinopyroxene phyrlic. Inside the caldera the main part of each sheet is porphyritic and only a thin outer margin is aphyric. Outside the caldera the central parts of the sheets are porphyritic and often vesicular, compared with wider, dense and aphyric outer margins (Fig. 5.13). The contacts between the vesicular and porphyritic centres and the dense and aphyric margins are rather sharp. The difference between the relative thicknesses of the aphyric margins inside and outside the caldera may be due to

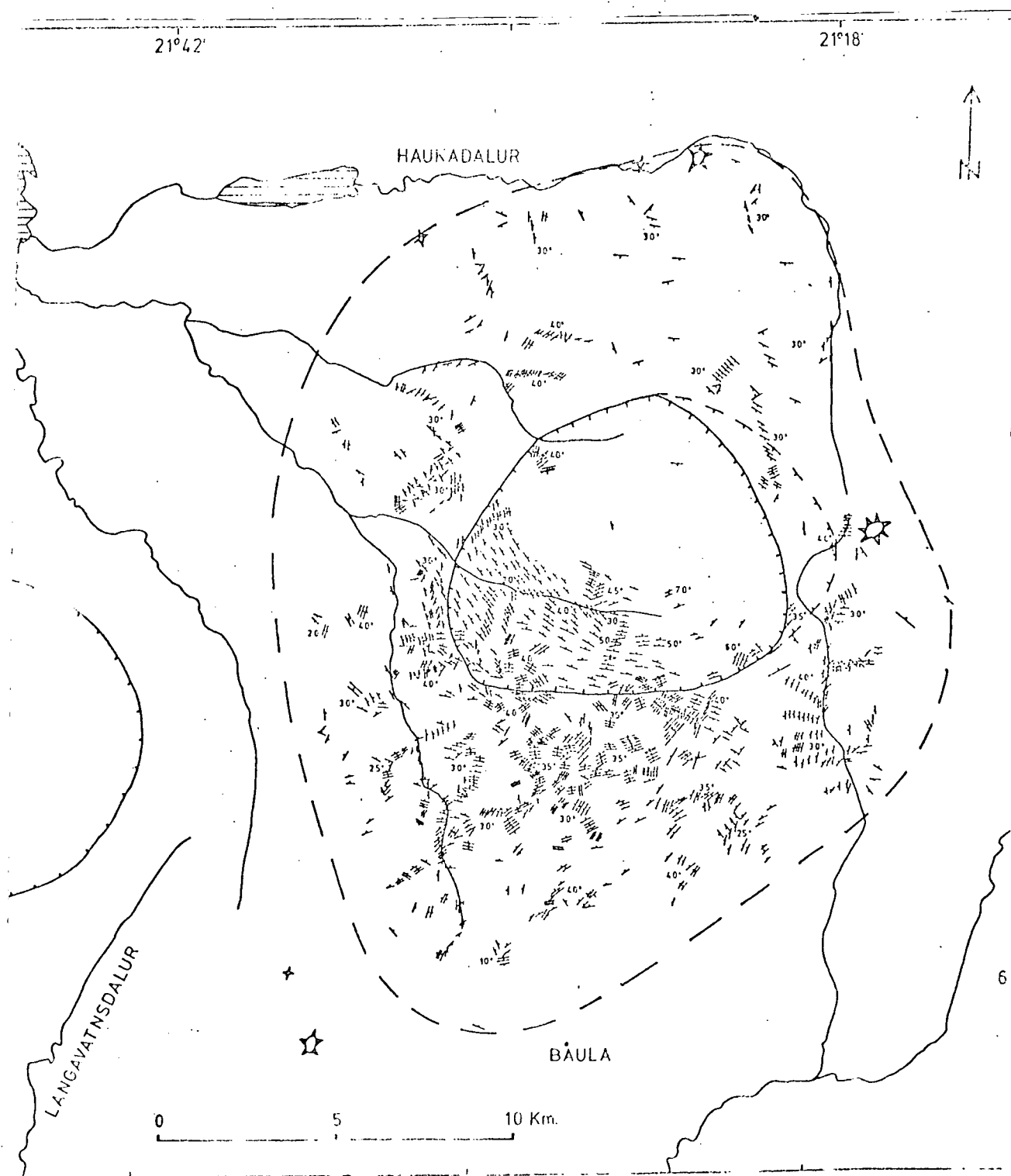


Fig. 5.12 The average strike and dip of cone sheets. The Reykjadalur and Laugardalur calderas are indicated and the broken line marks the outer limits of cone sheet occurrence; star-like symbols are basic plugs.

differences in temperature of the host rock; i.e. higher inside the caldera than outside (due to higher intrusive activity). The sheets intruded into the country rocks outside the caldera would thus tend to form thicker margins.

The dips and strikes of the sheets are variable and tend to comply with the dip and strike of the surrounding country rock. These irregularities tend to increase away from the caldera rim. The dip decreases outwards from the centre of the caldera, from 45° to 10° (Fig. 5.12). The intensity distribution of the sheets depends on the type of host rock. The sheets are most common in the ignimbrites of the Main Phase of differentiated extrusives, which they intrude to a great extent (Fig. 5.3). The cone sheets tend to form thicker sills in the ignimbrites (less than 30 m thick). The high concentration of sheets in the ignimbrites is reflected by a big magnetic anomaly over the areas where the ignimbrites are thickest (Fig. 2.5). The number of sheets is also higher in the thin-layered series, where they often reach 20% of the rocks compared with 5-10% for the thick-layered series. This difference is caused by the sheets intruding along the boundaries between the flows, rather than cutting the central parts of the flows.

Inside the caldera the sheets are accommodated in the talus-breccias and the rhyolitic flow(s) at the bottom of the Reykjadalur; here they form a more complex structure than outside the caldera. The oldest sheets are fine-grained and aphyric and they tend to follow the trend of the caldera rim. The younger sheets which are much more coarse-grained are confined to the southern part of the caldera, forming a NW-SE trending swarm. The swarm can be divided into 3 or 4 parallel units. The sheets are most intense inside each unit (up to 80%, Fig. 5.14) but drop in number between the units. The sheets dip on average about 45° towards the centre of the caldera, but some of the latest sheets are nearly vertical.



Fig. 5.13 Basic cone sheet with a vesicular, porphyritic core and a dense, aphyric margin.



Fig. 5.14 Basic cone sheets in Kalfagil in Reykjadalur

The lowest unit consists mostly of aphyric sheets but the topmost unit has the highest number of porphyritic sheets, often crystal cumulative or gabbroic in character.

3 Rhyolite cone sheets and intrusions from the final stages of the central activity in the area. A number of arched rhyolitic sheets and plugs occur inside and outside the caldera. These are younger than most of the extrusives from the volcano. The sheets are usually about 10-15 m thick. They display columnar jointing (Fig. 5.15) and have a dip of about 45° towards the centre of the caldera; each sheet can be traced for many kilometres - much longer than any basic sheet. The sheets are most common northeast and east of the caldera. By far the biggest sheet is found at the head of Sanddalur; it is about 100 m thick and forms an arched feature on the caldera rim. The sheet is bordered on both sides by basic sheets which are about 2 m thick. The inner dyke dips about 50° , and the outer about 30° inward. The contact between the basic and rhyolitic dykes is poorly exposed but seems fairly sharp. Enclosed in the rhyolite sheet are fragments of basic material. These have fine-grained margins (= chilled?). Similar features have been described from eastern Iceland (Blake, 1966). Blake *et al.* (1965) argue that composite dykes and net-veined complexes are the result of basic dykes transecting a body of acid magma. This heats up the acid material and mobilizes it until the basic magma is no longer able to pass through in the form of a dyke, but instead forms pillows, chilled against the acid magma. The acid magma may then rise along the centre of the basic dyke, and may possibly reach the surface. The fragments in the central part of the sheet described above could therefore be parts of the basic pillows brought up by the rhyolitic magma.

Small pitchstone plugs occur on the caldera rim and many of these can be traced into cone sheets. The most impressive of these plugs is

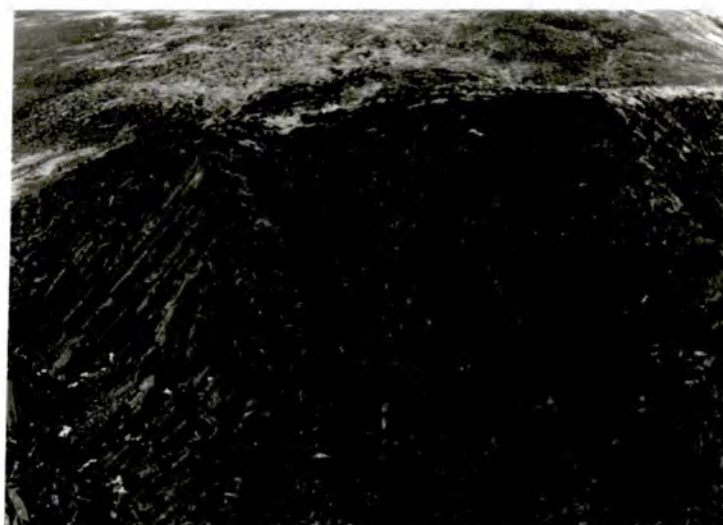


Fig. 5.15 A rhyolite cone sheet on the caldera rim in Sanddalur.



Fig. 5.16 A dacite plug on the northern rim of the Reykjadalur caldera. The plug merges with a cone sheet on the left (a).

Lambahnukur (Fig. 5.16), on the northern caldera rim, which is one of the youngest. It is columnar jointed and can be traced to a 1-2 m thick sheet which dips about 45° inwards. In the centre of the caldera is a rhyolitic plug which is severely affected by hydrothermal alteration.

The Baula complex (Figs. 5.17 and 5.18) was described by Rutten and van Bemmelen (1955) who argued that it was considerably younger than the surrounding lava pile and was probably of early Quaternary age. Mt. Baula itself is a pyramid-shaped body rising about 600 m above its visible base. It consists of white-grey, vesicular, rather coarse-grained rhyolite, which is usually columnar jointed. At the base of Mt. Baula, rhyolite dykes cut the intrusion and form concentrically inclined sheets (Fig. 5.19). These usually dip about 45° towards Baula. The intrusion arched up the lava flows on top forming a dome-like roof similar to that of the Sandfell laccolith in eastern Iceland (Hawkes and Hawkes, 1933). The only evidence for this dome-like roof is found on the north side of Baula, in Maelifellsgil and on Maelifell. The flows dip steeply outwards near the contact but the dip decreases gradually away from the contact. The flows underlying the intrusion seem to form a very shallow bowl, but the base of the intrusion is not exposed. Inclined rhyolite sheets spread over a wide area around Baula, with most of them dipping towards it (Fig. 5.19). The thickest sheets are the Litla Baula plug and the Skildingafell sheet, both east of Baula itself. On the western side of Baula, parts of the country rocks are brecciated due to the rhyolitic sheets intruding the contact between the intrusion and the lava pile. Field evidence suggests that Baula is a shallow intrusion.

Litla Baula differs from Baula in that the volcanism reached the surface, producing rhyolitic tephra. Litla Baula is a volcanic vent filled with rhyolitic breccias. These incorporate blocks from the

Fig. 5.17 Geological map of the Baula complex. Yellow, rhyolitic dykes and intrusions; pink, intermediate and rhyolite flows of the Main Phase of differentiated extrusives of the Reykjadalur central volcano; light-brown, rhyolitic vent breccias; brown, Baeli pillow lava from the last glaciation; blank, Tertiary flood basalt; black alluvium deposits.

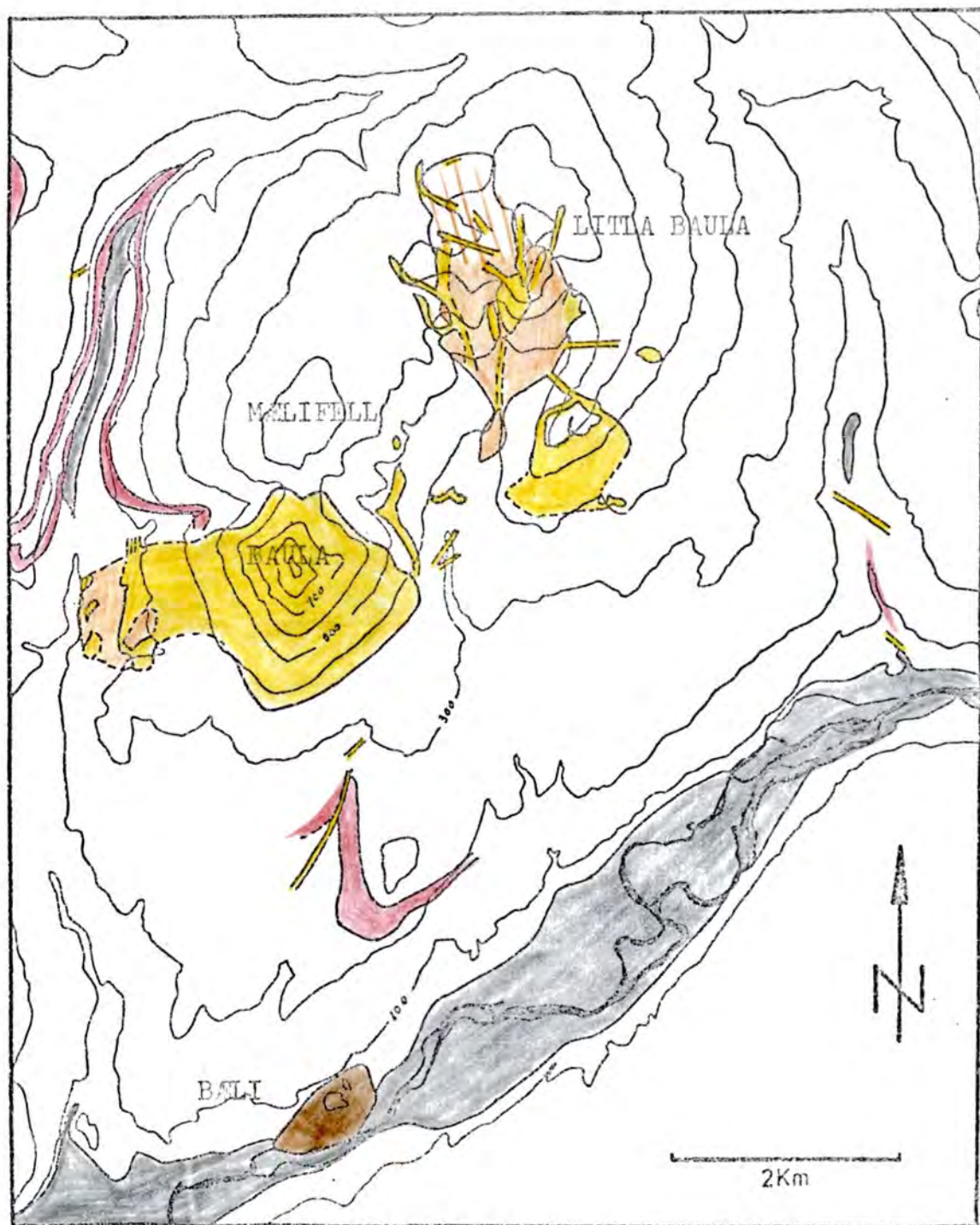




Fig. 5.18 The Baula complex. Baula intrusion (a), Litla Baula vent (b), and Skildingafell (c). The Grabrok Recent lava field is in the foreground.

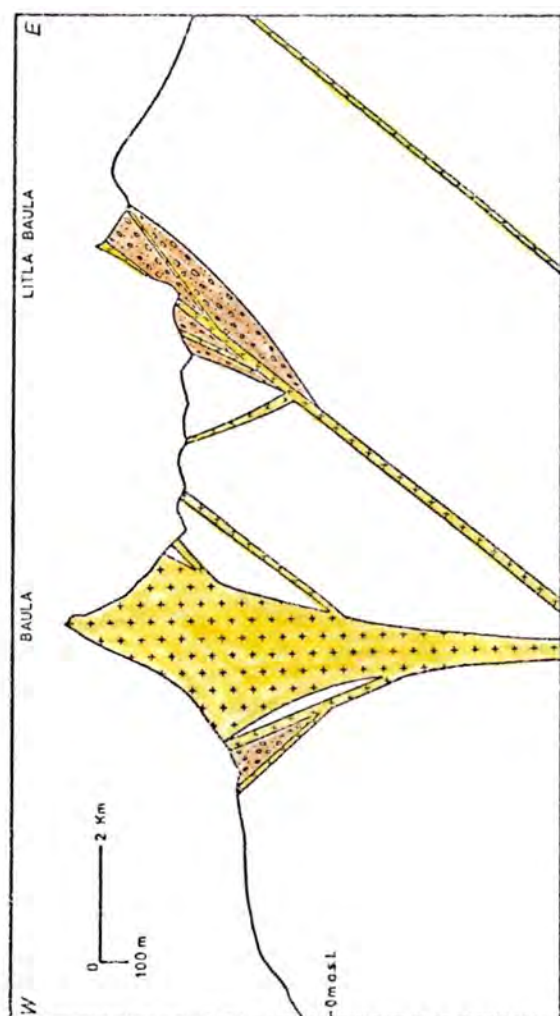


Fig. 5.19 A schematic section across the Baula complex. Yellow, rhyolitic intrusion and dykes; brown, rhyolitic vent breccias.

surrounding basalt flows, some reaching tens of metres in width.

The rhyolitic breccias consist mainly of small rhyolitic blocks in fine ash-like matrix. A sedimentary bed about 25 m thick occurs on the north side of Litla Baula. This was deposited in a valley cut into the Tertiary lava pile. The sediment consists of light-brown clay, with varying amounts of acid pumice and ash. The bed is laminated, and it dips slightly towards the mountain slope. The sediment merges with the breccia found on the southern slope and it may thus be of similar age to the eruption which formed the breccia. Rhyolitic dykes were intruded into the vent towards the end of the eruption. They cut both the breccia and the sedimentary bed. The dyke contacts consist of perlite, which suggests rapid cooling in a subaqueous or subglacial environment. Two basic and a few normal faults cut the vent breccias and the sedimentary bed.

Further west, on Hundadalshéidi, two near-circular rhyolitic vents are found, lined with obsidian. They are less than 20 m in diameter and may be related to the Baula complex.

Age Relations

A simple stratigraphic sequence is constructed in Fig. 5.20. It shows the palaeomagnetism of the various series and the age sequence of the main events in the life of the volcano. The palaeomagnetic polarity was measured by a fluxgate magnetometer but due to secondary magnetism in the rocks, caused by hydrothermal alteration, the results are probably not reliable. K. Albertsson (Ph.D. thesis, in prep.) has K-Ar-dated six samples from the volcanic sequence of the volcano. The datings are listed in Table 5.1.

The main episodes in the activity of the volcano can be dated by combining the palaeomagnetism and the K-Ar dates. The Main Phase of differentiated extrusives are dated from 5.2 to 5.8 m.y. old (i.e. Epoch 5), and the event may have lasted for a few hundred thousand

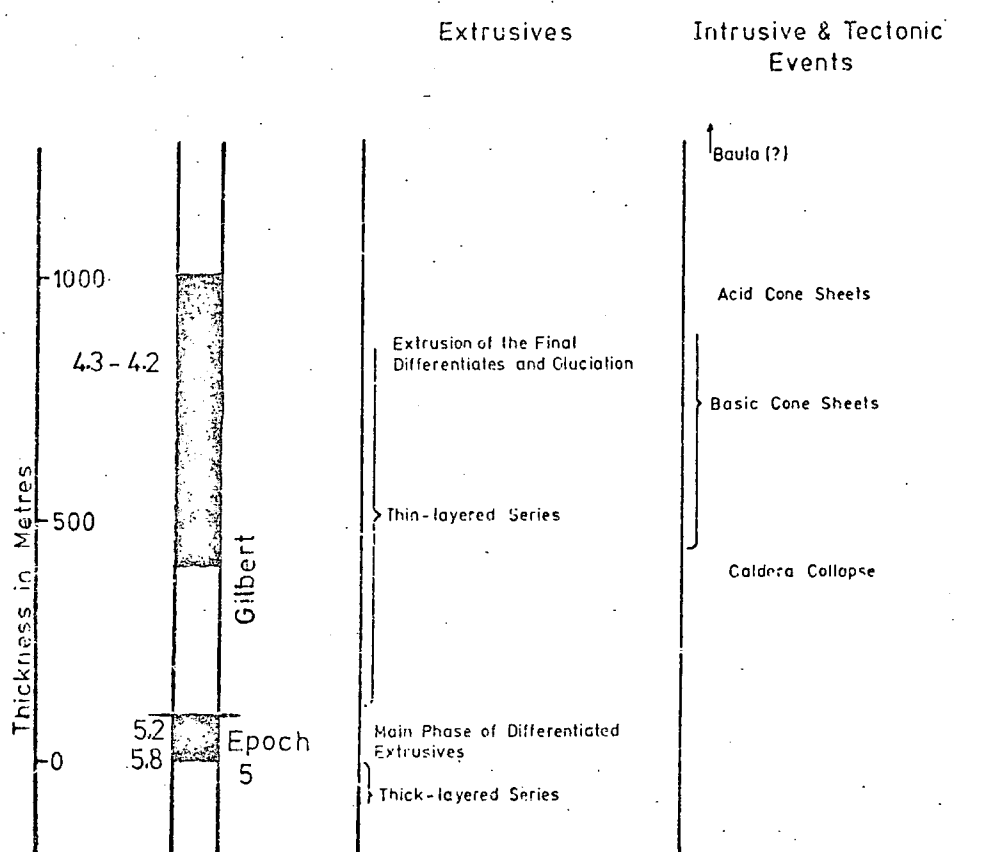


Fig. 5.20 A schematic diagram showing the main extrusive and intrusive events of the Reykjadalur central volcano, along with the palaeomagnetic polarity of the sequence and the available K-Ar datings.

H-24	(no. 85)	4.81 ± 0.13 m.y.
V-11	(no. 253)	5.79 ± 0.14 m.y.
M-4	(no. 170)	5.16 ± 0.15 m.y.
H-57	(no. 117)	4.34 ± 0.12 m.y.
H-16	(no. 79)	4.43 ± 0.18 m.y.
B-10	(no. 10)	3.39 ± 0.17 m.y.

- H-24 Icelandite flow in the gorge of the Haukadalsa river, north of Harrastadir.
- V-11 Icelandite flow from Einiberjagil in Vesturardalur. At the bottom of the Main Phase of differentiated extrusives.
- M-4 Icelandite flow from Beigaldagil in Austurardalur. Near the top of the Main Phase of differentiated extrusives.
- H-57 Icelandite flow from the top unit of the caldera filling, on the eastern side of Gamalhnukar.
- H-16 Olivine tholeiite flow from Svarthamar on Jörvamuli, overlying the tillite horizon in the thin-layered series.
- B-10 Baula rhyolitic intrusion.

Table 5.1 K-Ar ages of some rocks from the Reykjadalur central volcano. The numbers in brackets refer to chemical analyses in the Appendix. From K. Albertsson, Ph.D. thesis in prep.

years, according to these datings. The topmost volcanics of the caldera filling are about 4.3 to 4.4 m.y. old (i.e. Gilbert) and the Baula intrusion is as young as 3.4 m.y. The K-Ar date of the icelandite flow, in the gorge of the Haukadalsa river, is definitely far too young because the rocks overlying the flow are as old as 5.8 m.y. The true age of the flow may be in the region of 6.5 to 7.0 m.y.

It is not known at what time the caldera collapse took place. It is likely that it occurred after the extrusion of the Main Phase of the differentiated rocks and that subsidence had ceased by the time of deposition of the pillow lava and hyaloclastite horizon in the upper part of the thin-layered series. It is more than likely that subsidence was a gradual process, spanning thousands of years.

The glaciation, which occurred at the end of the activity of the Reykjadalur central volcano, is dated at about 4.3-4.4 m.y., which is considerably earlier than the onset of the Quaternary Ice Age which started about 3.0-3.1 m.y. ago (McDougall and Wensink, 1966).

The Baula complex is, according to the K-Ar-datings above, considerably younger than the other volcanics related to the Reykjadalur volcano, and it may be that Baula is related to the Snaefellsnes volcanic zone (fracture zone) which, according to Sigurdsson (1970)a, became active about 2.0 to 2.5 m.y. ago. The age difference, however, discourages postulating such a relationship.

If the Baula complex is excluded, the life-span of the Reykjadalur central volcano would have been in the region of 1.5 m.y., which is a much longer life-span than the 0.5 to 1.0 m.y. reported for other central volcanoes in Iceland (Saemundsson and Noll, 1974; Piper, 1971).

CHAPTER 6:

THE HOLTAVÖRDUHEIDI SEDIMENTARY HORIZON AND THE SNJOFJÖLL VOLCANIC SERIES

In the area east of Reykjadalur, in Holtavörduheidi and further east and south from there, is a thick sedimentary horizon which is of the same age as the tillites and the hyaloclastites around the Reykjadalur central volcano. Unconformably on top of the sedimentary horizon is a series of basalt flows and hyaloclastites of Matuyama age (Snjofjöll volcanic series).

Holtavörduheidi sedimentary horizon

This horizon rests on a group of plagioclase-phyric flows (R-magnetized), 20-30 m thick, and thin red beds which intercalate with the flows. The flows and the red beds rest on a 2 m thick layer of rhyolitic ash which can be traced westwards where it passes into a 10-20 m thick sedimentary bed, consisting of sandstone and fine conglomerate.

Towards the south the Holtavörduheidi sedimentary horizon becomes thinner and splits into 3-4 distinct horizons separated by units of basalt flows (see Chapter 3). The sediments were traced as far east as the gorge of the Hrútafjardara river where the sediments disappears down-dip; here the horizon rests on a thick series of thin olivine basalt flows which are part of a larger lava shield. At the head of Nordurardalur the horizon rests on an intermediate lava flow (N-magnetized). Towards the west the sedimentary horizon splits into two parts (Fig. 6.1). The lower one can be traced up the slopes of the Reykjadalur central volcano where it passes into the tillites and hyaloclastites described in Chapter 5; the upper one underlies the Snjofjöll series and rests on a 100 m thick (approx.) group of thin tholeiite flows (N-magnetized) from the Reykjadalur central volcano (Fig. 6.1), separating it from the lower part.

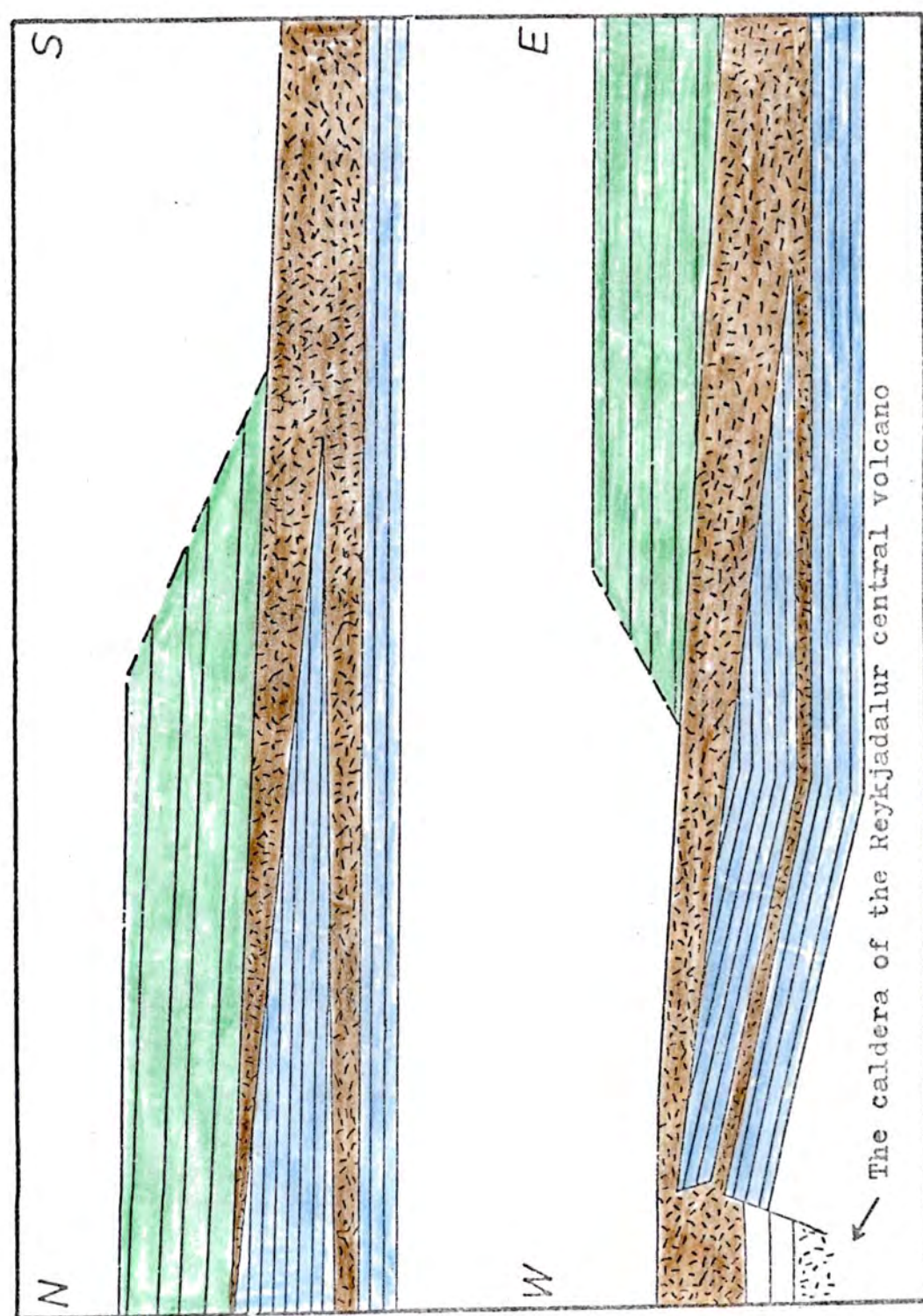


Fig. 6.1 Two schematic sections through the pile east of the Reykjadalur central volcano, in the Snjofjöll-Holtavörðuhéidi area (not to scale). Green: the Snjofjöll volcanic series; blue: the Reykjadalur thin-layered series; brown: the Holtavörðuhéidi sedimentary horizon and the contemporaneous rocks of the Reykjadalur central volcano.

There are great vertical and lateral variations in the sedimentary horizon and interbedded with the sediments are a few lava flows and hyaloclastites. In most parts of the horizon, three distinct divisions can be observed:

(a) The bottom of the sedimentary horizon is nearly always a tillite/conglomerate layer (Figs. 6.2 and 6.3), whose thickness varies from 2 to 10 m. The rock fragments are angular to rounded and up to 2 m in diameter. The layer shows very poor lamination and sometimes no lamination at all. The matrix consists of tuff, silt or fine grained sand. The underlying flows, where exposed, have had their rubbly top cleared off, but their surface has not been polished. This layer has been traced westwards and is probably the same as the tillite just outside the caldera rim of the Reykjadalur central volcano.

(b) Basic and intermediate hyaloclastites, pillow lavas and irregularly columnar jointed flows (entablature type, N-magnetized) overlie the tillite/conglomerate layer. The thickness varies laterally from a few metres to over 50 m. A single lava flow may change from hyaloclastite/pillow lava type through entablature type, suggesting an aqueous environment but not a deep lake, to ordinary subaerial flow. The intermediate flows have their origin nearby in the Reykjadalur central volcano, of which they constitute one of the lateral units.

(c) The bulk of the sedimentary horizon consists of sandstone, fine grained conglomerate, and in some places clay and siltstone occur. The sandstone, which forms the main part of this unit, is usually crossbedded and ripple-marks are very common. The thickness of the unit varies from 50 to 150 m or even more. The conglomerates contain boulders of various sizes (Fig. 6.4), embedded in a silty or sandy



Fig. 6.2 Tillite-like conglomerate at the base of the Holtavörduheidi sedimentary horizon, in Burfellssainnri in Nordurardalur. Note the gradual decrease in the number of boulders upwards.



Fig. 6.3 Tillite at the base of the Holtavörduheidi sedimentary horizon in Hvassardalur. Note the subangular to rounded shape of the boulders.



Fig. 6.4 Conglomerate interbedded in the sandstone of the Holtavörduheidi sedimentary horizon, at the head of the Nordurardalur.

matrix. The boulders are rounded and suggest transport by water. Interbedded with the sandstone are siltstone and numerous seams of lignite (up to 1 m thick) accompanied with three trunks; leaf impressions are common in the sandstone and siltstone. In the gullies at the head of Nordurardalur, thin layers of rhyolitic ash and diatomite are present and an ignimbrite layer was found in the innermost part of Thverarhlid (5-10 m thick).

Tr. Einarsson (1962) described part of these sediments and the interbedded flows and suggested a relatively young age for them, i.e. later Pliocene or early Pleistocene. Pflug (1959) has analysed lignite material from this horizon and found a "cool" flora with conifers, similar to that of Breidavik in Tjörnes. Einarsson (1962), however, points out that while the Breidavik flora refers to low ground, the flora of Holtavörduheidi could refer to much higher elevation, in which case its cool character is not necessarily an indication of recent age.

The Holtavörduheidi sedimentary horizon is in many aspects similar to the sands of the outwash-plains in southern Iceland today. It must be concluded that at the early stage of the formation of the sediments, a glacier was present on top of the Reykjadalur central volcano and covered at least the area east to the gorge of Hrútafjardara and the innermost part of Thverarhlid. Subglacial and/or subaquatic eruptions took place in the area, especially at the early stages. The volcanic activity was greatest in the Reykjadalur central volcano, where mountains of hyaloclastites were formed underneath the glacier. These loose materials were easily eroded and transported by glaciers and streams; the material was then deposited on the outwash-plain, probably after the glaciers had been reduced in size and were only confined to the high ground around the volcano.

The rivers constantly dug channels into the outwash-plain, along

which lava flows found their way. This is common in the upper part of the succession where compound lava flows (R-magnetized) flowed along some of these channels. These flows have their origin in the area north of Snjofjöll, where they have a much greater extent.

The sedimentary horizon was covered by younger rocks of which we have little or no traces left, due to severe erosion during the early part of the Quaternary glaciation until the formation of the Snjofjöll series.

There is a marked difference in the intensity of normal faults between the underlying strata and the strata on top of the sediments, suggesting a lower rate of faulting after the sediments had been laid down. The Snjofjöll series rests unconformably on top of the sediments in the area at the head of Nordurardalur; in the northern part of Thverarhlid, Tertiary lava flows lie unconformably on top of the sediments, but further south the unconformity gradually disappears. The sedimentary horizon thus represents a discontinuity in the volcanic production of the area. The length of this break is difficult to assess but the age difference between the underlying and the overlying volcanic series becomes greater towards the north. The volcanic activity did however, not cease altogether in the area. Later, a few basaltic plugs intruded the sediments.

The proposed glaciation, represented by the tillite near the base of the sediments, took place about 4.3-4.4 m.y. ago, which is considerably older than the oldest previously described of 3.1 m.y. (McDougall and Wensink, 1966; Saemundsson and Noll, 1974).

The Snjofjöll volcanic series

In the Snjofjöll area a late Quaternary volcanic series rests unconformably on top of the Holtavorduheidi sedimentary horizon. The

thickness of the series is about 350 m but the topmost part has been removed through glacial erosion. The series consists of olivine-rich subaerial lava flows, and hyaloclastites and pillow lavas formed under glacial conditions (Fig. 6.5). The hyaloclastites usually rest on tillites which in turn overlie a polished surface of the lava flows below.

The flows in the lower half of the series are rather thick and have a rubbly top, and red beds occur interbedded with them. On top of the platform south of Tröllakirkja, a 5-10 m thick sediment occurs, which consists of conglomerate and sandstone; it is poorly exposed and could possibly be of glacial origin. Higher up in the pile the lavas are overlain by a tillite, hyaloclastite, and pillow lava (Fig. 6.6). The tillite is reddish in colour and rests on a polished surface of the underlying flow (Fig. 6.7), and is usually less than 1 m thick. On top of the tillite lies a subglacial facies of the basaltic volcanism, with a pillow lava at the bottom and a hyaloclastite-breccia above. The thickness of the horizon varies from 20 m in the southern part of the area to 100 m in the northern part (Fig. 6.6). On top of the glacial horizon rests a 100-150 m thick sequence of basalt flows which have buried the uneven topography of the hyaloclastites. At the top of Tröllakirkja is the second tillite horizon above which are, again, hyaloclastite and pillow lava.

Normal faults, striking N-S, cut through the whole succession and are therefore younger than the pile. One basalt dyke (with N-S direction) was found near the top of Tröllakirkja, cutting through the topmost hyaloclastite.

The palaeomagnetism of the lava flows and the hyaloclastites are shown on Fig. 6.5; the lower part is R-magnetized and the upper part is N-magnetized but the dyke at the top of the series is N-

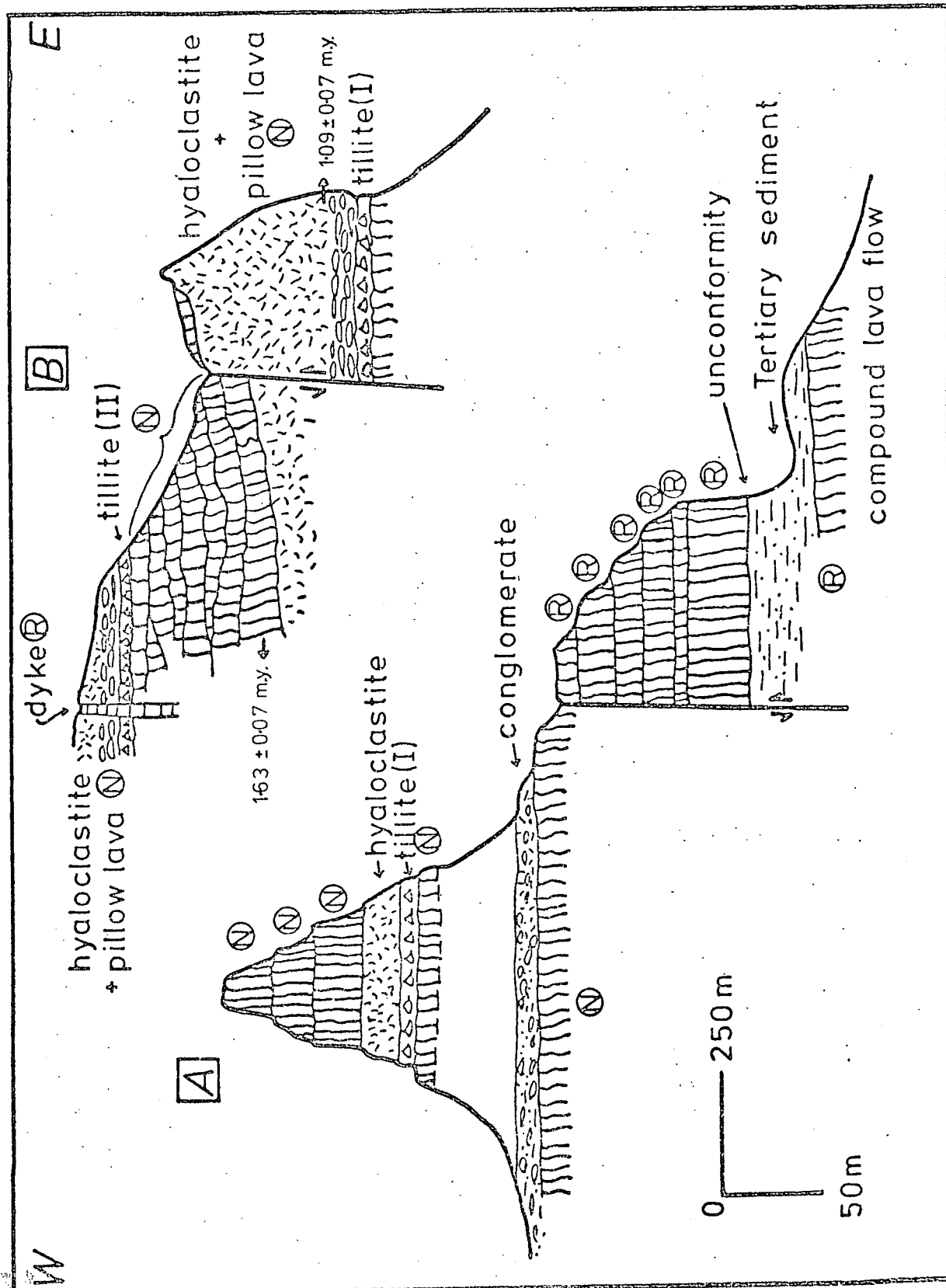


Fig. 6.5 Two schematic sections through the Snjofjöll series, in the Tröllakirkja area (rough scale). A: section through the southernmost part of Tröllakirkja; B: section through the northernmost part of Tröllakirkja. R and N are reversely and normally magnetized rocks, respectively.



Fig. 6.6 Northernmost part of Tröllakirkja (see Fig. 6.5, section B), consisting of the lower hyaloclastite horizon (about 100 m thick; a) and the overlying succession of lava flows (b).



Fig. 6.7 The base of the hyaloclastite horizon in Fig. 6.6. The hammer is resting on a polished surface of the underlying flow (a), followed by $\frac{1}{2}$ m of reddish tillite (b) which is overlain by pillow lava and pillow breccia (c).

magnetized. K. Albertsson (Ph.D. thesis in prep.) has made a K-Ar dating of two samples from the lower hyaloclastite/pillow lava horizon and from the overlying lava flow (Fig. 6.5). Preliminary values give an age of 1.09 ± 0.07 m.y. and 1.63 ± 0.07 m.y., which is upper Matuyama.

The datings indicate that the normally magnetized sequence either correlates with the Jaramillo or with the Gilsa event of the Matuyama epoch. A correlation with the Gilsa event is tentatively favoured because this long normal event is in better agreement with a sequence exceeding 150 m in thickness.

The Snjofjöll series must have been a part of a much bigger lava pile, formed during the latter half of the Matuyama epoch. Interglacial lava flows are found scattered over wide areas in northern and northwestern Iceland (Kjartansson, 1965), resting unconformably on top of the Tertiary lava pile. Some of these interglacial flows have been dated (Everts et al., 1972) and they are of middle or late Matuyama age. This suggests that at the end of the Matuyama epoch, the main part of the area from Snjofjöll to Hofsjökull in central Iceland, north to the valleys of Hunaflói and possibly all the way to the coast, was covered by young lava flows and hyaloclastites, resting unconformably on top of the Tertiary pile.

The tectonic framework within which this series originated is obscure because its position does not conform with the present pattern of the active volcanic zones. One possible explanation is that the volcanism in the Snjofjöll area developed on a transverse zone across central Iceland, continuing into the Snaefellsnes peninsula. The young volcanism there started about this time, after a lapse in the volcanic activity and a considerable early Quaternary erosion (Sigurdsson, 1970a).

CHAPTER 7:

THE LAUGARDALUR CENTRAL VOLCANO

The Laugardalur central volcano, located about 5 km west of the Reykjadalur central volcano (Fig. 2.3), was visited during a three days reconnaissance. The western part of the volcano is still completely unknown and the eastern part was mapped roughly. Based on this reconnaissance, an outline history of the volcano could, however, be established.

The eastern part of the volcano exposes a caldera and its filling, but no activity, prior to the caldera collapse, has been identified as part of the volcano. The caldera, which is about 10 km in diameter, is filled with sediments, intermediate lava flows and basic intrusions (Fig. 7.1). Stratigraphically the volcano can be divided into six groups:-

- (1) The caldera floor consists of thin tholeiite and plagioclase-phyric flows, which are not separable from the upper part of the Reykjadalur thin-layered flank succession. The regional dip outside the caldera is $3-4^{\circ}$ towards the north and northeast, but the dip changes across the caldera rim to about 25° into the caldera. The caldera rim is expressed as a tectonic flexure, on the eastern and southern side of the volcano (Fig. 7.2). Circular faults are present but the down-warping has been very gentle with little or no vertical displacement. The caldera rim on the northern side is, however, different and the underlying series have been cut by arcuate faults and differentiated cone sheets.
- (2) The oldest rock exposed inside the caldera is a green ignimbrite, at the mouth of Fotadalur. It contains numerous xenoliths, both granophyric and basic. The lateral extent of this layer is not known.

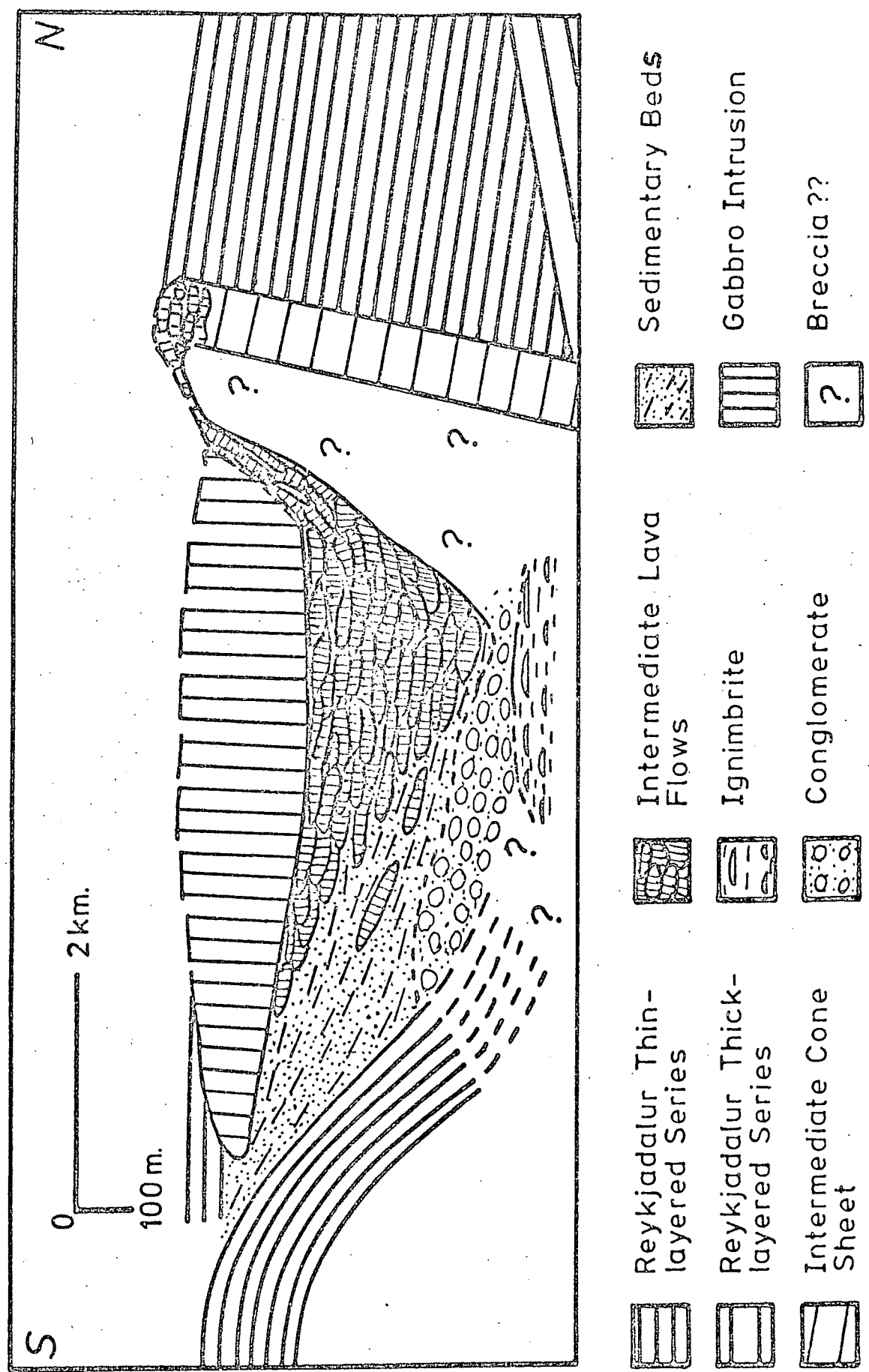


Fig. 7.1 A schematic N-S section through the Laugardalur central volcano. Note how the intermediate lava flows originate from the top of the cone sheet.



Fig. 7.2 The southern caldera rim of the Laugardalur central volcano. Note the joint in the centre of the photograph (arrowed), which shows little or no vertical displacement. The lava flows on the left of the joint dip about $3-4^{\circ}$ but about 25° on the right (into the caldera).

(3) The central and southern part of the caldera is occupied by a prominent sedimentary bed, which overlies the caldera floor. In a few places near the centre of the caldera, a coarse conglomerate is found which belongs to this group. The boulders may reach 5-10 m in size and the matrix is tuffaceous. Mingled with the boulders are pieces of rock with chilled margins, clearly from pillow-like bodies. The main part of the sedimentary bed consists of a layered siltstone and sandstone, but a fine-grained conglomerate is present in places. The present exposed thickness is about 100 m but overlying the bed is a gabbro intrusion which might have replaced part of the sediments (Fig. 7.3).

(4) Intermediate lava flows overlie the sediments. These are particularly prominent opposite Fotadalur, where they are at least 200 m thick, and are capped by a gabbro intrusion. Mixed with the lava flows are basic and intermediate hyaloclastites. The lava flows themselves have ponded into a lake, and they form sausage-like bodies (4-10 m thick) separated by breccias of the same lava flow.

(5) Some of the intermediate flows probably have their origin in some of the huge cone sheets (predominantly pitchstone sheets) encircling the eastern and northern caldera rim. The cone sheets, which are intermediate to rhyolitic in composition are thick, often 100 m, and each sheet is formed by means of multiple injection of magma during an eruption. Near the top of Hestur, one of the cone sheets displays a horizontal banding, which could probably be caused by the magma flowing horizontally from a vent down into the caldera lake (Fig. 7.1). Granophyric xenoliths can be found enclosed in the cone sheets and also in the intermediate flows.

(6) A basic magma was intruded into the rather loose caldera filling and formed a laccolith-type gabbro intrusion. The intrusion is at



Fig. 7.3 Tröllkonuskard in Laugardalur. A thick gabbro intrusion overlying intermediate lava flows and sedimentary beds.

least 200 m thick. The main host rock for the intrusion is the sediment, but it has also intruded the intermediate flows. The laccolith dips $2-3^{\circ}$ towards the northeast.

The age of this volcano relative to the Reykjadalur central volcano is obscure, although it seems to be slightly younger. The thin tholeiite flows, forming the floor of the caldera, are normally magnetized and belong probably to Epoch 5. A negative magnetic anomaly has been detected over the volcano (Fig. 2.5) which most likely is caused by a reversely magnetized intrusion, probably the one exposed inside the caldera. These supposed reversely magnetized rocks would presumably belong to the lower part of the Gilbert epoch (less than 5 m.y.).

No basic intrusions other than the gabbroic laccolith are present in or around the caldera, apart from a few dykes, most of which are younger than the volcano. The lack of such is reflected also in the complete absence of a high grade metamorphic aureole but, instead, an undisturbed zeolitic zonal assemblage.

However, minor changes occur in the gravity field over the volcano (Fig. 2.4).

The mechanism of the caldera collapse is also quite different from that of the Reykjadalur caldera. The northern part of the caldera collapsed along a clearcut fault. Debris from the fault walls accumulated on the bottom of the depression. At the same time the southern part of the caldera foundered along a curved flexure, indicated by a change in dip of the lavas across the rim.

Water accumulated in the depression, forming a caldera lake where subsequent subaqueous eruptions took place and into which lavas from the surroundings ponded and were partly brecciated upon contact with the water.



Erosion also took place in the areas outside the caldera and the material was subsequently transported by means of water into the caldera, forming the sediment. The sediment fans filled mainly the southern part of the caldera, probably because of a higher topography south of the caldera at the time of its formation. The caldera then gradually filled with sediment and lavas and in the end was buried altogether by lava flows, probably followed by the intrusion of the gabbro.

The magmatic processes that led to the Laugardalur caldera collapse are unknown. One might speculate that this collapse caldera was a parasite to the Reykjadalur central volcano, or perhaps the central activity shifted slightly westward at the time of decreasing activity in the Reykjadalur area.

CHAPTER 8:

LATE QUATERNARY AND RECENT VOLCANISM

Volcanic activity was revived in the south-western part of the research area in late Quaternary times. The activity is part of the volcanic zone or Snaefellsnes fracture zone which started in the outer parts of the Snaefellsnes peninsula in early Matuyama (Sigurdsson, 1970a) and stretched from there inland to join the main rifting zone near Langjökull (see Chapter 10, Fig. 10.6). The central part of the zone soon faded out and the main activity in late Quaternary times has taken place in the outer parts of the Snaefellsnes peninsula, decreasing south-eastwards and disappearing altogether east of Nordurardalur. The extent of this volcanism is shown on the geological map of mid-western Iceland (Kjartansson, 1968). Four formations belonging to this group occur in the research area (Fig. 8.1) and a few more in Langavatnsdalur:-

1. Baeli in Nordurardalur has been described by Jonsson (1964). It is a heap of pillow lava and pillow breccia, about 1 km long and 0.5 km wide. In the centre of the heap, a dyke-like body occurs running east-west. The eruption took place beneath a glacier during the latter half of the last glaciation.
2. Grabok lava field is a Recent but prehistoric lava flow in Nordurardalur. The eruption took place through three craters on a fissure stretching NW-SE. The flow is about 6.75 km^2 and it dammed the Nordura river and a lake nearly 15 km long was formed behind it. The river later cut its way through the lava and the lake was drained, leaving behind a flat plain of lake deposits. A C^{14} dating of organic material underlying the flow gives an age of 3700 ± 120 years (Schwarzbach, 1956) but according to the same reference the dating is not particularly reliable and it argues that the eruption occurred between 1100 and 3700 years ago.

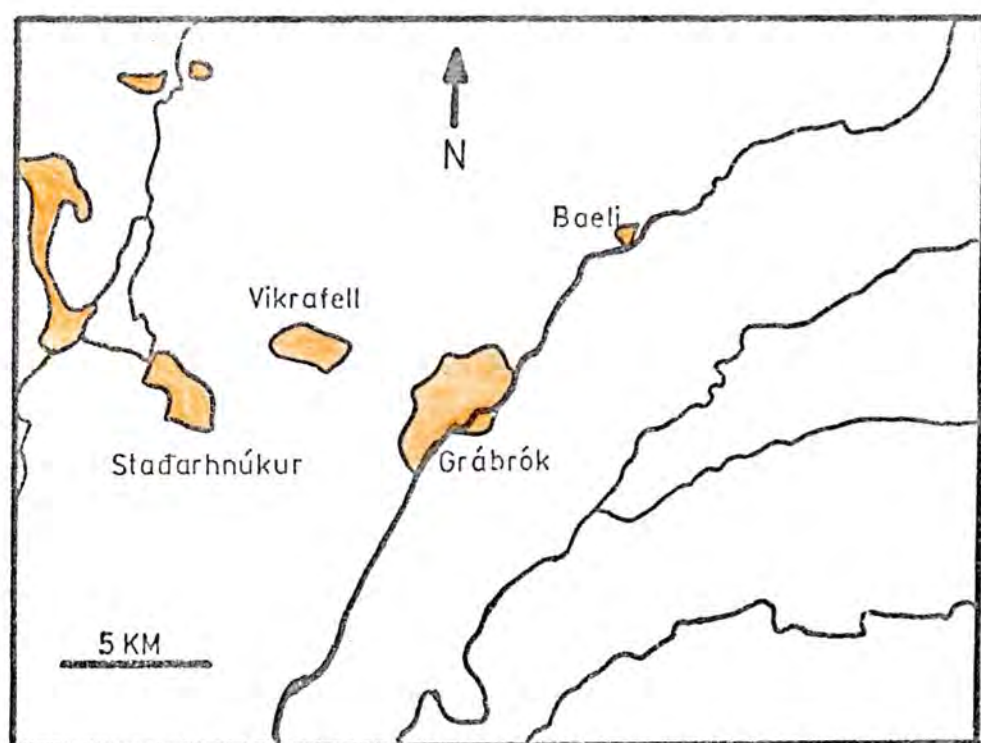


Fig. 8.1 Late Quaternary and Recent volcanics in the Borgarfjörður area.

3. Vikrafell is a 150 m high, WNW-ESE stretching ridge on top of the mountain range west of Lake Hredavatn in Nordurardalur. The base of the formation consists of pillow lava and pillow breccia covered by hyaloclastite. In a depression west of the easternmost peak, a heap of pillows from the very end of the eruption occurs. The eruption took place beneath a glacier, probably near the end of the last glaciation.

4. Stadarhnukur rises about 200 m above its surroundings and consists of lower pillow lava and pillow breccia, and upper hyaloclastite, covered with subaerial lava flow of the same eruption (i.e. Table mountain). On the northern edge of the mountain a WNW-ESE stretching dyke-line feature, about 2.5 km long, occurs. The eruption most likely occurred at the end of the last glaciation. Nearly all the volcanic products are accumulated on the southern, leeward side of the dyke, because the glacier covering the area at that time moved southwards, preventing the volcanics from spreading northwards.

The Recent volcanism outside the domain of the Snaefellsnesjökull central volcano took place along two parallel fault zones (Sigurdsson, 1970b) and the formations in the research area belong to the more northerly zone. The activity on the Snaefellsnes peninsula since the end of the last glaciation has been small compared with the activity in the main rifting zones in Iceland (Jakobsson, 1972). The last eruption took place around the year 900 BP (Eldborg in Myrar; Askelsson, 1955). It seems that the activity is periodic and that the last main outburst of activity occurred about 2000-3000 years ago when many eruptions occurred in the Hnappadalur area (Th. Einarsson, 1970) and once occurred in Nordurardalur, but C^{14} datings are not available from other areas on the Snaefellsnes peninsula.

The so-called Snaefellsnes fracture zone has been explained as the result of a different rate of spreading between north and south Iceland (Sigurdsson, 1970b), caused by only one rifting zone in northern Iceland compared with two in southern Iceland.

CHAPTER 9:

DYKE FEATURES

FIELD RELATIONS

Nearly 1200 dykes have been found in the research area (Fig. 9.1). Each dyke locality was transferred from an aerial photograph to the map and the thickness and direction measured in the field. The width of the dykes varies from 0.25 to 30 m (Fig. 9.2) but more than 60% of the dykes are between 1 and 3 metres wide and only a dozen or so are over 13 m wide.

Walker (1960) has shown that dyke intensity increases with depth in the lava pile in eastern Iceland; the same phenomenon is observed in western Iceland. This is best demonstrated in the area from Hvitarsida to Nordurardalur. The dyke intensity is small in the innermost part of Hvitarsida but increases gradually towards the west (down into the lava pile), until a sharp increase in the dyke intensity occurs west of Nordurardalur. The dykes west of Nordurardalur form a swarm which is associated with the Reykjadalur central volcano. Saemundsson (1974) has suggested that fault swarms associated with recent central volcanoes are presumable surface manifestations of the dyke swarms found cutting the well exposed volcanoes in eastern Iceland (Walker, 1963).

Most of the dykes cut the lava flows at right angles, suggesting that they were injected prior to the tilting of the lavas. Nearly all dykes, if followed along the strike, are en echelon. Nakamura (1970) has described en echelon fissures in the neovolcanic zone in the western Iceland, both eruptive and non-eruptive. The dykes have intruded most of the normal faults. Where the dyke intensity is highest, the dykes only make up 4-5% of the country rocks, which is considerably lower than in eastern Iceland (Walker, 1963).

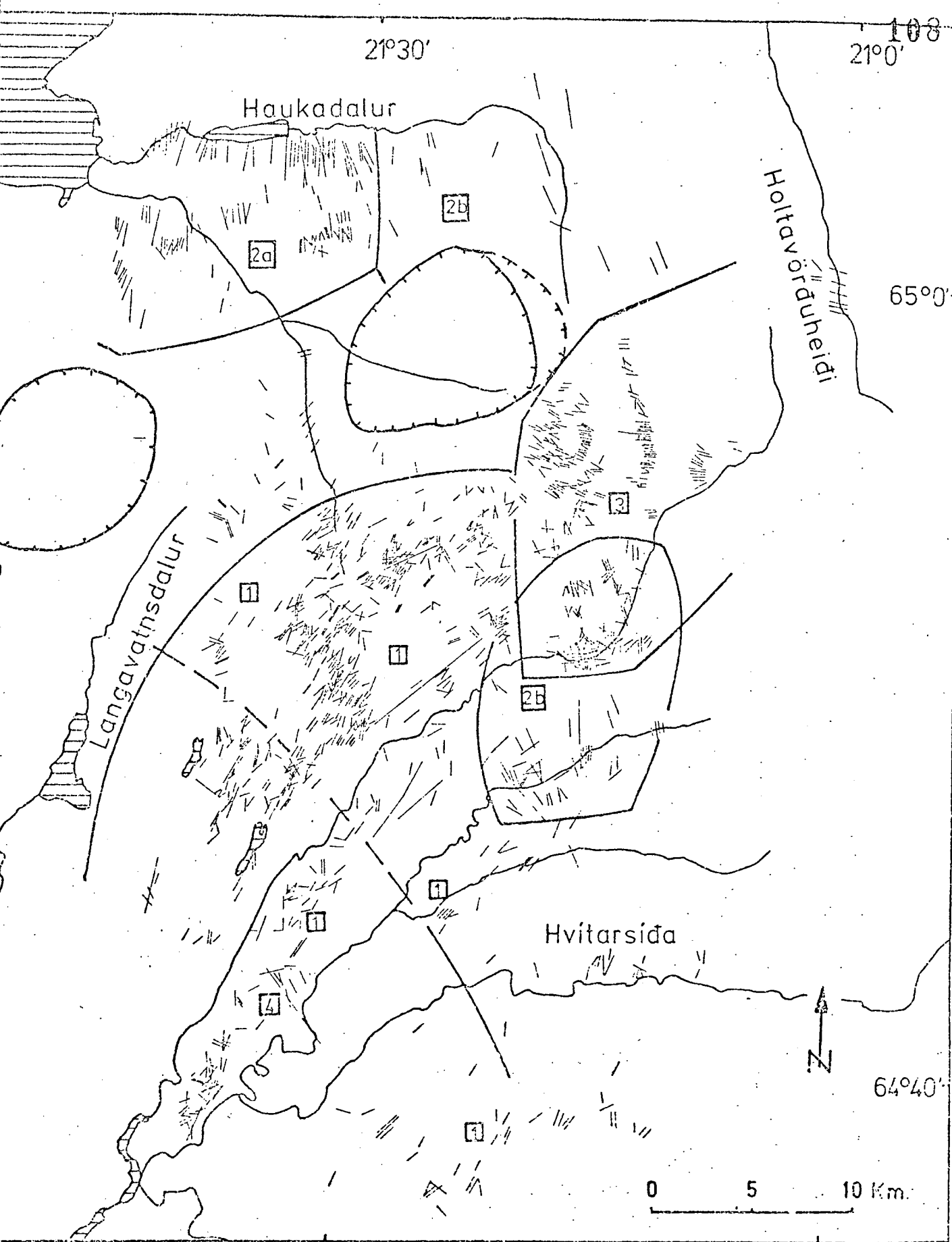


Fig. 9.1 The dyke distribution in the Borgarfjörður-Dalir area. The numbers (1, 2a etc.) represent the various dyke groups referred to in the text.

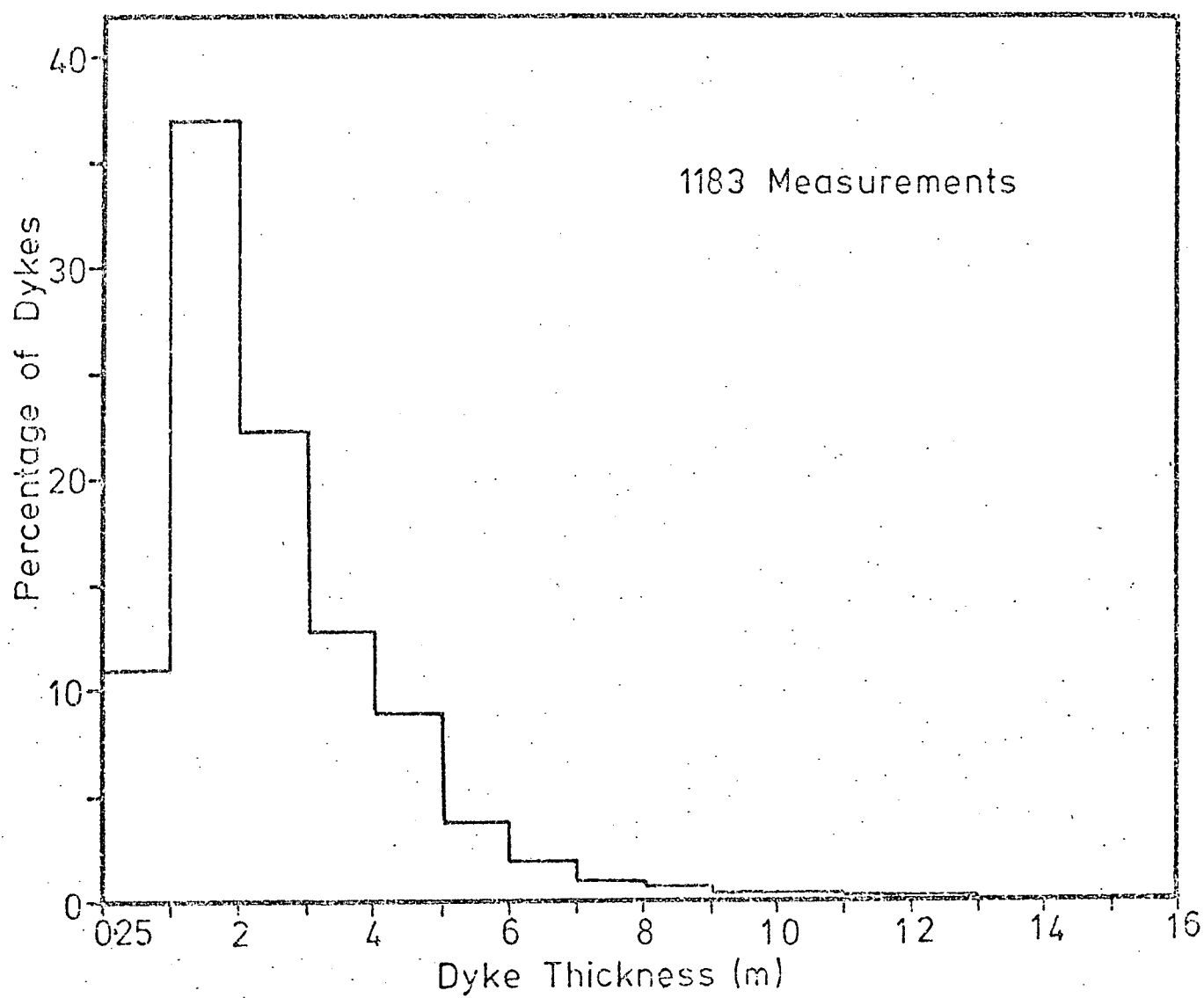


Fig. 9.2 A histogram showing the dyke thickness distribution in the Borgafjörður-Dalir area.

The dykes in the area can be divided into four main groups (Fig. 9.1), based on their direction, geographical distribution and age.

(1) Group 1, NE-SW Trending Dykes

This trend dominates the area south of the Reykjadalur central volcano, and there is considerable deviation within this group. The dyke intensity is low, apart from the dyke swarm west of Nordurardalur, which runs from Hredavatn northeastwards, towards the Reykjadalur volcano. The swarm is 5-7 km wide, but its extension towards the south and west has not been mapped in detail. North of Mt. Baula the trend of the swarm changes from NE-SW to a more easterly direction; finally the dykes disappear altogether further north. On the northern border of the swarm the dykes mingle with the cone sheets from the volcano. The relationship between the dykes and the cone sheets is not clear, but the cone sheets cut the dykes where they intersect.

The swarm is mainly confined to the thick-layered series underlying the volcano and a few dykes cut the overlying thin-layered series. The top of the thick-layered series and the lower half of the thin-layered series were probably produced by eruptions from these dykes.

Many of the dykes are porphyritic, mainly with plagioclase and clinopyroxene phenocrysts. Gabbroic xenoliths are abundant in some of the porphyritic dykes and the phenocrysts appear to have common origin with the xenoliths; a similar phenomenon has been observed in quite a few cone sheets.

(2) Group 2, N-S Trending Dykes

This group can be divided into two subgroups, 2a and 2b.

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Group 2 is rather uniform and deviation from the average trend is small. Group 2a is found in Haukadalur and Hördudalur, forming a swarm whose trend is towards the Reykjadalur and Laugardalur central volcanoes. This subgroup is confined to the thick-layered series and is of the same age as Group 1. Group 2b is found in Nordurardalur and on Grjóthals and a few in the inner part of Haukadalur. These dykes are younger than the dykes of Group 2b and cut the thin-layered series, although their number decreases upwards. Eruptions through these dykes have probably produced the upper part of the thin-layered series in the eastern part of the region. Most of the dykes are aphyric.

(3) Group 3, E-W Trending Dykes

These dykes dominate the area southeast and east of the Reykjadalur central volcano. The deviation from the main trend is small, and most of the dykes are aphyric. The dykes are found in the thin-layered series as far as the thick sediments in the Holtavörðuheidi area and a few dykes cut these sediments as well. These dykes are the youngest in the area along with some of Group 2b, and they always cut the cone sheets where they intersect.

(4) Group 4, NW-SE Trending Dykes

This is a rather obscure dyke swarm in the area southeast of Hredavatn, and extends as far as Skardsheidi. Most of these dykes are considerably more altered than the other dykes in the same area and they are, together with the NE-SW trending dykes, the oldest dykes in the Borjarfjörður area.

Relationships with Tectonic History

The dykes of Group 1 are parallel to the Reykjanes-Langjökull

neovolcanic zone and the dykes of Group 2 are parallel to the now extinct Langjökull-Skagi volcanic zone. These two sets of dykes have thus been formed in a volcanic zone nearly identical to the present zone, and probably located in a similar place, drifting westwards later. Group 2 gives a clue to this drift : 2a is older than 2b and is about 10-15 km further west. The age difference is less than 1 m.y., thus the spreading rate is in the region 1 cm/year which is in good agreement with the estimate of Talwani et al., (1971). The fieldwork suggests, however, that the displacement of the dyke swarm was not a gradual process but involved a jump of about 10 km towards the east.

The only comparable features to the E-W dyke swarm (Group 3) are a few E-W trending eruptive fissures northwest of Vatnajökull (Kjartansson, 1965) and easterly trending faults northwest of Langjökull (Saemundsson, 1967). No faults coincide with the dyke swarm in the research area but a few faults in the Thverarhlid area have an easterly trend. All these phenomena occur where the change from NE-SW to N-S trends of the volcanic zones takes place (around 65°N). These dykes and faults must be interpreted as a tensional feature at right angles to the main rifting.

The dykes of Group 4 are undoubtedly related to the Snaefellsnes fracture zone and indicate that the fracture zone was already active in Tertiary times (Chapter 10).

The direction of dyke swarms in the Vestfirðir area and in western Iceland can be divided into two principal groups (Fig. 9.3). One has a general trend near NW-SW to ENE-WSW and is present in Borgarfjörður, Snaefellsnes and in the southern part of Vestfirðir. The other has a general trend near N-S and is confined to the Dalir area and the northern part of Vestfirðir. The break from

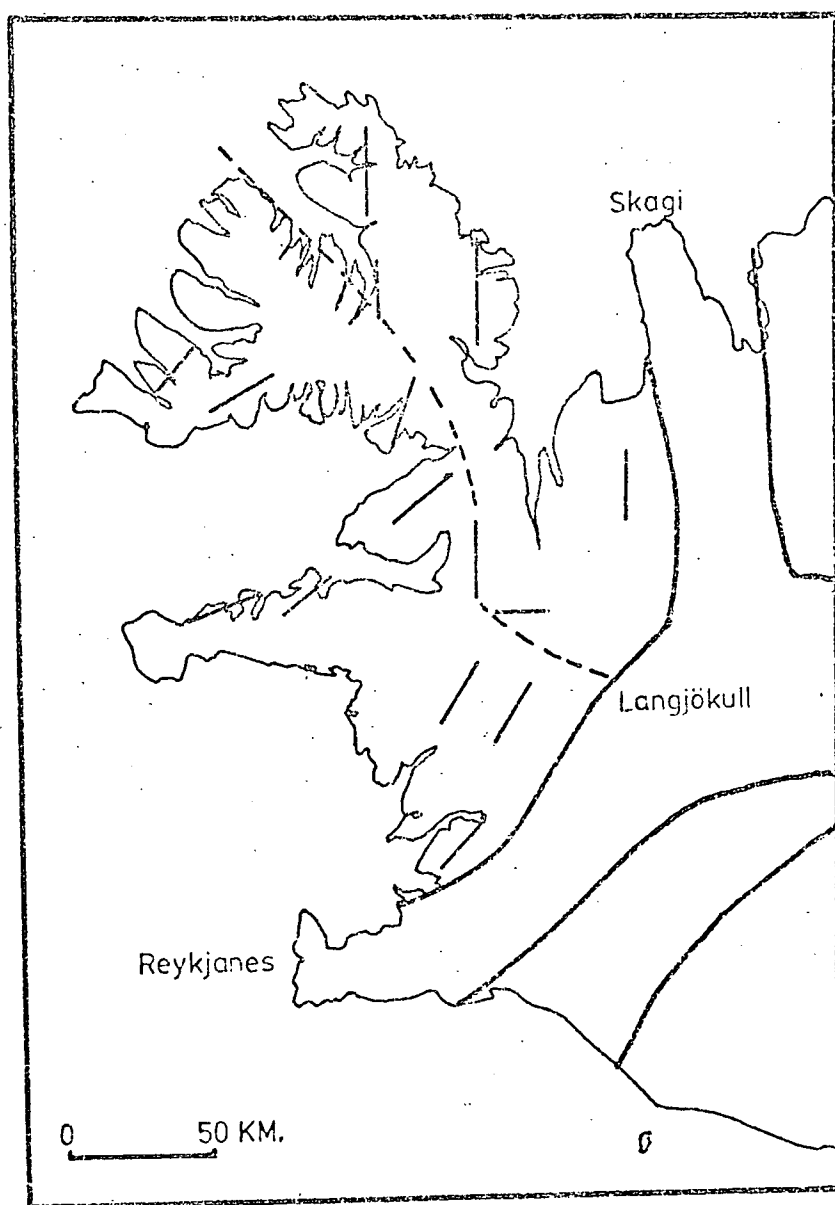


Fig. 9.3

Known dyke swarms in western Iceland and in Vestfirðir (heavy bars). The broken line marks the boundary between the NE-SW and N-S trending dykes. This boundary has migrated southeastward with time.

Sources : Annells, (1968), Friedrich, (1966), Hald et al., (1971), Kristjánsson et al., (1975), Sigurdsson, (1970a) and the author's observations.

NE-SW to N-S moves towards the southeast with time (the broken line on Fig. 9.3), indicating that the volcanic zones themselves have followed a similar pattern, or more correctly that the drift of the plate was towards the northwest.

CHAPTER 10:

TECTONIC FEATURES AND TECTONIC HISTORY

FIELD RELATIONS

The number of faults in the area is enormous (Fig. 10.1) and they display a very interesting pattern. Not all faults have been mapped but Fig. 10.1 is representative of the region, except for the area southeast of the Reykjadalur central volcano, where poor outcrops prevented accurate mapping. There are also a great number of joints with little or no displacement, which are not shown on the map.

The majority of faults observed in the field are normal faults. It can be difficult, however, to distinguish between a normal fault and a transcurrent fault, because the slicken-sides only show the effects of the final movements. The only way to identify a fault as a transcurrent fault is to map carefully its intersection with dykes. If two or more dykes, which are cut by a fault, show a horizontal displacement then the fault can be called a transcurrent fault; however, this is often made difficult by the fact that vertical and horizontal movements can occur simultaneously on most faults. The dip has also to be taken into account. Only two faults have so far been positively identified as transcurrent faults; one is exposed in Kalfagil in Bjarnadalur, where four dykes are offset by about 20-30 m. The other is in the pass between Bjarnadalur and Sudurardalur, where two dykes are offset by about 5-10 m. There are undoubtedly more faults of this type, especially amongst the NW-SE trending examples.

One reverse fault has been positively identified with the possibility of at least two others. It is beautifully exposed on Bani in Haukadalur (Figs. 10.2 and 10.3). The east wall of the fault has been pushed about 50 m up the fault plane, which dips 50° - 60° towards the east. This type of fault has not been described in

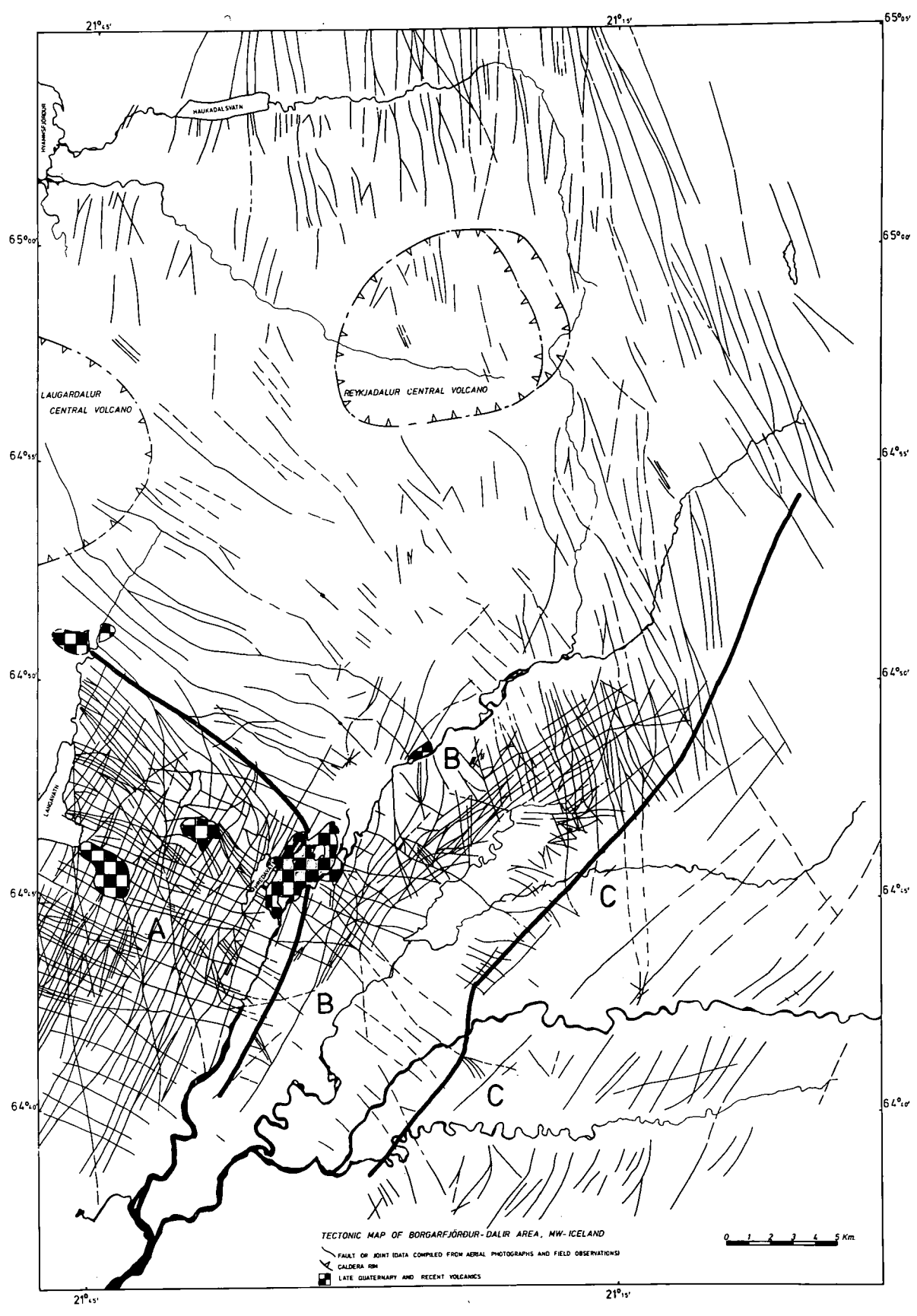


Fig. 10.1 Tectonic map of the Borgarfjörður-Dalir area. The two solid lines represent the Hredavatn beds and the Holtavörðuhéidi sedimentary horizon. A, B and C are areas with different fault density.

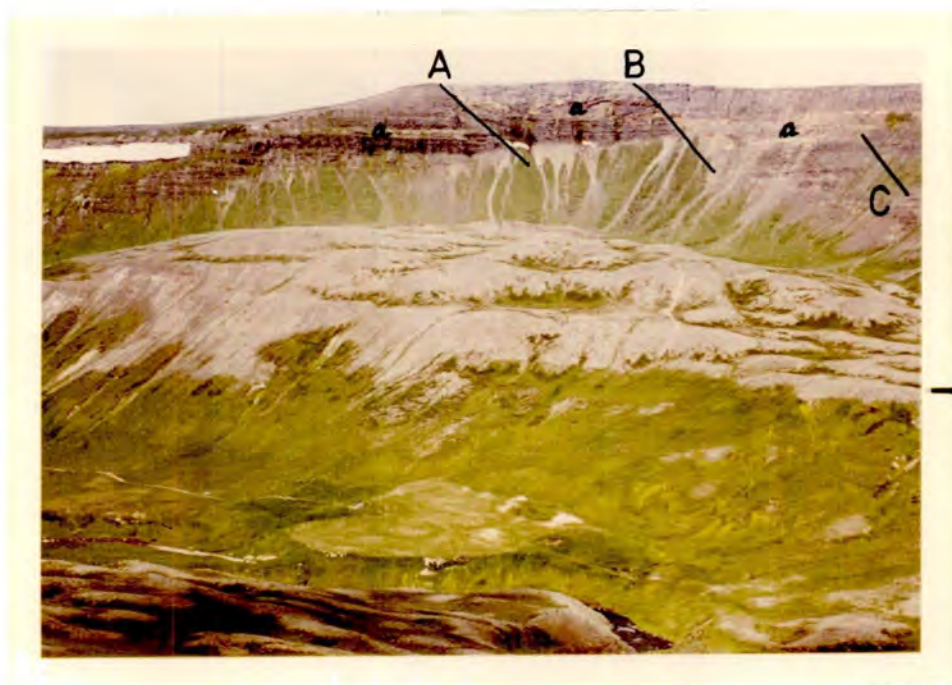


Fig. 10.2 Bani in Haukadalur. Three faults are exposed on the cliff-face. The light-brown layer (a) is a hyaloclastite contemporaneous to the Holtavörðuheidi sedimentary horizon. A: a reverse fault, B: a normal fault, C: a normal fault which was active prior to the formation of the hyaloclastite. The lava flows exposed belong to the upper part of the Reykjadalur thin-layered series and the landslide is of post-glacial age.

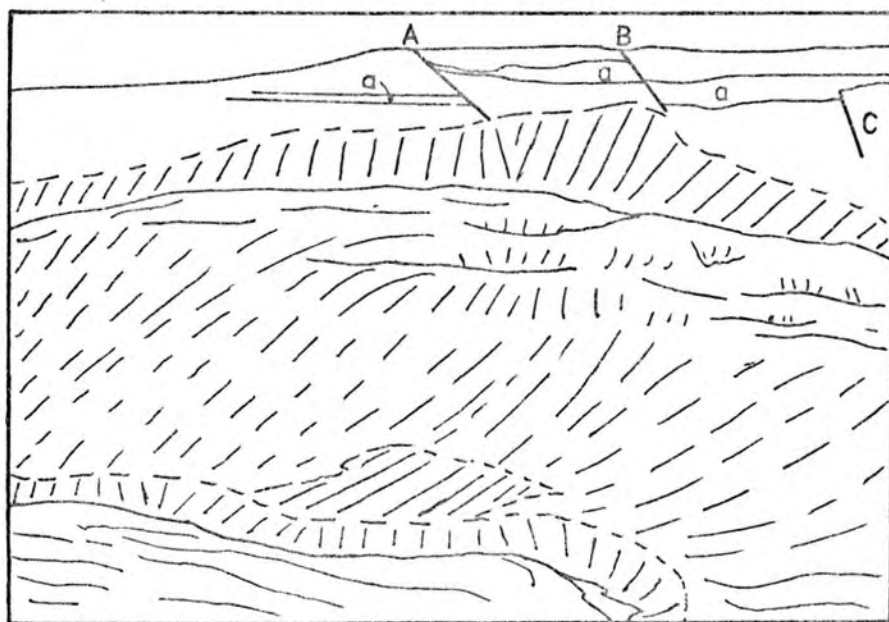


Fig. 10.3 Schematic sketch of Fig. 10.2.

Iceland before, and it indicates a compressional stress field instead of the usual tensional stress field of normal faults. This is puzzling in a region of otherwise obvious tensional tectonics.

The faults can be divided into four groups based on their different trends and geographical distribution (Fig. 10.1); as in the case of the dykes, the groups tend to overlap with each other.

(1) NE-SW trending faults

These occur only in the area south of the Reykjadalur central volcano. The number of faults is small in the southeastern part of the area but they form a prominent fault swarm in the Grjóthals area and west of Nordurardalur. The trend changes from NE-SW to ENE-WSW north along the Grjóthals ridge. The faults belonging to this group in Hvitarsída and Reykholtisdalur have been downthrown on their western side but in the main swarm the downthrow can be on either side. The size of the throw is from 1 to 150 m but most are in the region of 10-50 m. The fault planes are usually perpendicular to the dip of the lava flows which suggest that faulting took place prior to the tilting of the lava flows.

(2) N-S trending faults

These are the only faults found north of the two central volcanoes, but they are found as far south as Thverarhlid; very few are found south of Hredavatn (Fig. 10.1). The faults form a swarm in Haukadalur which cuts the Reykjadalur central volcano, and goes as far south as Grjóthals. The throw of the fault is from a few metres to 100-200 metres. Most examples have nearly vertical fault planes (except for the reverse fault(s)) and fault breccias are often missing (Fig. 10.4). One of these faults is a typical reverse fault (Figs. 10.2 and 10.3), and a few others are probably reverse faults as well.

(3) NW-SE trending faults

These faults are found in the southern part of the research area,

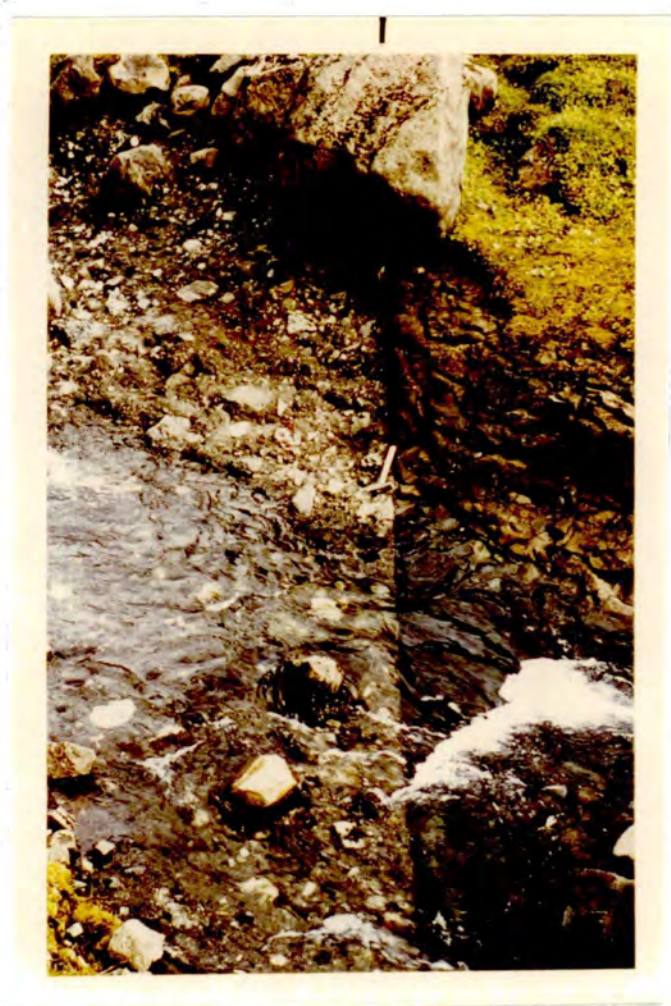


Fig. 10.4 A fault between a talus-breccia and a hyaloclastite inside the Reykjadalur caldera at the head of Reykjadalur. Note the remarkable linearity of the fault and the absence of fault breccia.



Fig. 10.5 The Dyngja fault (arrowed), west of Hredavatn. The flows on the left of the faults cannot be correlated to the flows on the right of the fault.

and form a distinct swarm west and southwest of Hredavatn, which dies but gradually towards the southeast and disappears altogether at the mouths of Hvítarsíða and Reykholtisdalur. The two transcurrent faults found in the area belong to this group, and also there is the possibility of others being present. Both these transcurrent faults show right-lateral movement. The throws of the normal faults are generally 10 to 75 m but a few are greater. The throw of one of the faults could not be established precisely but it exceeds 250-300 m. This fault has been named the Dyngja fault (Fig. 10.5); when traced towards the east from Dyngja it disappears suddenly underneath the volcanics which were erupted inside the graben (underneath the Hredavatn sedimentary horizon). The fault planes are mostly vertical.

(4) E-W trending faults

A few of these faults have been found in the Thverarhlid area and very little is known about them; they could possibly be part of the NW-SE trending fault swarm.

Tectonic relationships

As in the case of the dykes (Fig. 9.3), a good correlation between the trends of the active volcanic zones and the trends of the faults, in the research area, is present. The faults of Group 1 are parallel to those of the Reykjanes-Langjökull neovolcanic zone and the faults of Group 2 are parallel to the faults and fissures of the area north of Langjökull and Hofsjökull.

The faults of Group 4 have been partly dealt with in Chapter 9, and they could either be related to an E-W feature which is present at about 65°N , across central Iceland, or they could be a part of the NW-SE trending faults, bending more towards the east.

The NW-SE trend (Group 3) is part of the so-called Snaefellsnes "fracture" zone (Sigurdsson, 1970b; Ward, 1971) and has been explained

as the result of different spreading rates north and south of the zone (Sigurdsson, 1970b); it has also been regarded as a relatively young phenomenon.

The age relations between the various fault groups and within each group are complicated but they shed light on the origin of the fault systems and on the volcano-tectonic history of western Iceland. The Hredavatn beds and the Holtavörðuhéidi sedimentary horizon play a major role in the understanding of the tectonics of the area, because the fault intensity changes across both of them. The southern part of the research area can be divided into three distinct regions, each with a different fault pattern and fault density (Fig. 10.1).

Region A has the highest fault density and the faults form a mosaic pattern of NE-SW and NW-SE trending faults (a few N-S faults are also present). A study of the faults in the graben, west of Hredavatn, has revealed that faults of both trends were active simultaneously and often a fault of one trend bends and merges with a fault of the other trend. The number of faults, both NE-SW and NW-SE, decreases drastically across the Hredavatn beds. The only plausible explanation is that the faults disappear down-dip, underneath the Hredavatn beds, proving that the majority of these faults were active before the Hredavatn beds were laid down.

Region B, which stratigraphically overlies the Hredavatn beds, has a considerably lower fault density. In particular, the number of NW-SE faults has dropped drastically. However, the number of N-S faults increases markedly eastwards. The NE-SW trending faults decrease in number towards the north and tend to have a more easterly trend; they are not present north of Baula. The NW-SE trending faults also decrease in number towards the north. Most of the NW-SE and N-S trending faults disappear underneath the Holtavörðuhéidi sedimentary horizon.

Thus the N-S faults appear to be closely related in time to the

activity of the Reykjadalur central volcano. The fault pattern resembles the fault swarms of the North-Langjökull and Hofsjökull region (Walker, 1975a), which are centred upon the two central volcanoes there (Hveravellir and Kerlingafjöll volcanoes, Fig. 2.1).

In region C, the NW-SE trending faults are absent and N-S trending faults are rare. The main characteristic of region C is the evenly distributed NE-SW trending faults; their number increases slightly south, towards the Skardsheidi central volcano.

In spite of their apparent age, the activity of the NW-SE trending faults has continued up to recent times, though decreasing steadily in intensity. One of the faults, the Brekka fault, has been active during Postglacial times as can be seen in a marine terrace in Thverarhlid.

The history of the northern part of the research area is different from the southern part, and the N-S trending faults dominate it. As a rule, the faults get younger towards the east. In the outer part of Haukadalur the N-S trending faults cut the thick-layered series but not the overlying thin-layered series. Further east, however, the faults cut the thin-layered series as well. Some of the faults have obviously been active for a long time, making stratigraphical work difficult. On Bani in Haukadalur, one of the faults disappears midway up the face of the cliff (Figs. 10.2 and 10.3), but two others cut the whole pile. A few N-S trending faults cut the Snjofjöll series which is about 1-2 m.y. old, showing that these faults have been active more or less continuously from at least 6.0 m.y. until about 1.0 m.y. ago. The activity has, however, gradually moved eastwards with time. The change from NE-SW trending faults to N-S trending faults is very similar to that of the dykes (Fig. 9.3), emphasizing the close relationship between the faults and the dykes.

Tilting (Fig. 2.2) in the area is as complicated as the faulting.

The axis of the Borgarnes anticline runs northeast from Borgarnes to Vikravatn where it disappears down-dip underneath the Hredavatn beds. The overlying series have a northeasterly strike which bends around to a northwesterly strike from Nordurardalur to the Laugardalur central volcano (Fig. 2.2). The crest of the anticline is composed of a few small, parallel anticlines and synclines forming an anticlinorium. The flows dip from the anticlinorium towards the east, to the active neovolcanic zone, and westwards to the syncline in the Setberg area, which represents a Tertiary volcanic zone. These synclines have been explained as a result of sagging inside the volcanic zones (Walker, 1960). The Reykjadalur central volcano is situated in a bowl, where the underlying series dips towards the volcano from the N, W and S and the same is true for the Alftafjordur central volcano.

The tilting is a continuous process which takes place as the lava pile (or more correctly the plate) moves away from an active rift zone, the tilting being caused by sagging in the volcanic zone and erosion outside the zone (response to isostatic movements).

The rocks at the crest of the Borgarnes anticline are about 13.2 m.y. (Moorbath et al., 1968) but the rocks overlying the Hredavatn beds are about 7.0 m.y. old. A "gap" of 5-6 m.y. is therefore suggested in midwest Iceland, which either is a genuine time gap or is caused by an extremely slow effusion rate. The difference in the fault density across the Hredavatn beds supports the former explanation. The main activity of the NW-SE trending faults took place in this time interval and they undoubtedly formed a fracture zone, with right-lateral movement. The faulting decreased rapidly 7.0 m.y. ago and has been vanishingly small during the last 4.5 m.y. The NW-SE trending faults are present in the whole of Snæfellsnes but no detailed mapping has been carried out there. Thus very little is actually known about the extent and age relations of the faults west of the research area.

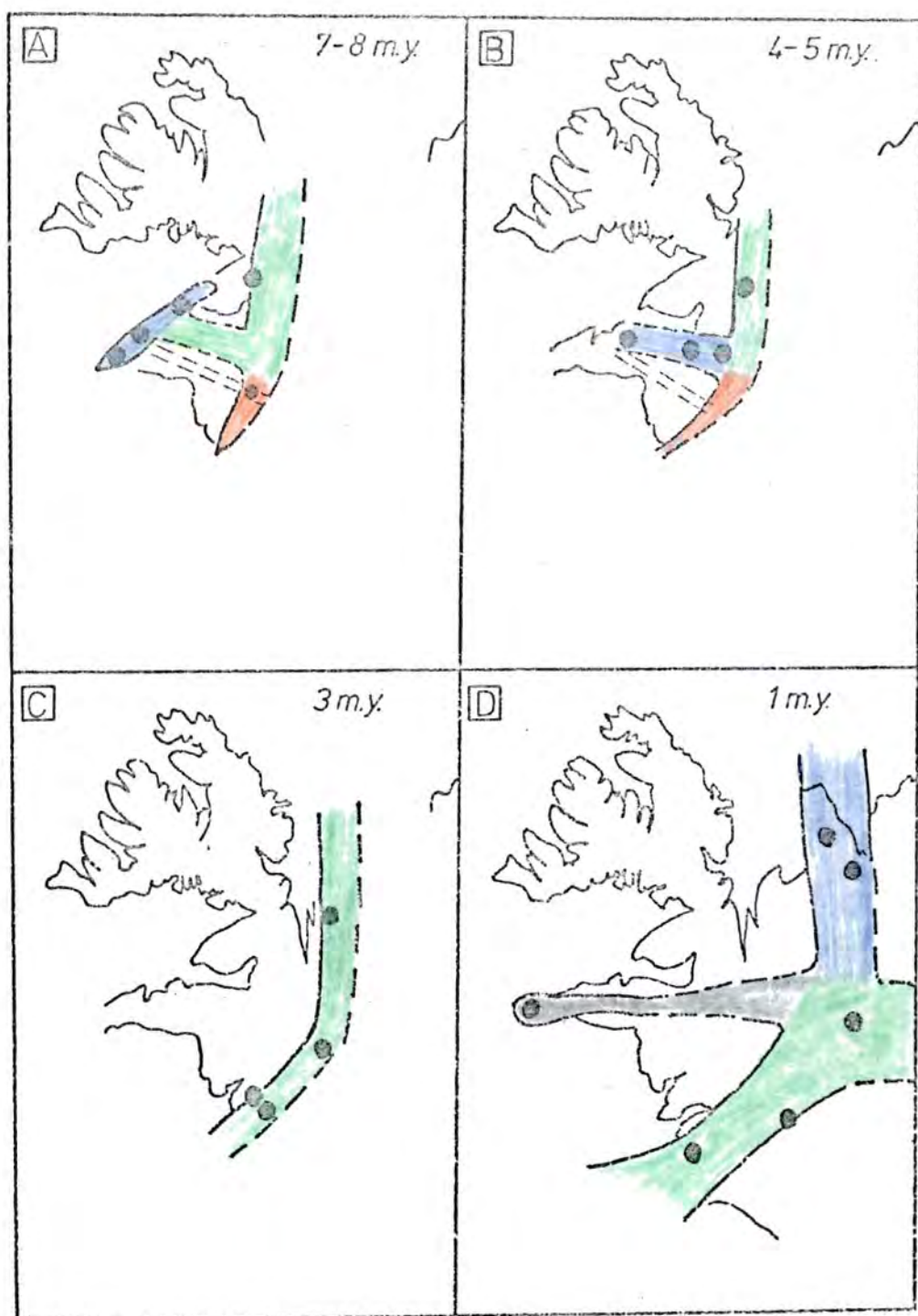
Fig. 10.6 shows a rough outline of the tectonic history of western Iceland. From the strike and dip relations and from the location of central volcanoes along Snaefellsnes (Figs. 2.2 and 2.3) one can conclude that an active volcanic zone extended westward from the main volcanic zone and probably joined another northeast-trending volcanic zone in the Setberg area about 7-8 m.y. ago (Fig. 10.6a). The northeast-trending Snaefellsnes zone became extinct some time between 7 and 5 m.y. ago. The zone linking it to the main zone became less active and died out about 5 m.y. ago (Fig. 10.6b). This was followed by a very low level of volcanic activity in the main volcanic zone and the subsequent accumulation of sediments (i.e. Holtavörduheidi sedimentary horizon). The activity increased later (approx. 4-4.5 m.y. ago) and has been more or less constant since (Fig. 10.6c).

The volcanic activity in the southern part of Borgarfjörður during the interval from 7-8 m.y. ago to about 4-4.5 m.y. ago (Fig. 10.6a,b) was far less than further north, and probably the zone terminated towards the south; however this part of the zone became more and more active as time passed and probably extended itself further and further south (Fig. 10.6c,d).

Between 1 and 2 m.y. ago (Fig. 10.6d) the activity of the northern part of the main zone (Langjökull to Skagi) decreased rapidly and it became extinct (or probably dormant) about 0.7 m.y. ago (Everts et al., 1972). At the same time, volcanic activity was revived on the Snaefellsnes peninsula (Sigurdsson, 1970a) and from there an active transverse zone stretched eastwards (Snjofjöll) and joined the main volcanic zone around 65°N (Langjökull, Fig. 10.6d). The central part of this zone ceased to exist at the end of the Matuyama epoch, but the activity has continued up to recent times on Snaefellsnes.

Fig. 10.6

A rough outline of the tectonic history of western Iceland. The solid circles represent volcanoes active at the specified time. Blue: decreasing activity, green: normal activity, red: increasing activity and black: temporary activity.



CHAPTER 11:

THERMAL METAMORPHISM OF THE LAVA PILE

Secondary mineralization in the Tertiary pile

As the lava flows were buried and sagged down (due to loading inside an active rifting zone), they underwent hydrothermal alteration, and secondary minerals such as zeolites, calcite and silica minerals were precipitated in cavities and vesicles of the flows. The type of mineral assemblage formed, depends on the temperature and chemistry of the flows; the olivine-rich flows are richer in zeolites than the more silica-rich flows and the zeolite type differs also from one flow to another. The silica-poor zeolites are common in the olivine-rich flows, whereas silica-rich zeolites, calcite and silica minerals characterise the saturated tholeiites (Walker, 1960).

During the present investigation the most significant minerals were identified in hand specimen except for the needle-like zeolites (thomsonite, mesolite and scolecite) which had to be identified in the laboratory. The most common zeolites are chabazite, analcime, thomsonite, stilbite, and less frequently scolecite, mesolite and a range of other minerals like calcite, chalcedony, opal, chlorophaeite, celadonite etc.

Walker (1960) has studied secondary mineralization in the basalt pile in eastern Iceland and he found that the amygdale minerals had a well-marked zonal distribution.

The zeolite zones in Borgarfjörður are similar to those in eastern Iceland (Fig. 11.1) but the zeolite-free zone at the top of the pile is missing altogether. The zones exposed in the research area are the chabazite-thomsonite zone, the analcime zone, and the top of the scolecite-mesolite zone. The scolecite-mesolite zone is exposed on low ground in Thverarhlid and in Nordurardalur. The zones dip slightly

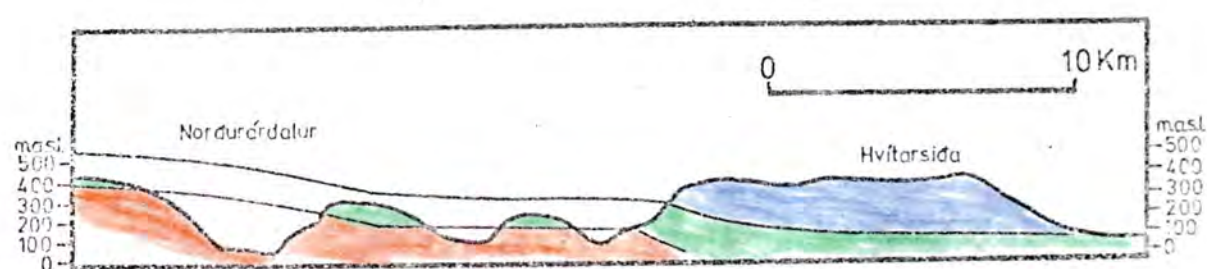


Fig. 11.1 A section across the Borgarfjörður area showing the zeolite zonal pattern. Blue, chabazite-thomsonite zone; green, analcime zone; red, scolecite-mesolite zone.

towards the Reykjanes-Langjökull neovolcanic zone but cut the stratification of the lava pile; the mineralization is thus mainly post-tilting. There are two distinct breaks in the gentle dip of the zones, one on the western slopes of Sidufjall and in Thverarhlid, and the other in Norduardalur and Grjóthals. The former break coincides with the thick sediments which are of the same age as the Holtavörduheidi sedimentary horizon. This break is present further south in Borgarfjörður and may be explained as a result of the eastward termination of the rather diffuse NW-SE dyke swarm (K. Saemundsson, pers. comm.). The other break is partly due to the Hallarmuli central volcano which slightly domes the zeolite zones but is mainly due to the high density of dykes, both NE-SW and NW-SE trending.

According to Walker (1960) the original top of the lava pile is about 600 m above the top of the analcime zone. The original top of the pile in Hvitarsida was thus about 700 m above the valley floor (800 m a.s.l.) and about 1200 m (1300 m a.s.l.) in Nordurardalur.

The central volcanoes present anomalous secondary mineralization as compared with the plateau basalts around them. The index minerals for the central volcanoes are laumontite and epidote, but many more are present and silica and calcite are found in great abundance. The secondary mineralization patterns of the three central volcanoes described in this thesis are variable due to their different geological history.

1. Hallarmuli central volcano. No high-grade zeolites are found but the low-grade zones are raised by about 100 m.
2. Laugardalur central volcano. No high-grade zeolites are found outside the caldera, and the low-grade zeolite zones rise slightly towards the caldera rim. Inside the caldera laumontite and a small amount of epidote occur in the ignimbrite unit at the bottom of the

caldera filling.

3. Reykjadalur central volcano. A conspicuous zoning of high-grade minerals is observed around the volcano (Fig. 11.2a,b). The chabazite-thomsonite, analcime, and scolecite-mesolite zones start to rise about 7-8 km outside the caldera rim, but they have not been detected in the near vicinity of the rim because the thin tholeiite flows do not contain any secondary minerals, except for calcite and silica minerals due to the tholeiitic nature of the flows. Laumontite is the most characteristic secondary mineral around the volcano and it starts to appear where the cone sheets exceed 20% of the lava pile, forming an annular zone about 15 km in diameter. The centre of the volcano is occupied by an epidote zone, which has a diameter of 10 km, but garnet was not found. The epidote is confined to areas where the cone sheets are densest (20-50%).

The caldera filling has been subjected to extensive hydrothermal activity, but because of the tholeiitic nature of the rocks low-grade zeolites are rare in the upper parts of the filling, thus making it impossible to establish the low-grade zeolite zones. In the centre of the caldera, a depression in the laumontite and epidote zones occurs (Fig. 11.2b), which is caused by a lower density of cone-sheet occurrence.

It is obvious from the evidence presented that the high-grade mineralization is closely related to the intrusive activity. No intrusives are observed in the Hallarmuli central volcano and no high-grade secondary minerals either. In the Laugardalur volcano the occurrences of laumontite and epidote are scarce and intrusives are also scarce. The Reykjadalur central volcano, on the other hand, does display a great variety of intrusives and consequently high-grade mineralization is extensive.

Present hot springs in the research area

Most of the hot springs active at the present time are shown on the

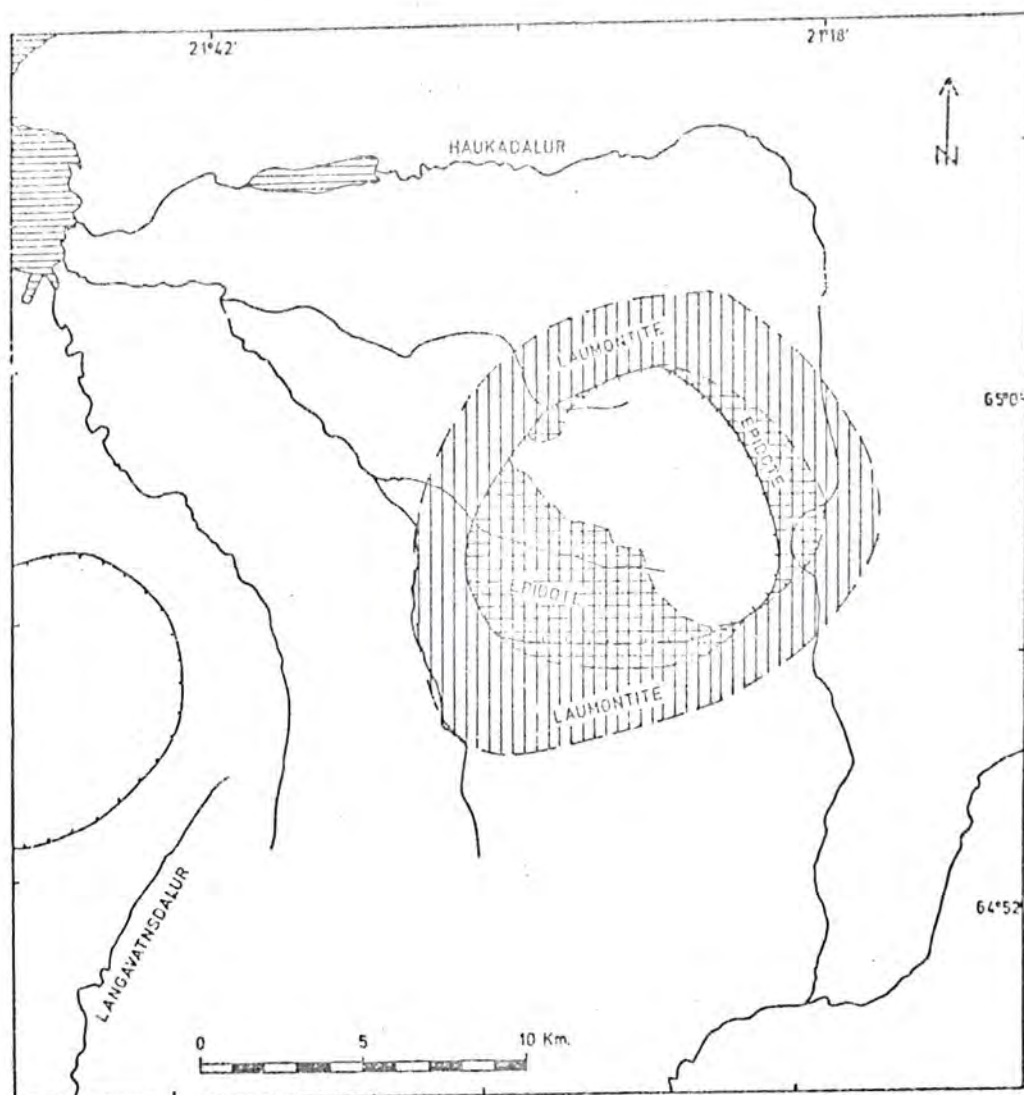


Fig. 11.2a Distribution of laumontite and epidote in the Reykjadalur central volcano.

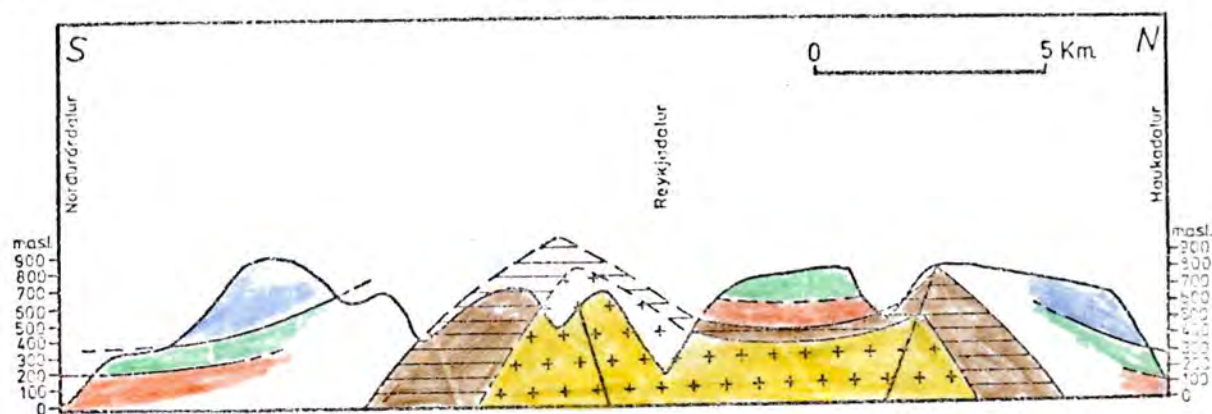


Fig. 11.2b A section through the Reykjadalur central volcano, showing the metamorphic zones around it. Blue, chabazite-thomsonite zone; green, analcime zone; red, scolecite-mesolite zone; brown, laumontite zone; yellow, epidote zone.

Geological Map (compiled from unpublished data-files of the Department of Natural Heat of the National Energy Authority); they are scattered over a wide area east of the Nordura river and south of Holtavörðuheidi, with the greatest concentration in Hvitarsida and Reykholtisdalur. Two hot springs occur outside this area, both being controlled structurally by the now-extinct central volcanoes; one occurs just inside the western caldera rim of the Reykjadalur central volcano and the other just outside the northern caldera rim of the Laugardalur central volcano. In the case of these two hot springs the meteoric water has been able to percolate sufficiently deep, despite the high secondary mineralization, and it probably rises along faults or, more likely, along the cone sheets to the surface near the caldera rims.

All the other hot springs in the research area are of a different structural origin. The temperatures tend to rise eastwards from Nordura river to Reykholtisdalur, although some exceptions exist; the quantity of water increases eastwards. If the geothermal gradient is in the range 60° - 100° C/km, the meteoric water must have reached a depth of 1 to 2 km to reach a temperature of 100° C, as shown by many of the springs in Reykholtisdalur. A very good aquifer(s) and possible, a big reservoir(s) at depth are needed to explain the great quantities of water rising to the surface (for example, about 170 litres/sec reach the surface in the Deildartunga hot spring). Sedimentary beds, which are abundant in the lava pile west of Reykholtisdalur, may provide the necessary aquifer rather than the dense basalts. The sediments are far more porous than the lava flows and thus can carry far greater quantities of water.

Fig. 11.3 shows a schematic section through the Borgarfjörður area, from Nordura to the Reykjanes-Langjökull rifting zone. The area with

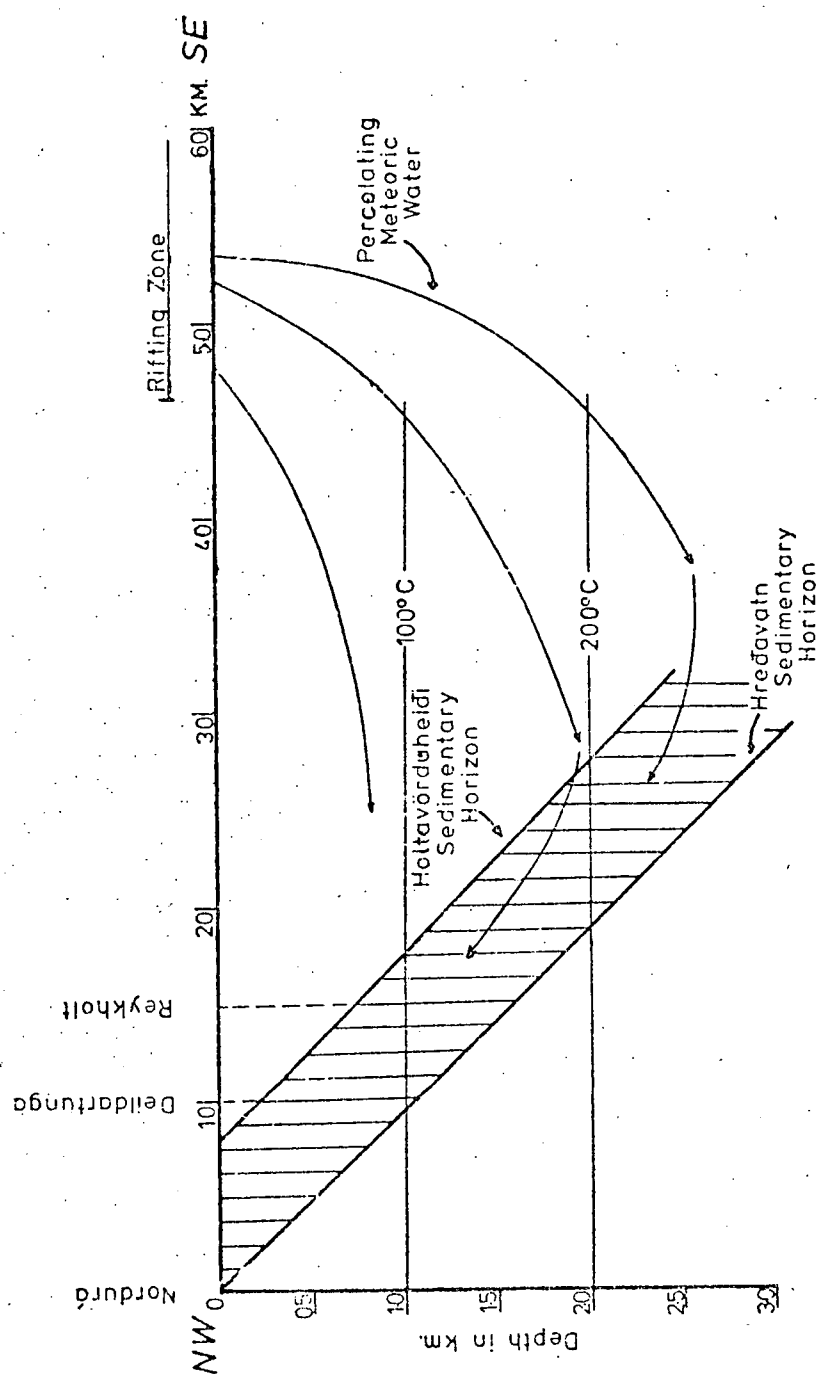


Fig. 11.3 Schematic section across the Borgarfjörður, from Nordura to Reykjanes-Langjökull volcanic zone, showing the possible path of the meteoric water. The stripes show the part of the lava pile richest in sediments. The isotherms are for a thermal gradient of 100°C/km.

the vertical stripes is that part of the lava pile richest in sedimentary beds, in the lowlands of Borgarfjörður (from Hredavatn beds to the Holtavörðuheidi sedimentary horizon). The average dip is about 6° and no corrections are made for normal faulting. If we assume a thermal gradient of $100^{\circ}\text{C}/\text{km}$, which is probably too high for an ordinary Tertiary pile, the expected temperature range of the water in the sediment-rich zone can be calculated. Water reaching the surface in Deildartunga and in Reykholt has been derived from a depth of 1 km or more.

Most of the hot springs lie on N-S trending lineaments. These lineaments are N-S trending normal faults or, in some cases, dykes, which probably cut the aquifers at depth allowing the hot water to reach the surface. These faults are probably relatively young features, and could perhaps be of similar age to the normal faults in the Snofjöll area which are as young as 1.5 m.y., or even younger.

Deuterium measurements show that the water in the hot springs in Reykjadalur has its origin in the Langjökull area, i.e. in the rifting zone (Arnason and Sigurgeirsson, 1968). The water percolates to depth along the open cracks and fissures in the rifting zone and its temperature increases. It subsequently flows laterally away from the rifting zone westwards, and is trapped in the sedimentary rocks.

The hot water flows upwards (Fig. 11.3) within the sedimentary horizon, until the aquifer is cut by the faults, these allowing the water to rise to the surface.

CHAPTER 12:

PETROGRAPHY

Classification

In the past, a large number of rock names were assigned to rocks similar to the ones described in this study, but since Carmichael (1964) published his account of the petrology of the Thingmuli central volcano the nomenclature has been simplified. Carmichael's classification is based predominantly on petrological features, but it fits the chemistry of the rocks remarkably well. Since then both Sigurdsson (1970a) and Grönvold (1972) have followed the same line, with minor variations.

The author has adopted the classification used by Grönvold (1972), for the intermediate and acid rocks, but has changed the term icelandesite to icelandite to show consistency with previous work.

In Table 12.1 the names used by Carmichael (1964), Sigurdsson (1970a), Grönvold (1972) and the present author are listed, along with their appropriate silica intervals.

All the rocks in the research area except for the Snjofjöll series and the Snaefellsnes volcanics, belong to the tholeiitic trend (Fig. 12.1). The tholeiites are divided into two groups, olivine tholeiites and quartz tholeiites, by using the CIPW-normative classification of Yoder and Tilley (1962). This division is greatly affected by the oxidation state of the samples, as the oxidation shifts the samples towards the quartz corner of the Di-Ol-Pl-Qz tetrahedron. Secondary oxidation takes place during and after magma eruption, and it continues as the flow sags down under the load of later volcanics. At depth the rocks undergo hydrothermal oxidation, which is responsible for most of the post-magmatic oxidation. The Tertiary basalts are

Carmichael

Basaltic andesite	Andesite (Icelandite)		Rhyolite
52.7-55.9	59.3-64.5		69.4-75.7

Sigurdsson

Basaltic andesite	Icelandite	Rhyodacite	Rhyolite
53-57	60-67	66-70	68-75

Grönvold

Basaltic icelandesite	Icelandesite	Dacite	Rhyolite
52-56	56-63	63-69	69-76

Present work

Basaltic icelandite	Icelandite	Dacite	Rhyolite
52-56	56-63	63-69	69-77

Table 12.1 Rock names used by Carmichael (1964), Sigurdsson (1970a), Grönvold (1972) and by the author with their appropriate silica values.

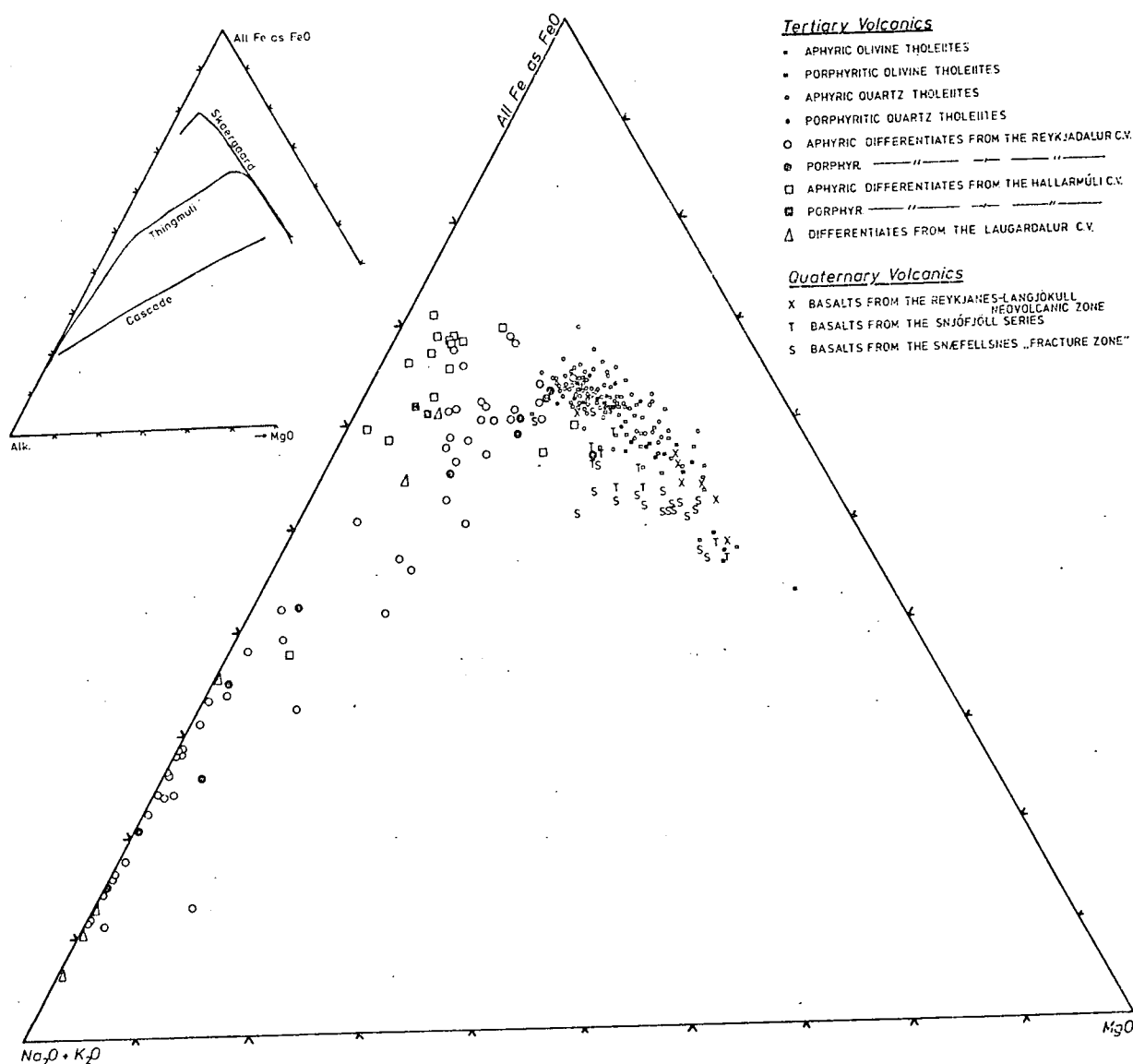


Fig. 12.1 Tertiary, late Quaternary and Recent samples from the Borgarfjordur-Dalir area plotted on an AFM diagram, and compared with the trends for Skaergaard (Wager, 1960), Thingmuli and the Cascade province (Carmichael, 1964).

nearly silica saturated, and a slight increase in oxidation can shift samples from being olivine normative, to being quartz normative.

The oxidation of the Tertiary samples increases slightly with increased age, and to avoid the effects of this variation in oxidation the norms were calculated by using a fixed $\text{Fe}_2\text{O}_3/\text{FeO}$ ratio. The ratio used ($\text{Fe}_2\text{O}_3/\text{FeO} = 0.25$) is a rounded figure based on 54 fresh, wet chemically analysed postglacial samples from Iceland (Jakobsson, 1972).

The term picrite is used in this thesis for olivine-rich, compound lava flows.

The classification of the alkalic rocks is complicated, and the transitional nature of many of the late Quaternary and Recent rocks makes classification even more difficult. Jakobsson (1972) used the Hawaiian division line on the alkali/silica diagram to distinguish between tholeiitic and alkaline basalts. According to this classification many samples, which are transitional in nature, would be classified as alkaline basalts (like the Snjofjöll series and some of the samples from the Nordurardalur-Langavatnsdalur area; Fig. 12.2). In this study the rocks belonging to the Snjofjöll series and the late Quaternary and Recent rocks from the Nordurardalur-Langavatnsdalur area, will be classified as transitional, because they are neither true tholeiites nor true alkaline basalts. The rocks from the Alftafjörður area are, however, true alkaline basalts, and are classified as such. They cover the range of alkaline basalts and hawaiites, and although the boundary between them is not clearly marked, the samples which contain ≥ 500 ppm Sr, and ≥ 20 ppm Rb, are classified as hawaiites, because no other practical method is available.

The analytical methods are described in the Appendix, but to

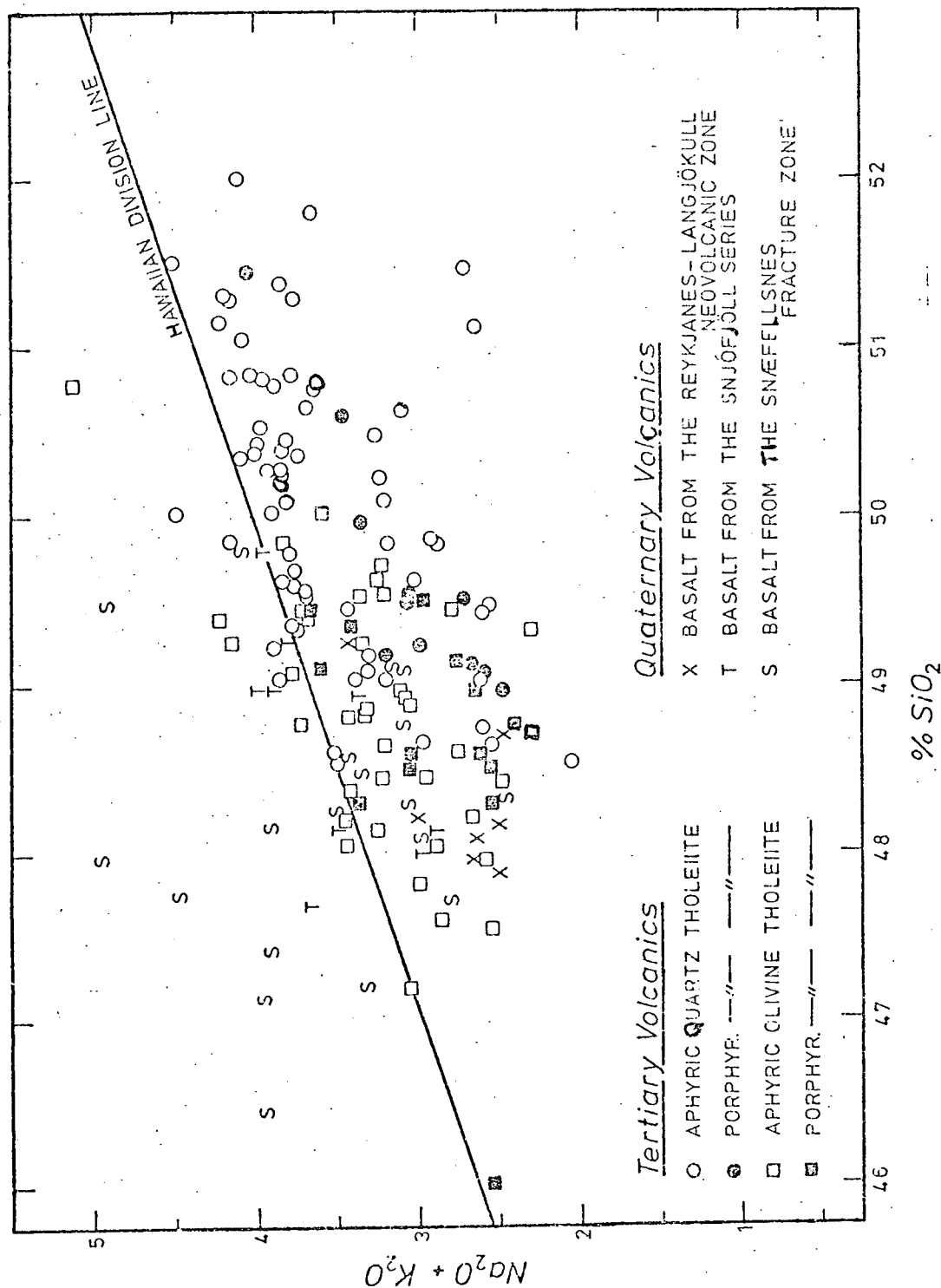


Fig. 12.2 Combined alkalis of all the analysed basaltic samples from the research area plotted against SiO_2 . Hawaiian division line, after Macdonald and Katsura (1964).

estimate the comparability of the whole rock analyses presented here, seven wet chemically analysed samples covering the compositional range from basalts to rhyolites, were run as unknowns on the Durham XRF. The seven samples were kindly made available by Dr. K. Grönvold. The results are shown on Fig. 12.3 along with the results obtained from a run of the same samples using the Bristol XRF (where they were used as standards and then re-run as unknowns). A very good correlation was obtained for SiO_2 , CaO , Na_2O and K_2O , and moderately good results for iron, TiO_2 , and MnO , but rather poor results for Al_2O_3 , MgO (above 5%) and P_2O_5 (above 0.5%), were obtained.

Rock types

Most of the rocks from the research area are fine grained, and accurate optical determinations of the mineral compositions was not feasible. The feldspar minerals were determined using Michel-Levy's method and by determining their 2V's and optical signs. Fayalitic olivine, from the intermediate and rhyolitic rocks, was distinguished from the ordinary olivine in the basic rocks by its smaller 2V. Ferroaugite was distinguished from augite by its pleochroism and hypersthene from augite by its parallel extinction and different optic sign. All the Tertiary specimens are altered to a certain extent, and some of the rocks originally analysed were so altered that they were omitted from this study.

Phenocrysts are present in most specimens, but in varying amounts from a few crystals to 50-60% of each thin section. The main phenocryst phase is plagioclase, which is present in all rock types. The crystals range in size from tiny microphenocrysts to 2-3 cm megacrysts (which are probably cognate xenocrysts rather than phenocrysts). In most samples the plagioclase phenocrysts occur in glomerophyric clusters. Olivine and clinopyroxene (augite to ferroaugite) are not so common

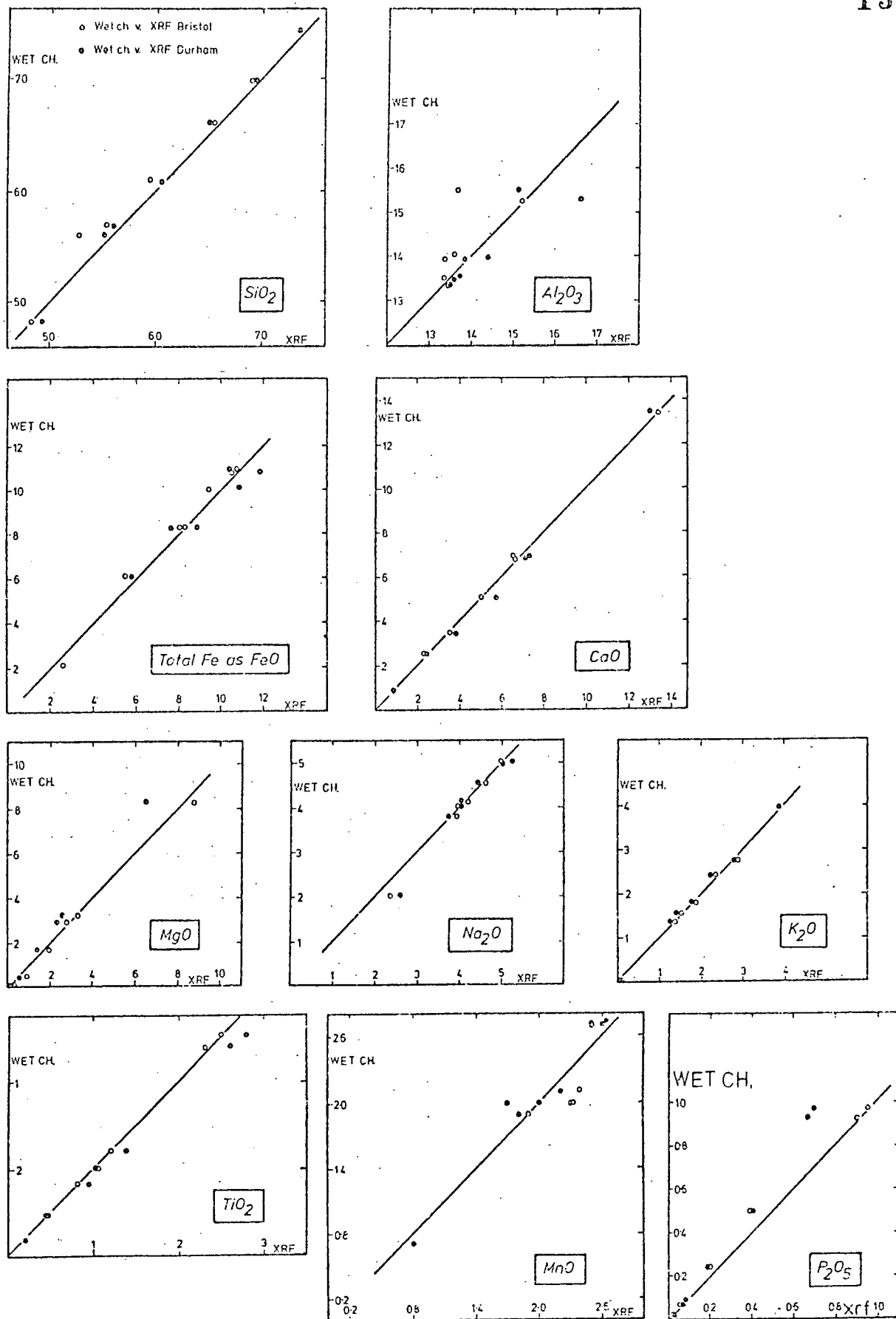


Fig. 12.3 Comparison of XRF and wet chemical analyses of samples covering the compositional range from basalts to rhyolites. The diagonal lines represent a perfect correlation.

Table 12.2

The petrological features of the analysed samples from the Borgarfjörður-
Dalir area.

Table 12.1

OLIVINE NORMATIVE THOLEIITES

SPEC. No.	PHENOCRYSTS					GROUNDMASS			
	Plag.	Ol.	Cipx.	Ore	Qtz.	Euhed. Ore	Interst. Ore	Suboph. Ore	Ol.
2						X			X
4	R					X	X	X	X
5							X		X
6	R		R				X		X
11	X	R	R				X		X
13	X	X	X				X		X
15	X		R				X		R
16	X		R				X		X
19	X						X		X
20	X						X		
21	X						X		
40						X	X		R
112	X					X			
117	M	M	M			X			X
118	X	R	N				X	X	
50	X						X		
58			M				X	X	X
79	M	M	M			X	X		X
86	X		X				X		R
87							X		X
89	X	X	X	X		X			
96							X		R
106	R						X		X
108	R		R				X		X
109	X	X	X				X		X
112	R		R	R		X			X
152	M			M		X	X		X
158	R		M				X		X
165	X	X	X				X	X	X
166	R		R				X	X	
167	R						X	X	
176	X						X	X	X
195	X	X					X	X	X
202							X		
205							X	X	X
209	X		R			X			
218	X		X			X	X		
222	R						X	X	
231	R						X		X
234	R		R				X		

R - rare, M - microphenocryst, H - rare hypersthene

Table 12.1 (cont'd)

SPEC. No.	PHENOCRYSTS					GROUNDMASS			
	Plag.	Ol.	Clpx.	Ore	Qtz.	Euhed. Ore	Interst. Ore	Subop. Ore	Ol.
237	X		M			X	X		X
238						X	X		X
240	R		R			X	X		X
245							X		X
247		X	X				X		X
250	X	R	M				X		X
251	R	X	X				X		X
255		X	X				X		X
286							X		X
292							X		X
296							X		
298	X						X		X
304	X	X					X		X
307	X						X		

QUARTZ NORMATIVE THOLEIITES

1	M					X	X		
3	M		M	X		X			
7							X		
9						X	X		
23							X		
24		R					X		
25		X					X		
26		R					X		
34							X		
35	M		M			X			
38	X	R					X		
39	X	R	R				X		R
41						X			
43						X			
44	M		M	M		X			
45	X						X	X	
46							X		X
51						X			
52	M					X			
57						X			
64						X	X		R
65	X						X		
68	X		X			X			
69	M					X			

R - rare, M - microphenocryst, H - rare hypersthene

* 254

x

x

SPEC. No.	PHENOCRYSTS					GROUNDMASS			
	Plag.	Ol.	Clpx.	Ore	Qtz.	Euhed. Ore	Interst. Ore	Subopt. Ore	Ol.
71	R			M		X			
72	X					X			
90							X		X
93	X		X			X			R
98						X			X
102	R					X			
107							X		
110	M		M			X			R
118				M		X			
119						X	X		X
149	R			M		X			
150	X		X			X			X
151						X			R
153						X			X
154							X	X	
155	M		M	M		X			R
157							X		
159						X	X		R
162							X		
164	X						X		R
172						X	X		
183						X	X		R
185						X			X
194	M	M	M	M		X			
197	M	M	M			X			
199	M		R						
201	X		X	M		X			
204	R					X			R
206	R		R			X	X		R
216						X			
217							X		
219	X					X			
220						X			
221	X						X	X	
223						X			R
224	R						X		
225	M		M	M		X			
226						X			
227						X			
228						X			

R - rare, M - microphenocryst, H - rare hypersthene

Table 12.1 (cont'd)

SPEC. No.	PHENOCRYSTS					GROUNDMASS			
	Plag	Ol.	Clpx.	Ore	Qtz.	Euhed. Ore	Interst. Ore	Suboph. Ore	Ol.
229	X		X			X			
230	R						X		
232	R						X		
233						X			
235	X						X		
236	X						X		
241						X			R
242						X	X		
243						X			
244						X	X		
290							X		
291						X			
299							X		
BASALTIC ICELANDITES									
29				R		X			
55	R		R	M		X			
66	R		R	M		X			
74						X			
100	M		R	R		X			
103	X		X			X			
104	X		X			X			
168				M		X			
181	R		R			X			
196	X					X			
198						X			
287						X			
289	X	M	M		R	X	X		X
303						X			
ICELANDITES									
8	M		M	M		X			
28	X	R	X	X		X			
30						X			R
31						X			R
32	X	X	X	X		X			
33						X			
36						X			
37						X	X		
53						X			

R - rare, M - microphenocryst, H - rare hypersthene

Table 12.1 (cont'd)

SPEC. No.	PHENOCRYSTS					GROUNDMASS			
	Plag.	Ol.	Clpx.	Ore	Qtz.	Euhed. Ore	Interst. Ore	Suboph. Ore	Ol.
59						X			R
60	R			R		X			
61	R	X	R			X			
62	M	X				X			R
63						X			
70	R					X			
75	R		R			X			
80	X		R			X			
85	M	M	M	M		X			
94	X	X	X	M		X			
111				M		X			
113	X					X			
117	X	X	X	M		X			
170				M		X			
171	R					X			
173						X			
175	X		X H	R		X			
177	X		M	R		X			
182			R			X			
252						X			R
253						X			
294	X	X	X	M		X			X
DACITES									
49	R	R	R	R		X			X
56						X			
76						X			
95	X	X	X	M		X			
97	M		M	M		X			
108							X		
211						X			
RHYOLITES									
10	X				M	X			
12	X			M		X			
17	X					X			
18	X				M	X			
22	R					X			
54	M		M			X			
67	X	R			M	X			

R - rare, M - microphenocryst, H - rare hypersthene

Table 12.1 (cont'd)

SPEC. No.	PHENOCRYSTS					GROUNDMASS			
	Plagg.	Ol.	Clpx.	Ore	Qtz.	Euhed. Ore	Interst. Ore	Suboph. Ore	Ol.
77	R			R		X			
78	X		X	M		R			
81	X			R		X			
82	X	X	X	M		X			
83	X			R		X			
84	X			R		X			
88	R					X			
91	X	R							
92	R								
99				R	X				
105	R	R		R		R			
114	R			R		X			
115					X	X			
116	R			R		X			
138						R			
160	X			M		X			
161	X			R					
163	R			R		R			
169	X		R	R		R			
174	X			R		R			
179	R			R	X	X			
190	R		R	R		X			
191	R		R	R		R			
207						X			
248	R			R		X			
249						R			
256	M			R		X			
SNJOFJÖLL TRANSITIONAL SERIES									
120	R	M					X	X	X
121	X	X	X H				X	R	X
122	X	X					X		X
123	X	X	R			X	X		X
285	X	X				X		X	X
288	X	X	R			X	X		X
293							X		X
301	X	X				X	X		X
306	X	X					X		X

R - rare, M - microphenocryst, H - rare hypersthene

R - rare, M - microphenocryst, H - rare hypersthene

as phenocrysts, but euhedral magnetite is common as a microphenocryst in the differentiated rocks.

Each rock type will be described separately for convenience, and the coarse grained plutonic rocks will be described in a separate section. The characteristic features of each group will be described, but not every specimen (only common exceptions will be mentioned). Table 12.2 shows the relevant petrographical data for the analysed rocks.

Tertiary volcanics

(a) Olivine tholeiites

The olivine tholeiites can be divided into two principal groups; picrites (olivine cumulative rocks), and ordinary olivine tholeiites (aphyric to plagioclase-phyric). Both groups display an intergranular texture with several specimens showing subophitic to ophitic texture.

The picrites occur as compound lava flows and, because of their high olivine content, they are more sensitive to hydrothermal alteration than any other rock type, and thus only one sample was fresh enough for analysis (no. 13, Fig. 12.4). It contains a large amount of big, euhedral to subhedral olivine phenocrysts, along with a few augite and occasional bytownite, (An₇₀₋₈₀) phenocrysts. The olivine crystals are as big as 0.5 cm, and they are usually rimmed by red-brown iddingsite and magnetite. Chrome spinel (picotite) occurs as small brown cubes enclosed in the olivine phenocrysts. The groundmass is coarse grained and consists of laths of labradorite (An₆₀₋₇₀), interstitial grains of pale-coloured augite, and anhedral magnetite which occasionally contains exsolved ilmenite lamellae. Subhedral grains of olivine rimmed by iddingsite occur in the groundmass as well.

The ordinary olivine tholeiites are finer grained than the

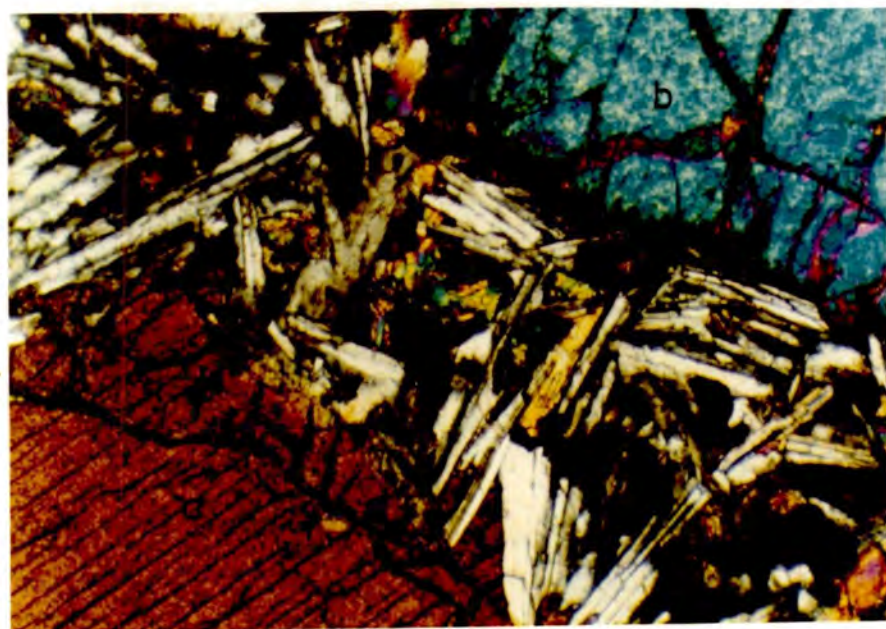


Fig. 12.4 Picrite lava flow containing augite (a) and olivine (b) phenocrysts. The groundmass consists of plagioclase laths, augite and olivine grains with interstitial ore. Sample no. 13, crossed polars, field length 1.7 mm.

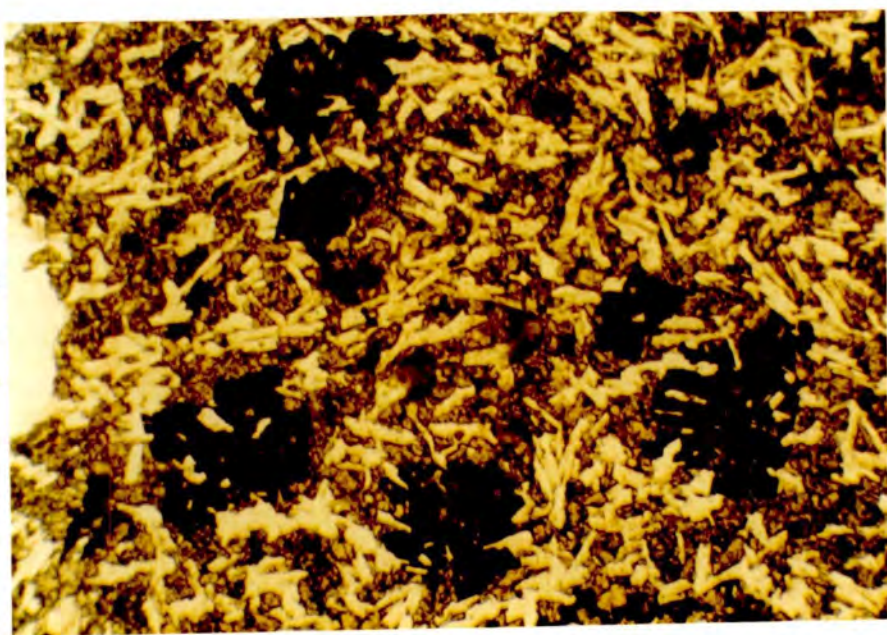


Fig. 12.5 Olivine tholeiite flow containing subophitic magnetite (a). Sample no. 222, ordinary light, field length 2.25 mm.

picrites, and they vary from aphyric to near plagioclase cumulative rocks. The plagioclase phenocrysts are labradorite to bytownite (An_{60-80}) sometimes rimmed with andesine (An_{40-50}), and vary in size from small microphenocrysts to 3 cm megacrysts. Oscillatory zoning is common and numerous ore and glass inclusions are present in some of the crystals. Olivine is usually represented by serpentinous pseudomorphs, but picotite is found in the olivines which are fresh. In one sample (no. 11) the olivine phenocrysts are rimmed by biotite. Sporadic phenocrysts of pale-green augite occur in a few samples. The groundmass pyroxene and ore are interstitial to the skeletal plagioclase laths. The pyroxene granules are a pale-green augite, occasionally occurring subophitic or ophitic to the plagioclase. Anhedral grains of olivine are found in the groundmass of most specimens, and they are usually severely altered. The groundmass plagioclase is a zoned labradorite-andesine (An_{40-60}). Unevenly distributed magnetite is either interstitial, subophitic, or both (Fig. 12.5), and acicular ilmenite occurs in many specimens. The plagioclase from those lava flows which solidified as lava pools inside the Reykjadalur are usually extremely zoned (no. 89).

(b) Quartz tholeiites

This group is still finer grained than group (a), and plagioclase is not common as a phenocryst. The most characteristic texture is intergranular, but subtrachytic textures occur in a few specimens.

Corroded phenocrysts of slightly zoned labradorite (An_{60-70}), occasionally with an andesine (An_{40-50}) rim, indicate that the calcic plagioclase was out of equilibrium with the liquid at the time of eruption. Plagioclase phenocrysts from the lava flows ponded inside the Reykjadalur caldera show extensive zoning (no. 90 and 244) which

is not present in any other specimen of this group, except for the gabbro of the Laugardalur central volcano (no. 98). The few pyroxene phenocrysts consist of pale-green augite, and pseudomorphs after olivine phenocrysts occur in a few specimens. The groundmass consists mainly of andesine laths with intergranular, pale-greenish augite. Olivine is very rare as a groundmass phase, and it is nearly always altered. The ore phase is different from the one of group (a); magnetite occurs regularly as euhedral grains evenly distributed throughout the rock, and in great abundance. The magnetite contains exsolved ilmenite lamellae in some grains. Acicular ilmenite does occur in some sections. The highly characteristic, interstitial and subophitic ore phase is present in a few samples, and in some others euhedral magnetite occurs as small microphenocrysts.

(c) Basaltic icelandites

The basaltic icelandites are yet finer grained than the basalts and show intergranular to trachytic texture. The optical determination of the groundmass phases is extremely difficult because of the minute size of the minerals.

Phenocrysts occur in most samples of this group, but only in small numbers. Sporadic crystals of plagioclase, with labradorite (An_{60-70}) core and andesine-oligoclase (An_{30-40}) margins (Fig. 12.6), contain inclusions of ore, pyroxene and glass. Pyroxene phenocrysts are rare, and they consist of pale-green augite, occasionally slightly pleochroic and approaching ferroaugite. Olivine does not occur in the basaltic icelandites, but a few grains of magnetite microphenocrysts occur regularly in about half of the samples. The groundmass consists of andesine-type plagioclase with pale-green, intergranular clinopyroxene (augite ?) and brownish interstitial glass. Magnetite is very common

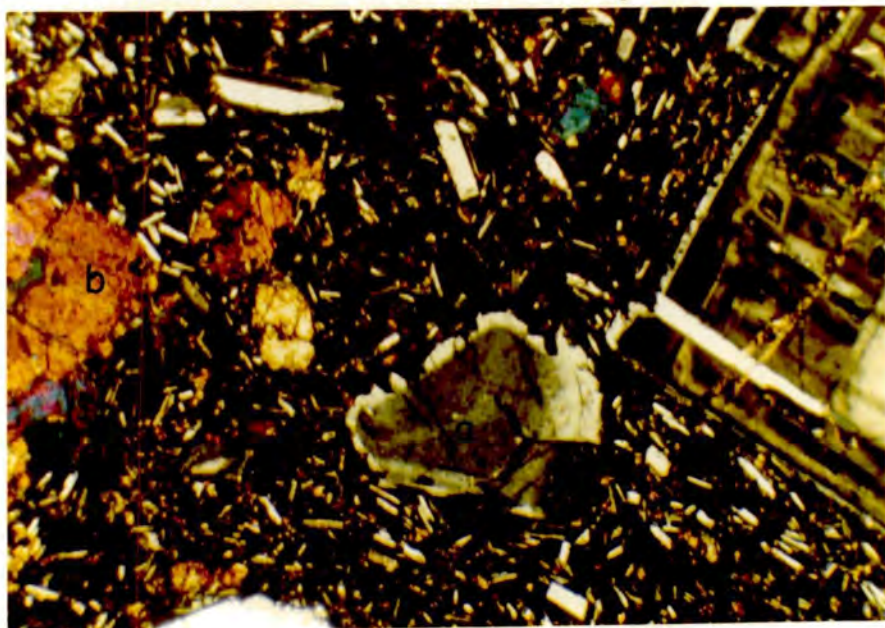


Fig. 12.6 Basaltic icelandite flow with zoned plagioclase (a); labradorite core and an outer rim of andesine-oligoclase. Augite phenocrysts (b) are common but the groundmass is fine grained with small euhedral grains of magnetite. Sample no. 103, crossed polars, field length 2.25 mm.

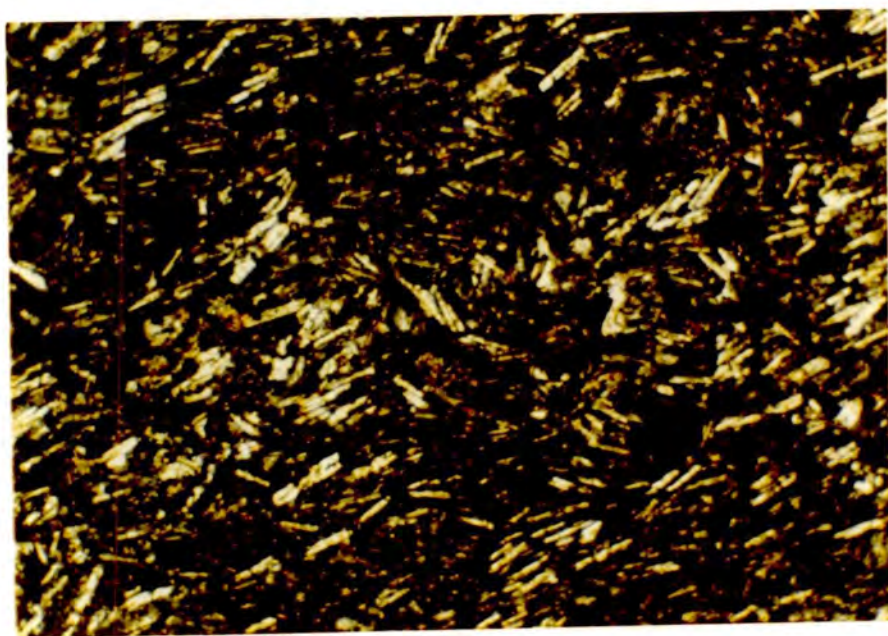


Fig. 12.7 Basaltic icelandite flow displaying a trachytic texture. Note the evenly distributed euhedral magnetite grains. Sample no. 168, crossed polars, field length 1.7 mm.

as minute euhedral grains, evenly distributed throughout the groundmass (Fig. 12.7).

(d) Icelandites

These rocks are extremely fine grained and often glassy, with subtrachytic and trachytic textures dominating. Phenocrysts are more common than in the basaltic icelandites.

Again plagioclase is the main phenocryst phase (Fig. 12.8); the plagioclase is usually zoned andesine (An_{40-45}) but labradorite does occur as well, and most of them are corroded to a certain extent. Pale green, slightly pleochroic ferroaugite is found in about a third of the specimens (Figs. 12.8 and 12.9) but in sample no. 175 a few phenocrysts of greenish hypersthene are present with serpentinized rims. Olivine is found in a few samples (Figs. 12.8 and 12.9), often severely altered, and of fayalitic composition. Euhedral magnetite grains occur as microphenocrysts in about a third of the samples, in most instances without ilmenite exsolution, and they are more prominent in the rocks of the Hallarmuli central volcano (Fig. 12.10) than in the rocks of the other two volcanoes in the research area. The magnetite microphenocrysts are occasionally enclosed in ferroaugite and olivine phenocrysts. The main groundmass phase is plagioclase along with a great deal of brownish, often devitrified glass. The groundmass pyroxene occurs as small grains of greenish augite (?), and olivine is occasionally found as small grains in the groundmass. The groundmass is charged with minute grains of euhedral magnetite.

(e) Dacites

These are extremely fine grained to glassy rocks, which show trachytic textures where crystalline. Only seven samples from the research area belong to this group, and one of them is actually a

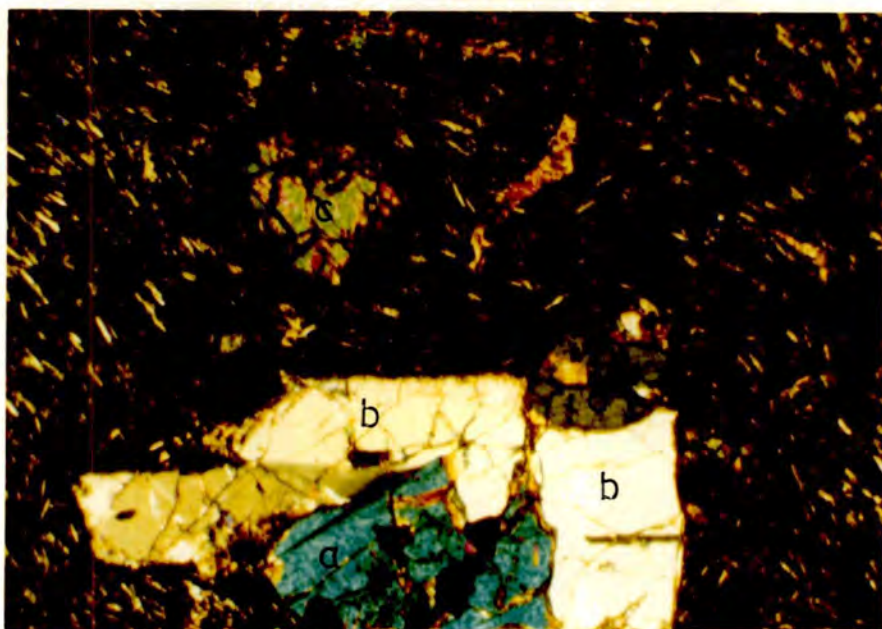


Fig. 12.8 Icelandite lava flow with ferroaugite (a), labradorite (b) and fayalitic olivine (c) phenocrysts. Note the trachytic features of the groundmass. Sample no. 94, crossed polars, field length 1.7 mm.

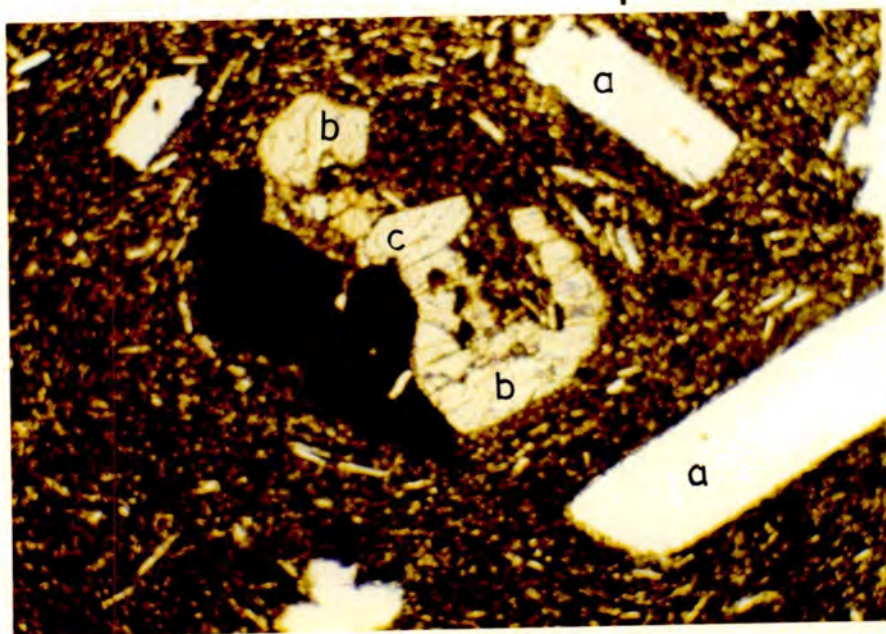


Fig 12.9 Icelandite lava flow containing plagioclase (a), ferroaugite (b) phenocrysts along with magnetite microphenocryst (c). Sample no. 117, ordinary light, field length 1.7 mm.

granophyre from a cone sheet which will be described later.

Phenocrysts are rare, except for sample no. 95. Plagioclase is the most common phenocryst, mainly andesine (An_{30-40}) which is usually zoned and corroded. Green, pleochroic and prismatic-shaped ferroaugite crystals are present, often with inclusions of euhedral, magnetite microphenocrysts. In sample no. 95 a few crystals of hypersthene are present. Fayalitic olivine is rather rare, and often more-or-less replaced by serpentinitoids. Magnetite occurs as microphenocrysts in most samples (Fig. 12.11), and does not contain, ilmenite exsolution lamellae. The groundmass is extremely fine grained, and the optical determination of minerals was impractical. The most prominent phases are plagioclase laths, and a brownish glass which is often devitrified. Greenish, granular pyroxene is present, but in much smaller amount than in the former groups. Euhedral grains of magnetite are evenly scattered throughout the groundmass.

(f) Rhyolites

The rhyolites, which are very prominent in the field, occur both as lava flows and cone sheets. All the specimens analysed are rather fine grained or even glassy; even relatively big intrusions like Baula are fine grained, and will thus be described here.

Sporadic plagioclase phenocrysts occur in nearly all the specimens, usually with an andesine core (An_{30-35}) and an oligoclase-albite (An_{15-25}) margin; corrosion is common. A few anorthoclase and sanidine crystals occur. Pseudomorphs of euhedral olivines occur in no. 67, and ragged patches of fayalitic olivines in no. 82 (Fig. 12.12). Minute grains of olivine are found in some samples, but they are often so small that they might not have been detected in many samples. Euhedral microphenocrysts of magnetite (rarely exsolved) are found in about half the samples (Fig. 12.12). The groundmass is extremely fine

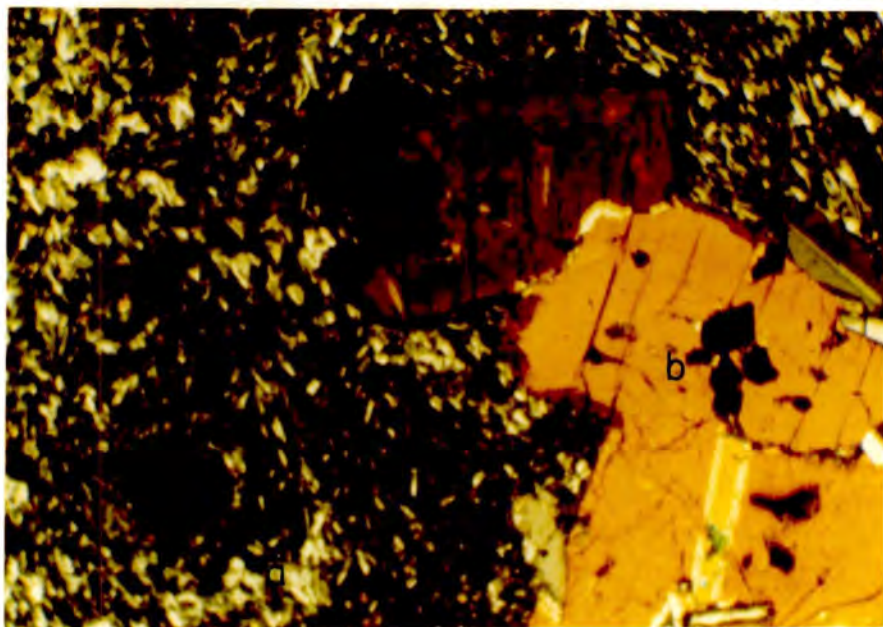


Fig. 12.10 Icelandite lava flow with microphenocrysts of magnetite (a) either enclosed within ferroaugite (b) or free in the groundmass. Sample no. 32, crossed polars, field length 2.25 mm.

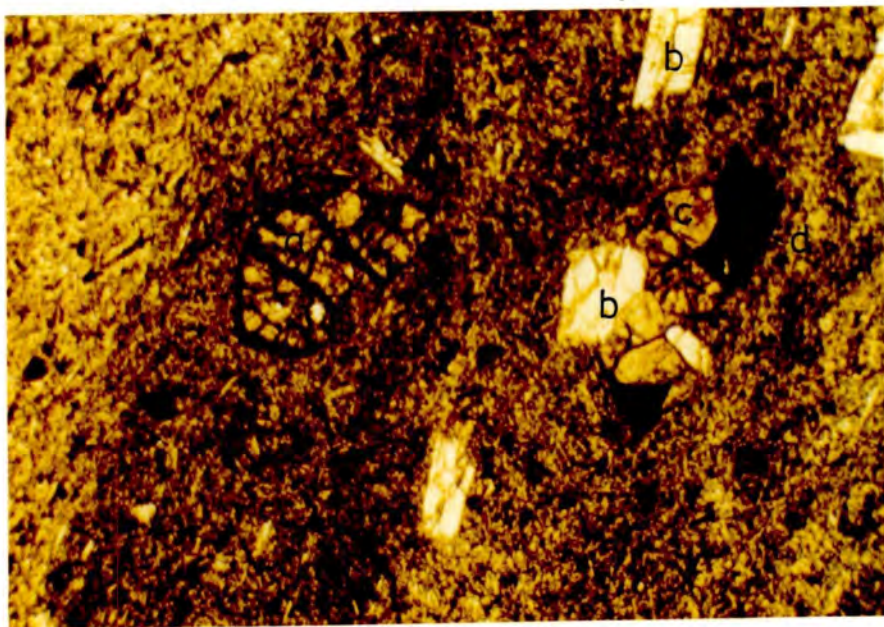


Fig. 12.11 Dacite lava flow with fayalitic olivine (a), andesine plagioclase (b), ferroaugite (c) and euhedral magnetite (d). Sample no. 98, ordinary light, field length 2.25 mm.

grained. It consists of an intergrowth of quartz and feldspar, which makes identification difficult, but the feldspar is probably an oligoclase-albite, or even K-feldspar type. Quartz sometimes occurs, as microphenocrysts (no. 10 and 18, Fig. 12.13), especially in cone sheet samples. Minute grains of euhedral magnetite are present, but in far smaller numbers than amongst the intermediate rocks.

Tertiary plutonics and xenoliths

Under this heading are classified all the coarse-grained rocks like gabbros and granophyres, most of which have not been chemically analyzed. Most of these rocks belong to the cone sheet swarm of the Reykjadalur central volcano and they have, in most cases, undergone severe alteration processes.

(a) Gabbros

Xenoliths embedded in the lava flows of the plateau basalt have a rather uniform mineralogy, consisting of labradorite and augite crystals with interstitial ore (usually magnetite with minor exsolution lamellae). The augite has interstitial or subophitic relationship with the labradorite. Olivine is never found in these xenoliths.

The gabbroic rocks belonging to the central volcanoes vary from pyroxene cumulate gabbros (Fig. 12.14) through to plagioclase cumulate gabbros, and basic crystal mush. Ordinary equigranular gabbros are most common. They consist of equigranular augite and labradorite (An₆₀₋₇₀) or the two minerals can possess a subophitic relationship. The ore is always interstitial and often contains exsolved material, but olivine is rarely present, except as pseudomorphs filled with secondary minerals. The plagioclase is usually zoned to a certain extent, but pyroxene is not zoned.

Where the intensity of cone sheets is greatest, inside the southern rim of the Reykjadalur caldera, peculiar gabbro sheets are

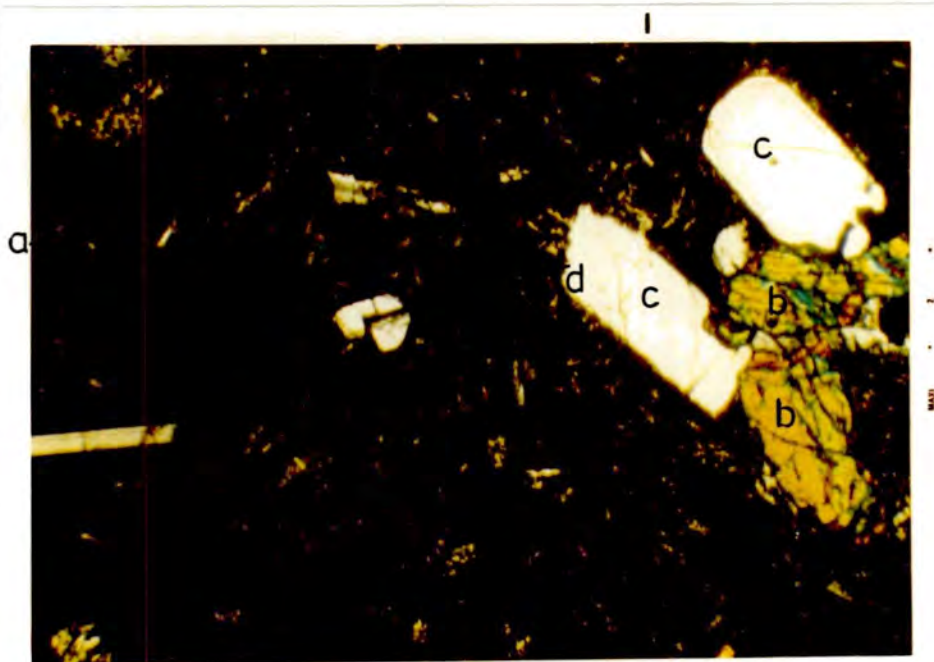


Fig. 12.12 Rhyolite lava flow with pseudomorph after olivine (a), ferroaugite (b), andesine (c) and euhedral magnetite (d). Sample no. 82, crossed polars, field length 2.25 mm.

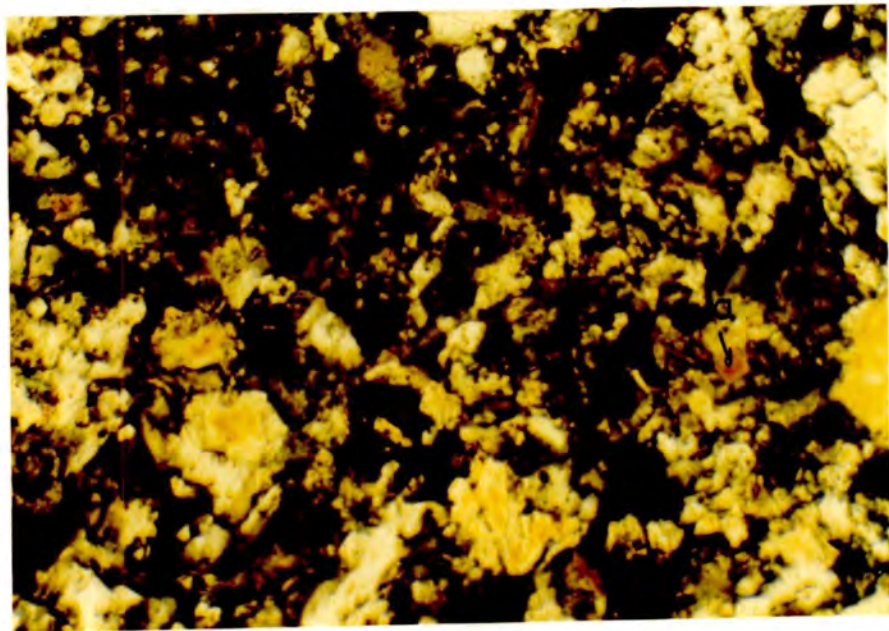


Fig. 12.13 Shallow rhyolite intrusion with small quartz microphenocrysts (a) in a mass of feathery K-feldspar-quartz intergrowths. Sample no. 10, crossed polars, field length 1.7 mm.

found. Most of them are ophitic pyroxenites, consisting of augite which is ophitic to laths of labradorites (Fig. 12.14). Others are plagioclase cumulative gabbros, where labradorite makes up the main bulk of the rocks with interstitial augite and sporadic ore.

A few samples of a very strange gabbro, from the same area, consists of a crystal mush with an interstitial, finer grained groundmass. The crystal mush consists of big laths of labradorite (An_{60-70}) which, together with smaller amount of augite, make up the main part of the rock. The interstitial material consists of much finer grained granules of plagioclase and euhedral magnetite, with a small amount of augite. The big augite crystals continued growing after the movement of the "magma" came to a halt, and they are rimmed by coronas of augite containing small grains from the groundmass (plagioclase and magnetite, Fig. 12.15).

(b) Granophyres

These rocks occur mainly as xenoliths in various rock types. They are characterized by an intergrowth of quartz and K-feldspar, but most of the granophyres from the cone sheets of the Reykjadalur volcano contain varying amounts of plagioclase and anorthoclase phenocrysts. Interstitial to the phenocrysts are intergrowths of quartz and K-feldspar (Fig. 12.16). In a few samples, quartz occurs as a microphenocryst. Pyroxene is rare, but is generally green, pleochroic ferroaugite. In many instances the pyroxene has been converted into amphibole. The K-feldspar is usually cloudy due to hydrothermal alteration.

Two xenoliths from the Laugardalur central volcano are of great interest. They are of granophyre with intergrowths of quartz and K-feldspar, but bigger crystals of sanidine-anorthoclase are common. The rocks contain small amounts of green ferroaugite and small

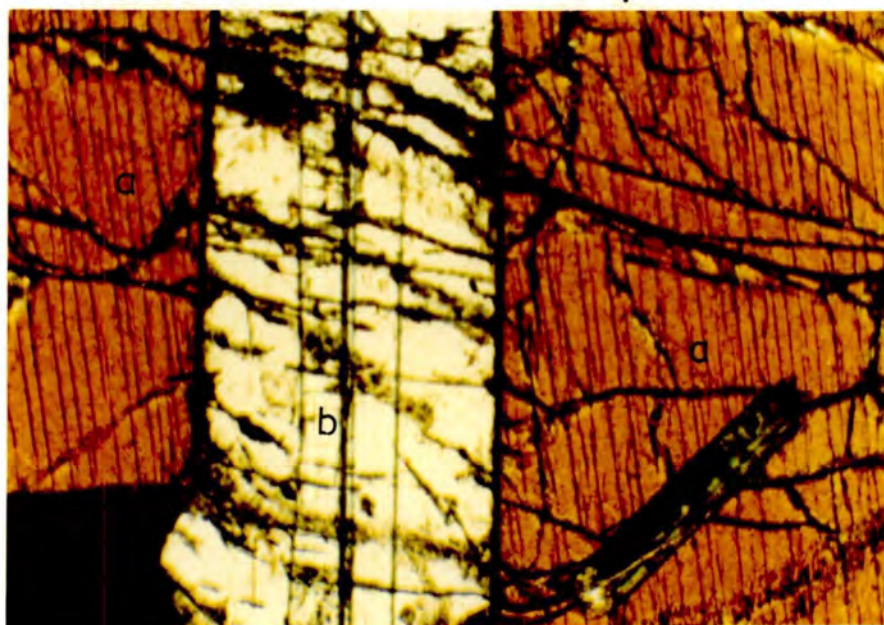


Fig. 12.14 Pyroxenite from a cone sheet in Hrossadalur in Reykjadalur. Augite (a) and labradorite (b). Crossed polars, field length 2.25 mm.

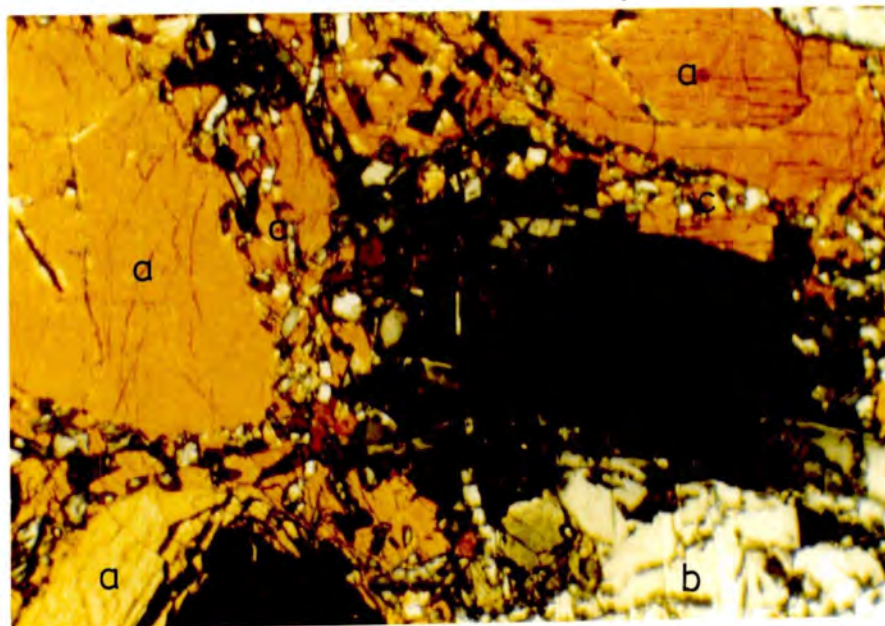


Fig. 12.15 Crystal mush from a cone sheet in Reykjadalur. Augite (a) and labradorite (b) phenocrysts with small interstitial grains of plagioclase and magnetite. Note the periphery (c) of the augite containing grains of plagioclase. Crossed polars, field length 2.25 mm.

crystals of rutile or zircon. The especially interesting feature of these specimens is that there are pockets of brown glass (the colour probably due to high iron content) around each of the ferroaugite crystals (Fig. 12.17). It seems that the ferroaugite lowers the melting temperature for the granophyre and therefore the re-melting starts around the ferroaugite crystals (perhaps due to cotectic melting). The granophyre xenoliths are enclosed in icelandite lava flow and intermediate ignimbrite, respectively. These intermediate magmas have higher melting temperatures ($> 1000^{\circ}\text{C}$) than the acid magmas and one can assume that the upmoving intermediate magma incorporated xenoliths from a granophyric intrusive body at depth; on the way up the xenoliths were heated by the magma and had started melting when they reached the surface, where the magma was rapidly cooled, thus preventing any further melting of the xenoliths.

Late Quaternary and Recent volcanism

(a) Snjofjöll series

The rocks belonging to this group are rather coarse grained and are all olivine rich. All the samples are both olivine-phyric and plagioclase-phyric, but pyroxene is rare as a phenocryst phase.

Olivine is the most prominent phenocryst phase (Fig. 12.18), and it occurs as euhedral or subhedral crystals, with picotite inclusions, grading in size from 0.5 cm down to the groundmass grains. Labradorite (An_{60-70}) is found in all samples but one, and is usually not zoned. Pale-green augite occurs in three samples, and one crystal of hypersthene was observed in a section of no. 121. The groundmass consists of intergranular, pale-green augite within a framework of labradorite (An_{50-60}) laths (occasionally andesine). Small anhedral grains of olivine are found in the groundmass of all the samples. The ore is interstitial magnetite, which often contains exsolved material,

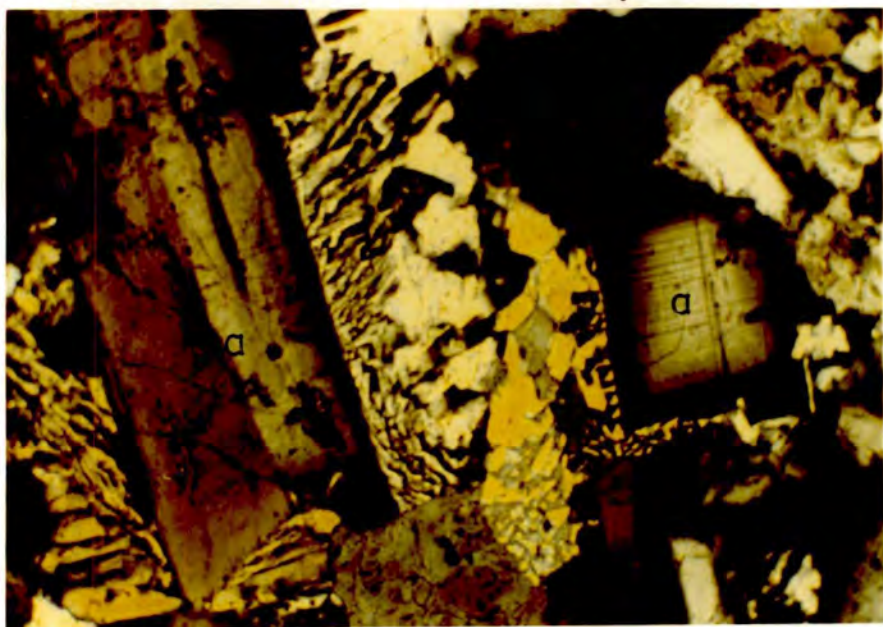


Fig. 12.16 Granophyre cone sheet from Reykjadalur. Zoned albite phenocrysts (a) enclosed within K-feldspar-quartz intergrowth. Crossed polars, field length 1.7 mm.

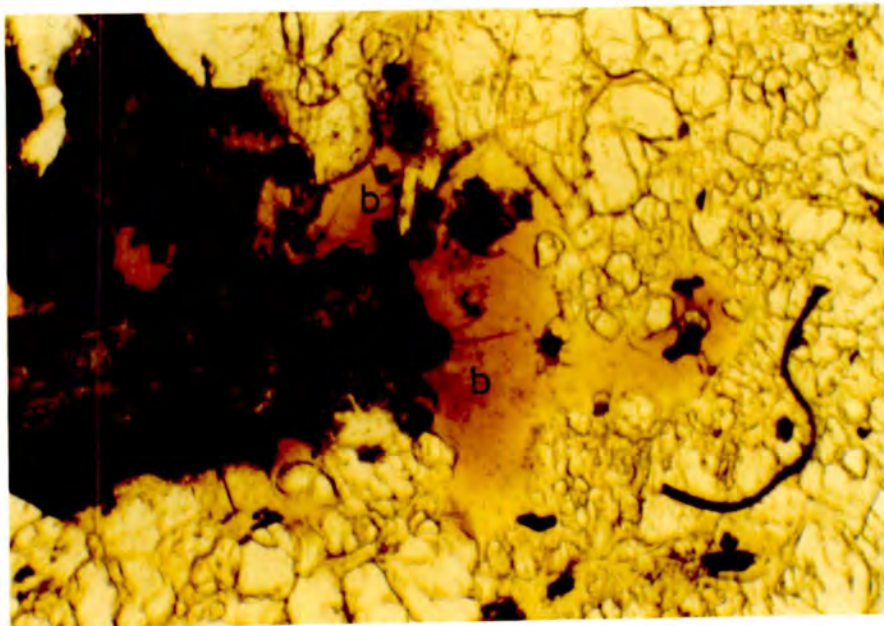


Fig. 12.17 Granophyre (xenolith) from Laugardalur. Green ferroaugite (a) in a cavity filled with brownish glass (b), which is invading the quartz-feldspar mass. Ordinary light, field length 2.25 mm.

but the magnetite is subophitic in two samples, and in four of them the magnetite also occurs as euhedral grains.

One gabbro xenolith was found in the Snjofjöll series. It is a labradorite-augite-olivine adcumulate (or mesocumulate), in which the crystals are subhedral and usually have triple junctions between the various crystals (Fig. 12.19).

(b) Reykjanes-Langjökull neovolcanic zone

These rocks are olivine rich, as are the rocks of group (a). The olivine occurs as a phenocryst in six out of seven analysed samples, is euhedral to subhedral, and contains small grains of picotite. Plagioclase is rare as a phenocryst, except in no. 277 where it occurs in great abundance as labradorite (An_{60-70}), which is weakly to strongly zoned with an outer rim of andesine. Pyroxene does not occur as a phenocryst in this group. The groundmass of often fine grained to glassy, due to rapid cooling. The groundmass plagioclase is zoned labradorite-andesine, usually in subophitic relationship with a pale-green augite (Fig. 12.20) which, in a few cases, has purplish-brown, titanium-rich margins. Small anhedral grains of olivine occur in all the samples, and interstitial ore is found along with fresh brown glass.

(c) Snaefellsnes volcanics

The main characteristic of this group is the abundance of phenocrysts, especially olivine. The group can be divided into two geographically distinct subgroups; rocks from the Nordurardalur-Langavatnsdalur area, and rocks from the Alftafjörður area. The former have the lower content of phenocrysts.

The olivine phenocrysts, which are euhedral to subhedral, contain grains of picotite and grade into the groundmass phase. Pyroxene is rare in the former group but common in the latter. It is a pale-green

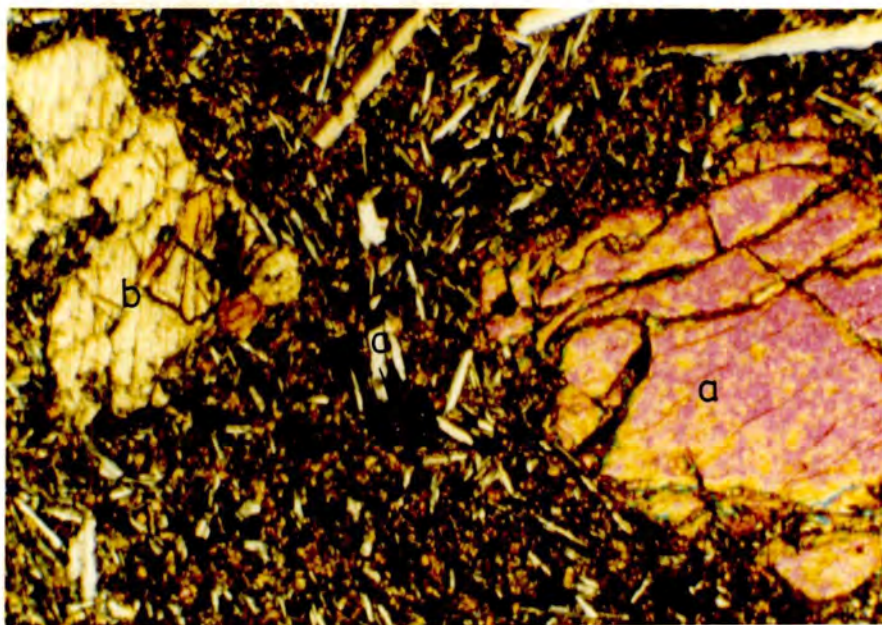


Fig. 12.18 Lava flow from the Snjofjöll series containing olivine (a) and augite (b) phenocrysts. Note the interstitial ore phase (c). Sample no. 121, crossed polars, field length 2.25 mm.

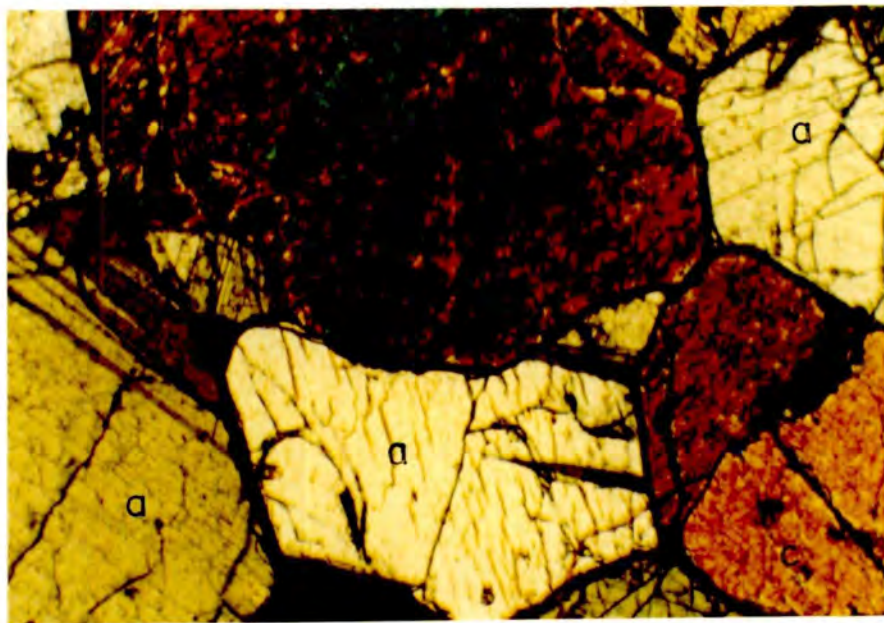


Fig. 12.19 A gabbroic xenolith from the Snjofjöll series. An adcumulate or mesocumulate, consisting of labradorite (a), augite (b) and olivine (c). Note the triple junction between the various grains. Crossed polars, field length 2.25 mm.

to brownish augite, in which zoning is common in some samples (Fig. 12.21). Some of the augite crystals are rimmed by purplish-brown, titaniferous augite (no. 268), and in others a brownish core is rimmed by greenish augite (no. 275). The plagioclase laths have corroded cores of labradorite (An_{60-70}) rimmed by andesine or oligoclase (An_{25-35}) (Fig. 12.22). Euhedral grains of magnetite micro-phenocrysts occur in a few samples of the latter group. The groundmass of most of the samples is rather fine grained or even glassy, due to rapid cooling, and it consists of andesine laths which grade in size into phenocrysts. Anhedral olivines, and pale-green augite grains, occur in interstitial relationship with the plagioclase. Ore is mainly interstitial magnetite, sometimes with ilmenite exsolution lamellae, but acicular ilmenite also occurs as a separate phase. In a few samples the magnetite forms euhedral grains.

Summary of the Petrography

Olivine is common in the olivine tholeiites but virtually absent in the quartz tholeiites. It reappears in the icelandites and dacites as a phenocryst phase. Clinopyroxene is present in all rock types, and it varies from augite in the basic rocks to ferroaugite in the more differentiated rocks, being almost absent as a groundmass phase in the rhyolites. Orthopyroxene is extremely rare. Pigeonite was not positively identified, probably because of the minute size of a possible pigeonite in the groundmass.

Plagioclase varies from labradorite in the basic rocks to oligoclase-albite to anorthoclase in the acid rocks.

The ore phase varies greatly in habit in the rocks, from interstitial and late crystallization in the olivine tholeiites, to early



Fig. 12.20 Olivine tholeiite lava flow from the Reykjanes-Langjökull neovolcanic zone. Note the subophitic relationship between augite and plagioclase. Sample no. 278, crossed polars, field length 2.25 mm.

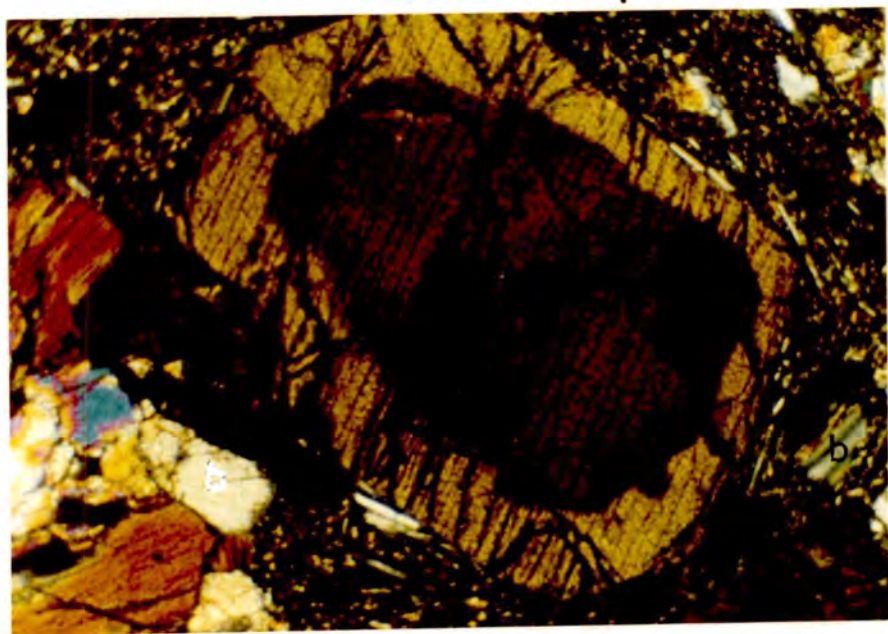


Fig. 12.21 Recent alkali olivine basalt flow from the Snaefellsnes zone containing olivine (a) and plagioclase (b) phenocrysts and a large zoned clinopyroxene (c). Sample no. 275, crossed polars, field length 1.7 mm.

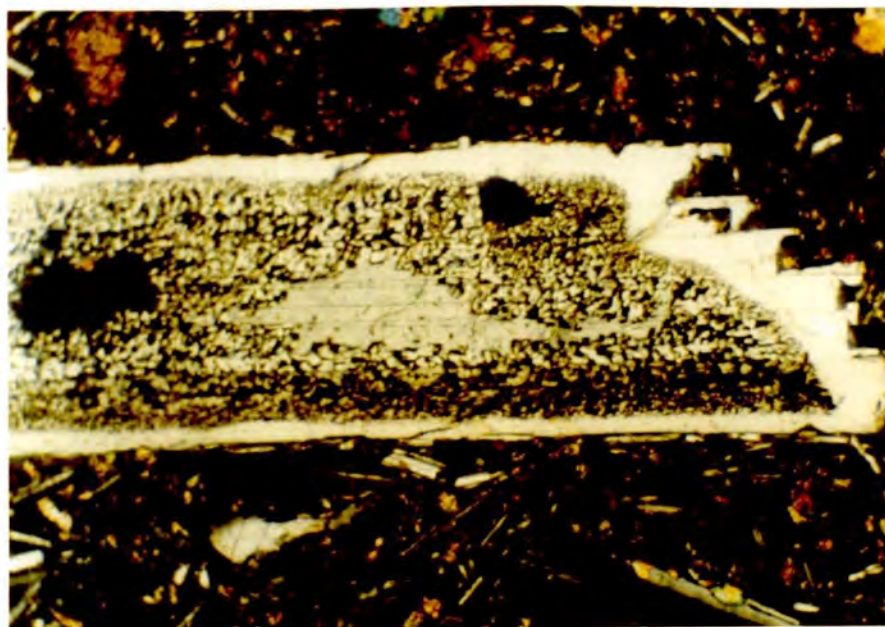


Fig. 12.22 Subglacial pillow lava from the Snaefellsnes zone. Corroded plagioclase phenocryst with labradorite core and andesine-oligoclase margin. Sample no. 270, crossed polars, field length 1.7 mm.

euohedral grains in the quartz tholeiites. In the more silica-rich tholeiites the ore starts to appear as microphenocrysts, and does so through to the rhyolitic rocks, along with minute euohedral grains of ore in the groundmass. The microphenocrysts of ore are sometimes enclosed in both pyroxene and olivine crystals. This suggests that crystallization of ore took place at two different stages; early along with plagioclase-pyroxene-olivine phenocrysts, and later as part of the crystallization of the groundmass.

CHAPTER 13:

GENERAL GEOCHEMICAL RELATIONS

Chemical characteristics of the basaltic rocks

The chemical characteristics of Icelandic basalts have been described by numerous authors (Carmichael, 1964; Sigvaldason, 1969; Sigurdsson, 1970a; Jakobsson, 1972; Grönvold, 1972) and they have pointed out the differences between the Icelandic basalts and ocean floor basalts. In this chapter the rocks in the research area will be compared with previously analysed rocks from Iceland, and with typical ocean floor basalts. All the analyses of the Tertiary samples are plotted on Fig. 13.1, and the late Quaternary and Recent samples are plotted on Fig. 13.2, along with the field of the Tertiary tholeiites.

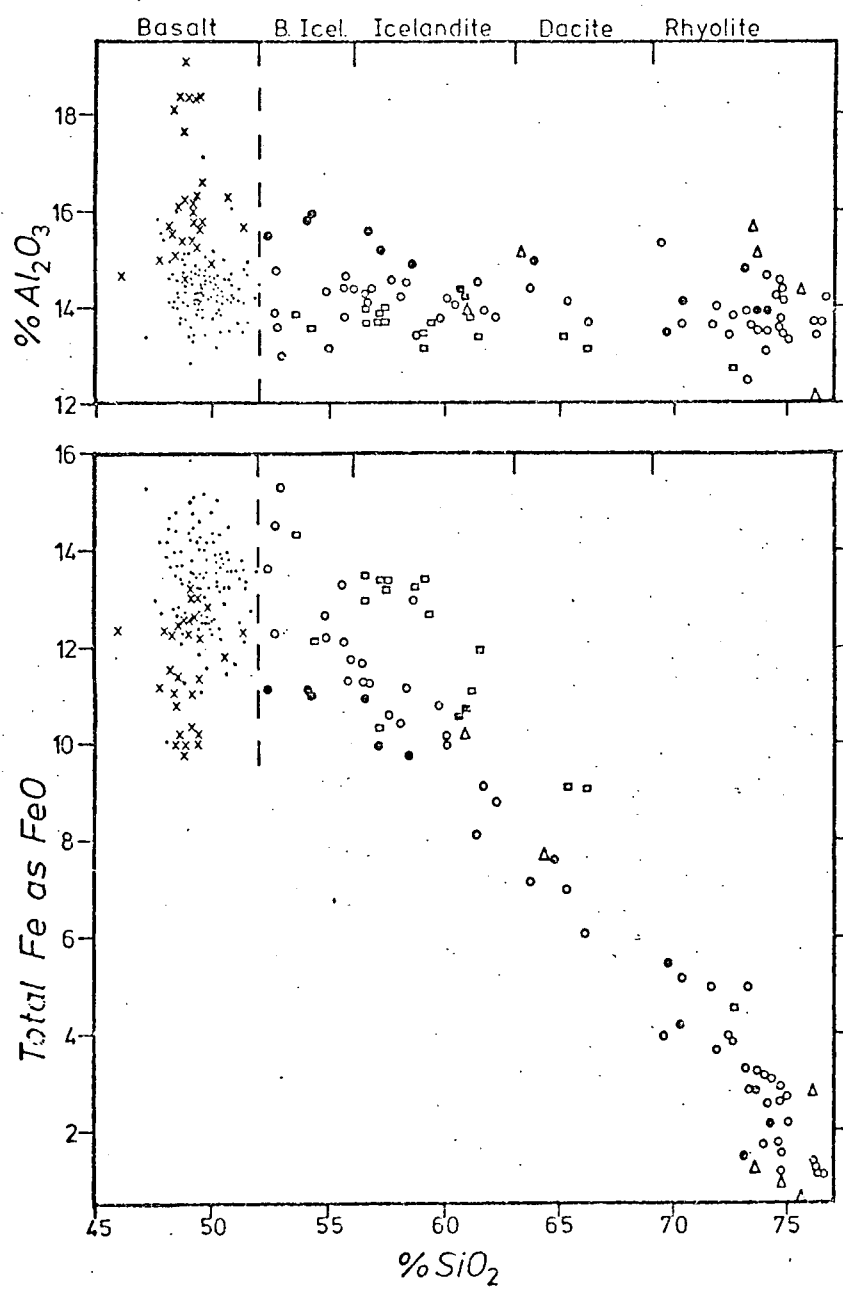
(a) Tertiary basalts

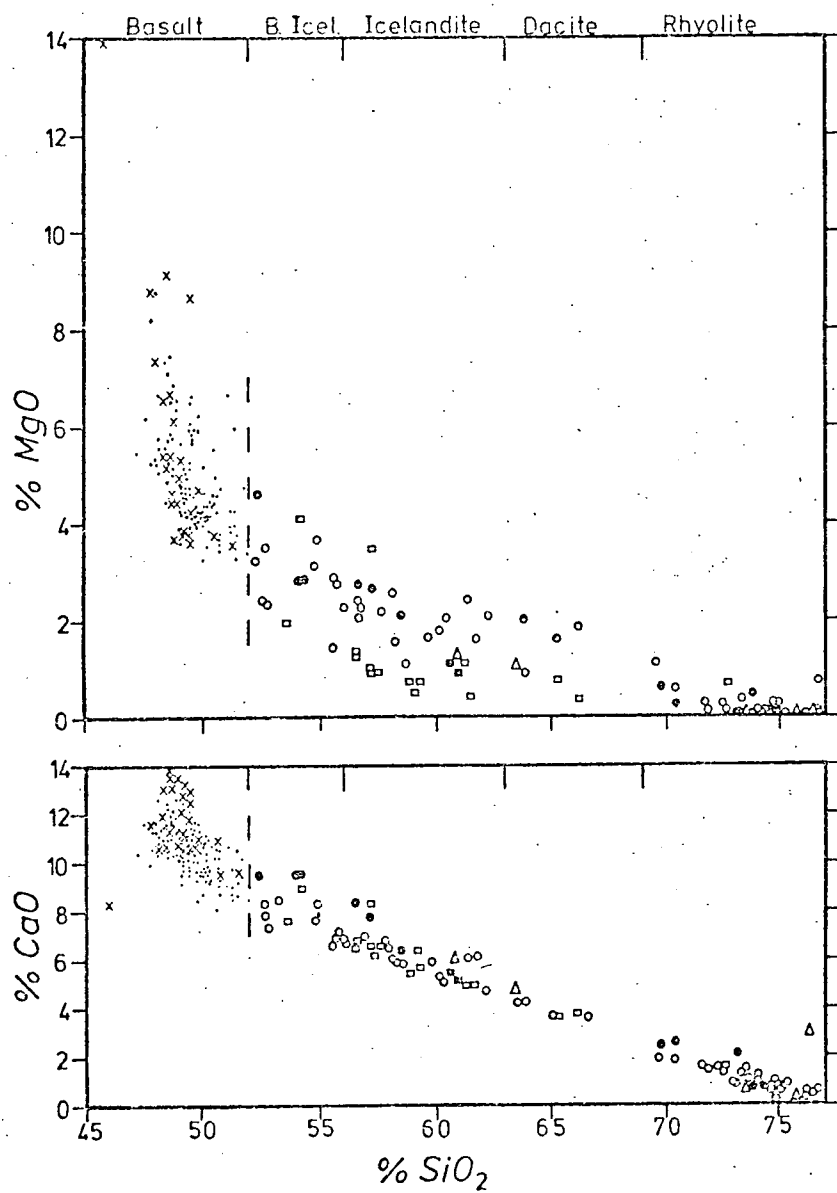
The Tertiary basalts of the research area are more silica-saturated than the basalts from the adjacent Reykjanes-Langjökull neovolcanic zone (Fig. 13.3) inside which many of the Tertiary rocks were extruded, before subsequently drifting westward. The volcanics of the neovolcanics zone are more primitive in character (Jakobsson, 1972). The Tertiary basalts of the area are similar in chemistry to the basalts of the Thingmuli central volcano (Carmichael, 1964) and of the Setberg central volcano (centre 1, Sigurdsson, 1970a).

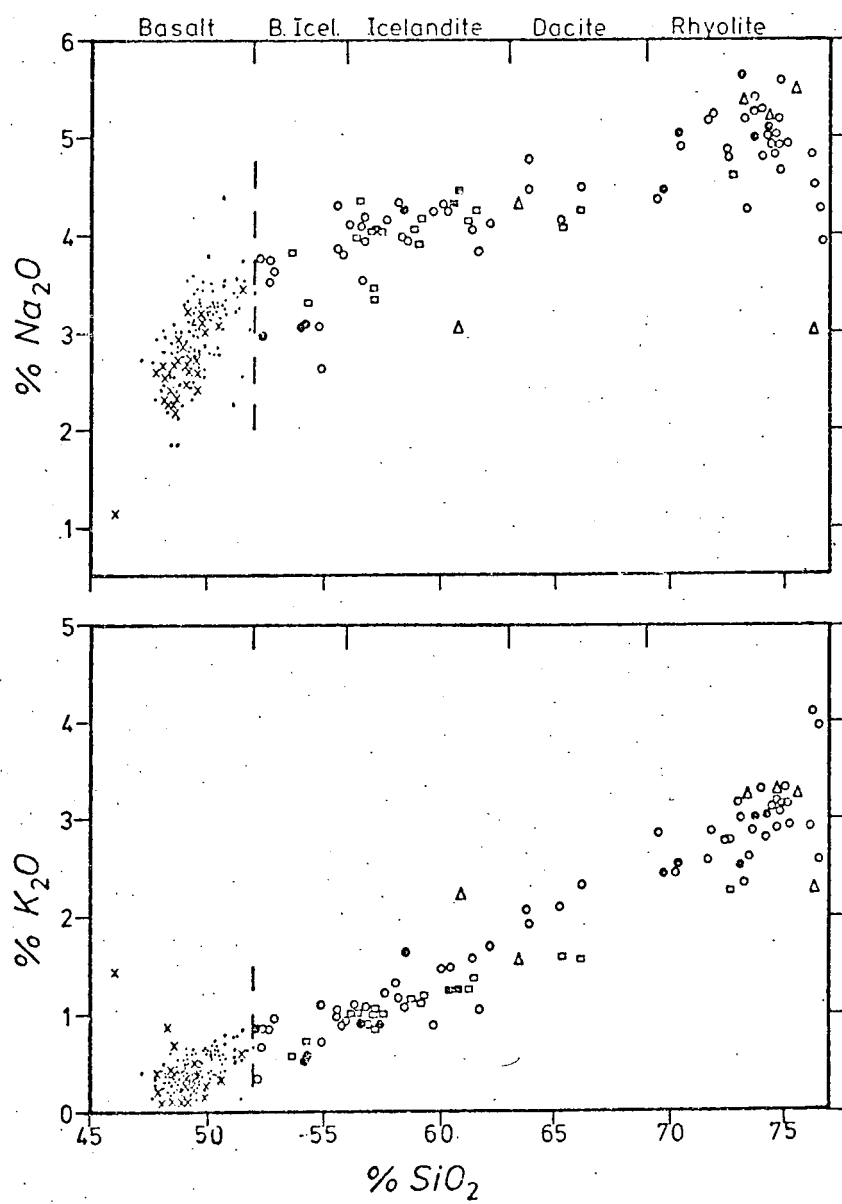
The Tertiary basalts differ from typical ocean-floor basalts in many aspects. They are, compared with the average of 94 selected ocean-floor samples (Caan, 1971), lower in Al_2O_3 and MgO , but higher in Na_2O , K_2O , MnO and P_2O_5 and considerably higher in iron and TiO_2 .

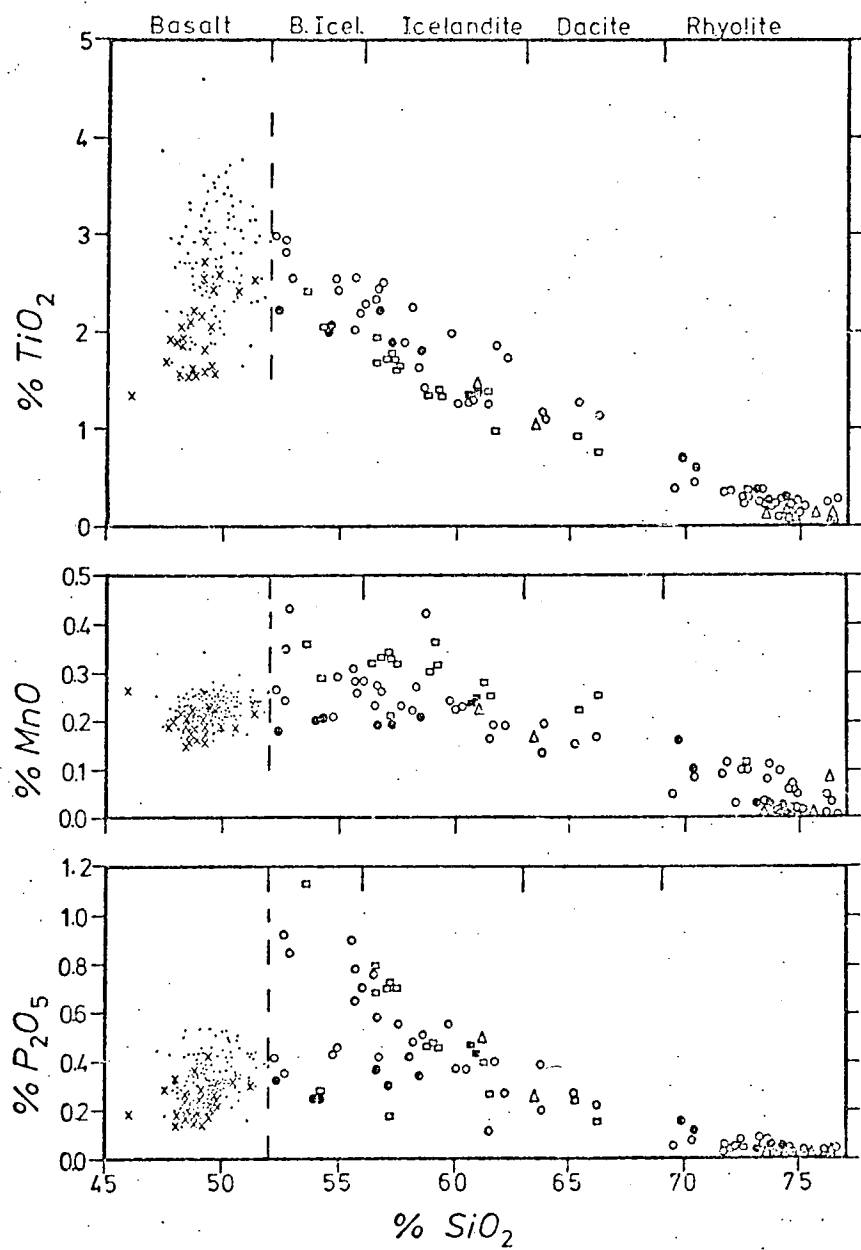
The quartz tholeiites of the neovolcanic zones in Iceland (Jakobsson, 1972) are, on average, higher in MgO , but lower in Na_2O , TiO_2 and P_2O_5 than the rocks for which data are presented in this thesis. The same is true for late Quaternary and Recent volcanics from northeastern Iceland

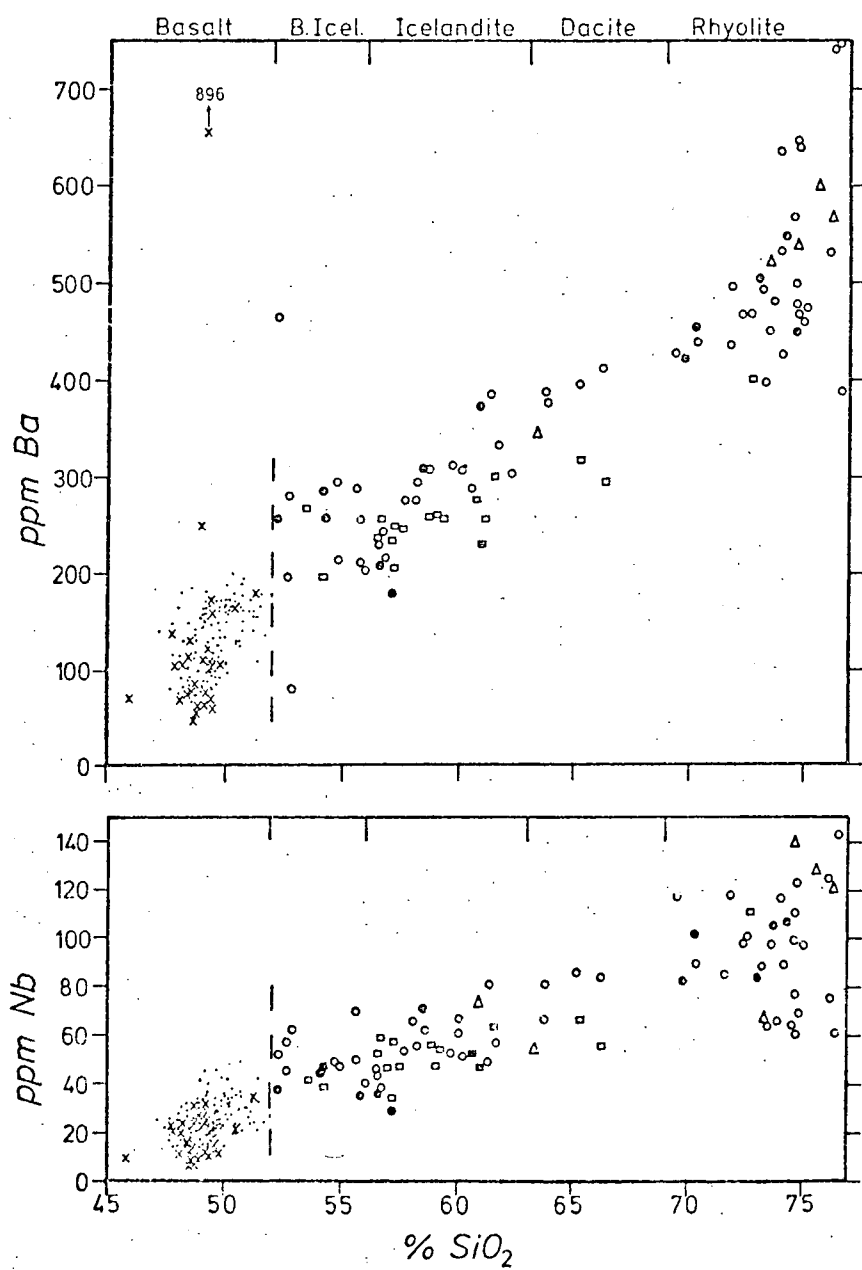
Fig. 13.1 Major and trace elements of the Tertiary rock samples from the Borgarfjörður-Dalir area, plotted against silica. The broken line marks the boundary between the basaltic rocks and the intermediate rocks. • , aphyric basalt; X, porphyritic basalt; ○ , aphyric differentiate of the Reykjadalur central volcano; ⊙ , porphyritic differentiate of the Reykjadalur central volcano; □ , aphyric differentiate of the Hallarmuli central volcano; ⊠ , porphyritic differentiate of the Hallarmuli central volcano; Δ , aphyric differentiate of the Laugardalur central volcano.

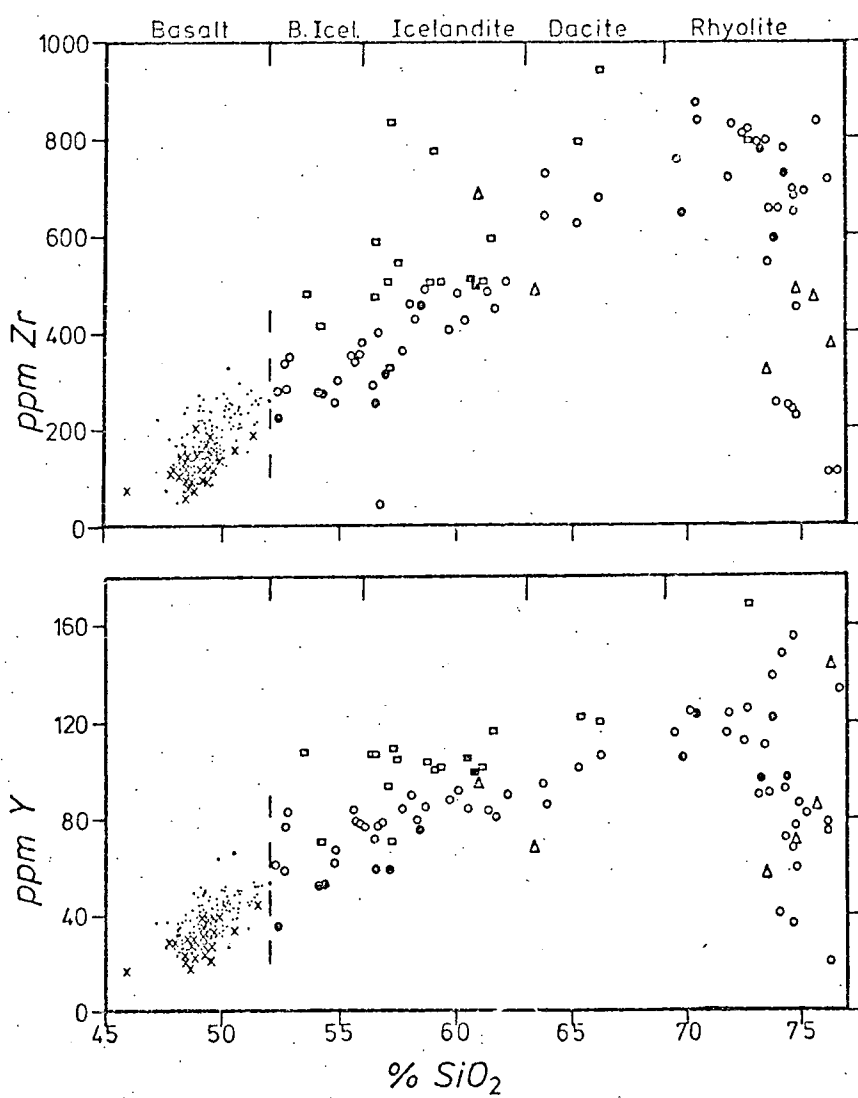


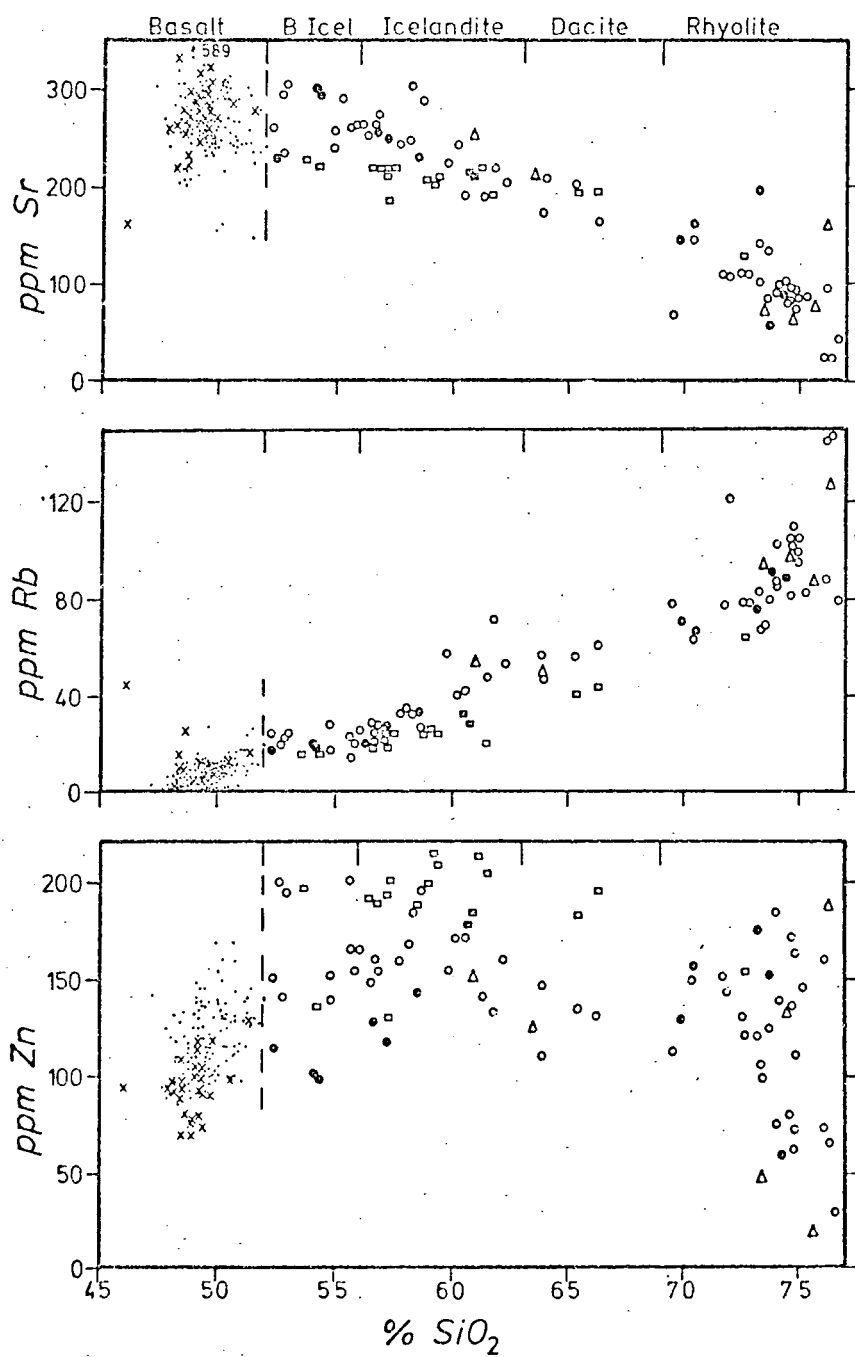












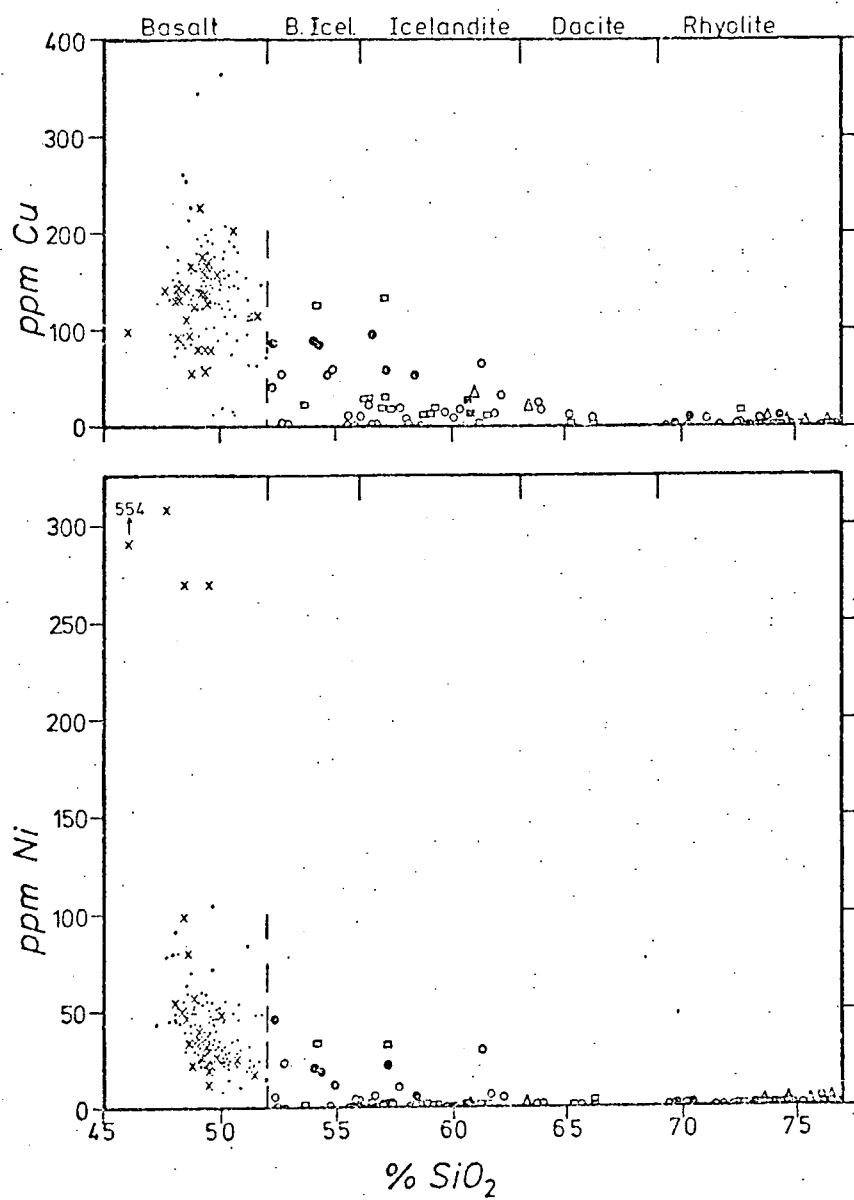
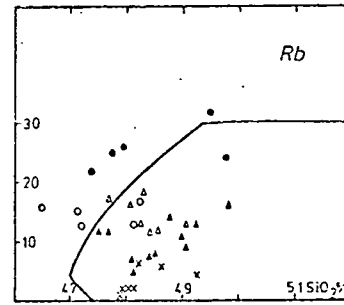
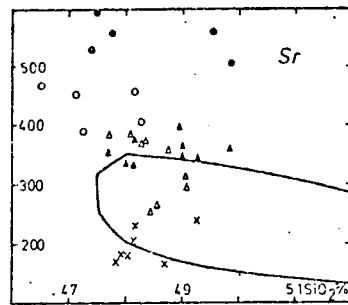
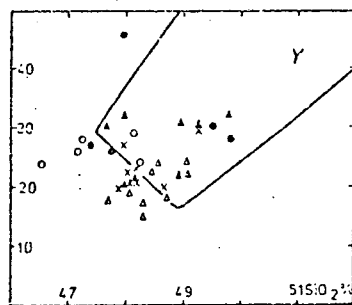
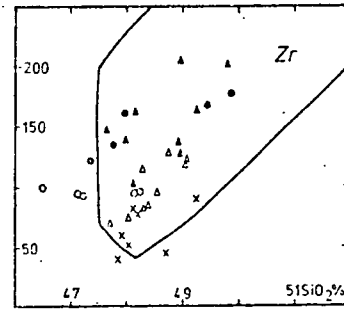
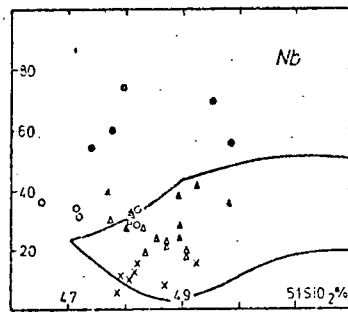
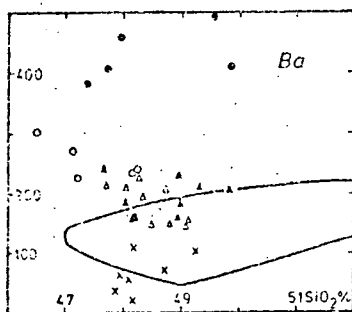
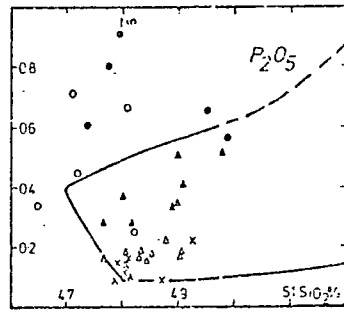
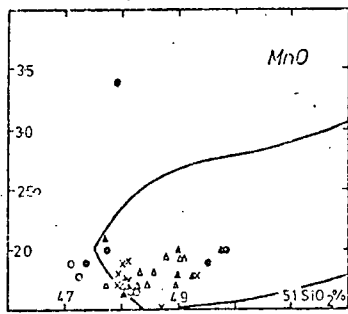
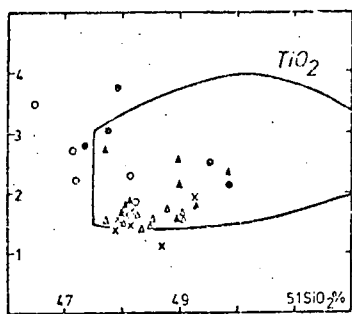
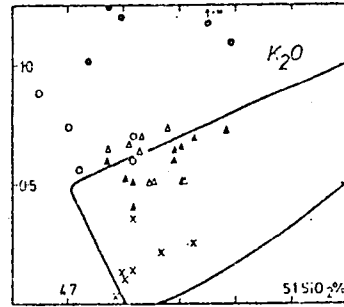
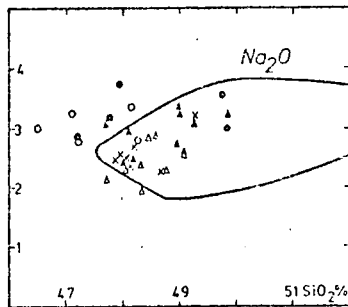
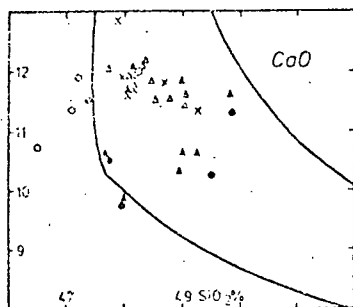
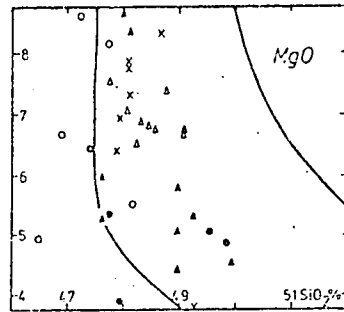
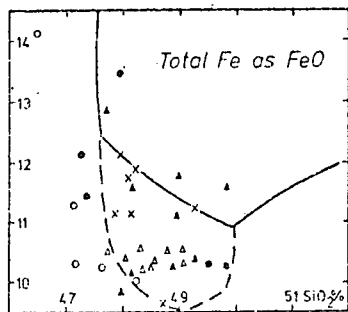
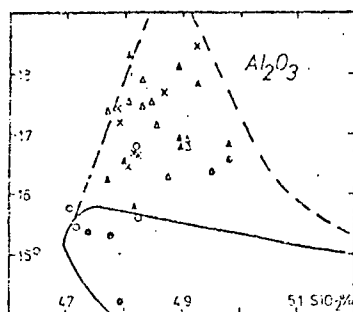


Fig. 13.2 Major and trace elements of the late Quaternary and Recent rock samples plotted against silica. The solid line represents the field covered by the Tertiary basalts. X, Reykjanes-Langjökull neovolcanic zone; Δ , sample from Nordurárdalur-Langavatnsdalur (Snaefellsnes zone); $\blacktriangle$, Snjofjöll series; O, alkali olivine basalt from Alftafjörður area (Snaefellsnes zone); $\odot$, hawaiite from the Alftafjörður area (Snaefellsnes zone).



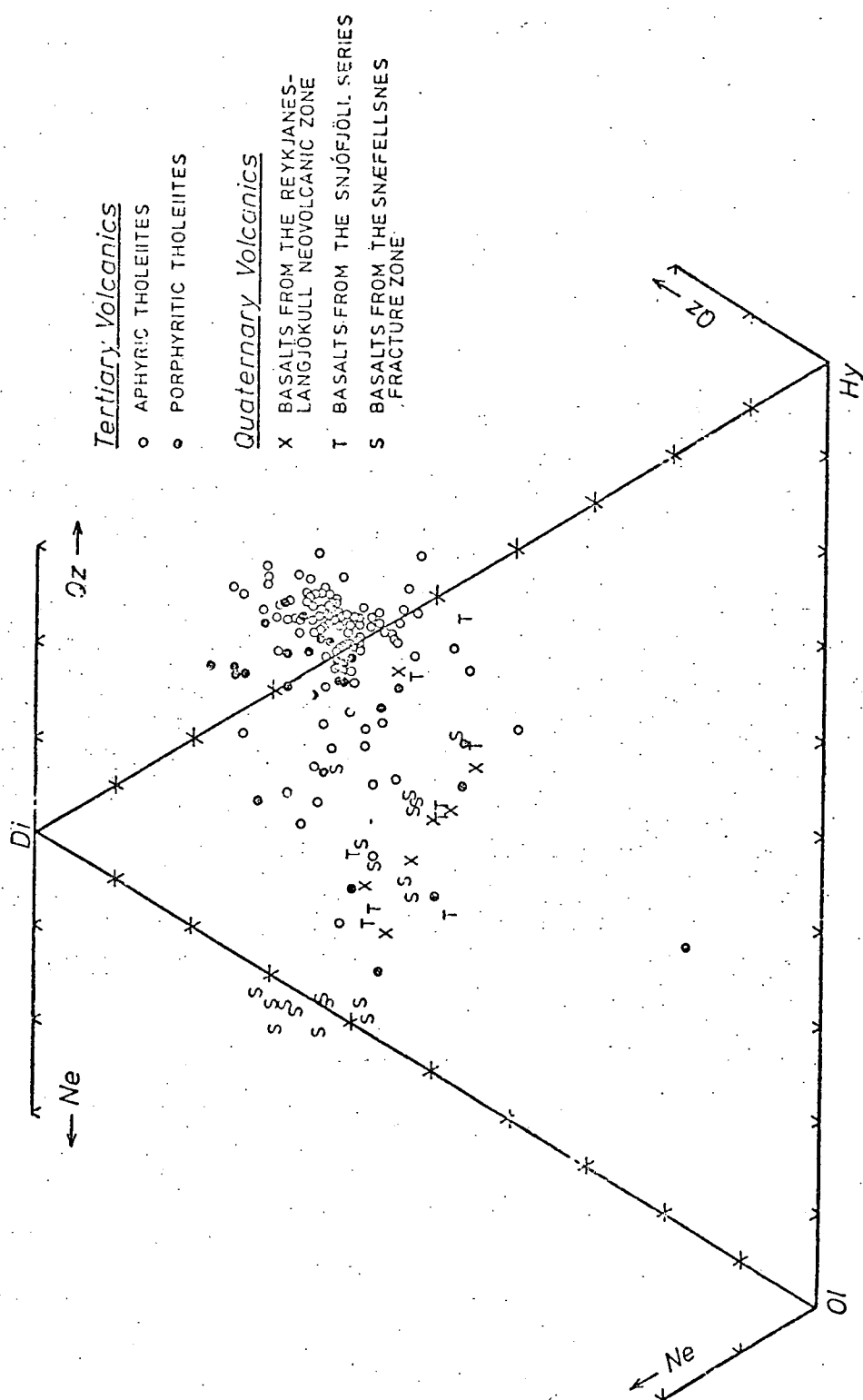


Fig. 13.3 Normative mineralogy of all the basalt samples analysed

(Sigvaldason, 1974a). These are higher in Al_2O_3 as well.

The Tertiary tholeiites are considerably higher in Sr, and lower in Ni, than the average ocean-floor basalt (Gast, 1970). Kempe (1974) reported the trace-element compositions of basalts from the Indian ocean (Leg 26). They are lower in Zr, Rb, Zn and Cu and much lower in Sr, but higher in Ni than the Icelandic Tertiary tholeiites. Bass et al. (1973) studied basalts from the central Pacific (Leg 17) which are found to be lower in Nb and Sr. The basalts of the Setberg area (Sigurdsson, 1970a) are lower in Ba and Sr, and the basalts of northeastern Iceland (Sigvaldason, 1974a) are generally lower in Y, Zr, Cu and much lower in Sr (Fig. 13.4), but higher in Ni than the tholeiites discussed in this study.

(b) Late Quaternary and Recent volcanics

The rocks of late Quaternary and Recent age in the research area include the Snjofjöll series, and a few formations in the Nordurardalur-Langavatnsdalur area. Samples from the Reykjanes-Langjökull neovolcanic zone, and from the Alftafjörður area (on the Snaefellsnes peninsula) are included in this study for comparison. The rocks can be divided into four groups, according to differences in chemistry and geographical distribution. They are all different from the Tertiary basalts, at least for some elements (see Fig. 13.2).

1. Olivine tholeiite of the Reykjanes-Langjökull neovolcanic zone are the most primitive basalts occurring in Iceland (Jakobsson, 1972). They are much higher in Al_2O_3 and MgO, but lower in iron, TiO_2 , Ba and Sr than the Tertiary tholeiites. The Sr and Ba values are similar to the values recorded by Sigvaldason (1974a) and Gast (1970). It is of great interest to compare this group of samples to the Tertiary tholeiites, some of which were extruded

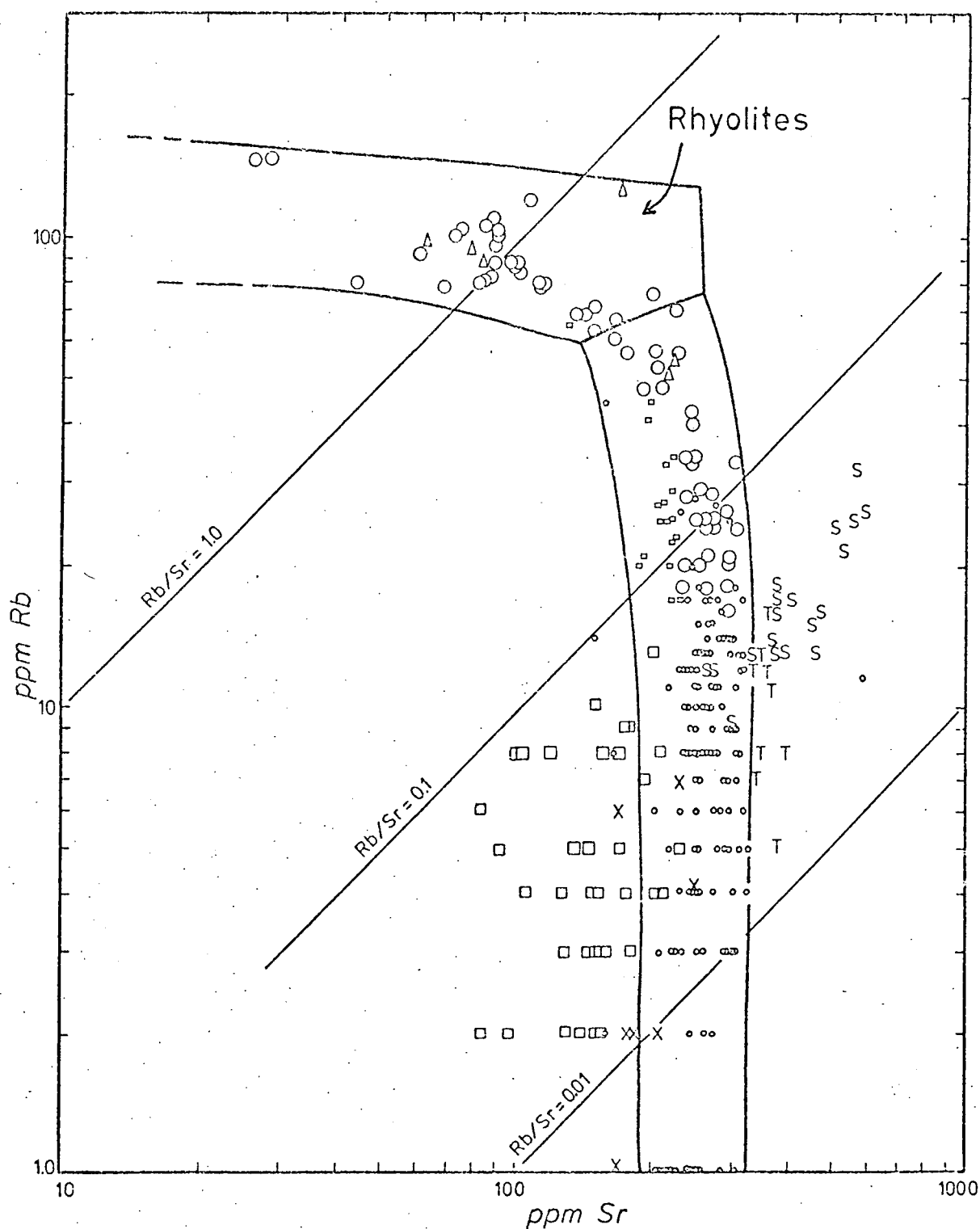


Fig. 13.4 Rb plotted against Sr on a log scale. $\square$, Hallarmuli differentiate; $\circ$, Reykjadalur differentiate; Δ , Laugardalur differentiate; $\bullet$, Tertiary basalt from the research area; $\square$, basalt from northeastern Iceland (Sigvaldason, 1974a); X, Reykjanes-Langjökull zone; T, Snjofjöll series; S, Snaefellsnes zone.

- inside the same volcanic zone. Some of the samples in this group are so high in Al_2O_3 that it is justifiable to call them "high-alumina basalts", although the term is not used in this study.
2. The Snjofjöll transitional series is of Matuyama age. It differs from the previous group in having higher P_2O_5 , Nb, Zr, Y and Sr. Both these two groups have a higher Al_2O_3 content, and a lower iron content, than the Tertiary tholeiites which, on average, have higher alkalis and Sr and a lower TiO_2 content, and are enriched in MgO relative to iron (Fig. 13.5).
 3. The Snaefellsnes volcanics in the Nordurardalur-Langavatnsdalur area are similar in many respects to those in the Snjofjöll series but are lower in iron, P_2O_5 and Zr, and higher in MgO.
 4. The Snaefellsnes volcanics in the Alftafjörður area include both alkali basalts and hawaiites. The alkali basalts are much richer in alkalis, especially potassium, compared with all other basalts described in this study, as well as being higher in P_2O_5 , Ba, Nb, Sr and Rb (but lower in iron). The hawaiites are higher in iron, K_2O , MnO, P_2O_5 , Ba, Nb, Zr, Sr, and Rb but lower in Al_2O_3 , MgO and CaO than alkali basalts.

(c) Variations in time and space

The chemistry of the Tertiary tholeiites and of the samples from the Reykjanes-Langjökull neovolcanic zone show a vague trend with time. Four of the elements have been plotted (Fig. 13.6), and a line is drawn to represent a trend.

The diagram can be divided into two different fields:

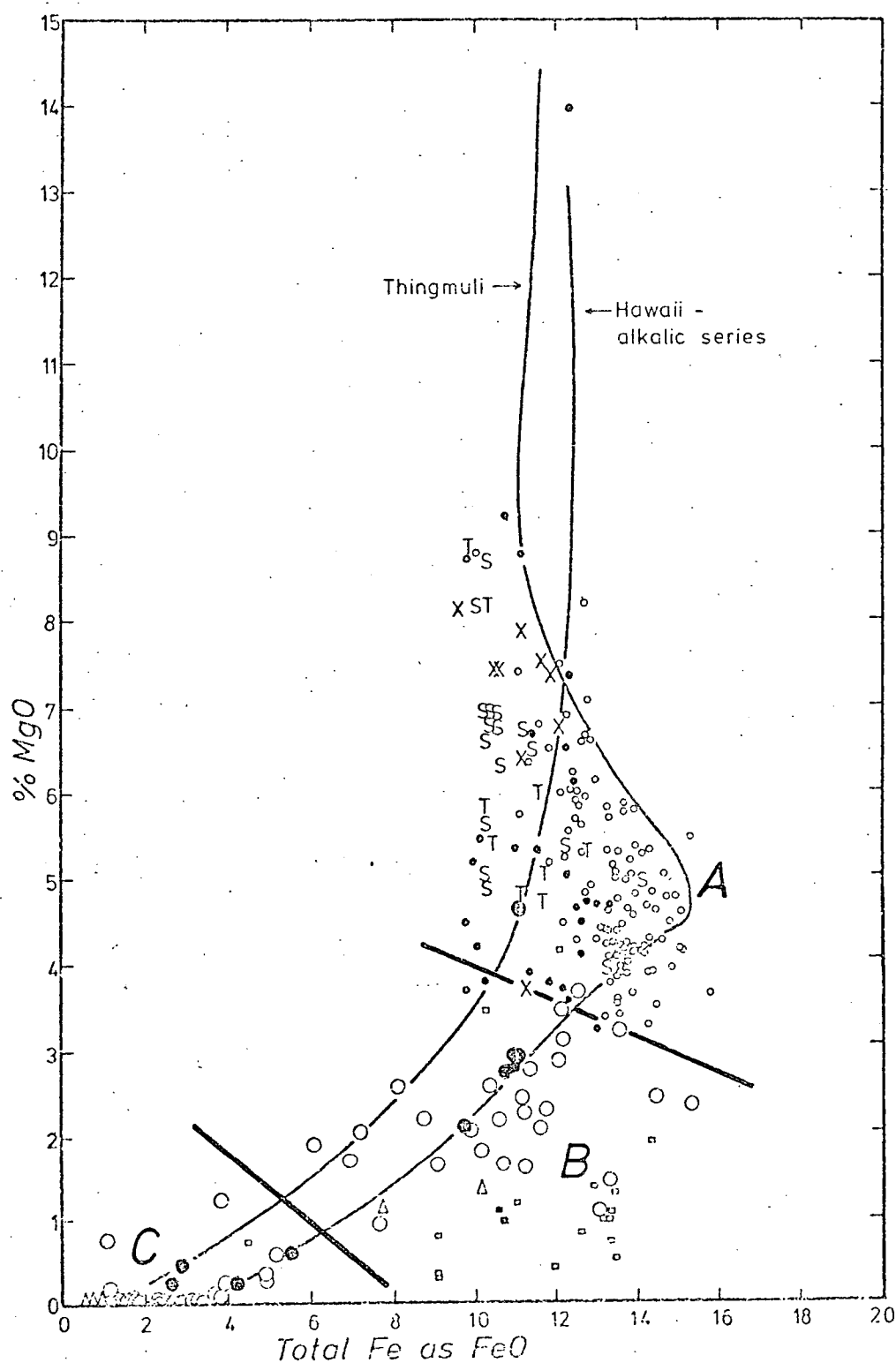


Fig. 13.5 MgO plotted against total iron. Symbols are the same as in Fig. 13.4, except that solid circles and squares represent porphyritic samples. The Thingmuli trend (Carmichael, 1964) and the Hawaiian alkalic trend (Macdonald and Katsura, 1964) are shown.

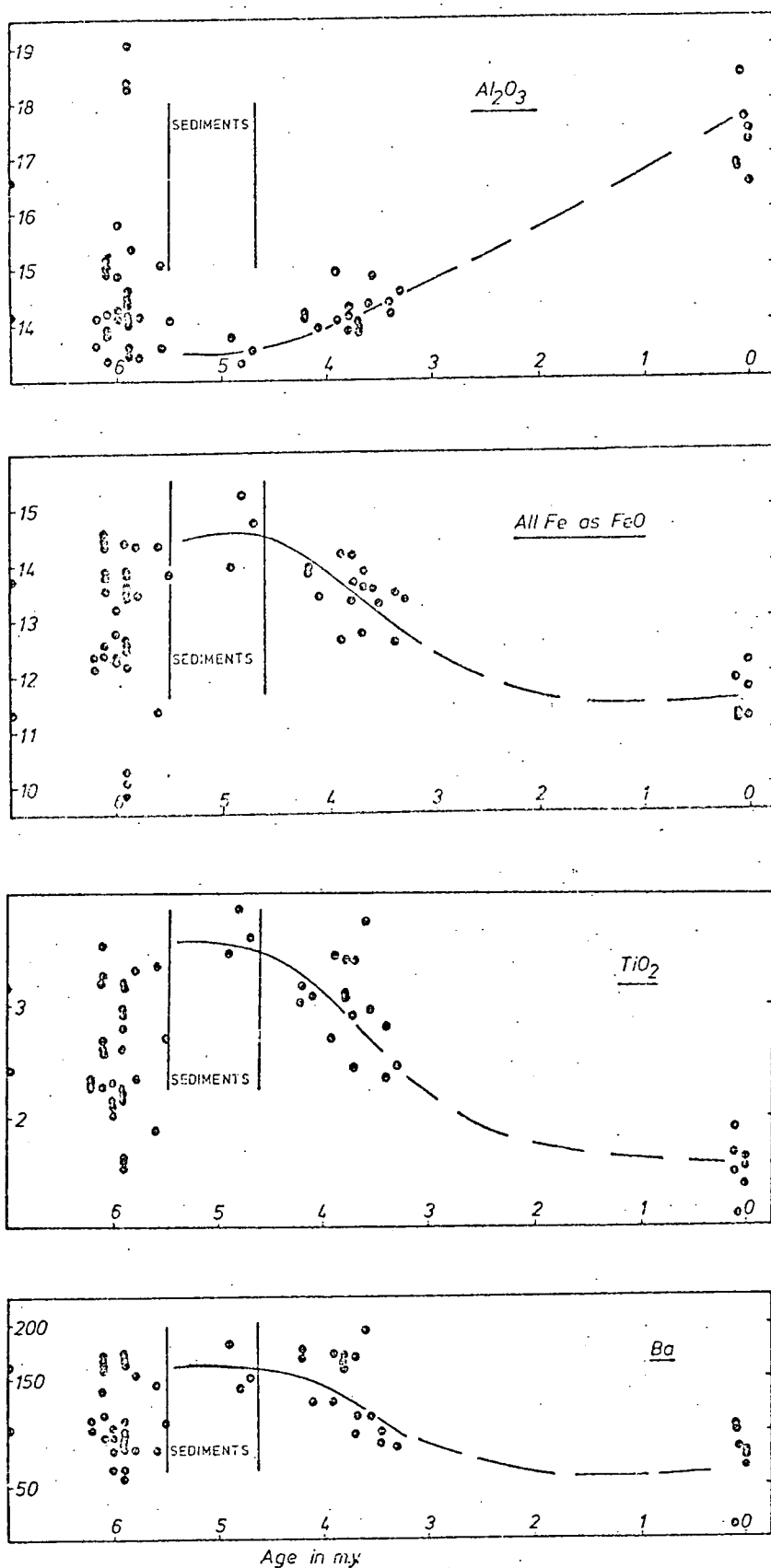


Fig. 13.6 Al_2O_3 , total iron, TiO_2 and Ba of a few basalt samples ages. The sediment-rich part of the lava pile is indicated.

1. Rocks older than 5.75 m.y. show a great variation which is partly caused by plagioclase-phyric samples.
2. Rocks younger than 5.75 m.y. display a smaller variation, and show either a gentle increase or a decrease up to recent times.

There is a gap of 3 m.y. represented by rocks from outside the research area, for which there is little or no chemical data, but the author is confident that no major break occurs. An abrupt change in chemistry occurs about 5.0 to 5.75 m.y. ago, which coincides with the introduction of sediments in the Thverarhlid area (see Chapter 3), suggesting that the rocks older than this break were extruded in a different volcanic-tectonic environment from the rocks younger than the break (which are presumably extruded inside the present Reykjanes-Langjökull zone).

Al_2O_3 increases significantly from Tertiary to Recent times, in contrast to iron, TiO_2 , and most trace elements. The differences between the Tertiary and the Recent volcanics are obvious from both major and trace element chemistry (e.g. Fig. 13.2), and they are also reflected in the initial Sr-isotope ratio which decreases from Tertiary to Recent times (O'Nions and Pankhurst, 1973). Also the olivine tholeiites are far more common in the Reykjanes-Langjökull volcanic zone today than in the Tertiary lava pile.

It is difficult to assess lateral variations in the Tertiary lava pile, because the area is not big enough (along strike) to reveal any major changes in the chemistry of the lava flows. However, a lateral variation does occur in the Reykjadalur thick-layered series around the Reykjadalur central volcano. The basalt flows increase in silica content towards the volcano, showing that the basaltic volcanism is closely related to the central volcano.

Another interesting variation in the basalts is the increase in

alkalis in the late Quaternary and Recent volcanics, outwards from the Reykjanes-Langjökull neovolcanic (axial rifting) zone and along the Snaefellsnes peninsula (Fig. 13.7). The increase is gradual, from the Reykjanes-Langjökull zone to Langavatnsdalur, but from there to the Alftafjörður area a sharp increase takes place. This increase in alkalis has been noted by Jakobsson (1972), and he suggests that the change is due to the increase in depth to Layer 4 (Palmason, 1971).

Oxide and trace elements variations in the Tertiary central volcanoes and the surrounding lava pile.

In his recent work, Grönvold (1972) compared the chemistry of all those central volcanoes in Iceland which have been studied from the geochemical aspect. He showed that of eight igneous suites, four have chemical trends that are nearly identical to the Thingmuli trend; three have higher combined alkalis relative to silica; and one has markedly lower alkalis relative to silica compared with the Thingmuli trend. In this study, the work of Grönvold (1972) will be used for comparison.

Fig. 13.1 shows variation diagrams (oxide or trace elements against silica) for all the analysed samples of Tertiary age, both basalts and differentiates, from the research area. Each central volcano is marked separately and aphyric and porphyritic samples are distinguished.

As mentioned earlier, the Tertiary suites of the area are tholeiitic in character (Fig. 12.1), and have a continuous compositional range except for a gap in the dacite region. No samples occur with silica values between 66 and 69%. This gap or break occurs in all the chemical diagrams. It is known as the "Daly gap" (Baker, 1968) in alkaline suites of oceanic islands, but intermediate rocks are scarce rather than absent there. In other Icelandic suites, no gap is apparently present but the rarity of these rocks is striking. Thompson (1972) found that

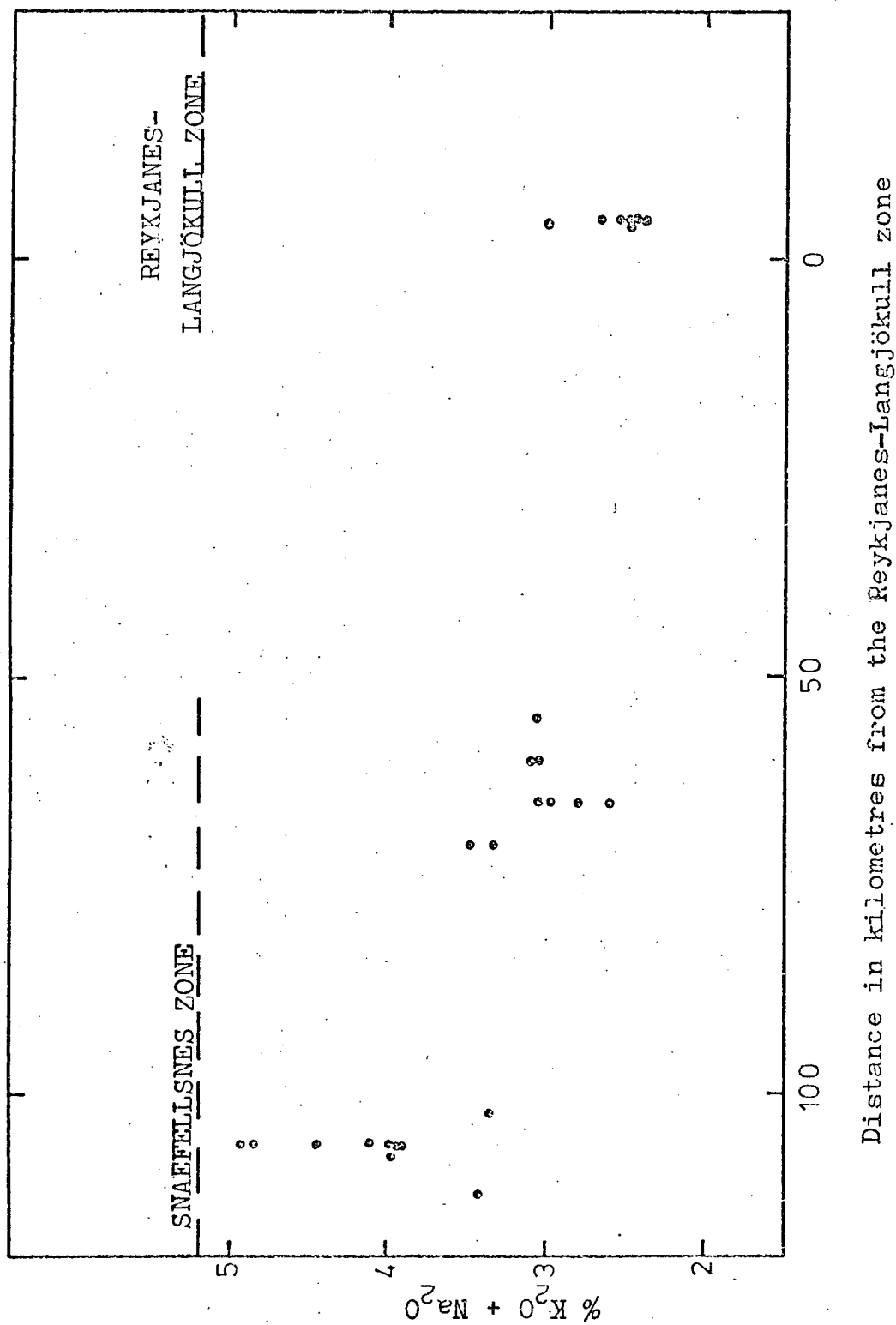


Fig. 13.7 The alkali content of the Late Quaternary and Recent samples plotted against distance from the Reykjanes-Langjökull rift zone.

a smaller compositional gap is present between the basalts and andesites in numerous anorogenic volcanic suites. The number of samples in the basaltic icelandite region of the rocks from the research area is low but no actual chemical gap is present.

Thus, there is a trimodal distribution pattern (Fig. 13.8), with an overwhelming majority of samples in the basalt region, icelandite region, and rhyolite region, but with only a few samples falling in the basaltic icelandite region and in the dacite region. Sampling error is ruled out as a reason for this trimodal distribution, because a special effort was made to sample as many acid and, especially, intermediate flows and intrusives as possible. It is interesting that changes on the differentiation trends tend to take place in these two regions.

The differentiation trends in Fig. 13.1 can be broken into four segments, each having a different slope marked by three breaks; (1) at the 50% silica mark, (2) at about the 52% silica mark and (3) in the dacite region (about 66-67% silica).

The first break occurs around 50% silica, and it marks roughly the boundary between the olivine tholeiites and the quartz tholeiites. The break is most noticable in Al_2O_3 , iron, MgO , CaO , Na_2O , Ba, and to a smaller extent in TiO_2 . MgO and CaO decrease at nearly constant silica until the break, but Na_2O , TiO_2 and Ba increase until the break, along with iron. This break is also present in other Icelandic volcanic suites (Grönvold, 1972).

The second break occurs at about 52% silica, where it marks the boundary between the basalts and the differentiated rocks. This break is distinct for MnO and P_2O_5 (Fig. 13.9) but is vague for the other major oxides. MnO jumps from about 0.2 to about 0.3-0.4% and P_2O_5 from about 0.4% to about 0.6-0.8%. P_2O_5 shows a great spread in amount, from 0.3% to 1% in the basaltic icelandite region, but the spread and

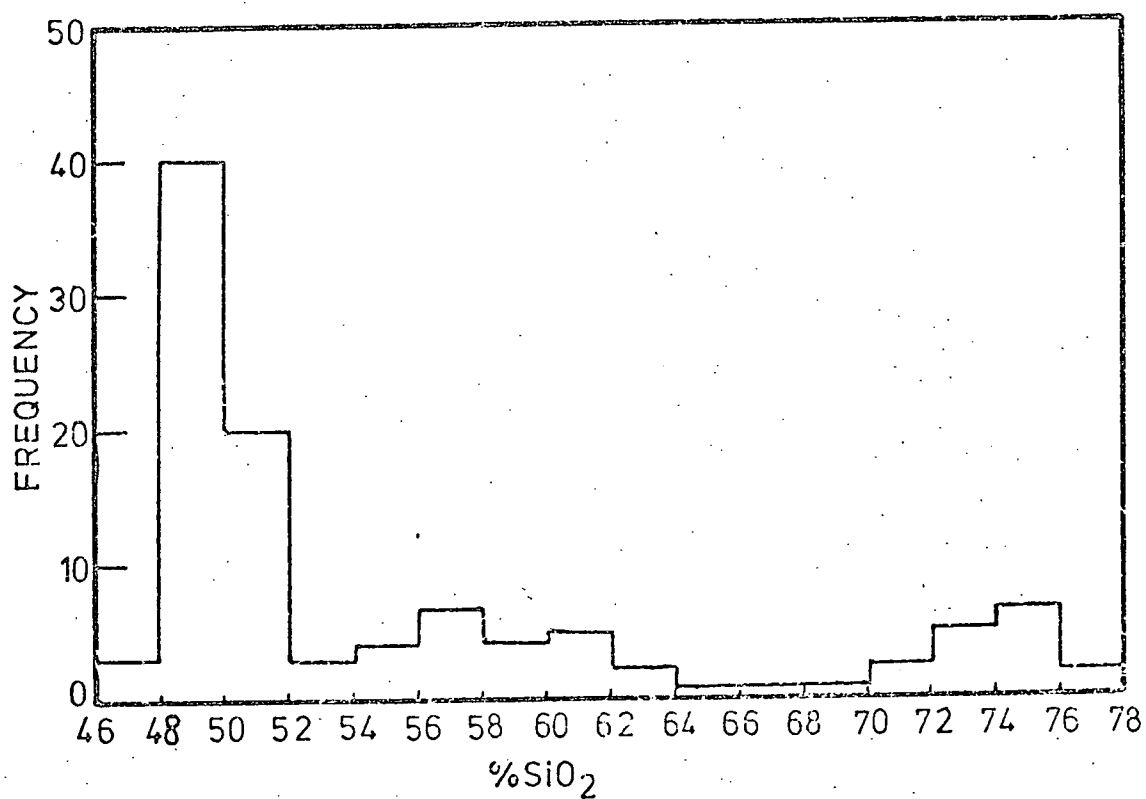


Fig. 13.8 Histogram of silica content of the Tertiary rocks, (206 samples) from the Borgarfjörður-Dalir area.

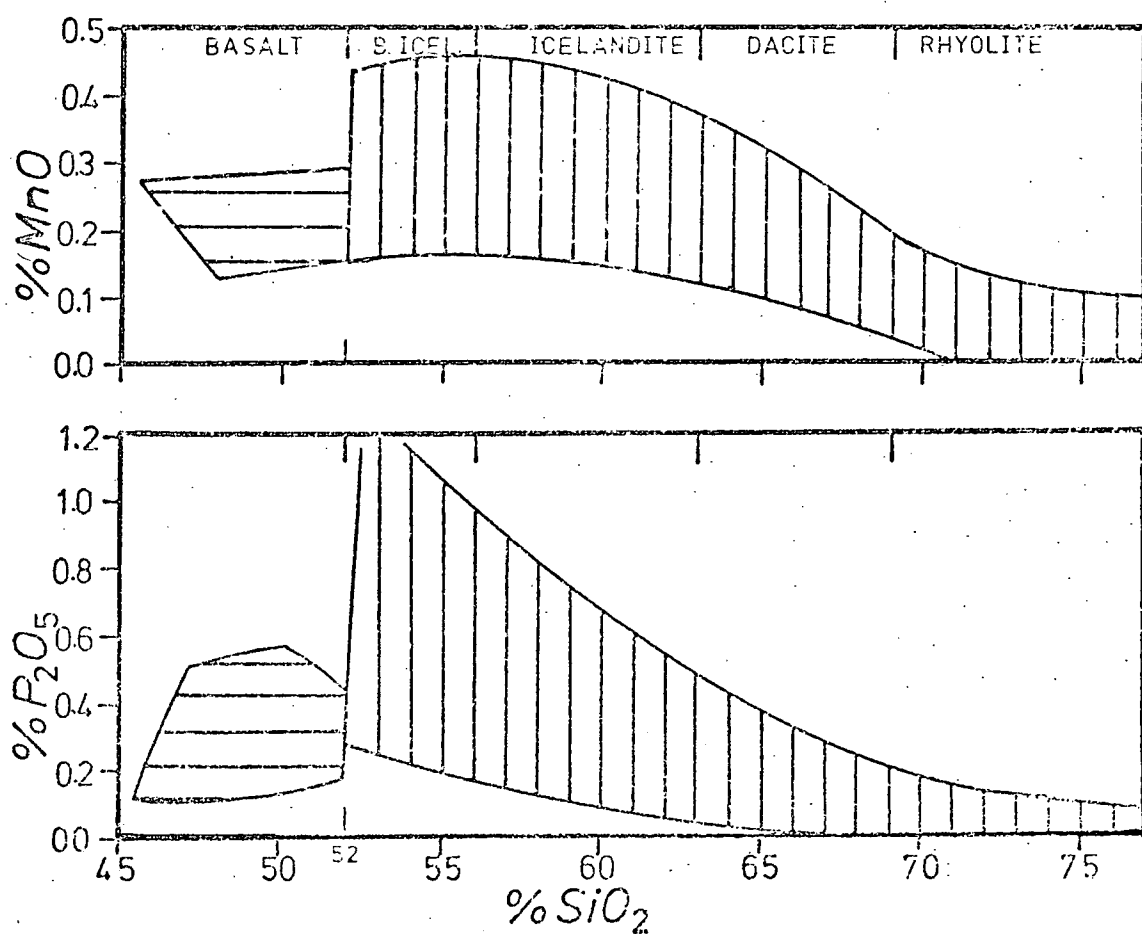


Fig. 13.9 MnO and P_2O_5 plotted against silica for the Tertiary samples. The vertical stripes show the compositional range of the intermediate and acid rocks, and the horizontal stripes show the compositional range of the basaltic samples.

the content gradually decrease with increasing silica. The high P_2O_5 values for the intermediate samples have been regarded as a peak and the fall off towards the acid end as caused by fractionation of apatite (Sigurdsson, 1970a), but as can be seen in Fig. 13.1, the concentration of P_2O_5 does not show any build-up from basalts to basaltic icelandite, only a sudden jump. This break is abrupt in nearly all the trace elements; Ba, Y and Zn show a jump in concentration, not a gradual trend as would be expected if crystal fractionation was involved.

The third break occurs in the dacite region (66-67% SiO_2). It is very prominent and by far the clearest of the breaks, especially amongst the trace elements. The trends have different slopes on each side of the break, and for many trace elements the trend in the rhyolitic region is nearly perpendicular to the main trend. Iron decreases faster with increasing silica in the rhyolitic region and Al_2O_3 is slightly higher than expected, resulting in corundum-normative rhyolites, which have only once before been reported from Iceland (Sigvaldason, 1974a). Ba and Rb increase faster while Zr, Y and Zn decrease faster with increasing silica in the rhyolitic region compared with the intermediate region.

On Figs. 13.5 and 13.10 the major elements which show the sharpest break are plotted against each other. The TiO_2/MgO diagram (Fig. 13.10) can be divided into three different fields, where the breaks in the basaltic icelandite region and in the dacite region mark the boundaries. This diagram has been discussed by Grönvold (1972), who came to similar conclusions as those of the present author. In the basalt region (A), the samples form a near-linear trend, but in the intermediate region (B) the samples are markedly spread in their distribution. In the rhyolite region the trend is, again, near-linear. The same arrangement is shown by iron versus MgO , but is even clearer (Fig. 13.5).

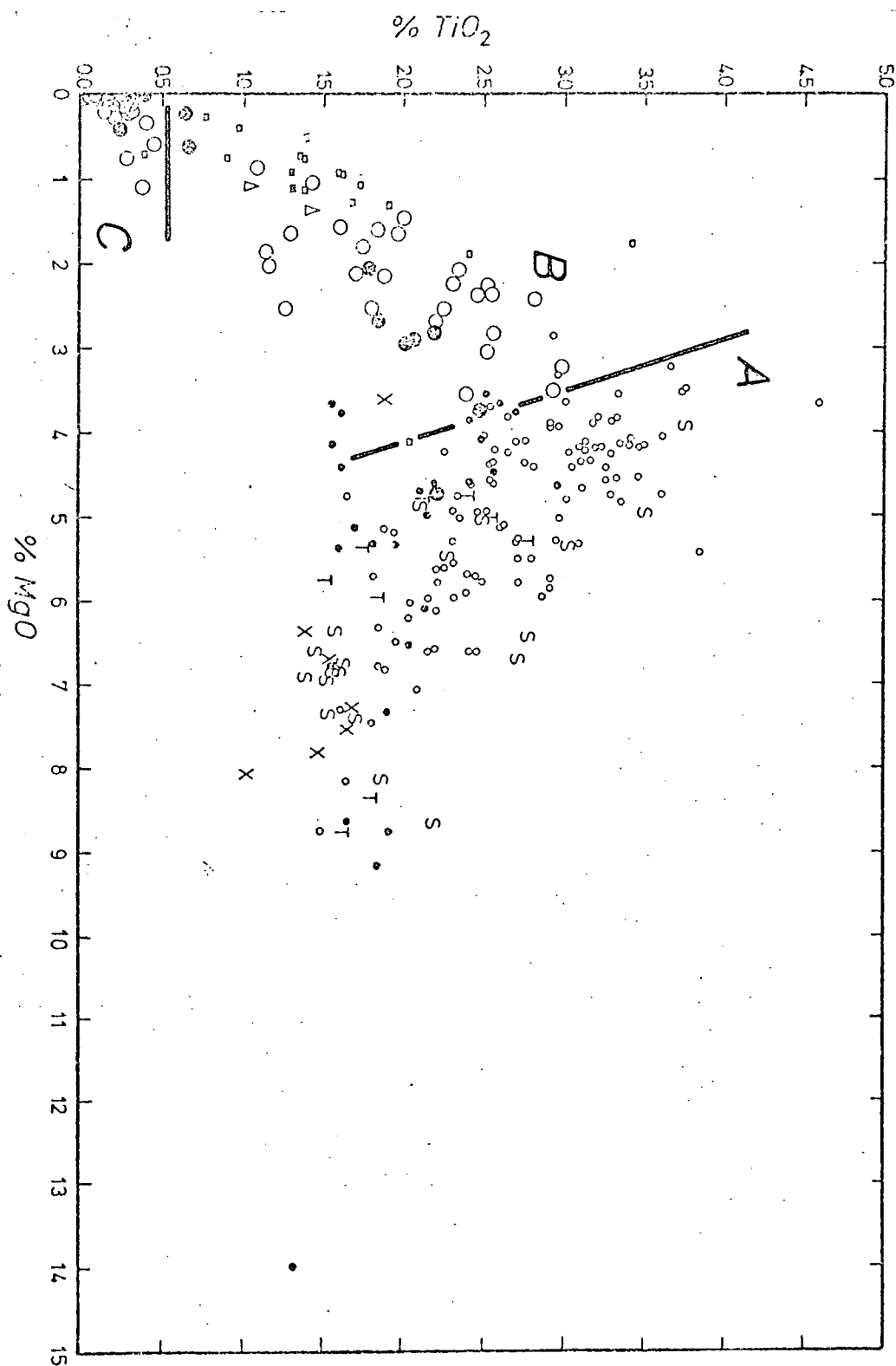


Fig. 13.10 TiO_2 plotted against MgO . Symbols are the same as in Fig. 13.5.

When Sr and Rb are plotted against each other on a log scale (Fig. 13.4), the break in the dacite region appears as an abrupt change of trend which probably cannot be accounted for by precipitation and subsequent removal of plagioclase from a magma.

All three breaks are closely reflected in the petrography of the rocks. The first break coincides with the disappearance of olivine, and a change from interstitial Fe-Ti oxides to euhedral Fe-Ti oxides. The second break coincides with the appearance of euhedral microphenocrysts of magnetite, along with the euhedral groundmass phase. The third break marks the arrival of quartz as a microphenocryst, a drastic reduction in the amount of magnetite, and the near disappearance of clinopyroxene as a groundmass phase.

The rocks of the Laugardalur central volcano and the Reykjadalur central volcano show similar chemical features, while the Hallarmuli central volcano is slightly different. The latter shows much stronger iron enrichment in the intermediate region than do the others. On the AFM-diagram (Fig. 12.1) the trend for Hallarmuli is midway between the Thingmuli trend and the Skaergaard trend. This chemical difference is reflected in the other constituents: Al_2O_3 , MgO, TiO_2 , Sr and Rb are slightly lower, but MnO, Zr, Y and Zn are higher in the Hallarmuli suite compared with the Laugardalur and the Reykjadalur suites. No comparison can be made in the rhyolitic region, because only one rhyolite lava flow was found in Hallarmuli (ignimbrites and ash were avoided because of possible aeolian differentiation).

CHAPTER 14:
PETROGENESIS

The Crustal Structure of Iceland

Palmason (1971) studied the crustal structure of Iceland in some detail, and showed it to be similar to that of the ocean floor, except that there is a considerably greater thickness of crust beneath Iceland.

He identified four crustal layers, which he named layers 0, 1, 2 and 3, and an anomalous Upper Mantle, layer 4. The average P-velocity and approximate density for each layer are listed in Table 14.1.

Layers 0, 1 and 2 correspond approximately to layer 2 in the oceanic crust, and layer 3 corresponds to the oceanic layer (bottom layer).

Layer 0 is a maximum 1 km thick, and is the surface layer in the neovolcanic zones. It consists of interglacial lava flows, pillow lavas and hyaloclastites, formed during the later part of the Quaternary Ice Age. Layers 1 and 2 consist of flood basalts. Layer 1 is exposed at the surface outside the neovolcanic zones, but layer 2 is only exposed in south-eastern Iceland.

The depth to the top of layer 3 has been mapped in detail by Palmason (1971) and it varies from 1-2 km underneath extinct central volcanoes, to about 8-10 km in southern Iceland. The thickness of the layer is usually in the range of 4-5 km, but that are indications that the layer is considerably thicker in northern Iceland (Palmason, 1971).

Two cross sections have been constructed from seismic data across the Borgarfjörður area (Figs. 40 and 41 in Palmason, 1971). One is NW to SE, along the Snæfellsnes peninsula and across Borgarfjörður and the neovolcanic zones in southern Iceland; the other is from SSW

Layer	Average P-velocity Km/sec	Average density g/cm ³
0	2.8	2.1-2.5
1	4.2	2.6
2	5.1	2.65
3	6.5	2.9
4	7.2	3.1

Table 14.1 Average P-velocities and average densities
for the various crustal layers in
Iceland (from Palmason, 1971).

to NNE, from Reykjanes peninsula north across the Borgarfjörður and Holtavörðuhéidi to Skagi. The depth to layer 3 is about 2-3 km in the area south of the Snaefellsnes fracture zone, and the depth to the Moho (to layer 4) is about 9 km. North of the zone the depth to layer 3 increases slightly (to about 4-5 km) and the depth to layer 4 increases drastically, to about 14-15 km. Layer 3 thus increases in thickness from 6 km to about 10-12 km. This increase in the thickness of layer 3 is difficult to explain, but it coincides with areas where the number of central volcanoes is greatest. Layer 3 is nowhere exposed at the surface, but it comes nearest to the surface where seismic profiles have been obtained across extinct central volcanoes.

The composition and structure of layer 3 are not known, and many hypotheses have been advanced to explain the nature and origin of the layer. Cann (1974) considered the oceanic crust and suggested that a pipe-shaped magma chamber is sited permanently in layer 3, and that dykes (inclined sheets) from the top of the chamber form the top of the layer, isotropic gabbros the central part, and layered gabbros the bottom part of the layer. Due to the high thermal gradient and the availability of water, the upper part of the layer may be metamorphosed to the amphibolite facies.

Christiansen (1970) studied the compressional wave velocities in rocks (in the laboratory) and found that the velocities were consistent with an oceanic crust composed of an assemblage of hornblende and plagioclase. He suggested that the oceanic layer (layer 3) is formed by tholeiitic magmas crystallized under hydrous conditions.

Layers 1 and 2 above layer 3 in Iceland, are basaltic in composition, and the different P-velocities and densities may be caused by differences in low-grade metamorphism (Tr. Einarsson, 1965) which, like the crustal layering, cuts the stratification of the lava pile.

Layer 4 (the Upper Mantle) probably consists of periodotite or

pyrolite of a kind capable of producing basaltic magma by partial melting.

Little is known about the composition of layer 3 in Iceland, but it is most likely basaltic in composition, and the 2/3 interface either represents a metamorphic isotherm, or it is formed by intrusive activity (Grönvold, 1972).

Grönvold came to the conclusion that layer 3 is intrusive, but otherwise compositionally similar to the higher layers. I.B. Fridleifsson (in prep.) also favours an intrusive origin for layer 3, but he believes that the upper limit of the layer is controlled by the type of host rock, and he suggests that the intrusive magma rises as high as the highly altered lavas, and then tends to spread out laterally rather than penetrating the progressively harder lava pile of layer 2. The 2/3 interface would therefore be a "metamorphic boundary" depending on the degree of alteration.

Walker (1957b) describes, in his recent paper, an intrusive sheet swarm in south-eastern Iceland and he argues that layer 3 could be composed of similar sheet swarms. He proposes that a magma reaches the surface only when its density is lower than that of the rocks through which it has to pass; the magma will tend to form intrusive sheets where its density equals the density of the country rocks. The density of the magma changes as it ascends and at some stage, in the upper crust, the magma boils (i.e. vesiculates); this is the "critical density level" where the density of the magma is drastically reduced. The depth of vesiculation depends on the amount of volatiles in the magma, but may be less than 1 km (Walker, 1975b). The magma will probably ascend quickly to the surface when it passes the "critical density level", because of the reductions in the magma density.

Grönvold (1972) believes that the mechanism of formation of layer 3 is as follows:- Magma, formed by partial melting of peridotite-type material

in the Upper Mantle, has a density of 2.65 to 2.70 g/cm³ and thus it can rise through the Upper Mantle and layer 3 until it reaches the layer 3/2 boundary where it loses its buoyancy because layer 2 is lighter than the magma. The magma is then pushed laterally by more magma from beneath. This magma then crystallises to form a part of layer 3 and subsides in a similar manner to the volcanic layers above. This process continues until layer 3 has thickened sufficiently for the magma to pass the "critical density level". The magma will then be able to rise to the surface, leading to thickening of the layers 1 and 2 until the top of layer 3 moves below the "critical density level" (Fig. 14.1).

Basalt Genesis

Icelandic basalts span the entire compositional range of the world's observed oceanic tholeiites, but when volume and frequency are taken into account the Icelandic basalts are distinctively higher in alkalis, and have higher iron/magnesium ratios (Sigvaldason, 1969). Oceanic basalts may be derived from the Upper Mantle through two possible processes:-

1. O'Hara (1968) concluded, from his experimental work, that the observed low pressure equilibrium relationships may, through fractionation during ascent from greater depths, actually represent initial high pressure derivation.
2. The other, now widely accepted hypothesis, is that oceanic tholeiites are formed at a relatively shallow depth, and that their chemical variations are a subtle reflection of the degree and depth of partial melting (Green and Ringwood, 1967).

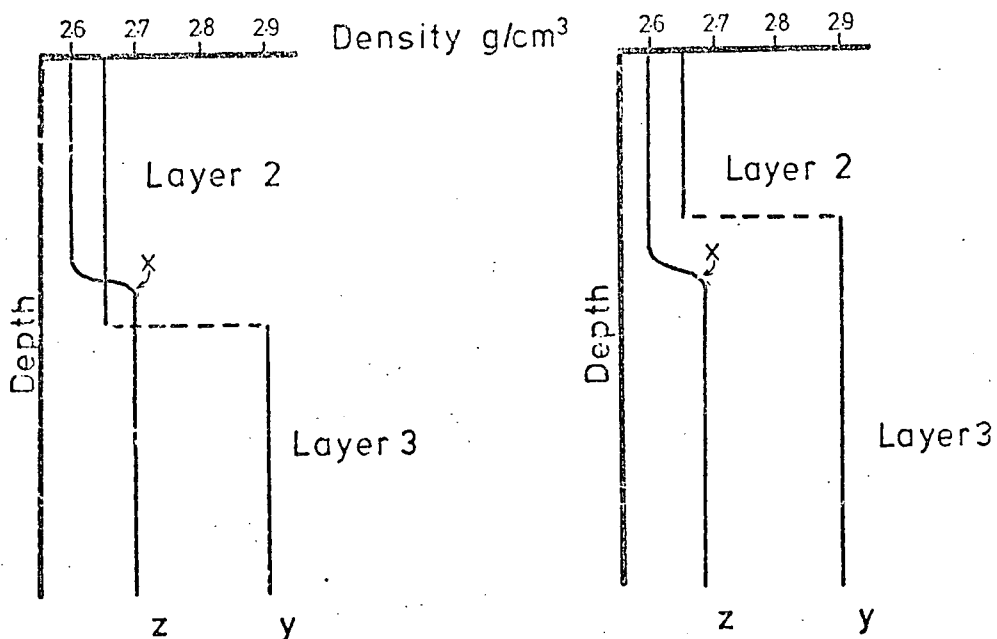


Fig. 14.1 A sketch demonstrating the relationships between the densities of rising magma and the crustal layers. z , density of rising magma; y , density of the crustal layers; x , onset of vesiculation ("critical density level").

The first hypothesis involves the fractionation of orthopyroxene from a primary magma at intermediate pressures or precipitation of olivine and plagioclase during ascent (Kay et al., 1970). Plagioclase fractionation can be ruled out, because of the small or absent negative Eu anomaly in Icelandic basalts (Shimokawa and Masuda, 1972; O'Nions and Gronvold, 1973). Samples which are high in Al_2O_3 are usually high in MgO, so that if plagioclase fractionation does not take place, then neither does olivine fractionation. Extensive fractionation of orthopyroxene, especially at intermediate pressures (9 kb), would create a continuum of basalts from olivine tholeiite to high-alumina basalt (Green and Ringwood, 1967). This also conflicts with the fact that high Al_2O_3 is usually accompanied by high MgO, and it may therefore preclude crystal fractionation as the explanation of the chemical variations found in oceanic tholeiites.

The second hypothesis is more attractive. Experiments relating to crystal fractionation have been carried out in the last two decades on various oceanic tholeiites, and the results have been applied to determine the liquid trends resulting from crystal fractionation, in closed systems, at different pressures. If the crystallizing phases are the same, fractional melting (or partial melting) may be considered as the reverse process of fractional crystallization (Green et al., 1967). Green and Ringwood (1967) have conducted detailed experimental studies on the genesis of basaltic magmas, and have demonstrated that changes in pressure may be the main controlling factor in the trend of fractional melting (partial melting) of mantle material (pyrolite), while Green (1971) asserts the importance of both depth and degree of partial melting on magma genesis. Partial melting of pyrolite at shallow depths (0-15 km) under corresponding P-T conditions would yield, with a low degree of partial melting, quartz tholeiitic liquids, yielding olivine tholeiites with a larger degree of partial melting.

At intermediate depths (15-35), partial melting would yield liquids of high-alumina basalt type, which itself may undergo fractional crystallization at shallower levels leading to quartz tholeiites. A large degree of partial melting at deeper levels (35-70 km) would yield olivine tholeiite, but a small degree of partial melting at the same depths yields alkali olivine basalt.

Trace elements may reflect partial melting relationships. Gast (1968) studied the partition coefficients of some trace elements during partial melting, and he found that K, Rb, Ba and Sr were greatly enriched in the first liquid produced. He suggested that the degree of partial melting is responsible for the different dispersed element contents of undersaturated and ocean ridge liquids, and in particular that ocean ridge basalts are produced by extensive partial melting during adiabatic decompression, associated with convection cells under the ridges, whereas alkaline basalts result from a much lower degree of partial melting. Sigvaldason (1974a) believes that potassium content reflects the degree of partial melting.

Trace element behaviour could also be applied to explain the differences between the olivine tholeiites and quartz tholeiites of the research area. The olivine tholeiites are lower in K, Rb, Ba and Sr than the quartz tholeiites, and they could therefore be explained by extensive partial melting (probably at slightly greater depths), when compared with quartz tholeiites formed by a smaller degree of partial melting.

TiO_2 and Zr are believed to be pressure (= depth) dependent (MacGregor, 1965). Fig. 14.2 shows a strong correlation between these two components in the Tertiary Icelandic samples. Even though it seems obvious that relationships between the olivine tholeiites and quartz tholeiites could be explained by the degree of partial melting, the depth (i.e. pressure) of the site of partial melting is also important.

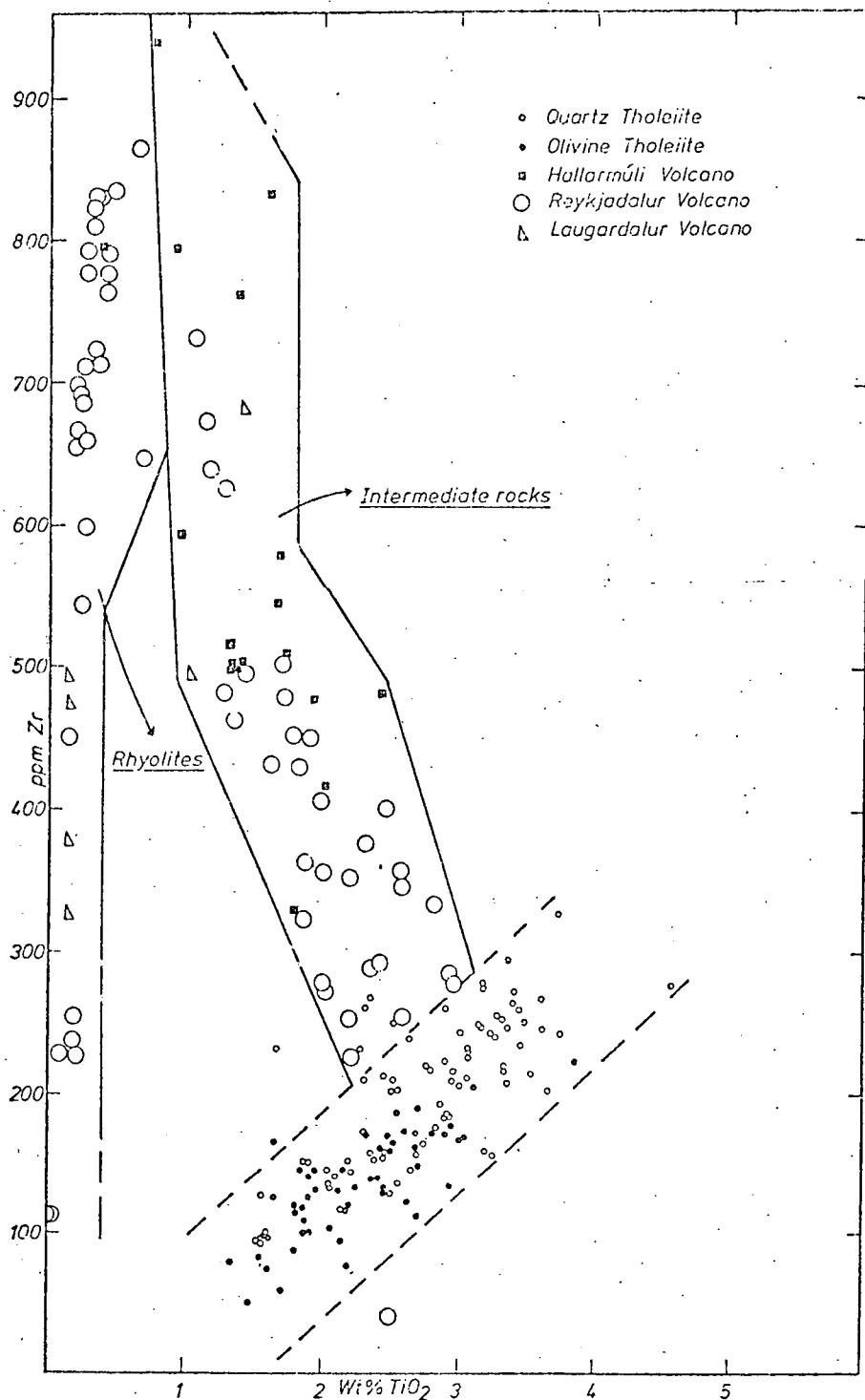


Fig. 14.2 TiO_2 plotted against Zr for all the Tertiary samples of the research area.

It is thus possible to conclude that the Tertiary basalt volcanics were formed by partial melting of the Upper Mantle, (peridotite or pyrolite-type material) and that the olivine tholeiites are formed by extensive partial melting at greater depths than the quartz tholeiites. In the light of the evidence discussed, the suggestion (Sigvaldason et al., 1974) that quartz tholeiites are formed at greater depths than olivine tholeiites is not acceptable.

The present-day pattern of volcanics in the Reykjanes-Langjökull neovolcanic zone (Jakobsson, 1972), and west along the Snaefellsnes peninsula, presents an interesting problem because of the change in the chemical characteristics of the volcanics away from the rifting axis. The transition from olivine tholeiites (even of high-alumina type) through transitional type basalts with increase in K_2O , Rb etc. (some of which are also very high in alumina), to alkali basalts (see Fig. 13.7) may reflect a lateral change in the structure and perhaps composition of the crust and Upper Mantle, or lateral differences in the thermal conditions of the crust and Upper Mantle.

The change in basalt type is probably caused by an increase in depth to the partial melting zone, and/or different degrees of partial melting. The thermal model proposed by Oxburgh and Turcotte (1968) can be applied to explain this variation. They argue that the isotherms form a mushroom-shaped pattern beneath the ocean ridge structure, such that the depth to a particular isotherm will increase away from a rifting axis. This would mean an increase in depth to the beginning of melting, away from the axis. The composition of the partial melt will change away from the axis because the composition will be affected by pressure. Even though pressure is an important factor, the extent of partial melting is also important. It is thus possible that both these factors are working concurrently and would result in a high alkali content in the liquids generated away from

the rifting axis. This process must occur at pressures of more than 9 kb (15 km), because of the low-pressure thermal divide between tholeiites and alkali basalts. Below 9 kb, alkali basalt cannot be produced from the same parental material as tholeiites (Yoder and Tilley, 1962).

The petrography reflects the origin of the Tertiary basalts. It supports the proposed mechanism, and even puts pressure limits on the formation of the quartz tholeiites. Olivine is rare as a phenocryst, and nearly absent as a groundmass phase in the quartz tholeiites. This suggests that the quartz tholeiites have been generated by partial melting at pressures less than 9 kb (15 km), because olivine is a liquidus phase up to that pressure but not at higher pressures (Green and Ringwood, 1967). Alternatively, the experimental data constrains the liquids so that the magma composition, fractionating as it rises, becomes quartz tholeiitic at depths less than 9 kb. There is no similar constraint on the depth of origin of the olivine tholeiite magmas, although geologically it might be suggested that they are derived at similar (or greater) depths to the quartz tholeiites, with larger degrees of partial melting.

Plagioclase is the most common and prominent phenocryst in the basic rocks, and its amount has caused some concern. Experimental work by Emslie (1971) on the synthetic system diopside-enstatite-anorthite₆₀ albite₄₀ shows that there is an expansion of the plagioclase volume at atmospheric pressure (mainly at the expense of diopside), compared with behaviour at 15 kb. Basaltic magmas which are cotectic at the depth of origin, will, when extruded, have a liquid composition which lies within the plagioclase phase volume; explaining the feldspar-phyric basalts with feldspar as the first phenocryst.

The Fe-Ti oxides differ in the two types of Tertiary basalt. An interstitial, latecrystallizing phase is found in the olivine

tholeiites, and an euhedral, early crystallizing phase occurs in the quartz tholeiites. Nesbitt and Hamilton (1970) described the effect of varying oxygen fugacity on the crystallization of alkali olivine basalts. Their results do not apply directly to the Tertiary tholeiites, because of the different chemistry. However, the data may indicate the main effect of changing the oxygen fugacity. They found that lowering the oxygen fugacity resulted in the later appearance of magnetite. This implies that the quartz tholeiites crystallized at a higher oxygen fugacity than the olivine tholeiites. The occurrence of euhedral microphenocrysts of magnetite along with euhedral groundmass phases, in more silicic rocks, indicates even higher oxygen fugacities, probably accompanied by shallower depths of origin.

The experimental evidence of Green and Ringwood (1967), which suggests that the quartz tholeiites are derived from depths of less than 15 km, is supported by magnetotelluric measurements carried out by Hermance and Grillo $\grave{t}$ (1974). These suggest that magmatic temperatures prevail now at 10-15 km depths beneath Iceland.

The differences in chemistry between the Icelandic basalts and oceanic tholeiites must be explained by differences in the composition of the Upper Mantle material which produces the partial melt. J-G. Schilling (IUGG meeting 1975) showed that REE and Sr^{87}/Sr^{86} ratios, as well as alkalis, are higher in Iceland. He postulated that Iceland and the Azores are "platform" areas along the Ridge, where magmas are derived from a different mantle source than the Ridge basalts. These differences cannot be related to different degrees of fractionation or partial melting, because Sr^{87}/Sr^{86} ratios differ. Rocks from the Iceland region show undepleted Sr-isotope ratios (O'Nions and Pankhurst, 1974) and undepleted REE patterns (Schilling, 1973) suggesting that the Upper Mantle beneath Iceland is undepleted material, probably derived from a great depth through convection which gives rise

to a mantle plume. The material then spreads out by asthenospheric flow away from the mantle plume (Vogt, 1971). Sigvaldason et al., (1974) argue that the mantle becomes chemically depleted, as it spreads further away from the ridge axis, through magma removal.

The Origin of Intermediate and Acid Rocks

The intermediate and acid rocks in Iceland are closely associated with central volcanoes and occur rarely outside them. The volume of acid rocks in Iceland has puzzled petrologists for some time. Acid rocks in eastern Iceland constitute up to 9% of the succession in restricted areas (Walker, 1966) and Sigurdsson (1966) estimated the volume of acid rocks in the whole country at about 10% of the exposed volcanics. In the research area, stratigraphically below the Holtavörduheidi sedimentary horizon, the intermediate and acid rocks make up, on average, about 15% of the lava pile, but up to 20% of more in the central volcanoes themselves. About two-thirds of these rocks are rhyolitic in composition.

Concerning the origin of the intermediate and acid magmas, the Sr-isotope ratios and Pb-isotope ratios are indistinguishable from those of the basaltic rocks (Moorbath and Walker, 1965; Welke et al., 1968). Refraction studies (Palmason, 1971) do not indicate the existence of a sialic layer underneath Iceland, thus excluding assimilation of acid material from sialic substrata. The intermediate and acid rocks must therefore be derived from a basaltic parent material, either by means of crystal fractionation or partial melting (or both). Carmichael (1964) and Sigurdsson (1970a) favoured crystal fractionation but Grönvold (1972) and Sigvaldason (1974b) favour partial melting.

Both field and geochemical evidence shed light on the origin and evolution of the intermediate and acid rocks.

(a) Field evidence

As mentioned above, the amount of intermediate and especially of acid rocks has caused concern, because of the small amount of acid liquid extractable from a basaltic parental magma. Carmichael (1964), on the basis of theoretical calculations, found that an extreme and thorough fractionation could yield 12% of acid liquid from a tholeiite basalt parent and 7% from an olivine basalt parent. Wager and Brown (1968) argued that between 0 and 7% of acid liquid might be produced by fractionation of an olivine tholeiite magma of Skaergaard-type. It is unlikely that fractionation of a basic magma would go to an extreme stage, without being interrupted by volcanic activity. The author believes that crystal fractionation cannot take place to any great extent except in tectonically quiet areas, which automatically excludes extensive fractionation beneath Icelandic central volcanoes. Thus, only small degrees of fractionation of basaltic magma can be used to account for the range of magma compositions from basic to acid.

Inside a central volcano like the Reykjadalur central volcano (which is about 25-30 km in diameter), the combined intermediate and acid rocks can make up to 15-20% or more of the exposed volcanics, with two-thirds of that volume being acid volcanics. If the rocks exposed at the surface are representative of the volcanic production during the life-time of the central volcano, this high proportion of acid rocks would exceed all reasonable models for crystal fractionation. Sigurdsson (1966) argued that the acid rocks exposed at the surface did not have to represent true volume relations, because the acid magmas were lighter and therefore tended to rise to the surface, rather than being trapped at depth in the pile. This is, however, doubtful because in south-eastern Iceland acid rocks occur

in layer 1 and to the limits of exposure, in the upper part of layer 2; there they even constitute a higher proportion of the pile than observed for the upper part of layer 1. This, if south-eastern Iceland is representative of Iceland as a whole, suggests that acid rocks are evenly distributed in central volcanoes, throughout layer 1 and at least the upper part of layer 2.

If crystal fractionation is responsible for the generation of the intermediate and acid rocks, huge layered basic intrusions could be expected at depth, presumably within the crust. No proper layered intrusions have been found in Iceland, but Roobol (1972) has described size-graded layering in a gabbro intrusion in south-eastern Iceland.

Simple calculations can indicate the volume of material involved in a crystal fractionation process of the scale needed to account for the amount of acid rocks observed. We can safely assume that acid rocks (i.e. rhyolitic in composition) make up 10% of the top 2 km in a central volcano 25 km in diameter. To simplify such a model it is assumed that no acid rocks are present in the crust from 2 km down to the layer 2/3 interface, which is highly unlikely.

Two crustal models will be used and they are schematically illustrated in Fig. 14.3. These crustal models are based on the two main types of crust present in the area (see Figs. 40 and 41 in Palmason, 1971):-

- (1) a structure similar to that of the southern part of the area and
- (2) similar to the thicker crustal structure north of the Snaefellsnes zone.

The volume of the top 2 km is about 980 km^3 and the acid rocks in these top 2 km amounts thus to about 98 km^3 . The volume of layer 3 amounts to 2700 km^3 and 4900 km^3 for options (1) and (2) respectively. The acid rocks in the top 2 km amount, to about 3.6% and 2.0% of layer 3 respectively. If we assume that the acid rocks in the top 2 km are 20%

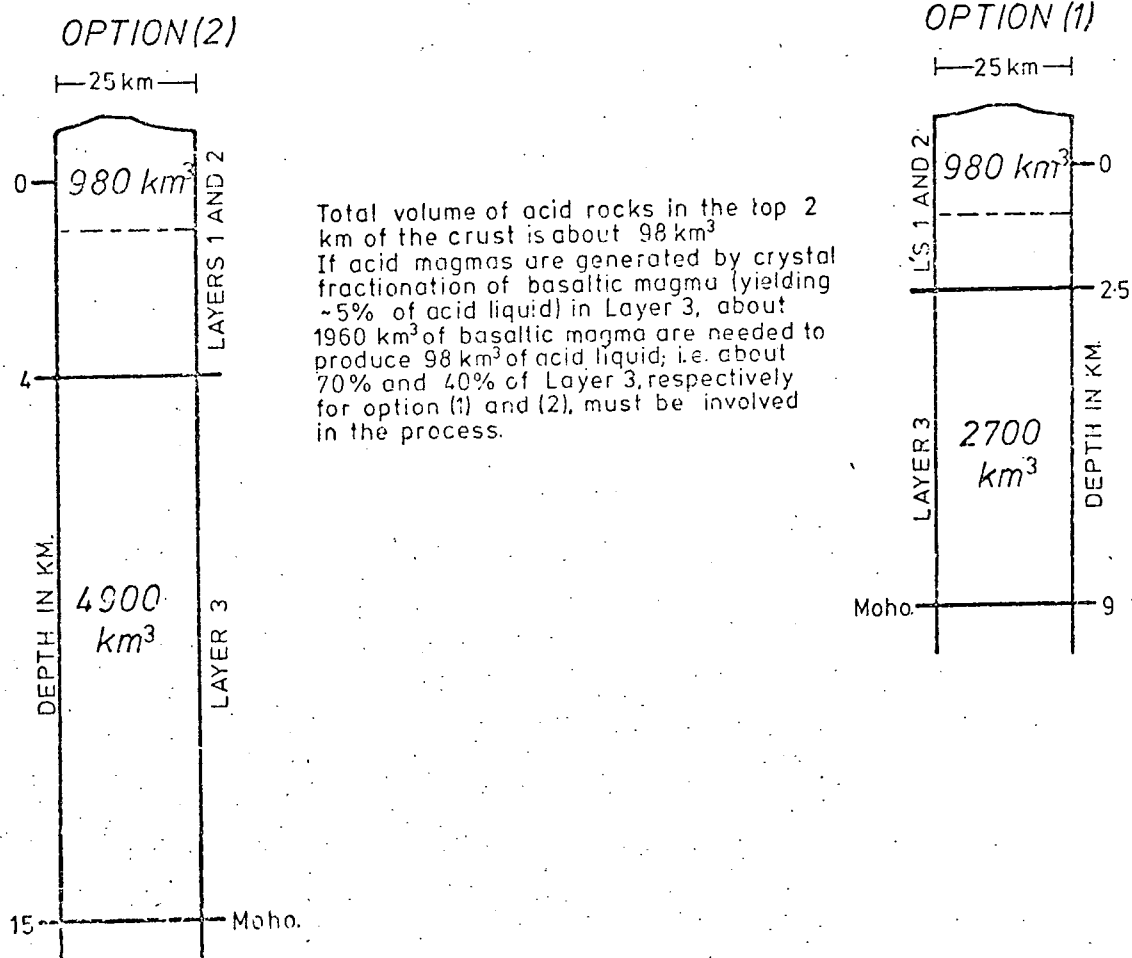


Fig. 14.3 Simple model demonstrating volume relations in the crust beneath central volcanoes.

of the pile the figures would be 7.2% and 4%.

Earlier, the amount of crystal fractionation was discussed and it was argued that it would never reach an extreme stage. If we assume that the crystal fractionation could yield about 5% of acid liquid, about 1960 km^3 are needed to produce the required volume of acid rocks, thus involving more than 70% of the total volume of layer 3 for option (1), and 40% for option (2). These figures rather discourage crystal fractionation as the process yielding large quantities of acid liquids, because it is highly unlikely that half or more of layer 3 is involved in the process over a geologically short period of time; furthermore, this would leave a considerable part of layer 3 as a more dense residuum, for which there is no evidence. No xenoliths of ultrabasic or layered basic rocks have been described from Iceland.

Another interesting feature, discovered during the fieldwork, is the extrusive sequence of the basaltic and acid rocks. Most of the intermediate and acid rocks of the Reykjadalur central volcano were extruded prior to the main basaltic volcanism in the central volcano (thin-layered series). The acid rocks also tend to be slightly earlier than the intermediate rocks. In the Hallarmuli central volcano, the acidic ignimbrites were extruded prior to most of the intermediate lava flows. Sigvaldason (1974b) studied the petrology and geochemistry of Hekla and found that the acid and intermediate liquids were separated in time, the acid liquid being earlier than the intermediate one, although considerable overlap existed. Thus it is clear that great volumes of intermediate and acid rocks are extruded early in the history of a central volcano and there is strong evidence that the acid rocks are extruded earlier than the intermediate rocks. This contradicts the crystal fractionation

model because it would be expected that the intermediate rocks would be generated earlier than the acid ones. It also might be expected that basaltic volcanism would be vigorous at the beginning of such a fractionation cycle.

The volume distribution between the intermediate and acid rocks is also interesting, because the acid rocks appear in much greater quantities than the intermediate rocks. The crystal fractionation hypothesis suggests the opposite and therefore crystal fractionation cannot explain this distribution pattern; while it favours a partial melting origin. Also, the composition gap between the acid and intermediate volcanics should be explained, and it is difficult to do this with a fractionation model.

(b) Geochemical evidence

The geochemistry of the intermediate and acid rocks was described in Chapter 13. The break in the basaltic field has been explained as the result of different degrees and/or depths of partial melting of Upper Mantle material. The second break, between the intermediate and basaltic rocks, is more pronounced for the trace constituents (including MnO and P_2O_5) than for the major elements. The main characteristic of this break is the abrupt increase or jump in the content of most trace constituents, especially MnO, P_2O_5 , Ba, Nb, Y, Rb and Zn.

Mn goes mainly into magnetite, ilmenite and iron-rich clinopyroxene, and Zn into magnetite, and therefore a covariation should be expected between MnO and TiO_2 or iron, or both, and between Zn and iron. This is not the case, because while MnO and Zn increase sharply, both TiO_2 and iron decrease steadily around this break. The offset of Ba is exceptionally large (50-75% increase) and hard to explain in terms of crystal fractionation, except by a massive removal of one or more of the major phases, which would be reflected in the major element chemistry. The other trace elements would have to be explained in

a similar way. Many of the trace elements, when plotted against each other (Fig. 14.2), show a surprisingly sharp break between the basaltic samples and the intermediate samples, suggesting that there is little genetic relationship between these two groups. Thus both major and trace elements discourage crystal fractionation as an explanation of the break between the basalts and the intermediate rocks.

The third break, in the dacite region, is not reflected distinctively in the major elements, except for iron which increases faster, in the rhyolite region than in the intermediate region with increasing silica. On the other hand the break is very sharp and distinctive for the trace elements (Fig. 13.1). Barium increases sharply with increasing silica in the rhyolite region along with Rb, but Y, Zr and Zn decrease rapidly in the same region. Zr goes mainly into zircon, Y into plagioclase, iron into ferroaugite, fayalite and magnetite, and Zn into magnetite. If this variation is due to crystal fractionation, zircon, plagioclase, magnetite and possibly fayalite and/or ferroaugite will have to be precipitated. Ba goes into K-feldspar and the increase in Ba indicates that K-feldspar has not been formed or removed from the magma. The order of the increase in Ba in some of the samples is great and can be explained as a result of large-scale fractionation which, however, is not reflected in the major elements. The decrease in the content of some of the trace elements may be due to removal of small amounts of accessory minerals like zircon and rutile without affecting the major element chemistry.

O'Nions and Grönvold (1973) studied REE patterns for rocks from some central volcanoes in Iceland and found that the negative Eu anomaly increases with increasing silica. The Eu anomaly is usually explained by plagioclase removal during a fractionation process, thus

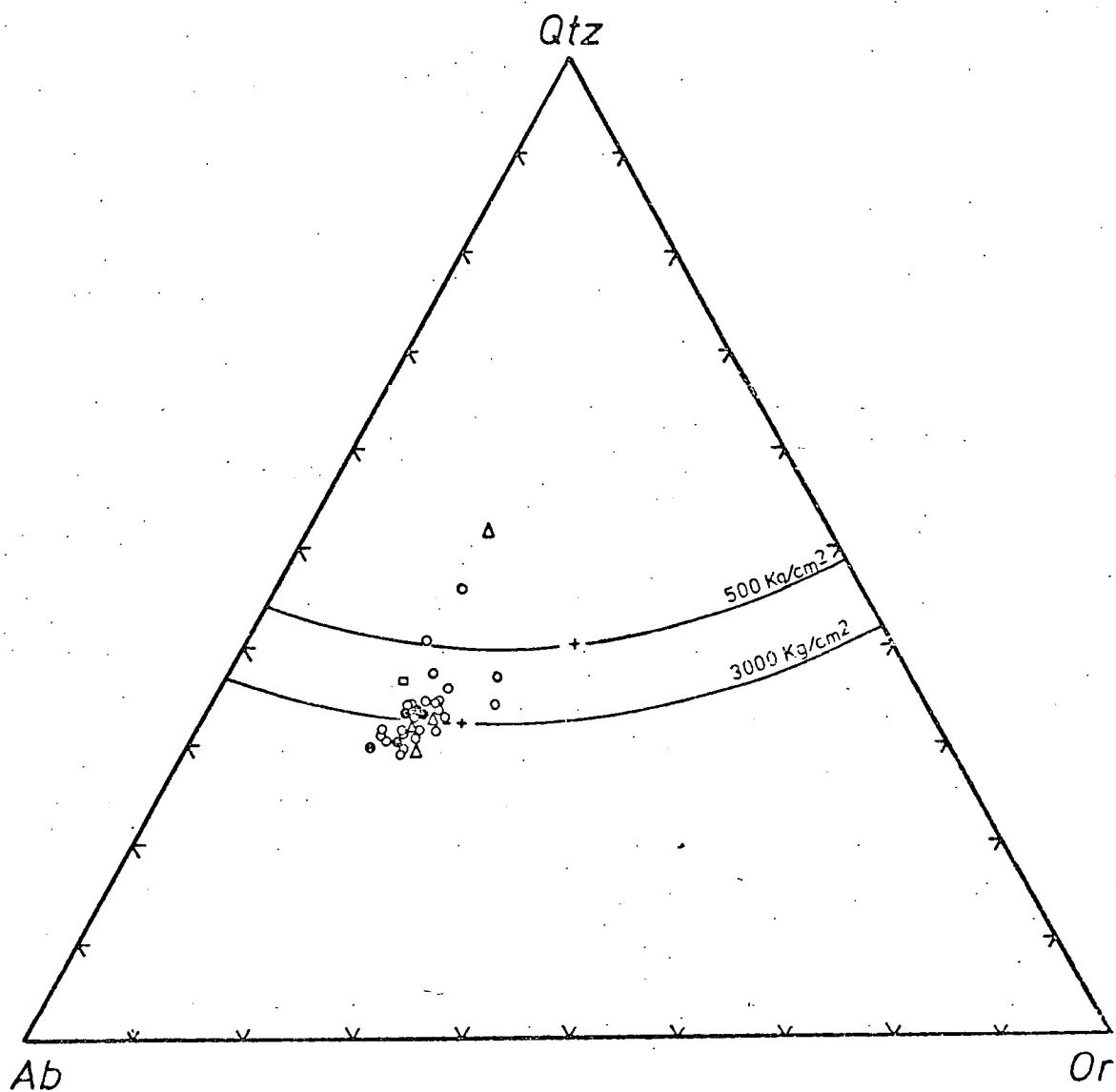


Fig. 14.4 Rhyolitic samples plotted in terms of Ab-Qtz-Or. The experimental boundary curves and minima are after Tuttle and Bowen (1958). Circles are rhyolites from the Reykjadalur central volcano (solid circles are porphyritic samples), triangles are from Laugardalur central volcano and the square is from the Hallarmuli central volcano.

supporting crystal fractionation rather than partial melting.

The 18O values for intermediate and acid rocks from Iceland are variable but generally lower than for the corresponding basalts (Muehlenbachs, 1973). If intermediate and acid rocks were derived from a basaltic magma by means of crystal fractionation, the 18O isotopes should be similar to those of the basaltic parent magmas. The 18O in meteoric water in Iceland is low (Muehlenbachs, 1973) and the variable and generally low 18O content of intermediate and acid rocks could be due to partial melting of hydrothermally altered basic rocks; it is likely that meteoric water percolates down to the bottom of layer 2 and it is more than possible that meteoritic water is involved in the metamorphism of layer 3.

In the light of the field and geochemical evidence discussed above, crystal fractionation can be ruled out as the process which generated the majority of the intermediate and acid rocks. We have therefore to look at the other alternative, the partial melting of basaltic material.

Kushiro (1969, 1972) has studied the system Di-Fo-Qtz, both under anhydrous and hydrous conditions at various pressures. He concluded that fractional melting occurred in two distinct steps. If a starting material in the quartz normative portion of the Di-Fo-Qtz system is heated under high water pressure (about 20 kb), fractional melting will start at about 960°C yielding acidic liquid. If the liquid is removed continuously, the melting will cease when the acid component of the rock has been exhausted. Melting is resumed at about 1220°C , producing andesitic liquid (Yoder, 1969).

Yoder (1971) pointed out that this two-step melting process could yield two different liquids from the same parental material, which have to be separated in time due to the temperature difference between the two melting steps. He concluded that up to 20% of acid

liquid could be generated by partial melting of quartz normative basalt, and about 22% of andesitic liquid.

A temperature of 960°C can be reached inside layer 3, i.e. at less than 10 km (for a thermal gradient of $100^{\circ}\text{C}/\text{km}$), but the effect of volatiles could lower the melting temperatures still further. Carmichael (1967) studied the Fe-Ti oxides in salic rocks and found that Icelandic rhyolites had liquidus temperatures around 900°C , allowing partial melting to start well inside layer 3. The water pressure inside layer 3 is not known. The normative salic constituents of the rhyolites (Fig. 14.4) suggest that the acid magmas had equilibrated at pressures slightly greater than 2000 kg/cm^2 (about 7 km) and left of the thermal valley; therefore not in layers 1 or 2, but probably in layer 3. A few rocks seem to have equilibrated at lower pressures than most of the samples; they may be due to the magma residing in a chamber at a shallower depth.

Therefore, rhyolites (acid liquids) may be formed by partial melting of basaltic rocks in layer 3; rocks which may have been metamorphosed to amphibolite. The temperature and possibly the degree of partial melting will depend upon the water content and possibly the presence of other volatiles. The intermediate liquids may be formed from the same material as the acid liquids, by further partial melting at higher temperatures, and at a later time.

This two-step partial melting of basaltic material yielding two different liquids, one acid and the other intermediate, would explain the compositional gap in the dacite region and the apparent time-lag between the acid and intermediate rocks, as well as explaining the volume relations between the acid and intermediate rocks. The sharp break between the intermediate and basaltic rocks would be because the intermediate magmas are derived from melting of layer 3, while the basaltic magmas are derived by ^{partial} melting of layer 4.

Volcanic-Tectonic Evolution of a Central Volcano

By combining the field and geochemical work presented in this thesis, a simple model of a central volcano, similar to the Reykjadalur central volcano can be constructed. This model is shown schematically in Fig. 14.5. Starting with a crustal structure (a), where layers 1 and 2 are relatively thick compared with layer 3, the rising basaltic magma will not reach the "critical density level", and thus not reach the surface in any quantity. Eruption rates will be relatively low and the series formed will tend to have thin sediments intercalated with the flows. The volcanic activity will be spread evenly throughout the area creating a flat landscape resulting in relatively thick basaltic flows. This series would correspond to the thick-layered tholeiite series underlying the Reykjadalur central volcano. Most of the rising magma will stop at the layer 2/3 boundary and form inclined sheets (Walker, 1975b). As the rifting progresses, layer 3 thickens at the expense of layers 1 and 2(b). The intrusive activity continues and the temperature rises inside layer 3 and partial melting of the bottom part starts to produce acid liquids (c) and batches of acid magma are extruded at the surface. The heat propagates upwards in layer 3 and the second stage of partial melting starts at the bottom of layer 3 (d) and acid and intermediate magmas are extruded simultaneously; this would correspond to the main intermediate and acid succession in both Reykjadalur and Hallarmuli central volcano. The intrusive activity underneath the volcano is intensive and the lower part of layer 2 is subsequently hydrothermally altered, probably allowing the basaltic magma to intrude and form sheets, effectively changing the nature of this part of layer 2 into material physically identical to layer 3; thus is formed the bulge in layer 3 observed by Palmason (1971), underneath extinct central volcanoes.

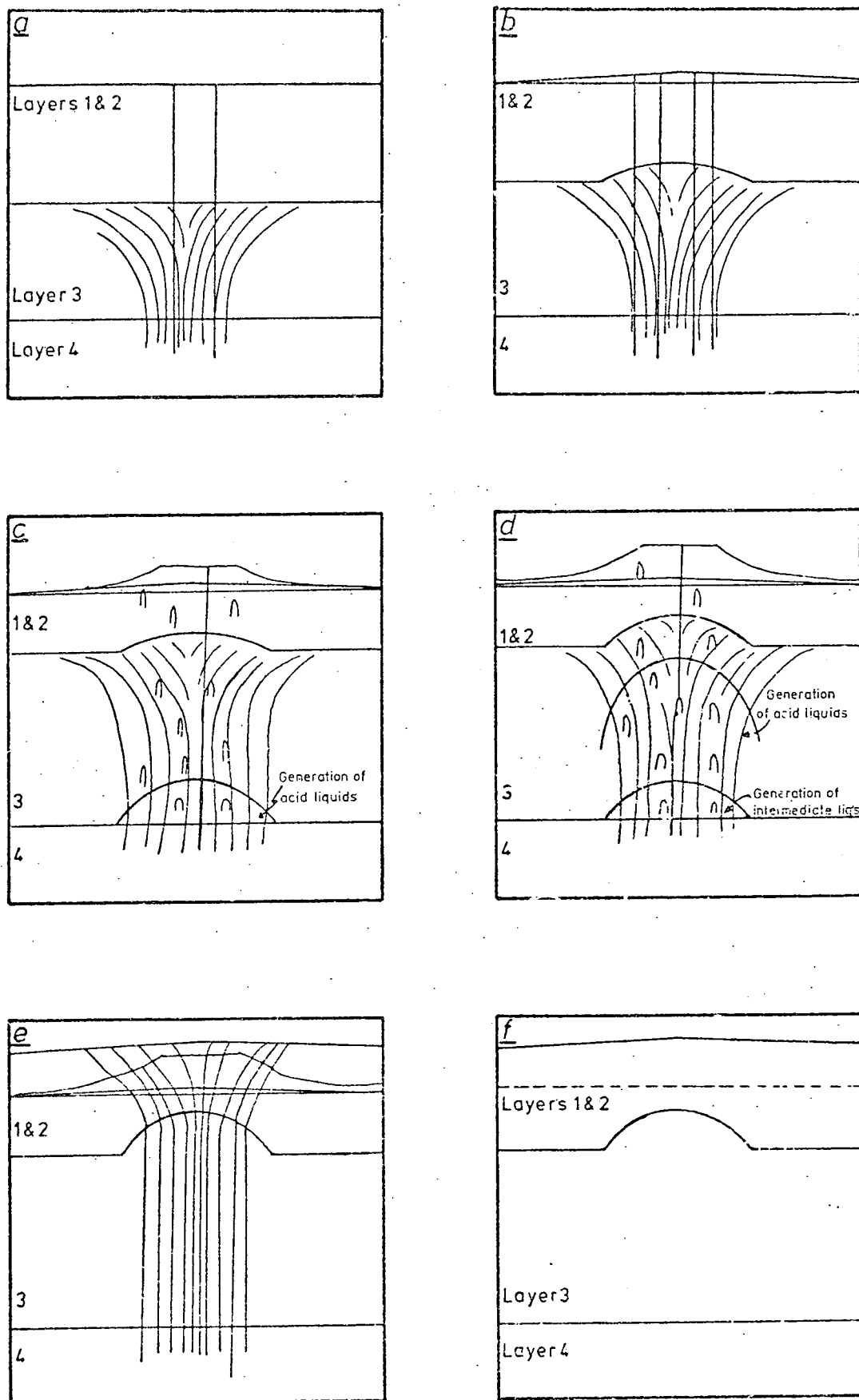


Fig. 14.5 A model of the evolution of a central volcano and the crust beneath it. For explanation see text.

As layer 3 is now very thick and layers 1 and 2 thin and the bulge in layer 3 has reached a shallow depth (perhaps less than 1 km), the basaltic magma passes the "critical density level", thus enabling it to reach the surface. At this stage there is no obstacle to the passage of basaltic magma up into the central volcano, and basaltic volcanism increases suddenly (e); and, due to the topography of the area, the flows tend to be thin and no sediments intercalate with the flows due to very high effusion rate. This would correspond to the thin-layered series of Reykjadalur central volcano and the Kolvidarholt series overlying the Hallarmuli central volcano. The basaltic magma is extruded mainly through cone sheets due to the circular stress-field around the central volcano. No change in the effusion rate takes place outside the central volcano because layers 1 and 2 are still too thick to allow the basaltic magma to pass to the surface. At this point, intrusive activity may effectively cease and therefore the generation of intermediate and acid liquids stops. The combined layer 1 and 2 thickens because of the newly formed volcanics and the process may be reversed, i.e. the load of the rocks extruded suppresses the crust so that the rising magma does not reach the "critical density level" and thus intrusive rather than extrusive activity starts again probably resulting in a delicate 'on-off' situation before the cycle stops as the area moves out of the active rifting zone.

The location of a central volcano within an active volcanic zone seems to be controlled by the en echelon fault swarms which are probably surface manifestations of dyke or sheet swarms at depth. The central volcanoes are usually in the centre of such swarms (Walker, 1963; Saemundsson, 1974). The volcanoes tend to be formed where the intrusive activity is greatest; the partial melting takes place in the centre of each swarm where there is more heat available.

The main structural difference between the Reykjadalur and Hallarmuli central volcanoes lies in the much smaller volumes of both basaltic and more siliceous rocks and the lack of any circular structures in the latter. At the time of the Hallarmuli central volcano, the volcanic activity in the area had just been resumed after a lapse of a few million years and the small volumes of more siliceous and basaltic rocks could be due to thinner layers 1 and 2 so that the "on-off" situation was reached early. The main volcanic activity then shifted with the rifting towards the north, to the area which became Reykjadalur central volcano.

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APPENDIXAnalytical methods

The samples were cleared of the weathered surfaces and were split into conveniently sized fragments using a hydraulic splitter. They were then crushed in a jaw crusher, and reduced to 50-150 gm samples by taking 1/2, 1/4 or 1/8 fractions. These fractions were then ground for 3-4 minutes to a fine powder in a swing-mill. A representative sample, of a few grams, was withdrawn for the FeO determination after 30 seconds. This was taken in order to avoid additional oxidation during grinding, as described by Fitton and Gill (1970).

The Durham University Department of Geological Sciences uses compressed-powder briquette procedure for major and trace elements. This is largely due to the great time saved compared to fusion techniques. A few drops of Mowiol solution was used as a binder during pelletizing. This was mixed thoroughly with the rock powder, which was then pressed under 800-900 kg/cm², using a hydraulic press.

The analyses were carried out on a Phillips PW1212 automatic spectrometer with TE108 Automatic Loader. Tables 1 and 2 give the operating conditions for the various elements.

In the analyses of major elements, three samples were run, along with a monitor. The method of "fixed counts" was used to minimize the instrumental errors and drift. In this method the time (T) taken to accumulate a pre-determined 'N' counts on a monitor is automatically recorded. The three samples are then counted over the same time interval (T), for the same element, and hence an allowance is made for possible drift in the count rate, as detected by the monitor.

A bank of international standards was used: G1, G2, W1, T1, S1,

Table 1

Operating conditions for Phillips PW1212 automatic spectrometer in the analyses of major elements.

Element	Position	Tube	Crystal	Counter	Time	Kv	mA	Collim.	Path
Si Pk	109.00	Cr	PE	F	FC 10 ⁵	60	16	Coarse	Vac.
Al Pk	145.00	Cr	PE	F	FC 10 ⁵	50	40	Coarse	Vac.
Fe Pk	57.46	Cr	LiF ₁₀₀	F+S	FC 10 ⁵	40	8	Coarse	Vac.
Mg Pk	43.00	Cr	KAP	F	FC 10 ⁴	50	40	Coarse	Vac.
Mg Bk	45.11	Cr	KAP	F	FC 10 ⁴	50	40	Coarse	Vac.
Ca Pk	113.08	Cr	LiF ₁₀₀	F	FC 10 ⁵	20	8	Coarse	Vac.
Na Pk	52.50	Cr	KAP	F	FC 10 ⁴	50	40	Coarse	Vac.
Na Bk	56.03	Cr	KAP	F	FC 10 ⁴	50	40	Coarse	Vac.
K Pk	136.61	Cr	LiF ₁₀₀	F	FC 10 ⁵	60	8	Coarse	Vac.
Ti Pk	86.12	Cr	LiF ₁₀₀	F	FC 10 ⁵	60	8	Coarse	Vac.
P Pk	89.51	Cr	PE	F	FC 10 ⁴	50	40	Fine	Vac.
P Bk	91.63	Cr	PE	F	FC 10 ⁴	50	40	Fine	Vac.
Mn Pk	95.25	W	LiF ₁₀₀	F	FC 3x10 ⁴	50	40	Coarse	Vac.
Mn Bk	97.20	W	LiF ₁₀₀	F	FC 3x10 ⁴	50	40	Coarse	Vac.

Table 2

Operating conditions for Phillips PW1212 automatic spectrometer in the analyses of trace elements.

Element	Position	Tube	Crystal	Counter	Time	Kv	mA	Collim.	Path
Ba Pk	15.46	W	LiF ₁₀₀	Scint.	40 sec.	80	24	Coarse	Vac.
Ba Bk	16.54	W	LiF ₁₀₀	Scint.	40 sec.	80	24	Coarse	Vac.
Nb Pk	30.30	W	LiF ₁₀₀	Scint.	100 sec.	80	24	Coarse	Vac.
Nb/Zr Bk	30.81	W	LiF ₁₀₀	Scint.	100 sec.	80	24	Coarse	Vac.
Zr Pk	32.00	W	LiF ₁₀₀	Scint.	100 sec.	80	24	Coarse	Vac.
Zr/Y Bk	32.89	W	LiF ₁₀₀	Scint.	100 sec.	80	24	Coarse	Vac.
Y Pk	33.75	W	LiF ₁₀₀	Scint.	100 sec.	80	24	Coarse	Vac.
Y/Sr Bk	34.78	W	LiF ₁₀₀	Scint.	100 sec.	80	24	Coarse	Vac.
Sr Pk	35.76	W	LiF ₁₀₀	Scint.	100 sec.	80	24	Coarse	Vac.
Sr/Rb Bk	36.77	W	LiF ₁₀₀	Scint.	100 sec.	80	24	Coarse	Vac.
Rb Pk	37.89	W	LiF ₁₀₀	Scint.	100 sec.	80	24	Coarse	Vac.
Rb Bk	39.60	W	LiF ₁₀₀	Scint.	100 sec.	80	24	Coarse	Vac.
Zn Bk	59.25	W	LiF ₁₀₀	Scint.	100 sec.	80	24	Coarse	Vac.
Zn Pk	60.50	W	LiF ₁₀₀	Scint.	100 sec.	80	24	Coarse	Vac.
Zn Bk	61.42	W	LiF ₁₀₀	Scint.	100 sec.	80	24	Coarse	Vac.
Cu Bk	64.83	W	LiF ₁₀₀	Scint.	100 sec.	80	24	Coarse	Vac.
Cu Pk	65.43	W	LiF ₁₀₀	Scint.	100 sec.	80	24	Coarse	Vac.
Cu Bk	66.50	W	LiF ₁₀₀	Scint.	100 sec.	80	24	Coarse	Vac.
Ni Bk	70.02	W	LiF ₁₀₀	Scint.	100 sec.	80	24	Coarse	Vac.
Ni Pk	71.15	W	LiF ₁₀₀	Scint.	100 sec.	80	24	Coarse	Vac.
Ni Bk	73.03	W	LiF ₁₀₀	Scint.	100 sec.	80	24	Coarse	Vac.

GR, GH, AGV1, BCR1, GSP1, DTS1, BS76, BS91 and BS98. The composition of the international standards used were those from reviews by Flanagan (1969, 1973).

The major element data were corrected for mass absorption differences between the standards and the unknowns by the iterative computer procedure described by Holland and Brindle (1966) and Reeves (1971). The analyses were subsequently normalized to 100% to obtain realistic analyses.

FeO was analysed wet chemically for all the samples involved, by the metavanadate method (Wilson, 1955). The rocks have been effected by secondary oxidation, and the analyses listed in Table 4 reflect the present oxidation state of the samples. As mentioned earlier a slight variation in oxidation will effect the % normative quartz, therefore the CIPW norms were calculated for a fixed $\text{Fe}_2\text{O}_3/\text{FeO}$ ratio (see Chapter 12).

An absolute method was used in the analyses of the trace elements. The analytical data were converted to concentrations (ppm) by the computer program "TRATIO" (Gill, 1972). The program uses the count rate function (peak intensity/background intensity-1). This function enables scattered background radiation to be used as an internal standard to compensate for matrix and mass absorption effects. This program also calculates the nominal detection limit for each element from the formula $3(\bar{B}1/2)$, where $\bar{B}$ is the mean background-under-peak in counts averaged over all the determinations processed (Table 3).

Standards used were synthetic spiked glasses prepared by the Pilkington Research Laboratory for use in Lunar investigations (Brown et al., 1970).

Table 3

Nominal detection limits for the trace elements
and the upper limit of standards in ppm.

	Detection limit (ppm)	Upper limit of standards (ppm)
Ba	8	5000
Nb	3	250
Zr	3	5000
Y	3	500
Sr	3	1100
Rb	2	1000
Zn	2	1000
Cu	2	1000
Ni	2	1000

Table 4

Major and trace element analyses, and CIPW norms, of the rock samples involved in the thesis.

The norms are calculated for $\text{Fe}_2\text{O}_3/\text{FeO}$ ratio of 0.25.

OLIVINE NORMATIVE THOLEIITES FROM MW-ICELAND (FEO*=ALL FE AS FEO)

	2	4	5	6	11	13	15	16	19	20
PERCENT										
SiO2	48.84	48.05	48.72	49.46	48.64	46.00	48.74	48.30	49.08	49.45
Al2O3	15.08	14.95	14.70	14.43	14.60	14.66	17.63	15.45	16.07	14.26
Fe2O3	5.23	3.94	5.55	4.66	4.87	2.28	5.20	5.59	4.11	3.67
FEO	9.05	10.73	7.05	7.65	6.98	10.34	5.48	7.18	9.31	10.19
MgO	4.95	5.29	7.45	6.49	6.67	13.98	5.40	6.51	3.77	4.71
CaO	10.31	10.37	11.99	12.12	13.93	8.38	13.16	11.94	10.85	11.02
Na2O	3.00	3.01	1.85	2.50	2.21	1.12	2.25	2.40	3.22	3.43
K2O	0.42	0.42	0.45	0.28	0.15	1.45	0.17	0.16	0.39	0.27
TiO2	2.55	2.69	1.81	1.97	1.57	1.34	1.61	2.07	2.70	2.46
MnO	0.25	0.25	0.21	0.20	0.20	0.26	0.17	0.21	0.20	0.25
P2O5	0.32	0.30	0.22	0.23	0.17	0.19	0.19	0.19	0.29	0.27
FEO*	13.76	14.28	12.05	11.85	11.37	12.39	10.16	12.22	13.01	13.50

PPM

BA	129	161	70	79	45	70	77	73	896	129
NB	20	23	11	15	7	9	13	11	25	21
ZR	187	174	120	132	82	79	96	102	113	133
Y	36	37	26	30	19	18	22	24	33	37
SR	256	259	589	233	224	163	266	223	275	247
RB	7	8	13	6	1	46	2	1	6	2
ZN	117	121	97	95	81	96	77	93	107	117
CU	103	75	89	136	113	100	95	133	226	180
NI	43	45	70	57	80	554	36	49	27	36

CIPW NCRM

QUtz	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Orth	2.51	2.45	2.69	1.67	0.90	8.55	1.01	0.96	2.33	1.62
Albt	25.45	25.46	15.65	21.21	18.72	9.50	19.13	20.36	27.22	29.04
Anor	26.44	26.04	30.57	27.35	29.54	30.62	37.57	30.99	28.26	22.68
Neph	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Diop	18.84	19.45	22.60	25.75	31.65	7.75	21.90	22.32	19.83	25.15
Hper	15.29	10.33	20.56	15.28	7.80	13.39	13.55	13.92	12.16	7.83
Oliv	1.75	6.18	0.38	0.90	4.61	23.51	0.29	3.43	0.49	4.34
Magn	4.11	4.26	3.59	3.53	3.39	3.70	3.03	3.64	3.88	4.03
Ilmn	4.85	5.10	3.44	3.74	2.99	2.54	3.07	3.94	5.13	4.67
ApAt	0.77	0.72	0.53	0.55	0.41	0.46	0.45	0.45	0.69	0.65

OLIVINE NORMATIVE THOLEIITES FROM MW-ICELAND (FEC*=ALL FE AS FEO)

	21	40	42	47	48	50	58	79	86	87
PERCENT										
SiO ₂	49.56	49.54	48.22	49.25	48.66	48.21	48.84	49.42	48.53	49.62
Al ₂ O ₃	15.73	14.28	14.07	14.18	15.34	14.68	14.28	14.31	18.28	17.08
Fe ₂ O ₃	6.55	4.63	5.80	5.75	5.04	5.88	5.70	2.98	4.21	2.48
FEO	5.98	9.04	8.42	8.62	7.91	7.64	8.15	10.80	6.14	8.86
MgO	5.15	5.25	5.73	5.14	6.11	6.62	5.78	4.99	5.14	5.72
CaO	11.52	10.58	11.11	10.45	11.32	11.66	11.06	10.91	13.10	10.80
Na ₂ O	2.73	3.01	2.80	3.00	2.35	2.44	2.78	3.15	2.28	2.81
K ₂ O	0.48	0.36	0.43	0.37	0.65	0.22	0.27	0.53	0.27	0.43
TiO ₂	1.88	2.33	2.91	2.61	2.13	2.20	2.49	2.46	1.71	1.81
MnO	0.16	0.24	0.22	0.34	0.22	0.23	0.21	0.24	0.15	0.17
P ₂ O ₅	0.25	0.29	0.27	0.27	0.24	0.20	0.43	0.21	0.20	0.21
FEO*	11.88	13.21	13.65	13.80	12.45	14.42	13.29	13.49	9.93	11.09
PPM										
PA	108	97	93	94	88	89	113	127	74	118
NB	20	16	21	15	14	14	28	22	16	17
ZR	100	171	171	174	129	119	159	128	58	89
Y	31	35	32	34	30	32	49	37	21	28
SR	245	244	309	255	231	206	248	250	281	249
RB	28	4	8	8	26	1	1	10	5	9
ZN	91	118	119	123	98	100	117	125	70	97
CU	128	156	172	168	144	82	131	198	143	149
NI	57	39	50	43	47	51	54	47	53	106
CIPW NORM										
QUZ	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ORTH	2.87	2.15	2.57	2.21	4.06	1.32	1.61	3.11	1.61	2.57
ALBT	23.18	25.52	23.73	25.45	19.94	20.72	23.55	26.64	19.30	23.76
ANOR	29.35	24.38	24.61	24.16	29.31	28.50	25.75	23.31	38.91	32.69
NEPH	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
DIOP	21.83	23.42	23.85	21.62	20.89	23.18	21.81	24.40	20.44	16.00
HPR	14.81	14.34	11.07	16.62	14.58	13.64	17.11	9.34	11.85	15.47
OLIV	0.24	1.13	3.92	0.21	2.88	4.11	0.43	4.00	1.20	2.27
MAGN	3.54	3.94	4.07	4.12	3.71	3.86	2.56	4.03	2.96	3.31
ILMN	3.59	4.42	5.54	4.96	4.05	4.19	4.75	4.67	3.26	3.43
APAT	0.60	0.70	0.65	0.65	0.57	0.48	1.03	0.50	0.48	0.50

OLIVINE NORMATIVE THOLEIITES FROM MW-ICELAND (FEC*=ALL FE AS FEO)

	89	96	106	108	109	112	152	158	165	166
PERCENT										
SiO2	49.24	48.84	47.62	49.07	48.82	50.78	47.84	49.65	48.42	48.60
Al2O3	14.73	14.39	15.82	14.48	16.20	14.38	15.53	14.41	15.92	14.58
Fe2O3	2.97	5.12	3.65	3.30	2.87	4.34	3.87	2.35	2.90	3.98
FEO	10.90	8.77	9.69	11.36	9.94	9.63	10.63	10.38	8.41	9.25
MgO	4.43	5.13	6.14	4.24	4.63	3.57	5.28	5.66	7.36	6.60
CaO	9.83	11.13	11.63	10.19	11.66	8.05	9.98	11.70	12.52	11.61
Na2O	3.56	2.77	2.70	3.28	2.90	4.39	2.94	2.87	2.25	2.56
K2O	0.60	0.54	0.16	0.52	0.42	0.74	0.33	0.26	0.23	0.20
TiO2	3.05	2.63	2.20	3.01	2.19	3.37	2.95	2.26	1.61	2.15
MnO	0.23	0.26	0.20	0.25	0.21	0.26	0.23	0.22	0.17	0.20
P2O5	0.46	0.42	0.18	0.30	0.17	0.49	0.42	0.23	0.20	0.26
FEO*	13.58	13.38	12.98	14.33	12.53	13.54	14.12	12.50	11.02	12.84

PPM										
BA	171	137	79	157	129	193	146	90	76	80
NB	35	25	22	32	22	49	25	12	13	16
ZR	176	123	77	168	118	295	179	134	75	94
Y	48	42	27	41	30	66	37	31	26	26
SR	261	267	271	263	270	269	257	235	220	223
RB	13	10	2	17	11	18	4	3	5	3
ZN	137	109	97	134	111	169	125	102	86	101
CU	143	226	185	141	169	15	131	204	149	140
NI	34	52	79	26	58	1	44	47	82	67

CIPW NORM										
QUtz	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ORTH	3.53	3.17	0.96	3.05	2.45	4.37	1.98	1.55	1.37	1.20
ALBT	30.06	23.47	22.86	27.69	24.48	37.17	24.85	24.22	19.06	21.66
ANOR	22.42	25.27	30.54	23.23	29.95	17.34	28.17	25.62	32.64	27.69
NEPH	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CIOP	19.43	22.62	21.40	21.12	22.24	16.30	15.45	25.46	22.98	23.21
HPER	9.91	15.05	7.09	12.66	8.52	11.58	15.30	13.55	10.68	14.00
OLIV	3.73	0.43	8.67	1.53	4.07	1.65	3.45	1.03	6.45	3.70
MAGN	4.05	3.99	2.87	4.28	3.74	4.04	4.22	3.73	3.29	3.83
ILMN	5.75	5.00	4.17	5.71	4.15	6.40	5.60	4.28	3.05	4.09
APAT	1.06	1.01	0.43	0.72	0.41	1.15	0.98	0.55	0.48	0.62

OLIVINE NORMATIVE THOLEIITES FROM MW-ICELAND (FEO*=ALL FE AS FEO)

	167	176	195	202	205	209	218	222	231	234
PERCENT										
SiO ₂	49.77	48.98	48.20	48.06	49.85	49.37	48.67	48.46	48.97	49.33
Al ₂ O ₃	14.71	18.31	13.92	14.56	14.63	15.20	14.90	14.30	14.02	14.15
Fe ₂ O ₃	2.41	4.39	4.04	4.54	2.65	4.07	4.25	5.19	4.77	6.90
FEO	11.32	5.80	11.01	6.99	11.23	9.34	8.84	8.80	8.40	7.24
MgO	4.39	4.44	5.03	8.76	4.12	4.67	5.28	5.52	6.59	5.06
CaO	10.59	13.47	10.89	12.68	10.47	11.07	11.62	11.44	11.13	11.16
Na ₂ O	3.34	2.43	2.97	2.35	3.46	3.14	2.89	2.63	2.78	2.94
K ₂ O	0.39	0.24	0.45	0.15	0.37	0.26	0.31	0.31	0.38	0.35
TiO ₂	2.54	1.55	2.94	1.45	2.65	2.42	2.70	2.81	2.43	2.37
MnO	0.23	0.16	0.24	0.18	0.24	0.22	0.21	0.23	0.22	0.24
P ₂ O ₅	0.31	0.18	0.26	0.19	0.30	0.24	0.33	0.30	0.29	0.24
FEO*	13.49	9.76	14.65	10.08	13.56	13.01	12.67	13.48	12.70	13.45
PPM										
BA	117	55	179	75	132	120	130	100	99	84
NB	19	7	27	14	24	21	27	17	21	18
ZR	166	56	134	50	163	140	190	173	161	140
Y	37	21	36	23	44	38	33	27	27	34
SR	247	257	256	322	243	253	303	272	290	256
RH	8	6	13	4	8	3	3	4	7	7
ZN	116	76	133	91	127	104	109	114	104	112
CU	188	59	158	151	128	172	217	88	165	124
NI	31	35	49	91	32	37	50	50	49	33
CIPW NORM										
QUZ	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ORTH	2.27	1.43	2.87	1.13	2.15	1.55	1.85	1.85	2.27	2.09
ALST	28.18	20.58	25.12	19.91	25.21	26.54	24.48	22.26	23.54	24.93
ANOR	23.96	38.42	23.20	28.67	23.26	26.64	26.77	26.34	24.69	24.48
NEPH	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
DIOP	22.06	22.62	24.22	26.89	22.25	22.21	23.74	23.60	23.58	24.50
HFER	13.01	10.54	9.14	4.34	12.81	12.82	11.08	15.68	12.90	14.49
CLIV	0.93	0.05	4.86	12.46	0.44	1.19	2.39	0.18	3.91	0.40
MAGN	4.03	2.90	4.38	3.30	4.07	3.88	3.78	4.02	3.79	4.01
ILMN	4.81	3.03	5.58	2.84	5.05	4.55	5.13	5.34	4.63	4.52
APAT	0.74	0.43	0.62	0.45	0.72	0.58	0.79	0.72	0.65	0.58

OLIVINE NORMATIVE THOLEIITES FROM MW-ICELAND (FEC*=ALL FE AS FEO)

	237	238	240	245	247	250	251	254	255	286
PERCENT										
SiO2	48.97	47.19	48.15	48.81	48.51	49.16	49.52	49.38	47.80	49.72
Al2O3	15.10	13.36	14.09	14.85	14.97	16.31	15.62	14.69	14.98	14.49
Fe2O3	3.84	7.25	6.42	5.22	2.68	4.18	2.95	3.73	3.04	3.26
FEO	7.89	8.71	8.03	7.58	8.38	7.23	7.27	10.18	8.41	9.60
MgO	6.33	5.47	5.52	6.87	9.18	5.35	8.68	4.16	8.73	5.99
CaO	12.41	10.35	11.34	12.07	10.92	12.75	10.86	9.96	11.66	10.99
Na2O	2.77	2.71	2.99	2.17	2.64	2.62	2.51	3.58	2.60	2.83
K2O	0.31	0.41	0.25	0.14	0.41	0.14	0.48	0.62	0.38	0.38
TiO2	1.86	3.85	2.71	1.88	1.85	1.82	1.66	3.12	1.92	2.17
MNO	0.19	0.25	0.22	0.21	0.19	0.20	0.18	0.23	0.19	0.21
P2O5	0.33	0.44	0.28	0.20	0.26	0.24	0.26	0.35	0.28	0.35
FEO*	11.35	15.24	13.81	12.28	10.79	11.00	9.93	13.54	11.15	12.56

PPM										
BA	83	140	117	74	117	74	159	162	136	116
NB	11	25	25	13	19	12	20	29	23	21
ZR	119	222	148	110	147	115	166	204	101	147
Y	26	37	33	22	26	30	26	41	28	35
SR	256	301	285	209	254	260	284	310	262	231
PB	5	4	1	3	11	3	10	13	8	4
ZN	88	142	117	92	95	93	90	139	95	109
CU	134	128	145	162	141	174	83	172	142	167
NI	57	43	43	50	270	55	269	38	311	44

CIPW NCRM										
QUTZ	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
GRTH	1.85	2.46	1.50	0.84	2.45	0.84	2.86	3.65	2.27	2.27
ALBT	23.42	22.99	25.36	18.40	22.30	22.22	21.26	30.24	21.96	23.96
ANOR	27.88	23.15	24.34	30.41	27.78	32.36	29.91	22.19	28.08	25.67
NEPH	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
DIOP	25.88	21.10	25.04	23.22	19.98	24.24	18.05	20.76	22.65	21.86
HPER	7.02	16.35	8.19	19.28	7.51	11.90	14.45	9.25	2.89	16.98
OLIV	6.24	1.02	5.63	0.15	12.64	1.15	6.73	3.12	14.50	0.57
MAGN	3.38	4.55	4.12	3.66	3.22	3.28	2.96	4.04	3.32	3.74
ILMN	3.53	7.34	5.15	3.57	3.51	3.45	3.16	5.92	3.64	4.11
APAT	0.79	1.06	0.67	0.48	0.62	0.57	0.62	0.84	0.67	0.84

OLIVINE NORMATIVE THOLEIITES FROM MW-ICELAND (FEO*=ALL FE AS FEO)

PERCENT

	292	296	298	304	307
SiO2	50.04	47.94	49.44	48.03	48.34
Al2O3	15.15	15.38	15.71	15.54	18.06
Fe2O3	1.93	6.42	2.23	6.23	3.45
FEO	10.50	6.86	9.68	6.67	7.38
MgO	5.20	8.18	4.10	7.34	5.31
CaO	11.12	10.49	10.90	10.77	11.81
Na2O	3.15	2.30	3.19	2.67	2.58
K2O	0.43	0.29	0.51	0.21	0.85
TiO2	1.95	1.65	2.49	1.91	1.94
MnO	0.21	0.19	0.23	0.21	0.17
P2O5	0.33	0.29	0.42	0.32	0.17
FEO*	12.25	12.70	12.68	12.33	11.52

PPM

BA	131	116	171	113	105
NB	23	16	31	22	23
ZR	147	126	171	126	141
Y	32	27	38	27	25
SR	164	242	278	263	335
RB	8	1	11	1	17
ZN	107	89	113	100	89
CU	364	97	127	133	90
NI	57	79	28	58	98

CIPW NCRM

QUTZ	0.00	0.00	0.00	0.00	0.00
ORTH	2.51	1.73	2.99	1.25	5.01
ALBT	26.61	19.51	26.96	22.67	21.87
ANCR	25.88	30.89	27.03	30.16	35.03
NEPH	0.00	0.00	0.00	0.00	0.00
DIOP	22.35	15.89	20.23	17.45	18.50
HPER	11.56	16.66	12.87	12.09	4.42
OLIV	2.57	7.70	0.41	8.31	7.56
MAGN	3.65	3.77	3.78	3.66	3.12
ILMN	3.69	3.15	4.72	3.63	3.68
APAT	0.79	0.69	1.01	0.77	0.41

QUARTZ NORMATIVE THOLEIITES FROM MW-ICELAND (FEC*=ALL FE AS FEO)

	1	3	7	9	23	24	25	26	34	35
PERCENT										
SI02	51.28	52.01	49.22	50.27	50.28	50.67	49.61	51.82	50.46	51.48
AL2O3	15.12	14.43	13.33	13.85	14.62	14.27	14.21	14.12	14.14	13.63
FE2O3	3.56	4.01	5.45	3.45	3.48	5.09	5.09	5.46	7.04	7.20
FEO	9.30	9.94	9.54	10.40	10.23	8.70	7.97	7.79	5.99	5.62
MGO	4.27	3.39	4.58	4.19	4.28	4.23	6.64	4.78	5.57	5.99
CAO	9.79	8.55	10.15	10.08	10.44	10.12	10.60	9.41	10.70	10.55
NA2O	3.21	3.43	3.17	3.32	3.50	3.15	2.65	3.01	2.85	2.56
K2O	0.53	0.68	0.65	0.60	0.36	0.53	0.20	0.64	0.39	0.14
TIO2	2.27	2.91	3.26	3.23	2.50	2.63	2.46	2.35	2.31	2.31
MNO	0.25	0.26	0.25	0.24	0.23	0.25	0.23	0.22	0.17	0.24
P2O5	0.42	0.38	0.39	0.36	0.26	0.36	0.33	0.39	0.38	0.30
FEO*	12.51	13.55	14.45	13.51	13.37	13.29	12.66	12.71	12.33	12.11

PPM										
BA	139	176	162	158	786	130	83	134	125	108
NB	23	27	23	27	25	23	23	24	19	21
ZR	232	260	241	243	127	239	214	268	210	261
Y	44	53	38	36	36	49	43	52	38	52
SR	259	241	307	297	260	241	254	239	302	221
RB	8	20	11	14	10	8	4	12	1	3
ZN	117	139	132	131	117	129	111	129	109	127
CU	115	71	63	177	207	146	146	147	159	117
NI	33	16	29	32	28	50	72	48	37	49

CIPW NORM

QU TZ	2.74	4.70	0.21	1.52	0.12	2.32	0.98	4.08	1.93	5.00
ORTH	3.11	4.01	3.82	3.53	2.15	3.11	1.20	3.77	2.33	0.84
ALBT	27.12	29.03	26.83	28.09	29.63	26.72	22.42	25.50	24.21	21.73
ANOR	25.31	21.93	20.26	21.09	23.08	23.26	26.34	23.20	24.73	25.38
NEPH	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CLCP	17.08	15.09	23.00	22.10	22.56	20.56	15.84	17.44	21.49	20.74
HPER	15.60	14.72	14.42	12.65	13.10	14.21	20.00	15.82	16.32	17.60
GLIV	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
MAGN	3.73	4.04	4.31	4.03	3.99	3.96	3.74	3.79	3.67	3.61
ILMN	4.30	5.52	6.20	6.13	4.75	5.00	4.69	4.48	4.40	4.40
APAT	1.01	0.91	0.94	0.86	0.62	0.86	0.79	0.93	0.91	0.72

QUARTZ NORMATIVE THOLEIITES FROM MW-ICELAND (FEC*=ALL FE AS FEC)

	38	39	41	43	44	45	46	51	52	57
PERCENT										
SiO2	49.49	49.47	49.48	51.32	51.17	49.12	50.11	49.56	49.63	50.82
Al2O3	16.59	18.30	14.13	13.46	13.66	15.78	14.37	13.89	14.41	14.18
Fe2O3	4.87	4.10	4.66	5.58	5.31	5.19	4.67	4.25	4.42	3.41
FeO	6.55	6.37	8.18	8.02	8.80	7.61	8.37	10.75	8.57	10.76
MgO	3.88	4.18	6.06	4.23	3.91	5.00	5.62	4.24	5.81	3.99
CaO	12.20	12.93	12.42	8.99	9.08	12.05	10.95	9.44	11.43	9.34
Na2O	2.72	2.47	2.39	3.35	3.43	2.45	2.81	3.26	2.78	3.56
K2O	0.35	0.23	0.16	0.79	0.75	0.22	0.39	0.42	0.23	0.40
TiO2	2.41	1.55	2.06	3.17	3.18	2.15	2.20	3.54	2.22	2.54
MnO	0.23	0.18	0.22	0.23	0.24	0.21	0.23	0.28	0.23	0.24
P2O5	0.30	0.21	0.23	0.41	0.43	0.22	0.28	0.38	0.25	0.35
FEO*	11.34	10.06	12.38	13.41	13.58	12.29	12.58	14.58	12.55	13.83

PPM										
EA	101	59	81	169	170	65	96	173	94	162
NB	15	11	14	32	30	11	14	21	18	28
ZR	154	94	135	278	277	117	153	215	144	183
Y	31	22	30	46	45	27	35	48	35	48
SR	324	301	236	295	302	250	249	252	241	248
R8	5	3	1	25	18	1	6	5	1	4
ZN	93	76	95	134	138	100	101	139	101	128
CU	165	82	148	132	95	62	149	138	162	87
NI	37	28	53	24	20	38	44	23	46	13

CIPW NORM										
QUTZ	1.68	1.09	0.84	3.11	2.56	1.13	0.86	1.84	0.18	2.05
CRTH	2.09	1.37	0.96	4.66	4.67	1.31	2.33	2.45	1.37	2.33
ALBT	23.08	20.92	20.28	28.77	29.04	20.79	23.79	27.61	23.54	30.07
ANDR	32.06	38.22	27.36	19.21	19.58	31.44	25.46	22.00	26.19	21.53
NEPH	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
DIOP	22.15	20.43	27.05	19.01	18.96	22.39	22.39	18.68	23.88	18.77
HPER	10.27	11.53	15.35	14.23	13.66	14.65	16.57	15.46	16.27	14.75
OLIV	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
MAGN	3.38	3.00	3.69	4.00	4.05	3.66	3.75	4.35	3.74	4.13
ILMN	4.59	2.95	3.92	6.03	6.06	4.09	4.19	6.72	4.23	5.58
APAT	0.72	0.50	0.55	0.98	1.03	0.53	0.67	0.89	0.60	0.84

QUARTZ NORMATIVE THOLEIITES FROM MW-ICELAND (FEC*=ALL FE AS FEO)

	64	65	68	69	71	72	90	93	98	102
PERCENT										
SiO2	50.43	49.97	51.44	49.18	49.05	49.52	49.78	49.06	50.86	50.74
Al2O3	14.31	14.84	15.62	13.27	13.35	16.00	15.06	14.59	16.04	14.48
Fe2O3	3.94	7.01	3.48	4.89	5.14	6.22	2.38	3.85	1.90	4.17
FEO	9.64	6.47	9.16	10.63	10.31	6.58	10.81	10.78	9.78	9.49
MgO	4.45	4.70	3.55	4.59	4.76	3.69	4.26	3.86	4.77	4.62
CaO	9.74	11.05	9.67	10.19	10.17	11.56	10.63	10.19	10.55	9.84
Na2O	3.33	3.02	3.41	2.87	2.92	2.74	3.24	3.31	3.22	3.12
K2O	0.65	0.33	0.64	0.41	0.37	0.29	0.54	0.52	0.56	0.54
TiO2	2.80	2.10	2.51	3.34	3.30	2.58	2.67	3.20	1.66	2.55
MNO	0.21	0.22	0.22	0.26	0.26	0.19	0.21	0.25	0.21	0.21
P2O5	0.49	0.29	0.31	0.36	0.36	0.23	0.42	0.39	0.45	0.24
FEO*	12.19	12.79	12.30	15.04	14.94	12.18	12.95	14.25	11.49	13.25

PPM										
BA	162	106	174	155	154	108	148	164	149	166
NB	32	23	34	45	41	21	28	30	29	35
ZR	217	142	191	221	217	127	144	160	231	204
Y	48	39	45	49	52	39	41	44	45	40
SP	305	272	279	264	265	291	274	268	239	251
RB	9	8	17	14	15	9	8	13	10	12
ZN	116	107	128	146	148	116	112	127	100	117
CU	58	154	114	188	182	159	104	92	118	184
NI	27	41	18	20	34	13	45	25	53	41

CIPW NORM										
QUtz	1.27	0.70	2.66	2.01	1.50	2.27	0.20	0.08	0.28	1.94
ORTh	3.83	1.97	3.76	2.40	2.22	1.73	3.17	3.05	3.28	3.17
AlSt	28.17	25.68	28.83	24.27	24.70	23.27	27.39	28.03	27.19	26.39
ANOr	22.19	26.02	25.42	22.16	22.24	30.57	24.91	23.38	27.63	23.94
NEPH	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
DIOP	19.10	22.53	17.16	21.75	21.57	22.90	20.88	20.64	18.01	19.38
HPER	15.03	14.55	12.99	15.71	16.18	10.16	13.55	13.57	15.98	15.81
CLIV	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
MAGN	3.94	3.81	3.67	4.49	4.46	3.63	3.87	4.26	3.43	3.95
ILMN	5.32	4.00	4.76	6.35	6.27	4.92	5.05	6.08	3.15	4.84
APAT	1.15	0.69	0.74	0.86	0.86	0.55	0.98	0.91	1.05	0.58

QUARTZ NORMATIVE THOLEIITES FROM MW-ICELAND (FEG*=ALL FF AS FEO)

	107	110	118	119	149	150	151	153	154	155
PERCENT										
SI02	51.12	50.53	49.85	50.02	51.38	50.63	51.29	50.78	48.53	50.24
AL2O3	14.34	14.91	14.60	14.59	14.76	14.56	14.05	13.48	14.19	13.13
FE2O3	5.81	2.92	3.94	3.05	4.37	3.98	3.13	4.39	5.48	5.23
FEO	6.40	10.54	10.61	11.59	9.58	9.30	10.97	9.87	7.93	10.35
MGO	6.77	4.40	4.08	3.24	3.93	4.98	3.86	4.62	7.07	4.15
CAO	10.70	9.77	8.36	8.72	8.68	10.62	8.58	10.14	12.21	9.61
NA2O	2.27	3.28	3.52	3.81	3.22	2.78	3.56	3.25	1.87	2.78
K2O	0.37	0.68	0.65	0.68	0.62	0.30	0.58	0.38	0.19	0.43
TiO2	1.87	2.52	3.61	3.67	2.90	2.32	3.29	2.54	2.08	3.49
MNO	0.17	0.23	0.26	0.27	0.24	0.23	0.26	0.25	0.23	0.26
P2O5	0.16	0.22	0.51	0.36	0.32	0.30	0.43	0.28	0.23	0.32
FEO*	11.63	13.17	14.16	14.34	13.52	12.89	13.79	13.83	12.87	15.06

PPM										
SA	160	171	171	165	157	130	156	123	88	148
NB	26	34	45	42	23	19	28	23	14	26
ZR	153	204	268	204	224	175	256	210	134	251
Y	34	42	63	50	47	39	54	43	30	52
SR	245	256	262	270	239	248	245	235	208	218
RB	12	18	13	12	18	1	9	12	1	11
ZN	99	126	169	155	131	112	141	129	98	162
CU	156	193	14	18	117	145	65	181	82	153
NI	86	35	1	1	23	36	20	32	56	28

CIPW NORM										
QUtz	3.36	0.59	1.62	0.88	4.14	2.90	3.36	1.76	0.74	4.85
CRTH	2.21	4.01	3.83	4.01	3.65	1.75	3.41	2.27	1.14	2.52
ALBT	19.24	27.75	29.74	32.14	27.24	23.54	30.07	27.50	15.84	23.50
ANOR	27.93	23.90	22.13	20.69	24.00	26.34	20.63	21.07	29.82	22.12
NEPH	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
DIOP	19.89	19.23	13.38	16.98	14.21	20.25	15.97	22.87	24.11	19.67
HPER	19.95	15.28	17.02	13.20	16.44	16.22	15.19	14.90	20.02	15.43
CLIV	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
MAGN	3.47	3.93	4.23	4.29	4.03	3.84	4.12	4.13	3.84	4.50
ILMN	3.57	4.79	6.82	6.96	5.52	4.40	6.23	4.83	3.56	6.64
APAT	5.38	0.53	1.20	0.84	0.77	0.72	1.01	0.67	0.55	0.77

QUARTZ NORMATIVE THOLEIITES FROM MW-ICELAND (FEC*=ALL FE AS FEC)

	157	159	162	164	172	183	185	194	197	199
PERCENT										
SiO2	49.43	49.69	49.06	50.61	50.86	51.52	50.79	49.37	49.51	49.14
Al2O3	13.89	13.37	12.86	16.25	14.68	14.90	14.27	13.84	14.05	15.36
Fe2O3	5.92	3.44	4.94	1.87	1.93	1.72	2.09	3.34	3.31	3.66
FEC	7.37	12.01	11.44	10.15	11.83	11.65	12.60	11.21	11.01	9.36
MgO	5.94	4.16	3.66	3.77	3.78	3.33	3.49	4.68	4.78	4.46
CaO	11.44	9.67	9.28	10.90	9.54	8.69	8.71	10.15	10.10	11.67
Na2O	2.33	3.30	2.74	3.10	3.51	3.71	3.28	3.14	3.16	2.83
K2O	0.26	0.44	0.63	0.36	0.51	0.82	0.59	0.59	0.50	0.35
TiO2	2.87	3.37	4.58	2.47	2.77	2.97	3.76	3.09	3.01	2.56
MnO	0.22	0.27	0.27	0.19	0.24	0.24	0.29	0.24	0.24	0.22
P2O5	0.32	0.28	0.54	0.32	0.35	0.45	0.33	0.34	0.33	0.27
FEC*	12.70	15.11	15.89	11.84	13.57	13.20	14.48	14.22	13.59	12.66

PPM										
BA	97	124	142	164	138	175	189	154	157	243
NB	23	27	33	21	20	42	35	36	39	30
ZR	194	208	277	157	210	217	243	212	206	135
Y	30	41	47	34	43	52	49	50	46	37
SR	302	251	266	287	244	277	268	255	256	285
RB	9	13	10	16	12	27	15	15	11	6
ZN	110	145	150	99	115	144	161	138	145	103
CU	155	154	345	203	163	63	17	198	192	137
NI	62	20	21	24	23	2	3	35	39	38

CIPW NCRM										
QUTZ	2.68	1.29	5.03	2.46	1.74	2.39	4.30	0.15	0.33	0.60
ORTH	1.55	2.58	3.72	2.15	2.99	4.84	3.47	3.47	2.93	2.09
ALBT	19.77	27.88	23.18	26.17	29.64	31.34	27.69	26.57	26.73	23.56
ANOR	26.74	20.35	20.92	29.30	22.72	21.49	21.86	21.89	22.65	28.16
NEPH	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
DIOP	23.09	21.52	18.16	18.81	18.65	15.62	16.05	21.80	20.98	22.71
HPER	16.16	14.80	14.29	12.13	14.13	13.69	14.41	15.20	15.69	12.95
OLIV	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
MAGN	3.79	4.52	4.75	3.53	4.06	3.94	4.33	4.25	4.18	3.78
ILMN	5.46	6.39	8.69	4.68	5.25	5.63	7.12	5.87	5.71	4.86
APAT	0.77	0.67	1.27	0.77	0.82	1.05	0.77	0.82	0.79	0.89

QUARTZ NORMATIVE THOLEIITES FROM MW-ICELAND (FEC*=ALL FE AS FEO)

	201	204	206	216	217	219	220	221	223	224
PERCENT										
SI02	48.58	50.03	49.87	50.39	48.38	49.31	50.33	49.22	49.58	49.84
AL2O3	14.18	13.77	14.58	14.07	13.93	14.06	14.31	14.83	13.79	14.16
FE2O3	4.22	4.55	3.34	5.31	6.98	4.86	4.07	5.60	5.19	5.09
FEC	10.95	10.63	10.70	9.05	7.64	9.78	9.87	8.23	9.30	7.99
MGO	4.43	3.95	4.11	4.19	5.37	4.20	3.53	4.66	4.55	5.53
CAO	10.22	9.55	10.35	9.31	10.96	9.91	9.28	10.94	9.62	11.26
NA2O	3.11	3.24	3.45	3.20	2.61	3.20	3.40	2.71	3.11	2.52
K2O	0.38	0.64	0.33	0.64	0.33	0.55	0.70	0.28	0.64	0.36
TiO2	3.25	2.92	2.75	3.18	3.09	3.45	3.73	2.96	3.45	2.37
MNO	0.26	0.27	0.23	0.23	0.22	0.25	0.25	0.21	0.23	0.20
P2O5	0.42	0.45	0.28	0.44	0.49	0.44	0.53	0.36	0.54	0.25
FEO*	14.75	14.73	13.71	13.83	13.93	14.16	13.54	13.28	13.98	12.58

PPM										
BA	187	189	136	171	129	173	155	114	165	91
NB	32	33	28	33	30	35	41	25	34	16
ZR	157	185	174	248	232	260	326	210	234	159
Y	40	50	46	42	37	42	45	32	42	29
SR	291	300	240	271	293	309	311	318	282	290
RB	5	9	10	9	3	13	12	6	14	6
ZN	129	140	132	134	112	138	151	118	135	104
CU	94	141	126	74	138	146	117	81	58	173
NI	28	11	34	26	39	29	22	25	31	51

CIPW NORM.

QUtz	0.17	1.62	0.15	2.74	1.05	1.25	3.02	2.27	1.90	1.49
ORTH	2.22	3.77	1.97	3.77	1.97	3.23	4.13	1.67	3.77	2.15
ALBT	26.32	27.44	29.13	27.07	22.19	27.08	28.77	22.95	26.31	21.40
ANOR	23.61	21.13	23.31	22.18	25.36	22.40	21.72	27.53	21.82	26.27
NEPH	C.OO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
DIOP	20.35	19.58	21.85	17.68	21.49	19.99	17.48	20.34	18.68	23.19
HPER	15.77	15.45	13.60	15.34	16.73	14.24	12.51	14.79	15.52	16.64
OLIV	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
MAGN	4.41	4.40	4.09	4.13	4.15	4.23	4.04	3.96	4.17	3.75
ILMN	6.18	5.54	5.21	6.04	5.88	6.56	7.07	5.63	6.56	4.51
APAT	0.98	1.06	0.67	1.06	1.17	1.03	1.25	0.86	1.27	0.60

QUARTZ NORMATIVE THOLEIITES FROM MW-ICELAND (FEC*=ALL FF AS FEC)

	225	226	227	228	229	230	232	233	235	236
PERCENT										
SI02	50.37	50.12	48.63	48.55	48.74	50.38	49.02	49.12	48.95	49.29
AL2O3	13.98	13.86	13.71	13.64	13.71	13.42	14.57	13.54	19.02	18.30
FE2O3	4.68	3.46	4.21	5.31	6.79	7.97	5.05	5.14	4.95	5.35
FEO	9.65	11.05	10.20	9.59	7.50	7.16	8.79	10.12	5.35	5.42
MGO	4.17	4.11	5.78	4.81	5.87	3.82	5.70	4.74	3.69	3.76
CAU	9.46	9.60	11.58	10.50	11.22	9.26	11.27	9.78	13.67	13.23
NA2O	3.22	3.21	2.34	2.84	2.34	3.28	2.47	2.78	2.25	2.44
K2O	0.51	0.50	0.23	0.63	0.35	0.73	0.16	0.50	0.20	0.25
TiO2	3.40	3.41	2.70	3.36	2.91	3.32	2.47	3.61	1.56	1.60
MNO	0.26	0.25	0.24	0.24	0.22	0.24	0.22	0.25	0.16	0.17
P2O5	0.40	0.32	0.36	0.53	0.34	0.41	0.29	0.43	0.18	0.19
FEO*	13.87	14.17	13.99	14.37	13.62	14.34	13.34	14.75	9.81	11.24

PPM										
BA	170	166	66	146	117	156	86	152	62	69
NB	31	36	14	29	20	30	16	28	11	12
ZR	264	271	156	245	184	253	162	247	93	100
Y	42	44	39	39	27	46	38	44	22	24
SR	298	310	203	277	324	292	216	291	258	301
RB	13	8	6	11	5	14	1	7	3	3
ZN	138	138	121	134	116	131	115	142	71	79
CU	163	151	257	263	126	121	194	122	125	125
NI	26	25	61	44	39	17	59	27	23	24

CIPW NORM										
QUTZ	3.06	2.17	1.22	0.59	1.62	2.80	1.33	2.64	1.35	1.22
ORTH	2.99	3.53	1.38	3.71	2.09	4.31	0.96	2.93	1.19	1.49
ALBT	27.24	27.17	19.80	24.08	19.87	27.86	20.90	23.50	19.12	20.67
ANOR	21.93	21.60	26.23	22.62	25.95	19.83	28.23	23.04	41.29	38.36
NEPH	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
DIOP	18.65	19.55	23.86	21.71	22.83	19.78	21.38	18.94	21.25	21.81
HPR	14.53	14.11	17.34	15.35	17.23	13.81	17.85	16.68	9.48	9.90
OLIV	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
MAGN	4.14	4.23	4.18	4.29	4.06	4.28	3.99	4.40	2.92	3.05
ILMN	6.46	6.46	5.14	6.39	5.54	6.33	4.65	6.85	2.97	3.05
APAT	0.96	0.77	0.86	1.25	0.82	0.98	0.70	1.01	0.43	0.45

QUARTZ NORMATIVE THOLEIITES FROM NW-ICELAND (FEC*=ALL FE AS FEC)

	241	242	243	244	290	291	299
PERCENT							
SiO2	50.20	50.46	50.85	50.22	51.55	49.90	49.44
Al2O3	14.30	14.12	14.16	14.17	14.65	14.20	14.74
Fe2O3	3.38	4.04	4.55	3.76	4.05	4.29	5.07
FEO	10.64	9.71	9.83	10.31	9.60	8.51	8.64
MgO	4.18	4.38	3.65	4.34	3.72	6.22	4.39
CaO	9.64	9.68	9.06	9.62	9.20	11.45	10.89
Na2O	3.26	3.21	3.36	3.20	3.54	2.62	2.91
K2O	0.58	0.61	0.81	0.66	0.54	0.22	0.50
TiO2	3.09	3.09	3.01	3.17	2.54	2.05	2.75
MnO	0.22	0.22	0.21	0.22	0.23	0.19	0.24
P2O5	0.52	0.49	0.51	0.32	0.37	0.31	0.44
FEO*	13.69	13.35	13.93	13.70	13.28	12.41	13.25

ppm							
BA	171	163	175	160	165	104	140
NB	34	37	35	31	33	22	31
ZR	227	229	244	248	250	146	163
Y	43	44	50	45	48	33	32
SR	311	315	293	301	149	158	279
RB	7	12	14	14	14	2	8
ZN	134	131	144	127	130	105	114
CU	122	130	146	181	115	89	100
NI	26	26	32	27	23	53	28

CIPW NCRM							
QUtz	2.04	2.41	2.77	1.76	2.77	0.84	1.29
ORTh	3.41	3.59	4.79	3.89	3.17	1.31	2.93
AlBT	27.58	27.15	28.44	27.08	29.97	22.16	24.66
ANUR	22.64	22.33	21.17	22.35	22.50	26.36	25.71
NEPH	0.00	0.00	0.00	0.00	0.00	0.00	0.00
DiCP	18.16	18.74	17.20	19.35	17.36	23.59	21.21
HPER	14.99	14.80	14.57	14.70	14.56	17.41	13.97
OLIV	0.00	0.00	0.00	0.00	0.00	0.00	0.00
MAGN	4.09	3.98	4.16	4.09	3.95	3.69	3.94
ILMN	5.86	5.86	5.71	6.02	4.92	3.90	5.23
APAT	1.22	1.15	1.20	0.77	0.89	0.74	1.05

BASALTIC ICELANDITES FROM C.V. IN MW-ICELAND (FEO*=ALL FE AS FEO)

	29	55	66	74	100	103	104	168	181	196
PERCENT										
SI02	53.63	54.26	52.32	55.58	52.71	54.34	54.24	55.88	55.67	54.95
AL2O3	13.82	13.52	13.87	14.37	14.68	15.85	15.80	14.63	13.74	13.17
FE2O3	4.47	3.73	3.63	2.80	3.74	3.52	3.85	4.19	5.58	6.27
FEO	10.30	8.74	10.32	10.72	8.88	7.79	7.58	7.52	7.09	7.00
MO	1.91	4.14	3.25	1.47	3.52	2.89	2.89	2.73	2.84	3.67
CAO	7.56	8.97	8.53	6.66	8.37	9.44	9.53	7.06	6.74	8.36
NA2O	3.81	3.30	3.76	4.40	3.73	3.12	3.06	3.83	3.84	2.66
K2O	0.59	0.71	0.68	0.98	0.85	0.58	0.53	0.91	1.01	0.77
TI02	2.42	2.06	2.98	2.00	2.92	2.01	2.05	2.20	2.57	2.41
MNO	0.36	0.29	0.26	0.31	0.24	0.20	0.20	0.26	0.28	0.28
P2O5	1.13	0.28	0.41	0.70	0.35	0.27	0.27	0.73	0.65	0.45
FEO*	14.33	12.10	13.59	13.24	12.25	10.96	11.05	11.30	12.12	12.65

PPM	BA	NB	ZR	Y	SR	RB	ZN	CU	NI
	271	42	482	108	230	17	198	24	1
	199	39	417	70	224	17	137	127	35
	465	52	279	60	263	25	151	42	6
	288	69	357	83	290	16	203	7	1
	193	45	283	58	239	20	141	56	23
	259	46	277	52	294	18	98	85	19
	286	42	274	52	296	20	104	87	21
	211	35	354	78	267	21	155	4	3
	254	50	345	79	262	24	165	8	1
	214	47	293	66	260	18	153	58	11

CIPW NORM

QUtz	8.54	6.60	4.05	7.42	4.06	8.66	8.91	9.78	9.53	11.97
GRTH	3.47	4.18	4.01	5.80	5.02	3.40	3.16	5.27	5.97	4.54
ALBT	32.22	27.89	31.78	37.16	31.57	26.41	25.90	32.47	32.58	22.59
ANOR	18.86	20.00	18.95	16.54	20.80	27.56	27.81	20.04	17.29	21.78
NEPH	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
DIOP	9.63	18.90	17.43	10.27	15.41	14.73	14.90	8.39	10.10	14.11
HPR	15.72	14.24	13.12	13.42	13.10	11.51	11.48	14.56	14.49	15.57
CLIV	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NAGN	4.28	3.61	4.06	3.95	3.65	3.26	3.29	3.36	3.61	3.77
ILMN	4.60	3.92	5.65	3.79	5.55	3.82	3.89	4.18	4.89	4.59
APAT	2.69	0.67	0.96	1.65	0.94	0.65	0.65	1.84	1.53	1.08

BASALTIC ICELANDITES FROM C.V. IN MW-ICELAND (FEO*=ALL FE AS FEO)

198 287 289 303

PERCENT

SiO ₂	54.87	52.69	52.38	52.95
Al ₂ O ₃	14.31	13.54	15.48	12.98
Fe ₂ O ₃	4.59	5.17	2.84	5.40
FEO	8.03	9.80	8.51	10.40
MgO	3.11	2.41	4.66	2.36
CaO	7.72	7.93	9.57	7.41
Na ₂ O	3.07	3.51	2.99	3.69
K ₂ O	1.12	0.87	0.85	0.97
TiO ₂	2.53	2.80	2.21	2.56
MnO	0.21	0.35	0.18	0.43
P ₂ O ₅	0.43	0.92	0.32	0.85
FEO*	12.17	14.50	11.09	15.31

PPM

BA	292	280	256	80
NB	48	57	38	61
ZR	257	334	229	359
Y	51	76	37	82
SR	240	297	232	306
RB	28	21	18	24
ZN	140	203	115	196
CU	57	3	83	1
NI	1	1	47	1

CIPW NORM

QUTZ	10.02	7.10	4.06	6.32
CRTH	6.63	5.15	5.01	5.75
ALBT	26.00	29.74	25.30	31.22
ANOR	21.98	18.63	26.29	15.99
NEPH	0.00	0.00	0.00	0.00
DIOP	11.35	12.54	15.75	13.02
HPR	14.55	15.02	15.31	16.26
CLIV	0.00	0.00	0.00	0.00
MAGN	3.63	4.31	3.30	4.56
ILMN	4.82	5.23	4.20	4.87
APAT	1.03	2.18	0.77	2.02

ICELANDITES FROM CENTRAL VOLCANCES IN MW-ICFLAND (FEO*=ALL FE AS FEO)

	8	28	20	21	32	33	36	37	53	59
PERCENT										
SI02	62.22	60.91	61.11	57.08	60.70	57.49	59.04	57.19	56.58	57.34
AL2O3	13.77	14.23	13.75	13.67	14.38	13.65	13.09	13.86	13.95	13.94
FE2O3	3.50	3.30	5.65	3.96	4.17	3.58	4.71	2.26	3.89	3.63
FEO	5.67	7.80	5.97	9.81	6.77	9.97	9.18	8.28	9.58	10.05
MGO	2.13	0.93	1.17	1.09	1.16	0.98	0.50	3.43	1.29	0.99
CAO	4.73	5.12	4.91	6.57	5.27	6.52	6.25	8.47	6.66	6.35
NA2O	4.12	4.47	4.15	4.02	4.28	4.06	3.91	3.47	3.92	4.02
K2O	1.68	1.24	1.23	1.00	1.25	1.04	1.11	0.87	1.04	1.05
TI02	1.70	1.31	1.39	1.73	1.31	1.64	1.38	1.78	1.68	1.60
MAC	0.19	0.25	0.28	0.34	0.23	0.22	0.36	0.20	0.32	0.33
P2O5	0.27	0.43	0.39	0.73	0.47	0.70	0.47	0.18	0.69	0.70
FEO*	8.82	10.77	11.06	13.38	10.53	13.22	13.42	10.32	13.49	13.32

PPM										
BA	302	229	256	233	274	245	261	203	235	249
N8	60	47	48	46	52	47	46	34	58	57
ZR	506	498	503	509	518	543	764	330	580	836
Y	90	99	100	94	106	105	100	70	107	109
SR	205	216	222	216	219	220	204	189	221	224
RB	53	33	34	25	29	25	27	20	22	23
ZN	160	184	217	195	179	188	215	132	193	201
CU	31	15	3	21	27	22	17	133	30	31
NI	6	2	1	1	1	1	1	37	1	1

CIPW NCRM										
QUtz	16.68	14.83	16.65	11.54	15.16	11.83	14.57	10.34	10.69	11.75
OPH	9.95	7.34	7.28	5.52	7.40	6.16	6.58	5.13	6.16	6.22
ALBT	34.89	37.85	35.21	33.99	36.20	34.33	33.14	29.38	33.14	33.99
ANOR	14.15	15.07	15.30	16.28	16.32	16.04	14.87	16.64	17.39	16.88
NEPH	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
DIOP	6.39	6.51	5.70	10.05	5.85	10.23	11.57	17.65	9.68	8.75
HPFR	11.44	11.66	12.99	13.22	12.22	12.71	11.56	10.98	14.10	13.75
CLIV	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
MAGN	2.62	3.21	3.29	3.99	3.13	3.94	4.00	3.07	4.02	3.97
ILMN	3.24	2.49	2.65	3.29	2.49	3.11	2.61	3.37	3.10	3.04
APAT	0.64	1.03	0.93	1.73	1.12	1.45	1.10	0.43	1.63	1.65

ICELANDITES FROM CENTRAL VOLCANOES IN MW-ICELAND (FEC#=ALL FE AS FEC)

	60	61	62	63	70	75	80	85	94	111
PERCENT										
SI02	56.61	61.54	58.93	59.30	57.74	59.76	56.68	58.31	60.98	56.56
AL2O3	13.62	13.36	13.47	13.65	14.51	13.70	15.55	14.46	13.90	14.26
FE2O3	2.45	6.41	6.64	3.37	3.51	2.65	4.50	6.86	2.78	3.76
FEO	10.75	6.17	7.31	9.65	7.41	8.38	6.89	4.98	7.75	8.24
MGO	1.33	0.41	0.73	0.78	2.16	1.62	2.78	1.58	1.34	2.09
CAO	6.73	5.00	5.55	5.76	6.61	5.99	8.40	5.96	5.85	6.71
NA2O	4.37	4.26	4.14	4.20	4.17	4.23	3.52	4.33	3.05	3.98
K2O	1.08	1.34	1.16	1.15	1.22	0.88	0.92	1.18	2.23	1.07
TIO2	1.93	0.98	1.32	1.36	1.89	1.98	2.20	1.61	1.41	2.35
MNO	0.33	0.25	0.30	0.32	0.23	0.24	0.19	0.27	0.23	0.23
P2O5	0.80	0.27	0.45	0.47	0.56	0.57	0.37	0.48	0.46	0.75
FEO*	12.56	11.95	13.29	12.69	10.57	10.77	10.94	11.16	10.26	11.63

PPM										
RA	257	300	259	255	273	311	205	271	371	231
NB	52	63	55	54	54	52	36	55	73	45
ZR	479	595	501	501	363	403	256	431	683	289
Y	106	115	103	101	84	87	59	79	95	71
SR	220	191	212	217	247	227	255	305	220	253
RB	20	21	25	27	33	57	20	33	55	29
ZN	191	206	198	212	160	156	128	185	152	149
CU	24	15	16	17	19	17	69	7	27	24
NI	1	1	1	1	11	1	1	1	1	1

CIPW NORM										
QUZ	9.09	16.46	13.54	13.52	10.39	15.03	7.75	11.26	17.88	10.68
GRTH	6.40	7.95	6.88	6.81	7.22	5.19	5.43	6.98	13.18	6.33
ALBT	36.89	36.19	35.11	35.52	35.27	35.79	29.82	36.75	25.79	33.68
ANOR	14.33	13.41	14.80	14.98	17.28	15.77	23.96	16.62	17.65	17.89
NEPH	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
DIOP	11.93	8.54	8.63	9.22	10.03	8.76	12.90	8.49	7.19	8.94
HPR	11.96	11.38	13.49	12.49	11.75	11.14	11.82	12.36	11.47	12.78
CLIV	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
MAGN	3.87	3.56	3.96	3.78	3.15	3.21	3.26	3.32	3.06	3.46
ILMN	3.65	1.86	2.53	2.57	3.58	3.76	4.18	3.07	2.68	4.47
APAT	1.89	0.65	1.08	1.10	1.34	1.37	0.88	1.15	1.10	1.77

ICELANDITES FROM CENTRAL VOLCANES IN NW-ICELAND (FEC*=ALL FE AS FEC)

	113	117	17C	171	173	175	177	182	252	253
PERCENT										
SiO2	61.42	58.55	56.00	56.74	56.82	57.22	61.71	58.10	60.49	60.15
Al2O3	14.50	14.82	14.35	14.98	14.35	15.16	13.68	14.21	14.00	14.09
Fe2O3	1.51	2.01	4.37	4.07	3.56	4.97	2.13	4.51	3.88	4.53
FeO	6.75	7.93	7.82	7.62	8.07	5.46	7.18	6.34	6.39	6.09
MgO	2.55	2.09	2.27	2.40	2.25	2.72	1.58	2.57	2.02	1.79
CaO	6.14	6.39	6.88	6.74	6.57	7.82	6.18	6.07	5.15	5.30
Na2O	4.04	4.25	4.10	4.08	4.17	3.33	3.81	3.97	4.26	4.27
K2O	1.55	1.63	0.92	0.97	1.01	0.98	1.06	1.35	1.41	1.42
TiO2	1.25	1.79	2.30	2.45	2.50	1.84	1.87	2.25	1.80	1.74
MnO	0.16	0.21	0.28	0.27	0.26	0.20	0.19	0.22	0.23	0.23
P2O5	0.12	0.24	0.70	0.58	0.42	0.30	0.40	0.42	0.37	0.37
FEO*	8.11	9.74	11.76	11.29	11.28	9.94	9.10	10.40	9.89	10.17

PPM										
BA	336	309	201	241	213	176	332	293	284	308
NB	80	70	40	44	38	29	56	65	51	66
ZR	485	453	378	400	40	324	452	464	430	478
Y	83	75	78	76	77	53	80	89	83	91
SR	190	231	265	263	273	250	223	250	243	244
RB	48	34	25	24	28	25	72	34	42	40
ZN	138	143	167	161	157	118	133	168	173	173
CU	66	54	10	6	5	59	14	8	7	4
NI	31	4	2	2	1	21	5	1	2	1

CIPW NCRM										
QUTZ	13.96	9.75	9.30	10.34	9.90	12.22	18.93	11.63	14.24	13.74
ORTH	9.17	9.60	5.43	5.73	5.57	5.78	6.26	7.99	8.35	8.41
ALBT	34.13	35.93	34.71	34.53	35.30	28.26	32.25	33.65	36.11	36.20
ANOR	6.81	16.55	18.07	17.27	17.46	23.58	17.62	16.99	14.91	15.11
NEPH	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
DIOP	10.75	10.92	9.82	10.53	10.50	11.20	8.86	8.74	6.98	7.49
HFER	10.05	10.15	13.14	12.22	11.74	11.77	8.88	12.62	12.16	11.82
CLIV	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
MACN	2.41	2.90	3.50	3.36	3.26	2.96	2.71	3.10	2.94	3.03
ILMN	2.37	3.39	4.37	4.66	4.76	3.51	3.54	4.27	3.43	3.32
APAT	0.20	0.81	1.65	1.36	1.00	0.72	0.66	1.00	0.88	0.88

ICELANDITES FROM CENTRAL VOLCANCES IN MW-ICELAND (FEO*=ALL FE AS FEO)

294

PERCENT	
SiO ₂	58.77
Al ₂ O ₃	13.38
Fe ₂ O ₃	6.09
FEO	7.50
MgO	1.10
CaO	5.73
Na ₂ O	3.96
K ₂ O	1.14
TiO ₂	1.39
MnO	0.42
P ₂ O ₅	0.51
FEO*	13.04

PPM	
BA	306
NB	61
ZR	497
Y	84
SR	290
RB	26
ZN	197
CU	1
NI	1

CIPW NORM	
QUTZ	13.82
ORTH	6.76
ALBT	33.56
ANCR	15.43
NEPH	0.00
DIOP	8.46
HPEK	14.23
CLIV	0.00
MAGN	3.87
ILMN	2.65
APAT	1.22

DACITES FROM CENTRAL VOLCANOES IN NW-ICELAND (FEC*=ALL FE AS FEO)

	49	56	76	95	97	188	211
PERCENT							
SiO2	66.18	65.35	65.32	63.93	63.40	63.82	66.20
Al2O3	13.09	13.36	14.12	14.90	15.13	14.32	13.71
Fe2O3	5.61	5.78	4.03	1.94	3.58	3.20	3.11
FEO	4.00	3.89	3.22	5.52	4.56	4.25	3.25
MgO	0.33	0.74	1.66	0.87	1.12	2.00	1.85
CaO	3.81	3.83	3.62	4.29	4.89	4.19	3.62
Na2O	4.23	4.09	4.16	4.76	4.32	4.45	4.44
K2O	1.56	1.59	2.08	1.90	1.55	2.07	2.29
TiO2	0.77	0.90	1.28	1.09	1.02	1.17	1.14
MnO	0.25	0.22	0.15	0.19	0.17	0.13	0.17
P2O5	0.16	0.24	0.26	0.20	0.26	0.39	0.22
FEO*	9.05	9.10	6.95	7.67	7.79	7.13	6.05

PPM							
BA	296	319	395	374	347	387	411
NB	56	67	86	80	55	66	84
ZR	941	796	626	732	497	642	675
Y	120	122	101	85	67	93	106
SR	198	195	202	209	215	175	165
RB	44	41	57	48	51	57	61
ZN	194	183	137	144	127	42	132
CU	1	3	4	18	23	24	3
NI	3	1	1	1	1	1	1

CIPW NORM							
QUtz	23.60	22.78	20.91	16.36	17.97	16.73	20.06
ORTH	9.24	9.41	12.31	11.25	9.17	12.25	13.55
ALBT	35.92	34.72	35.25	40.30	36.64	37.73	37.60
ANOR	12.18	13.46	13.78	13.66	17.34	13.00	10.76
NEPH	0.00	0.00	0.00	0.00	0.00	0.00	0.00
DIOP	5.05	3.49	2.14	5.44	4.50	4.42	4.86
HPER	9.46	11.12	10.48	8.16	9.52	10.61	8.67
CLIV	0.00	0.00	0.00	0.00	0.00	0.00	0.00
MAGN	2.69	2.71	2.06	2.28	2.31	2.12	1.80
ILMN	1.47	1.72	2.45	2.07	1.93	2.22	2.19
APAT	0.38	0.57	0.62	0.48	0.62	0.53	0.52

RHYOLITES FROM CENTRAL VOLCANOES IN MW-ICELAND (FEC*=ALL FE AS FEO)

	10	12	17	18	22	54	67	77	78	81
PERCENT										
SI02	74.83	73.13	74.63	74.00	76.60	72.77	74.34	72.54	70.46	72.63
AL2O3	14.07	14.74	14.50	14.61	14.16	12.72	13.93	13.38	14.05	13.71
FE2O3	0.63	0.71	1.39	1.06	0.63	2.69	2.19	3.23	2.00	3.28
FEO	1.06	0.82	0.47	0.74	0.48	2.11	0.15	1.07	2.34	C.84
NGO	0.04	0.00	0.07	0.00	0.75	0.70	0.00	0.25	0.23	0.10
CAO	0.96	2.05	0.86	0.99	0.57	1.60	0.89	1.42	2.60	1.39
NA2O	5.14	5.62	4.82	5.29	3.91	4.60	5.09	4.67	5.01	4.81
K2O	3.09	2.48	3.12	3.17	2.58	2.25	3.03	2.78	2.50	2.77
TIO2	0.10	0.38	0.10	0.10	0.28	0.38	0.30	0.31	0.65	C.31
MNO	0.06	0.03	0.02	0.02	0.00	0.12	0.02	0.10	0.10	0.10
P2O5	0.02	0.03	0.02	0.01	0.04	0.05	0.05	0.05	0.12	0.05
FEO*	2.63	1.46	1.72	1.70	1.95	4.53	2.12	3.98	4.14	3.80

PPM

BA	638	502	569	636	388	402	547	466	453	466
NB	60	82	64	66	143	111	106	98	101	100
ZR	239	779	249	256	834	795	724	807	868	814
Y	59	96	36	40	133	168	97	112	123	125
SR	90	198	85	90	44	130	89	116	164	112
RB	100	76	105	103	80	65	88	79	67	79
ZN	73	176	79	76	30	158	66	131	163	122
CU	2	2	1	1	1	19	4	2	9	3
NI	1	2	2	2	1	1	1	1	1	1

CIPW NORM

QUTZ	30.09	26.49	31.79	28.01	41.33	30.61	30.33	28.17	24.81	28.95
CORU	0.57	0.00	1.67	0.69	3.99	0.00	0.78	0.00	0.00	0.38
ORTH	18.29	14.67	18.47	18.76	15.26	13.29	17.94	16.49	14.77	16.42
ALBT	43.47	47.61	40.85	44.84	33.12	39.00	43.16	41.28	42.47	40.84
ANOR	4.64	7.65	4.14	4.85	2.57	7.44	4.10	6.45	8.46	6.59
DIOP	0.00	2.08	0.00	0.00	0.00	0.18	0.00	0.25	3.20	0.00
HFER	2.22	0.26	2.34	2.13	2.80	7.30	2.37	5.46	3.54	4.98
CLIV	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
MAGN	0.48	0.43	0.51	0.50	0.31	1.34	0.63	1.18	1.23	1.12
ILMN	0.19	0.72	0.19	0.19	0.53	0.72	0.57	0.59	1.24	0.59
APAT	0.05	0.07	0.05	0.02	0.09	0.12	0.12	0.12	0.29	0.12

RHYOLITES FROM CENTRAL VOLCANES IN NW-ICELAND (FEO*=ALL FE AS FEO)

	82	83	84	88	91	92	99	105	114	115
PERCENT										
SiO ₂	69.84	75.14	74.66	76.15	75.57	76.18	73.47	74.01	73.68	69.54
Al ₂ O ₃	13.43	13.32	13.53	13.69	14.37	12.13	15.63	12.92	13.44	15.34
Fe ₂ O ₃	3.28	2.47	2.73	1.42	0.64	1.79	1.36	1.22	2.06	3.79
FeO	2.50	0.03	0.06	0.04	0.01	1.27	0.01	2.13	1.33	0.58
MgO	0.62	0.05	0.14	0.00	0.00	0.00	0.00	0.00	0.00	1.12
CaO	2.41	0.89	0.70	0.67	0.49	3.05	0.69	1.26	1.04	1.92
Na ₂ O	4.49	4.95	5.05	4.83	5.49	3.02	5.38	4.78	5.27	4.36
K ₂ O	2.43	2.90	2.88	2.91	3.25	2.29	3.24	3.30	2.85	2.87
TiO ₂	0.69	0.20	0.19	0.25	0.15	0.15	0.17	0.25	0.18	0.38
MnO	0.16	0.02	0.02	0.01	0.01	0.08	0.02	0.10	0.11	0.05
P ₂ O ₅	0.15	0.03	0.03	0.03	0.02	0.03	0.03	0.03	0.03	0.05
FEO*	5.46	2.26	2.52	1.32	0.59	2.88	1.24	3.23	3.19	3.99

PPM										
RA	421	473	477	531	598	567	522	533	479	425
NB	82	57	99	125	128	121	67	117	97	117
ZR	647	691	695	711	473	379	329	659	654	766
Y	105	81	67	74	85	143	57	147	139	115
SR	149	88	86	97	83	169	78	99	84	68
RB	71	82	82	88	88	129	95	86	80	79
ZN	132	144	136	164	19	189	49	185	125	114
CU	3	2	1	1	1	1	5	1	1	3
NI	1	1	1	1	1	1	1	1	1	2

CIPW NORM										
QUtz	26.24	32.18	31.30	34.99	29.97	42.18	27.77	29.55	28.20	25.43
CRP	0.00	0.49	0.91	1.45	0.98	0.00	2.09	0.00	0.00	1.69
ORTH	14.37	17.17	17.06	17.22	19.22	13.57	19.17	19.50	16.89	17.02
ALBT	38.09	41.97	42.84	40.92	46.48	25.62	45.58	40.48	44.63	37.02
ANOR	9.33	4.23	3.28	3.13	2.30	12.76	3.23	4.06	4.60	9.23
DIOP	1.43	0.00	0.00	0.00	0.00	1.98	0.00	1.80	0.33	0.00
HPR	7.24	2.83	3.43	1.26	0.55	2.69	1.40	3.11	3.98	7.58
CLIV	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
MAGN	1.62	0.67	0.75	0.39	0.17	0.85	0.37	0.96	0.95	1.18
ILMN	1.32	0.38	0.36	0.48	0.29	0.29	0.32	0.48	0.34	0.72
APAT	0.36	0.07	0.07	0.07	0.05	0.07	0.07	0.07	0.07	0.12

RHYOLITES FROM CENTRAL VOLCANOS IN NW-ICELAND (FEO*=ALL FE AS FEO)

	191	207	248	249	256
PERCENT					
SiO2	73.45	71.94	74.18	76.47	76.25
Al2O3	13.58	13.97	13.43	13.66	13.37
Fe2O3	1.62	1.67	3.07	0.49	0.31
FFO	1.41	2.17	0.30	0.64	0.87
MGO	0.07	0.13	0.03	0.00	0.00
CAO	1.54	1.54	0.82	0.40	0.48
NA2O	5.38	5.22	5.09	4.26	4.51
K2O	2.60	2.87	2.79	3.97	4.11
TiO2	0.22	0.32	0.27	0.05	0.03
MNG	0.08	0.11	0.02	0.04	0.05
P2O5	0.05	0.05	0.00	0.01	0.02
FEO*	2.87	3.68	3.07	1.08	1.15

PPM					
RA	450	496	426	748	735
NB	64	118	89	60	75
ZR	543	832	779	112	112
Y	90	123	91	20	78
SR	137	106	100	28	26
RB	69	121	87	147	145
ZN	99	141	138	64	73
CU	9	4	1	1	1
NI	1	1	1	2	1

CIPW NORM					
QUTZ	27.77	25.40	30.48	35.00	32.60
CORU	0.00	0.00	0.54	1.64	0.67
ORTH	15.40	16.96	16.54	23.48	24.32
ALBT	45.56	44.23	43.20	36.08	38.13
ANOR	5.23	6.22	4.08	1.92	2.25
DIOP	1.86	0.98	0.00	0.00	0.00
HPER	2.79	4.38	3.75	1.43	1.58
OLIV	0.00	0.00	0.00	0.00	0.00
MAGN	0.85	1.09	0.91	0.32	0.34
ILMN	0.42	0.61	0.51	0.10	0.06
APAT	0.12	0.12	0.00	0.02	0.05

LATE QUATERNARY AND RECENT VOLCANICS (FEO*=ALL FE AS FEO)

PERCENT	120	121	122	123	257	258	259	260	261	262
SiO ₂	49.26	48.17	47.68	48.99	48.15	48.31	48.76	49.08	49.08	48.57
Al ₂ O ₃	17.87	15.81	16.25	16.81	16.72	17.93	16.33	16.90	16.82	17.17
Fe ₂ O ₃	2.61	2.17	3.79	9.72	1.92	1.92	2.08	2.25	2.19	1.70
FEO	8.06	8.21	9.46	2.36	9.43	8.48	8.64	8.30	8.59	8.81
MgO	5.35	8.37	5.29	4.72	7.80	6.92	7.40	6.80	6.76	6.83
CaO	10.65	12.10	10.61	10.67	11.68	12.08	11.56	11.62	11.42	11.56
Na ₂ O	3.09	2.49	3.06	3.35	2.35	1.95	2.33	2.57	2.62	2.89
K ₂ O	0.73	0.41	0.60	0.65	0.14	0.64	0.75	0.52	0.53	0.57
TiO ₂	1.79	1.82	2.76	2.16	1.48	1.43	1.72	1.58	1.63	1.54
MnO	0.18	0.17	0.21	0.18	0.19	0.18	0.19	0.19	0.19	0.18
P ₂ O ₅	0.41	0.28	0.29	0.39	0.14	0.18	0.23	0.20	0.18	0.18
FEO*	10.41	10.17	12.87	11.12	11.16	10.21	10.51	10.33	10.56	10.34

PPM

BA	216	165	242	186	23	199	208	148	159	155
NB	42	32	40	29	13	19	24	18	19	24
ZR	166	103	149	130	83	116	129	123	121	94
Y	30	22	30	32	22	15	18	24	22	24
SR	349	335	358	366	206	373	362	299	315	267
RB	13	7	12	11	2	18	14	9	13	12
ZN	97	84	115	100	89	79	81	79	82	84
CU	61	84	108	125	140	59	77	88	96	109
NI	71	254	71	44	224	106	172	132	162	177

CIPW NORM

QUTZ	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ORTH	4.29	2.44	3.53	3.88	0.84	3.76	4.41	3.04	3.10	3.34
ALST	26.13	21.00	25.85	28.55	19.83	16.48	19.73	21.69	22.13	24.43
ANOR	32.73	30.73	28.85	29.11	34.60	38.26	31.84	33.05	32.55	32.16
NEPH	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
DICP	14.31	22.22	18.09	17.89	18.22	16.70	19.51	18.98	18.70	19.56
HPER	8.06	4.50	4.34	5.39	11.04	13.07	9.66	9.85	9.72	0.57
CLIV	7.00	11.96	9.56	6.81	9.01	5.60	7.89	6.84	7.13	13.51
MAGN	3.10	3.03	3.84	3.31	3.33	3.04	2.13	3.08	3.15	3.08
ILMN	3.39	3.45	5.24	4.12	2.80	2.66	3.26	2.99	3.09	2.91
APAT	0.98	0.67	0.69	0.93	0.32	0.43	0.55	0.48	0.43	0.43

LATE QUATERNARY AND RECENT VOLCANICS. (FFO*=ALL FE AS FEO)

	263	264	265	266	267	268	269	270	271	272
PERCENT										
SiO ₂	48.44	48.29	48.09	47.71	48.16	47.75	47.98	47.38	49.81	46.52
Al ₂ O ₃	17.56	17.48	17.57	17.42	16.79	15.29	14.22	15.39	16.58	15.08
Fe ₂ O ₃	2.16	2.30	2.31	2.55	2.82	4.40	3.28	3.76	2.74	4.61
FEO	8.29	8.52	8.41	8.23	7.72	8.21	10.47	8.02	7.78	9.98
MgO	6.59	6.29	6.82	7.36	5.49	5.31	3.91	6.44	4.85	4.99
CaO	11.84	12.14	11.96	12.07	11.99	10.52	9.71	11.52	11.28	10.75
Na ₂ O	2.82	2.34	2.29	2.13	3.30	3.18	3.70	2.88	3.00	3.08
K ₂ O	0.51	0.70	0.67	0.66	0.61	1.26	1.23	1.03	1.10	0.89
TiO ₂	1.47	1.60	1.53	1.54	2.29	3.07	3.74	2.78	2.12	3.50
MnO	0.17	0.17	0.17	0.17	0.17	0.20	0.34	0.19	0.20	0.25
P ₂ O ₅	0.16	0.18	0.18	0.16	0.67	0.80	1.43	0.61	0.56	0.34
FEO*	10.24	10.59	10.49	10.53	10.26	12.16	13.43	11.41	10.25	14.13

PPM										
BA	146	229	211	217	236	409	458	381	410	303
NB	22	27	29	30	28	60	74	54	55	36
ZR	85	78	75	72	97	136	162	122	179	100
Y	23	17	19	18	29	26	46	27	28	24
SR	256	372	385	385	456	556	592	529	507	469
RB	12	13	16	17	13	25	26	22	24	16
ZN	78	89	86	85	75	105	147	95	91	109
CU	114	85	77	81	58	51	7	71	59	52
NI	173	99	120	113	75	122	1	148	72	30

CIPW NORM										
QUtz	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ORTH	2.98	4.12	3.94	3.88	3.58	7.47	7.23	6.09	6.50	5.27
ALBT	23.83	19.82	19.35	18.03	26.16	26.94	31.24	22.92	25.36	24.20
ANOR	33.73	35.09	35.65	36.02	29.19	23.73	18.56	26.04	28.51	24.70
NEPH	0.00	0.00	0.00	0.00	0.96	0.00	0.00	0.78	0.00	1.00
DIOP	19.55	19.58	18.37	18.58	21.25	19.20	16.85	22.21	19.59	21.93
HFER	0.83	6.26	6.37	6.08	0.00	0.05	5.52	0.00	7.91	0.00
CLIV	12.84	8.52	9.83	10.98	6.88	11.26	6.12	11.85	3.74	11.21
MAGN	3.05	3.16	3.13	3.14	3.05	3.63	4.00	3.40	3.05	4.22
ILMN	2.80	3.03	2.90	2.91	4.35	5.84	7.09	5.28	4.02	6.66
APAT	0.39	0.43	0.43	0.38	1.58	1.89	3.38	1.44	1.31	0.82

LATE QUATERNARY AND RECENT VOLCANICS. (FEC*=ALL FE AS FEC)

PERCENT	273	274	275	276	277	278	279	280	281	282
SiO2	47.14	47.22	48.24	49.53	49.25	48.19	48.70	47.96	48.09	47.87
Al2O3	15.78	15.45	15.60	16.44	18.47	16.70	17.66	17.22	16.48	17.46
Fe2O3	0.71	2.19	2.55	2.58	3.75	1.73	4.62	1.36	0.78	2.16
FeO	10.68	8.39	7.70	7.59	7.87	9.33	5.45	10.33	11.01	9.21
MgO	6.70	8.68	8.12	5.02	3.62	7.29	8.01	6.68	7.48	6.37
CaO	11.39	11.90	12.00	10.22	11.33	11.74	11.76	11.91	11.63	12.79
Na2O	3.23	2.78	2.79	3.53	3.15	2.66	2.25	2.54	2.45	2.44
K2O	0.74	0.55	0.70	1.35	0.24	0.34	0.20	0.13	0.10	0.06
TiO2	2.73	2.22	1.88	2.49	1.91	1.68	1.11	1.54	1.65	1.39
MnO	0.19	0.18	0.17	0.19	0.18	0.17	0.15	0.18	0.19	0.17
P2O5	0.71	0.45	0.25	0.65	0.23	0.16	0.09	0.14	0.12	0.09
FEO*	11.32	10.36	10.00	10.28	11.25	11.89	9.61	12.18	11.71	11.16

PPM	273	274	275	276	277	278	279	280	281	282
RA	272	226	241	492	102	108	69	63	59	39
NB	34	32	33	65	15	16	8	11	10	6
ZR	94	94	98	169	88	79	44	61	51	40
Y	26	28	24	30	30	23	20	27	22	20
SR	449	388	403	560	244	230	166	178	178	173
RR	15	13	17	32	4	7	6	2	2	1
ZN	83	83	74	99	94	92	82	97	100	89
CU	110	80	91	50	209	135	95	110	180	155
NI	164	237	239	56	35	217	295	168	192	168

CIPW NGRM	273	274	275	276	277	278	279	280	281	282
QUTZ	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ORTH	4.36	3.22	4.11	7.99	1.43	2.03	1.19	0.78	0.60	0.36
ALBT	23.62	21.09	21.65	29.88	26.67	22.48	19.12	21.46	20.70	20.60
ANOR	26.27	28.04	28.01	25.01	35.55	32.56	37.54	35.10	33.54	36.47
NFPH	1.98	1.30	1.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00
DIGP	20.77	22.63	24.21	17.65	16.02	20.01	16.51	18.83	18.98	21.61
HPFR	0.00	0.00	0.00	0.11	11.46	4.21	12.91	7.47	10.10	5.39
CLIV	12.80	15.34	13.85	10.04	1.34	11.89	7.54	9.66	9.17	9.40
MAGN	3.38	3.09	2.98	3.06	3.35	3.25	2.86	3.45	3.50	3.33
ILMN	5.16	4.22	3.56	4.73	3.63	3.18	2.11	2.92	3.13	2.63
APAT	1.67	1.08	0.60	1.53	0.55	0.38	0.22	0.34	0.29	0.22

LATE QUATERNARY AND RECENT VOLCANICS (FEO*=ALL FE AS FEO)

	285	288	293	301	306
PERCENT					
SiO2	49.80	48.00	48.93	48.98	48.16
Al2O3	16.84	16.57	18.14	16.92	18.30
Fe2O3	0.03	3.03	1.72	0.89	3.78
FEO	11.60	7.11	8.73	10.49	7.16
MGO	4.72	8.72	5.77	5.06	5.96
CAO	9.99	11.43	11.32	9.97	11.04
NA2O	3.20	2.42	2.76	3.24	2.97
K2O	0.73	0.53	0.60	0.67	0.51
TiO2	2.36	1.64	1.52	2.57	1.85
MNO	0.20	0.17	0.17	0.20	0.17
P2O5	0.52	0.36	0.34	0.51	0.10
FEO*	11.63	9.86	10.29	11.80	11.60

PERCENT

	285	288	293	301	306
SiO2	49.80	48.00	48.93	48.98	48.16
Al2O3	16.84	16.57	18.14	16.92	18.30
Fe2O3	0.03	3.03	1.72	0.89	3.78
FEO	11.60	7.11	8.73	10.49	7.16
MGO	4.72	8.72	5.77	5.06	5.96
CAO	9.99	11.43	11.32	9.97	11.04
NA2O	3.20	2.42	2.76	3.24	2.97
K2O	0.73	0.53	0.60	0.67	0.51
TiO2	2.36	1.64	1.52	2.57	1.85
MNO	0.20	0.17	0.17	0.20	0.17
P2O5	0.52	0.36	0.34	0.51	0.10
FEO*	11.63	9.86	10.29	11.80	11.60

PPM

	285	288	293	301	306
BA	208	186	159	236	161
NB	36	28	24	38	30
ZR	200	140	137	204	163
Y	32	21	22	31	22
SR	361	334	399	349	373
RB	16	12	8	8	5
ZN	43	80	82	71	87
CU	88	95	86	42	76
NI	136	252	93	34	68

CIPW NORM

	285	288	293	301	306
QUTZ	0.00	0.00	0.00	0.00	0.00
ORTH	4.30	3.16	3.52	3.97	3.04
ALBT	26.93	20.49	23.31	27.36	25.11
ANCR	29.33	36.78	35.31	29.54	35.13
NEPH	0.00	0.00	0.00	0.00	0.00
DICP	13.81	17.45	15.22	13.59	15.63
HPER	15.06	6.49	8.84	10.90	2.15
OLIV	1.41	12.72	7.05	5.10	12.04
MAGN	3.48	2.93	3.06	3.52	3.15
ILMN	4.47	3.12	2.88	4.86	3.51
APAT	1.22	0.86	0.81	1.20	0.24

KEY TO TABLE 4

LIST OF ANALYSED SPECIMENS AND SAMPLE LOCALITIES

- 1 Quartz tholeiite flow, 1 km west of Hreimstadir in Nordurardalur
 (Reykjadalur thick-layered series).
- 2 Olivine tholeiite flow, 0.5 km west of Baeli in Nordurardalur
 (Reykjadalur thick-layered series).
- 3 Quartz tholeiite flow, Bjarnafoss in Bjarnadalur (Reykjadalur thick-
 layered series).
- 4 Olivine tholeiite flow, 0.5 km west of Baeli in Nordurardalur
 (Reykjadalur thick-layered series).
- 5 Olivine tholeiite dyke (NE-SW), Hrutborg about 1.5 km northeast
 of Litla Baula.
- 6 Olivine tholeiite cone sheet, Draugagil in Litlaardalur (Reykjadalur
 central volcano).
- 7 Quartz tholeiite flow, 0.5 km west of Dalsmynni in Nordurardalur
 (Reykjadalur thick-layered series).
- 8 Icelandite flow, 1 km west of Dyrastadir in Nordurardalur (Reykjadalur
 c.v.).
- 9 Quartz tholeiite flow, 0.5 km west of Dalsmynni in Nordurardalur
 (Reykjadalur thick-layered series).
- 10 Rhyolite intrusion, Baula (Reykjadalur c.v.).
- 11 Plagioclase-phyric flow (ol. norm.), 0.5 km west of Dalsmynni in
 Nordurardalur (Reykjadalur thick-layered series).
- 12 Plagioclase-phyric rhyolite plug, Litla Baula (Reykjadalur c.v.).
- 13 Olivine cumulate flow, Skutagil in Bjarnadalur (Reykjadalur thick-
 layered series).
- 15 Plagioclase-phyric flow (Ol. norm.), 250 m northeast of Litla Baula
 (Reykjadalur thin-layered series).

- 16 Plagioclase-phyric flow (ol. norm.), 250 m northeast of Litla Baula (Reykjadalur thin-layered series).
- 17 Rhyolite intrusion, Skildingafell in Nordurardalur, (Reykjadalur c.v.).
- 18 Rhyolite intrusion, Skildingafell in Nordurardalur (Reykjadalur c.v.).
- 19 Plagioclase-phyric dyke (ol. norm., E-W), Hvassardalur.
- 20 Olivine tholeiite flow, Hvassardalur (Reykjadalur thin-layered series).
- 21 Olivine tholeiite dyke (E-W), Hvassardalur.
- 22 Rhyolite dyke, Hvassardalur (Reykjadalur c.v.).
- 23 Quartz tholeiite dyke (E-W), Hvassardalur.
- 24 Quartz tholeiite sill (bottom), Torfdalur in Nordurardalur.
- 25 Quartz tholeiite sill (centre), Torfdalur in Nordurardalur.
- 26 Quartz tholeiite sill (top), Torfdalur in Nordurardalur.
- 28 Icelandite flow, Torfdalur (Hallarmuli c.v.).
- 29 Basaltic icelandite flow, Torfdalur (Hallarmuli c.v.).
- 30 Icelandite flow, Torfdalur (Hallarmuli c.v.).
- 31 Icelandite flow, Torfdalur (Hallarmuli c.v.).
- 32 Icelandite flow, Torfdalur (Hallarmuli c.v.).
- 33 Icelandite flow, Torfdalur (Hallarmuli c.v.).
- 34 Quartz tholeiite flow, Torfdalur (Hallarmuli c.v.?).
- 35 Quartz tholeiite flow, Svartagil (Kolvidarholt series).
- 36 Icelandite flow, Svartagil (Hallarmuli c.v.).
- 37 Icelandite sill (?), Svartagil (Hallarmuli c.v.).
- 38 Plagioclase-phyric flow (qtz. norm.), Veidilaekur in Nordurardalur (Hredavatn series).
- 39 Plagioclase-phyric flow (qtz. norm.), 1 km south of Kviar in Thverarhlid (Grjothals thin-layered series).
- 40 Olivine tholeiite flow, Karlsdalur in Nordurardalur (Grjothals thick-layered series).

- 41 Quartz tholeiite flow, Holmavátn on Grjóthals (Grjóthals thick-layered series).
- 42 Olivine tholeiite flow, Hrodnyjarvátn on Grjóthals (Grjóthals thin-layered series).
- 43 Quartz tholeiite flow, Lundslaekur in Thverarhlid (Grjóthals thin-layered series).
- 44 Quartz tholeiite flow, Lundslaekur in Thverarhlid (Grjóthals thin-layered series).
- 45 Plagioclase-phyric flow (qtz. norm.), Holmavátn on Grjóthals (Grjóthals thick-layered series).
- 46 Quartz tholeiite flow, 2 km northeast of Skardshamrar in Nordurardalur (Grjóthals thick-layered series).
- 47 Olivine tholeiite flow, Selheidi on Grjóthals (Grjóthals thick-layered series).
- 48 Plagioclase-phyric flow (ol. norm.), Mjoavátn on Grjóthals (Grjóthals thin-layered series).
- 49 Dacite flow, 0.5 km northwest of Hamraendar in Stafholtstungur (Hallarmuli c.v.).
- 50 Olivine tholeiite flow, Hrodnyjarvátn on Grjóthals (Grjóthals thin-layered series).
- 51 Quartz tholeiite flow, Karlsdalur in Nordurardalur (Grjóthals thick-layered series).
- 52 Quartz tholeiite flow, Mjoavátn on Grjóthals (Grjóthals thin-layered series).
- 53 Icelandite flow, 1 km southwest of Glitstadir in Nordurardalur (Hallarmuli c.v.).
- 54 Rhyolite flow, 0.5 km south of Hamraendar in Stafholtstungur (Hallarmuli c.v.).
- 55 Basaltic icelandite flow, 0.5 km south of Hamarendar in Stafholtstungur (Hallarmuli c.v.).

- 56 Dacite flow, Hofstadir in Stafholtstungur, (Hallarmuli c.v.).
- 57 Quartz tholeiite flow, Mjoavatn on Grjothals (Grjothals thin-layered series).
- 58 Olivine tholeiite flow, 1 km west of Hamraendar in Stafholtstungur (Hredavatn series).
- 59 Icelandite flow, 0.5 km northwest of Hamraendar in Stafholtstungur (Hallarmuli c.v.).
- 60 Icelandite flow, 1 km south of Varmaland (Hallarmuli c.v.).
- 61 Icelandite flow, 0.5 km east of Varmaland (Hallarmuli c.v.).
- 62 Icelandite flow, 1 km west of Hjardarholt in Stafholtstungur (Hallarmuli c.v.).
- 63 Icelandite flow, 1 km northeast of Varmaland (Hallarmuli c.v.).
- 64 Quartz tholeiite flow, Lundslaekur in Thverarhlid (Grjothals thin-layered series).
- 65 Plagioclase-phyric flow (qtz. norm.), Selheidi on Grjothals (Grjothals thick-layered series).
- 66 Basaltic icelandite flow, Kalfagilstungur in Reykjadalur (Reykjadalur c.v.).
- 67 Rhyolite plug, Kalfagilstungur in Reykjadalur (Reykjadalur c.v.).
- 68 Plagioclase-phyric flow (qtz. norm), Kalfagilstungur in Reykjadalur (Reykjadalur c.v.).
- 69 Quartz tholeiite flow, Kalfagilstungur in Reykjadalur (Reykjadalur c.v.).
- 70 Icelandite flow, Saurstadagil in Haukadalur (Reykjadalur c.v.).
- 71 Quartz tholeiite flow, Saurstadagil in Haukadalur (Reykjadalur thin-layered series).
- 72 Plagioclase-phyric palagonite (qtz. norm.), at the mouth of Slettidalur in Haukadalur (Reykjadalur thin-layered series).
- 74 Basaltic icelandite flow, Gamalhnukar (Reykjadalur c.v.).

- 75 Pitchstone cone sheet (icelandite), on the caldera rim east of Gamalhnukar (Reykjadalur c.v.).
- 76 Dacite flow, Erpsstadir in Middalir (Reykjadalur c.v.).
- 77 Rhyolite flow, Fremragil in Geldingadalur (Reykjadalur c.v.).
- 78 Porphyritic rhyolite flow, Svarthamar on Jorvahnukur, underlying the tillite (Reykjadalur c.v.).
- 79 Olivine tholeiite pillow lava, Svarthamar on Jorvahnukur (Reykjadalur thin-layered series).
- 80 Plagioclase-phyric icelandite flow, Heimragil in Geldingadalur (Reykjadalur c.v.).
- 81 Rhyolite flow, Fremragil in Geldingadalur (Reykjadalur c.v.).
- 82 Rhyolite flow, 0.5 km east of Hamragil in Haukadalur (Reykjadalur c.v.).
- 83 Rhyolite flow, Baer in Middalir (Reykjadalur c.v.).
- 84 Rhyolite flow, Baer in Middalir (Reykjadalur c.v.).
- 85 Icelandite flow, Haukadalsa-river gorge about 1 km north of Harrastadir (Reykjadalur c.v.).
- 86 Olivine tholeiite dyke (N-S), on the south side of Haukadalsvatn.
- 87 Olivine tholeiite dyke (N-S), on the south side of Haukadalsvatn.
- 88 Rhyolite dyke, 0.5 km east of Lambahnukur (Reykjadalur c.v.).
- 89 Olivine tholeiite flow, Kambur in Geldingadalur (Reykjadalur c.v.).
- 90 Quartz tholeiite flow, Nordurfossar in Geldingadalur (Reykjadalur c.v.).
- 91 Rhyolite dyke, Tröllkonuskard in Laugardalur (Laugardalur c.v.).
- 92 Rhyolite flow, Sata in Laugardalur (Laugardalur c.v.).
- 93 Quartz tholeiite flow, Kambshaus in Geldingadalur (Reykjadalur c.v.).
- 94 Plagioclase-phyric rhyolite flow, Tröllkonuskard in Laugardalur (Laugardalur c.v.).
- 95 Plagioclase-phyric dacite plug, Lambahnukur (Reykjadalur c.v.).

- 96 Olivine tholeiite flow, Kambur in Geldingadalur, (Reykjadalur c.v.).
- 97 Dacite cone sheet, Einhamar in Laugardalur (Laugardalur c.v.).
- 98 Quartz norm, gabbro intrusion (base), Tröllkonuskard in Laugardalur (Laugardalur c.v.).
- 99 Rhyolite flow (?), Gyltugil in Laugardalur (Laugardalur c.v.).
- 100 Basaltic icelandite flow, Gloppugil in Vifilsdalur, (Reykjadalur c.v.).
- 102 Plagioclase-phyric flow (qtz. norm.), Kerlingarnef near Gamalhnukar (Reykjadalur c.v.).
- 103 Plagioclase-phyric basaltic icelandite flow, Seljafjall in Reykjadalur (Reykjadalur c.v.).
- 104 Plagioclase-phyric basaltic icelandite flow, Seljafjall in Reykjadalur (Reykjadalur c.v.).
- 105 Rhyolite dyke (pitchstone contact), Gamalhnukar (Reykjadalur c.v.).
- 106 Olivine tholeiite intrusive sill, Gamalhnukar (Reykjadalur c.v.).
- 107 Quartz tholeiite flow, Kambur in Geldingadalur (Reykjadalur c.v.).
- 108 Olivine tholeiite flow, Seljafjall in Reykjadalur (Reykjadalur c.v.).
- 109 Plagioclase-phyric flow (ol. norm.), Seljafjall in Reykjadalur (Reykjadalur c.v.).
- 110 Quartz tholeiite flow, Kerlingarnef near Gamalhnukar (Reykjadalur c.v.).
- 111 Icelandite flow, 0.5 km west of Mjoaból in Haukadalur (Reykjadalur c.v.).
- 112 Olivine tholeiite flow, Krossbrun in Haukadalur (Reykjadalur thin-layered series).
- 113 Icelandite flow, Gamalhnukar (Reykjadalur c.v.).
- 114 Rhyolite flow, near Oddsgil in Vifilsdalur (Reykjadalur c.v.).
- 115 Rhyolite cone sheet, Satudalur in Sanddalur (Reykjadalur c.v.).
- 116 Rhyolite flow/plug, Slettafell in Vifilsdalur (Reykjadalur c.v.).

- 117 Icelandite flow, Gamalhnukar (Reykjadalur c.v.).
- 118 Quartz tholeiite flow, Slettafell in Vifilsdalur (Reykjadalur thick-layered series).
- 119 Quartz tholeiite pillow lava. Gamalhnukar (Reykjadalur c.v.).
- 120 Transitional basalt flow, Tröllakirkja (Snjofjöll series).
- 121 Olivine-phyric transitional basalt flow, Tröllakirkja (Snjofjöll series).
- 122 Transitional pillow lava, Tröllakirkja (Snjofjöll series).
- 123 Transitional basalt flow, Tröllakirkja (Snjofjöll series).
- 138 Rhyolite cone sheet, Rangardalur in Vifilsdalur (Laugardalur c.v.).
- 149 Quartz tholeiite flow, 0.5 km east of Sprengibrekka in Mjoidalur (Reykjadalur thick-layered series).
- 150 Quartz tholeiite flow, 0.5 km north of Krokur in Nordurardalur (Reykjadalur thin-layered series).
- 151 Quartz tholeiite flow, 0.5 km west of the Sanddalur farm in Sanddalur (Reykjadalur thick-layered series).
- 152 Olivine tholeiite plug, Sata east of Sanddalur.
- 153 Quartz tholeiite dyke (NNE-SSW), Ljosbaksstadagil in Sanddalur.
- 154 Quartz tholeiite flow, Hvammsmuli in Nordurardalur (Reykjadalur thin-layered series).
- 155 Quartz tholeiite dyke (NNE-SSW), Krubbugil in Sanddalur.
- 157 Quartz tholeiite dyke (N-S), at the junction of Nordurardalur and Hellisdalur.
- 158 Olivine tholeiite dyke (E-W), Ormstadagil in Sanddalur.
- 159 Quartz tholeiite dyke (E-W), Ormstadagil in Sanddalur.
- 160 Plagioclase-phyric rhyolite cone sheet, at the head of Sanddalur (Reykjadalur c.v.).
- 161 Rhyolite cone sheet, Fremra Hadegisgil in Sanddalur (Reykjadalur c.v.).

- 162 Quartz tholeiite dyke (N-S), Sveinatunga in Nordurardalur.
- 163 Rhyolite cone sheet, Urdarmuli in Sanddalur (Reykjadalur c.v.).
- 164 Plagioclase-phyric quartz tholeiite dyke (E-W), Stapagil in Sanddalur.
- 165 Olivine tholeiite sill/cone sheet, Svinagil in Mjoidalur (Reykjadalur c.v.).
- 166 Olivine tholeiite flow, Hvamsmuli in Nordurardalur (Reykjadalur thin-layered series).
- 167 Plag. and px. phyric sill (ol. norm.), Grafarmuli in Sökkolfsdalur (Reykjadalur c.v.).
- 168 Basaltic icelandite flow, Beigaldagil in Austurardalur (Reykjadalur c.v.).
- 169 Rhyolite flow, Beigaldagil in Austurardalur (Reykjadalur c.v.).
- 170 Icelandite flow, Beigaldagil in Austurardalur (Reykjadalur c.v.).
- 171 Icelandite flow, Beigaldagil in Austurardalur (Reykjadalur c.v.).
- 172 Quartz tholeiite cone sheet, Beigaldagil in Austurardalur (Reykjadalur c.v.).
- 173 Icelandite flow, Ofaerugil in Austurardalur (Reykjadalur c.v.).
- 174 Rhyolite cone sheet, 0.5 km east of Sprengibrekka in Mjoidalur (Reykjadalur c.v.).
- 175 Plag. and px. phyric icelandite flow, Grafarmuli in Sökkolfsdalur (Reykjadalur thick-layered series).
- 176 Plagioclase-phyric flow (ol. norm.), Hlidartunsfjall in Sökkolfsdalur (Reykjadalur thick-layered series).
- 177 Pitchstone cone sheet (icelandite), Öxl in Sökkolfsdalur (Reykjadalur c.v.).
- 179 Rhyolite flow, Braudgil in Sudurardalur (Reykjadalur c.v.).
- 180 Rhyolite flow, Braudgil in Sudurardalur (Reykjadalur c.v.).
- 181 Basaltic icelandite flow, Raudsteinagil in Sudurardalur (Reykjadalur c.v.).

- 182 Icelandite flow, Raudsteinagil in Sudurardalur (Reykjadalur c.v.).
- 183 Quartz tholeiite dyke (NE-SW), at the head of Sudurardalur.
- 185 Quartz tholeiite flow, Gamalhnukar (Reykjadalur c.v.).
- 188 Dacite cone sheet, Hrossadalsgil in Reykjadalur (Reykjadalur c.v.).
- 190 Granophyre cone sheet, Hrossadalsgil in Reykjadalur (Reykjadalur c.v.).
- 191 Rhyolite flow, Kalfagil in Reykjadalur (Reykjadalur c.v.).
- 194 Quartz tholeiite flow, Kalfagil in Reykjadalur (Reykjadalur c.v.).
- 195 Olivine tholeiite flow, Kalfagil in Reykjadalur (Reykjadalur c.v.).
- 196 Basaltic icelandite plug, Hafur in Reykjadalur (Reykjadalur c.v.).
- 197 Quartz tholeiite flow, Kalfagil in Reykjadalur (Reykjadalur c.v.).
- 198 Basaltic icelandite sill/flow, Mogilstungur in Reykjadalur (Reykjadalur c.v.).
- 199 Plagioclase-phyric flow (qtz. norm.), 0.5 km west of Mogil in Reykjadalur (Reykjadalur c.v.).
- 201 Quartz tholeiite flow, west of Hrafnagil in Reykjadalur (Reykjadalur c.v.).
- 202 Gabbro cone sheet (ol. norm.), Mogil in Reykjadalur (Reykjadalur c.v.).
- 204 Quartz tholeiite flow, at the head of Hvanngil in Reykjadalur (Reykjadalur c.v.).
- 205 Olivine tholeiite flow, Tungugil in Reykjadalur (Reykjadalur c.v.).
- 206 Quartz tholeiite cone sheet, Bifgrösgil in Reykjadalur (Reykjadalur c.v.).
- 207 Rhyolite cone sheet, Graenuhjallagil in Reykjadalur (Reykjadalur c.v.).
- 209 Plagioclase-phyric sill (ol. norm.), Hrafnagil in Reykjadalur (Reykjadalur c.v.).
- 211 Granophyre cone sheet (dacitic), Hrossadalsgil in Reykjadalur (Reykjadalur c.v.).

- 216 Quartz tholeiite flow, Thorgautsstadagil in Hvitarsida (Sidufjall series).
- 217 Quartz tholeiite flow, Thorgautsstadagil in Hvitarsida (Sidufjall series).
- 218 Olivine tholeiite flow, Thorgautsstadagil in Hvitarsida (Thorgautsstadir series).
- 219 Quartz tholeiite flow, Thorgautsstadagil in Hvitarsida (Haafell series).
- 220 Quartz tholeiite flow, Haukagil in Hvitarsida (Haukagil series).
- 221 Plagioclase-phyric flow (qtz. norm.), Midgil in Hvitarsida (Midgil series).
- 222 Olivine tholeiite flow, Hvammsgil in Hvitarsida (Kinnargil series).
- 223 Quartz tholeiite flow, 0.5 km south of Sleggjulaekur (Sleggjulaekur series).
- 224 Quartz tholeiite flow, Hvammsgil in Hvitarsida (Kinnargil series).
- 225 Quartz tholeiite flow, Husagil (Samsstadir) in Hvitarsida (Haukagil series).
- 226 Quartz tholeiite flow, Teigsa in Hvitarsida (Haafell series).
- 227 Quartz tholeiite dyke (NW-SE), Husagil (Samsstadir) in Hvitarsida.
- 228 Quartz tholeiite flow, 1 km east of Helgavatn in Thverarhlid (Sleggjulaekur series).
- 229 Quartz tholeiite flow, Husagil (Samsstadir) in Hvitarsida (Haukagil series).
- 230 Quartz tholeiite flow, 0.5 km east of Kvia in Thverarhlid (Sleggjulaekur series).
- 231 Olivine tholeiite flow, Husagil (Samsstadir) in Hvitarsida (Haukagil series).
- 232 Quartz tholeiite flow, Kinnargil in Hvitarsida (Kinnargil series).
- 233 Quartz tholeiite flow, Sidufjall about 1 km south of Sleggjulaekur (Sidufjall series).

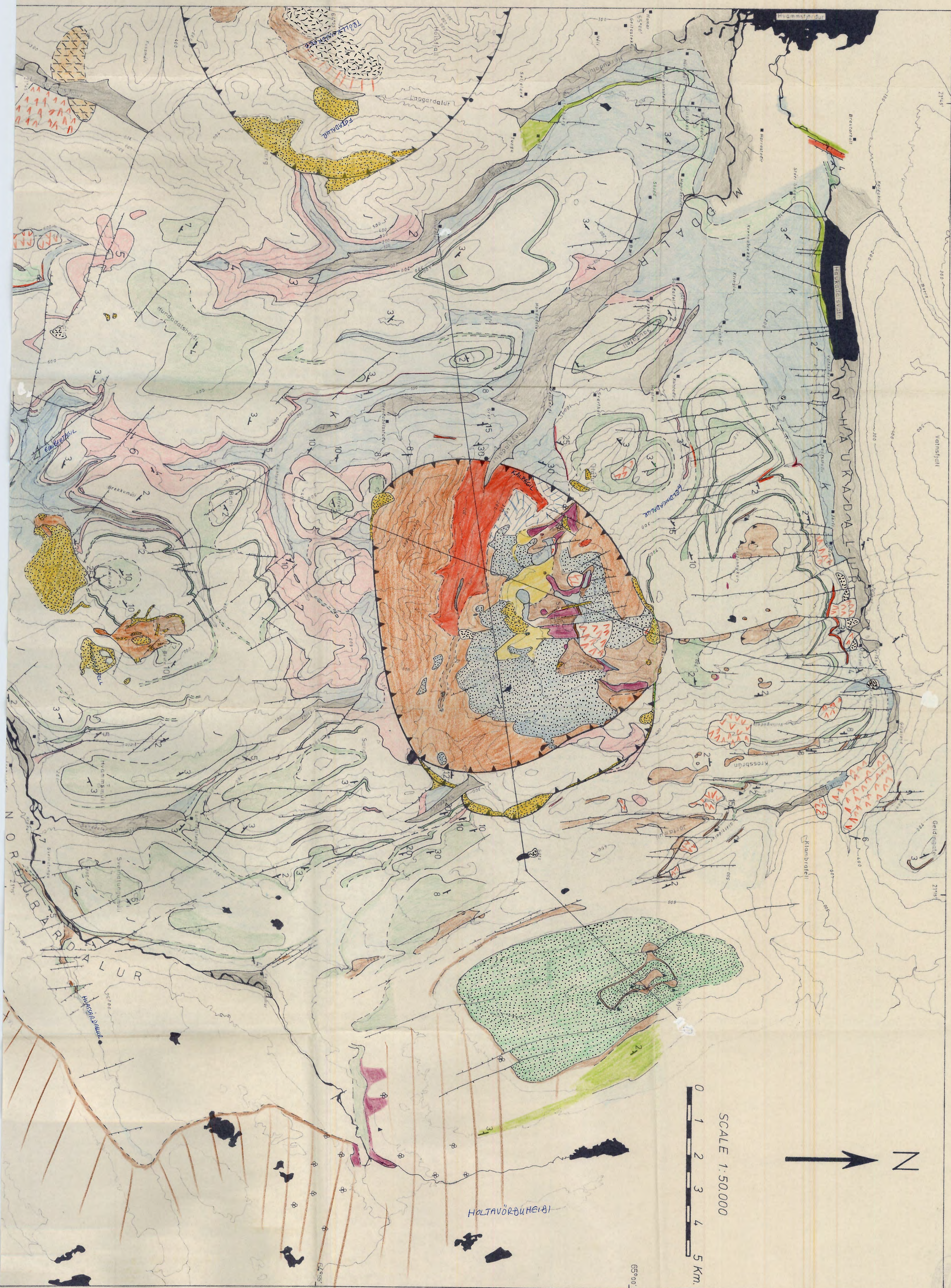
- 234 Olivine tholeiite flow, Threngslagil in Thverarhlid (Sleggjulaekur series).
- 235 Plagioclase-phyric flow (qtz. norm.), 1 km southwest of Kviar in Thverarhlid (Grjothals thin-layered series).
- 236 Plagioclase phyric flow (qtz. norm.), 1 km southwest of Kviar in Thverarhlid (Grjothals thin-layered series).
- 237 Olivine tholeiite flow, 1 km east of Helgavatn in Thverarhlid (Sleggjulaekur series).
- 238 Olivine tholeiite flow, Sidufjall about 1 km south of Sleggjulaekur (Sidufjall series).
- 240 Olivine tholeiite flow, Kleifar west of Sidufjall (Sleggjulaekur series).
- 241 Quartz tholeiite flow, Teigsa in Hvitarsida (Haafell series).
- 242 Quartz tholeiite flow, Teigsa in Hvitarsida (Haafell series).
- 243 Quartz tholeiite flow, Sidufjall about 1.5 km southeast of Sleggjulaekur (Sidufjall series).
- 244 Quartz tholeiite flow, Brekka in Nordurardalur (Hredavatn series).
- 245 Olivine tholeiite flow, Hredavatn in Nordurardalur (Hredavatn series).
- 247 Ol. and px. phyric plug (ol. norm.), Sata west of Vesturardalur.
- 248 Rhyolite flow, Satumuli southwest of Hundadalsheidi (Reykjadalur c.v.).
- 249 Rhyolite plug/intrusion, Hundadalsheidi (Reykjadalur c.v.).
- 250 Plagioclase-phyric flow (ol. norm.), Hundadalsheidi (Reykjadalur thin-layered series).
- 251 Px. and ol. phyric plug (ol. norm.), Hundadalsheidi.
- 252 Icelandite flow, south side of Vesturardalur (Reykjadalur c.v.).
- 253 Icelandite flow, Einiberjagil in Vesturardalur (Reykjadalur c.v.).
- 254 Olivine tholeiite flow, Efrifossar in Fossadalur (Reykjadalur thick-layered series).

- 255 Ol. and px. phyric plug (ol. norm.), Sata west of Vesturardalur.
- 256 Obsidian contact of a rhyolite plug (same as 249), Hundadalsheidi (Reykjadalur c.v.).
- 257 Olivine tholeiite flow (last interglacial), Stedji in Flokadalur (Reykjanes-Langjökull neovolcanic zone).
- 258 Transitional pillow lava (Late Quaternary), Vikrafell in Nordurardalur (Snaefellsnes fracture zone).
- 259 Transitional pillow lava (Late Quaternary), Baeli in Nordurardalur (Snaefellsnes fracture zone).
- 260 Transitional basalt flow (Recent), Grabrokarhraun (Snaefellsnes fracture zone).
- 261 Transitional basalt flow (Recent), Grabrokarhraun (Snaefellsnes fracture zone).
- 262 Transitional pillow lava (Late Quaternary), Stadarhnukur (Snaefellsnes fracture zone).
- 263 Transitional pillow lava (Late Quaternary), Stadarhnukur (Snaefellsnes fracture zone).
- 264 Transitional pillow lava (Late Quaternary), Vikrafell in Nordurardalur (Snaefellsnes fracture zone).
- 265 Transitional pillow lava (Late Quaternary), Vikrafell in Nordurardalur (Snaefellsnes fracture zone).
- 266 Transitional pillow lava (Late Quaternary), Vikrafell in Nordurardalur (Snaefellsnes fracture zone).
- 267 Alkali olivine basalt flow (last interglacial?), Ljosufjöll (Snaefellsnes fracture zone).
- 268 Hawaiiite pillow lava (Late Quaternary), Ljosufjöll (Snaefellsnes fracture zone).
- 269 Hawaiiite pillow lava (Late Quaternary), Ljosufjöll (Snaefellsnes fracture zone).

- 270 Hawaiiite pillow lava (Late Quaternary), Ljosufjöll (Snaefellsnes fracture zone).
- 271 Hawaiiite pillow lava (Late Quaternary), Ljosufjöll (Snaefellsnes fracture zone).
- 272 Alkali olivine basalt flow (last interglacial), Ljosufjöll (Snaefellsnes fracture zone).
- 273 Alkali olivine basalt flow (last interglacial), Alftafjörður (Snaefellsnes fracture zone).
- 274 Alkali olivine basalt flow (Recent), Stori-Langidalur (Snaefellsnes fracture zone).
- 275 Alkali olivine basalt flow (Recent), Raudukuluhraun east of Drapuhlidarfjall (Snaefellsnes fracture zone).
- 276 Hawaiiite flow (last interglacial), Ljosufjöll (Snaefellsnes fracture zone).
- 277 Olivine tholeiite flow (last interglacial), Kaldidalur southeast of Ok (Reykjanes-Langjökull neovolcanic zone).
- 278 Olivine tholeiite flow (last interglacial), Stori-As in Hvítarsíða (Reykjanes-Langjökull neovolcanic zone).
- 279 Olivine tholeiite pillow lava (Late Quaternary), a ridge southwest of Thorisjökull (Reykjanes-Langjökull neovolcanic zone).
- 280 Olivine tholeiite flow (Recent), Hallmundarhraun near Bjarnastadir (Reykjanes-Langjökull neovolcanic zone).
- 281 Olivine tholeiite flow (Recent), Hallmundarhraun near Husafell (Reykjanes-Langjökull neovolcanic zone).
- 282 Olivine tholeiite flow (Recent shield volcano), Skjaldbreidur south-east of Kvigindisfell (Reykjanes-Langjökull neovolcanic zone).
- 285 Transitional basalt flow, Snjofjallakambur (Snjofjöll series).
- 286 Olivine tholeiite sill, Bani in Austurardalur (Reykjadalur c.v.).
- 287 Basaltic icelandite flow, Burfellsa-ytri in Nordurardalur

(Reykjadalur c.v.).

- 288 Transitional basalt flow, Snjofjallakambur (Snjofjöll series).
- 289 Basaltic icelandite dyke (NW-SE), Litla Baula.
- 290 Quartz tholeiite flow, Bani in Austurardalur (Reykjadalur thin-layered series).
- 291 Quartz tholeiite flow, Bani in Austurardalur (Reykjadalur thin-layered series).
- 292 Olivine tholeiite flow, Bani in Haukadalur (Reykjadalur thin-layered series).
- 293 Transitional basalt flow, Snjofjallakambur (Snjofjöll series).
- 294 Icelandite flow, Heidarspordur at the head of Nordurardalur (Reykjadalur c.v.).
- 296 Olivine tholeiite flow, Hlidartunsfjall in Sökkolfsdalur (Reykjadalur thick-layered series).
- 298 Olivine tholeiite flow, Kambur in Geldingadalur (Reykjadalur c.v.).
- 299 Quartz tholeiite flow, Kambur in Geldingadalur (Reykjadalur c.v.).
- 301 Transitional basalt flow, Tröllakirkja (Snjofjöll series).
- 303 Basaltic icelandite pillow lava, Eurfellsa-innri in Nordurardalur (Reykjadalur c.v.).
- 304 Plag. and ol. phyric flow (ol. norm.), Eurfellsa-innri in Nordurardalur (Reykjadalur thin-layered series).
- 306 Transitional basalt flow, Snjofjallakambur (Snjofjöll series).
- 307 Plagioclase phyric flow (ol. norm.), Litla Thvera 3 km northeast of Kviar (Sleggjulaekur series).



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SCALE 1:50,000
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HOLTAVÖRÐUNEIÐ

HÁUKADALUR

LAUGARÐALUR

LAUGARÐALUR

HUNDALANDSNEÐI

BRÉKUMÚLI

SVENJUNGSVALLI

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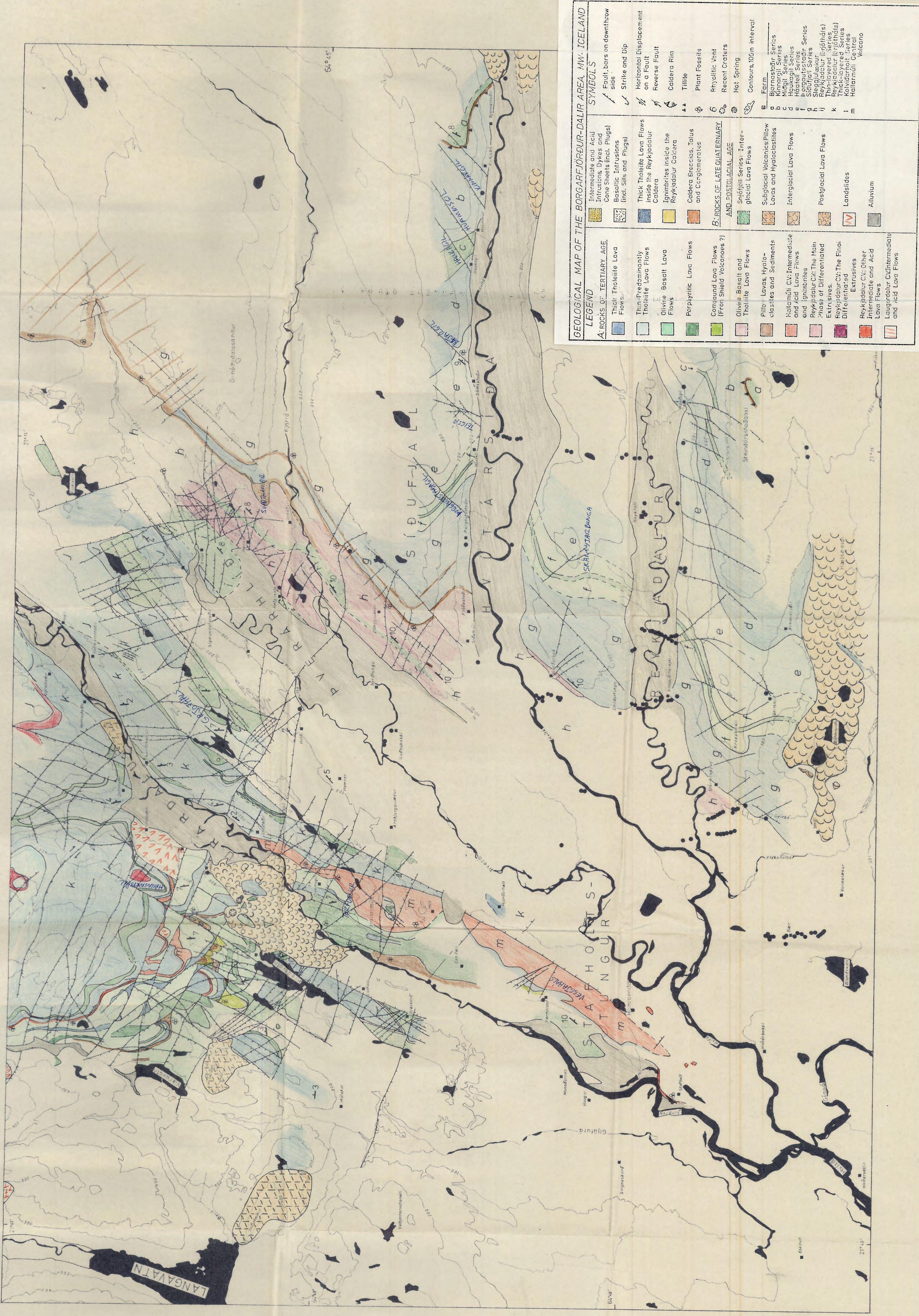
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GEOLOGICAL MAP OF THE BORGARFJÖRÐUR-DALIR AREA, NW ICELAND

LEGEND		SYMBOLS	
A. ROCKS OF TERTIARY AGE		Intermediate and Acid Intrusions, Dykes and Cone Sheets (incl. Plugs)	
Thick: Tholeiite Lava Flows	Thin: Predominantly Tholeiite Lava Flows	Basaltic Intrusions (incl. Sills and Plugs)	Thick Tholeiite Lava Flows inside the Reykjadalur Caldera
Olivine Basalt Lava Flows	Periphyritic Lava Flows	Thick Tholeiite Lava Flows inside the Reykjadalur Caldera	Ignimbrites inside the Reykjadalur Caldera
Compound Lava Flows (from Shield Volcanoes?)	Olivine Basalt and Tholeiite Lava Flows	Caldera Breccias, Tuffs and Conglomerates	Caldera Breccias, Tuffs and Conglomerates
Pillar Lavas, Hyaloclastites and Sediments	Hallamli CV: Intermediate and Acid Lava Flows and Ignimbrites	Subglacial Volcanics, Pillow Lavas and Hyaloclastites	Interglacial Lava Flows
Reykjadalur CV: The Main Phase of Differentiated Extrusives	Reykjadalur CV: The Final Differentiated Extrusives	Postglacial Lava Flows	Landslides
Reykjadalur CV: Other Intermediate and Acid Lava Flows	Laugardalur CV: Intermediate and Acid Lava Flows		Alluvium
		B. ROCKS OF LATE QUATERNARY AND POSTGLACIAL AGE	
		Snjófjall Series: Inter-glacial Lava Flows	Subglacial Volcanics, Pillow Lavas and Hyaloclastites
		Hot Spring	Contours, 100m Interval
		Recent Craters	Recent Craters
		Rhyolitic Vent	Rhyolitic Vent
		Plant Fossils	Plant Fossils
		Tillite	Tillite
		Caldera Rim	Caldera Rim
		Reverse Fault	Reverse Fault
		Horizontal Displacement on a Fault	Horizontal Displacement on a Fault
		Strike and Dip	Strike and Dip
		Fault, bars on downthrow side	Fault, bars on downthrow side