ACTA NATURALIA ISLANDICA

26

Petrology of Recent basalts of the Eastern Volcanic Zone, Iceland

SVEINN PETER JAKOBSSON

NÁTTÚRUFRAEÐISTOFNUN ÍSLANDS
ICELANDIC MUSEUM OF NATURAL HISTORY
REYKJAVÍK 1979

Dedicated
to
Prof. emer.
ARNE NOE-NYGAARD

Denne afhandling er af det naturvidenskabelige fakultetsråd ved Københavns Universitet antaget til offentligt at forsvares for den naturvidenskabelige doktorgrad i forbindelse med nedennævnte 2 arbejder:

1 S. P. JAKOBSSON. 1972. Chemistry and distribution pattern of Recent basaltic rocks in Iceland. Lithos 5, 365—386.

2 S. P. JAKOBSSON, J. JÓNSSON and F. SHIDO. 1978. Petrology of the western Reykjanes peninsula, Iceland. Journ. of Petrology 19, 669—705.

København, den 31. august 1979

Claus Nielsen
dekan

PRENTSMIÐJAN ODDI HF.

Petrology of Recent basalts of the Eastern Volcanic Zone, Iceland

SVEINN PETER JAKOBSSON
Icelandic Museum of Natural History
P. O. Box 5320
Reykjavík, Iceland

and

Geological Museum, University of Copenhagen
Østervoldgade 5-7, DK 1350
Copenhagen K., Denmark

(Received December 20, 1978; revised and accepted October 5, 1979)

Abstract. A survey of the Postglacial volcanic petrology of the Eastern Volcanic Zone is presented. Altogether 211 subaerial basalt eruption units were identified, representing a total of some 175 km^3 of extrusives. The eruption sites were found to group geographically and petrographically into nine volcanic systems. The volcanic systems are described in detail, and each is found to have developed a distinct rock suite and is therefore considered to be a closed petrologic system. Various volcanological and petrographical features of the basalts are discussed and correlations between chemistry, field morphology of eruption sites and lavas, and phenocryst mineralogy and texture are demonstrated.

Distinction is made between micro- and macrophenocrysts, and the petrographical analysis indicates that at least half of the basalt lavas have either lost or accumuated macrophenocrysts and that most of the lavas crystalized at near-cotectic conditions. It is therefore questionable if any of the extruded basalts with the possible exception of the alkali olivine basalts of the VE I-type, are primary liquids.

Three distinct rock series have been produced simutaneously: a tholeiitic series, a transitional alkalic series and an alkalic series. The series are discussed both from the point of view of nomenclature as well as regards general characteristics and geographical distribution.

Finally, the origin of the basalts is discussed. It is suggested that parental (primary) liquids to each rock series originate independently in the mantle, but that these liquids have also evolved during ascent through the crust.

TABLE OF CONTENTS

INTRODUCTION

In 1970, after the main results concerning the existence of the Recent petrological zones in Iceland had been produced (Jakobsson 1972), it appeared desirable to conduct a more detailed petrological analysis on restricted areas within these zones. One area appeared to be of special interest, the Eastern Volcanic Zone in South Iceland (Fig. 1). In this zone, a distinct petrochemical gradient had been observed, going from an alkaline area in the southwest, through a transitional alkaline area and then into a tholeiitic area in the northeast.

It was felt that a detailed analysis of this area, taking into account the accessible tectonic, volcanological and general petrological information, might reveal some interesting features as regards the igneous petrology of the basalts. Furthermore, a detailed description of this area would be of interest in connection with the studies which were being conducted on the Mid-Atlantic ridge.

Field work started in 1970, and in the beginning the intention was to acquire a representative collection of Postglacial (Holocene) lava samples on the basis of the Geological Map of Iceland, Sheet 6 (Kjartansson 1962). It soon became evident, however, that although Kjartansson's map is accurate as regards the total area of distribution of lavas, he did not distinguish between individual lavas in many areas. Therefore a number of lavas and eruption sites, which are of petrological interest, are missing on his map. It was therefore decided, in 1971, to map the southern part of the Eastern Volcanic Zone in the scale 1:50000, with respect to the Postglacial volcanism, and collect samples of all exposed extrusives. This project was later extended to cover the whole zone northwards as far as Vatnajökull. The southernmost end, the Vestmannaeyjar archipelago has been mapped and worked out in detail previously, and some of the data have been published by Jakobsson (1968, 1971) and Jakobsson et al. (1973). The field work in the Eastern Volcanic Zone (Fig. 1) was finally terminated in 1977, altogether 146 active days having been spent in the field, including field work in the Vestmannaeyjar.

The present study of the Eastern Volcanic Zone covers basaltic lavas which have formed within Postglacial Time, i.e. in the last 9—11 thousand years. In the Vestmannaeyjar area the ice cover may have disappeared some 10—11 thousand years ago, inland perhaps some 9 thousand years ago. All basaltic andesites are included, with the exception of a few of the Hekla lavas. Reference is made to some of the andesite lavas, whereas more acid rocks are not considered. Only the most easily identified basaltic tephra layers are included in the present study. This has meant the omission of many basaltic eruptions which have occurred within the last 9—10 thousand years within the volcanic zone where it is covered by Vatnajökull and especially Mýrdalsjökull. The identification and mapping of tephra layers is obviously best dealt with in special, independent projects and several investigators are actively engaged in such studies on tephra layers which originate in the Eastern Volcanic Zone.

As pointed out in a comparative study on the western Reykjanes Peninsula (Jakobsson et al. 1978), there are many advantages in carrying out a systematic petrological study on Postglacial basalts. Freshness of the rocks, combined with a wealth of information from the field which usually is hidden in older formations, such as morphological features, volume, and site of craters, make it an exciting field of study.

Previous studies

The Eastern Volcanic Zone (EVZ) has attracted many geologists since the middle of the 19th century, and a number of papers and books have been written on various aspects of the volcanology and petrology of the region. It is only possible to mention the most important works here.

On the regional-volcanological works it is appropriate to start with the writings of Thorvaldur Thoroddsen. He travelled through the EVZ and surroundings on horseback in 1889 and 1893. His very thorough travel diaries were published in Ferdabók (Thoroddsen 1913—1915). In additon, Thoroddsen (1905—1906) delineated for the first time the zones of volcanic activity in Iceland and described all the major volcanoes and all the historic volcanic eruptions known to him (Thoroddsen 1925).

Sapper (1908) gave detailed volcanological descriptions with coloured maps of the Laki fissure of 1783—1784 and surroundings and the Eldgjá area. He also investigated the Krakatindur area near Hekla and Bunuhólar in Sída.

The first fairly up to date petrological account on the EVZ is the work of Bäckström (1892) on the Postglacial acidic lavas of the Torfajökull region and on Pleistocene acid rocks from Raudfossafjöll and Sudurnámar.

Peacock (1925) gave a short description of the petrography of the Dómadalur lava and recognized the presence of an "Inter-and Postglacial series of mildly alkalic character", which he later (1931) defined as "alkali-calcic" with reference to rocks from Snaefellsnes and the Torfajökull region.

Thorarinsson (1944, 1954) carried on the volcanological research, mainly studying acid tephra layers from Hekla which form the base of his tephrochronology. By this method, many of the lavas in the EVZ have been dated fairly accurately. The eruption of the volcano Hekla in 1947—1948 and its products, both acid and andesitic rocks, were studied in detail, mainly by Thorarinsson, Kjartansson and Einarsson and were published in the series "The Eruption of Hekla 1947—1948" (Societas Scientia Islandica).

Noe-Nygaard (1951, 1952a & 1952b) gave a detailed description of the petrology of the tephra of the Grímsvötn 1934 eruption and the nunataks southwest of Grímsvötn. Robson (1957) wrote a dissertation on Eldgjá and the volcanic geology of the area east of Mýrdalsjökull. His detailed map of Eldgjá and surroundings has been adopted in Plate IV with minor corrections, whereas his maps of the main lava field south of Eldgjá have been completely revised.

An important contribution to the geological knowledge of the EVZ and adjacent regions has been the Geological Map of Iceland by Kjartansson (Sheet 6, 1962 and Sheet 5, 1964), which has been an indispensable base for this study.

Steinthórsson (1964) describes the petrography of ankaramite sills in Hvammsmúli, Eyjafjöll. Ankaramitic rocks, which are the most basic rocks found within the EVZ, have only been discovered in the Eyjafjöll and Katla volcanic systems.

A number of papers have been written on Surtsey which formed during 1963—1967 in the southern part of the Vestmannaeyjar archipelago. The course of the eruption and morphology has been described by Thorarinsson et al. (1964), Thorarinsson (1968) and Kjartansson (1966) and the petrography and the chemistry of the extruded alkali olivine basalt and xenoliths by Steinthórsson (1966, 1967) and Sigurdsson (1968). A survey of the geology and petrography of the Vestmannaeyjar (Jakobsson 1968) showed that this archipelago is made up of alkalic rocks with alkali olivine basalts dominating.

A valuable contribution to the volcanology of the EVZ are the writings of Sigurdur Thorarinsson on the eruptions of Hekla, Katla and Grímsvötn in historical times (Thorarinsson 1967a, 1974, 1975). A detailed knowledge of the eruption history of these three prominent volcanoes is of great importance for any petrological research in the area. Thorarinsson's (1967a) map of the andesitic lavas from Hekla has been adopted here, with only minor corrections. Thorarinsson (1969) has also given a detailed description of the 1783—1784 Lakagígar eruption.

The renewed activity of Hekla in 1970 resulted in several publications (Thorarinsson & Sigvaldason 1972a, Baldridge et al. 1973 and Sigvaldason 1974a). Besides descriptions of the

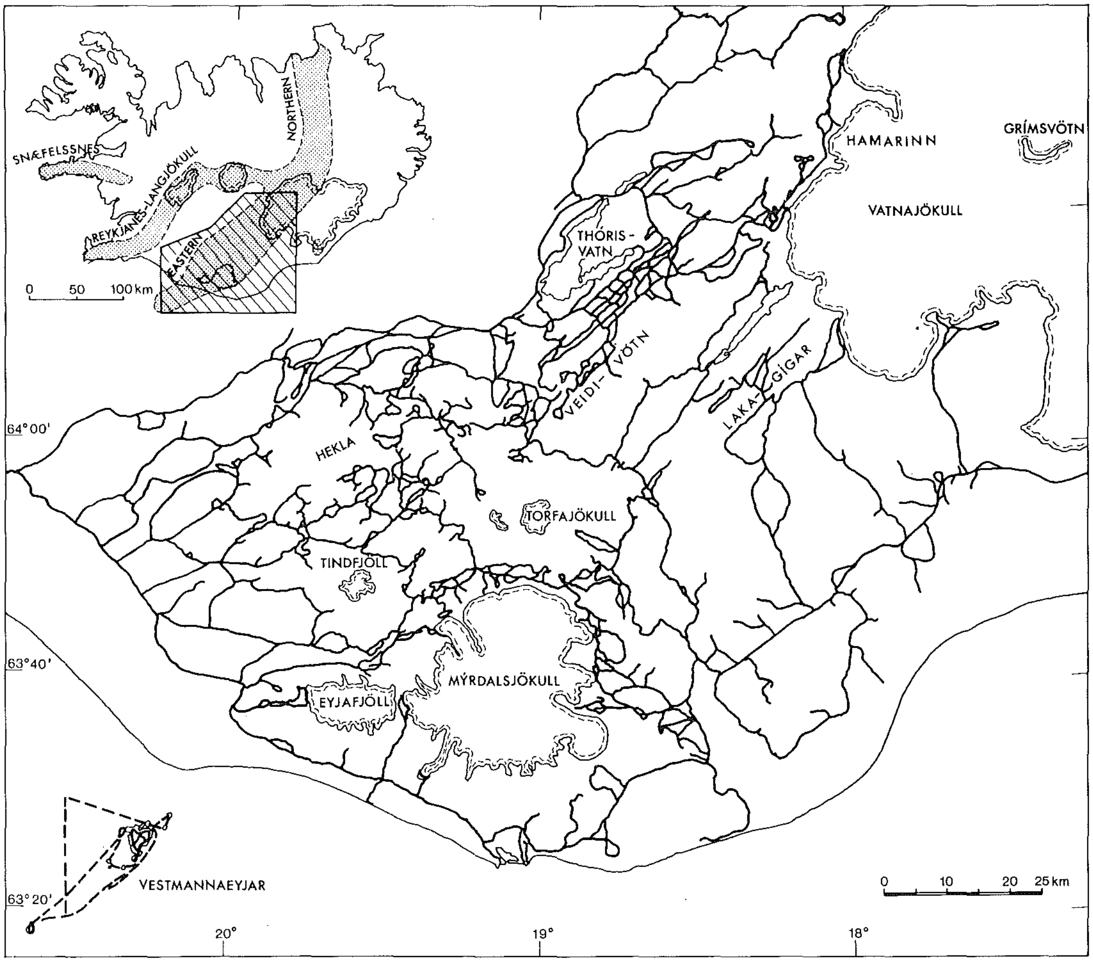


Fig. 1. Surface travel routes during the exploration of the Eastern Volcanic Zone 1966—1967 and 1970—1977. On the inset map the extent of the active volcanic zones of Iceland is indicated, cf. Fig. 25.

eruption, detailed chemical analyses were presented of the erupted basaltic andesite and inclusions of acid material in the tephra.

Sigurdsson (1970) described in brief the petrology of acid rocks from Eyjafjallajökull (Eyjafjöll), Torfajökull and Mýrdalsjökull, which he tentatively defined as alkalic centres, along with Tindfjallajökull. He identified and described peralkaline rocks in the Torfajökull area and on Snaefellsnes, the first recorded case of such rocks in Iceland. Grönvold (1972) discussed the chemistry of the Postglacial basaltic andesite and acid lavas of the Torfajökull area and compared it to Hekla and tholeiitic central volcanoes. Saemundsson (1972) described the geology of the Torfajökull area. He demonstrated that the recent volcanic activity of that area is in direct southwestward continuation of the Veidivötn fissure swarm and that basalts in the southern end of the swarm apparently erupted simultaneously with andesite, dacite and rhyolite lavas in the Torfajökull area.

In 1973 there was once again volcanic activity in the Vestmannaeyjar system, this time hawaiite was erupted on Heimaey (Thorarinsson et al. 1973, Jakobsson et al. 1973). An outline of the eruption history and the petrology of the extrusives of the first two weeks, including comparisons with the surrounding islands, was given.

The extensive geological work of the National Energy Authority in connection with the evaluation and construction of hydroelectrical and thermoelectrical power stations has resulted in a great number of reports and articles. The work of Vilmundardóttir (1977) is a thorough study of the 11 Tungná lavas (from the Veidivötn volcanic system), based on information from 202 drillholes and other field work. Jónsson (1979) presented a thorough description of five lava flows in V.-Skaftafellssýsla.

Jørgensen (1976) has completed a detailed geological-petrological study on the Thórsmörk area, with emphasis on a hybrid ignimbrite layer from Tindfjallajökull.

Regional setting

The Eastern Volcanic Zone (EVZ) is that branch of the Pleistocene-Holocene active volcanic zone which lies in southern Iceland (Fig. 1 and Fig. 24). The northeastern end of the EVZ is ice-covered and may unite with the active volcanic zone north of Vatnajökull. However, there are no indications of Postglacial volcanic activity in the Bárdarbunga area, and there may thus be a natural boundary between the EVZ and the Northern Zone. In the southwest the EVZ terminates in Surtsey and small seamounts south and west of Surtsey. The EVZ is thus about 215 km in length and its maximum width is about 72 km.

Morphologically the EVZ can be divided into two main parts: The Vestmannaeyjar archipelago, where volcanism has occurred on a shallow shelf and where some eighteen islands have been built up, and the southern highland of Iceland where the Postglacial volcanism is confined to areas above 300 m.a.s.l. (Fig. 24). In the Eyjafjallajökull, Hekla and Grímsvötn central volcanoes eruptions have occurred up to a height of 1400—1600 m.a.s.l.

Relatively large areas of the EVZ, or some 20 per cent, are ice covered, the two largest ice caps being Vatnajökull and Mýrdalsjökull. The southern highland is more or less bound by old sea cliffs to the southwest and southeast, below which spread the coastal lowlands. Most of these lowlands are sandur (outwash) plains, formed during Postglacial Time.

When the topography of the area of the EVZ is compared with the map of the volcanic systems (Fig. 24), it is evident that what has been defined as the centre of activity (i.e. area of intermediate and acid rocks) in each system coincides with a topographical high in each particular area, the only exception being the Veidivötn system.

There has been some confusion in the recent literature as regards the nomenclature of the various branches of the active volcanic zones in Iceland. The name "active volcanic zone(s)" to cover the areas where volcanic activity has occurred during Postglacial Time is favoured instead of the often used term "neovolcanic zone" as the latter term carries the dubious implication that comparable volcanic zones from earlier times have been identified elsewhere. What is here called the Eastern Volcanic Zone has had many names, as a quick survey of the literature since 1960 will demonstrate: "Middle South area", "eastern branch", "southern part", "eastern zone", and "south eastern zone"". It seems logical to define the tholeiitic zones with the prominent rifting and faulting tectonics as an axial rift zone (Saemundsson 1978), since it can be aligned with the crest of the Mid-Atlantic Ridge both south and north of Iceland. This axial zone is labelled "Reykjanes-Langjökull Zone" in southwest and central Iceland and "Northern Zone" north of Vatnajökull (Fig. 1, Plate I). The flank zones (Jakobsson 1972) or lateral zones of Saemundsson (1978), are then logically termed as the Snaefellsnes (Western) zone, and the Eastern Zone.

Mapping and collection of field data

As a topographical basis for the mapping of the Eastern Volcanic Zone both the map sheets of the US Army Map Service, (at a scale of 1:50000), and air photographs, (mainly at a scale of 1:36000), from the Icelandic Geodetic Survey, Reykjavík were used. Stereo-pairs of the air photographs were used for pre-fieldwork studies and again for mapping purposes following field-work and sample collection. The more complicated areas required repetition of this proceedure.

The extrusives were divided into eruption units. Each unit is the product of one eruptional event, i.e. what can be judged to be one independent volcanic eruption. Most of the eruptions are assumed to have occurred within a well-defined, relatively short time interval, like most witnessed volcanic eruptions. In such cases one or a few lava flows or tephra layers have formed. Some eruption events may occur at widely separated sites, possibly within a longer time interval. The Surtsey eruptional unit (Table 1), for example, was produced from five eruption fissures during Nov. 1963 — June 1967.

The eruption sites and the lavas were classified according to morphology, and the degree of weathering and erosion of the lava surface was noted. The rock was examined macroscopically and nodules and xenoliths searched for. Samples were collected of all the identified eruption units, and a few of the subglacial tephra layers were also sampled, on the average two samples from each unit. The average weight of each lava sample was about 1.3 kg. When possible samples were collected from below the surface layer (uppermost 20 cm), and not farther down than about 1 m below surface. It became clear after the first field season, that the most favourable level for collection of samples is at about 0.2—0.4 m below the lava surface. Deuteric oxidation is usually minimal at this depth, and the rock is usually fine grained to aphanitic and does not therefore conceal phenocryst phases, which is an important study object. Where the cooling rate is of importance, as in the consideration of textures, only samples from this depth are discussed.

Petrographic analyses

All the identified lavas of the Eastern Volcanic Zone were examined in thin section before selection for chemical analyses. Those samples chosen for chemical analyses were then further examined, in particular as regards texture and mineralogy, as well as size, habit and amount of phenocrysts. This was comparable with the study of the western Reykjanes Peninsula lavas (Jakobsson et al. 1978). Such petrographic criteria, besides chemical analyses of the rocks and phenocrysts, are of importance in any petrogenetic model and also with respect to the comparison of the EVZ basalts with older basaltic rocks of Iceland and with basaltic rocks of other volcanic areas. The work of reference as regards the petrography of the basic extrusives is that of Johannsen (1939), except where otherwise stated.

Volumes of phenocrysts were determined with a Swift Point Counter. For the less porphyritic lavas an average of 2100 points in one thin section were counted while for the more porphyritic ones two thin sections were occasionally used. The volume determinations are rather inaccurate for irregularly distributed phenocrysts of low average diameter (< 0.5 mm), and the accuracy can fall as low as $\pm$ 40 per cent when such phenocrysts amount to less than about 2—3 per cent of the volume. This applies especially to plagioclase which seems to have a more irregular distribution than the other phenocryst phases.

Crystal sizes were measured by estimating the diameter of circle with approximately the same area as the section of the crystal. Crystals formed by synneusis (Vance 1969) were taken as one individual, whereas the different individuals of a glomerophyrric cluster were measured separately.

Chemical analyses

Samples chosen for chemical analysis were first crushed in a jaw-crusher to 1/2 cm-pieces, out of which some 15—40 g were hand-picked. This fraction was then crushed in a wolfram carbide mortar to the 100 mesh fraction. Samples with large phenocrysts ($\sim$3—4 mm) were cut into slices 1/2 cm thick, then gently crushed with a rubber hammer to prevent crumbling of phenocrysts, before they were put into the mortar. Before preparation of the samples for analysis, they were dried in an oven at 105°C for 10 minutes, in order to get rid of hygroscopical water.

The major element chemical analyses were made using the X-ray fluorescence facilities at the Chemical Laboratory of the Geological Survey of Greenland, under the direction of Ib Sørensen. The method used is described in Bailey & Sørensen (1976). Analyses nos. 6, 10 and 11, Table 1, were analysed by the present author at the same laboratory, using a rapid silicate method, described by Borgen (1967). Analyses nos. 3—5 and 13—15, Table 1, were analysed by the U. S. Geological Survey Analytical Laboratory (L. Shapiro) using a single solution procedure.

DESCRIPTION OF THE VOLCANIC SYSTEMS

The EVZ divides into nine well demarcated Postglacial volcanic systems. For definition of a volcanic system (Smith & Shaw 1975), see p. 52. Six of these systems have the characteristics of volcanic eruptive fissure swarms and are comparable to those described from the Northern Zone (Saemundsson 1974) and the Reykjanes-Langjökull Zone (Jakobsson et al. 1978), and which have been compared to the Tertiary dyke swarms in eastern Iceland (Walker 1963). These are the Veidivötn, Grímsvötn, Katla, Hekla, Vatnafjöll and Vestmannaeyjar volcanic systems. Three of the systems would be defined by most geologists as central volcanoes (or "major volcanic centres") comparable to those described from eastern Iceland (Walker 1963). They are the Eyjafjöll, Tindfjöll and Torfajökull complexes. As will be discussed later, it seems probable that the three last-named complexes actually represent eruptive fissure swarms at a mature stage.

Each volcanic system has its own characteristic petrography, rock chemistry and structural development. Each unit will therefore be described separately in the following sections, beginning with the alkalic Vestmannaeyjar system in the southwest and ending with the tholeiitic systems in the northeast (cf. Fig. 24). Only a short account is given of the Torfajökull, Eyjafjöll and Tindfjöll volcanic systems as they have produced only a negligible amount of basalts in Postglacial Time, and are currently under investigation. Following the local descriptions, some general features of the volcanology, petrography and chemistry of the EVZ will be discussed.

The Vestmannaeyjar volcanic system

Geology. The Vestmannaeyjar (Westman Islands) archipelago forms the southernmost part of the Eastern Volcanic Zone (Figs. 1 and 24). These alkalic volcanic islands, along with a few submarine eruption sites on the surrounding sea floor, constitute the Vestmannaeyjar volcanic system. The system is, geographically as well as petrologically speaking, clearly separated from the rest of the EVZ. It is situated on a shallow shelf (depths from around 50 to 140 m), gently dipping to the southwest.

Vestmannaeyjar are made up of about eighteen islands along with a number of skerries, the largest islands being Heimaey (13.4 km^2) and Surtsey (2.5 km^2). A summary of the general geology of Vestmannaeyjar has been given by Jakobsson (1968, 1971) and Jakobsson et al. (1973), and the reader is referred to these papers for geological maps of the whole area.

The oldest rocks are exposed on the northernmost part of Heimaey, which has been called the Nordurklettar formation (Fig. 2). These are tuffs and tuff breccias with cappings of lavas, and are probably from the final stages of the last glaciation. Recently a 1565 m deep hole was drilled on Heimaey (Tómasson 1967a). Basalts and tuffs were found down to about 180 m below sea level, followed by marine tuffaceous sediments down to about 740 m depth, and then followed by altered basalt lavas to the bottom. It is believed that the rocks in the uppermost 180 m are of Upper Pleistocene age and belong to the Vestmannaeyjar volcanic system, which means that the present alkalic volcanic activity is of very recent age in the Heimaey area. Chemical analyses of basalts from cores taken below 740 m depth show that they are transitional alkali basalts, similar in composition to the basalts which at present are

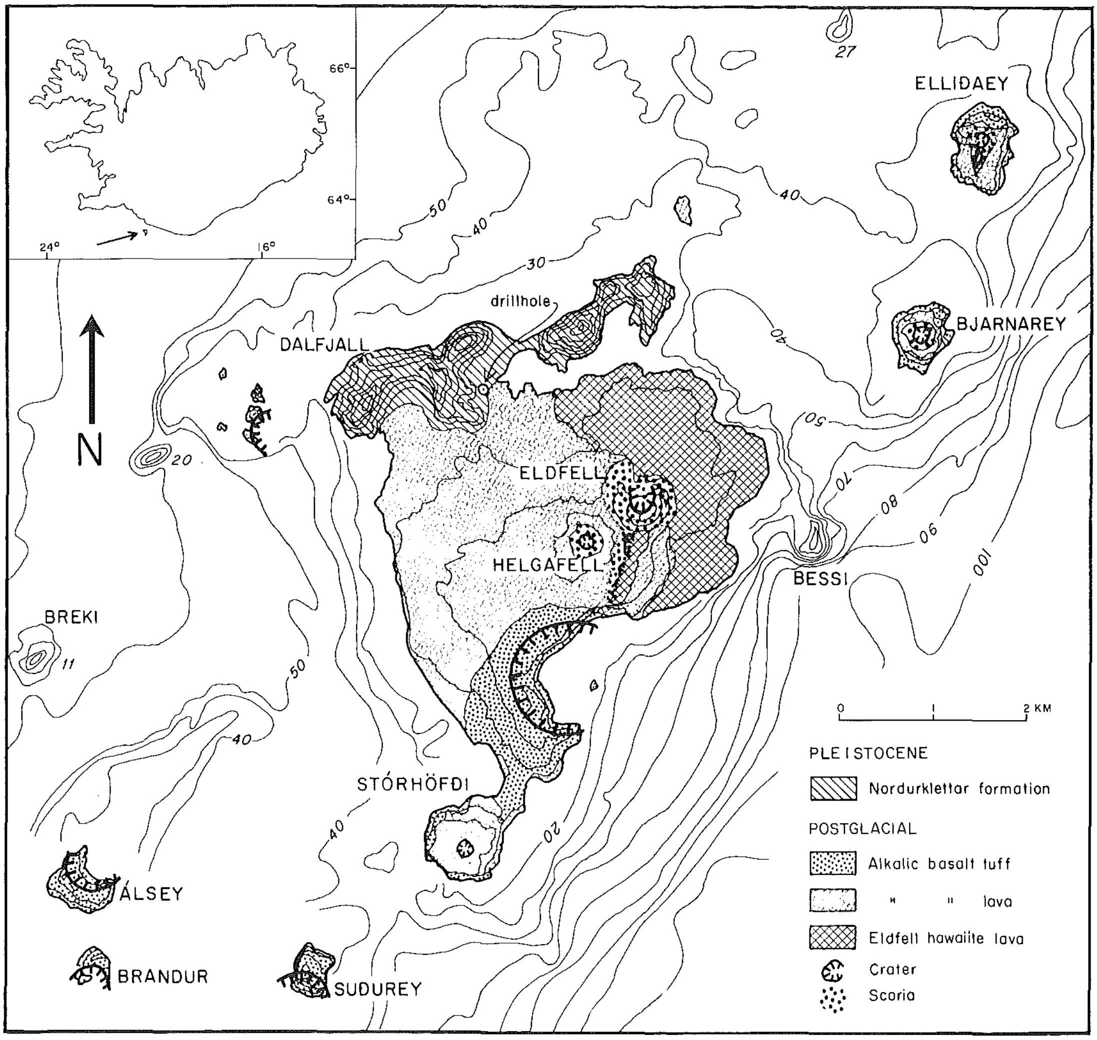


Fig. 2. Simplified geological map of Heimaey, the largest island in Vestmannaeyjar, and nearby islands. Contour interval 10 metres on sea bottom and 40 metres on land.

being formed in the Hekla volcanic system (Jakobsson, in prep.).

Volcanism during Postglacial Time has been of low intensity. Seventeen independent eruption units have been located above sealevel, three of which are on Heimaey. Two volcanic eruptions are known with certainty from historic time (i.e. after 900 A. D.). These are the Surtsey eruptions of 1963—1967, which produced alkali olivine basalts (Thorarinsson et al. 1964, Steinthórsson 1966), and the Eldfell 1973 eruption on Heimaey which produced hawaiite, approaching mugearite in the beginning of the eruption, (Thorarinsson et al. 1973, Jakobsson et al. 1973). A small submarine eruption may have occurred south or southeast of Hellisey in 1896 (Thorarinsson 1965). Dredge hauls recently collected in the area, revealed that at least four of the submarine hills on the shelf (Skötuhryggur, unnamed hill southeast of Surtsey, Rófubodi and Nýjahraun) are probably Postglacial eruption sites. Thus altogether 22 Postglacial eruption sites are known in the Vestmannaeyjar system (Jakobsson, in prep.), and there may be several sites in addition on the sea floor. The outline of the system cannot therefore be delineated exactly, but is about 38 km long and 29 km across (Fig. 24).

The geological map of the Vestmannaeyjar area (Jakobsson 1971, Plate 1) shows that there is a main belt of volcanism with the trend 040° and which includes both Surtsey and Heimaey. Another less active belt runs towards the northwest (326°) from the Súlnasker-Hellisey area. The main volcanic activity has been in the Heimaey area (Fig. 2), which accordingly forms a topographical high in the system. Moreover, the only two occurrences of intermediate rocks in the area (no acid rocks are found) are in Heimaey. This suggests that Heimaey is evolving into a central volcano. No sign of hydrothemal activity has been discovered on the surface of this system. This along with the fact that the geothermal gradient in the 1565 m deep drill-hole was only measured to be 60°C/km, may indicate that high-level magma chambers do not exist.

There are strong indications that the volcanism in the Vestmannaeyjar area has been episodic. The late glacial tuffs and lavas on northern Heimaey have evidently been deposited within a short time interval. Tephrocronological research (Jakobsson, in prep.) indicates that Álsey may have an age of about 8000 years, and Brandur, Sudurey and Hellisey may be of similar age. A major volcanic episode occurred between 5000—6000 y.b.p. with the formation of Stórhöfdi, Bjarnarey, Ellidaey and Saefell-Helgafell. The most recent episode is currently going on and may have started with the reported submarine eruption in 1896, to be followed with the Surtsey eruptions of 1963—1967 and the Eldfell eruption of 1973.

Lavas and lava eruption sites fall into two groups by morphology, which is in accordance with the petrological division of the alkali olivine basalts into two groups, the primitive VE I group and the more evolved VE II group. The VE I lavas have been very fluid and often form thin (1/2—1 m) flows and tend to build up lava shields (Icel. dyngja), although the eruptions have probably in all cases started as fissure eruptions. These eruption sites, to which the western lava crater of Surtsey, Stórhöfdi and Brandur (?) belong, produce only little scoria. The VE II craters develop cinder cones, as in Bjarnarey and Helgafell, or cinder cone rows, as in Ellidaey. The VE II lavas tend to be thicker than the VE I lavas. By surface morphology both the VE I and VE II lavas can be classified as rough pahoehoe (helluhraun) lavas. The only Postglacial andesitic eruption, the Eldfell eruption, produced a rough aa lava (apalhraun), in places up to 110 m thick. The twofold division of the basalt volcanism in Vestmannaeyjar is in many respects comparable with the division into lava shields and fissure lavas in the tholeiitic western Reykjanes Peninsula (Jakobsson et al. 1978).

The volume of Postglacial extrusives has been calculated, although this is often difficult because of heavy erosion by wave action. The original shape and extent of the various islands has been estimated with reference to Surtsey. The volume of individual basaltic eruption sites and their extrusives varies between about 0.01 km^3 and 1.2 km^3, the average value being 0.17 km^3. The total volume of the alkali olivine basalts of Postglacial age is $\geq$ 3.2 km^3, but the addition of possible as yet unidentified submarine eruption sites may increase this figure slightly. The volume of intermediate products is 0.25 km^3 (one eruption). Fig. 28 shows the total measured volume of extruded material in the system as a function of the FeO*/MgO ratio of the extrusives.

Petrography. Samples were obtained from 19 of the 22 known basaltic eruption sites in the system. The Vestmannaeyjar alkali olivine basalts fall into two groups, called VE I and VE II, respectively (Jakobsson 1968). The composition of both groups varies within narrow limits (Table 1).

The *VE I basalts* are phanerocrystalline to microcrystalline and always prophyritic. The colour of fresh specimens is generally medium gray to medium dark-gray (cf. Rock-color chart, Goddard et al. 1948). The groundmass texture is predominantly intergranular near the surface, while in several cases a gradation towards ophitic texture in the centre of lavas was observed. Futher discussion on textures and

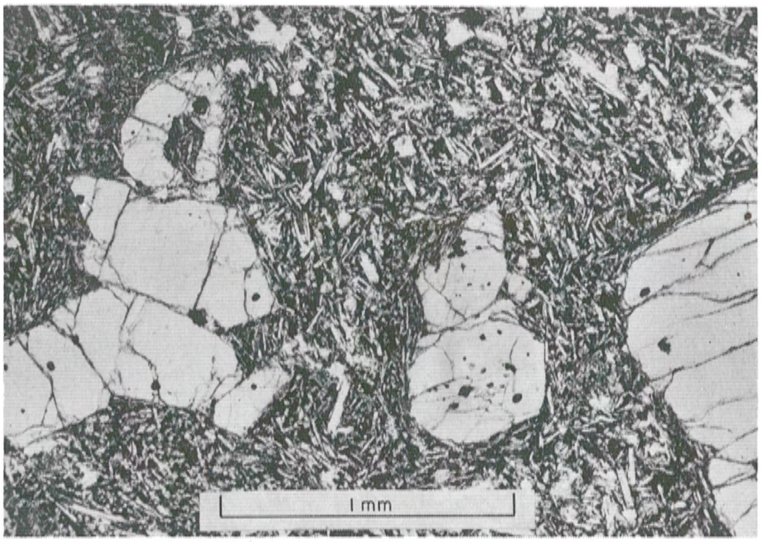


Fig. 3A. Alkali olivine basalt, the SU18-Surtsey lava (N1333). Macrophenocrysts of olivine (Fo84) with inclusions of picotite. Intergranular texture.

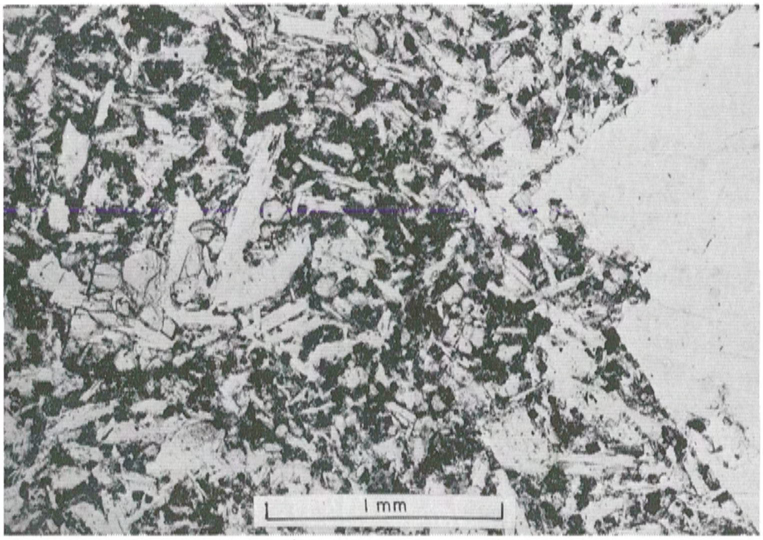


Fig. 3B. Alkali olivine basalt, the VE67-Helgafell lava (MM67). Macrophenocryst of plagioclase (An 65) and microphenocrysts of olivine and plagioclase. Intergranular texture.

their relation to rock chemistry is given in a later section.

The groundmass mineralogy has several of the characteristics of alkaline basalts. The feldspar is labradorite, the only pyroxene found is titaniferous augite, which in coarse grained parts of lavas is occasionally zoned to aegerine-augite. Olivine is common (3—7 vol. per cent). Titanomagnetite forms up to 12 per cent of the lavas. Apatite is found in minor amounts.

As discussed in detail on p. 63 to 70, it is of importance to distinguish between macro- and microphenocrysts in the EVZ basalts.

Chromium spinel (picotite) is common as tiny inclusions in olivine macrophenocrysts, it is also observed separately in the groundmass in quenched parts of lavas. It does not exceed 0.7 per cent of the volume of these lavas. Euhedral and sometimes slightly resorbed olivine macrophenocrysts up to 3 mm in size are found in all the VE I lavas and constitute 12—17 per cent of the volume. Their composition lies between Fo 81—86 and they show a slight normal zoning. These olivine phenocrysts are probably in equilibrium with the VE I magma. Plagioclase macrophenocrysts do not exceed 2 per cent of volume of the VE I lavas and form two populations. First are rare embayed crystals up to 6 cm across (commonly 3—5 cm^3) and of a composition of either An 63—66 or An 50—52. Second are euhedral zoned crystals up to 1.5 cm across, also with a composition of An 64—67. No pyroxene phenocrysts were found.

In the VE I lavas the amount of microphenocrysts does not exceed 2.2 per cent of the volume, and appears to consist only of plagioclase, which is labradorite by composition. As an example of a VE I lava, a microphotograph of the Surtsey lava of 1966 is presented in Fig. 3A.

The alkali olivine basalts of VE I-type exhibit their rather primitive character with the presence of euhedral unzoned picotite phenocrysts and the abundance of olivine phenocrysts of Fo 81—86. This, and in addition their high MgO content (9.1—10.1 per cent wt.), make the VE I-type a good candidate as parent for the VE II alkali olivine basalts and the hawaiites of the Vestmannaeyjar system.

The alkali olivine basalts of the *VE II-type* have the same mineralogy as the VE I basalts, with the following exceptions: The groundmass feldspar is labradorite-andesine. Occasionally tiny nepheline crystals may be found in residual pockets along with apatite, aegerine-augite and glass. Olivine macrophenocrysts only occur sporadically. The amount of plagioclase macrophenocrysts (both groups) varies from 0 to 12 volume per cent. An important petrogenetical point is that the VE II-lavas contain minor amounts of olivine and plagioclase macrophenocrysts of the same composition as in the VE I-lavas, although there is a clear difference in chemistry of these two groups. This strongly suggests that the VE II-lavas are derivative. Both plagioclase and olivine are also found as microphenocrysts. When found together in glomerophyric clusters, olivine is always found to start crystallizing first (Table 12). This is in agreement with melting experiments by Tilley et al. (1967) on a Surtsey lava from 1964. A microphotograph of the VE-67-Helgafell lava is presented in Fig. 3B, as an example of a VE II-type lava. A description on the first extruded hawaiite lava of Eldfell in 1973 has been given by Jakobsson et al. (1973).

Basanitic segregation veins and pockets occur, mainly in intrusives of the late glacial tuffs, but also in lavas. A variety of minerals occur in these veins, besides those found in the lavas: alkali feldspar, nepheline, analcime, aegerine, aenigmatite and amphiboles.

Gabbroic nodules have been found in the SU42-Surtsey lava, the VE67-Helgafell lava and the VE111-Eldfell mugearitic hawaiite. The nodules in the first two lavas exhibit what usually is described as cumulate textures. The gabbroic nodules in the VE111-Eldfell lava are xenolithic and have been described by Jakobsson et al. (1973). No ultramafic nodules were discovered. For a brief general discussion on gabbroic nodules in the EVZ, see p. 72.

A number of acid xenoliths (cf. p. 75) have been found on Surtsey (Sigurdsson 1968), and also in the VE30-Thrídrangar tuff and the VE-111-Eldfell hawaiite on Heimaey. The acid xenoliths are in various stages of fusion. The least affected granitic xenoliths appear to belong to the tholeiitic line of descent according to the analyses of Sigurdsson (1968), and must therefore be accidental fragments from intrusives. The acid xenoliths from Thrídrangar and Eldfell have not been investigated, but they are in hand specimen indistinguishable from those of Surtsey. No acid rocks are exposed in the Vestmannaeyjar area. The most evolved rock extruded has a composition on the border of mugearite-hawaiite (Table 1, no. 15). The relatively great number of acid inclusions is therefore an enigma.

The trend of the eruption fissures varies between 012°—045°. The average value is 030°, which differs from the trend of the main volcanic belt which is 040°. No open tectonic fissures or faults have been discovered in this system.

Chemistry. Fifteen major element chemical analyses of the Vestmannaeyjar basalt and basaltic andesite lavas are presented in Table 1. Samples were selected to cover the whole range of composition and it was attempted to ensure an even distribution in space and time. All are new chemical analyses, except nos. 6 and 11,

TABLE 1. CHEMICAL ANALYSES AND CIPW-NORMS (WT.%) OF THE VESTMANNAEYJAR LAVAS.
ANALYSES 6 AND 11 HAVE PREVIOUSLY BEEN PUBLISHED IN JAKOBSSON (1968).
ANALYSTS: GREENL. GEOL. SURVEY, CHEM. LAB., I. SØRENSEN: 1,2,7,8,9,12.
GREENL. GEOL. SURVEY, CHEM. LAB., S.P. JAKOBSSON: 6,10,11.
U. S. GEOL. SURVEY, ANAL. LABORATORY, L. SHAPIRO: 3,4,5,13,14,15.

ROCK. NO	VE61	4649	SU42 —	SU11 —	SU24	VE43	4640	4639	VE48	VE24	VE67	4650
SiO2	46.71	46.40	46.7	46.4	46.9	46.49	46.24	46.50	47.41	46.80	47.27	46.66
TiO2	1.81	2.14	2.1	1.6	2.2	2.17	2.27	2.49	2.33	2.62	2.36	2.82
Al2O3	14.60	14.77	15.5	15.3	14.8	15.55	15.87	15.88	17.17	15.85	16.98	16.19
Fe2O3	1.31	1.56	2.0	1.8	2.8	5.73	1.76	2.88	2.94	4.65	2.66	2.26
FeO	9.89	9.71	10.2	10.0	9.6	6.15	10.68	9.93	8.84	8.40	9.10	10.77
MnO	.23	.23	.18	.17	.18	.20	.26	.27	.25	.17	.15	.27
MgO	10.03	9.49	9.2	11.7	10.1	9.05	8.21	7.36	5.86	6.07	5.38	5.75
CaO	12.03	10.53	10.5	9.7	9.8	10.88	9.30	9.64	10.47	9.88	10.43	9.76
Na2O	2.36	2.83	3.1	2.7	2.9	2.67	3.78	3.37	3.42	3.66	3.63	3.60
K2O	.31	.64	.47	.32	.39	.38	.59	.67	.67	.67	.70	.82
P2O5	.05	.17	.32	.21	.25	.28	.25	.25	.17	.34	.37	.31
H2O	.56	.97	.35	.34	.30	.38	1.14	.56	.49	.45	.48	.32
Sum	99.89	99.44	100.6	100.2	100.2	99.93	100.35	99.80	100.02	99.56	99.51	99.53
CIPW WEIGHT-NORM												
OR	1.83	3.78	2.78	1.89	2.30	2.25	3.49	3.96	3.96	3.96	4.14	4.85
AB	17.19	19.62	21.26	21.09	24.54	22.59	21.97	24.72	25.79	28.47	26.32	24.72
AN	28.33	25.71	26.99	28.68	26.22	29.32	24.59	26.23	29.52	24.84	27.97	25.60
NE	1.51	2.35	2.69	.95			5.43	2.05	1.71	1.35	2.38	3.11
DI	25.23	20.66	18.74	14.63	16.80	18.03	16.31	16.31	17.44	17.78	17.55	17.19
HY					.80	6.68						
OL	19.79	19.64	20.18	26.52	20.44	7.60	19.99	16.49	12.03	10.20	11.48	14.40
MT	1.90	2.26	2.90	2.61	4.06	8.31	2.55	4.18	4.26	6.74	3.86	3.28
IL	3.44	4.06	3.99	3.04	4.18	4.12	4.31	4.73	4.43	4.98	4.48	5.36
AP	.12	.39	.74	.49	.58	.65	.58	.58	.39	.79	.86	.72
	99.33	98.47	100.27	99.90	99.92	99.55	99.21	99.24	99.53	99.11	99.03	99.21
Fe2O3/FeO	.13	.16	.20	.18	.29	.93	.16	.29	.33	.55	.29	.21
Fi-index	20.53	25.75	26.73	23.93	26.84	24.84	30.88	30.74	31.45	33.78	32.84	32.68
FeO*/MgO	1.10	1.17	1.30	.99	1.20	1.25	1.49	1.70	1.96	2.07	2.14	2.23

ROCK. NO	VE158 —	VE114 —	VE111
SiO2	47.7	48.8	50.7
TiO2	3.2	3.1	2.5
Al2O3	16.3	16.3	16.8
Fe2O3	2.8	3.1	2.3
FeO	11.2	10.2	10.3
MnO	.23	.24	.25
MgO	4.5	3.9	3.2
CaO	8.3	7.5	6.4
Na2O	4.5	4.9	5.4
K2O	1.0	1.2	1.3
P2O5	.53	.70	.64
H2O	.33	.40	.44
Sum	100.5	100.3	100.2
CIPW WEIGHT-NORM			
OR	5.91	7.09	7.68
AB	31.03	36.14	41.41
AN	21.32	18.94	17.76
NE	3.82	2.88	2.32
DI	13.65	11.40	8.26
OL	13.17	11.48	12.79
MT	4.06	4.49	3.33
IL	6.08	5.89	4.75
AP	1.23	1.62	1.48
	100.26	99.94	99.79
Fe2O3/FeO	.25	.30	.22
Fi-index	40.76	46.12	51.41
FeO*/MgO	3.05	3.33	3.87

Key to Table 1. The FI-index is the Thornton Tuttle index = Q + OR + AB + NE. FeO* means total iron calculated as FeO.

In the following list of chemically analysed samples "surface" means that the sample is collected in the uppermost 0.2 m section of the flow or body, but below the surfical crusty layer. "At surface" means at approximately 0.2—0.4 m depth below surface.

Alkali olivine basalts, VE I.

1.	VE61	—	Stórhöfdi lava	at surface
2.	4649	—	Nýjahraun scoria	dredge haul
3.	SU42	—	Surtsey July 1964 lava	at surface
4.	(SU11)	—	Surtsey Apr. 1965 lava	1 m below surface
5.	(SU24)	—	Surtsey Dec. 1966 lava	surface
6.	VE43	—	Brandur volcanic plug	centre

Alkali olivine basalts, VE II.

7.	4640	—	Skötuhryggur tephra	dredge haul
8.	4639	—	pillow (?) lava	dredge haul
9.	VE48	—	Hellisey lava	at surface
10.	VE24	—	Ellidaey lava	at surface
11.	VE67	—	Helgafell lava	at surface
12.	4650	—	Rófubodi scoria	dredge haul

Hawaiites

13.	VE158	—	Eldfell May 1973 lava	at surface
14.	(VE114)	—	Eldfell Jan. 30, 1973, volc. bomb	centre
15.	(VE111)	—	Eldfell Jan. 23, 1973 lava	surface

which are quoted from Jakobsson (1968). Various chemical data have presiously been published in a number of papers in connection with the Surtsey and Eldfell eruptions, e.g. Steinthórsson (1966), Jakobsson (1968), Thorarinsson et al. (1973), Jakobsson et al. (1973), and O'Nions et al. (1973).

The chemical analyses (Table 1) reveal that the lavas constitute a typical mildly alkalic suite (cf. Carmichael et al. 1974). All the rocks are nepheline normative, except nos. 5 and 6 which have suffered high-temperature late-stage oxidation of Fe-Ti oxides and olivine. The basalts are alkali olivine basalts and the basaltic andesites are hawaiites.

No rocks of picritic basaltic composition have been observed in the Vestmannaeyjar. The basalts have a FeO*/MgO ratio ranging from 1.10 to 2.14, and fall into two groups, VE I and VE II, a grouping which is supported by differences in the phenocryst mineralogy and the morphology of the lavas, as mentioned before.

The MgO-content of the VE I-lavas varies between 9.1 and 10.1 per cent wt. for 5 of the lavas in this group; these lavas show no signs of gravity fractionation or flowage differentiation of olivine. The Surtsey sample SU11 which contains 11.7 per cent MgO is, however, probably from a slightly olivine cumulated part of the lava. The VE II lavas have a MgO-content of 5.4—8.2 per cent wt.; as mentioned above, their petrography suggests that they are derivative rocks, and it might be suggested that they are fractionated VE I-magma. Alkali basaltic andesite is only represented by one eruption unit, the Eldfell (Heimaey) 1973 lava. In this eruption (Jakobsson et al. 1973) a gradational change in chemistry from hawaiite close to mugearite composition (see page 80) to basic hawaiite was recorded (Table 1, nos. 13—15). This strongly suggests that the magma derived from a magma chamber with a gradational layering of the liquid. Schau & Gasparini (1974) studied the chemical composition of glasses in tephra and a volcanic bomb collected during the Eldfell eruption in Jan. 1973. A considerable variation within the primary glass was demonstrated, compositions ranging from basic mugearite to benmoreite. However, the degree of crystallization of these samples was not given.

In the alkali:silica diagram of Fig. 4 the range of compositions of the mildly alkalic Vestmannaeyjar lavas is demonstrated. There is a clear gap in composition between the basalts and the hawaiites, which is also retained when analyses from the Upper Pleistocene rocks on Heimaey are considered.

Several preliminary calculation tests were made on the Vestmannaeyjar lavas to see if their general chemical trend could be evaluated in terms of low-pressure fractional crystallization, making use of a least square mixing program developed by T. S. Petersen, The University of Copenhagen. The observed phenocryst compositions were used. These calculations indicate that it is not possible to explain the trend of the Vestmannaeyjar rocks by low pressure fractional crystallization. In most cases there are serious discrepancies, mainly as regards the elements K, Ti, P and Ca.

Of special interest is that it is also not possible to explain the first Eldfell hawaiite as formed by fractional crystallization from the last erupted hawaiite (Table 1, no. 15 and 13), using the observed phenocryst phases, although it must be anticipated that the magma of the Eldfell eruption had been stored in a magma chamber at relatively shallow depth. This suggests evidently that some other gravity-controlled differentiation process has operated in this case, possibly along with fractional crystallization.

In the four volcanic episodes which tentatively are suggested to have occurred since late Upper Pleistocene, the VE II-type has been produced in all of them and the VE I type occurs in all but the last one which may currently be running its course. Hawaiite was extruded in the first episode (in Dalfjall on Heimaey) and recently in the Eldfell 1973 eruption. Some sort of cyclic activity is indicated with some 2000—5000 years between the cycles (or episodes). There are no indications of any overall change in chemistry with time since alkalic basalts started to form in the area.

In the Vestmannaeyjar system, as well as in most of the other systems of the EVZ, a spatial

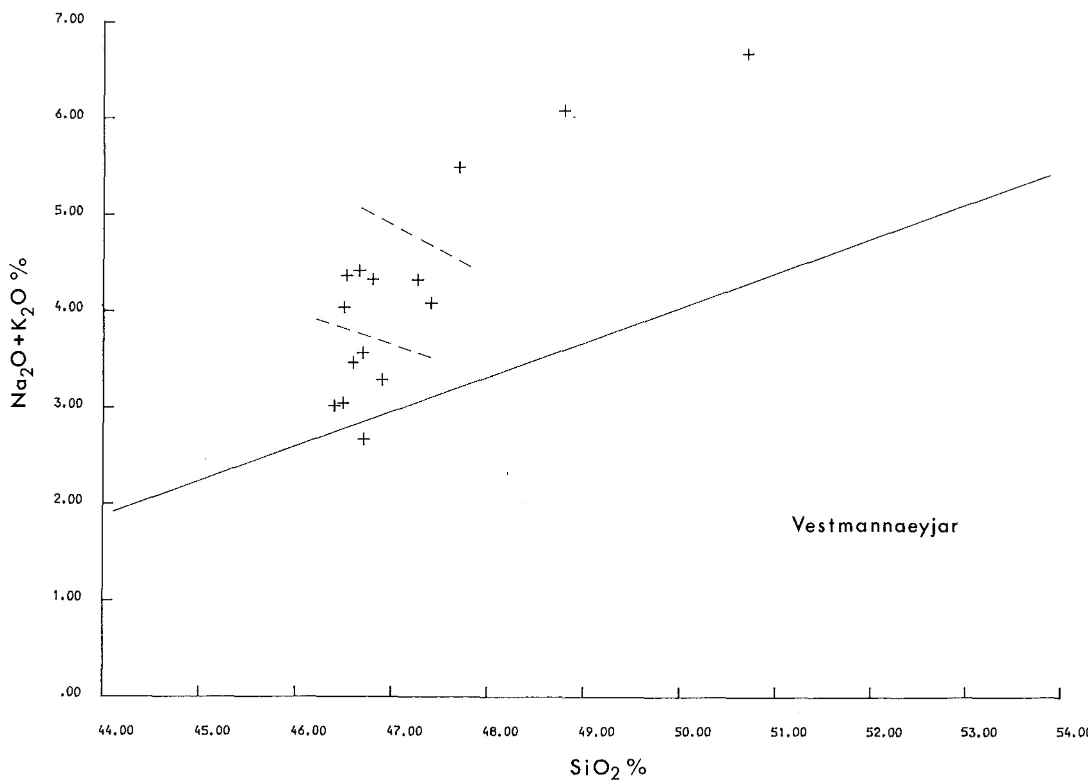


Fig. 4. Alkali:silica diagram of the Vestmannaeyjar lavas. The solid line is the Hawaiian boundary line between the alkalic and tholeiitic series (Macdonald, 1968). The two dashed lines separate the VE I group, the VE II group and the hawaiites. Oxides are given in weight per cent, analyses indicating more than 0.6 per cent H_2O being adjusted to that level, as in all subsequent chemical plots.

chemical pattern can be demonstrated. The two known hawaiite extrusions have both occurred on Heimaey. Moreover, most of the evolved VE II-type lavas and also the most voluminous ones have occurred on Heimaey and its surroundings. The VE I-type of lava is found throughout the system. The range of chemical composition of the extrusives therefore reaches a maximum in Heimaey, where a central volcano may be developing.

The overall chemistry of the Vestmannaeyjar is similar to the Pleistocene to Recent alkalic suite of the Setberg region, described in detail by Sigurdsson (1970). In the Setberg suite compositions were found to range from ankaramites to benmoreites. A comparison with the recent alkalic zone of the Snaefellsnes peninsula is difficult because of meagre data. However, the eastern part of the Snaefellsnes volcanic zone is probably similar to the Vestmannaeyjar, whereas the Snaefellsjökull complex is different, e.g. in having a higher K-content (Peacock 1925).

Alkali olivine basalts of a composition similar to the VE I-type in Vestmannaeyjar have been found on the Mid-Atlantic Ridge near 45°N (Aumento 1968). The sample VE43-Brandur plug (Table 1, no. 6) is for example fairly close to sample 1—7, Table II, in Aumento (1968). The Vestmannaeyjar basalts are apparently very similar or possibly identical to the plateau magma type of the Mull magma series. The Surtsey analyses, for example, are very close to analyses "A" and "III", given as examples for the plateau magma type by Bailey et al. (1924), and by Tilley & Muir (1962, in Table 2, no. 1 and Table 3, no. 1). It is also significant that there are petrographic similarities between these two areas, thus Bailey et al. (op. cit.) note that augite does not occur as phenocrysts in the plateau magma type, just as is the case in Vestmannaeyjar. A comparison with the alkali basalt-benmoreite suite of Skye (Thompson et al. 1972), and the Group I basalt of the Mull lavas (Beckinsale et al. 1978) gives a similar result, although the Mull lavas have a considerably higher Na/K ratio.

The Hekla volcanic system

Geology. The famous volcano Hekla has attracted the attention of many geologists. Largely through the works of S. Thorarinsson, the activity of Hekla, particularly during historical time, is well documented. The petrology of the intermediate and acid lavas and tephras of Hekla has been treated by Einarsson (1950a), Tómasson (1967b), Baldridge et al. (1973), Sigvaldason (1974a) and Wetzel et al. (1978) and is now fairly well known. The great volume of basalts which surrounds the volcano has attracted less attention, although most of the authors in their treatment of the evolved rocks have discussed one or two of the basalt lavas. These transitional alkali basalts, which have been extruded during Postglacial Time in the immediate vicinity of Hekla, must be assumed to belong to the Hekla volcano itself, and thus to form a volcanic system comparable with those found in other parts of the EVZ.

The Hekla volcanic system is situated on the western border of the EVZ (Fig. 24) and has natural boundaries except towards the east where it adjoins the Vatnafjöll volcanic system. The basalt lavas of the Hekla system, together with the intermediate and acid rocks, display a distinct petrochemical trend which in several respects can be distinguished from the trend of the Vatnafjöll system. The Hekla system is thus about 40 km long and 7 km in width. A geological map of the Hekla system is presented in Plate II, where distinction is made between basalt, intermediate and acid lavas.

The topography of the area is mountainous and reaches a high in the Hekla ridge (1491 m) (Fig. 5). Hyaloclastite mountains and ridges, belonging to the Upper Pleistocene "Móberg formation" are exposed in several places (Kjartansson 1962). They have not been investigated, but most of these hyaloclastites are probably from the last glaciation while one interglacial basalt lava flow was mapped west of Bjólfell. As the recent volcanism has occurred in elevated areas and no eruption site is found with certainty below 300 m height, it is probable that the system has been situated in this area for a considerable time, possibly since the last interglacial or longer.

Volcanism has been vigorous in the system during Postglacial Time. Activity of the Hekla central volcano is assumed to have started with the outburst of the acid tephra layer H_4, which has a C^{14} age of 6150 years (Thorarinsson 1954, 1971). Since that time the Hekla central volcano has produced about 6.7 km^3 of acid rocks and 12.0 km^3 of intermediate rocks, but no basalts. During historical time there have been 15 eruptions (Thorarinsson & Sigvaldason 1972a). For each eruption the initial chemical composition is a roughly linear function of the length of the preceeding quiescent period (Thorarinsson 1954, 1967a). The volume of extruded material in each eruption is also a function of the length of the quiescent period, i.e. the longer the period, the greater the total volume erupted (Sigvaldason 1974a). These relationships indicate the presence of large magma chamber(s), however, the fact that no caldera has been formed and no traces of high-temperature thermal activity are found, may point to a deep-seated magma chamber.

All major Hekla eruptions occur in Heklugjá, the 5.5 km long summit fissure and its extension to the southwest and northeast. Besides these, many eruptions have occurred on the flanks of Hekla in which probably solely basaltic andesite products have been produced such as in the 1970 eruption (Thorarinsson & Sigvaldason 1972a). The intermediate and acid rocks of Hekla have not been studied by the present author, except for a few of the lavas, and the geological maps of Thorarinsson (1967a) and Thorarinsson & Sigvaldason (1972a) have been incorporated in Plate II, with minor corrections.

During historical time (i.e. after 900 A. D.), 5

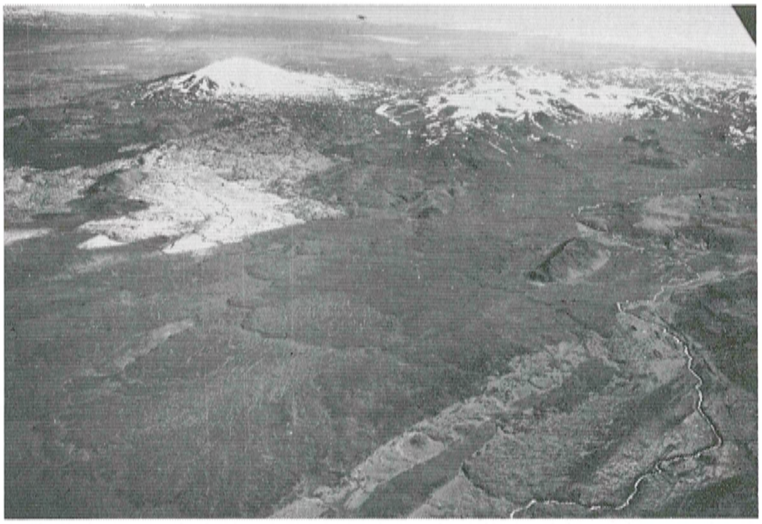


Fig. 5. The southern parts of the Hekla and Vatnafjöll volcanic systems. Hekla (1491 m) is seen to the left, and Vatnafjöll-Raudfossafjöll (1235 m) to the right, both snow-covered. The river Eystri-Rangá is seen in the lower right of the picture. Air photograph by the Danish Geodetic Survey, autumn 1938.

basaltic eruptions are known to have occurred in the Hekla system (Thorarinsson 1967a, Thorarinsson & Sigvaldason 1972a). These are the 1913 eruption of the 012-Lambafit and Mundafell lavas (Bárdarson 1930), the 1878 eruption of the 075-Nýjahraun, the 1725 eruption of the 252-lava, the 1554 eruption of the 447-Pálssteinshraun and an eruption ca. 1440, of an unknown lava flow which may be the 253-Trippafjöll lava.

Altogether 27 individual basaltic eruption sites have been identified in the Hekla volcanic system besides several centres and lavas maybe hidden, especially in the southeastern part. The number of eruption sites producing andesitic rocks is not known. As mentioned above, Thorarinsson has defined 15 eruptions during the last thousand years from Hekla proper, all of which probably have produced andesite and basaltic andesite. It seems, however, very unlikely that there has been as great activity in prehistoric time. The acid rocks, including the only acid lava, the Háahraun (Plate II), appear all to have been extruded from the summit fissure Heklugjá.

When the distribution of eruption sites in the Hekla system is considered with regard to rock types, it is found that all the basaltic andesites and the more evolved rocks which have been extruded during Postglacial Time, come from eruption sites which are less than 9 km from Heklugjá. Probably all andesites and acid rocks are extruded from Heklugjá. These relations are comparable to those found in the Eyjafjöll and Torfajökull systems (Fig. 24).

The Hekla volcano should be regarded as the centre of the swarm, inasmuch this is the site of highest productivity and the only site where evolved rocks are produced. It is a central volcano as envisaged by Walker (1963), or an expression of "secondary volcanism" (Einarsson 1950b).

Tephrochronological dating of many Postglacial lavas, and particularly the intermediate lavas, from the Hekla region, has been carried out by Thorarinsson (1967a). In addition, the present author has dated a few basalt lavas by using known tephra layers, and G. Larsen has kindly dated 4 lavas. Fig. 8 shows the age distribution of the Hekla and Vatnafjöll basalt lavas along the volcanic systems from southwest to northeast. It is of interest to note, that in the Hekla system, a period of vigorous activity in the southern half around 8000—5000 y.b.p., was followed by activity in the northern half, presumably continuously up to the present. Basaltic volcanic activity was again resumed around 1000—1500 y.b.p. in the southern half. In the Vatnafjöll system, the basalt volcanism appears to have moved continuously northwards during the period 7000—1000 y.b.p.

All eruption sites in the Hekla system are

Table 2

Volume (km^3) of observed extruded lava and tephra during Postglacial Time in the Hekla and Vatnafjöll systems. Volumes of basaltic andesites to rhyolites are modified after Thorarinsson (1967b).

	Prehistoric		Historic (<A.D. 900)			Total
	Hekla	Vatna-fjöll	Hekla	Vatna-fjöll		
basalts	7.1	9.4	0.6	0	:	17.1
basaltic andesites	9.3	0	4.5	0	:	13.8
andesites	2.7	0	1.0	0	:	3.7
dacites-rhyolites	6.7	0	0.5	0	:	7.2
	25.8	9.4	6.6	0	:	41.8 km^3

subaerial eruption fissures. Most common are cinder/spatter cone rows (in 18 cases), then cinder cone rows (in 5 cases) and finally spatter cone rows (5 cases). It is noteworthy that the only known explosion fissure, the 017-Valagjá row (Thorarinsson 1960, Noll 1967) produced basaltic-andesite (Table 3, no. 14). The frequency of cinder and cinder/spatter rows in the Hekla system is a sign of the relatively high explosivity of these eruptions, in contrast for instance to the tholeiitic eruption sites of the Veidivötn and Grímsvötn systems. The average length of 10 well-exposed basaltic eruption fissures is 4.0 km.

Lava morphology is uniform; of 25 lavas which are classified, all are aa lava (apalhraun) except one which is classified as pahoehoe lava (helluhraun). The Hekla basalts have thus been definitively more viscous than the alkalic basalts and the tholeiites of the EVZ.

The trend of the basaltic eruption fissures varies between 028° and 053°, the average being 042°, which is about the same as the general trend of the system itself. In the Hekla central volcano the picture is more complex. No open fissures of faults have been discovered in the system.

The total amount of observed lavas in the system is 7.7 km^3 while the volume of single lavas varies from 0.005 to 1.2 km^3. In Fig. 28, the volume of the basalts is plotted against the FeO*/MgO index. The fact that the volume of extruded basalts approaches the volume of basaltic andesites (Table 2) is highly relevant to any petrogenetic model for this volcanic system. This has not been considered before, because most attention has been paid to Hekla proper, the central volcano of the system, where no basalts are produced.

Petrography. Samples were collected from all the 27 basaltic eruption units which were detected in the Hekla volcanic system. These transitional alkali basalts (p. 77) vary within relatively narrow limits (Table 3), and can be treated as one group as regards petrography and mineralogy. The basalts are generally aphanitic and sometimes aphyric. Under the microscope the groundmass is found to be microcrystalline and sometimes cryptocrystalline. The colour (Goddard et al. 1948) of fresh handspecimens is medium dark grey to dark grey. With reference to the 0.2—0.4 m depth level in the lavas, the predominant texture is intergranular, often towards pilotaxitic while subophitic to ophitic textures are also found (cf. p. 70).

Phenocryst phases have been identified, although the composition has not yet been determined. The only published data on the composition of phenocrysts appear to be that of Wetzel et al. (1978), who mention that the 012-Lambafit lava contains plagioclase phenocrysts (microphenocrysts?) of composition An 58—74.

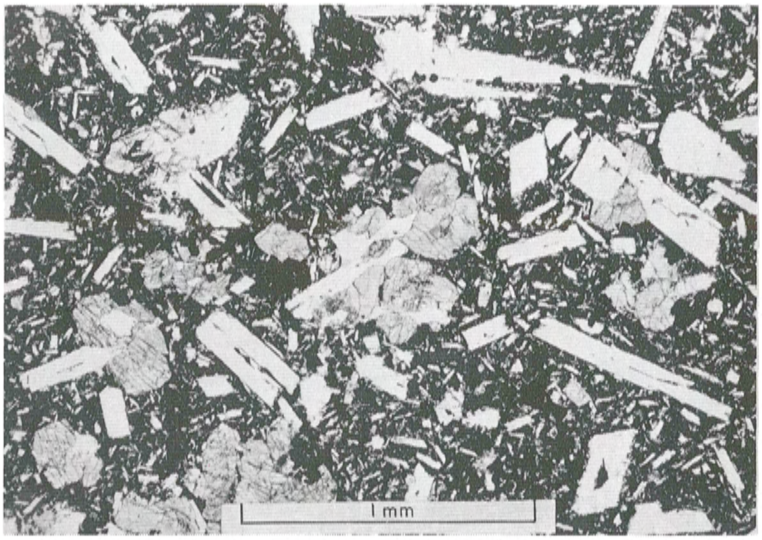


Fig. 6A. Transitional alkali basalt, the 252-lava of A.D. 1725 (N654). Microphenocrysts of plagioclase, curved augite, olivine and magnetite. Glassy groundmass.

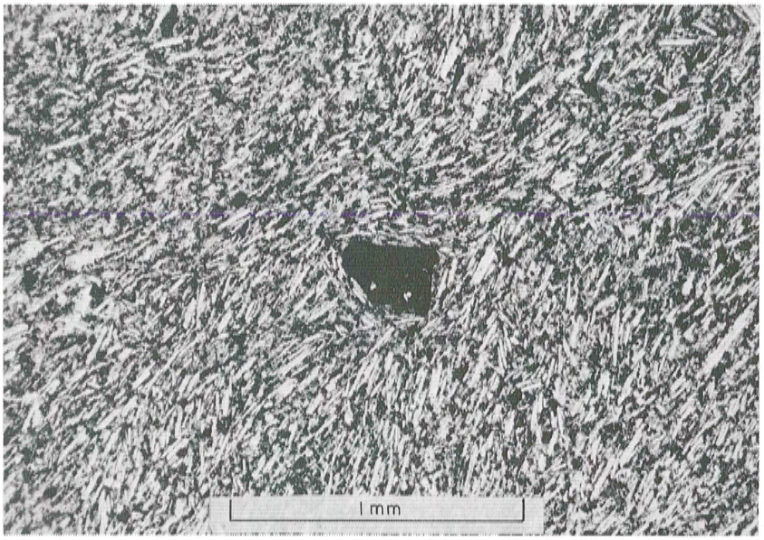


Fig. 6B. Transitional basaltic andesite, the 017-Valagjá lava (N051). Microphenocryst of magnetite. Fluidal texture.

The phenocryst mineralogy of the basaltic andesites and andesites of the Hekla central volcano has, however, been investigated in detail (Tómasson 1967b, Baldridge et al. 1973, Sigvaldason 1974a and Wetzel et al. 1978).

The Hekla basalts contain only minor amounts of macrophenocrysts (p. 64). Only in two lavas do plagioclase, olivine and augite phenocrysts exceed 1/2 per cent of total volume. The plagioclases and olivines are stout and euhedral, and only moderately zoned. They occasionally reach an average size of 5—6 mm. Augite is very rare as macrophenocrysts. Picotite was found as tiny inclusions in olivine phenocrysts in two lavas, which had relatively high MgO-content (above 6 per cent). Magnetite macrophenocrysts were only observed in the 240-Öxi lava, where they occur in glomerophyric growth with plagioclase and augite.

The amount of microphenocrysts varies from 0 to 23 per cent of volume. The microphenocrysts are usually distinct from the macrophenocrysts as regards habit, and their average maximum size is less than about 0.7 mm (cf. p. 64). Magnetite (*sensu latu*) microphenocrysts occur in a few lavas, and are euhedral and often

TABLE 3. CHEMICAL ANALYSES AND CIPW-NORMS (WT.%) OF THE HEKLA BASALTS AND BASALTIC ANDESITES.
ANALYST: GREENL. GEOL. SURVEY, CHEM. LAB., I. SØRENSEN.

ROCK. NO	252	014	235	33	12	43	181	239	240	236	75	230
SiO2	48.02	46.20	46.49	46.55	46.50	46.43	47.22	49.45	46.28	46.88	47.26	49.35
TiO2	3.34	3.91	4.04	4.14	3.96	4.73	4.58	3.21	3.97	4.11	4.66	3.69
Al2O3	14.01	13.52	13.43	13.60	13.80	13.39	13.26	14.06	13.88	13.59	13.24	13.90
Fe2O3	2.57	1.86	2.56	2.48	2.74	2.65	2.78	2.24	2.77	3.72	2.36	2.27
FeO	11.26	13.10	12.20	12.58	12.04	13.28	12.86	11.26	13.39	12.44	13.29	12.03
MnO	.23	.23	.23	.23	.23	.24	.26	.25	.24	.24	.25	.27
MgO	6.07	6.37	6.22	6.27	6.38	5.65	5.15	5.25	5.64	5.58	5.17	4.47
CaO	9.96	10.50	10.29	10.20	10.41	9.71	9.10	9.10	9.32	9.40	9.23	8.23
Na2O	2.89	2.69	2.77	2.76	2.84	2.95	3.10	3.18	2.90	2.92	3.03	3.38
K2O	.58	.50	.52	.55	.54	.60	.71	.75	.59	.62	.67	.84
P2O5	.52	.50	.49	.50	.48	.55	.63	.67	.49	.51	.61	.73
H2O	.33	.22	.38	.26	.24	.13	.47	.40	.55	.55	.35	.52
Sum	99.78	99.60	99.62	100.12	100.16	100.31	100.12	99.82	100.02	100.56	100.12	99.68
CIPW	WEIGHT-NORM											
Q								.35				.98
OR	3.43	2.95	3.07	3.25	3.19	3.55	4.20	4.43	3.49	3.66	3.96	4.96
AB	24.46	22.76	23.44	23.36	24.03	24.96	26.23	26.91	24.54	24.71	25.64	28.60
AN	23.54	23.34	22.68	23.10	23.31	21.52	20.17	21.88	23.11	22.14	20.55	20.28
DI	18.53	21.12	20.76	20.02	20.75	19.11	17.32	15.67	16.57	17.49	17.69	13.19
HY	14.87	6.84	9.81	9.64	6.75	9.97	14.98	19.28	10.82	14.71	15.30	19.16
OL	3.36	11.09	6.96	7.88	9.28	6.97	2.57		8.26	2.92	2.94	
MT	3.73	2.70	3.71	3.60	3.97	3.84	4.03	3.25	4.02	5.39	3.42	3.29
IL	6.34	7.43	7.67	7.86	7.52	8.98	8.70	6.10	7.54	7.81	8.85	7.01
AP	1.20	1.16	1.14	1.16	1.11	1.27	1.46	1.55	1.14	1.18	1.41	1.69
	99.45	99.38	99.24	99.86	99.92	100.18	99.65	99.42	99.47	100.01	99.77	99.16
Fe2O3/FeO	.23	.14	.21	.20	.23	.20	.22	.20	.21	.30	.18	.19
Fi-index	27.88	25.72	26.51	26.61	27.22	28.51	30.43	31.70	28.03	28.37	29.60	34.55
FeO*/MgO	2.24	2.32	2.33	2.36	2.27	2.77	2.98	2.53	2.82	2.83	2.98	3.15

ROCK. NO	483	17	482	231	435
SiO2	50.77	52.42	52.85	53.48	53.24
TiO2	3.19	2.64	2.58	2.41	2.66
Al2O3	14.18	14.16	14.39	14.27	14.31
Fe2O3	5.88	3.08	1.49	2.46	1.63
FeO	8.10	9.52	11.04	9.53	10.73
MnO	.27	.27	.27	.27	.27
MgO	4.00	3.54	3.48	3.25	3.33
CaO	7.71	7.42	7.25	7.08	7.18
Na2O	3.64	3.86	3.72	4.01	3.87
K2O	.94	1.03	1.14	1.12	1.11
MnO	.27	.27	.27	.27	.27
P2O5	.85	1.44	1.14	1.25	.86
H2O	.37	.60	.39	.29	.70
Sum	99.90	99.98	99.74	99.42	99.89
CIPW	WEIGHT-NORM				
Q	6.35	5.84	4.39	5.93	4.47
OR	5.56	6.09	6.74	6.62	6.56
AB	30.80	32.66	31.48	33.93	32.75
AN	19.58	18.27	19.20	17.63	18.40
DI	10.64	7.62	7.87	7.83	9.79
HY	10.05	16.09	19.98	16.15	17.82
MT	8.53	4.47	2.16	3.57	2.36
IL	6.06	5.01	4.90	4.58	5.05
AP	1.97	3.34	2.64	2.90	1.99
	99.53	99.39	99.35	99.14	99.19
Fe2O3/FeO	.73	.32	.13	.26	.15
Fi-index	42.71	44.59	42.61	46.48	43.78
FeO*/MgO	3.35	3.47	3.56	3.61	3.66

Key to Table 3. Locations of chemically analysed samples are shown on Plate II. See text to Table 1.

Transitional alkali basalts

1.	252	—	A.D. 1725 lava	surface
2.	014	—	Taglgígar lava	surface
3.	235	—	Helliskvísl lava	surface
4.	033	—	lava	at surface
5.	012	—	Lambafit 1918 lava	surface
6.	(043)	—	Lambafit 1918 lava	surface
7.	(181)	—	Lambafit (Mundafell l.)	surface
8.	239	—	Eldividur lava	at surface
9.	240	—	Öxi lava	at surface
10.	236	—	Raudkollur volc. bomb	surface
11.	075	—	A.D. 1878 lava	surface
12.	230	—	Raudkembingar lava	surface

Transitional basaltic andesites

13.	483	—	lava	surface
14.	017	—	Völugjá lava-apron	0.5 m below surface
15.	482	—	lava	at surface
16.	231	—	lava	surface
17.	435	—	lava	at surface

included in other phenocrysts, especially augite. Olivine and plagioclase are euhedral and only slightly zoned, while augite is euhedral to subhedral and is often curved. The microphenocrysts very often form glomerophyric clusters. The silicate phases have crystallized nearly simultaneously, which indicates near-cotectic conditions. However, the sequence of first appearance of phases can usually be detected. In the Hekla basalts, the following sequence of initial crystallization is found, when all phases are present: magnetite-olivine-plagioclase-augite (Table 12), the last three phases often grow simultaneously. Microphotographs of two lavas of the Hekla system are shown in Fig. 6. Petrographically as well as chemically, the Hekla basalts appear to grade into basaltic andesites of the Hekla central volcano.

Gabbroic nodules were only found in one lava, the 240-Öxi lava; the chemical analysis is given in Table 14. Acid xenoliths are common in the basaltic andesites and andesites of Hekla (Tryggvason 1965, Sigvaldason 1974a). A brief general discussion of gabbroic nodules and acid xenoliths is given on p. 71—75.

Chemistry. Twelve new major element chemical analyses of the Hekla basalts and five basaltic andesites are presented in Table 3. The chemical composition of only 3 of the 27 basalt lavas have been published before, but the chemistry of the basaltic andesites is known through numerous chemical analyses, e.g. in Einarsson (1950a), Thorarinsson (1967a) and especially Sigvaldason (1974a).

The Hekla basalts and basaltic andesites are assigned to the transitional series for reasons discussed on p. 77. This series is identical to what Miyashiro (1978) has called hypersthene normative alkalic trend or "Coombs-trend". All the lavas are Hy-normative (Table 3). The basalts are also all Ol-normative with the exeption of the 230-Raudkembingar lava (Table 3, no. 12) which in the same plots appears as intermediate between basalts and basaltic andesites. The basaltic andesites are all Qz-normative. No picrite basalts were observed in the Hekla system, either among the Postglacial or the Upper Pleistocene extrusives or intrusives. The FeO*/MgO ratio of the basalts ranges from 2.24 to 3.15. There appear only to be minor chemical differences between the Hekla system and the adjacent Vatnafjöll system. However, as will be discussed in the following section, the Vatnafjöll is defined as an independent system for several reasons.

In the alkali silica diagram in Fig. 7 the basalts and the basaltic andesites exhibit a broad linear variation. It is noted that the basalts grade into the basaltic andesites, at the boundary which is marked with a stimpled line in Fig. 7. However, only a few samples fall in this part of the plot, and there may actually be a minor gap between the two types of composition, both in the alkali:silica diagram as well as in many other plots. The most basic Hekla lavas plot among the VE I-type of Vestmannaeyjar alkali olivine basalts, but straddle the alkalic/tholeiitic division line near the transition to the basaltic andesites.

No systematic changes in the chemical composition of the Hekla basalt lavas can be observed through time. As is the case in Vestmannaeyjar, the range in composition, (e.g. K_2O) rises towards the centre and reaches a maximum in the intermediate and acid rocks.

The chemistry and the trend of the Hekla central volcano is in some respects comparable to the tholeiitic Thingmúli trend (Grönvold 1972), and Baldridge et al. (1973) state that the Hekla volcano trend is nearly indistinguishable from the Thingmúli trend with reference to the Harker diagram and the AFM diagram. However, this is in the fact only an illusory resemblance and demonstrates how critical the interpretation of these two diagrams can be. The basaltic end of the Hekla suite falls entirely above the alkalic/tholeiitic division line in the alkalic:silica diagram (Fig. 7), and the Hekla suite belongs therefore to be transitional or hypersthene-normative alkalic series.

A transitional rock series identical to the present one has not been described from Iceland before, with the possible exception of the Quaternary Snjófjöll suite in Borgarfjördur (Jóhannesson 1975). Some of the basalts of the Skagi area, recently described by Sigurdsson et al. (1978), are similar to the Hekla basalts. As

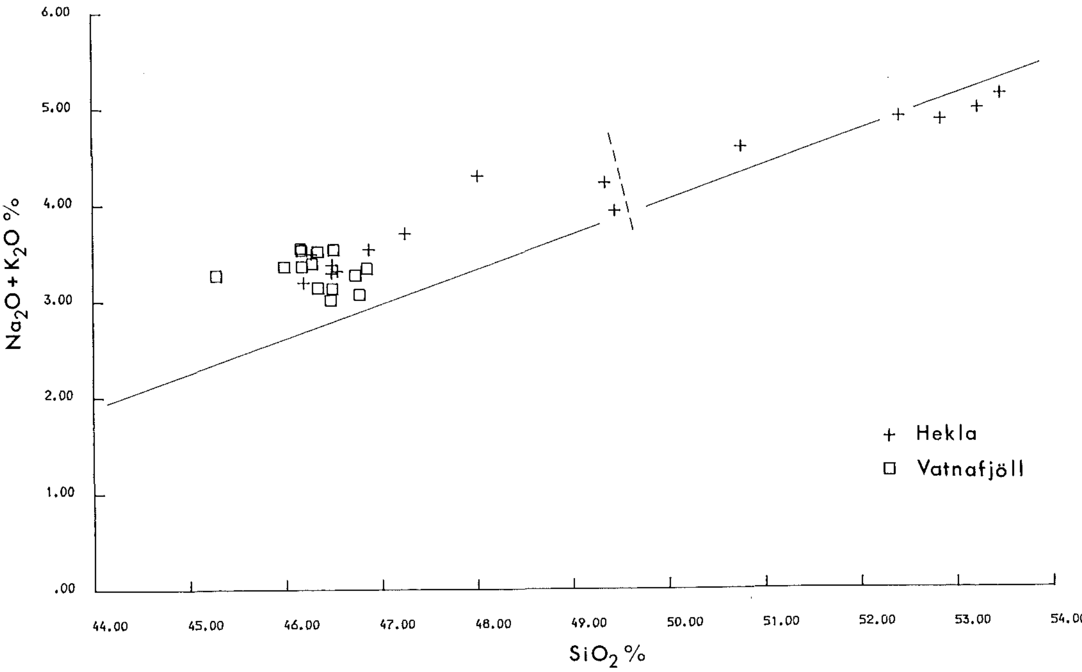


Fig. 7. Alkali:silica diagram of the basalts and basaltic andesites of the Hekla and Vatnafjöll systems. The solid line is the Hawaiian boundary between the alkalic and tholeiitic series. The dashed line is the suggested boundary between the transitional alkali basalts and the basaltic andesites.

noted by Miyashiro (1978) this Hy-normative rock series, which is often characterized by high contents of TiO_2 and FeO* as in the Hekla system, is being formed under various circumstances as e.g. in Easter Island (Baker et al. 1974). Two analyses of basalts of Bald Mountain, at the 45°N, the Mid-Atlantic Ridge (Aumento & Loncarevic 1969) indicate a close relationship between these basalts and those of Hekla.

The Vatnafjöll volcanic system

Geology. This volcanic system is situated immediatly southeast of the Hekla system (Fig. 24). The basalts of Vatnafjöll system are closely related to those of the Hekla system, however, with reference to the geographical and topographical distinction (Fig. 5) and the persistent, although minor differences in petrochemistry between these two systems, the volcanic area of Vatnafjöll-Raudfossafjöll is separated as the Vatnafjöll volcanic system. The system is about 40 km in length and 9 km in width.

Very little has been published on the volcanology and petrology of this area with the exception of the Geological Map of Iceland, sheet 6, published by G. Kjartansson (1962), which however, only shows about one third of the Postglacial eruption sites in this area, and a description of a sample of rhyolite from Raudfossafjöll (Bäckström 1892).

A new map of the Postglacial extrusives is presented in Plate II. The topography of the area is comparable to the Hekla area and reaches a high in Raudfossafjöll (1235 m). The voluminous Upper Pleistocene hyaloclastites of Vatnafjöll and Grasleysufjöll and the mountains to the northeast of these probably all belong to this system. A large area (about 35 km²) of acid rocks of similar age is exposed in the Raudfossafjöll. This acid area has been considered to belong to the Torfajökull rhyolites (Saemundsson 1972), however, Raudfossafjöll are partly isolated from the Torfajökull area,

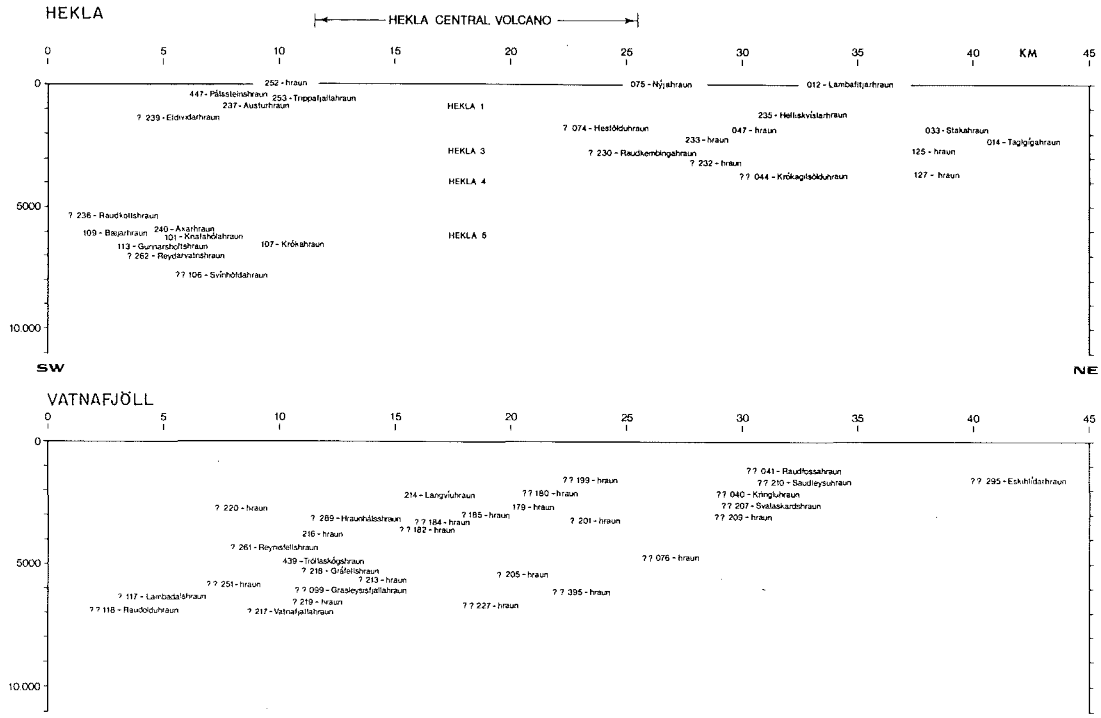


Fig. 8. The age sequence of the basalt lavas of the Hekla and Vatnafjöll systems with regard to their location in a SW-NE section. Lavas are dated by tephrochronology to an accuracy of ± 500—1000 y., except those marked by a single question-mark (± 1000—2000 y.) and those with a double question-mark (approx. ± 2000—3000 y.). HEKLA 1, 3, 4 and 5 refer to the four known acid tephra layers from the Hekla central volcano. Age, as in all subsequent cases, is the uncorrected C^{14}-age, half-life 5568 y. (Thorarinsson, 1971).

and an analysis presented by Bäckström (1892) indicates that the Raudfossafjöll rhyolites are e.g. much lower in alkalies than the Torfajökull rhyolites and therefore closer to the Hekla acid rocks. The present author has also found new outcrops of acid rocks both southwest and northeast of Raudfossafjöll. The abovementioned basic and acid subglacial rocks are probably mainly from the last glaciation and it seems impossible to trace the age of the system farther back in time. No geothermal activity connected to this system has been detected on the surface.

Altogether 31 individual eruptive units have been indentified in the Vatnafjöll volcanic system, all are transitional alkali basalts. One unnamed eruption site north of Raudfossafjöll may have produced both basalt and acid rock in the same eruption. The lavas appear all to be prehistoric, and four of these have been dated by tephrocronology. Fig. 8 shows the tentative age sequence of the Vatnafjöll lavas. It appears that volcanism in this system has moved from southwest to northeast during the period 7000 to 1000 y.b.p.

All the eruption sites are fissures, of 27 registered cases, 17 are cinder cone rows, 9 cinder/spatter cone rows and 1 a spatter cone row. As in the Hekla volcanic system, the frequency of cinder cones rows, — of which 14 were measured to have a crater diameter more than 300 m —, suggests a relatively high explosivity of these eruptions, especially as compared to other systems in the EVZ (see p. 59). This is in line with the suggestion of Moore (1970), that the gas content is higher in alkalic basalt magmas than in tholeiitic magmas. Lava morphology is extremely uniform, all lavas are classified

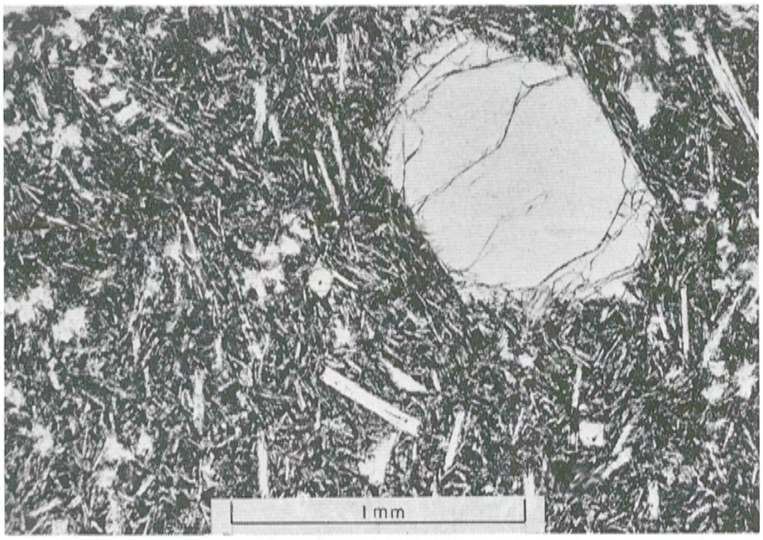


Fig. 9A. Transitional alkali basalt, the 199-lava (N547). Macrophenocryst of olivine, microphenocrysts of plagioclase and olivine. Intergranular-pilotaxitic texture.

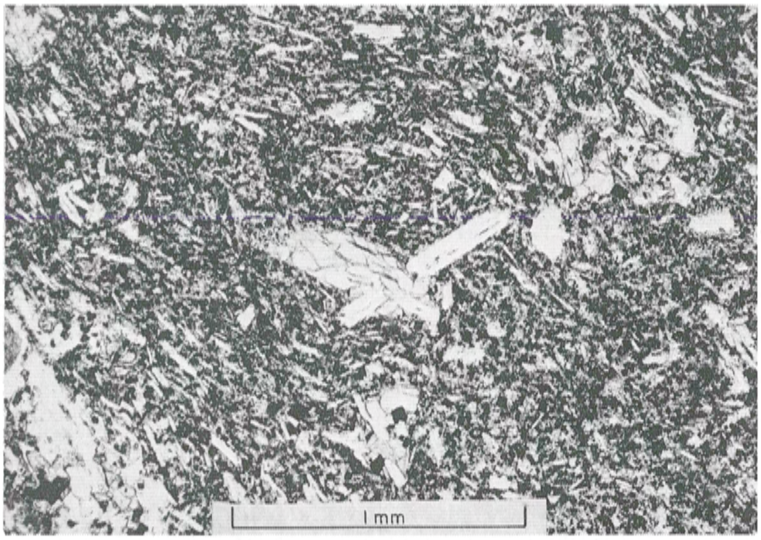


Fig. 9B. Transitional alkali basalt, the 216-lava (N508). Microphenocrysts of magnetite, olivine and plagioclase. Intergranular texture.

as aa-lava except one which is pahoehoe lava. The total volume of the basalts of the Vatnafjöll system is about 9.4 km³ (Table 2).

The length of the eruption fissures varies between about 1.8 and 4.4 km, the average being about 3 km. The trend of the fissures varies between 22° and 85° with the average being 46°. No tectonic fissures or faults were found to cut the Postglacial extrusives of the Vatnafjöll system.

Petrography. Samples were collected from all the 31 identified eruption units. All the lavas are transitional alkali basalts and form a rather coherent group. The general colour of hand-specimens, crystallinity, texture and mineralogy is very similar to that of the aphanitic basalts of the Hekla system. Only one lava, the 199-lava, contains more than 0.5 per cent by volume of the macrophenocrysts olivine, plagioclase and augite (4.9 per cent olivine, Fig. 9A), and two other lavas between 0.1—0.5 per cent, the rest contain less than 0.1 per cent macrophenocrysts. The content of the microphenocrysts varies between 0.1 and 14 per cent and they were found to crystallize in the

TABLE 4. CHEMICAL ANALYSES AND CIPW-NORMS (WT.%) OF THE VATNAFJÖLL BASALTS.
ANALYST: GREENL. GEOL. SURVEY, CHEM. LAB., I. SØRENSEN.

ROCK. NO	199	220	117	217	295	201	40	205	99	76	182	207
SiO2	46.50	46.48	46.78	46.86	46.35	46.74	46.18	46.00	45.29	46.29	46.35	46.51
TiO2	3.59	3.25	3.23	3.06	3.48	3.67	3.62	3.68	3.74	4.39	3.98	3.67
Al2O3	13.47	14.48	14.56	14.75	14.24	13.84	14.20	14.10	13.96	13.52	13.87	14.11
Fe2O3	2.79	2.85	2.34	3.91	3.64	2.42	3.42	4.06	4.31	4.41	3.71	3.59
FeO	11.50	11.42	11.80	10.57	11.74	12.78	12.39	11.92	11.89	11.46	12.43	12.43
MnO	.22	.21	.20	.21	.21	.23	.22	.23	.23	.24	.24	.23
MgO	7.14	6.77	6.67	6.31	6.37	6.21	6.16	6.14	6.05	5.92	5.68	5.64
CaO	10.59	10.61	10.70	9.95	10.11	10.01	9.82	9.90	9.76	9.74	9.26	9.17
Na2O	2.62	2.58	2.59	2.84	2.63	2.74	2.86	2.83	2.77	2.84	2.96	2.97
K2O	.51	.43	.48	.50	.51	.53	.50	.53	.50	.55	.56	.57
P2O5	.45	.42	.43	.38	.41	.49	.43	.43	.43	.53	.48	.44
H2O	.37	.35	.46	.48	.47	.36	.31	.31	.54	.40	.44	.48
Sum	99.75	99.85	100.24	99.82	100.16	100.02	100.11	100.13	99.47	100.29	99.96	99.81
CIPW	WEIGHT-NORM											
OR	3.01	2.54	2.84	2.95	3.01	3.13	2.95	3.13	2.95	3.25	3.31	3.37
AB	22.17	21.83	21.92	24.03	22.26	23.19	24.20	23.95	23.44	24.03	25.05	25.13
AN	23.49	26.66	26.69	26.02	25.54	23.90	24.43	24.21	24.18	22.52	22.91	23.49
DI	21.40	19.09	19.44	17.08	18.04	18.68	17.73	18.18	17.62	18.29	16.45	15.84
HY	8.76	9.85	8.93	11.53	12.02	11.05	8.53	8.94	9.42	14.38	12.53	12.40
OL	8.64	8.25	9.44	5.35	5.98	8.10	9.12	7.54	6.96	1.46	5.24	5.91
MT	4.05	4.13	3.39	5.67	5.28	3.51	4.96	5.89	6.25	6.39	5.38	5.21
IL	6.82	6.17	6.13	5.81	6.61	6.97	6.88	6.99	7.10	8.34	7.56	6.97
AP	1.04	.97	1.00	.88	.95	1.14	1.00	1.00	1.00	1.23	1.11	1.02
	99.38	99.50	99.78	99.34	99.69	99.66	99.80	99.82	98.93	99.89	99.52	99.33
Fe2O3/FeO	.24	.25	.20	.37	.31	.19	.28	.34	.36	.38	.30	.29
Fi-index	25.18	24.37	24.75	26.99	25.27	26.32	27.16	27.08	26.39	27.28	28.36	28.50
FeO*/MgO	1.96	2.07	2.08	2.23	2.36	2.41	2.51	2.54	2.61	2.61	2.78	2.78

ROCK. NO	216	214
SiO2	46.17	46.18
TiO2	3.97	4.26
Al2O3	13.87	13.72
Fe2O3	4.04	3.31
FeO	12.24	13.06
MnO	.24	.25
MgO	5.62	5.54
CaO	9.26	9.24
Na2O	2.99	2.92
K2O	.56	.61
P2O5	.49	.60
H2O	.54	.36
Sum	99.99	100.05
CIPW	WEIGHT-NORM	
OR	3.31	3.60
AB	25.30	24.71
AN	22.77	22.53
DI	16.48	16.08
HY	11.98	12.86
OL	5.07	5.63
MT	5.86	4.80
IL	7.54	8.09
AP	1.14	1.39
	99.45	99.69
Fe2O3/FeO	.33	.25
Fi-index	28.61	28.31
FeO*/MgO	2.82	2.90

Key to Table 4. Locations of chemically analysed samples are shown on Plate II. See text to Table 1.

Transitional alkali basalts

1.	199	—	lava	at surface
2.	220	—	lava	at surface
3.	117	—	Lambadalur lava	surface
4.	217	—	Vatnafjöll lava	surface
5.	295	—	Eskihlíd lava	surface
6.	201	—	lava	at surface
7.	040	—	Kringla lava	at surface
8.	205	—	lava	surface
9.	099	—	Grasleysufjöll lava	at surface
10.	076	—	lava	surface
11.	182	—	lava	surface
12.	207	—	Svalaskard lava	at surface
13.	216	—	lava	surface
14.	214	—	Langvía lava	surface

following general order: Magnetite-olivine-plagioclase-augite. The last three phases often crystallize simultaneously. Microphotographs of two Vatnafjöll basalts are shown in Fig. 9.

Traces of dark mica (about 0.1 × 0.03 mm) were found in the groundmass of the 217-Vatnafjöll lava, preferably in vugs. This is the only case where H_2O-minerals have been observed in the Vatnafjöll system. Gabbroic nodules were found in one lava, the 217-Vatnafjöll lava, see chemical analysis in Table 14. Acid xenoliths, usually partly melted, are common in lavas which have erupted in the vicinity of the acid area of Raudfossafjöll.

Chemistry. Fourteen new major element chemical analyses are presented in Table 4. No chemical data on basalts from the Vatnafjöll area have been published previously. All the lavas are transitional alkali basalts with a Hy-content lying between 8.5 and 14.4 per cent, and they are also all Ol-normative (1.5—9.4 per cent), the FeO*/MgO ratio being between 1.96 and 2.90. As mentioned before, these basalt lavas are close in composition to the Hekla system basalts. In the alkali:silica diagram (Fig. 7), they e.g. plot among the most basic lavas of the Hekla system. There are, however, significant differences, in the Vatnafjöll system the basalts are lower in K_2O, P_2O_5 and TiO_2, but higher in MgO and Al_2O_3, at similar FeO*/MgO ratios.

Another difference between the Hekla and the Vatnafjöll systems lies in the display of Recent volcanism. In the Hekla system a dominating central volcano has been built up during Postglacial Time of basic, intermediate and acid extrusives, in the Vatnafjöll system, only basalts have been produced. In Upper Pleistocene, a large volume of acid rocks has been extruded in Raudfossafjöll, which thus may be regarded as the central complex of the Vatnafjöll system, however, no intermediate rocks have been observed.

The Torfajökull, Tindfjöll and Eyjafjöll volcanic systems

Torfajökull. In the centre of the EVZ is situated the largest area of acid and intermediate rocks in Iceland, the Torfajökull area (Fig. 10). The structure of this area, where acid and a minor amount of intermediate rocks cover some 415 km^3, has recently been described by Saemundsson (1972) who defines it as a single central volcano. During Postglacial Time only a narrow zone across the western part of the Torfajökull area has been active, a fissure swarm about 31 km long and 6 km broad. Although this swarm distinguishes itself as a separate volcanic system, it is a direct continuation of the Veidivötn fissure swarm (Plates II and V). This is a unique situation in the EVZ, as elsewhere the volcanic systems (swarms of complexes) are structurally as well as petrologically clearly separated. The rocks of the Torfajökull area are alkalic, as has already been shown by Sigurdsson (1970) and Grönvold (1972), whereas the Veidivötn volcanic system produces typical tholeiites. Although there is evidence of simultaneous eruptions from a 40 km long fissure which reaches some 8 km into the Torfajökull area, it is difficult to suggest any genetic links between these two areas. Most probably, preexisting magmas of different genesis have escaped to the surface during a major tectonic event, which has cut across a petrological boundary.

The Torfajökull complex is mountainous, the highest areas being Kaldaklofsfjöll (1278 m) and Hábarmur (1192 m). In the southeast corner of the acid area is the small Torfajökull glacier, after which the area is named. The oldest exposed rocks are rhyolite flows dating from the last interglacial period. Vigorous rhyolite volcanism continued during the last glaciation and up to the present time. A caldera about 12 km in diameter was formed early during the last glaciation. The extent of Postglacial acid lavas as shown in Plate II is traced directly after the maps of Saemundsson (1972). Only minor amounts of basaltic and intermediate lavas have been extruded in the Torfajökull volcanic system during the last glaciation and Postglacial Time, and these eruptions have apparently only been in the outskirts of the area, i.e. in Mógilshöfdar, near Laufafell and around Frostastadavatn.

During Postglacial Time approximately

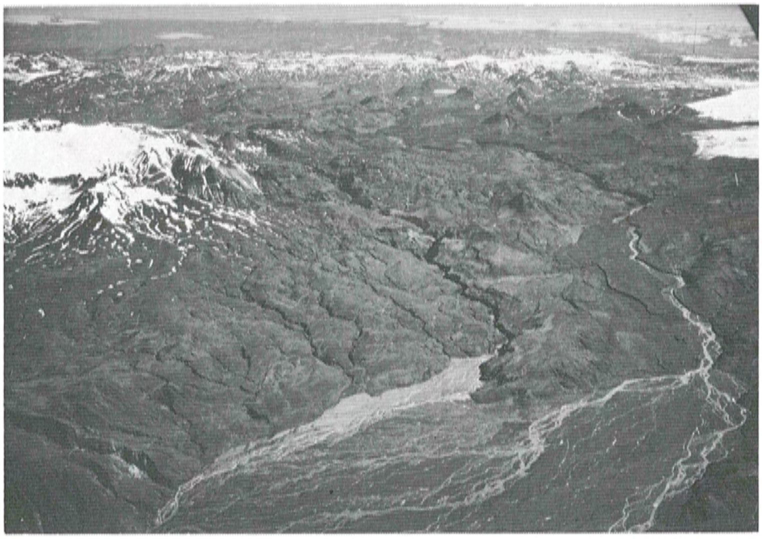


Fig. 10. Part of the Tindfjöll (Tindfjallajökull) complex (1462 m) is seen to the left, the large Torfajökull complex is seen snowcovered in the uppermost part of the picture. To the right the river Markarfljót has cut through the 440-lava of the Katla volcanic system. View towards northeast. Air photography by the Danish Geodetic survey, autumn 1938.

12—18 lavas have been erupted in the Torfajökull volcanic system. Of these 5—7 are rhyolite-rhyodacite lavas and 5—6 are intermediate, mainly basaltic andesites (Grönvold 1972, Sigurdsson 1970). The number of basaltic eruptions which belong to the system may be 3—5 but it is difficult to tell exactly as the basalts in the transition zone to the northeast resemble the tholeiitic lavas of the Veidivötn system and a chemical analysis is needed for classification. In the southwest there is only one basaltic lava, the 385-Lauf lava, which in composition is actually transitional to basaltic andesite. In historical time, 3—4 volcanic episodes may have occurred in the area (Thorarinsson 1967a, G. Larsen pers. inform), two of which are of considerable petrological interest. In the 9th century, or just at the time of the settlement of Iceland, a large tholeiitic eruption occurred in the 18 km long Vatnaöldur fissure within the Veidivötn system. The Hrafntinnuhraun, which is comenditic rhyolite, probably erupted simultaneously. In the 16th century, according to G. Larsen (pers. inform.) there was an eruption from a 40 km long fissure stretching from Hraunvötn in the Veidivötn area in the northeast to the Laugahraun fissure within the Torfajökull caldera in the southeast. One of the lavas, the Dómadalur lava, is a composite lava, where the dominating acid component resembles the Hrafntinnuhraun and the basic component is similar to the plagioclase-phyric basalts (Sigurdsson 1970). This is the only recorded case of mixing of magmas in the EVZ.

It appears that nearly half of the Postglacial eruptions in the Torfajökull system have occurred around 800—1600 A. D., and this may represent an especially active volcanic period similar to those found in many of the other volcanic systems. The volume of extruded lavas during Postglacial Time is approximately: 0.8 km^3 of basalt lavas, 0.12 km^3 of intermediate lavas and 0.87 km^3 of acid lavas. The volume of intermediate and acid tephras is unknown.

In the Torfajökull complex is situated one of the largest high-temperature areas of Iceland (Saemundsson 1972). The hydrothermal area is found within and at the borders of the large caldera. These relations are probably indicative of the presence of magma chamber(s) at shallow depth.

The petrography of the basalts which are believed to belong to this volcanic system in some respect resembles the petrography of the Veidivötn tholeiites. The rocks are very porphyritic, macrophenocrysts of plagioclase (An ~ 80—90) being typical, as well as of augite and occassionally of olivine (Fo ~ 80—85). However, these phenocrysts are more often corroded than in the Veidivötn lavas. The groundmass is

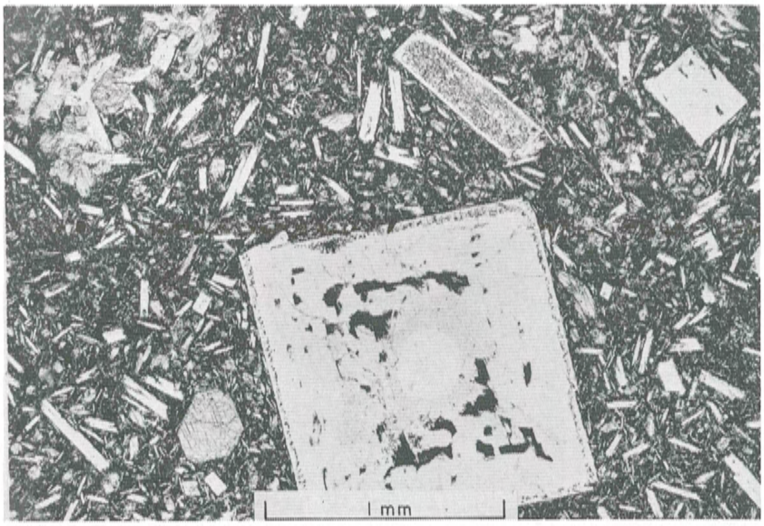


Fig. 11A. Transitional basaltic andesite, the 385-Lauf lava (N168) from the Torfajökull system. Macrophenocrysts of plagioclase, microphenocrysts of plagioclase, olivine and augite. Glassy groundmass.

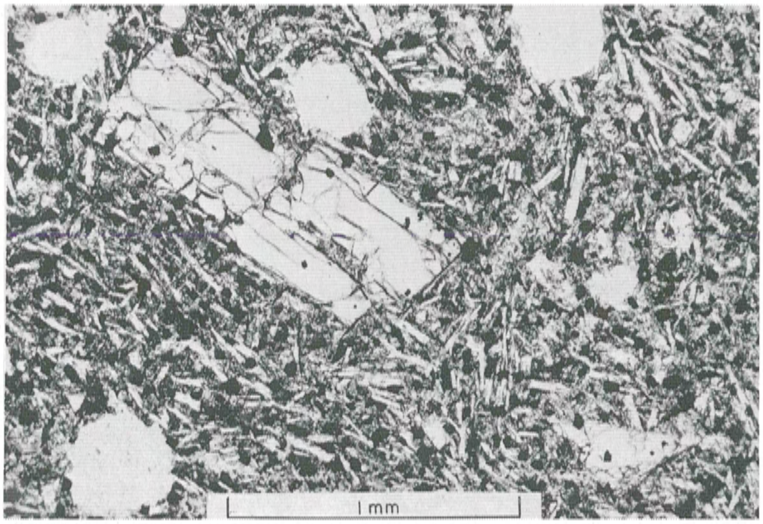


Fig. 11B. Transitional alkali basalt, the 191-volcanic bomb (N504) from the Eyjafjöll system. Macrophenocryst of olivine, with inclusions of picotite, microphenocrysts of plagioclase. Texture intergranular-pilotaxitic.

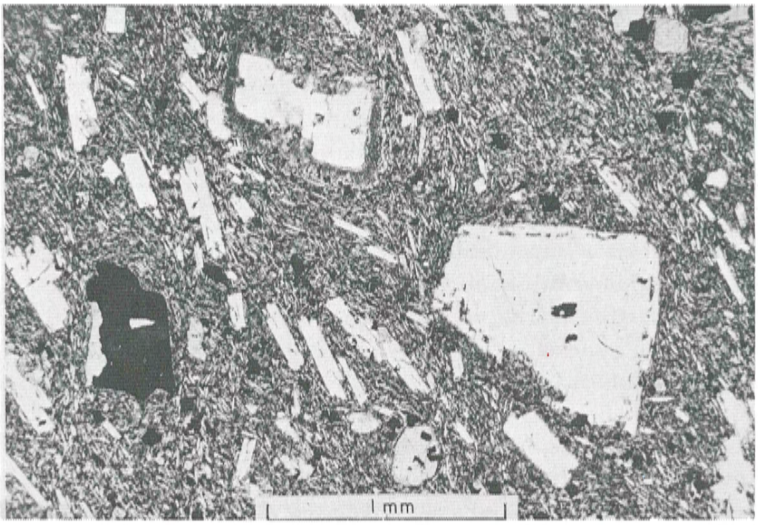


Fig. 11C. Transitional basaltic andesite, the 308-Hamragardar lava (N682) from the Eyjafjöll system. Macrophenocrysts of plagioclase, microphenocrysts of magnetite, plagioclase, and augite. Texture pilotaxitic-fluidal.

TABLE 5. CHEMICAL ANALYSES AND CIPW-NORMS (WT.%) OF THE TORFAJÖKULL, TINDFJÖLL AND EYJAFJÖLL BASALTS AND BASALTIC ANDESITES.
ANALYST: GREENL. GEOL. SURVEY, CHEM. LAB., I.SØRENSEN:

ROCK. NO	147	385	198	416	191	308	398	396
SiO2	50.98	49.97	52.58	51.33	46.72	52.06	51.52	49.20
TiO2	1.98	2.52	2.47	2.96	3.30	2.43	2.46	3.16
Al2O3	14.97	14.51	14.31	14.56	14.23	14.76	15.86	16.19
Fe2O3	1.59	1.88	1.95	2.29	4.04	6.27	3.20	2.56
FeO	9.29	9.04	8.47	9.29	8.91	5.48	7.68	9.00
MnO	.18	.17	.17	.18	.18	.18	.21	.19
MgO	5.68	5.56	4.93	4.97	7.36	4.13	3.85	3.91
CaO	10.45	10.32	8.60	8.64	11.06	8.52	7.59	9.55
Na2O	2.86	3.21	3.75	3.35	2.54	4.03	4.66	3.66
K2O	.83	1.13	1.47	1.09	.49	1.02	1.31	.86
P2O5	.30	.35	.36	.44	.36	.68	.55	.56
H2O	.63	.55	.67	.64	.59	.54	.52	.47
Sum	99.74	99.21	99.73	99.74	99.78	100.10	99.41	99.31
CIPW	WEIGHT-NORM							
Q	.57		.59	2.15		5.70		
OR	4.91	6.68	8.69	6.44	2.90	6.03	7.74	5.08
AB	24.20	27.16	31.73	28.35	21.49	34.10	39.43	30.97
AN	25.56	21.85	17.87	21.47	25.98	19.17	18.49	25.21
DI	20.06	22.24	18.45	15.25	21.40	14.70	12.80	15.31
HY	17.05	7.75	13.37	15.48	10.67	4.58	6.45	10.02
OL		4.66			3.79		3.39	1.24
MT	2.31	2.73	2.83	3.32	5.86	9.09	4.64	3.71
IL	3.76	4.79	4.69	5.62	6.27	4.62	4.67	6.00
AP	.70	.81	.83	1.02	.83	1.58	1.27	1.30
	99.11	98.66	99.06	99.10	99.19	99.56	98.89	98.84
Fe2O3/FeO	.17	.21	.23	.25	.45	1.14	.42	.28
Fi-index	29.68	33.84	41.01	36.94	24.39	45.83	47.18	36.05
FeO*/MgO	1.89	1.93	2.07	2.28	1.70	2.69	2.74	2.89

Key to Table 5. Locations of chemically analysed samples are shown on Plate II (Torfajökull, Tindfjöll) and Plate III (Eyjafjöll). See text to Table 1.

Torfajökull volcanic system

Transitional alkali basalt

1. 147 — Tjörvi lava — 8.5 m below surface

Transitional basaltic andesites

2. 385 — Lauf lava — centre
3. 198 — Laufafell lava — surface

Tindfjöll volcanic system

Transitional alkali basalt

4. 416 — Vördufell lava — at surface

Eyjafjöll volcanic system

Transitional alkali basalt

5. 191 — volcanic bomb — surface

Transitional basaltic andesites

6. 308 — Hamragardar l. — surface
7. 398 — Midskálaheidi l. — at surf.
8. 396 — Írá lava — at surf.

finegrained or glassy. The basaltic andesites are all highly porphyritic with highly zoned plagioclase, augite and olivine macrophenocrysts, and are therefore markedly distinct from the basaltic andesites of Hekla, which contain only minor amounts of phenocrysts and are sometimes aphyric. A microphotograph and a description of the 385-Lauf lava is presented in Fig. 11A as an example of a basaltic andesite from the Torfajökull volcanic system.

Only one basalt lava from this system has been analysed (Table 5). It was only realized at a late stage of the research, that basalts had been produced during Postglacial Time. A few basalt lavas at the northeastern border evidently belong to the system although these lavas were formerly thought to belong to the Veidivötn volcanic system, as by field criteria they resemble the Veidivötn tholeiites (Jakobsson 1972, Vilmundardóttir 1977).

The Torfajökull rocks belong to the transitional alkalic series (p. 77). Sigurdsson (1970) studied the acid rocks of this area, and Grönvold (1972) has made chemical analyses of most of the Postglacial basaltic andesites and the acid lavas, and compared them to the rock suite of the Hekla system and several tholeiitic centres. He found that compositions of between 55 and 64 per cent SiO_2 have not been extruded during the Postglacial period. Important is the discovery of comendites in this area (Sigurdsson 1970), which is in agreement with the existence of the transitional basaltic rocks. According to Bailey & MacDonald (1970) the Torfajökull peralkaline rocks are similar to the comendites of oceanic islands.

The basalts and the basaltic andesites of the system appear to resemble those of the Eyjafjöll and perhaps the Tindfjöll systems (Fig. 13). The Torfajökull lavas, however, distinguish themselves when the incompatible elements are considered. For example in the Na_2O : K_2O diagram (Fig. 16) the Torfajökull lavas plot separately from the neighbouring volcanic systems by virtue of their relatively high K_2O content. Generally the lavas are characterized by high K_2O and MgO and relatively low P_2O_5 and TiO_2.

Tindfjöll (Tindfjallajökull). This volcanic system is situated in the western part of the EVZ, south of Hekla and Vatnafjöll (Plate II). Very little has been published on Tindfjöll, (Kunsky & Roth 1946), but investigations are presently being carried out by Larsen and Jørgensen (in prep.), and the Thórsmörk ignimbrite which originates from the Tindfjöll complex has been studied in detail by Jørgensen (in press). The top of the complex is covered by a small glacier, and reaches a height of 1462 m a.s.l. (Fig. 10). The present author made only one cursory visit to the area.

This volcanic system, which covers an area of about 360 km² is probably the oldest one still active (?) in the EVZ and was probably mainly built up during the last three glaciations and last two interglacials (Jørgensen 1976). Aphyric transitional basaltic rocks dominate the lower parts of the complex, while intercalated are intermediate and acid rocks. The Thórsmörk ignimbrite dates from the second last interglacial and is made up of two magma components, a dominating salic component, which is a comendite, and a basic (mugearitic) component. A caldera, 5 km in diameter, was formed early in the history of the volcano. During the last interglacial and glacial periods a variety of rocks ranging from basalts to peralkaline rhyolites, was produced both in the caldera and on the flanks of the volcano. The youngest basaltic rocks of the Tindfjöll system are characteristically highly porphyritic.

About twelve small volcanic eruptions may have occurred in the complex during the final stages of the last glaciation and in early Postglacial Time (Plate II) (Larsen & Jørgensen, in prep.), one very small eruption, at the northeastern edge of the caldera, produced an acid lava. All the others lavas on Plate II are shown as basalt lavas although several of them may be basaltic andesites. No eruptions are known from historical time in the Tindfjöll system. The volume of these late glacial/Postglacial lavas is very low, being approximately of the order of 0.1 km³.

One sample from the 416-Vördufell lava was chemically investigated. This is a transitional alkali basalt, very close to a basaltic andesite in chemical composition (Table 5).

Eyjafjöll. The volcanic system of Eyjafjöll (or, the Eyjafjallajökull volcano) (Fig. 12), is situated immediately south of the Tindfjöll complex and borders on the Katla volcanic system (Fig. 24). The Eyjafjöll system is little known. Sigurdsson (1970) has described and listed chemical analyses of three rock samples, and Jørgensen (1976) has given a brief description of the structure.

The Eyjafjöll volcanic system may be compared morphologically to the Hekla central volcano, which has been described as a volcanic stratified ridge (Thorarinsson 1960). The complex is partly covered by a glacier (Fig. 12) and reaches a height of 1668 m a.s.l. On the top a 2.5 km wide caldera has developed. Eyjafjöll was built up during the last two glacial periods and last interglacial period (Jørgensen 1976). During the last glacial period, considerable amounts of intermediate and acid rocks were

Fig. 12. The Eyjafjöll (Eyjafjallajökull) complex (1668 m). View towards eastsoutheast. The summit caldera and volcanic ridges radiating from it are conspicuous. Air photograph by B. Adalsteinsson, Febr. 1977.

deposited which are mainly exposed at Gígjökull. Ankaramites have been found at four localities in the complex, see p. 90. In addition, several lavas and tuffs on both the south and north sides of the complex appear to be ankaramitic in handspecimen. Petrographically, all these rocks appear to be porphyritic, (usually plagioclase, olivine and augite) and the rocks tend to become more porphyritic with increasing age of the complex.

A preliminary map of the Postglacial lavas of this east-west orientated volcanic system was compiled and is presented in Plate III. It proved difficult to distinguish Postglacial lavas from older lavas. There appear to be all gradiations from heavily glaciated lavas to rough unmodified lava surfaces. This is probably because of the height at which the lavas are exposed (mostly 500—900 m a.s.l.) where a fluctuating ice margin would probably have existed, with periodic advances of the glacier at times. Altogether 20 individual lava units were identified as being Postglacial, but a few of these may actually be interstadial. Four eruption centres are evidently covered by ice at the present time.

Only two of the examined Eyjafjöll lavas are of basalt composition, both on Fimmvörduháls, while 17 lavas are of intermediate composition. One lava is probably quartz-trachytic. This is the small 418-lava which is exposed just west of the Gígjökull (NNW of the caldera, Plate III).

Only one eruption is known to have occurred with certainty during historical time in Eyjafjöll, the 1821—1823 eruption in the main crater (caldera) which produced intermediate to acid tephra (Thoroddsen 1925). Thorarinsson (1975) considers it certain that the eruption of 1612 which Thoroddsen ascribes to Eyjafjöll, was a Katla eruption.

There are no age determinations available on the Postglacial lavas of the Eyjafjöll system. However, judged from the weathered surface and high erosion of the lavas, and the comparatively thick soil layer on the 308-Hamragardar lava, which is of the youngest appearance, all the lavas must be very old. Some of the lavas may in fact, as mentioned before, even be in-

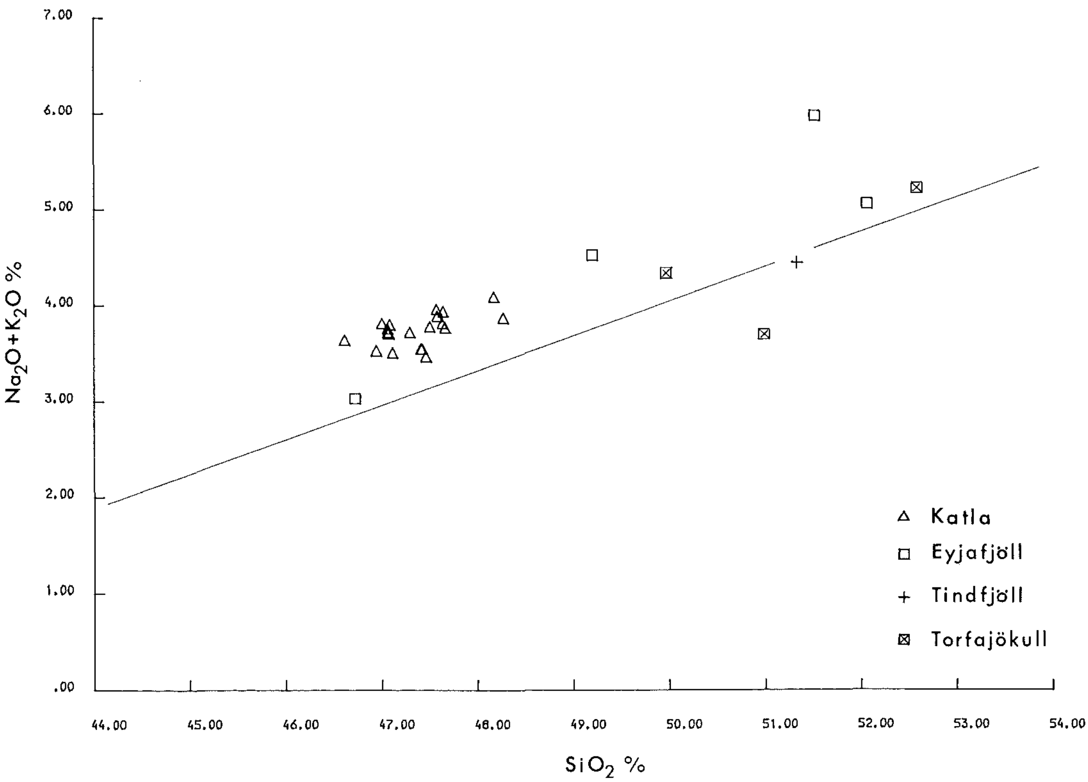


Fig. 13. Alkali:silica diagram of the basalts and basaltic andesites of the Katla volcanic system and the Eyjafjöll, Tindfjöll and Torfajökull systems.

terstadial. It appears probable that the lavas are formed at the very end of the last glaciation and during the first few thousand years of Postglacial Time. Kjartansson (1958) suggested that the 308-Hamragardar and the 123-Kambagil lavas might have flowed on to a glacier which would have filled the valley of the Markarfljót at the final stages of the last glaciation, as he found that these lavas were deprived at their distal ends. There is, however, no doubt that the end of the Kambagil lava is exposed as a solid flow in a gully above the farm Mid-Mörk. The central part of the flow is fragmented, as Kjartansson has noted and the explanation may be that the lava has flowed across a large snowdrift.

The total volume of extruded Postglacial lavas in the Eyjafjöll system is only about 0.26 km^3. In addition an unknown volume of tephra has been extruded from the ice-filled caldera. Only about 0.006 km^3 of the lavas are basalts, 0.24 km^3 are "basaltic andesites", and approx. 0.02 km^3 is acid (one lava).

The two basalts discovered in Eyjafjöll are transitional alkali basalts, but resemble the Vestmannaeyjar basalts in their petrography. The 191-volcanic bomb (Table 5, no. 5) has olivine macrophenocrysts with inclusions of picotite and sparse microphenocrysts of plagioclase (Fig. 11B). The basaltic andesites vary considerably in their petrography, but are mostly very porphyritic; besides magnetite, strongly zoned and occasionally corroded phenocrysts of olivine, plagioclase and augite are common. The 308-Hamragardar lava is shown in Fig. 11C to represent a typical porphyritic basaltic andesite from the Eyjafjöll system. Primary amphiboles were found in three lavas, the 398-Midskálaheidi, the 306-Höfdi and the 401-Sker lavas. In the Midskálaheidi lava,

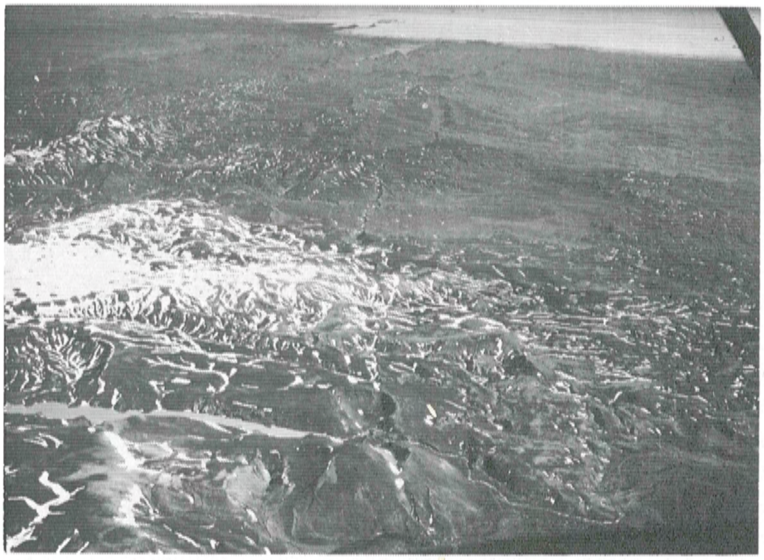


Fig. 14. Northernmost part of the Katla volcanic system. View towards northeast. In the foreground the Raudibotn crater, a part of the 086-Brytalækir fissure. In the central part of the picture, the 168-Eldgjá crater-row. Svartahnúksfjöll (901 m) to the left and Vatnajökull in the background. Air photograph by the Danish Geodetic Survey, Autumn 1938.

amphibole is common in the groundmass and occurs also in gabbroic nodules which are quite common in this lava. In the 306-Höfdi lava amphibole is found in reaction zones in gabbroic nodules. It also occasionally occurs in vugs in the groundmass in this lava as is also the case in the 401-Sker lava.

As in the case of the Torfajökull and Tindfjöll volcanic systems, only a few chemical analyses are available from Eyjafjöll (Table 5, nos. 5—8). Sigurdsson (1970) described briefly a benmoreite and two quartz-trachytes from Eyjafjöll and found that the acid rocks correspond to the mildly alkalic differentiates of transitional or alkalic provinces.

The basalt (Table 5, no. 5) resembles the Vestmannaeyjar VE I alkali olivine basalts (Fig. 13), the difference being in higher amounts of TiO_2 and total FeO, which is modally expressed in higher groundmass modes of iron titanium oxides (Fig. 11B). The usually highly porphyritic basaltic andesites resemble the Torfajökull basaltic andesites (Fig. 11A), although a difference in the content of incompatible elements and the $Na_2O : K_2O$ ratio (Fig. 16) can be demonstrated. In some respects the Eyjafjöll and Torfajökull basaltic andesites resemble orogenic andesites in their petrography and chemistry.

The Katla volcanic system

Geology. The investigation on this volcanic system is hindered by the fact that a major part of its presumed area is covered by the glacier Mýrdalsjökull (Fig. 24). The Katla area (Plate IV) under the southeastern part of the glacier is famous through numerous subglacial eruptions in Postglacial Time. Generally, however, the region around and beneath Mýrdalsjökull is only little known. Robson (1957) gave detailed descriptions of the 168-Eldgjá and 086-Brytalækir eruption sites and lavas (Fig. 14) and described for the first time intermediate and acid rocks in the areas northeast and southeast of Katla. Sigurdsson (1970) recognized an acid centre in the eastern part of Mýrdalsjökull, and Sigbjarnarson (1973) and Jørgensen (1976) consider the Mýrdalsjökull area as a single volcanic complex. Because of the great homogenity of the Postglacial basalt lavas around Mýrdalsjökull, which petrochemically are easily distinguished from the neighbouring volcanic units, the Mýrdalsjökull area and the fissure swarm northeast of it are here treated as one volcanic system. Such defined, the system is about 30 km broad in its southwestern part, narrowing gradually to the northeast, and reaches a length of 78 km. A geological map of the ice-free areas of the system is presented in Plate IV.

The Katla volcanic system is situated in the southernmost part of the EVZ and adjoins the Eyjafjöll system. The areas around Mýrdalsjökull rise generally in height towards the glacier except on the north side, and the glacier itself reaches a height of about 1450 m in Háabunga. The topography under the southern part of Mýrdalsjökull has recently been investigated by Björnsson (1978), using radio-echo equipment, and his map has been incorporated in Plate IV. The history of the Katla volcanic system may go back to the next last glaciation (Robson 1957, Jørgensen 1976). Hyaloclastites dominate the rock sequence, basaltic flows being relatively rare. Intermediate rocks (trachybasalts) were found in Sandfell at the eastern side of the glacier by Robson (1957), who also described acid subaerial flows in Huldufjöll and Kötlukollar. Acid rocks have also been discovered in Gvendarfell at the southern side (Pétursson, pers. comm.) and in Godaland on the western side of the glacier (Jørgensen 1976).

In the ice-free areas of the volcanic system, there has been only moderate volcanic activity, altogether 34 individual eruptions units having been identified, which are all basalts. Under Mýrdalsjökull, mainly in the "Katla area" (Plate IV), there has, however, been intense volcanic activity. According to Thorarinsson (1975), 17 eruptions are known from the Katla area in historical time. The number of prehistoric eruptions is not known, but it may approach 100 (Larsen, pers. comm.). Thorarinsson (1975) estimates that as much as 30—35 km^3 of tephra may have been produced from this area during Postglacial Time. Although most of these subglacial eruptions may have occurred in the Katla area, probably at least two jökulhlaups of historical age have flowed towards the southwest, which indicates volcanic activity somewhere in the Godabunga-Háabunga area (Plate IV). In this connection it is of interest to note that P. Einarsson (1977) found that epicenters of the 1976 earthquake swarm which occurred under Mýrdalsjökull fall in two distinct areas, one in the Katla area and another in the Godabunga area, the depth of foci varying from just below the surface down to 30 km depth. During the field work it was noticed that there are clear signs of repeated jökulhlaups from underneath the glacier between Öldufell and Kötlujökull and also from Entujökull. There is therefore no doubt that volcanism has occurred subglacially over wide areas beneath Mýrdalsjökull. It appears possible that Mýrdalsjökull covers two volcanic complexes, one in the eastern side and one in the northwestern side. A large caldera may be situated under the eastern part of the glacier, and if so thus includes the Katla eruption sites (Sigbjarnarson 1973).

No intermediate or acid eruptions appear to have been assigned to the swarm by any author, although Thorarinsson (1975) mentions that most of the tephra layers from Katla contain intermediate and acid grains. In soil profiles south of Mýrdalsjökull at least four coarse grained light tephra layers can be seen, two of which are associated with dark layers. It appears probable that these acid layers originate from beneath Mýrdalsjökull, probably from the Katla area. As mentioned above, many interglacial acid lavas outcrop in the nunataks around the Katla area. A hydrothermal area is evidently situated under the southern part of Mýrdalsjökull as the rivers at the south side smell with hydrogen sulfide (Sigvaldason 1963).

Besides the dated eruptions of the Katla area, the age of several lavas east of Mýrdalsjökull has been investigated. Thorarinsson (1955) and Larsen (1979) have suggested that the 168-Eldgjá lava and the 301-Álftaver lava were erupted in the 10th century. The 301-Álftaver lava is overlapped by the 069-Hólmsá lava, the 302-Rjúpnafell lava and the 303-Jökulkvísl lava. This is therefore suggestive of a major volcanic event some 9—11 hundred years ago. The lavas of the Emstrur area are evidently very old, possibly from the first thousand years of the Postglacial period.

Volume calculations of the identified lavas from the ice-free regions indicate a total amount of 14.8 km^3, all of which are basalts with a very narrow compositional range. To this value must be added the 30—35 km^3 of basaltic material

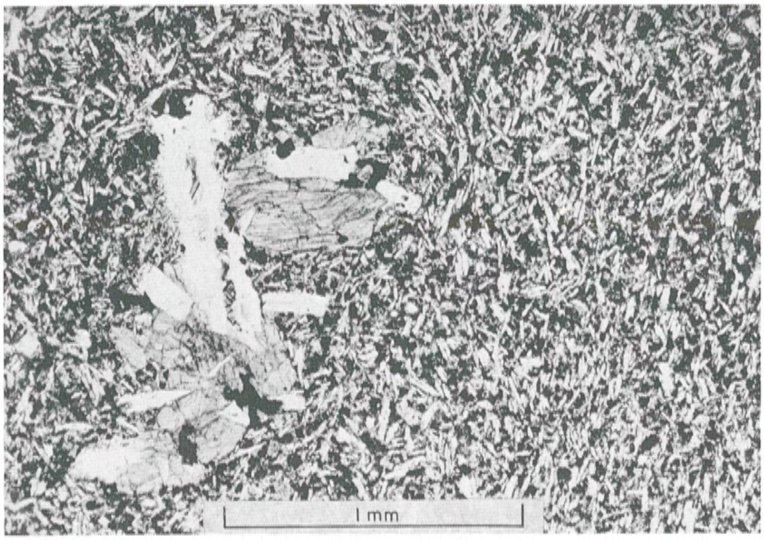


Fig. 15A. Transitional alkali basalt, the 168-Eldgjá lava (N303). Microphenocrysts of magnetite, plagioclase and augite. Texture intergranular to pilotaxitic.

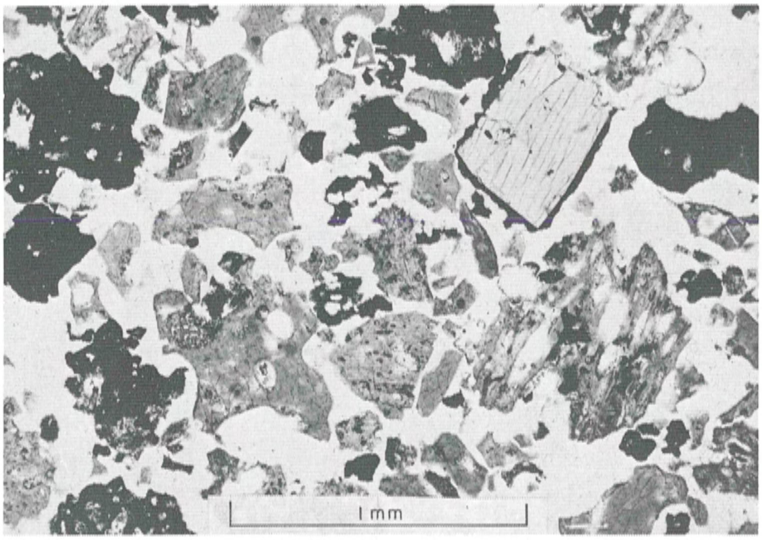


Fig. 15B. Transitional alkali basalt, the Katla 1625 tephra (N1090). Grains of sideromelane and tachylyte, not palagonitized. Macrophenocryst of augite.

which Thorarinsson (1975) estimates has been produced subglacially. The volume of intermediate and acid material is unknown, but is presumably low. The volume of single lavas varies between 0.01 and 3.7 km^3, the average size being 0.35 km^3.

The types of eruption sites are cinder cone rows (10 cases), cinder/spatter cone rows (3 cases) and explosion fissures (3 cases). Most lavas are pahoehoe, although several lavas in the eastern part are aa lavas. The majority of the eruption fissures are with a northeasterly trend, the average being 035°, which is about the overall trend of the system itself. In the western part of the system, several of the eruption fissures have a northwestern trend.

In association with the eruption of the 086-Brytalaekir, the 168-Eldgjá and the 158-Kambar lavas, a narrow (200—400 m wide) graben with subsidence a few meters was formed. In the case of the 086-Brytalaekir lava in Raudibotn (Fig. 14) (which may be contemperaneous to the 168-Eldgjá lava) it is evident that the main part of the subsidence occurred during the formation of the crater rows. Graben subsidence is only seen in the northeasternmost part of the Katla system, elsewhere in the transitional and alkali areas, no tectonic fissures or

TABLE 6. CHEMICAL ANALYSES AND CIPW-NORMS (WT.%) OF BASALTS OF THE KATLA SYSTEM
ANALYST: GREENL. GEOL. SURVEY, CHEM. LAB., I. SØRENSEN.

ROCK. NO	79	428	326	86	324	168 —	85 —	84	158 —	159 —	161 —	298
SiO2	47.11	47.06	48.27	46.94	47.29	47.08	45.94	46.77	47.41	45.83	46.66	47.66
TiO2	4.38	4.38	4.01	4.51	4.41	4.63	4.46	4.43	4.71	4.51	4.49	4.61
Al2O3	12.92	12.90	13.04	13.08	13.21	12.71	12.83	12.96	12.91	12.72	12.89	12.91
Fe2O3	3.15	3.55	3.12	3.97	2.34	4.24	2.89	3.53	2.63	4.50	4.23	2.41
FeO	12.38	11.58	11.37	11.69	12.79	11.23	12.81	12.13	12.79	11.24	11.51	12.73
MnO	.20	.21	.21	.20	.20	.22	.20	.20	.21	.21	.20	.21
MgO	5.51	5.26	4.97	5.34	5.21	5.06	5.44	5.39	5.09	5.23	5.39	4.98
CaO	10.54	10.08	9.70	10.31	9.93	9.91	10.59	10.43	9.85	10.34	10.46	9.74
Na2O	2.86	3.01	3.03	2.86	2.95	3.08	2.82	2.78	2.79	2.73	2.67	3.03
K2O	.65	.75	.84	.67	.77	.72	.61	.66	.76	.64	.68	.74
P2O5	.46	.50	.59	.47	.49	.57	.46	.47	.58	.48	.49	.56
H2O	.46	.57	.66	.51	.42	.31	.36	.53	.22	.51	.42	.62
Sum	100.62	99.85	99.81	100.55	100.01	99.76	99.41	100.28	99.95	98.94	100.09	100.20
CIPW WEIGHT-NORM												
Q			.75			.51			.19	.37	.57	
OR	3.84	4.43	4.96	3.96	4.55	4.26	3.60	3.90	4.49	3.78	4.02	4.37
AB	24.20	25.47	25.64	24.20	24.96	26.06	23.86	23.52	23.61	23.10	22.59	25.64
AN	20.50	19.47	19.50	20.87	20.53	18.73	20.55	20.94	20.46	20.56	21.18	19.44
DI	23.80	22.47	20.48	22.38	21.22	21.93	24.02	22.89	20.44	22.63	22.59	20.97
HY	10.14	10.90	14.31	12.74	10.81	11.71	6.32	12.08	16.45	11.79	12.92	14.16
OL	3.74	1.92		.48	4.62		6.97	1.80				1.46
MT	4.57	5.15	4.52	5.76	3.39	6.15	4.19	5.12	3.81	6.52	6.13	3.49
IL	8.32	8.32	7.62	8.57	8.38	8.79	8.47	8.41	8.95	8.57	8.53	8.76
AP	1.07	1.16	1.37	1.09	1.14	1.32	1.07	1.09	1.34	1.11	1.14	1.30
	100.16	99.28	99.15	100.04	99.59	99.45	99.05	99.75	99.73	98.43	99.67	99.58
Fe2O3/FeO	.25	.31	.27	.34	.18	.38	.23	.29	.21	.40	.37	.19
Fi-index	28.04	29.90	31.36	28.16	29.51	30.82	27.47	27.43	28.29	27.25	27.19	30.01
FeO*/MgO	2.76	2.81	2.85	2.86	2.86	2.97	2.83	2.84	2.98	2.92	2.84	2.99

ROCK. NO	440	224	325	302	194	301	333	196	89	172	92	241
SiO2	47.06	47.58	47.46	47.50	47.07	47.63	47.42	47.57	46.61	47.00	48.17	47.64
TiO2	4.42	4.12	4.38	4.68	4.67	4.70	4.60	4.39	4.51	4.72	4.51	4.49
Al2O3	12.89	13.05	13.11	12.80	12.77	12.87	12.83	12.99	12.78	12.76	13.07	12.69
Fe2O3	2.89	2.92	3.76	3.06	2.23	2.26	2.58	3.04	2.97	2.76	2.74	2.48
FeO	12.30	12.13	11.45	12.18	12.96	12.93	12.77	12.32	12.54	12.79	12.39	12.55
MnO	.21	.21	.20	.21	.21	.21	.21	.22	.21	.21	.21	.22
MgO	5.18	5.09	5.05	5.08	5.07	5.04	5.05	4.97	5.01	5.02	4.81	4.66
CaO	10.09	9.69	9.85	9.65	9.89	9.67	9.90	9.64	9.89	9.89	9.38	9.37
Na2O	2.97	3.10	2.74	2.99	2.99	3.03	3.05	3.14	2.91	3.05	3.20	3.13
K2O	.75	.79	.73	.79	.72	.78	.73	.82	.73	.76	.89	.81
P2O5	.50	.50	.50	.59	.55	.57	.55	.52	.51	.59	.60	.60
H2O	.40	.64	.55	.52	.62	.37	.44	.49	.57	.44	.51	1.04
Sum	99.66	99.82	99.78	100.05	99.75	100.06	100.13	100.11	99.24	99.99	100.48	99.68
CIPW WEIGHT-NORM												
Q			1.71	.17								
OR	4.43	4.67	4.31	4.67	4.26	4.61	4.31	4.85	4.31	4.49	5.26	4.79
AB	25.13	26.23	23.19	25.30	25.30	25.64	25.81	26.57	24.62	25.81	27.08	26.49
AN	19.63	19.36	21.32	19.17	19.30	19.21	19.16	18.93	19.65	18.88	18.67	18.18
DI	22.50	21.10	20.01	20.55	21.77	20.82	21.90	21.15	21.64	21.86	19.89	20.30
HY	10.45	11.66	13.77	14.97	11.48	13.60	11.82	11.45	11.97	10.62	14.09	15.06
OL	3.38	2.94			3.66	2.28	2.94	2.73	2.41	3.56	1.06	.30
MT	4.19	4.23	5.45	4.44	3.23	3.28	3.74	4.41	4.31	4.00	3.97	3.60
IL	8.39	7.82	8.32	8.89	8.87	8.93	8.74	8.34	8.57	8.96	8.57	8.53
AP	1.16	1.16	1.16	1.37	1.27	1.32	1.27	1.20	1.18	1.37	1.39	1.39
	99.26	99.18	99.23	99.53	99.13	99.69	99.69	99.62	98.67	99.55	99.97	98.64
Fe2O3/FeO	.23	.24	.33	.25	.17	.17	.20	.25	.24	.22	.22	.20
Fi-index	29.56	30.90	29.21	30.14	29.56	30.25	30.12	31.42	28.94	30.30	32.34	31.27
FeO*/MgO	2.88	2.90	2.94	2.94	2.95	2.97	2.99	3.03	3.04	3.04	3.09	3.17

faults have been observed to cut Postglacial formations.

Petrography. Samples were collected from all 34 identified eruption units from the ice-free regions of the Katla volcanic system. The lavas, which are all classified as transitional alkali basalts, are of very restricted chemical composition (Fig. 13) and form one group. In addition, samples of 10 tephra layers from the "Katla area" were examined. However, some 90—100 subglacial eruptions which may also have occurred under Mýrdalsjökull are not considered in this work.

The lavas of the Katla system are very homogeneous in their petrography. They are similar to many of the lavas in the Vatnafjöll volcanic system. The groundmass of the lavas is micro- to cryptocrystalline and sometimes aphyric. Fresh specimens display a medium dark grey colour. The predominant texture is intergranular to pilotaxitic, occasionally granular, or equigranular.

Macrophenocrysts of plagioclase, olivine and augite occur sporadically, each phase being less than 1 per cent of the volume, except in two lavas which contain 1.5 per cent by volume of olivine and augite respectively. The macrophenocrysts are usually stout and euhedral, the plagioclases and olivines being usually moderately zoned. The augites however, are sometimes resorbed. In size they do not normally exceed a few mm, although Robson (1957) reports olivines up to 1 cm across. The composition of the macrophenocrysts has not been determined by the present author, but, according to Robson the olivines in the lava he examined had the restricted composition of Fo 85—88. As the FeO*/MgO ratio of the lavas is rather high (Table 6), this must mean that the olivines are not in equilibrium with the magma. Occasionally the macrophenocrysts form glomerophyrs, the texture of these glomerophyrs indicating a simultaneous crystallization of the three silicate phases, perhaps with plagioclase as the first phase to nucleate.

The amount of microphenocrysts is usually low and never exceeds 7.5 per cent by volume. The plagioclases are lath-shaped and moderately zoned; according to Robson the composition of small phenocrysts in the lava east of Mýrdalsjökull lie around An 70. The olivines are only slightly zoned, occasionally lath-shaped or skeletal; their composition (Robson 1957) is probably mainly around Fo 75. The augite phenocrysts are often curved, and mostly have undulatory extinction. Textural evidence indicates the following order of initial crystallization: Magnetite-plagioclase-olivine-augite. The last three phases often crystallize simultaneously. In Fig. 15 microphotographs are presented of the 168-Eldgjá lava and the Katla tephra of A. D. 1625.

No H_2O-minerals were discovered in the lavas of the Katla volcanic system. Not a single gabbroic nodule was recovered although large glomerophyric clusters were found in a few cases.

Key to Table 6. Locations of chemically analysed samples are shown on Plate IV. See text to Table 1.

Transitional alkali basalts

1.	079	—	Hólmsá lava	4 m below surf.
2.	428	—	Almenningar l.	at surface
3.	326	—	tephra	surface
4.	086	—	Brytalækir lava	at surface
5.	324	—	lava	0.3 m below surf.
6.	168	—	Eldgjá lava	2 m below surf.
7.	(085)	—	Eldgjá lava	at surface
8.	(084)	—	Eldgjá lava	3 m below surf.
9.	158	—	Kambar lava	at surface
10.	(159)	—	Kambar lava	2 m below surf.
11.	(161)	—	Kambar lava	2 m below surf.
12.	(298)	—	Kambar lava	1 m below surf.
13.	440	—	Fljót lava	0.5 m below surf.
14.	224	—	Tuddi lava	1 m below surf.
15.	325	—	Álftakvísl lava	3 m below surf.
16.	302	—	Rjúpnafell lava	at surface
17.	194	—	Midkvísl lava	at surface
18.	301	—	Álftaver lava	1 m below surf.
19.	333	—	Öldufell tephra	surface
20.	196	—	Vedurháls lava	at surface
21.	089	—	Mælifellssandur l.	at surface
22.	172	—	Kriki lava	3 m below surf.
23.	092	—	Emstrur lava	0.5 m below surf.
24.	241	—	lava[1]	

1 collected by G. R. Robson (1957, cf. Table 6, no. 21).

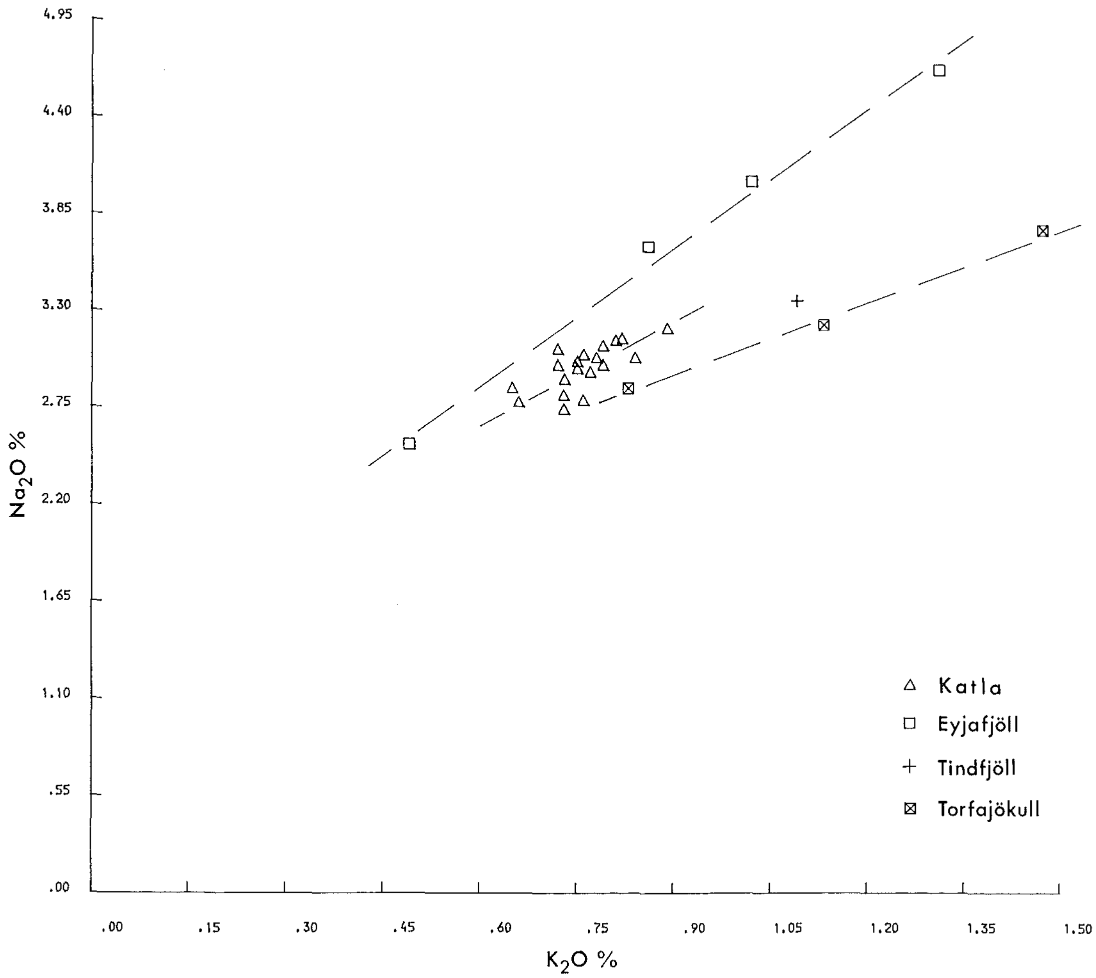


Fig. 16. Na_2O plotted versus K_2O for the basalts and basaltic andesites of the Katla, Eyjafjöll, Tindfjöll and Torfajökull volcanic systems. Trends of evolution are tentatively indicated.

Grains of acid glass are common in many of the tephras from the subglacial Katla area (Thorarinsson 1975), but these have not been observed in the lavas.

Chemistry. Twenty four new major element chemical analyses of the Katla system basalts are presented in Table 6. The lavas show a remarkably limited composition range. From a petrogenetical point of view, it is significant that variations within individual lavas (Fig. 36) are for many components nearly of the same range as the variation in the whole group (Fig. 13). A detailed chemical study of some of the Katla system basalts was given by Robson (1957). His results are in overall agreement with the results of the present study. One of the samples of Table 6, the 241-lava, was analysed and described in detail by Robson.

The lavas are typical transitional alkali basalts (p. 77). All the analysed samples are Hy-normative, and all are Ol-normative except 8 samples which have suffered late stage high-temperature oxidation. By correction of the Fe_2O_3/FeO ratio to 0.17 (Fig. 34), these 8 analyses become Ol-normative. The FeO*/MgO ratio of the basalts is high, or between 2.76 and 3.17. In the alkali:silica diagram (Fig. 13), the basalts plot well above the alkalic/tholeiitic division line, and as in the case of the Hekla and

Vatnafjöll systems a trend oblique to the alkalic/tholeiitic division line is indicated. Although there is a slight overlap in chemistry with the Hekla basalts, (cf. Fig. 7), the Eldgjá basalts are characterized by a higher TiO_2 content, or 4.0—4.7 per cent, and high FeO* content, or 14.1—15.4 per cent by weight (Table 6). The tephras from the Katla area are of very similar composition to the subaerial lavas, as e.g. the Katla tephras of 1755 and 1918 (Steinthórsson 1978). The chemistry of the lavas is further discussed on p. 87 along with the other lavas of the EVZ.

As a consequence of the narrow compositional range of the lavas, no significant variation in space or time can be recognised within the system, and there are no indications of cyclic volcanic activity during Postglacial Time.

No basalts indentical with the high TiO_2 and FeO* transitional alkali basalts of the Katla system have been observed in Iceland outside the EVZ. Those which come closest are the basalts of the Snjófjöll series (Jóhannesson 1975), although they resemble more the Hekla basalts, which are somewhat lower in TiO_2, K_2O and FeO*, and higher in MgO than the basalts of the Katla system. Basalts of very similar composition have formed on many oceanic islands, like the Galapagos islands (MacBirney & Williams 1969, Table 10), although these rocks have been given different names (cf. p. 78). Similarily the Easter Island basalts are close in composition to the Katla system basalts. (Baker et al. 1974).

The Grímsvötn volcanic system

Geology. As is the case with the Katla volcanic system, the major part of the presumed area of the Grímsvötn volcanic system is covered by ice, in this case the Vatnajökull, (Fig. 24).

The subglacial Grímsvötn central volcano in Vatnajökull has been highly active, at least in historical time. Thorarinsson (1974) lists 19 probable eruptions since 1598. Considering the close relationship of the tholeiite lavas southwest of Vatnajökull to the recent Grímsvötn products (Fig. 19) and the fact that volcanism is known to have occurred subglacially southwest of Grímsvötn, there is little doubt that this is an independent volcanic system comparable to, for example, the Veidivötn system. It is not possible to tell how far it reaches towards the northeast, but no volcanism appears to have been recorded between Grímsvötn and Kverkfjöll (Thorarinsson 1950). The system is thus about 100 km long and may have an average width of about 15 km. A geological map of the ice-free region of this volcanic system is presented in Plate IV.

The Grímsvötn volcanic system constitutes the easternmost part of the EVZ. The height of the terrain rises gradually from 300 m a.s.l. in the southwest towards the northeast and reaches a maximum at Grímsvötn (1749 m), see Fig. 17. Knowledge of this volcanic system is fragmentary because of the ice cover. In the ice-free areas the hyaloclastite ridges (of last glaciation age ?) southwest of Sídujökull and Skaftárjökull probably belong to this system. The nunataks of the Grímsvötn area and the area southwest of Grímsvötn, which have been investigated by Noe-Nygaard (1950, 1951, 1952a and 1952b), are made up of basic hyaloclastites and rhyolitic rocks, probably of Upper Pleistocene age. It appears probable, that these nunataks belong to the system. The Grímsvötn central volcano has developed a large caldera (35 km²) and is also the site of a high-temperature hydrothermal area (Thorarinsson 1974).

Only 8 individual eruption units have been identified in the region outside Vatnajökull. Of the 19 eruptions believed to have occurred in the "Grímsvötn area" since about 1598, four of these have probably occurred southwest of Grímsvötn, in 1783, 1867, 1887, and 1903 (Thorarinsson 1974). Knowledge about volcanic activity during historical time before 1598 is very fragmentary and there is unfortunately no information available on prehistoric subglacial activity in the area.

There are no indications of any intermediate or acid volcanic activity during Postglacial Time. However, the hyaloclastites of Hágöngur at Sídujökull are of basaltic-andesite composition (Noe-Nygaard 1950) and intermediate rock fragments are found in the moraine

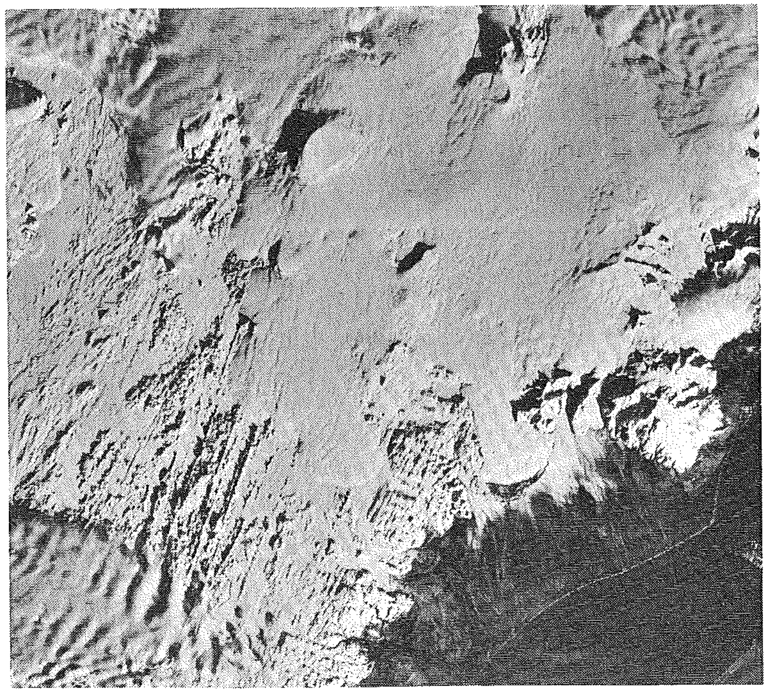


Fig. 17. ERTS-1 satellite image of the Vatnajökull glacier and the area southwest of it, taken at 920 km altitude. The prominent volcanic lineations southwest of Vatnajökull belong mainly to the Veidivötn and Grímsvötn volcanic systems. In the lower left the Heljargjá graben with the tephra ring Fontur is conspicuous. The large caldera subsidence near the centre of Vatnajökull is Grímsvötn.

southeast of Sídujökull. Geirvörtur, Thórdarhyrna and Pálsfjall are entirely made up of tholeiitic rhyolites of Upper Pleistocene age (Noe-Nygaard 1952b). The volume of the basalt lavas extruded in the ice-free region of the Grímsvötn system is about 18.7 km^3, of which 12 km^3 (or 65%) formed in the well-known Skaftáreldar eruption of 1783—1784. The volume of basalts extruded subglacially can only be roughly estimated. Thorarinsson (1974) has calculated the volume of three subglacial eruptions, and if it is assumed that they are near-average eruptions and that the volcanic activity has been similar throughout Postglacial Time then some 30—35 km^3 may have been erupted subglacially, and the total production of the system may thus be about 50—55 km^3.

Most of the subaerial lavas have been dated approximately by tephrocronology (Jónsson 1979) and they appear to have erupted about 2000—6000 years ago. The eruption sites are dominantly cinder-spatter cone rows, and all lavas are of the aa type.

As in the case of the northeastern part of the Katla volcanic system, a narrow disconnected tectonic graben has been formed associated with the eruption of the 080-Lakagígar lava, and also with the 156-Núpar lava. The trend of the four major subaerial eruption fissures is about 044° which coincides with the trend of the system. In the southwestern part of the system, however, the fissures trend about 012°—015°.

Petrography. Besides the 8 identified subaerial lavas, 3 subglacial tephras were examined. The eight lavas are very similar in their petrography, the differences encountered in handspecimens being mainly due to variations in the amount of microphenocrysts. The lavas are very similar to many of the lavas of the tholeiitic Veidivötn system, but are easily distinguished from the transitional alkali basalts by their high phenocryst content.

The groundmass is generally microcrystalline (at the 0.2—0.6 m depth level), and all lavas are porphyritic. Their colour is medium dark grey, when unoxidized. The predominant texture is intergranular towards subophitic (cf. Fig. 32).

Macrophenocrysts of plagioclase, olivine and augite, a few millimeters across are found in minor amounts, except in the 163-Lambavatn

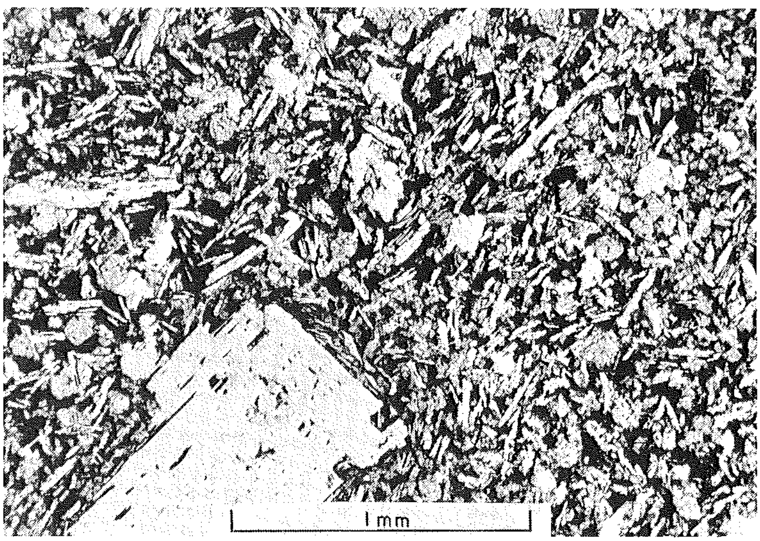


Fig. 18A. Tholeiite, the 080-Lakagígar lava (N1149). Macrophenocryst of plagioclase, microphenocrysts of plagioclase and augite, Texture intergranular-subophitic.

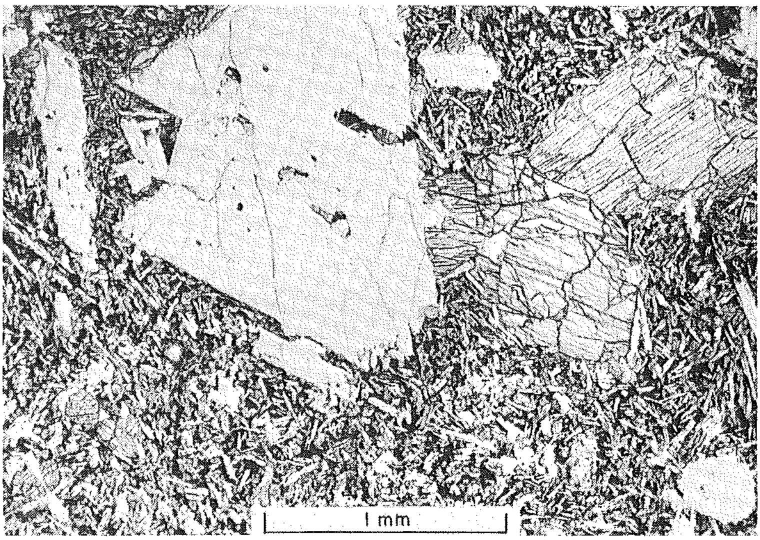


Fig. 18B. Tholeiite, the 351-Bergvatnsá lava (N064). Macrophenocrysts of plagioclases and augites attached. Microphenocrysts of plagioclase and augite. Interstitial glass.

lava which contains about 12 per cent by volume. Each plagioclase phenocryst is really usually a cluster of individuals, possibly in synneusis (Vance 1969). Where the three phases form glomerophyric clusters, the plagioclase is usually the first phase to crystallize shortly followed by olivine and augite. Plagioclase macrophenocrysts (?) in the Grímsvötn 1934 extrusives were found to have a composition of An 80—85 and zoned to An 72 (Noe-Nygaard 1951). The 163-Lambavatn lava may be accumulative with regard to the macrophenocrysts (cf. p. 83).

The amount of microphenocrysts varies from 3 to 11 per cent by volume and can vary considerably in individual lavas as e.g. in the 080-Lakagígur and the 351-Bergvatnsá lavas. In the 083-Hálsagígar lava the amount of microphenocrysts may approach 20—25 per cent by volume. The plagioclases are lath-shaped and only slightly zoned. Their composition has been determined in both the 156-Núpar lava (Noe-Nygaard 1952a) and in the 310-Grímsvötn tephra (Noe-Nygaard 1951), and was found to be about An 70—75 in both cases. The olivines are euhedral and sometimes skeletal while the

TABLE 7. CHEMICAL ANALYSES AND CIPW-NORMS (WT.%) OF BASALTS OF THE GRÍMSVÖTN SYSTEM
ANALYST: GREENL. GEOL. SURVEY, CHEM. LAB., I.SØRENSEN.

ROCK. NO	163	83	351	167	156	355	80	484	310
SiO2	48.54	48.12	49.26	49.09	49.05	49.90	50.37	49.59	50.77
TiO2	2.35	2.40	2.48	2.69	2.59	2.87	2.90	2.95	3.07
Al2O3	15.02	14.86	14.55	13.89	13.90	13.46	13.53	13.47	13.56
Fe2O3	1.92	2.30	1.73	2.12	2.26	1.71	2.32	2.76	2.61
FeO	9.79	9.87	10.24	10.74	10.61	11.72	11.34	11.09	11.37
MnO	.19	.19	.23	.20	.20	.21	.21	.21	.21
MgO	6.71	6.40	6.08	6.40	6.04	5.64	5.70	5.61	4.77
CaO	11.77	11.32	11.15	11.04	10.88	10.35	10.31	10.28	9.43
Na2O	2.27	2.60	2.83	2.68	2.58	2.67	2.62	2.44	2.89
K2O	.26	.27	.43	.38	.37	.45	.44	.44	.52
P2O5	.25	.28	.30	.29	.28	.34	.38	.33	.39
H2O	.33	.52	.20	.54	.50	.67	.30	.70	.42
Sum	99.40	99.13	99.48	100.06	99.26	99.99	100.42	99.87	100.01
CIPW	WEIGHT-NORM								
Q					.66	1.40	2.68	3.31	4.05
OR	1.54	1.60	2.54	2.25	2.19	2.66	2.60	2.60	3.07
AB	19.21	22.00	23.95	22.68	21.83	22.59	22.17	20.65	24.46
AN	30.03	28.08	25.73	24.75	25.26	23.41	23.86	24.50	22.49
DI	21.93	21.55	22.79	23.17	22.18	21.36	20.54	20.12	18.09
HY	17.83	13.77	12.95	16.20	17.80	19.18	18.52	17.61	16.91
OL	.72	3.07	3.42	1.63					
MT	2.78	3.33	2.51	3.07	3.28	2.48	3.36	4.00	3.78
IL	4.46	4.56	4.71	5.11	4.92	5.45	5.51	5.60	5.83
AP	.58	.65	.70	.67	.65	.79	.88	.76	.90
	99.07	98.61	99.28	99.52	98.76	99.32	100.12	99.17	99.59
Fe2O3/FeO	.20	.23	.17	.20	.21	.15	.20	.25	.23
Fi-index	20.75	23.60	26.49	24.92	24.68	26.65	27.45	26.56	31.58
FeO*/MgO	1.72	1.87	1.94	1.98	2.09	2.35	2.36	2.42	2.88

Key to Table 7. Locations of chemically analysed samples are shown on Plate IV. See text to Table 1.

Tholeiites

1.	163	—	Lambavatn lava	0.5 m below surf.
2.	083	—	Hálsagígar lava	at surface
3.	351	—	Bergvatnsá lava	at surface
4.	167	—	Bunuhólar lava	2 m below surf.
5.	156	—	Núpar lava	4 m below surf.
6.	355	—	Fljótsoddi lava	0.4 m below surf.
7.	080	—	Lakagígar lava	3 m below surf.
8.	484	—	Lyngfell lava[1]	surface
9.	310	—	Grímsvötn 1934[2]	

1 collected by B. Jónasson (1974, No. SKP17).
2 collected by A. Noe-Nygaard (1951, cf. Table 2).

augites usually exhibit undulatory extinction and are often curved. The order of beginning crystallization is generally plagioclase before olivine before augite, although almost simultaneously (cf. Table 12). Microphotographs of the 080-Lakagígar and 351-Bergvatnsá lavas are shown in Fig. 18 to represent the lavas of the Grímsvötn system. Several gabbroic nodules were collected and there appears to be a complete gradation from glomerophyric clusters to true gabbroic nodules (cf. p. 72). The primocryst phases of the nodules are generally indistinguishable from the macrophenocrysts of the lavas.

Chemistry. Nine new major element chemical analyses of the Grímsvötn system basalts are presented in Table 7. A thorough description and a chemical analysis of one of the samples, the 310-Grímsvötn 1934 tephra (Table 7, no. 9), has previously been given by Noe-Nygaard (1951), who also discussed the petrology of the Grímsvötn 1922 and the Thórdarhyrna 1903 tephras. Moreover, Steinthórsson (1978) has presented several chemical analyses on Grímsvötn tephras from the Bárdarbunga ice core.

The basalts are tholeiites (p. 77), and analysed samples, which cover all the 8 subaerial eruption units and 1 subglacial eruption, show a

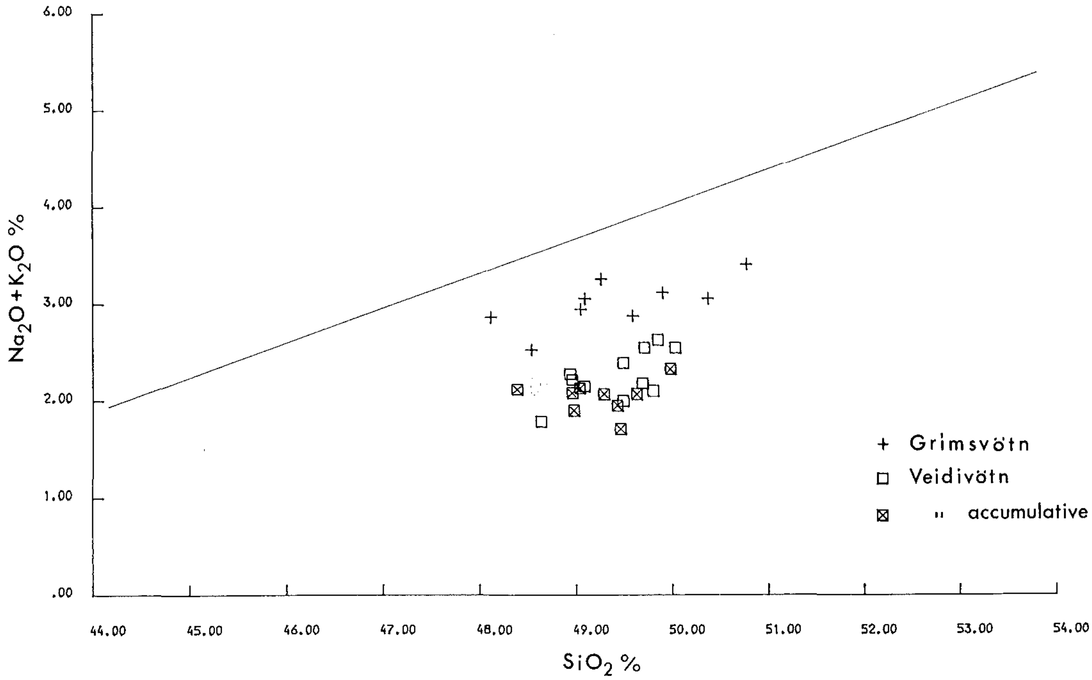


Fig. 19. Alkali:silica diagram of the basalts of the Grímsvötn and Veidivötn volcanic systems. The plagioclase accumulative Veidivötn lavas are indicated.

rather limited compositional range. With reference to a stabilized Fe_2O_3/FeO ratio of 0.14 (cf. Fig. 34), analyses nos. 1—5 are Ol-normative and analyses nos. 6—9 Qz-normative (Table 7), the shift occurring at a FeO*/MgO ratio of 2.2. The content of normative Hy varies from 12.2 to 20.2 per cent after correction for oxidation. The MgO content is low, or between 4.8 and 6.7 per cent.

In the alkali:silica diagram (Fig. 19), the basalts plot well below the alkalic/tholeiitic division line, although at a comparatively high alkali content for a tholeiitic suite. The lavas form an elongated group roughly parallel to the alkalic/tholeiitic division line and thus coincide with the Thingmúli trend (Fig. 23). In this plot they separate well from the only other tholeiitic system of the EVZ, the Veidivötn system.

The basalts of the Grímsvötn system appear to be in chemical composition very similar to the tholeiites of Thingmúli (Carmichael 1964). An analyses of a dyke east of Ketilhnúkur (Carmichael op. cit. Table 2, no. 3) is for instance nearly indistinguishable from the 355-Fljótsoddi lava. Some of the basalts from the Northern Zone (Sigvaldason 1974b) are also similar, see Fig. 23. It is interesting to note that the non-porphyritic magma type in Mull (Bailey et al. 1924, Table II, no. I) is quite similar in chemistry to the Grímsvötn system basalts, with only minor differences in SiO_2, TiO_2 and FeO*. At 45°N on the Mid-Atlantic Ridge, both in Confederation Peak and Bald Mountain (Aumento 1968, Aumento & Loncarevic 1969), tholeiites of similar composition have also been produced.

The Veidivötn volcanic system

Geology. The Veidivötn volcanic system (Fig. 24) differs from the other systems in the EVZ, in that there is no acid centre (central volcano) associated with it. From a structural point of view, the Torfajökull complex might be considered (cf. p. 28), but this is unacceptable from

Fig. 20. Part of the Veidivötn volcanic system. View northeastwards along the Heljargjá graben. The tuff ring Fontur is seen to the left, and the tuff ring Máni farther to the northeast, both straddling Heljargjá. Vatnajökull in the background to the right. Air photograph by the Danish Geodetic Survey, autumn 1938.

a petrochemical point of view. The Veidivötn tholeiites and the Torfajökull transitional alkali basalts belong to two different rock series, the tholeiitic and the transitional series, respectively. Thorarinsson et al. (1974) have on the basis of satellite images tentatively suggested that Hamarinn and Bárdarbunga in Vatnajökull (in a northeast continuation of the Veidivötn system) might be central volcanoes. However, because of the lack of any volcanological and petrological evidence these topographic highs cannot reasonably be connected to the Veidivötn system. A geological map of the Veidivötn volcanic system is presented in Plate V. A map of the extensive Tungná lavas, which have flowed to the southwest is given by Vilmundardóttir (1977).

The northeasternmost part of the Veidivötn system is covered by ice, the Köldukvíslarjökull, an outlet of Vatnajökull (Figs. 17 and 20). There are no indications that the system reaches further than to the Hamarinn massif northeast of the Köldukvíslarjökull. The Veidivötn system is thus probably about 86 km long and usually about 10—12 km in width. The topography is smooth (Fig. 20), rising gradually from 550 m a.s.l. in the southwest to some 1000 m in the northeast. As no central volcano is developed, there is no marked topographic high. The geomorphology of the southwestern part has been described by Nielsen (1933), and the hydrology and general geology of the area has been treated by Sigbjarnarson (1972). Several hyaloclastite ridges, which petrographically resemble the lavas of the Veidivötn system, outcrop within and just outside the present area of the system. Extensive areas of similar rocks in the Graenifjallgardur-Tungnárfjöll region to the southeast may indicate that the fissure system has moved to the northwest since Upper Pleistocene times.

Altogether 75 individual eruption units have tentatively been identified in the volcanic system, all of them basaltic. This number is uncertain as it is often difficult to distinguish the lavas both in field and in thin section. Moreover, several lavas may be totally covered in the central region where faulting and subsidence is great. At least two eruptions within the system have occurred in historical time. The 052-Veidivötn lava and the 292-Svartikrókur tephra have been produced after the Norse settlement (Thorarinsson 1967a) and even as late as in the 16th century (Larsen, pers. comm.). The 021-Ljótipollur tephra and the rhyolitic Sydrinámur and Laugar lavas in the Torfajökull complex were erupted at the same time. It has also suggested Larsen (pers. comm.) that the 268-Vatnaöldur and the 293-Hnausapollur tephras erupted in the 9th century, simult-

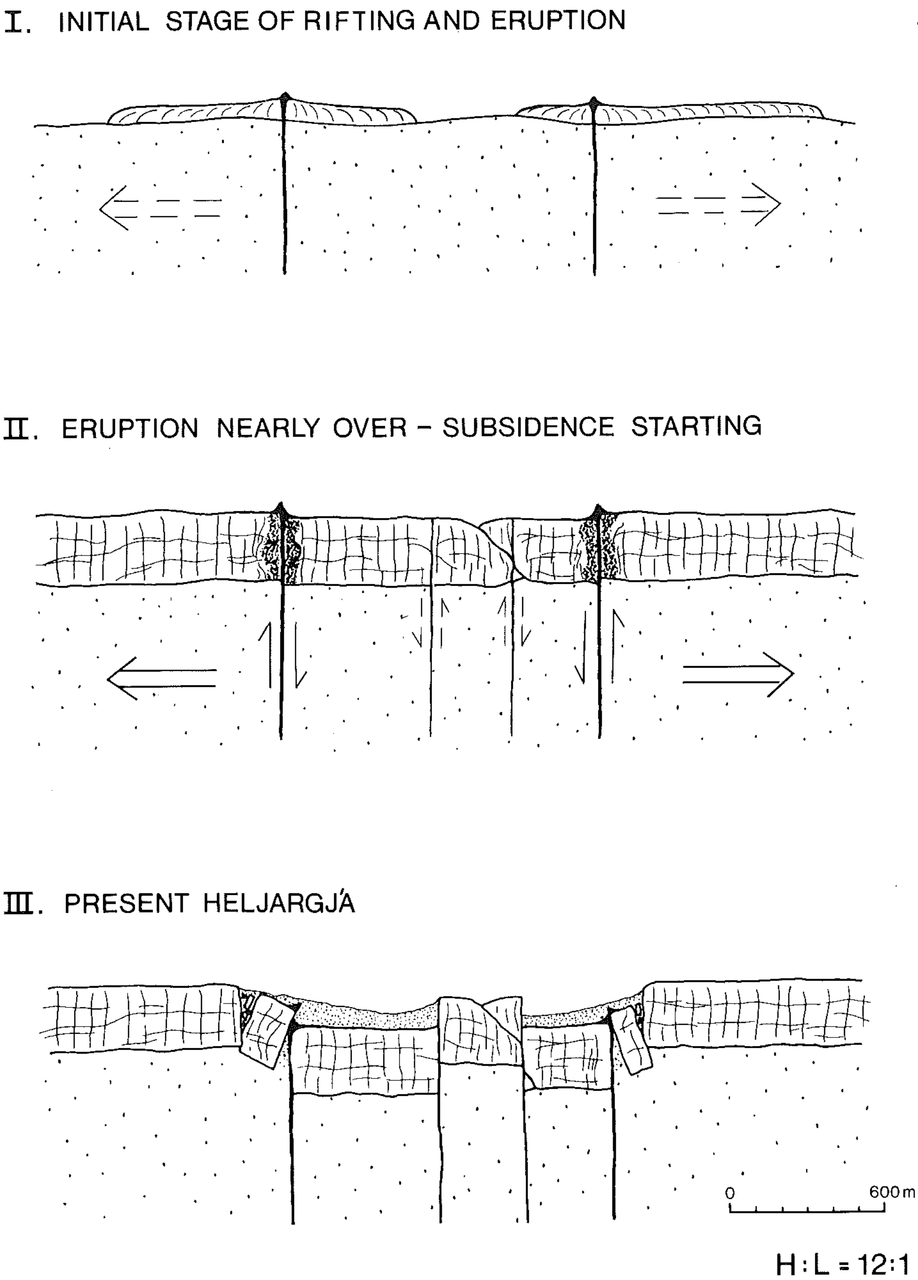


Fig. 21. Sketches illustrating the formation of the 388-Heljargjá lava and Heljargjá graben in the Veidivötn volcanic system. About 1.7 km^3 of lava was erupted within a very short time interval from fissures along a 6 km long section. Only minor crater walls were formed. Subsidence took place mainly during eruption. Parallels may be drawn to the events in Krafla, which started in 1975 (Björnsson et al., 1977). The section is about 3 km NE of the tuff ring Máni (cf. Fig. 20).

aneously with the Hrafntinnuhraun in the Torfajökull system.

Although no central volcano has apparently developed within the system, there are several signs that the area between Klofnafell and Máni is developing into such a centre (Fig. 20). In this area the subsidence is apparently greater and the number of eruptions greater than in other parts of the system. It is also significant that the number of gabbroic nodules in lavas reaches a maximum in this area, which may indicate that magma reservoirs are larger or more common in the crust below this area than elsewhere in the system.

The volume of the Veidivötn tholeiitic lavas north of Tungná is calculated to be 16.0 km^3. Vilmundardóttir (1977) has made a thorough investigation of the 11 lavas ("Tungná lavas") which are found south of the Tungná river. These lavas amount to 35 km^3. The 147-Tjörvi lava (THj) which is usually counted with the Tungná lavas actually belongs to the Torfajökull volcanic system, and is not included here. The volume of the smallest lavas is about 0.02(?) km^3, while the largest is the Tungná lava TH_b which is 13.5 km^3 and this is also the largest lava erupted in the EVZ during Postglacial Time. No intermediate or acid extrusives are found in the Veidivötn volcanic system, and no signs of any hydrothermal high-temperature activity has been discovered.

Much of the lava and tephra of the southern part of the system has been dated by the aid of tephrochronology. The age of the 10 Tungná lavas which belong to the system is fairly well known (Vilmundardóttir 1977), however, it has only been possible to identify the eruption site of one of these lavas. There are indications that there were two distinct eruption periods in the southern part of the system, one from approximately 11000 to 6500(?) y.b.p., and another 4000—0 y.b.p. (Vilmundardóttir 1977).

The Veidivötn volcanic system is characterized by long eruption fissures, which in many cases extend tens of kilometers (cf. Fig. 17). The most common type of eruption site is the spatter cone row (19 cases), while cinder-spatter cone rows were found in 11 cases and cinder cone rows in 9 cases. The surface morphology of the lavas is quite variable, many of the lavas being aa-lavas but a morphology which can be classified as "rough pahoehoe lava" is also common.

Tectonic activity has been strong in the system and many open fissures and narrow grabens intersect the lavas throughout the system. The average trend of the eruption fissures is 046°. Most of the eruptions probably occur at the same time as graben subsidence and dilatation and may therefore be due to a similar mechanism as is occurring in the Krafla area at present (Björnsson et al. 1977). The largest graben is the Heljargjá (Fig. 20), which can be traced from near Thóristindur in the southwest into the Mókollar in the northeast, a distance of some 53 km. The formation of Heljargjá is sketched in Fig. 21.

Petrography. Samples were obtained from all the 75 basaltic eruption units which were identified in the Veidivötn system. The relatively large variation in the rock chemistry of the lavas is probably due to variations in the amounts of macrophenocrysts (p. 68). The less porphyritic lavas resembles in their petrography the lavas of the other tholeiitic system, Grímsvötn. The groundmass of the lavas is normally micro- to phanerocrystalline. All the lavas are porphyritic, and lavas with about 6—20 per cent by volume of plagioclase macrophenocrysts are typical for this system. The rock colour is mainly medium dark grey, and the predominant groundmass texture is intergranular to subophitic.

Macrophenocrysts of plagioclase are found in all lavas and may reach 27.5 per cent by volume, whereas olivine and augite do not exceed about 2 per cent by volume, respectively. The composition of the plagioclase phenocrysts has been determined optically in 6 of the socalled Tungná lavas (Vilmundardóttir 1977) and indicated a composition of An 85—90. Chemical analyses by Sørensen (1950) and Wetzel et al. (1978) on plagioclases in the 142-Kvísl lava (TH_f) indicate a plagioclase composition of An 85—88. The olivines were found

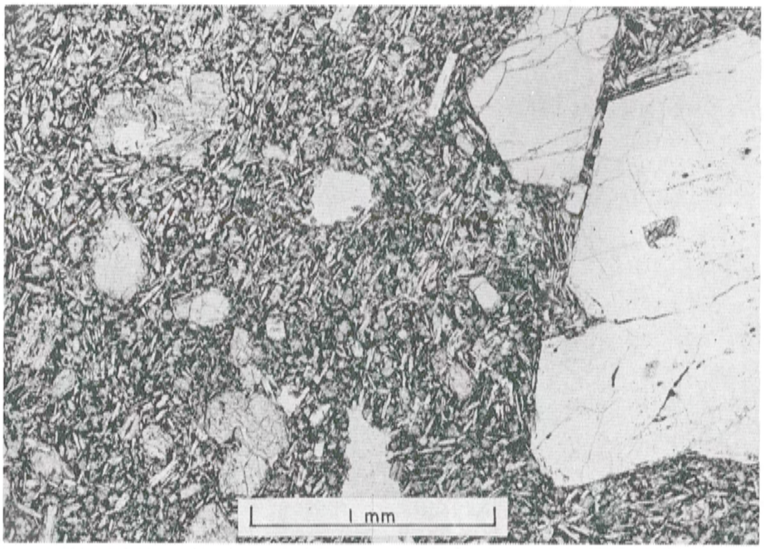


Fig. 22A. Tholeiite, the 063-lava (N710). Macrophenocrysts of olivine and plagioclase, microphenocrysts of plagioclase, augite and olivine. Intergranular texture.

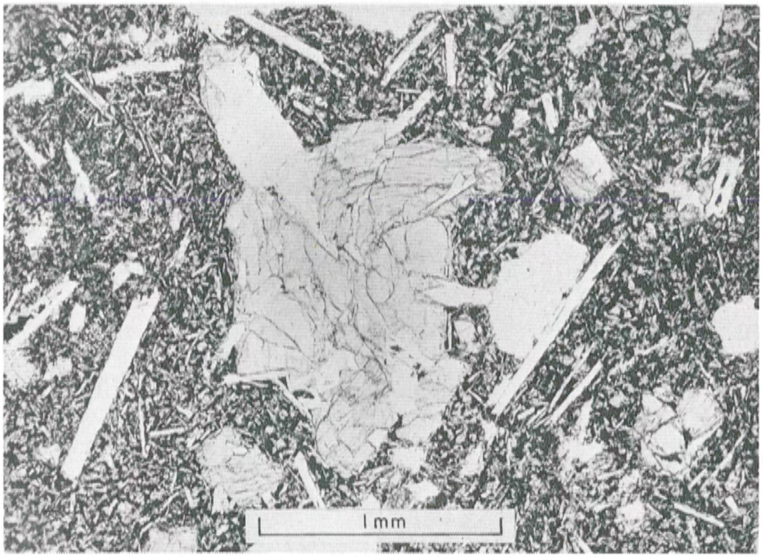


Fig. 22B. Tholeiite, the 363-Brydja lava (N797). Microphenocrysts of plagioclase, curved augite and olivine, some very large. Texture intergranular.

by optical methods (Vilmundardóttir 1977) to have a composition of Fo 70—90. The composition of the augite macrophenocrysts is unknown.

The amount of microphenocrysts varies usually between 3 and 5 per cent by volume, occasionally reaching 14 per cent by volume. Their habit is very similar to those of the lavas of the Grímsvötn system, The composition of the plagioclase microphenocrysts is known in a few of Tungná lavas (Vilmundardóttir 1977), and is around An 70, or of similar composition as in the Grímsvötn system. As regards the order of initial crystallization of both macro- and microphenocrysts the same relationships are valid as for the Grímsvötn system, (cf. Table 12). Clots of tiny clinopyroxene grains were noticed in a few of the lavas of the Veidivötn system. These clots might be the final stage of resorption and reaction of some higher P-T mineral to lower P-T conditions. Microphotographs of two lavas, which were chosen to represent the system are presented in Fig. 22.

A great number of gabbroic nodules were

TABLE 8. CHEMICAL ANALYSES AND CIPW-NORMS (WT.%) OF BASALTS OF THE VEIDIVÖTN SYSTEM
ANALYST: GREENL. GEOL. SURVEY, CHEM. LAB., I. SØRENSEN.

ROCK. NO	51	371	63	282	479	280	388—	—389—	—249	277	56	358
SiO2	48.64	48.98	49.04	49.80	49.69	49.63	48.39	48.60	48.77	49.46	49.29	49.49
TiO2	.83	1.06	1.17	1.28	1.32	1.25	1.34	1.36	1.17	1.57	1.26	1.48
Al2O3	18.67	16.09	15.80	14.40	14.85	14.97	17.84	17.61	19.34	14.53	16.00	14.32
Fe2O3	1.35	1.21	2.21	1.29	6.83	1.71	1.84	2.98	1.00	1.39	2.71	1.85
FeO	6.54	8.33	7.88	9.26	3.78	8.62	7.26	6.38	7.10	9.52	7.29	9.20
MnO	.14	.17	.17	.18	.17	.18	.15	.16	.14	.19	.17	.18
MgO	7.20	8.26	7.80	8.13	7.75	7.82	6.43	6.70	6.06	7.91	7.12	7.78
CaO	13.98	13.17	13.00	13.13	12.80	13.13	13.50	13.46	13.94	12.79	13.34	12.82
Na2O	1.73	1.78	1.99	1.98	2.03	1.98	2.01	2.03	1.89	2.14	1.98	2.09
K2O	.06	.12	.14	.12	.15	.09	.11	.14	.13	.13	.09	.13
P2O5	.13	.16	.18	.16	.16	.16	.18	.19	.17	.19	.16	.17
H2O	.43	.52	.54	.41	.52	.46	.48	.42	.28	.28	.37	.41
Sum	99.70	99.85	99.92	100.14	100.05	100.00	99.53	100.03	99.99	100.10	99.78	99.92
CIPW WEIGHT-NORM												
Q					5.58			.47			1.02	
OR	.35	.71	.83	.71	.89	.53	.65	.83	.77	.77	.53	.77
AB	14.64	15.06	16.84	16.75	17.18	16.75	17.01	17.18	15.99	18.11	16.75	17.69
AN	43.00	35.56	33.77	30.05	30.97	31.70	39.33	38.53	43.91	29.66	34.51	29.31
DI	20.70	23.42	24.02	27.84	24.52	26.44	21.56	21.79	19.74	26.64	24.84	27.12
HY	14.29	16.24	16.26	16.79	7.93	17.95	13.50	13.48	13.25	15.04	15.06	17.06
OL	2.45	4.20	1.83	2.91		.95	1.37		1.98	4.17		1.69
HE					.68							
MT	1.96	1.75	3.20	1.87	8.91	2.48	2.67	4.32	1.45	2.02	3.93	2.68
IL	1.58	2.01	2.22	2.43	2.51	2.37	2.54	2.58	2.22	2.98	2.39	2.81
AP	.30	.37	.42	.37	.37	.37	.42	.44	.39	.44	.37	.39
	99.27	99.33	99.38	99.73	99.53	99.54	99.05	99.61	99.71	99.82	99.41	99.51
Fe2O3/FeO	.21	.15	.28	.14	1.81	.20	.25	.47	.14	.15	.37	.20
Fi-index	14.99	15.77	17.67	17.46	23.64	17.29	17.66	18.47	16.76	18.88	18.31	18.45
FeO*/MgO	1.08	1.14	1.27	1.28	1.28	1.30	1.39	1.35	1.32	1.36	1.37	1.40

ROCK. NO	473	274	456—	—455	459	463	278	366	52	372	363
SiO2	48.94	49.09	48.96	49.55	48.96	49.43	49.98	49.49	50.03	49.71	49.85
TiO2	1.57	1.60	1.28	1.85	1.66	1.55	1.47	1.69	1.75	1.88	2.02
Al2O3	14.70	14.41	18.72	13.96	15.36	15.71	16.03	14.01	14.19	13.82	14.25
Fe2O3	1.43	8.33	1.98	2.05	2.05	2.57	1.46	1.69	1.57	1.39	1.91
FeO	9.50	3.45	6.85	10.18	8.91	8.08	8.98	10.03	10.36	11.11	10.45
MnO	.18	.19	.15	.20	.18	.18	.18	.19	.21	.20	.21
MgO	7.62	7.68	5.92	7.21	7.30	7.07	6.69	7.24	6.91	6.81	6.35
CaO	12.74	12.69	13.70	12.20	12.75	12.98	12.28	12.20	11.99	11.60	11.48
Na2O	2.12	1.98	1.94	2.23	2.08	1.79	2.09	2.22	2.34	2.36	2.34
K2O	.16	.17	.14	.16	.14	.16	.24	.17	.21	.19	.29
P2O5	.19	.20	.18	.20	.19	.20	.20	.20	.23	.22	.28
H2O	.46	.38	.36	.46	.49	.54	.63	.46	.37	.52	.52
Sum	99.61	100.17	100.18	100.25	100.07	100.26	100.23	99.59	100.16	99.81	99.95
CIPW WEIGHT-NORM											
Q		5.70	.68			2.04	.78				1.13
OR	.95	1.00	.83	.95	.83	.95	1.42	1.00	1.24	1.12	1.71
AB	17.94	16.75	16.42	18.87	17.60	15.15	17.69	18.79	19.80	19.97	19.80
AN	30.12	29.93	41.96	27.61	32.16	34.36	33.65	27.76	27.60	26.56	27.52
DI	26.08	24.69	20.23	25.96	24.39	23.38	21.32	25.85	25.04	24.43	22.78
HY	14.13	7.68	13.99	19.31	16.75	16.71	19.37	18.81	19.70	20.35	19.22
OL	4.43			.15	1.29			.80	.28	.76	
HE		3.43									
MT	2.07	7.10	2.87	2.97	2.97	3.73	2.12	2.45	2.28	2.02	2.77
IL	2.98	3.04	2.43	3.51	3.15	2.94	2.79	3.21	3.32	3.57	3.84
AP	.44	.46	.42	.46	.44	.46	.46	.46	.53	.51	.65
	99.15	99.79	99.82	99.79	99.58	99.72	99.60	99.13	99.79	99.29	99.43
Fe2O3/FeO	.15	2.41	.29	.20	.23	.32	.16	.17	.15	.13	.18
Fi-index	18.89	23.46	17.92	19.82	18.43	18.14	19.89	19.79	21.04	21.09	22.65
FeO*/MgO	1.42	1.43	1.46	1.67	1.47	1.47	1.54	1.60	1.70	1.82	1.92

found in the extrusives of this system. Most often, the greatest number of nodules are found in the more porphyritic lavas. The spatial distribution of gabbroic nodules is such, that they are most abundant in lavas which have extruded between Klofnafell and Máni (Plate V).

Chemistry. Twenty three major element chemical analyses of the Veidivötn system basalts are presented in Table 8. while the number of analyses is relatively fewer than in the other systems, it is nevertheless believed that they cover all compositions in space and time. Vilmundardóttir (1977) has previously published 9 chemical analyses of the Tungná lavas and has compared them to other recent tholeiites of Iceland. Thorarinsson & Sigvaldason (1972b) have published an analyses and description of the 486-Tröll lava of A. D. 1862—1864.

The lavas, which are all tholeiites, are typically highly plagioclase porphyritic, and it can be suggested that all lavas with a plagioclase macrophenocryst content exceeding about 8—9 per cent by volume are accumulative with respect to plagioclase, see p. 83. Correction of these cumulative samples will narrow the compositional range of the Veidivötn system lavas considerably in many chemical plots, although it has little effect in the alkali:silica diagram (Fig. 19). In Table 8, no. 15—16 the effect of flowage differentiation of the 456-Rendur lava can be seen. Analysis no. 15 is of the most porphyritic part of this lava (32.5 per cent plagioclase macrophenocrysts) and no. 16 is of the least porphyritic part (0.8 per cent plagioclase phenocrysts).

All the lavas, except no. 3, are olivine normative, and the content of normative hypersthene varies between 11.7 and 21.9 after correction of the Fe_2O_3/FeO ratio to 0.14 (cf. Fig. 34). The FeO*/MgO ratio varies from 1.28 to 1.94, and the MgO-content is somewhat higher than in the Grímsvötn system, or about 6.4 to 8.1 per cent MgO in the non-accumulated lavas.

In the alkali:silica diagram the lavas plot at a very low level and form a distinct group clearly separated from the Grímsvötn tholeiites (Fig. 19).

Vilmundardóttir (1977) has observed that the great Tungná lavas, which originate from the southwesternmost part of the swarm, tend to change in composition with time. The content of alkalies and silica appears to decrease towards the present. In other parts of the systems this has not been observed. There is a certain tendency for the lavas which are highest in incompatible elements to be grouped in the areas of Klofnafell-Máni, and Askar (northeast of Bláfjöll) (Plate V).

Only a very few descriptions of rocks directly comparable with the plagioclase porphyritic tholeiites of Veidivötn have been found in the literature. In Iceland, some of the tholeiites of the Northern Zone (Sigvaldason 1974b) are very similar (Fig. 23). Outside Iceland the rocks of the porphyritic central magma Type of Mull (Bailey et al. 1924, Table VI, no. III) are fairly close in composition to the accumulated Veidivötn lavas.

Key to Table 8. Locations of chemically analyses samples are shown on Plate V. See text to Table 1.

Tholeiites

1.	051	—	Fellsendi lava	surface
2.	371	—	Tungnárbotnar l.	surface
3.	063	—	lava	surface
4.	282	—	Flögd lava	surface
5.	479	—	tephra	surface
6.	280	—	Helgrindur lava	surface
7.	388	—	Heljargjá lava	1.5 m below surf.
8.	(389)	—	Heljargjá lava	1.5 m above l. surf.
9.	(249)	—	Heljargjá lava	1.4 m below surf.
10.	277	—	tephra	surface
11.	056	—	lava	surface
12.	358	—	Kaldakvísl lava	at surface
13.	473	—	lava	surface
14.	274	—	tephra	surface
15.	456	—	Rendur lava	2.7 m below surf.
16.	(455)	—	Rendur lava	1.5 m below surf.
17.	459	—	Litladyngja lava	1 m below surf.
18.	463	—	Dreki lava	0.5 m below surf.
19.	278	—	Botnar lava	surface
20.	366	—	Askar lava	0.5 m below surf.
21.	052	—	Veidivötn lava	at surface
22.	372	—	Dvergar lava	at surface
23.	363	—	Brydja lava	1 m below surf.

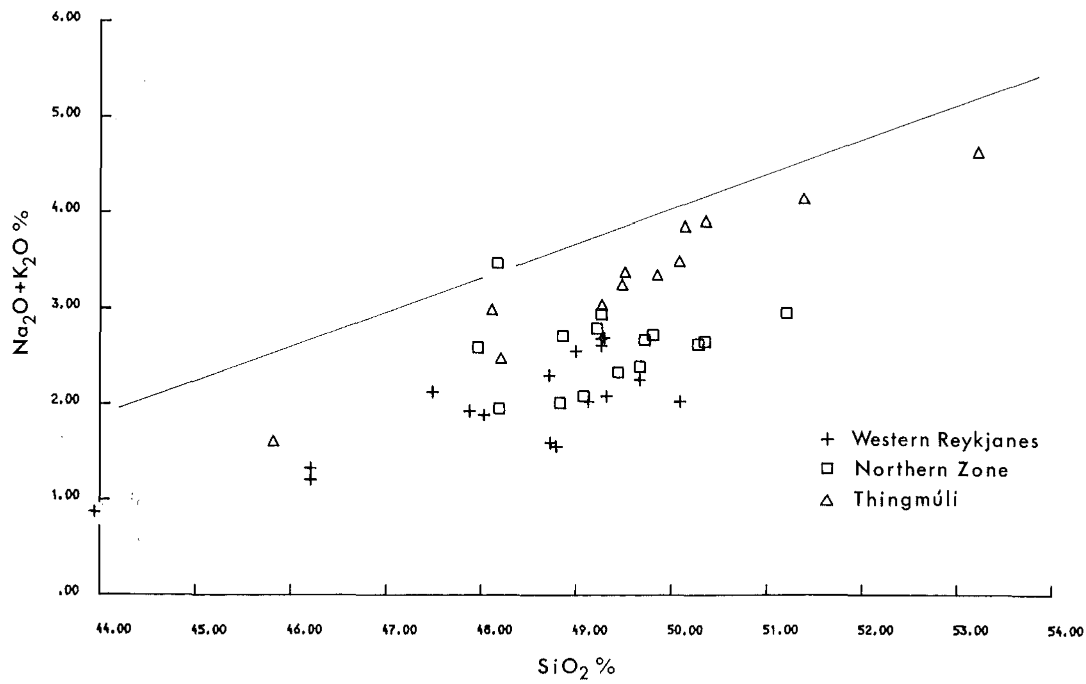


Fig. 23. Alkali:silica diagram of tholeiitic basalts from the western Reykjanes Peninsula (Jakobsson et al., 1978), the Northern Zone (Sigvaldason, 1974b) and the Tertiary Thingmúli volcano (Carmichael, 1964).

The reason for the scarcity of descriptions of similar rocks is possibly the tendency among many petrologists to avoid porphyritic igneous rocks in their work. Very often a petrological study is limited to rocks with less than 10 per cent by volume of phenocrysts. Such an approach to the rocks of the EVZ, would have meant considering less than 30 per cent of the Grímsvötn and Veidivötn tholeiite lavas, which would have limited the value of the study considerably.

GENERAL FEATURES

The volcanic systems

A fundamental conclusion of the present study is that the Eastern Volcanic Zone can be divided into nine volcanic systems active in Upper Pleistocene and Postglacial Time, and that each of these systems has a characteristic petrology.

As discussed above six of the volcanic systems could be described as volcanic fissure swarms and three as central volcanoes. These concepts are not old in Icelandic geological literature. Walker (1963, 1974) was first to describe and define a central volcano in Iceland, and before that several authors had discussed the existence of stratovolcanoes such as Hekla, Eyjafjallajökull and Öraefajökull within the active volcanic zones (Einarsson 1950b, Thorarinsson 1960). Walker also found that a narrow basaltic dyke swarm passes through the core of each of the Tertiary central volcanoes of eastern Iceland, closely resembling those associated with the Mull and other Tertiary volcanic centres in the British Isles. He mentioned Hekla and the Mývatn region as probable recent counterparts to the Tertiary volcanoes.

It also soon became evident that Postglacial eruption sites in Iceland tend to form groups or swarms and that these were possible surface equivalents to dyke swarms like those found in eastern Iceland. This grouping of eruption sites is in most cases evident when the geologic maps of SW- and central South-Iceland, published by Kuthan (1943) and Kjartansson (1960 and 1962), are studied. Gradually the presence of these Postglacial volcanic fissure swarms and central volcanoes in Iceland was acknowledged (e.g. Tryggvason 1968) and described from various parts of the volcanic zones (Saemundsson 1972 & 1974, Jakobsson 1974, Jakobsson et al. 1978 and Saemundsson 1978).

In the Northern Zone, Saemundsson (1974) found that the relationship between the central volcanoes and the fissure swarms are quite comparable to those described by Walker in eastern Iceland, and he consequently considered them as surface expressions of the eroded volcanoes and associated dyke swarms from the Tertiary. In the western Reykjanes Peninsula Jakobsson et al. (1978) demonstrated the existence of similar basaltic fissure swarms, and while no central volcanic complexes have developed, some strongly related features are present, like the high temperature thermal areas. Finally Saemundsson (1978) has shown that the active volcanic zones can be divided into swarms and central volcanoes.

In the present paper the term volcanic system is introduced to cover both the terms volcanic fissure swarm and central volcano. Based on the present author's results from the EVZ and western Reykjanes Peninsula the following broad definition of a volcanic system can be made: A *volcanic system* is a spatial grouping of eruption sites in a certain period of time (short in the geologic sense), with particular characteristics of tectonics, petrography and geochemistry. At a primitive stage the system has the characteristics of an eruptive fissure swarm, with basaltic rocks dominating. Later, evolved rocks start to develop in a certain area or areas (centres), and the ratio between evolved rocks/basalts will gradually rise with time. In the same area a caldera and a high-temperature thermal field mostly develops leading in the end to the formation of a "central volcano". The dimensions of a volcanic system on the surface vary between 17 and 105 km in length and 4 and 30 km in width. It is anticipated that each system has a lifetime of 300,000—500,000 years (Saemundsson 1978), some systems may even reach an age of 2 to 2.5 million years (Jóhannesson 1975), as in case of the large central volcanoes. The term volcanic system is used here in a similar sense as by Smith & Shaw (1975) for the volcanic structures and associated hydrothermal systems in the western United States.

Fig. 24 shows the volcanic systems of the EVZ as defined from a petrological point of view. These volcanic systems are more variable in structure and petrology than in any other region of Iceland, which is probably a consequence of the fact that the EVZ is a flank zone which is connected to the axial zone (Jakobsson 1972). Different rock series have been developed in this tectonically complex region and moreover, there are indications that the volcanic systems are in different stages of evolution or maturity. In Table 9, the nine volcanic systems are tentatively listed according to the present stage of evolution as inferred by the ratio between evolved rocks and basalts, the development of a central caldera and a high-temperature thermal area. As far as is known, the order of the systems in Table 9 is in agreement with the highest observed age in the field, as discussed in the previous sections.

The division of the EVZ into nine volcanic systems is a straightforward and natural one, where each system is separated geographically, petrographically and by chemistry, as shown above. In each volcanic system a centre of especially intense volcanism can be defined as shown in Fig. 24. In the case of the Veidivötn and Katla systems and possibly also the Grímsvötn system two such closely related centres are probably present. It appears possible that all the centres may with time evolve into individual central volcanoes. Each of these centres of intense volcanism incorporates all the Postglacial and Upper Pleistocene intermediate and acid rocks which are exposed in each volcanic system as well as all the high-temperature hydrothermal fields. The area covered by the centres of high volcanic intensity is as shown in Fig. 25, about 65 per cent of the total area of the nine volcanic systems. These

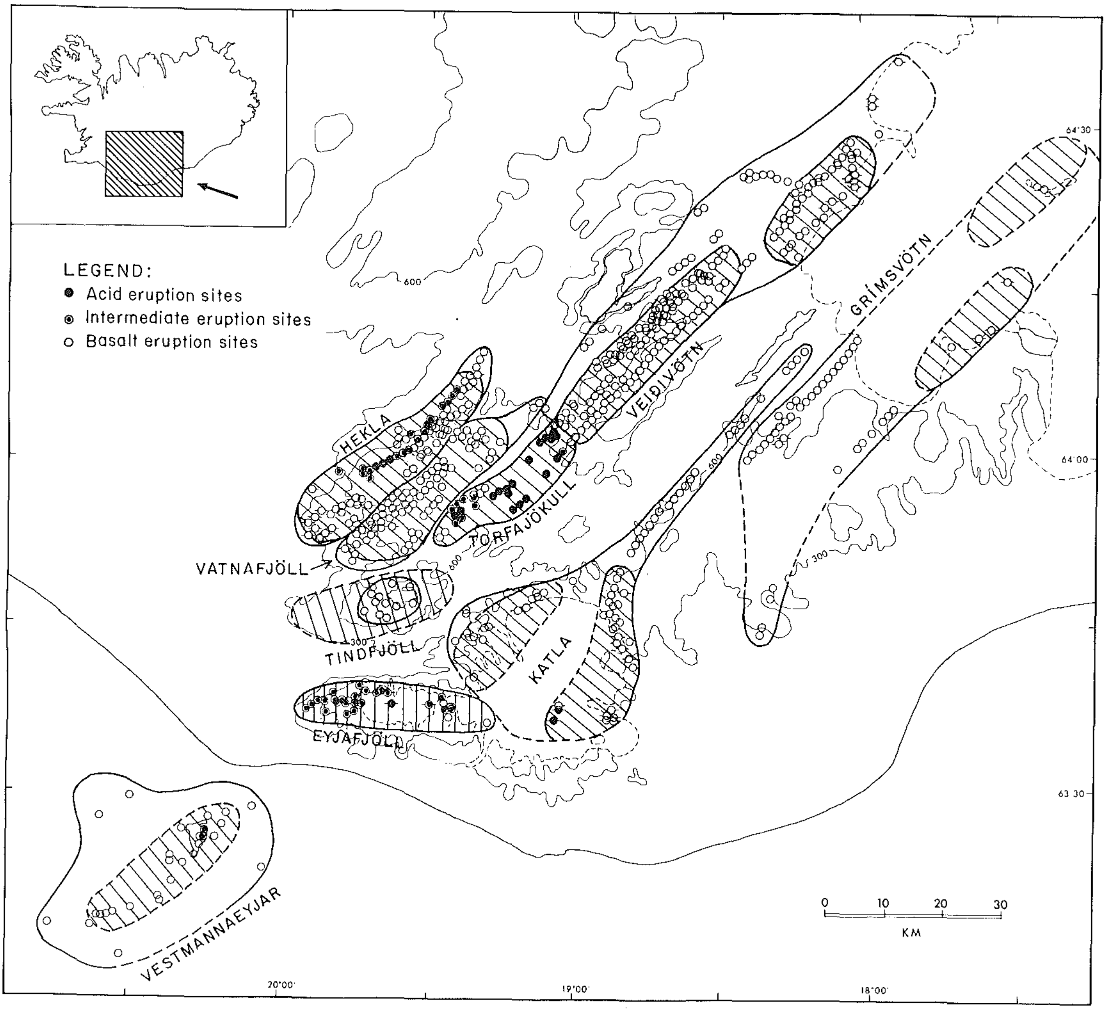


Fig. 24. Map showing the 9 volcanic systems of the EVZ. All known Postglacial eruption sites are shown by circles and dots (diam. 1.2 km); circles with horizontal bar indicate locations approximately known. The intensely active centres (see p. 53) are indicated by oblique lines.

active areas have nevertheless produced about 95 per cent of the volcanic rocks extruded in Postglacial Time in the EVZ.

As already mentioned on p. 19, the distribution of eruption sites within each centre which in Postglacial Time has extruded evolved compositions, is such that the acid rocks are only erupted in the central area, the intermediate rocks are erupted in a zone surrounding the acid core and finally the basalts are extruded in the surroundings (Fig. 24).

The active centres are of very similar surface dimensions, or 9 ($\pm$ 2) $\times$ 35($\pm$ 8) km. Twelve such centres are suggested in the EVZ (Fig. 24) and these are probably directly comparable to the so-called central volcanoes from the Tertiary and Quaternary periods in Iceland. It should be added that in the case of Tindfjöll the main topographical high of this Late Quaternary volcano in included, and in addition the position and existence of the two active areas in the Grímsvötn system is somewhat speculative.

Although the Postglacial volcanic systems have been compared to the Tertiary volcanic swarms of Iceland as described by Walker (1963) there is an important difference between the

Table 9

Tentative classification of the Recent volcanic systems in the Eastern Volcanic Zone according to present stage of evolution in terms of the ratio evolved rocks to basalts, development of caldera and high temperature thermal areas.

Volcanic system	Ratio of evolv. rocks/basalts	Caldera	High temp. thermal area
Veidivötn			
Vestm.eyjar	X		
Vatnafjöll	X ?		
Hekla	XX		
Grímsvötn	?	XX	X
Katla	?	XXX ?	X ?
Eyjafjöll	XXX	XX	
Torfajökull	XXX	XXX	XXX
Tindfjöll	XXX	XX	?

Increasing maturity ↓

X: small XX: moderate XXX: large

model of the present paper and that of Walker.

In the Postglacial volcanic zones, and certainly in the EVZ and the Reykjanes Peninsula, it is found that the volcanic systems (swarms or central volcanoes) embrace *all* the eruption sites, whereas the model of Walker (1963) and indeed also that of Einarsson (1950b) assume that the central volcanoes are superimposed on a vaguely defined regional volcanic zone, which create the flood basalts. The present model is compatible with that of Gibson (1966, 1969), who pointed out that dyke swarm volcanism would produce lenticular masses, and presented some evidence that the Tertiary lava pile of Eastern Iceland was actually made up of such lenses.

Fig. 25 was compiled on the basis of the present author's field data and on a survey of the literature, to show the number and extent of active volcanic systems in Iceland. Four of altogether 29 volcanic systems are alkalic, i.e. Vestmannaeyjar and the three in the Snaefellsnes zone. Seven are of transitional nature i.e. Hekla, Vatnafjöll, Torfajökull, Tindfjöll, Eyjafjöll and Katla, and probably also Öraefajökull. The remaining eighteen systems are tholeiitic. Fig. 25 differs from that of Saemundsson (1978, Fig. 1) in that the present divisions are volcano-petrological whereas Saemundsson's are based on tectonics and structure.

Recognition of the fact that the active volcanic zones actually consist of separate volcanic systems with swarms and central volcanoes, is of fundamental importance to any petrogenetic model which seeks to explain the origin of the basalts and the evolved rocks. Each volcanic system can be considered as a closed petrological system evolving its own typical rock suite.

Another aspect is one of nomenclature. When it is accepted that a volcanic fissure swarm is a volcanic system in the same right as a central volcano, it seems illogical not to treat the Vestmannaeyjar as one volcano just as much as for example the Eyjafjöll complex. The difference between these two systems is primarily one of topography. Single eruption sites in the volcanic systems have commonly been called volcanoes, as for example the VE67-Helgafell cinder cone in the Vestmannaeyjar system (Thoroddsen 1925, Thorarinsson 1960), and the 017-Valagjá explosion fissure in the Hekla system (Thorarinsson 1960). This is of course in agreement with the common usage of the term volcano, which can be used both for a vent through which magma erupts and the form or structure produced by the ejected material (Gary et al. 1972: Glossary of Geology). However, when eruption sites comparable to Helgafell for example are situated on a structure like the Eyjafjöll complex, they would be termed parasite craters. This is very unfortunate since the relative position and importance of these eruption sites is essentially the same in both cases. Here it would actually be more sensible to restrict the usage of the term *volcano* to the whole system, and use the term eruption site or crater for single vents like Helgafell and Valagjá. These are single eruption sites, which belong to a larger volcanic structure and experience suggests that they will not erupt again.

Lateral magma flow

In the current rifting episode in northern Iceland which started in December 1975, the

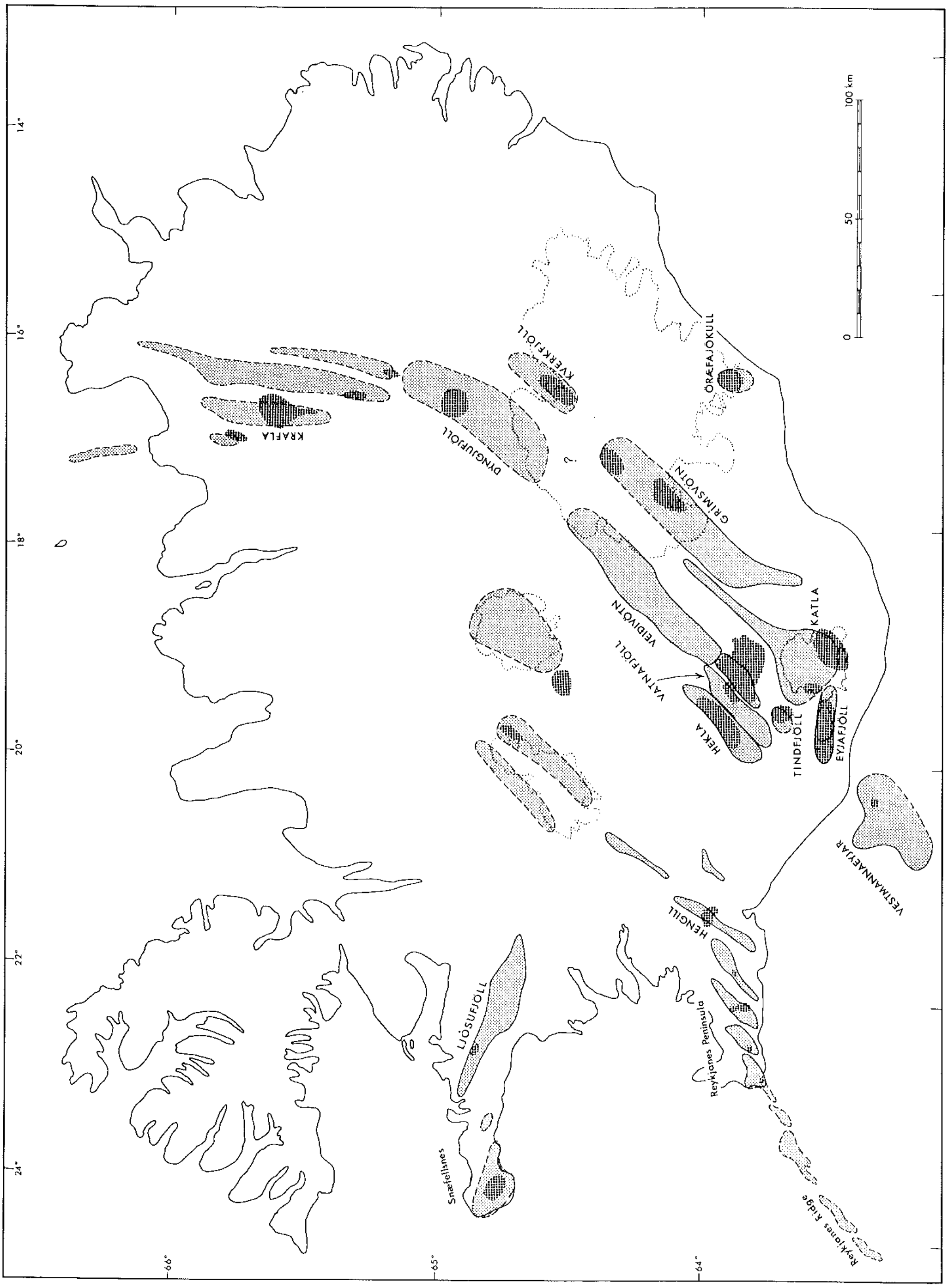


Fig. 25. The volcanic zones of Iceland divided into the 29 volcanic systems (shaded). The position of the differentiated central complexes (Pleistocene-Postglacial) which are thought to be connected with the systems are shown by cross-hatching.

repeated inflation-deflation cycles of the floor of the Krafla central volcano have been interpreted as being caused by magma injection at shallow depth followed by the flow of basalt magma into the fault swarm as far as 50 km towards the north and some 10 km towards the south (Björnsson et al. 1977). Sigurdsson & Sparks (1978) as well as Saemundsson (1978) and Steinthórsson (1978), have proposed that basaltic magmas may flow laterally (approx. horizontally) for up to 70 km from high-level magma reservors in Icelandic central volcanoes. The first authors present three cases to support this hypothesis, the contemporaneous volcanic events in Grímsvötn and Lakagígar in 1783—1784, comparable episode in Askja and Sveinagjá in 1875, and finally they suggest that the (168-?) -Eldgjá eruption may be the result of lateral flow from the Katla caldera. No direct evidence has been found during the present study for such lateral flow at shallow depth of magma in the EVZ. However, such a process has been considered in the interpretation of several of the EVZ data, especially in connection with the spatial distribution pattern of geochemical elements.

It would be logical first to consider the possibility of lateral magma flow having occurred in recent volcanic event in the EVZ which are well recorded or studied. The Grímsvötn-Lakagígar eruption of 1783—1784 in the Grímsvötn volcanic system is probably the most likely case. As noted by Sigurdsson & Sparks (1978), the chemistry of the 080-Lakagígar lava and average compositions of recently erupted material from Grímsvötn match closely, although present data shows the difference to be greater than they reckoned with, cf. Table 7, nos. 7 and 9. Samples from the 1783—1784 Grímsvötn eruption were not available, but all other investigated Grímsvötn basalts are slightly more evolved than the subaerial lavas. It seems possible that in this case magma *may* have flowed laterally from the Grímsvötn caldera, although there is no substanial evidence for this.

The Lambafit-Mundafell eruptions of 1913 in the Hekla system (Bárdarson 1930), may also be considered as a good case. Eruptions started in the Lambafit area from a 5.0 km long fissure and were continued soon after from the 4.4 km long Mundafell fissure in the south (Plate II). The substantial differences in chemical composition between the two lava streams (Table 3, nos. 5 and 7) do not however support the idea of lateral magma flow.

The Surtsey eruptions of 1963—1967 in the Vestmannaeyjar volcanic system might also be considered here. In this case one would expect the lava to flow from the Heimaey area, which is developing into a centre for the Vestmannaeyjar system (p. 12); however, no indication whatsoever was found for any lateral magma flow at shallow depth. The six en echelon eruption fissures formed during the Surtsey eruption were probably fed from small shallow magma pockets, which are best explained as branches of a joint feeder. During the eruptions earthquake foci were located at 0—5 km and 20—25 km depth under and around Surtsey, (Einarsson 1974).

In the case of the tholeiitic Reykjanes Peninsula it seems possible that the eruptive fissures at each end of the fissure swarms are fed by lateral flow of magma. The five volcanic fissure swarms lie en echelon on the inferred plate boundary (Jakobsson et al. 1978, Fig. 1). The intersection between the plate boundary and each swarm may be the main site of upwelling of magma, with lateral flow to each end of the swarm as a result.

In support of the case of lateral magma flow in the EVZ is the fact that the shape of the southwestern end of the Grímsvötn system and the northeastern end of the Katla system is more readily explained assuming flow from the central volcanoes of Grímsvötn and Katla (Fig. 24). The close proximity of eruption fissures producing tholeiite and transitional alkali basalt, respectively, in this area, is also more understandable if one assumes a flow of transitional alkali basalt magma from the SW and tholeiite magma from the NE (Sigurdsson & Sparks 1978, Steinthórsson 1978). A comparable case is to be found where the Hekla and the Veidivötn systems meet (Fig. 24). The surprising homogeneity of extruded material along the large fissures, such as the

080-Lakagígar, the 168-Eldgjá and the 158-Kambar eruption fissures for example, is also better understood by lateral flow. For instance, a 24 km long magma chamber beneath the 1783-1784 Lakagígar fissure would be expected to result in heterogenous basalt magma.

Although lateral flow of basalt magma must thus be considered as possible, it is surprising that no evidence (except in the case of the acid Dómadalur lava) was found in either the field or geochemical data for the case of lateral flow. It is worth mentioning that neither has any such evidence been presented from the study of dyke swarms in Eastern Iceland (Walker 1963, 1974, Gibson & Piper 1972).

In conclusion, lateral magma flow at shallow depth may be important in the EVZ and is most likely to have happened in the tectonically active areas, i.e. within the tholeiitic Grímsvötn and Veidivötn systems and in the northern end of the transitional Katla system. In the other main part of the transitional area and in the alkalic area (Vestmannaeyjar), where tectonic fissures are much less pronounced and strike-slip movements are probably common, lateral flow is very unlikely to be of major importance. It can be tantatively suggested that the centres of the volcanic systems as shown in Fig. 24 are the main areas of magma upwelling and that the areas outside these are preferably fed by lateral magma flow. As is obvious from Fig. 24, these border areas are relatively much smaller in the transitional and alkalic systems than in the tholeiitic systems. This model implies that only basaltic magma flows laterally, as only basalts are found to have extruded in the border areas.

Eruption sites and lava morphology

The subaerial basalt eruption sites where classified according to morphology. Five genetical types can be distinguished within the EVZ and the western Reykjanes Peninsula, and their main features are given below.

1. *Shield crater* (Icel. dyngja): circular or elliptical shape, very little or no tephra produced; usually only one crater; produces a lava shield of compound lava flows.
2. *Spatter cone row:* a volcanic fissure where the craters are made up of yielded spatters, very little cinder; some craters are of the "eldborg type" (Thorarinsson 1960).
3. *Cinder/spatter cone row:* a volcanic fissure where the craters are made up of both spatter and cinder, the latter amounting to some 30—60 per cent by volume.
4. *Cinder cone row:* a volcanic fissure where the craters are mainly made up of cinder, i.e. $\geq$60 per cent by estimate.
5. *Explosion fissure:* craters of elliptical shape, maar-like; large production of cinder, and little lava; very rare in basalt volcanism.

The following two additional types can occur depending on external forces.

Tuff ring (Icel. "hverfjall"); entirely made up of tephra; forms when magma is granulated by contact with water.

Eldgjá (Thorarinsson 1960): resembles an explosion fissure, but is larger and with more or less parallel crater walls; probably forms when a relatively explosive eruption is associated with a narrow graben subsidence, as in Eldgjá for example (Fig. 14).

The field classification was sometimes problematical as in several cases more than one type of eruption site has developed on the same volcanic fissure. However, in most cases the dominating type could be identified. The shield crater type was not observed in the EVZ, but it is common on the Reykjanes Peninsula. Although the shield craters and the associated lava shields do not usually display any linear structures, they may nevertheless have started as fissure eruptions, as they erupt in regions where extensional strains.is prevalent (Jakobsson et al. 1978).

The five genetical types of eruption sites are listed above in order of increasing cinder amount from the shield crater type to the explosion fissure type. The explosive index of Rittmann (1960) thus rises in the same order, and this can be assumed to be due to a rising amount of volatiles in the magma, if the effects

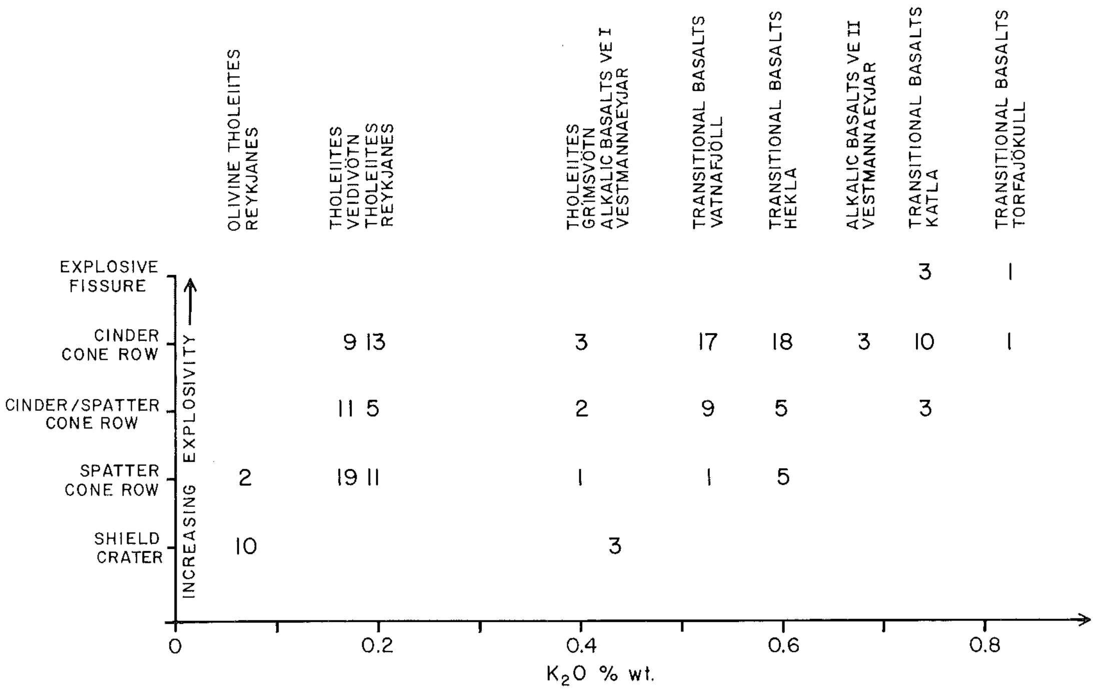


Fig. 26. A plot of the types of basalt eruption sites observed and the average K_2O content of each volcanic system from the EVZ and western Reykjanes Peninsula. The types of eruption sites are arbitrarily placed at equal intervals on the ordinate.

of high ground water level or lakes on the eruptions are excluded.

Both Nielsen (1929) and Thorarinsson (1960) have previously attempted a classification of Icelandic volcanic forms. The present classification is basically the same as theirs, in that the types are arranged according to their explosivity. However, the present author's field work in the EVZ and Reykjanes does not indicate that the areal and central eruptions of Nielsen, or the punctual eruptions of Thorarinsson actually occur. Neither are the types of eruption sites classified with regard to the number of eruptions (Thorarinsson 1960). All the basalt eruption sites investigated during the course of the present study are considered to be monogenetic, and they do not erupt again as far as experience shows.

Fig. 26 shows a comparison between the distribution of types of eruption sites and the average content of K_2O for each volcanic system of the EVZ and western Reykjanes Peninsula. In general the amount of K_2O increases as the degree of explosive activity and therefore amount of volatiles increase. A slightly poorer correlation is obtained when Na_2O is considered with K_2O. Each of the 3 rock series, the tholeiitic, the transitional alkalic and the alkalic series may have its own trend of development.

Moore (1970) has, on the basis of analyses of deep sea basalts, deduced that alkalic basalt magmas are richer in both water and other volatiles than tholeiitic basalt magmas. In the EVZ, the examination of the basalt eruption sites also indicates that the transitional alkalic basalt magmas contain larger amounts of volatile elements than do the tholeiite magmas of EVZ and Reykjanes. However, the available data on the alkalic eruption sites in the EVZ may indicate that the alkalic magma has a similar content of volatiles as the tholeiitic magma.

Similar relationships are observed when lava morphology and chemistry is compared. Roughness of the lava surface was classified us-

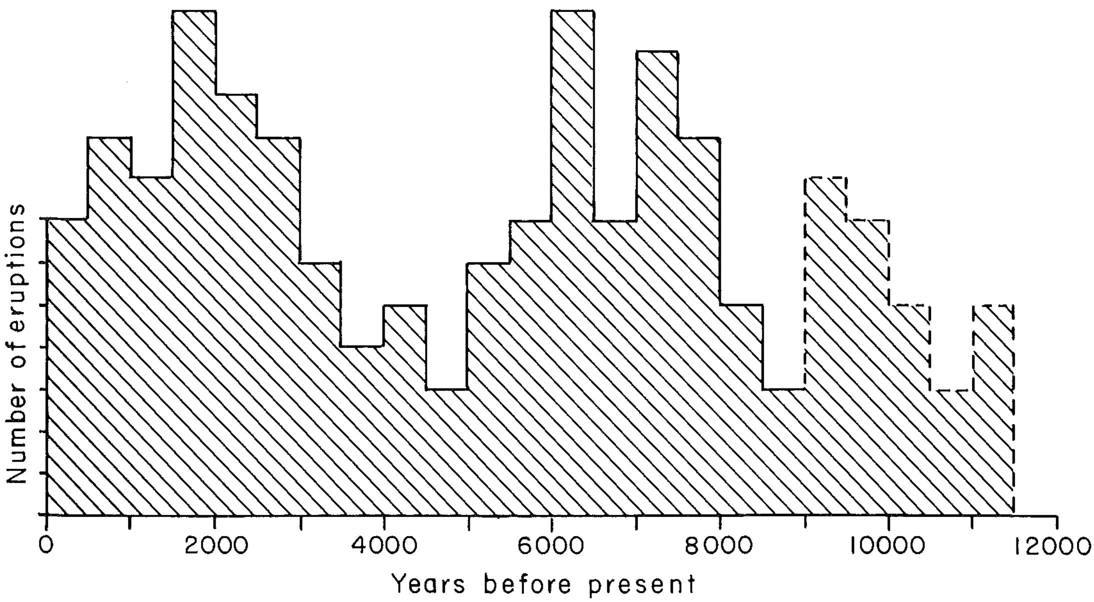


Fig. 27. Frequency histogram of 161 basaltic eruptions during Postglacial Time in the EVZ, as calculated for 500 year periods.

ing a fourfold division; smooth pahoehoe, rough pahoehoe, smooth aa-lavas, rough aa-lava. The smoothest and therefore the most fluid lavas are the pahoehoe lava shields of Reykjanes and the VE I lavas of the alkalic Vestmannaeyjar, followed by the Reykjanes and Veidivötn tholeiites and the alkalic VE II lavas. The roughest lavas are those of the transitional Hekla and Katla systems which are highest in potassium and are close to basaltic andesite in composition.

Frequency of basaltic eruptions

Altogether about 211 subaerial basaltic volcanic eruptions of Postglacial age were discovered in the EVZ. Although it is very difficult to estimate the number of subglacial eruptions for the same period, 140—160 seems a reasonable figure, and thus about 57—60 per cent of the estimated total number of eruptions has been considered in the present study.

In the previous sections mention was made of the ages of basalt eruptions which are known with some certainity from individual volcanic systems. In several systems, especially the Vestmannaeyjar, Hekla and Eyjafjöll systems, there are strong indications that the eruptions occur in phases (or events), perhaps of a few thousand or possibly even of a few hundred years duration. This is especially clear in those systems where many lavas are dated.

The age sequence of the basalt lavas of the Hekla and Vatnafjöll systems was shown in Fig. 8. Similar diagrams have been constructed for all the other volcanic systems of the EVZ. Fig. 27 shows the cumulated frequency histogram for 161 basaltic eruptions from the systems in the EVZ. Excluded are eruptions in the northern end of the Veidivötn system and others which are poorly dated. Although the age of many eruptions is only approximately known, the histogram (Fig. 27), shows without doubt, that there have been two main periods of volcanic activity in the EVZ, i.e. between about 0—2000 y.b.p. and 5000—8000 y.b.p. There are indications that there was a third active period in early Postglacial Time, but data from this early period are neccessarily poorer.

It should be stressed that most of the systems have been more or less active throughout Pos-

Table 10

Volume (km^3) of extruded rocks during Postglacial Time in the volcanic systems of the Eastern Volcanic Zone. For the basalts the estimated volume of hidden lavas and produced tephra is given separately. Where only question marks are shown, there are no ways of estimating the volume at present, however, the volume is probably very small in these cases, except possibly for the Katla system.

			Basalts						
			measured	estimated addition	Basaltic andesites	Andesites	Dacites – rhyolites		Total
Vestmannaeyjar	alkalic	:	3.1	0.6	0.2	0	0	=	3.9
Hekla	transitional	:	7.7	1.0	13.8	3.7	~7.2	=	33.4
Vatnafjöll	transitional	:	9.4	0.8	0	0	0	=	10.2
Torfajökull	transitional	:	0.8	0	0.1	?	$\gg$ 0.9	=	$\gg$ 1.8
Tindfjöll	transitional	:	0.1?	0	?	0	0	=	0.1
Eyjafjöll	transitional	:	0.2	0.2	0.1	?	$\gg$ 0.1	=	$\gg$ 0.6
Katla	transitional	:	14.8	30 ?	?	?	?	=	45
Grímsvötn	tholeiitic	:	18.7	35 ?	0 ?	0	0	=	54
Veidivötn	tholeiitic	:	50.9	2 ?	0	0	0	=	53
			105.7	70 ?	$\gg$14.2	$\gg$ 3.7	$\gg$8.2	=	$\gg$202 km^3

tglacial Time although evidently with varying intensity. The frequency of volcanic eruptions has therefore varied simultaneously in time on a regional scale in most of the EVZ. The Eyjafjöll and Tindfjöll systems have though apparently only erupted during the period 5000—8000 y.b.p. At present, it is only possible to suggest that these fluctuations are due to a regional tectonic control.

It is of interest to note that where accurate age determinations are available from volcanic systems outside the EVZ, they fall within either of the two younger active periods discussed above. Thorarinsson (1960) and Saemundsson et al. (1971) have demonstrated that where the age of volcanic activity is known in the Krafla system it falls in two periods, one between 5500—7500 y.b.p. and the other from 0—2000 y.b.p. The small Grímsnes volcanic system in the Reykjanes — Langjökull zone appears to have formed between 5500—6500 y.b.p. (Jakobsson 1977). Thus it appears that similar fluctuations have occurred throughout the active volcanic zone of Iceland. Tr. Einarsson (1977) has already noted that age determinations on volcanic eruptions available at that time, were mainly grouped at approximately 5000—6000 y.b.p. and 0—2500 y.b.p.

Volume relationships

Volumes of individual eruption units were calculated using the field maps, which are in the scale 1:50 000. In Table 10 are listed the calculated volumes of the basalts, along with estimates for the maximum amount of lavas and subglacial tephra which may be hidden. The total production of basalts thus calculated in the EVZ is approximately 175 km^3. The tholeiitic systems are the most productive, closely followed by the Katla and Hekla systems, whereas the old transitional systems and the alkalic system have produced much less. Table 10 also lists volumes of intermediate and acid extrusives, adding up to a total production of approximately 202 km^3 in the entire EVZ in Postglacial Time. When the volcanic systems of the EVZ are compared, it has to be borne in mind that these systems may be in a different stage of maturity, and also that their tectonic environment is different and the ratio of extruded magma to underground-stored magma can not be determined.

Fig. 28 shows the total Postglacial production of basalt and basaltic andesites in each volcanic system, divided according to the FeO*/MgO of the lavas. Those lavas which are not chemically analysed are classified after comparing their

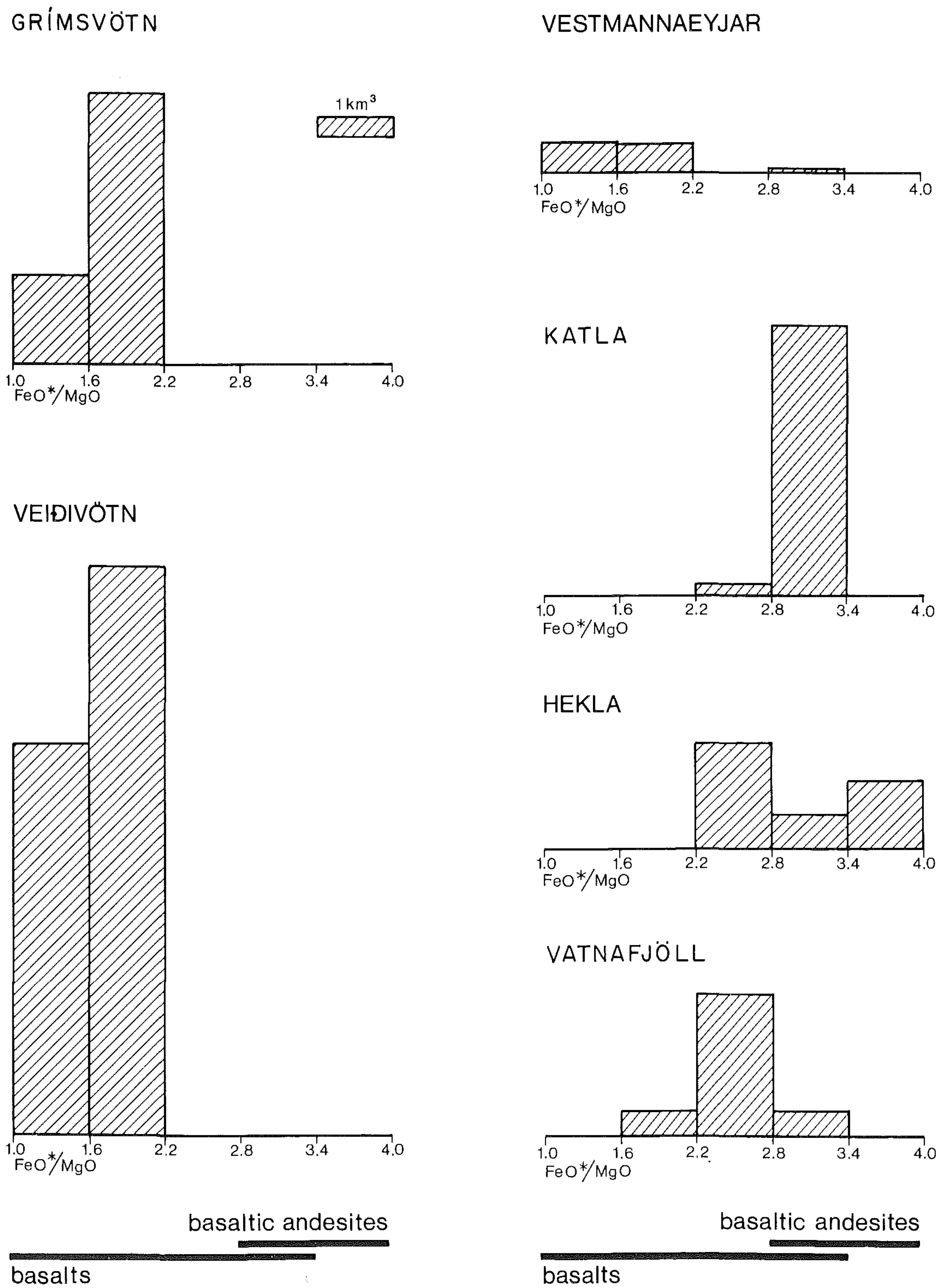


Fig. 28. Total production of observed Postglacial basalts and basaltic andesites within six volcanic systems with respect to the FeO*/MgO ratio of the lavas.

Table 11

Average volume of basalts erupted in each system, and the productivity per unit area of centre(s) and system. The Eyjafjöll, Tindafjöll and Torfajökull systems are not included because of meagre data.

	Number of eruptions	Area (km^2) of centres	Area (km^2) of system	Volume (km^3) of basalts	Av. volume (km^3) of eruption	Discharge $km^3/100\ km^2$ of centre(s)	Discharge $km^3/100\ km^2$ of system
Vestmannaeyjar	22	242	875	3.7	0.17	1.5	0.4
Vatnafjöll	31	279	333	10.2	0.33	3.7	3.1
Hekla	27	324	360	8.7	0.32	2.7	2.4
Katla	≈130	336	1025	45	~0.35	13.4	4.4
Veidivötn	75	400	1275	53	0.71	13.3	4.2
Grímsvötn	?	~532	~1500	54	?	~10.2	~3.6

petrography to the analysed lavas. The division of the FeO*/MgO scale was made after consulting the oxides: FeO*/MgO plots in order to ascertain that each histogram column represents the grouping of analyses in these diagrams as far as possible. The histograms (Fig. 28) demonstrate that the basic rocks within each system lie within very narrow compositional limits.

Calculations on the average volume of extruded basalts in the six best known systems are shown in Table 11. A clear relation between chemistry and the average volume is evident. Largest are the tholeiite lavas which have an average volume of 0.71 km^3. The transitional systems have an average volume which is only half the tholeiitic value and the alkalic system at 0.17 km^3 is only half the average of the transitional basalts.

Table 11 also shows calculations of the discharge from these systems, but because of the possibility of lateral magma flow, the discharge is calculated both on the basis of the area of the centre(s) and the whole volcanic system. More realistic values are probably obtained when the discharge is calculated on the basis of the whole system. A similar discharge from the transitional and the tholeiitic systems is indicated.

Phenocryst mode and mineralogy

During the course of the study 1050 thin sections (450 rock samples) were examined under the microscope. All the lavas proved to be porphyritc, although several of the Vatnajökull and Hekla basalts carry less than 0.1 per cent by volume of phenocrysts. Those samples, which have been quenched or have a cryptocrystalline groundmass prove that the phenocryst phases are formed before extrusion and are therefore definitively intratelluric. There are indications that the microphenocrysts especially, continue to grow after extrusion, in slowly cooled lavas. However, this effect can largely be overcome by excluding the more slowly cooled coarse-grained samples in the volumetric analysis.

The variation in the amount of phenocrysts is considerable, particularily within the tholeiitic systems. For reasons of space, the modal analyses can not be presented here. Fig. 29 shows the variation in total amounts of olivine and plagioclase in all the chemically analysed lavas and 46 other lavas from the EVZ. It is noteworthy that the lavas plot along the olivine and plagioclase axes. The distribution in Fig. 29 allows for some distinction to be made between the various basalt types, i.e. if the olivine phenocryst content exceeds 3 per cent and plagioclase exceeds 11 per cent by volume.

The silicate phenocryst phases appear to form two groups according to size and are termed macrophenocrysts and microphenocrysts. This was confirmed by detailed investigation on a number of lavas from the three rock series.

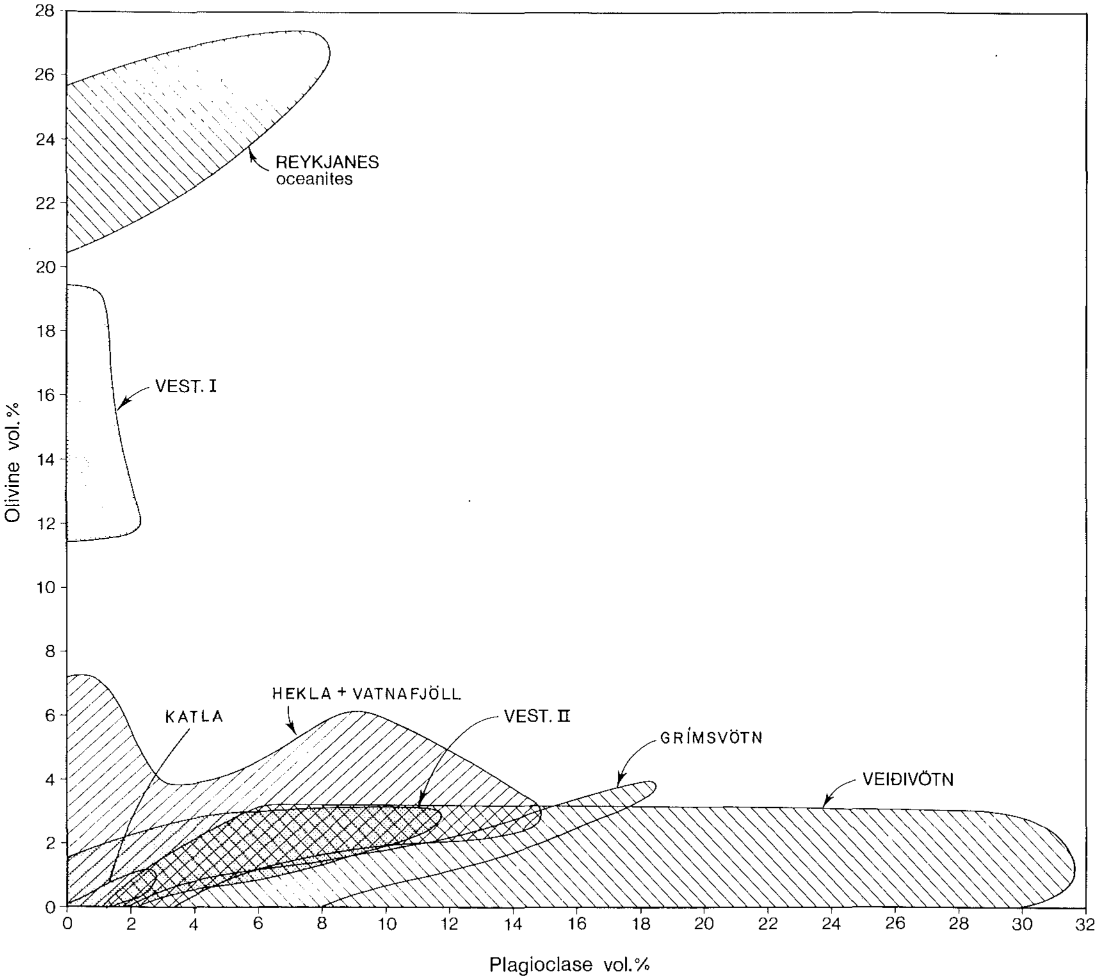


Fig. 29. Variations in total amount of olivine and plagioclase phenocrysts in the EVZ basalt lavas, including the picrite basalts (oceanites) of the western Reykjanes Peninsula (Jakobsson et al., 1978). The olivine tholeiites and tholeiites of the Reykjanes Peninsula fall within the field of the Veidivötn system.

The macrophenocrysts have an average diameter > 0.7 mm but are commonly about 1—2 mm and reach occasionally a length of 1.5 cm (about 0.5—0.6 m^3). These crystals are usually stout, exhibit moderate to heavy zoning, while oscillatory zoning is quite common in plagioclase and is occasionally found in augites. Resorption is not unusual, especially of olivines and augites. Synneusis of plagioclase crystals appears to be very common, especially in samples from the tholeiitic Veidivötn and Grímsvötn systems. Glomerophyric growth of macrophenocrysts is relatively rare, except in the Grímsvötn system where plagioclase, olivine and augite have often grown together. Generally it can be said that the macrophenocrysts indicate slow cooling at depth. Characteristics which are generally attributed to rapid cooling (see below) are not seen in the macrophenocrysts.

The microphenocrysts have an average diameter < 0.7 mm, and are always euhedral to subhedral. The plagioclase crystals are generally lath-shaped and usually only slightly zoned. The olivines are usually stout, although skeletal crystals occur often and sometimes lath-shaped crystals. The augites are stout, undulatory or irregular extinction is very common and sector zoning is not uncommon. Skeletal growth of olivines has been attributed to rapid growth (Drever & Johnston 1957), and Leung (1974) has suggested that sector-zoned titan-augites originate from disequilibrium crystallization at shallow depth, and the same may be valid for the augites of the EVZ lavas. Very often the three silicate phenocryst phases exhibit glomerophyric growth, though the size of individual crystals is below 0.7 mm. Generally the microphenocrysts are best explained as being formed by rapid growth before eruption at shallow depth, at cotectic conditions. In the EVZ lavas the volume of microphenocrysts varies from 0.2 per cent to a maximum of 22.5 per cent.

A third group of plagioclase phenocrysts is found in the alkali olivine basalts of the Vestmannaeyjar system. These are absorbed macrophenocrysts (or megaphenocrysts) generally between 3—5 cm^3 in volume. The spinel phase was only found as macrophenocryst in one case (Fig. 33A), but is common as microphenocrysts in the transitional alkalic systems.

The lower size limit for the microphenocrysts was set at 0.10 mm since the average grain size of the groundmass reaches this level in most of the analysed lava samples. In some cases a complete gradation exists between the two. The real content of microphenocrysts may therefore be greater than actually measured although the values used are considered suitable to allow comparison between lavas. The distinction between macrophenocrysts and microphenocrysts is on the other hand much clearer.

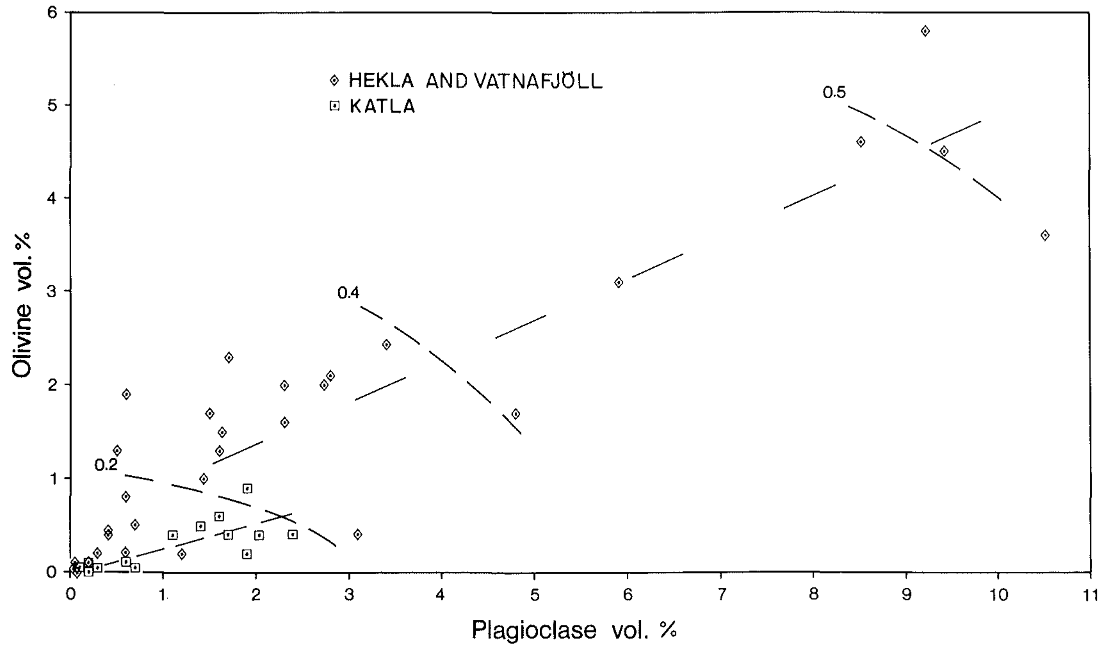
It is of value to consider the relationships between the silicate microphenocryst phases. Fig. 30 shows plots of olivine against plagioclase in individual lavas from five volcanic systems. A few samples are omitted where the groundmass is coarse or where it proved impossible to distinguish between macro- and microphenocrysts during the point counting.

Although there is a considerable scatter of values for each system, positive correlation between the amounts of the individual microphenocryst phases is indicated, with the exception of the spinel phase, which was only observed in the transitional systems, and always in amounts of less than 0.5 per cent. The scatter of values is noticeably greatest in the case of the Hekla system. The reason for this is unknown, but skeletal olivines are unusually common in these lavas. In the light of the experiments by Lofgren et al. (1974), who were able to produce skeletal phenocryst phases at linear cooling rates it seems possible that some olivine microphenocrysts of some of the Hekla basalt lavas are not intratelluric.

Since the microphenocrysts are very small, (< 0.7 mm) and since many lie in glomerophyric clusters (< 2 mm) where two to four of the phases crystallize almost simultaneously and are therefore close to the specific gravity of the magma itself, it is *a priori* unlikely that the microphenocrysts are able to sink or float measureably in these magmas. Accordingly thin section examination of the 450 lava samples did not reveal any signs of accumulation of microphenocrysts.

If this suggestion is right, the linear variation in the microphenocryst phases indicated in Fig. 30 would not be due to accumulation but to different degrees of crystallization at shallow depth. No systematic variation has been found to exist between the whole-rock chemistry of the lavas and the total amount of microphenocrysts. In each system the chemical spectrum of the basalts is quite narrow (e.g. Figs. 7, 13 and 19). In the case of the Hekla system basalts for instance, the Al_2O_3 varies within 14.1 ± 0.6 per cent by weight, although the amount of microphenocrysts in these lavas varies as much as from 0.1 to 22.5 per cent by volume. The amount of microphenocrysts can also vary appreciably in otherwise homogenous, voluminous single lavas which have erupted from different parts of long fissures.

The limited range of the chemical composition of the lavas and the lack of correlation between composition and the amount of microphenocrysts, seems to rule out differences in nucleation rates and crystal growth rates as an explanation for the variation in the amount of microphenocrysts. Neither does it seem likely that the variation is due to differential loss of water vapour during ascent, as Anderson (1973) has tentatively suggested for high alumina



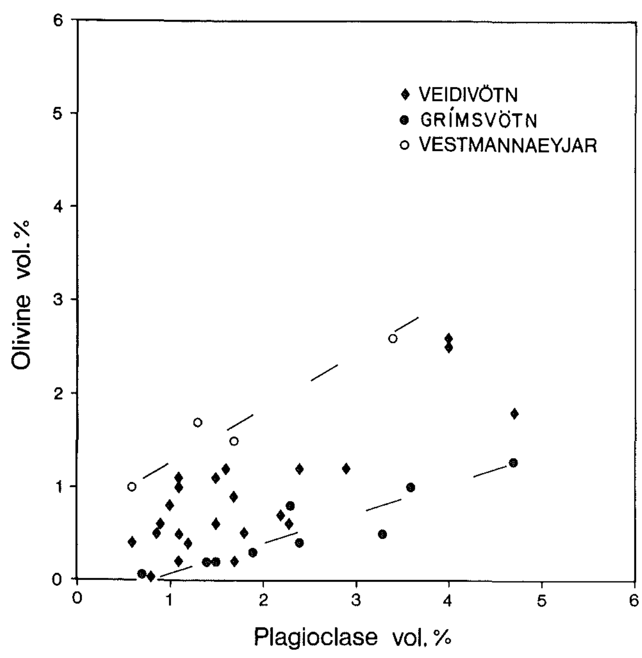


Fig. 30. Variations in amounts of olivine and plagioclase microphenocrysts in the basalt lavas of six systems. Lines of correlation are tentatively drawn. In the case of Hekla and Vatnajökull the variation of the average size of olivine (mm) is indicated.

basalts. The amount of water in these basalts is presumeably very low and there are no indications of any substantial variation in water content. The time factor seems therefore a more plausible explanation.

As mentioned above, the glomerophyric growth indicates near-cotectic conditions. However, the microscopic texture analysis shows that the order of initial crystallization of the minerals can usually be established.

Table 12

Order of crystallization as indicated by microphenocryst textures of chemically analysed basalt lavas and by interpretation of diagrams (e.g. Fig. 30), compared with 1 atm. experiments under anhydrous conditions on individual lavas. Note that the petrographic analyses on the Vestmannaeyjar basalts are done on the VE II basalts, but the melting experiment on a VE I basalt. The sign — indicates that the order of crystallization is well established. The sign ~ indicates that the two phases appear to have crystallized simultaneously.

Swarm	Method	Order of crystallization
Vestmannaeyjar	microscope (VE II) :	picotite — olivine — plagioclase
	diagrams (VEII) :	olivine — plagioclase
	experimental[1] (SU42-lava, VE I) :	olivine — plagioclase — clinopx. 1220°C 1180°C 1155°C
Hekla and Vatnafjöll	microscope :	magnetite — olivine~plagioclase~augite
	diagrams :	olivine~plagioclase — augite
Katla	microscope :	magnetite — plagioclase~olivine~augite
	diagrams :	plagioclase~olivine~augite
	experimental[2] (335-lava) :	plagioclase~clinopx. — olivine 1140°C 1120°C
	experimental[3] (079-lava) :	olivine~plagioclase — clinopx. 1140°C 1130°C
Veidivötn	microscope :	plagioclase~olivine~augite
	diagrams :	plagioclase~olivine~augite
Grímsvötn	microscope :	plagioclase~olivine~augite
	diagrams :	plagioclase — augite~olivine
	experimental[3] (080-lava) :	plagioclase — olivine — clinopx. ~1175°C ~1160°C ~1150°C

1 1 atm. anhydrous experiments with temperatures of appearance of phases by Tilley et al. (1967).
2 1 atm. experiments by Tilley et al. (1964).
3 1 atm. experiments by Bell & Humphries (1972).

Furthermore tentative correlation lines for the various systems in the microphenocryst plots (Fig. 30, for example) will cut the axes when extrapolated.

This might suggest that the various silicate phases nucleated in a certain order. In Fig. 30, for example, olivine would be expected to start to nucleate before plagioclase in the case of the Vestmannaeyjar alkali olivine basalts, whereas plagioclase should come before olivine in the case of the tholeiitic Grímsvötn system and possibly also in the Veidivötn system. In this way it seems possible to establish the order of initial crystallization for the microphenocrysts and determine, at least for lavas with a low phenocryst content, which mineral is at liquidus in each case.

Table 12 shows the results of this approach, compared with the order of initial crystallization of microphenocrysts as deduced quite independently from the microscopic texture analysis. The agreement is satisfactory and indicates that by either method it is possible to detect the order of crystallization. It can be noted here that from the petrographic analysis it is evident that the spinel phase was the first mineral to crystallize in most cases. Table 12 also shows the result of melting experiments which have been carried out on EVZ lavas. These experiments are carried out at atmospheric pressure under anhydrous conditions and the samples do not contain appreciable amounts of macrophenocrysts and most probably represent true liquid compositions.

The good correlation between the order of appearance of phases as found in this study and that found in the melting experiments further underlines that the microphenocryst assemblage of these EVZ basalt lavas (with the possible exception of the Hekla basalts) are low pressure (shallow depth) crystallization products formed at near-cotectic conditions.

If it is correct that the amount of microphenocrysts in a basalt lava of these volcanic systems is a measure of the time of ascent in the uppermost crust then it will be of interest to see if this has affected the distribution and amount of the macrophenocrysts in these lavas. In Fig. 31A the volume of microphenocrysts is plotted against the volume of the dense macrophenocrysts olivine and augite. Although the data is scanty there is nevertheless a distinct tendency for the heavy macrophenocrysts to concentrate in lavas which have a low microphenocrysts content i.e. where time of ascent has been presumably short. All lavas with more than 6 per cent of microphenocrysts contain less than 0.3 per cent by volume of heavy macrophenocrysts. This indicates that lavas with a high amount of microphenocrysts have lost most of their heavy macrophenocrysts during ascent, this may also indeed be the case to some extent where the microphenocryst content is low. Only one point in Fig. 31A falls outside the general trend and that is for of the 163-Lambavatn lava and the reason for this seems obvious. In this lava most of the heavy macrophenocrysts are attached to plagioclase crystals in glomerophyric clusters and have therefore been able to float along with the plagioclase.

The situation is different when the amount of plagioclase macrophenocrysts is plotted against the amount of microphenocrysts, as in Fig. 31B. No clear relationship can be found for the transitional basalts (Hekla, Vatnafjöll and Katla), but when the tholeiites (Veidivötn and Grímsvötn) are considered, a fan-shaped distribution of the plagioclase macrophenocrysts is evident. For the Grímsvötn system a positive correlation is suggested, so that the greater the amount of microphenocrysts (longer time of ascent), the larger is the volume of plagioclase macrophenocrysts. A prerequisite here is that the composition of the macrophenocrysts in each system is about the same.

It is of further relevance to examine Fig. 37, where Al_2O_3 in wt. per cent is plotted against the FeO^*/MgO ratio. Below about 15.2 per cent Al_2O_3, the Veidivötn lavas (Fig. 37A) demonstrate a general falling trend with rising FeO^*/MgO ratio. Above 15.2 per cent Al_2O_3, however, the Al_2O_3 content rises linearly at an approximately constant FeO^*/MgO ratio. It does not seem possible to explain the latter trend by any process except accumulation of plagioclase. A comparison of Fig. 37A and B with Fig. 31 strongly suggests that plagioclase is accumulated by floating in the more porphyritic lavas. The vertical stippled line in Fig. 31B shows where the two trends from Fig. 37A meet. All lavas to the right of this line are defined as plagioclase accumulative, and some of the lavas on the left (e.g. at 5—8 per cent plagioclase macrophenocrysts) may also be accumulative. Similarily, the 163-Lambavatn lava of the Grímsvötn system and probably also the 083-Hálsagígar lava are accumulative.

McBirney & Noyes (1979) have recently presented evidence that seems to rule out that plagioclase settling could have occurred in any of the Skaergaard liquids, but on the other hand that floating of plagioclase would have been possible provided the size was large enough. The composition of the initial Skaergaard magma and that of the Veidivötn and Grímsvötn tholeiite magmas is comparable for this purpose. Assuming similar density and viscosity for the magmas, the Veidivötn and Grímsvötn plagioclase macrophenocrysts (An 85—88), whose average maximum diameter is about 4

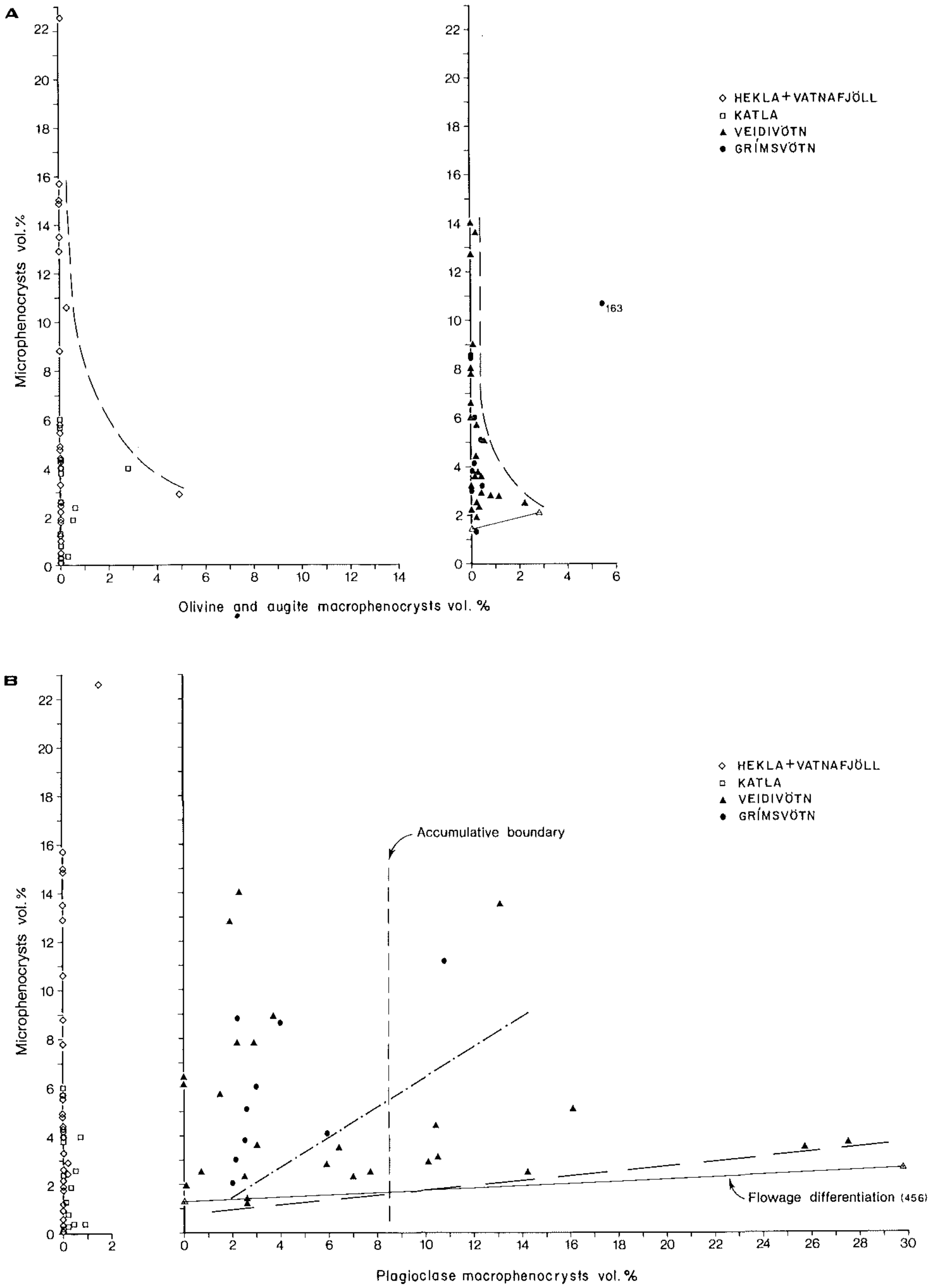


Fig. 31A. Total amount of microphenocrysts plotted against the amount of the heavy microphenocrysts olivine and augite for the transitional alkali basalts and tholeiites, respectively. — B. Microphenocrysts plotted against plagioclase macrophenocrysts. The approximate boundary line for accumulative and non-accumulative rocks is shown by a vertical dashed line. The extent of maximum flowage differentiation in the 456-Rendur lava is also indicated.

Table 13

An outline to show the relation between the various texture terms used for the lavas, with respect to the orientation of groundmass plagioclase and size ratio of plagioclase/pyroxene.

Orientation of plagioclase				
azimuthal distribution within ~~90°~~ 30°	pilotaxitic			
azimuthal distribution within 90°		intergranular	subophitic — ophitic	
random				poikilitic
	Size ratio of plagioclase/pyroxene generally decreasing →			

mm, would just have been able to stay where they formed, or to float (MacBirney & Noyes, 1979, Figs. 2 and 3). As the vertical trend of the Veidivötn tholeiites in the Al_2O_3:FeO*/MgO plot (Fig. 37) rules out the possibility that the plagioclases stayed in the same magma as they were formed in, they must have floated. The reason for the great scatter of points in Fig. 31B may be due to small differences in density between plagioclase and the magma.

The petrographic exercise indicates that the microphenocrysts which occur in the Grímsvötn, Katla, Vestmannaeyjar VE II basalt lavas and possibly all the Hekla and Vatnafjöll basalt lavas, were formed at near-cotectic conditions at shallow depths by relatively rapid cooling, without accumulation. The macrophenocrysts were formed at a deeper level and by slower cooling. In most cases, the macrophenocrysts are probably not in equilibrium with the extruded lava. Although they cannot be termed xenocrysts they are probably formed in parental liquids to the extruded lavas, or even in the same liquid at different P-T conditions. There are indications (Fig. 31) that about half of the basalts of the EVZ have either lost or accumulated macrophenocrysts and cannot therefore be primary liquids. The other half, with the exception of the VE I-lavas, may not be primary liquids either since they appear to have precipiated microphenocrysts at near-cotectic conditions (cf. O'Hara 1976). On the other hand the Vestmannaeyjar VE I-lavas (e.g. Surtsey), exhibit a primitive mineralogy and may therefore be reasonably close to the primary liquid in composition.

Groundmass texture of the lavas

The texture of the groundmass was determined for all the chemically analysed specimens during the routine microscopical work in order to see to what extent the textures are dependent on the chemistry of the rock. The predominant texture in each sample was noted, although this was in some cases very difficult because of variations, even within the same thin section. The texture is obviously very dependent on the cooling rate, as shown by the experiments of Lofgren et al. (1974) on a moon basalt. The following discussion is therefore restricted to samples which are collected at a depth of 0.2—0.4 m below the surface, so that for comparative purposes the cooling rates may be assumed to be similar. The tholeiitic lavas of the western Reykjanes Peninsula are included in the discussion to broaden the chemical field of the study.

It was found that the following texture terms

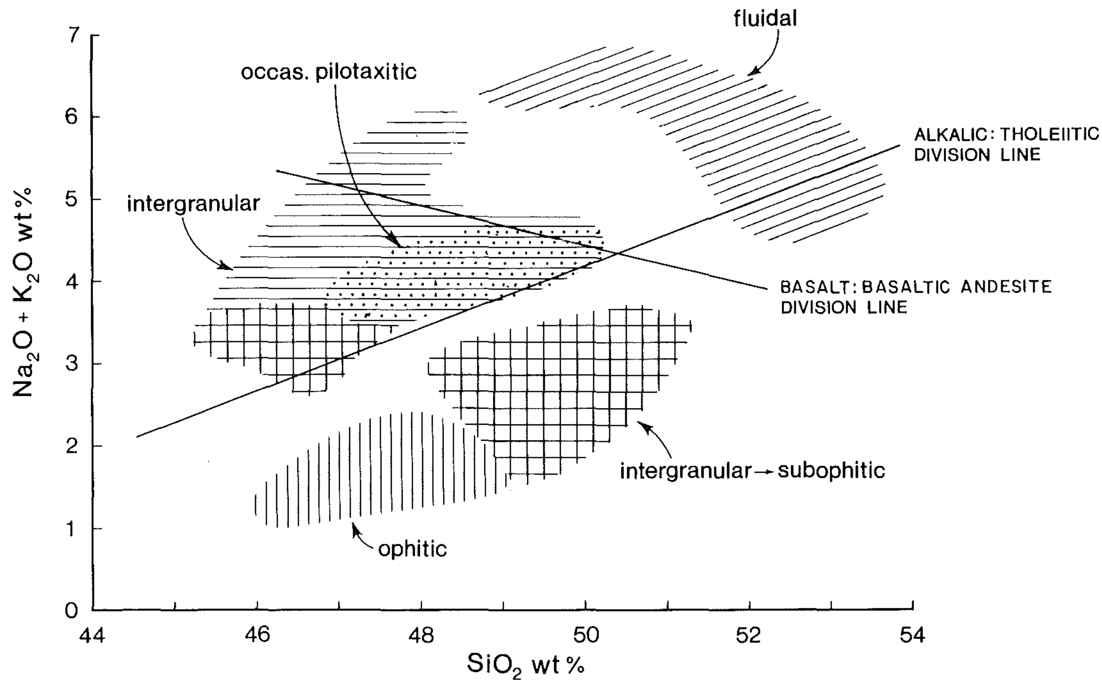


Fig. 32. Distribution of predominant texture types with regard to the alkali:silica content of basalts and basaltic andesites in the EVZ and the western Reykjanes Peninsula. The alkalic/tholeiitic and the basalt/basaltic andesite division lines are shown.

adequately covered the textures formed in the lavas of the EVZ. *Poikilitic* (McBirney & Williams 1969, Fig. 3A); *ophitic* (Tyrrell 1946, Fig. 37C; Williams et al. 1954, Fig. 3B); *hyaloophitic* (Williams et al. 1954, Fig. 5C); *intersertal* (Williams et al. 1954, Fig. 5B); *subophitic* (Williams et al. 1954, Fig. 3C; McBirney & Williams 1969, Fig. 6B); *intergranular* (Johannsen 1939, Vol. 1, Fig. 67; McBirney & Williams 1969, Fig. 12b); *pilotaxitic* (Johannsen 1939, Vol. 1, Fig. 71) and *fluidal* (Williams et al. 1954, Fig. 6A).

As the relation between these texture terms is unclear and some confusion exists as regards their use, they will be discussed shortly here. Most of the above-mentioned textures take into account the internal relationship between plagioclase and pyroxene and the degree of orientation of plagioclase in the groundmass. This is natural, as plagioclase and pyroxene are usually the dominant minerals in the rocks for which these textures are used. In the basic lavas of the EVZ, these two mineral groups together make up some 76—88 per cent of the volume. Consequently, the relationship of these textures can be demonstrated in terms of the size ratio of plagioclase to pyroxene (augite) and the degree of orientation of plagioclase.

In order to demonstrate tentatively the relationship between these textures Table 13 was constructed, leaving out the textures hyaloophitic and intersertal, as the rock is not fully crystallized in these cases. The division into groups of various degrees of orientation of plagioclase in Table 13 is arbitrary. Azimuthal distribution within 90° (45° to each side) probably corresponds to what many petrologists would call subparallel and distribution within 30° to parallel. It is anticipated that the solidification relationships for plagioclase-pyroxene are similar for the rocks which exhibit these textures.

Examples of typical textures of the EVZ basic lavas are shown in Figs. 3, 6, 9, 11, 15 and 18. In Fig. 32 the distribution of the predominant textures in the basalts and the basaltic andesites of the EVZ is indicated with respect to content of alkalies and silica in the analysed rock. The consistency within each area is variable. In the area designated "ophitic" and "fluidal" more than 90 per cent of the texture analyses indicated these textures respectively; in the "intergranular-subophitic" field some 70—80 per cent of the analyses gave these texture types. Too few suitable samples were available to define the empty area between the intergranular and fluidal textures in Fig. 32; presumably there is a graduation between these two texture types in this area.

The distribution of texture types which arises can be observed in Fig. 32, going from the lower left to the upper right. In the least evolved tholeiitic lavas ophitic texture predominates (lava shields of Reykjanes Peninsula), followed by an area of intergranular-subophitic textures found both in the alkalic and tholeiitic suites, then come intergranular and occasionally pilotaxitic textures possibly only in the alkalic area, finally followed by fluidal texture. Further evaluation of the distribution of texture types is difficult on the basis of the present data. It might be noted, that lavas which exhibit intergranular and pilotaxitic textures near the surface, often develop subophitic or ophitic textures with slow cooling rates in the interior of the flow, whereas lavas with ophitic texture near the surface are usually ophitic within the lava.

Gabbroic nodules and acid xenoliths

Gabbroic nodules were found in all the volcanic systems except the Katla system and in altogether 51 basalt and basaltic andesite eruption units. It is thought that all instances where gabbroic nodules are common or abundant, have been located, whereas occurrences of small numbers of nodules have been mapped haphazardly. No peridotitic or eclogitic nodules were found, even in the alkalic Vestmannaeyjar system, where a special search was made.

There appear to be all gradations between a glomerophyric cluster of macrophenocrysts and an unambiguous gabbroic nodule as found in the basalts. A glomerophyric cluster is a group of phenocrysts (cf. Fig. 33A), which may have grown somewhat after adhesion. These clusters are less than 2—3 cm across and are common in most systems, they have previously been discussed along with the phenocrysts. When a crystal aggregate has reached a size above 2—3 cm it can not usually be treated as a simple crystal cluster, but has developed its own texture (Fig. 33B).

The gabbroic nodules are frequently friable and porous and reach a size of 19 cm. Broken surfaces or truncations against the host rock were not observed and it can be suggested that they are formed freely floating. The nodules are most common in the Veidivötn system, especially in the 473-, 271-Fontur, 274- and 278-Botnar extrusives and in some of the Tindfjöll lavas. In the 473-lava the nodules may make up as much as 0.5 per cent of the volume. All those nodules which were examined from the basalts, appear to have formed floating in the magma, and only faint reaction relationships with the magma were observed, although zoning of border crystals is often larger than inside the nodule.

The gabbroic nodules of the basaltic andesites group separately. They are obviously broken chips of solid rock, show strong reaction relationships to the magma and may all be of exogenetic origin. The gabbroic nodules found in the first extrusives of the 1973-Eldfell eruption in the Vestmannaeyjar system were discussed by Jakobsson et al. (1973). These were found to contain hypersthene and are therefore xenoliths in the hawaiite magma. Some xenoliths have reacted with the magma to form pargasitic hornblende and kaersutite. It was argued that this reaction had occurred at a total pressure well below 8—9 kbar. and at a gas pressure higher than 1 kbar.

In the gabbroic nodules of the basalt lavas plagioclase was found to be the dominating mineral, usually making up as much as 80—90 per cent of the volume, some nodules even being anorthositic. Olivine, clinopyroxene, magnetite, orthopyroxene, amphibole and apatite were also identified. Often there appear to be relationships between the overall mineralogy of the nodule and the phenocryst mineralogy of its host lava. For example, the plagioclases in nodules from the Veidivötn system are usually

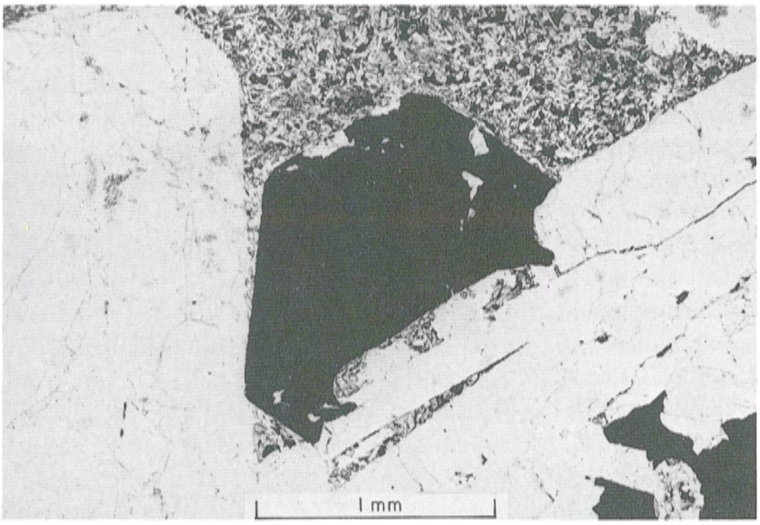


Fig. 33A. Glomerophyric cluster of plagioclase and magnetite macrophenocrysts (N660), the 240-Öxi lava, Hekla system.

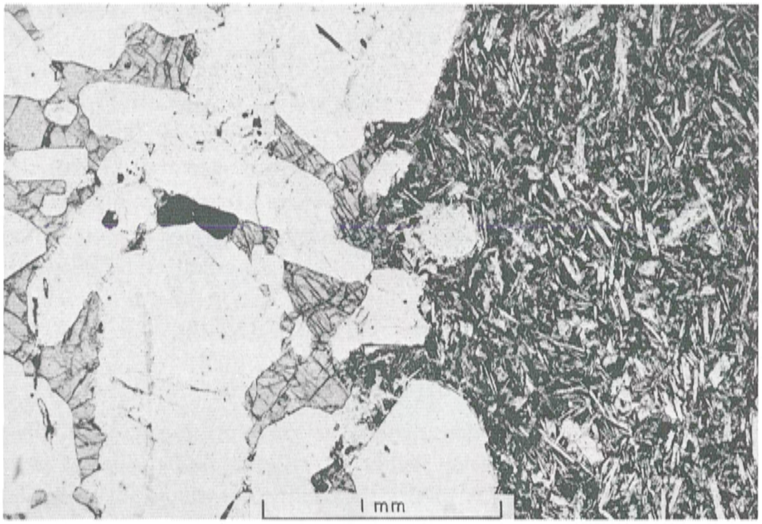


Fig. 33B. Gabbroic nodule (N1308), from the 217-Vatnafjöll lava, Vatnafjöll system. Plagioclase heteradcumulate texture.

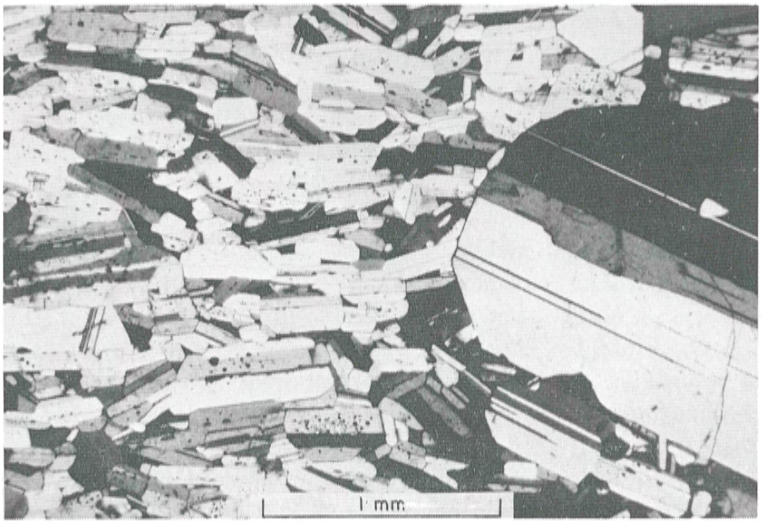


Fig. 33C. Anorthositic nodule (N1318), from the 465-lava, Veidivötn system. Laminated plagioclase with macrophenocrysts.

not distinguishable from the macrophenocrysts of the Veidivötn lavas. Similarly magnetite is only found in nodules from the transitional alkaline lavas, which is the only rock series in the EVZ which carries magnetite phenocrysts. Plagioclase was always found to be the first silicate phase to form, except in a few cases where plagioclase and olivine appeared to crystallize simultaneously. This is similar to the relationships found among the macrophenocrysts.

Many of the nodules exhibit textures which are very similar to those which are taken to be indicative of cumulate textures (Wager et al. 1960, Wager & Brown 1967). There appears though to be gradation in texture from a glomerophyric cluster of macrophenocrysts through nodules where heteradcumulate or adcumulate textures are beginning to develop, to nodules were a "cumulate texture" is fully developed, mainly plagioclase heteradcumulate texture (Fig. 33B). Only four nodules from the EVZ (in the Veidivötn system) showed signs of mechanical stress, i.e. cracks (sometimes healed) penetrating many crystals, and undulating extinction of the plagioclase. One nodule showed lamination of plagioclase (Fig. 33C) and one has a well-developed rythmic layering, caused by repeated size grading of the plagioclase.

Although there is thus much which supports a cumulative origin for the nodules, there are several facts which are contradictory to such an origin, wether by a floating or sinking mechanism. The apparent gradation from clusters of macrophenocrysts to freely formed nodules with fully developed "cumulate texture" would argue against a cumulative origin. The considerable size grading of the plagioclase seen in many nodules with heteradcumulate texture (Fig. 33B) is also contradictory to the idea of a cumulative origin, but this is similar to a textural example from the Skaergaard intrusion mentioned by McBirney & Noyes (1979, Fig. 9) as indicative of *in situ* crystallisation of the plagioclase. The occurrence of bubble holes in the poikilitic augite in a nodule from the 217-Vatnafjöll lava shows that the poikilitic augite must have grown relatively rapidly at relatively shallow depth. The nodule with the laminated plagioclase (Fig. 33C) is especially interesting in this connection. This nodule is plagioclase porphyritic, where the plagioclase crystals are, in habit and volume, directly comparable to the phenocrysts of the host lava. These large plagioclase crystals are enclosed in finely laminated plagioclase, which is often truncated against the large plagioclase phenocrysts. These relationships are of course irreconcilable with an accumulative origin, but could be explained by a diffusion mechanism

TABLE 14. CHEMICAL ANALYSES AND CIPW-NORMS (WT.%) OF GABBROIC NODULES.
ANALYST: GREENL.GEOL.SURVEY, CHEM. LAB., I. SØRENSEN.

ROCK. NO	5817	6576	5845
SiO2	48.65	46.56	47.06
TiO2	.34	.20	.23
Al2O3	27.26	29.22	29.44
Fe2O3	1.02	1.46	.82
FeO	1.48	1.01	1.56
MnO	.05	.05	.05
MgO	2.39	2.95	2.35
CaO	15.74	16.01	16.57
Na2O	1.92	1.42	1.39
K2O	.04	.01	.03
P2O5	.09	.10	.10
H2O	.29	.25	.23
Sum	99.27	99.24	99.83
CIPW	WEIGHT-NORM		
Q	2.21	.83	.89
OR	.24	.06	.18
AB	16.25	12.02	11.76
AN	65.65	73.33	74.01
DI	9.43	4.26	6.05
HY	2.88	5.77	4.86
MT	1.48	2.12	1.19
IL	.65	.38	.44
AP	.21	.23	.23
	98.98	98.99	99.60
Fe2O3/FeO	.69	1.45	.53
FI-index	18.69	12.90	12.83
FeO*/MgO	1.00	.79	.98

Key to Table 14. See text to Table 1.

5817: Nodule, 2 cm across. Host rock the 240-Öxi lava in the Hekla system, (Table 3, no. 9).

6576: Nodule, 9 cm across. Host rock the 479-lava, the Veidivötn system, (Table 8, no. 5).

5845: Nodule, 6 cm across. Host rock the 271-tephra, the Veidivötn system.

like that advocated by McBirney & Noyes (1979).

The above preliminary study of these gabbroic nodules indicates that they are formed at very shallow depth, possibly simultaneously with and at similar conditions to the macrophenocrysts of the lavas. The nodules are probably formed by grouping of floating crystals in the magma, but not by gravitational settling.

Three nodules, one from a transitional alkali basalt and two from tholeiites, were chemically analysed and are listed in Table 14. There are only slight, but probably important differences between the chemistry of the nodules. This is best seen in the normative composition of the plagioclase, which is An 86 in the Veidivötn lavas, or of about the same composition as the macrophenocrysts in these lavas, and An 80 in the transitional alkali basalt.

When the distribution of gabbroic nodules is considered, an interesting relation is found within the Veidivötn volcanic system. The gabbroic nodules are most abundant in the area between Klofnafell and Máni (Fig. 20), exactly where the subsidence is greatest and the more evolved compositions are found. The nodules are mainly found in porphyritic macrophenocryst-bearing extrusives, a fact which underlines the close relationship between the nodules and the macrophenocrysts. A similar relationship was found by Saemundsson (1967), who noted that in the Hengill area gabbroic nodules were only found in strongly porphyritic rocks.

Acid xenoliths were found in twelve extrusives in the Vestmannaeyjar, Hekla, Vatnafjöll and Veidivötn systems. Previously, Tryggvason (1965) has described two types of acid xenoliths from the Hekla 1947—1948 eruption. He suggested that they were fragments of plutonic rocks, one of them a granophyre, but found no conclusive evidence for their relationships to the Hekla extrusives. Sigurdsson (1968) described a number of acid xenoliths from Surtsey and Hekla and eleven other localities in Iceland. He showed that the acid xenoliths of Surtsey are granitic, and in different stages of partial fusion. He found that the granitic xenoliths could have resulted from crystal fractionation. However, this seems very unlikely in the case of Surtsey, as the least affected acid xenoliths of Surtsey are acid rocks of the tholeiitic series, according to the chemical analyses of Sigurdsson.

The acid xenoliths collected by the present author have not been studied under the microscope, but judging from handspecimens they are in various stages of fusion, as those decribed by Sigurdsson (1968). No signs of any noticeable assimilation of the acid material were found. Most probably these acid xenoliths are accidental fragments of plutonic acid rocks. The distribution of known occurrences of Postglacial and Upper Pleistocene acid xenoliths is such, that with the exception of the Vestmannaeyjar, all are within 10 km distance from outcrops of acid rocks. These relationships do not lend support to the hypothesis of the presence of a sial layer beneath Iceland, which have recently been revived (Wetzel et al. 1978).

Oxidation state of the lavas

The chemical analyses of the basalts (Tables 1 to 8) show that the Fe_2O_3/FeO ratio of the analysed samples is mainly within the range 0.14—0.40. Only 7 samples have a Fe_2O_3/FeO ratio above 0.40, and the average ratio for the 110 samples of Postglacial lavas is 0.26. This is regarded as conclusive evidence for the very fresh nature of the samples. Nevertheless, the thin section inspection suggests that several of the samples have suffered late-stage deuteric oxidation.

Fig. 34 shows the frequency distribution of the observed Fe_2O_3/FeO ratios in the basalt lavas of six EVZ systems excluding those values above 0.40. The tholeiites of the western Reykjanes Peninsula are included for comparison. As the chemistry of the basalts within each system is very similar, it may be suggested that there is a certain fixed minimum value for each system as indicated by an arrow in Fig. 34. The higher Fe_2O_3/FeO ratios can then be suggested to be due to deuteric oxidation.

It is well known that in the event of significant secondary oxidation it is necessary to correct the Fe_2O_3/FeO ratio because of its effect on

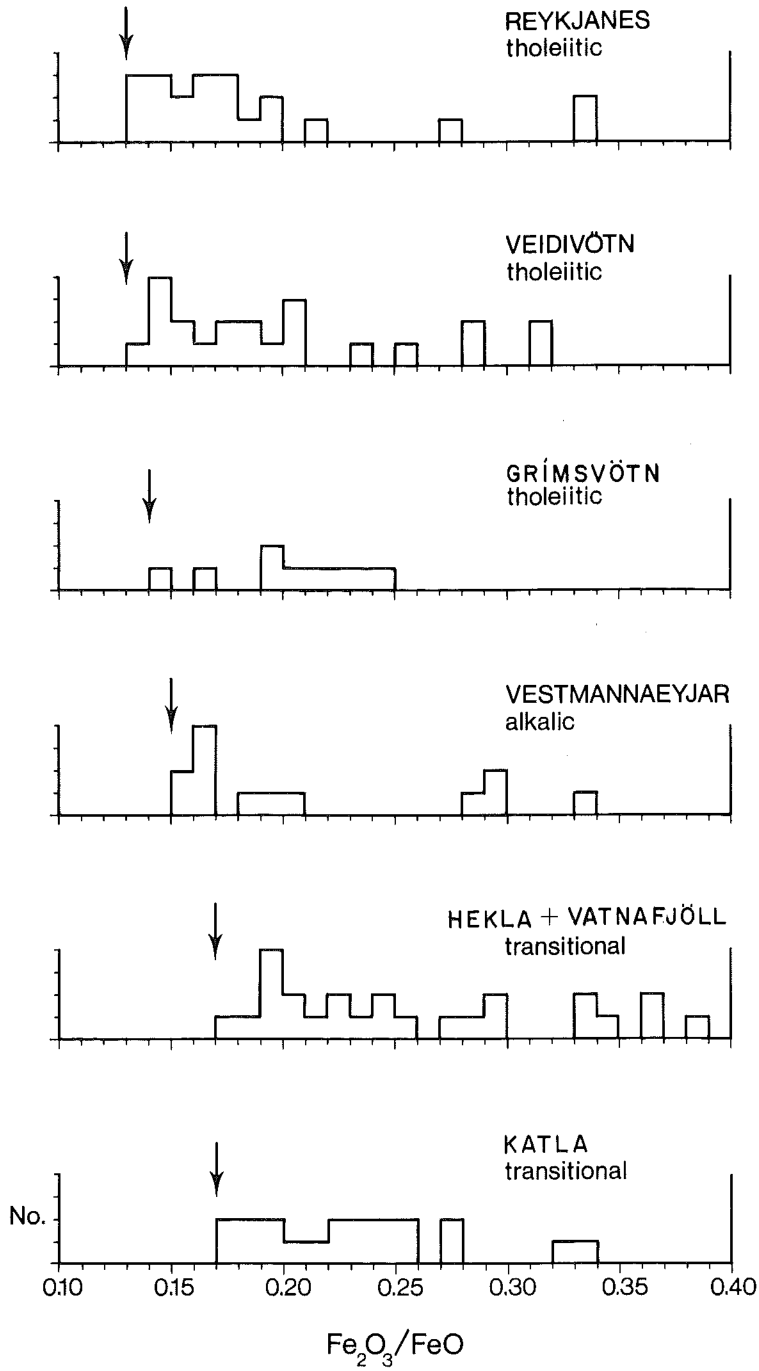


Fig. 34. Frequency distribution of the observed Fe_2O_3/FeO ratios in the EVZ lavas, cf. Tables 1 to 8. Samples with a ratio above 0.40 are excluded. An arrow shows the suggested initial value for each system.

the norm calculation, especially when the basalts are classified into various types, as in this work. Various methods have been used, and Brooks (1976) has suggested the adoption of a value for the Fe_2O_3/FeO ratio of 0.15. The average of the minimum values in the basalts of the six EVZ systems and on the Reykjanes Peninsula is exactly 0.15 (Fig. 34), which indicates that this is a reasonable Fe_2O_3/FeO ratio for adaptation for basalts in general. However, there is a clear indication that the Fe_2O_3/FeO ratio is higher in the transitional basalt magmas of the EVZ than in the tholeiitic and alkalic magmas, i.e. 0.17 and 0.13—0.14, respectively.

Nomenclature of the lavas

The present study has revealed that there are three main types of basic rocks being formed in the EVZ at present. This is the same threefold division as previously used by the present author for the postglacial basalts: i.e. tholeiites, transitional alkali basalts and alkali olivine basalts (Jakobsson 1972, p. 368).

The tholeiites are found in the Veidivötn and Grímsvötn systems, where there are slight but persistent chemical and phenocryst-mineralogical differences between the two systems. Rocks which I had provisionally labelled "transitional alkali basalts" in 1972 are found in the Hekla, Vatnafjöll and Katla systems, and evidently also in the Torfajökull, Tindfjöll and Eyjafjöll systems. Again there are relatively slight but persistent chemical and sometimes phenocryst-mineralogical differences between the various systems. The alkali olivine basalts occur in the Vestmannaeyjar system.

Identification, and distinction between the tholeiitic and the alkalic groups is straightforward, as briefly discussed (Jakobsson 1972). Examination of the new chemical and mineralogical data presented in this paper further supports the classification. The tholeiites and the alkali olivine basalts of the EVZ plot in the tholeiite and the alkali olivine basalt fields of the alkali:silica diagram of Tilley (1950). Comparison with the tholeiitic and alkalic rocks of the Hebridean (Bailey et al. 1924, Thompson et al. 1972 and Esson et al. 1975) and the Hawaiian (Macdonald & Katsura 1964) provinces provides further justification of the division. Finally these two groups would be labelled as olivine tholeiites or tholeiites, and alkali basalts respectively, using the basalt classification of Yoder & Tilley (1962).

It is, however, more of a problem to classify the "transitional alkali basalts". These lavas were named so as they "have clear alkalic affinities" but are "in many respects transitional between the two main groups" (Jakobsson 1972 p. 368).

These high Fe-Ti lavas (Tables 3 to 6) are all Hy-normative. In many plots where alkali content is considered, they plot among the alkali olivine basalts of Vestmannaeyjar (e.g. in the alkali:silica diagram). In other cases as for example the AFM and the Al_2O_3:FeO^*/MgO diagrams they plot as an extension of the Veidivötn and Grímsvötn trends. These lavas are therefore in some respects transitional and it is not acceptable to call them olivine tholeiites as would be the case using the classification of Yoder & Tilley (1962), because of their relatively high content of alkalies. By major element composition these lavas are very similar to the basalts which Coombs (1963) called mildly alkaline basalts and were exemplified by for example analyses from Easter Island, Ascension Island, Galapagos, Mauritius and Reunion. The high Fe-Ti lavas of the EVZ have, however, little in common with the tholeiitic Skjaldbreid lavas (Tryggvason 1943) which Coombs (op. cit.) surprisingly cited as the Icelandic example of his mildly alkaline basalts.

The high Fe-Ti Hy-normative basalts of the EVZ apparently belong to what Miyashiro (1978) labels "Coombs-trend" basalt or hypersthene-normative alkalic basalt.

Thus while there is no doubt about the alkalic nature of the high Fe-Ti lavas, they are in many respects transitional between the true alkali olivine basalts and the tholeiites. Until more evidence is brought forward as regards the nature, orgin and distribution of these basalts in general, it is suggested, to avoid further confusion, that the provisional name "*transitional* *alkali basalt*" is retained for the high Fe- Ti Hy-normative lavas of the EVZ.

Of the divisions of each rock series, the tholeiite series will be considered first. In 1972 the author had divided the Postglacial tholeiites into olivine and quartz tholeiites, respectively, according to the normative content of either of these minerals. It soon became obvious, however, that this is an unnatural method of classification, and Jakobsson et al. (1978) therefore suggested a division of the tholeiitic rocks where the rock is called tholeiite when the cation norm content lies between 8 per cent olivine and about 4 per cent quartz, olivine tholeiite with 8 to 25 per cent normative olivine and picrite basalts (oceanite) when the normative olivine content is above 25 per cent.

The new chemical analyses and the preliminary petrographic data of the tholeiitic EVZ lavas fit this classification well. Fig. 35A is a frequency histogram for analysed postglacial tholeiitic rocks of the western Reykjanes (Jakobsson et al. 1978) and Eastern Volcanic Zones (this study) with respect to the normative cation per cent of either quartz or olivine. Before normative calculation the Fe_2O_3/FeO ratio of all analyses was corrected to the lowest ratio as observed in Fig. 34. The cation norm is used, as this norm is more directly comparable with the mode. As is evident from Fig. 35A, a distinctive group lies between 3 per cent normative quartz and 7 per cent normative olivine, which means that the values straddle the zero point. A classification scheme such as that of Yoder & Tilley (1962) where the tholeiites are classified according to the calculated content of quartz or olivine, is very inconvenient in this case, as the division line cuts the group in two around the mean value. The analyses which fall between 9 and 16 per cent Ol (all from Reykjanes) may indicate the presence of another population. Finally, the three picrite basalts (oceanites) analysed from the western Reykjanes Peninsula form a quite separate group.

Fig. 35A also shows the suggested names and division lines for each group, which is in accordance with that presented by Jakobsson et al. (1978). The classification suggested here is close to that used by Macdonald & Katsura (1964), the difference being that they used 5 per cent modal olivine as the division point between tholeiite and olivine tholeiite. No Postglacial basaltic icelandites (Jóhannesson 1975) of the tholeiitic series have been discovered in the western Reykjanes Peninsula or the EVZ. The division line between the tholeiites and the basaltic andesites is based on data from Thingmúli (Carmichael 1964).

An interesting volcanological-morphological feature lends support to the suggested division between the tholeiites and the olivine tholeiites. This is that all lavas with an olivine content above 9 per cent are lava shields (which as previously noted do not occur in the EVZ), while all the lavas with olivine below 7 per cent are apparently fissure eruptions. When the analyses of Sigvaldason (1974b) from the tholeiitic Northern Zone are compared with the histogram in Fig. 35A they largely substantiate the division, although several lavas which he defines as being of shield volcano type (i.e. lava shields) fall in the interval between 6 and 8 per cent olivine.

As relatively few lavas can be regarded as plagioclase cumulative and probably none are purely olivine or pyroxene cumulative, a freqency plot with regard to an oxide taken directly from the chemical analyses may also be considered in the classification scheme. The MgO per cent by weight content seems to distinguish adequately between the various rock types within each group. The MgO histogram (Fig. 35B) allows the boundaries to be drawn at the same intervals in the tholeiite series. The Thingmúli basalts (Carmichael 1964) compare well with the groups in Figs. 35A and B,except that one of Carmichael's olivine tholeiites is a tholeiite in the present classification.

In the MgO histogram (Fig. 35B) the transitional alkali basalts form one distinct population. The transitional alkali basalts are comparable to the ferrobasalts of Galapagos (McBirney & Williams 1969). These were defined as having more than 12 or 13 per cent FeO* and less than 6 per cent MgO. The basalts of the Katla system would be ferrobasalts by this definition, as would many of the Hekla and Vatnafjöll basalts. The basaltic andesites are

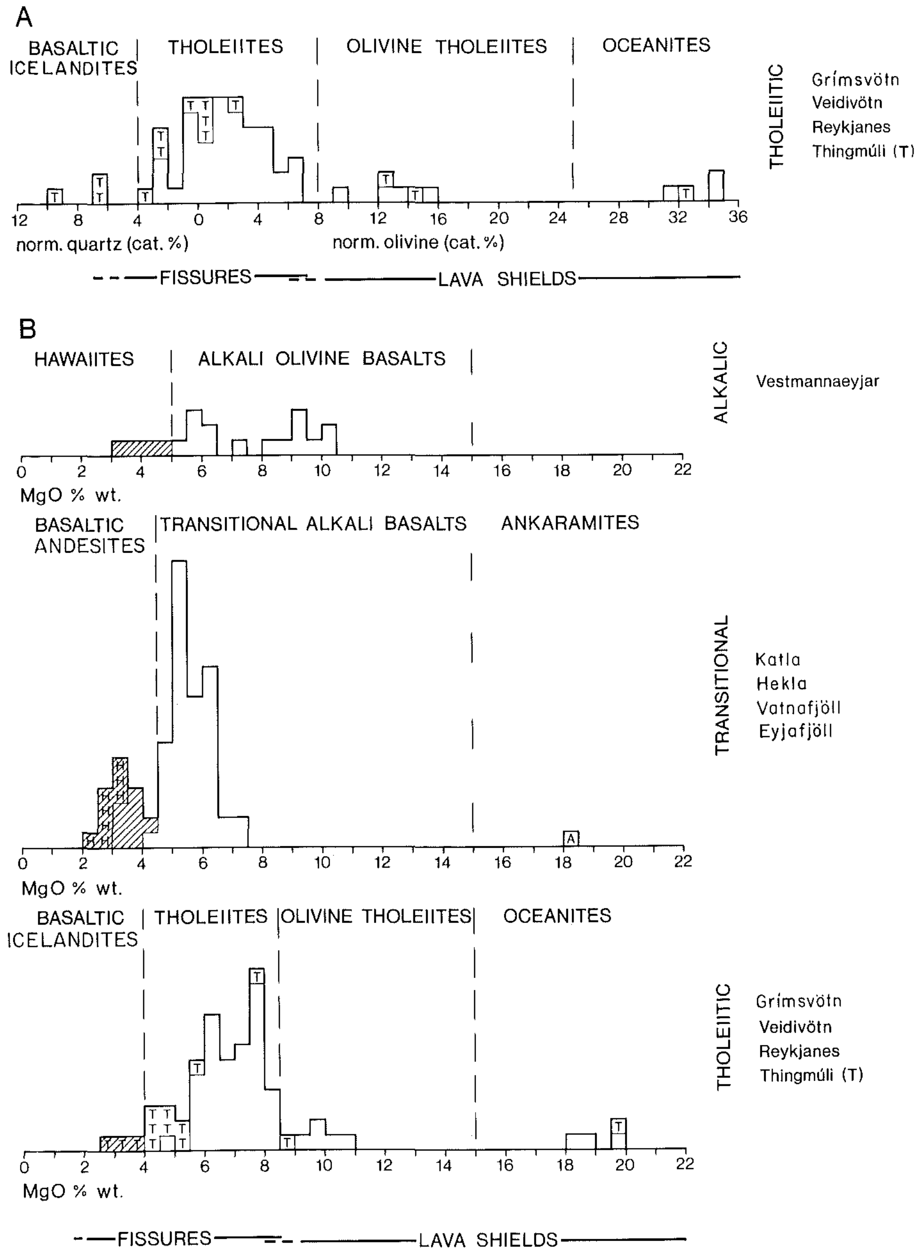


Fig. 35A. Frequency distribution of the analysed tholeiitic rocks of the EVZ with respect to the normative content (cation %) of either olivine or quartz. Also included are the tholeiitic rocks of the Western Reykjanes Peninsula (Jakobsson et al., 1978), and Thingmúli (Carmichael, 1964), marked (T). — B. Frequency distribution of the EVZ lavas with respect to their content of MgO %, including tholeiitic rocks from the Reykjanes Peninsula, Thingmúli, marked (T), ankaramite from Eyjafjöll, marked (A), and basaltic andesites of the Hekla central volcano (from Thorarinsson, 1967 and Sigvaldason, 1974b), marked (H).

indicated with cross hatching and are so labelled after comparison of major chemical elements with analyses of basaltic andesites of the Hebridean and the Hawaiian provinces and other volcanic areas. The division line is best placed at 4.5 per cent by weight of MgO, when only one basalt will plot among the basaltic andesites and only one basaltic andesite among the basalts. It is of interest to note that the boundary between the basalts and the basaltic andesites chosen here corresponds exactly to the shift from olivine normative to quartz normative rocks, (see Table 3).

Two lavas, the 385-Lauf lava (Torfajökull) and 416-Vördufell lava (Tindfjöll), which fall in the basalt field in Fig. 35B have the appearance of basaltic andesites, although they straddle the boundary in many plots. As the rocks are actually part of an alkalic rock series the terms hawaiite and mugearite could be employed here and the analysed transitional basaltic andesites from the EVZ would then all be termed hawaiites. On the other hand, if the original definition of hawaiite (Iddings 1909) is used, where the normative plagioclase content is determinative (An 30—50), then many of the transitional alkali basalts are hawaiites, (e.g. most of the Katla system lavas). This is another example of an inconvenient classification, as the distinct population of the transitional alkali basalts (Fig. 35B) would then be cut in two.

The alkali olivine basalts of Vestmannaeyjar form two small populations (p. 16). The evolved basalts grade into the hawaiites close to a MgO content of 5.0 per cent by weight which also approximately marks the shift from normative labradorite to normative andesine. An alkali basalt with less than 5 per cent olivine (Macdonald & Katsura 1964) was not found in Vestmannaeyjar. The first magma extruded in the Eldfell (Heimaey) 1973 eruption was labelled mugearite by Jakobsson et al. (1973), on the basis of a chemical analysis. A new analysis of the same sample indicates, however, a lower content of alkalies (Table 1, no. 15). With reference to the Hebridean and Hawaiian provinces this appears to place the first extruded Eldfell magma in the hawaiite field, although the normative An-content is still below 30.

As is evident it seems impractical to place the basalt/basaltic andesite boundary at the same MgO value for the three series. Thompson (1973) has suggested that an apparent discontinuity at 6 weight per cent MgO and 1150°C in a MgO versus silicate liquidus temperature plot at one atmosphere might be used to mark the boundary between basalts and andesitic rocks. This does not appear to be a convenient division line for the EVZ basalts as is evident from Fig. 35B.

No postglacial picrite basalts have been found in the EVZ, although late Quaternary ankaramites have been found in several places in the Eyjafjöll area (Steinthórsson 1964, Carswell 1978), see p. 90. The classification of Macdonald & Katsura (1964) for picrite basalts has been adopted here.

As mentioned above, the Yoder & Tilley (1962) classification is not very suitable for the tholeiites and the transitional alkali basalts, and the same can be said about the Irvine and Baragar (1971) classification guide which recently (Imsland 1978) has been used to classify Icelandic basalts. For the purpose of comparison all the present EVZ analyses were classified according to the Irvine & Baragar guide, using a computer program. The classification of some of the transitional alkalic rocks proved to be awkward, as one example clearly illustrates. The four lavas analysed from the Eyjafjöll volcanic system (191, 308, 398 and 396, Table 5) were classified as follows: ol.-tholeiite (191), calcalkaline basalt (308), alkaline hawaiite (398) and ol.-tholeiite (396). This is most unfortunate since these rocks seem to be closely related petrochemically (Figs. 13 and 16).

In Fig. 35A and B the histograms express the distribution of the number of analyses. As the lavas selected for analyses are considered to be well distributed in space and time, the histograms will approximately correspond to the number of eruptions in Postglacial Time. If a histogram of volume values was constructed instead, the various populations of rock types would probably be more prominent. This would apply for example to the olivine tholeiites of Reykjanes Peninsula, which are produced in a few eruptions of large volume (Jakobsson et al. 1978).

In summary, the geochemical and petrographical data of the Postglacial basic rocks found in the EVZ and the western Reykjanes Peninsula, suggest the following classification as being the most natural one:

1. Tholeiitic series. In this the rocks plot below the division line of the alkali:silica plot (Fig. 19), and may be further subdivided as follows:
   a. Oceanite, with abundant phenocrysts of olivine and more than 25 per cent normative (cation norm) olivine (Fig. 35A).
   b. Olivine tholeiite, with 8—25 per cent normative olivine.
   c. Tholeiite, between 8 per cent olivine and 4 per cent quartz in the norm.
2. Transitional alkalic series, the rocks are Hy-normative, but plot above the division line in the alkali:silica plot (Fig. 13), except for the basaltic andesites which straddle the division line. The following rock types are found:
   a. Ankaramite, with abundant phenocrysts of augite and olivine and more than 25 per cent normative olivine.
   b. Transitional alkali basalt, with 4.5—8 per cent MgO (Fig. 35B) and about 16 per cent normative olivine to 2 per cent quartz.
   c. Transitional basaltic andesite, with 2—4.5 per cent MgO and about 0—10 per cent normative quartz.
3. Alkalic series. The rocks are Ne-normative and plot above the division line in the alkali:silica plot in Fig. 4. There are two types:
   a. Alkaline olivine basalt, with 5—11 per cent MgO (Fig. 35B) and normative plagioclase above An 50.
   b. Hawaiite, with 3—5 per cent MgO and in which the normative feldspar is andesine.

Internal lava variations

Before the chemical analyses are evaluated it is necessary to examine the variation of chemical composition within single basaltic lavas in Iceland. It is envisaged that heterogeneity in the chemical composition of a fresh lava is dependent mainly on two factors, a) changes in magma composition during eruption and b) variation which has occurred after eruption, but prior to complete consolidation and degassing.

Published data from four basic eruptions in Iceland supposedly show the maximum compositional variation during these eruptions. Two of these, the Eldfell (Heimaey) 1973 eruption and the Hekla 1970 eruption produced basaltic andesites and show relatively great compositional variation. The present author's experience from the field work is that basaltic andesites and andesites in general show much more variation than basalts. The results of Grönvold (1972), who investigated intermediate lavas from the Kerlingarfjöll central volcano and the Krafla-Námafjall volcanic system agree with this observation. Fig. 36 shows the chemical variation observed during these eruptions in terms of total alkalies and silica. The Eldfell 1973 lava displays very great variation (Jakobsson et al. 1973 and Table 1, this paper), starting with hawaiite (close to mugearite), and ending with basic hawaiite. The Hekla 1970 eruption, however, produced relatively homogenous lavas (Sigvaldason 1974a). According to two analyses of the Askja 1961 tholeiite lava (Thorarinsson & Sigvaldason 1962), variation in chemical composition is less than the analytical error. The Surtsey alkali basalt lavas, (1.2 km^3), which were erupted from five different sites during 1964—1967, show rather great variation (Steinthórsson 1967, and Table 1, this paper), which is most probably due to variation in the amount of olivine phenocrysts.

Grönvold (1972) has tested the homogeneity of the 080-Lakagígar lava of 1783—1784. One hundred samples were collected and from these twelve samples were analysed, representing as large a time interval in extrusion as possible. Three of these chemical analyses are shown in Fig. 36. The homogeneity of this tholeiite flow, which has been estimated to be 12 km^3, is surprising.

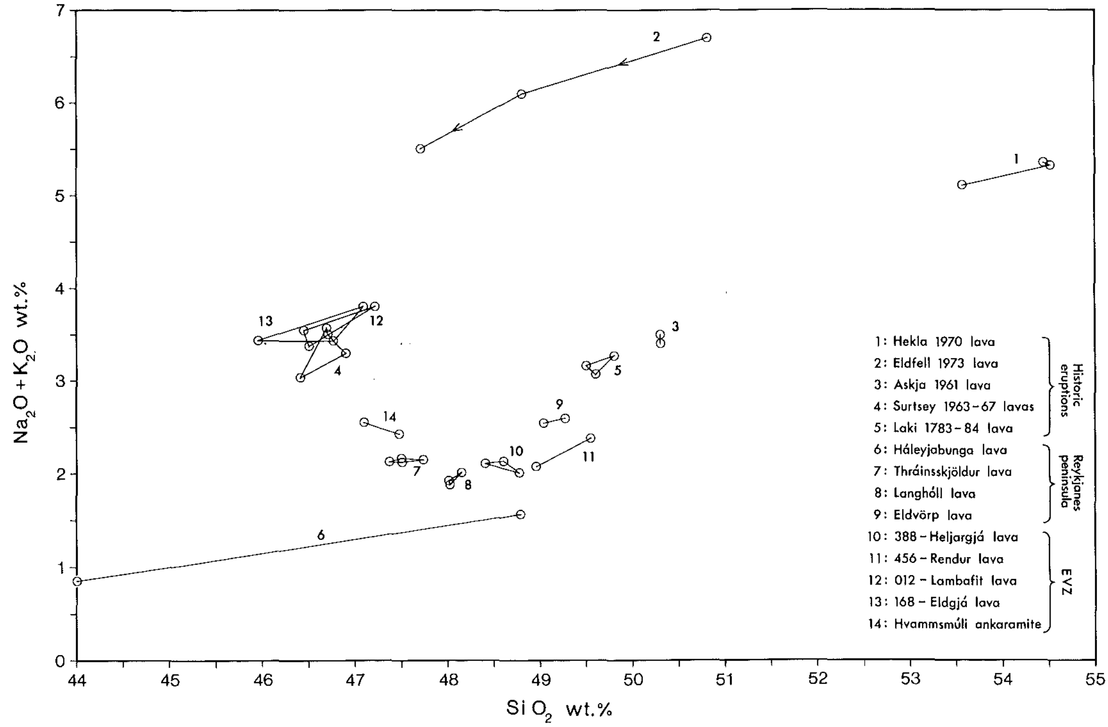


Fig. 36. Compositional variation within thirteen single Postglacial lavas and one intrusive ankaramite, illustrated by an alkali:silica diagram. For reference to chemical analyses, see text on p. 81—83.

Fig. 36 also includes values from four Postglacial lavas on the western Reykjanes Peninsula (Jakobsson et al. 1978, p. 687—692). For this area it was concluded that the lava shield olivine tholeiites and the fissure tholeiites are homogenous as regards significant chemistry (Fig. 36, nos. 7, 8 and 9), whereas the picrite basalts of lava shields can exhibit great variation (e.g. Fig. 36, no. 6). The variation in the picrite basalt is probably mainly due to gravitational fractionation and flowage differentiation after extrusion.

Four lavas from the EVZ were tested for homogeneity (Fig. 36). The 388-Heljargjá lava (Veidivötn system, Table 8), is surprisingly homogenous in spite of its porphyritic character (about 26% plagioclase macrophenocrysts), and size (1.7 km^3). The two samples of the 456-Rendur lava (Veidivötn system, Table 8) were chosen to include the greatest variation according to field criteria. This plagioclase porphyritic lava is one of the very few in the EVZ, which exhibit flowage differentiation. As expected the chemical variation is relatively large. Finally the two transitional alkali basalts which were tested, the 012-Lambafit lava (Hekla system, Table 3) and the 168-Eldgjá lava (Katla system, Table 6) show about three times as much variation as the tholeiites for most major components (Fig. 36). In the 012-Lambafit lava the variation in MgO is between 5.15—6.38 per cent and in K_2O between 0.54—0.71 per cent. Judging from field criteria these variations in the transitional alkali basalts are probably due to variation in chemistry during eruption and/or variation in erupted material along the eruption fissure. Also included in Fig. 36 are two analyses of the Hvammsmúli ankaramite (Table 15), of both porphyritic and non-porphyritic phases.

Sampling techniques greatly affect the significance of such homogeneity measurements. When one or two samples are taken of each eruption unit as in this study they must represent the average rock composition in the exposure, which are usually large in the Postglacial lavas. The samples discussed above and plotted in Fig. 36 are mostly chosen to show the maximum variation likely.

The chemical variation might prove to be greater if the very first erupted material was available for inclusion in the analyses. However, the *main mass* of the lava is represented by the sample as collected in this work. It appears safe to conclude that provided samples are carefully collected, the tholeiites and olivine tholeiites in the EVZ and the Reykjanes Peninsula can be regarded as homogenous for the purpose of the present paper and that one carefully chosen sample can give a good idea of the lava chemistry. The transitional alkali basalts, and possibly also the alkali olivine basalts of the EVZ appear to be more heterogenous than the tholeiites, as judged from Fig. 36, and this heterogeneity must be taken into account when the overall chemistry and chemical trends of the Katla, Hekla, Vatnafjöll and Vestmannaeyjar systems are considered. The petrography of the lavas of the Eyjafjöll systems suggests that they may also exhibit compositional variations.

Watkins et al. (1970) investigated the major and trace element variation across a tholeiite lava in the Tertiary rocks of Eastern Iceland. A considerable spread of values was found. However, as Wood et al. (1976) have pointed out, the flow in question has suffered high-grade zeolitisation, and the results are therefore probably not comparable with those obtained from the Postglacial lavas in the present study.

Major element chemistry of the lavas

Accumulated lavas. As discussed previously (p.68), the petrographic analysis strongly suggested that some of the lavas are accumulated with respect to macrophenocrysts (Fig. 31). It was indicated that plagioclase macrophenocrysts were accumulated in several cases, though there is no definitive case of olivine, clinopyroxene or spinel accumulation. No attempt was made to exclude the porphyritic lavas, and selection of samples for chemical analysis was conducted so as to cover all lava compositions in space and time. It is therefore of interest to see if accumulated lavas can be distinguished in a chemical plot. The Al_2O_3:FeO*/MgO plot for example is suitable for this purpose as the "control lines" for plagioclase and olivine lie very differently in this plot.

In Fig. 37A, it can be seen that the lavas of the Veidivötn system form two different trends which meet at 14.6 per cent Al_2O_3 and a FeO*/MgO ratio of 1.35. The lower trend is parallel to the main trend of the tholeiitic Reykjanes Peninsula lavas in Fig. 37B, which are not accumulative (Jakobsson et al. 1978). The upper trend is nearly vertical and cannot be explained otherwise than by accumulation of plagioclase macrophenocrysts (An 88). The An 88 line is shown in Fig. 37A, along with the flowage differentiated 456-Rendur lava (Table 8, no. 15—16) and the average content of plagioclase macrophenocrysts. The dashed line in Fig. 37A is the suggested demarcation line between the accumulated and non--accumulated lavas and is directly comparable with the dashed line in Fig. 31B. It is indicated that two of the Grímsvötn system lavas are also accumulative, which agrees with the petrographic results.

The comparable demarcation line for plagioclase accumulated lavas will lie at higher values for the Reykjanes lavas (Fig. 37B), since the Reykjanes Peninsula is situated in a transition zone to the abyssal part of the MAR (Jakobsson et al. 1978) and is therefore characterized by higher Al_2O_3 values than the tholeiitic suites inland. Some of the tholeiite lavas of the Northern Zone (Sigvaldason 1974b) can be predicted to be accumulative by analogy with the Veidivötn trend (Fig. 37B).

The accumulated lavas can be identified (Fig. 37C, D and E) in the other systems, in the same way as for the Veidivötn system. The following sixteen lavas were found to be accumulative:

Veidivötn:	051, 371, 063, 388, 056, 456, 459, 463, 278; cf. Table 8.
Grímsvötn:	163, 083?; cf. Table 7.
Torfajökull:	147; cf. Table 5.

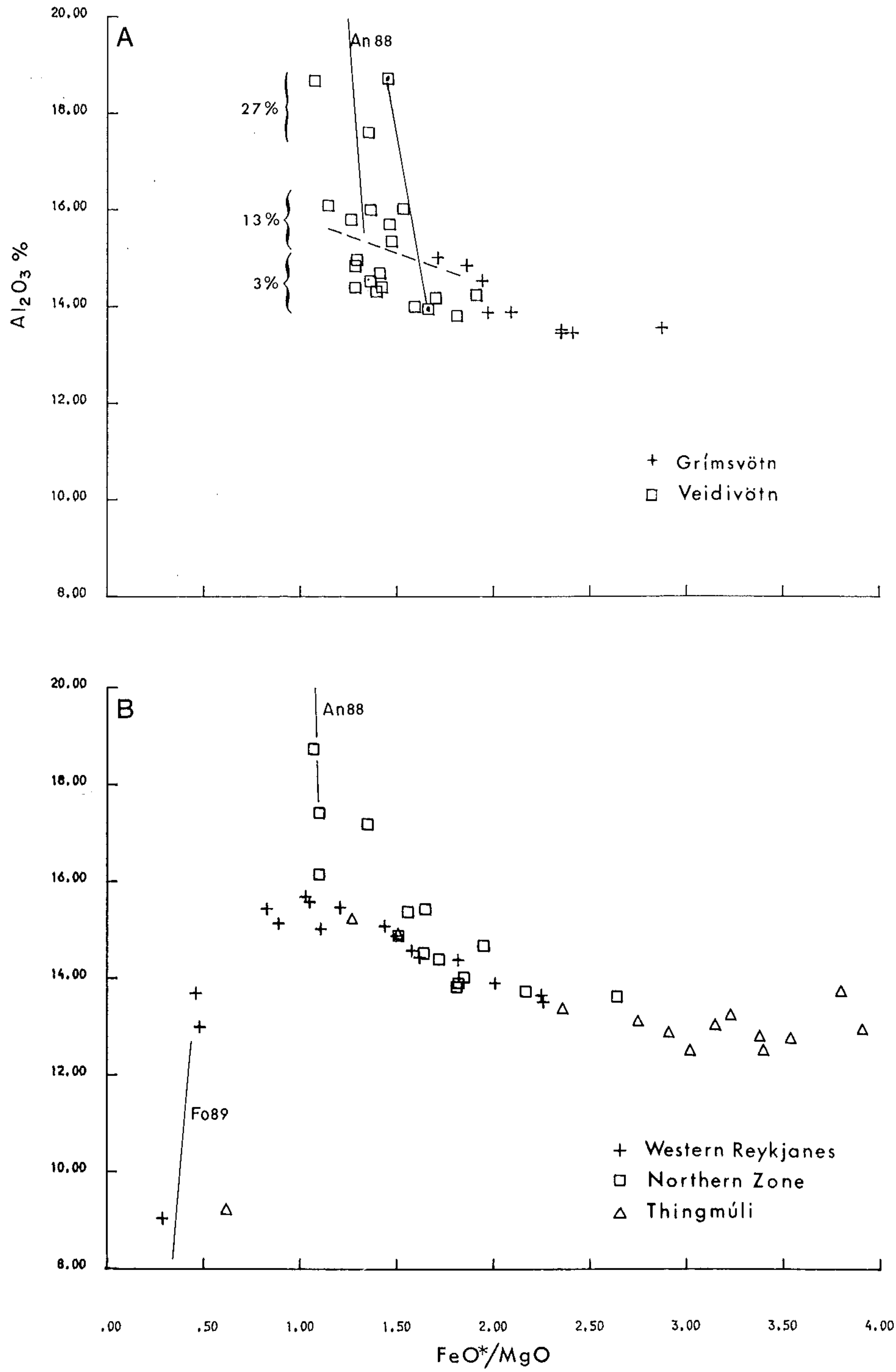
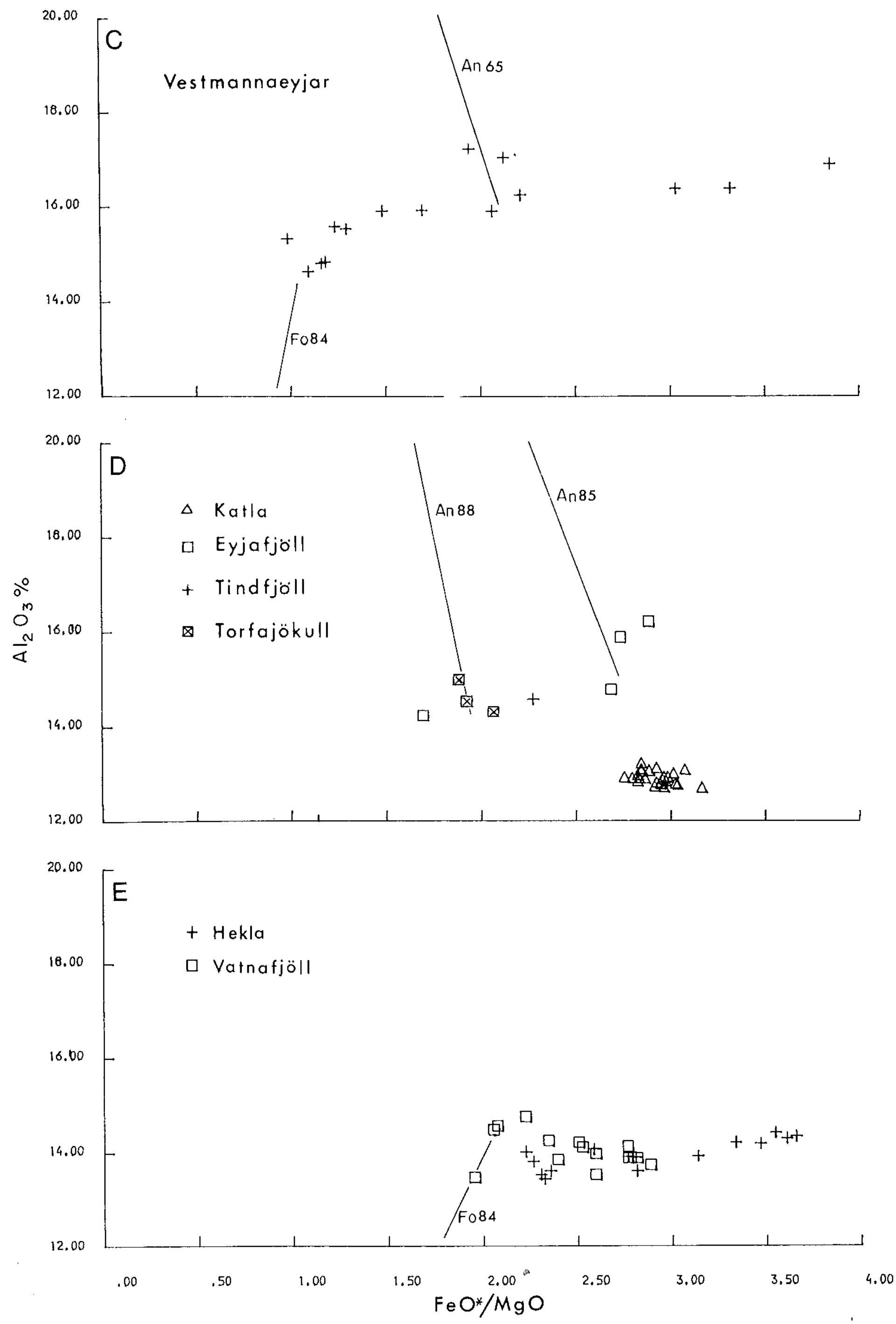


Fig. 37. An Al_2O_3:FeO*/MgO diagram of the analysed EVZ lavas. Also included are selected analyses from the western Reykjanes lavas (Jakobsson et al., 1978), the Northern Zone (Sigvaldason, 1974b) and analyses from the picrite basalt — basaltic andesite range of Thingmúli (Carmichael, 1964). A: The tholeiitic Veidivötn and Grímsvötn systems. The plagioclase An 88 line is shown and the dashed line indicates the boundary of cumulated and non-cumulated lavas. Tie-line between two Veidivötn analyses indicates flowage



differentiation in the 456-Rendur lava. Average volume (percentage) of plagioclase macrophenocrysts is indicated for the Veidivötn lavas. — B.—E.: Tholeiites of the western Reykjanes Peninsula, the Northern Zone and Thingmúli; alkali olivine basalts of Vestmannaeyjar; transitional alkali basalts of Katla, Eyjafjöll, Tindafjöll, Torfajökull, Hekla and Vatnafjöll systems. The plagioclase and olivine control lines are indicated.

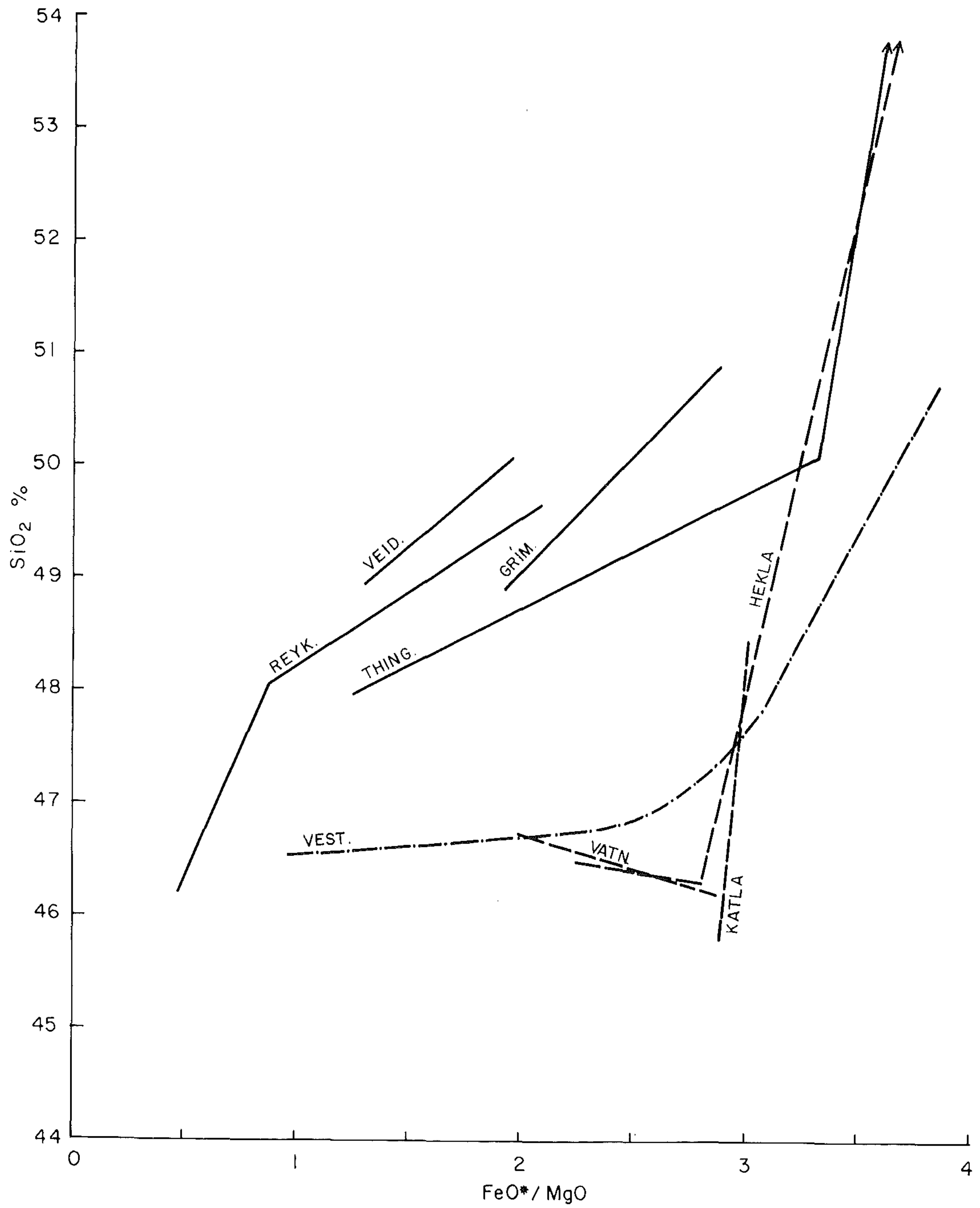


Fig. 38. A SiO_2:FeO*/MgO diagram showing the Postglacial trends of the volcanic systems in the EVZ, the western Reykjanes Peninsula, and Thingmúli. Basaltic andesites are included where developed. Continuous lines: tholeiitic suites; dashed lines: transitional alkalic suites; and dot and dash line: the alkalic suite.

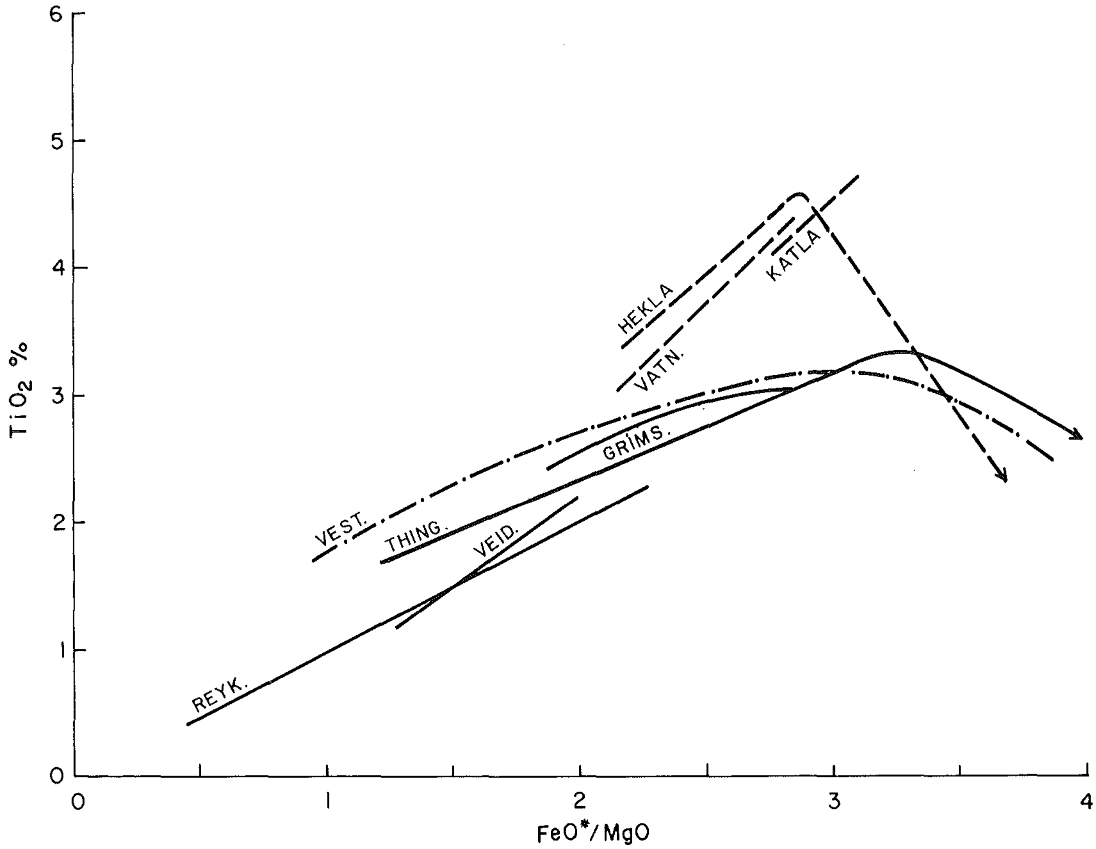


Fig. 39. A TiO_2:FeO*/MgO diagram showing the Postglacial trends of the volcanic systems in the EVZ, the western Reykjanes Peninsula, and Thingmúli. Basaltic andesites are included where developed. Key as in Fig. 38.

Eyjafjöll: 398, 396?; cf. Table 5.
Vestmannaeyjar: VE48, VE67; cf. Table 1.

The 16 lavas represent about 16 per cent of the analysed eruption units of the EVZ. All the above — mentioned lavas are plagioclase accumulative, and in the listed lavas of the Grímsvötn and Eyjafjöll systems, accumulation of both plagioclase and olivine may have occurred. As mentioned previously (p. 65), there are no signs of accumulation of micropheno-crysts. After distinction of the accumulated lavas, it appears that the variation trends become smoother (Fig. 37).

Variation Diagrams. The compositional trend of each volcanic system, was discussed previously in terms of the alkali:silica and Al_2O_3:FeO*/MgO diagrams. In the following section some chemical plots are considered further to demonstrate in particular, differences and similarities between the three rock series and some of their petrochemical characteristics. The accumulated lavas are excluded.

For clarity only the trend of each volcanic system is shown, the individual plots being omitted. However, the distribution of points in these diagrams is usually similar to that of the alkali:silica diagrams.

Variations in major oxides against the FeO*/MgO ratio (Miyashiro et al. 1969) may first be considered. These plots are convenient for many basic rocks as the various trends often separate effectively, the ratio is easy to calculate and variations in amounts of phenocrysts (up to some 3—4 per cent by volume) do not affect the ratio significantly.

The SiO_2:FeO*/MgO diagram is presented

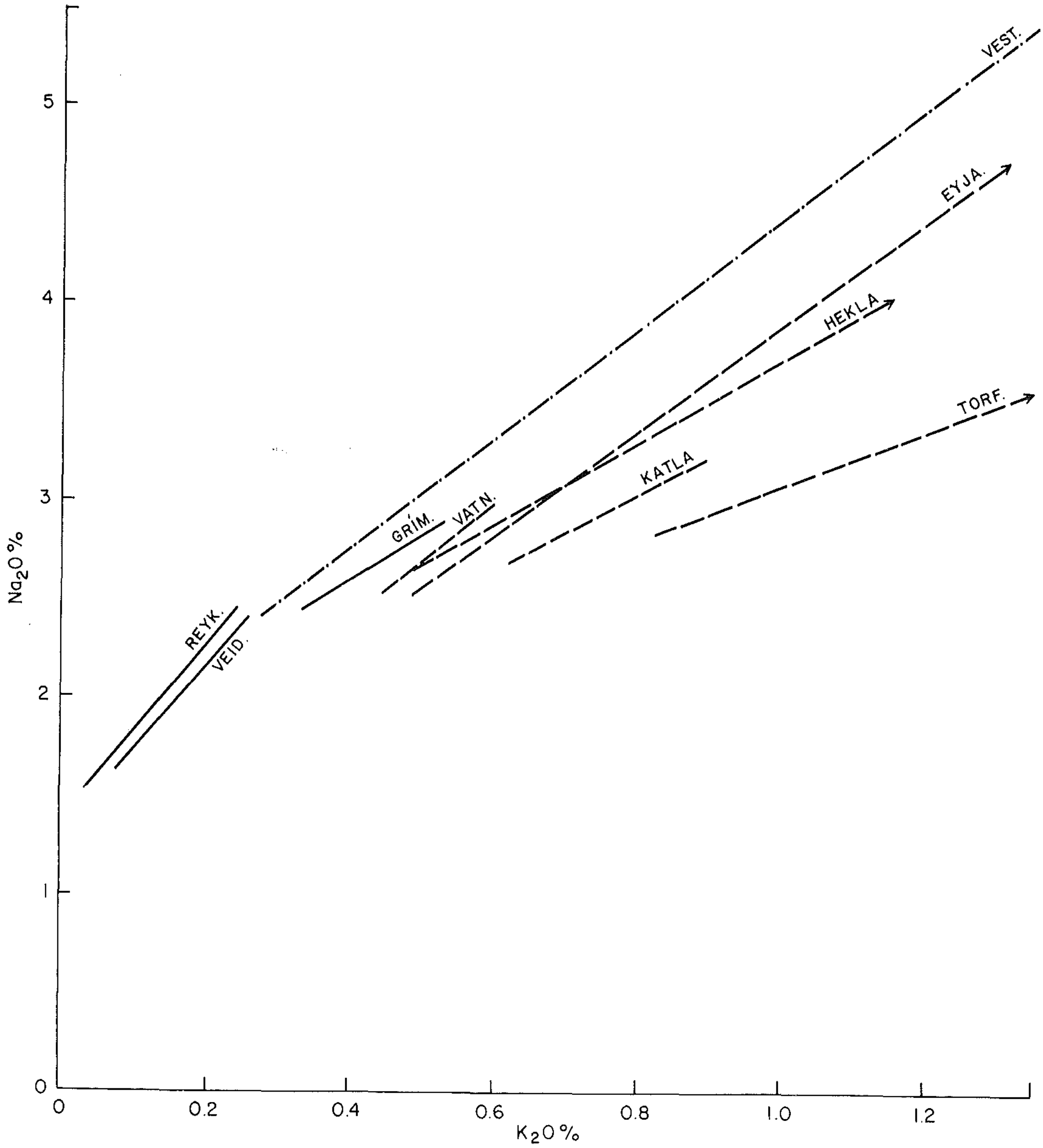


Fig. 40. A Na_2O:K_2O diagram showing the trend of each volcanic system in the EVZ, and the western Reykjanes Peninsula. Compare Fig. 16. Key as in Fig. 38.

in Fig. 38. The compositional trends are drawn from computer plots, comparable to Fig. 37. The tholeiitic trends in Fig. 38 exhibit a continuous increase in the FeO*/MgO ratio of between 1 and 3. The transitional trends show a slight fall up to a FeO*/MgO ratio of 2.8—2.9 followed by a sharp rise. The Torfajökull and Eyjafjöll trends are difficult to evaluate because of scanty data, porphyritic nature and complex mineralogy. These systems are therefore not included here. The alkalic Vestmannaeyjar suite shows only a minor increase in SiO_2 at first, but at the basalt/basaltic andesite boundary the increase becomes rapid. In this diagram, the

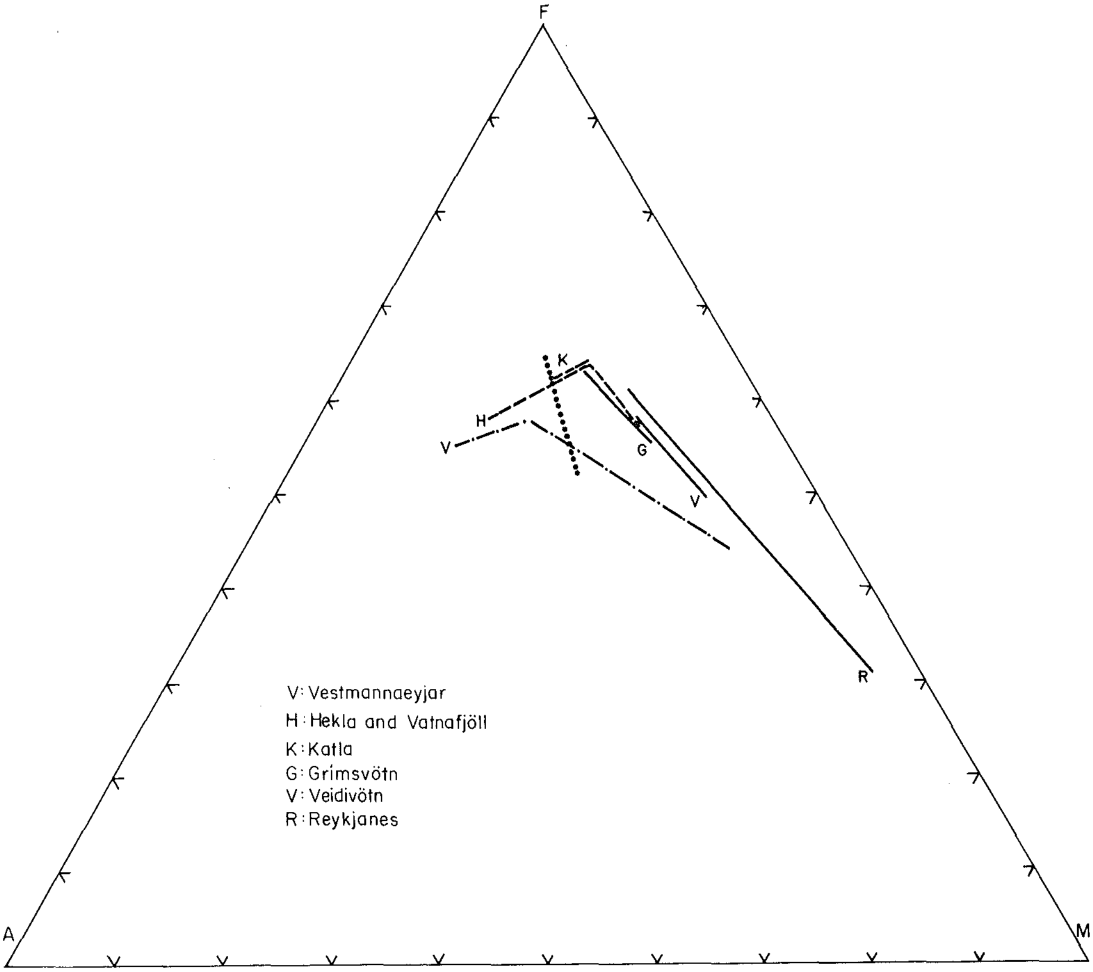


Fig. 41. AFM diagram showing the trends of the volcanic systems of the EVZ and the Reykjanes Peninsula. The dot line is the approximate location of the basalt/basaltic andesite boundary.

basalts of the tholeiitic systems, and the transitional alkalic and alkalic systems separate clearly.

The SiO_2:FeO*/MgO plot in Fig. 38 is to all intents and purposes the same plot as Carmichael presents for the Thingmúli suite (1964, Fig. 4). He notes that the change of trend coincides generally with the appearance of magnetite as a phenocryst phase. This may possibly apply to the tholeiitic series and the alkalic series of the EVZ, but not to the transitional alkalic series, where magnetite is present from the beginning as a microphenocryst phase and only one grain of a magnetite macrophenocryst (Fig. 33A) was observed.

The TiO_2:FeO*/MgO (Fig. 39) plot exhibits the relatively great variations in the TiO_2-content typical of the EVZ. If older chemical analyses of questionable quality are excluded, the highest TiO_2-concentrations observed in Iceland are between 4.70 and 4.73 per cent in some of the lavas of the Hekla and Katla systems, the maximum being noticeably sharp for the Hekla trend. The Vestmannaeyjar and Grímsvötn suites do not separate in this plot. Similarily, the petrographic analysis of the EVZ lavas does not indicate that the sharp bend in the TiO_2 curves is due to a sudden fractionation of magnetite.

The Na_2O:K_2O (Fig. 40) diagram is included because of the well-defined straight lines of correlation obtained for all the systems. The transitional alkalic suites group together in this plot. A distinct fanshaped arrangement of the trends is noticeable, i.e. the Na:K ratio decreases with an increase in the K_2O content of the most basic extrusives in each system. Another interesting feature of Fig. 40 is that the most evolved end of the Veidivötn and Reykjanes Postglacial suites and the most primitive end of the other suites can be connected approximately by a straight line.

The extreme iron-enrichment of the tholeiitic and transitional series, which is so typical for Iceland, is seen in the AFM diagram (Fig. 41). The Vestmannaeyjar trend separates well from the tholeiitic and the transitional trends, whereas some of the tholeiitic and transitional suites coincide.

Other plots have also been considered although not listed here. The Al_2O_3:alkali plot (Kuno 1960, Fig. 5) for example, shows a complete distinction between the alkalic and tholeiitic rocks, with the exception of the VE-61-Stórhöfdi lava of the Vestmannaeyjar system, which appears as tholeiite. The transitional lavas plot as a continuation of the tholeiites. None of the lavas, including the plagioclase accumulated ones, fall in the high-alumina field. It seems therefore to be established (Jakobsson 1972) that high-alumina basalts do not occur in Iceland.

Generally the various systems and also the three rock series can be easily separated by use of carefully selected chemical plots.

TABLE. 15. CHEMICAL ANALYSES AND CIPW-NORMS (WT%) OF UPPER PLEISTOCENE PICRITE BASALTS. ANALYST (EXCEPT S12): GREEN. GEOL. SURVEY, CHEM. LAB., I. SØRENSEN.

ROCK. NO	3534	654POR	654NON	S12
SiO2	49.78	47.08	47.47	45.49
TiO2	1.63	2.33	2.36	1.30
Al2O3	11.78	12.25	13.78	8.16
Fe2O3	3.32	2.46	2.88	2.60
FeO	6.05	9.40	7.98	7.80
MnO	.18	.19	.17	.16
MgO	11.06	11.70	9.23	18.49
CaO	11.99	11.40	12.17	11.04
Na2O	2.02	2.13	1.98	1.18
K2O	.69	.43	.44	.34
P2O5	.24	.26	.22	.13
H2O	1.09	.34	.62	3.36
Sum	99.83	99.97	99.30	100.18
CIPW	WEIGHT-NORM			
OR	4.08	2.54	2.60	2.01
AB	17.09	18.02	16.75	9.99
AN	21.04	22.60	27.41	15.97
DI	29.30	25.97	25.34	30.17
HY	16.56	5.17	12.00	7.00
OL	2.20	16.74	5.41	25.02
MT	4.81	3.57	4.18	3.77
IL	3.10	4.43	4.48	2.47
AP	.56	.60	.51	.30
	98.74	99.63	98.68	96.69
Fe2O3/FeO	.55	.26	.36	.33
FI-index	21.17	20.57	19.36	11.99
FeO*/MgO	.82	.99	1.15	.55

Key to Table 15. See text to Table 1.

3534:	Loose boulder from a moraine in Kriki, NE of Katla, Katla system.
654POR:	Hvammsmúli ankaramite, intrusive. Porphyritic part of the sample, cf. below. Eyjafjöll system. Collected by A. Noe-Nygaard.
654NON:	Hvammsmúli ankaramite, non-porphyritic part of the sample, formed by flowage differentiation; cf. above.
S12:	Jökulhaus ankaramite, breccia. Eyjafjöll system. After Carswell (1978).

UPPER PLEISTOCENE ROCKS

The discussion in the previous chapters has centered on the Postglacial volcanic petrology. As this is a very short time period in the geologic sense, a few data on the basaltic rocks of Upper Pleistocene age (between 0.01 and 0.7 m.y.) will be presented here.

Picritic rocks

As mentioned previously, no picritic lavas appear to have been extruded in the EVZ during Postglacial Time. However, ankaramites of Upper Pleistocene age are known to occur in the Eyjafjöll complex. Three localities are known from the south side of the complex (Plate III), Hvammsmúli (Steinthórsson, 1964) Arnar-

TABLE 16. CHEMICAL ANALYSES AND CIPW-NORMS (WT%) OF UPPER PLEISTOCENE BASALTS. ANALYST: GREENL. GEOL. SURVEY, CHEM. LAB., I. SØRENSEN.

ROCK. NO	6203	6615	4414	4447	4418	6616	4453	4456	6209	4430	4026
SiO2	46.35	46.86	49.72	50.30	49.62	50.16	49.86	49.92	49.45	48.07	49.24
TiO2	2.62	4.45	3.99	3.74	2.16	3.23	3.22	3.48	1.54	1.32	1.57
Al2O3	15.60	13.08	13.38	12.79	13.77	12.58	13.16	12.92	14.09	18.18	15.29
Fe2O3	4.27	4.13	5.43	4.64	3.23	3.35	5.72	4.56	2.96	2.65	3.24
FeO	9.07	10.64	8.46	10.80	9.43	12.52	8.76	10.48	8.08	6.54	7.75
MnO	.19	.21	.20	.24	.20	.24	.24	.24	.19	.15	.18
MgO	7.43	5.50	4.72	4.49	6.83	4.78	4.96	4.96	7.81	6.71	7.38
CaO	10.72	10.42	9.27	8.79	11.49	9.10	9.20	9.40	12.72	13.23	12.29
Na2O	2.52	2.96	3.28	2.98	2.33	2.84	3.18	2.88	2.52	1.87	2.09
K2O	.36	.65	.96	.55	.23	.52	.58	.45	.17	.14	.16
P2O5	.31	.52	.50	.49	.27	.38	.47	.42	.19	.17	.20
H2O	.42	.34	.33	.34	.62	.32	.48	.46	.42	.47	.65
Sum	99.86	99.76	100.24	100.15	100.18	100.02	99.83	100.17	100.14	99.50	100.04
CIPW	WEIGHT-NORM										
Q			4.41	6.47	2.15	4.00	5.30	5.40		.30	1.47
OR	2.13	3.84	5.67	3.25	1.36	3.07	3.43	2.66	1.00	.83	.95
AB	21.32	25.05	27.76	25.22	19.72	24.03	26.91	24.37	21.32	15.82	17.69
AN	30.19	20.48	18.95	19.90	26.44	20.04	19.92	21.00	26.63	40.80	31.87
DI	16.97	22.72	19.15	16.92	23.53	18.88	18.37	18.82	28.57	19.18	22.52
HY	10.37	11.48	7.36	13.09	16.96	17.81	9.93	13.27	11.21	15.35	16.77
OL	6.57	.20							3.33		
MT	6.19	5.99	7.87	6.73	4.68	4.86	8.29	6.61	4.29	3.84	4.70
IL	4.98	8.45	7.58	7.10	4.10	6.13	6.12	6.61	2.92	2.51	2.98
AP	.72	1.20	1.16	1.14	.63	.88	1.09	.97	.44	.39	.46
	99.44	99.42	99.91	99.81	99.56	99.70	99.35	99.71	99.72	99.03	99.39
Fe2O3/FeO	.47	.39	.64	.43	.34	.27	.65	.44	.37	.41	.42
FI-index	23.45	28.89	37.84	34.93	23.23	31.10	35.63	32.43	22.33	16.95	20.10
FeO*/MgO	1.74	2.61	2.83	3.34	1.81	3.25	2.80	2.94	1.38	1.33	1.45

Key to Table 16. See text to Table 1.

Transitional alkali basalts

1. 6203, pillow lava. Bjólfell, at Hekla volcanic system.
2. 6615, volcanic plug. Grafarhóll, at Katla volcanic system.
3. 4414, volcanic plug. Hjörleifshöfdi, at Katla volcanic system.
4. 4447, breccia. Tindafjöll NE of Mýrdalsjökull, at Katla volcanic system.

Tholeiites

5. 4418, breccia. NE of Faxi, at Grímsvötn volcanic system.
6. 6616, volcanic bomb. Grettir, at Grímsvötn volcanic system.
7. 4453, lava. Eyjan at Thverá, at Grímsvötn volcanic system.
8. 4456, pillow lava. Tröllhamar, at Grímsvötn volcanic system.
9. 6209, breccia. N of Breidbakur, at Veidivötn volcanic system.
10. 4430, pillow lava, Skuggafjöll at Veidivötn volcanic system.
11. 4026, lava. Ljósuöldur, at Veidivötn volcanic system.

klettur, and Jökulhaus (Carswell, 1978). The ankaramites are probably intrusive both in Hvammsmúli and Arnarklettur, while in Jökulhaus it forms a breccia(?). At Útigönguhöfdi, on the northern flank of Eyjafjöll, a picrite basalt from the second last glaciation is exposed (Jørgensen 1976). In addition, one loose block of picrite basalt was found in Kriki on the east of Mýrdalsjökull. These are the only known localities of true ultramafic rocks in the whole EVZ.

Steinthórsson (1964) has presented a detailed petrographic analysis of the Hvammsmúli ankaramite. Macrophenocrysts of olivine (Fo 83), diopsidic augite and plagioclase constitute about a third of the rock.

Three new analyses of picrite basalts from Hvammsmúli and Kriki are presented in Table

15, along with an analysis of the Jökulhaus ankaramite (from Carswell, 1978). Some of these rocks may be cumulative. However, the non-porphyritic phase of the Hvammsmúli ankaramite demonstrates that these are very primitive compositions, and are therefore possible candidates as parent (or possibly primary) liquids for the transitional alkalic basalts. However, a preliminary fractionation calculation test, using a least-squares mixing program, indicated that it is not possible to fractionate the Hvammsmúli ankaramite towards a transitional alkali basalt composition, or in fact, any alkali olivine basalt or tholeiite with a composition such as has been extruded in the EVZ. It is also surprising to find that all the above-mentioned picrite basalts plot in the tholeiitic field of the alkali:silica plot, although they apparently belong to the transitional alkalic series.

The ankaramites of the EVZ are similar in composition to the ankaramites of the alkalic Setberg region, as described by Sigurdsson (1970). In this connection it is of interest to note that only picrite basalts of oceanitic composition are found in the tholeiitic Reykjanes Peninsula (Jakobsson et al. 1978). This indicates that we in Iceland have a similar situation as in Hawaii, where oceanite is a member of the tholeiitic series, but ankaramite a member of the alkalic series (Macdonald & Katsura 1964).

In the EVZ the ankaramites are only found in two volcanic systems, which both have produced a transitional alkalic series, although according to Sigurdsson (op. cit.) ankaramite is also found belonging to the alkalic series of the Setberg region.

Basalts

A number of basalts of Upper Pleistocene age were sampled. A petrographical inspection indicates that similar rock compositions were extruded in this period within or at the border of the present volcanic systems, as during Postglacial Time. Previously (Jakobsson 1968) it has been shown that the late glacial rocks of Vestmannaeyjar are not distinguishable from the Postglacial compositions met with in these islands.

Table 16 presents 11 chemical analyses of Upper Pleistocene basalts. The analysed rocks are mainly from the last glacial and last interglacial periods. When the individual analyses of Table 16 are compared to the chemical analyses of the Postglacial basalts of the respective volcanic systems, it is seen that in 9 cases nearly identical compositions can be found among the Postglacial lavas. The Grafarhóll (6615) volcanic plug is close in composition to the 079-Hólmsá lava (Table 6, no. 1) and the Skuggafjöll (4430) pillow lava is close to the cumulative 388-Heljargjá lava (Table 8, no 7—9), to mention two examples.

The two exceptions are the Bjólfell (6203) pillow lava and the Tindafjöll (4447) breccia. The first is a transitional alkali basalt, but more primitive than any extruded Hekla system basalt from Postglacial Time. The Tindafjöll breccia has a composition which is at the border of basalt andesite composition, and is the most evolved rock of the transitional series in the EVZ encountered in the present study.

In general there are indications that each volcanic system of the EVZ had a similar location, and overall produced similar rock compositions during the last part of the Upper Pleistocene period, as during Postglacial Time.

DISCUSSION

The three rock series

Each of the nine volcanic systems of the EVZ has developed a rock suite which is easily distinguished from those of the neighbouring systems, as has been demonstrated above. However, the various suites group into three main igneous rock series or magma series, as has been described and defined in the chapter on "nonomenclature of the lavas". These are the *tholeiitic series,* the *transitional alkalic series,* and the *alkalic series.* Comparison with the tholeiitic Reykjanes Peninsula (Jakobsson et al. 1978) and other parts of the active volcanic zones of

Table 17 Average compositions of the non-cumulative basalt lavas of six volcanic systems in the EVZ.

Rock series:	Tholeiitic		Tholeiitic		Alkalic		Transit. alkalic		Transit. alkalic		Transit. alkalic	
Volc. system:	Veidivötn		Grímsvötn		Vestmannaeyjar		Vatnafjöll		Hekla		Katla	
No. of anal.	11		7		8		13		10		19	
	Aver.	Range	Aver.	Range	Aver.	Range	Aver.	Range	Aver.	Range	Aver.	Range
SiO_2	49.56	48.94—50.03	49.72	49.05—50.77	46.56	46.40—46.80	46.32	45.29—46.86	47.29	46.20—49.45	47.22	45.83—48.27
TiO_2	1.58	1.28— 2.02	2.79	2.48— 3.07	2.30	1.81— 2.82	3.69	3.06— 4.39	3.98	3.21— 4.73	4.47	4.01— 4.72
Al_2O_3	14.40	13.82—14.97	13.77	13.47—14.55	15.53	14.60—16.19	14.09	13.47—14.75	13.66	13.24—14.06	12.91	12.69—13.21
Fe_2O_3	2.67	1.29— 8.33	2.22	1.71— 2.76	2.77	1.31— 5.73	3.54	2.34— 4.41	2.55	1.86— 3.72	3.01	2.23— 4.50
FeO	8.66	3.45—11.11	11.02	10.24—11.72	9.47	6.15—10.77	12.01	10.57—13.06	12.48	11.26—13.39	12.27	11.24—12.96
MnO	0.19	0.17— 0.21	0.21	0.20— 0.23	0.23	0.17— 0.27	0.23	0.20— 0.25	0.24	0.23— 0.27	0.21	0.20— 0.22
MgO	7.45	6.35— 8.13	5.75	4.77— 6.40	8.15	5.75—10.03	6.08	5.54— 7.14	5.67	4.47— 6.37	5.10	4.66— 5.51
CaO	12.49	11.48—13.13	10.49	9.43—11.15	10.32	9.64—12.03	9.81	9.17—10.70	9.59	8.23—10.50	9.92	9.37—10.59
Na_2O	2.14	1.98— 2.36	2.67	2.44— 2.89	3.17	2.36— 3.78	2.81	2.58— 2.99	2.95	2.69— 3.38	2.98	2.73— 3.20
K_2O	0.16	0.09— 0.29	0.43	0.38— 0.52	0.57	0.31— 0.82	0.53	0.43— 0.61	0.62	0.50— 0.84	0.76	0.61— 0.89
P_2O_5	0.20	0.16— 0.28	0.33	0.28— 0.39	0.25	0.05— 0.34	0.46	0.38— 0.60	0.56	0.49— 0.73	0.53	0.46— 0.60
H_2O	0.44	0.28— 0.52	0.48	0.20— 0.70	0.59	0.32— 1.14	0.42	0.31— 0.54	0.37	0.13— 0.55	0.53	0.36— 1.04
Total	99.94		99.88		99.91		99.99		99.96		99.91	

Iceland indicate that all the Recent basaltic rocks of Iceland fall naturally into one of these three series and that there is no grading between them. There may be difficulties in grouping single lavas in little known areas, in which case the trend of basalt/basaltic andesites in the area in question should be established.

The *tholeiitic series* is generally characterized by a relatively high content of Fe and Ti and a low content of Al and Ca. The content of normative hypersthene of the basalts is mainly between 10—19 per cent, and the rocks plot below the division line in the alkali:silica diagram (cf. Fig. 19). The tholeiitic series is made up of the following main rock types: oceanite, olivine tholeiite, tholeiite, basaltic icelandite, icelandite (andesite), dacite and rhyolite. Two volcanic systems of the EVZ, Veidivötn and Grímsvötn, belong to this series, apart from about sixteen other volcanic systems within the active volcanic zones.

The *transitional series* is a hypersthene normative alkalic series. The basic rocks are usually characterized by a high content of Fe and Ti, and low Al. The basalts of this series will plot above the division line in the alkali:silica diagram (Fig. 7), but evolved compositions on the other hand plot below the division line. This series is made up of the following main rock types: ankaramite, transitional basalt, basaltic andesite, andesite, trachyte (?) and comenditic rhyolite. Six volcanic systems of the EVZ, Hekla, Vatnajökull, Torfajökull, Tindfjöll, Eyjafjöll and Katla, belong to this series, besides probably also the Öræfajökull volcanic system.

The *alkalic series* is of mild character, the rocks are nepheline normative and plot above the division line in the alkali:silica diagram (Fig. 4). The alkalic series is made up of alkali olivine basalt, hawaiite, mugearite, benmoreite, trachyte (?) and alkalic rhyolite. One volcanic system of the EVZ, Vestmannaeyjar, belongs to this series, in addition to probably three others in the Snaefellsnes volcanic zone.

Compositional variation within each rock series is perceptible, i.e. the exact trend of differentiation of a volcanic system may vary from that of others belonging to the same rock series. However, each rock series has characteristics

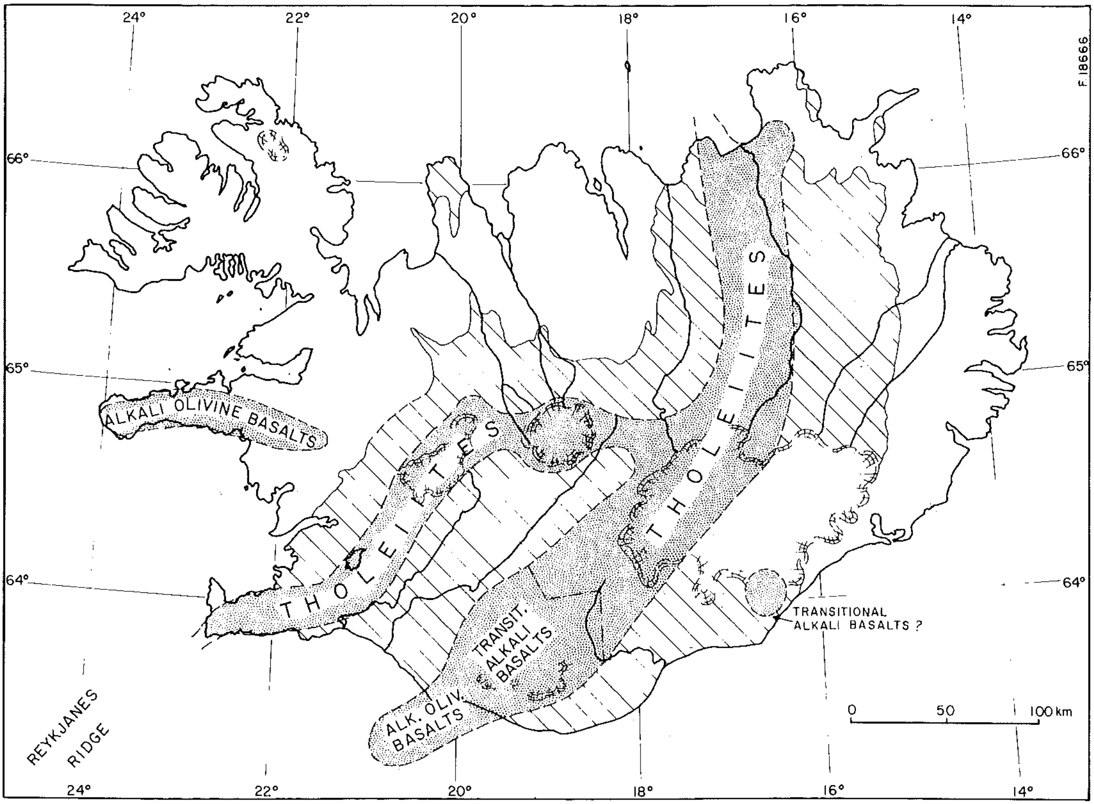


Fig. 42. Map of Iceland showing the Postglacial petrological zones (shaded) based on Jakobsson (1972) and other data, see text; and Plio-Pleistocene formations (oblique lines) and Tertiary formations (white) after Saemundsson (1978).

which are retained, e.g. the trends in the alkali:silica diagram. The average compositions of the non-cumulated basalt lavas of six of the volcanic systems of the EVZ are presented in Table 17. Figure 42 shows the distribution of the three rock series within the active volcanic zones of Iceland. The figure shows that the distribution pattern presented by Jakobsson (1972, Fig. 5) is correct as far as it goes, and is based on data from this study, as well as unpublished data of the present author, and chemical data of Sigvaldason (1974b) and Imsland (1978).

It is of interest to note that Sigurdsson (1970) also found three basalt series in the Setberg region of Snaefellsnes, a tholeiitic, a transitional and an alkalic series. His transitional series is probably of similar nature to the transitional series of the EVZ, although the Setberg series is relatively much lower in Fe and Ti.

Since the term magma series (or igneous rock series) was first introduced in the Hebridean volcanic province, much discussion has centred around whether it is justifiable to think in terms of only a limited number of magma series. In his study of the trends and affinities of basaltic magmas, Coombs (1963) suggested that there is a continuous series of basaltic magmas if plotted on the normative Di-Ne-Ol-Qz diagram, ranging from calcalkaline and tholeiitic at one extreme through a transitional type to the typical alkali basalts and thence to basanites at the other extreme.

Carmichael et al. (1974) also take the view that there is an unlimited number of magma compositions. The present data from the EVZ and Reykjanes Peninsula, and probably from elsewhere in the volcanic zones of Iceland is not compatible with this view. Three distinct series appear to be developed simultaneously, although spatially separated, in the same volcanic zone.

At this point the cosanguinity is again stressed of the active volcanic zones of Iceland and the Hebridean volcanic province, which previously has been mentioned by various authors, like Noe-Nygaard (1966) and Heier et al. (1966). The Vestmannaeyjar alkalic suite appears to be nearly identical to the plateau magma type, and the tholeiitic Grímsvötn basalts nearly identical to the non-porphyritic central magma type, whereas the Veidivötn suite appears to be related to the porphyritic central type. In addition the tholeiitic Reykjanes suite is very closely related to the "low alkali, high calcium" type of Skye, or the Preshal Mhor magma type (Thompson et al. 1972; Mattey et al. 1977). The main difference lies in the fact that the transitional series of the EVZ has not been observed in the Hebridean province.

It is often stated that rock compositions are serial, as for example by Carmichael (1964) in connection with Thingmúli. This may also be the case for the EVZ series. It is interesting, however, not only from a nomenclature point of view, that the frequency and volume of compositions encountered in each series varies (Fig. 35), and in some cases there may actually be a small gap between populations. This had previously been noted in the case of the Reykjanes Peninsula (Jakobsson et al. 1978), and is of importance from a petrogenetical point of view, since apparently certain compositions are favoured in the process of evolution of the extrusives.

Ideas on the origin of the lavas

The present study of the EVZ is thought to cover the whole compositional spectrum of extruded basic rocks during Postglacial Time. The extruded magma compositions which group into three rock series, are produced within nine volcanic systems. Each system can be treated as closed in a perological sense, as it develops a characteristic rock suite. Chemical zoning of extrusives, in many cases formation of high-temperature areas and calderas, are all taken as indicative of a relatively shallow magma reservoir under the central area of each system.

The petrographic analysis indicates (p. 65) that low-pressure fractionation has been operating in that the extruded lava compositions had probably crystallized microphenocrysts at near-cotectic conditions, with the exception of the VE I-type of the alkali olivine basalts. These relations indicate that these liquids are not primary (O'Hara 1976) and have undergone fractional crystallization to some degree. The study of the relationships between micro- and macrophenocrysts suggests that some 16 per cent of the investigated lavas have accumulated plagioclase by a floating mechanism at shallow depth. It is also suggested that many or possibly the majority of those lavas which contain large amounts of microphenocrysts have lost an unknown amount of heavy macrophenocrysts, i.e. mainly olivine and clinopyroxene, by sinking. This leaves the Vestmannaeyjar VE I-lavas, as possible primary examples.

There are all indications that the microphenocrysts are formed at shallow depth in the crust, say at less than 1 km depth. The macrophenocrysts are formed in the stability range of plagioclase, and by comparison of studies on similar rocks to some of those of the EVZ, e.g. by Shibata (1976) is seems likely that they are formed at a depth of about 3—10 km. The gabbroic nodules are most probably from a similar depth.

As the macrophenocryst mineralogy of the EVZ lavas has not been investigated except in the Vestmannaeyjar a fractional crystallization model cannot be evaluated for the tholeiites and the transitional alkali basalts. In the case of the Vestmannaeyjar, it was found that low-pressure fractional crystallization, using the observed phenocryst compositions did not account adequately for the observed variations, and an analysis on the western Reykjanes lavas gave a similar result (Jakobsson et al. 1978). There are many indications, however, as mentioned above, that fractional crystallization has been operating. Other graviational processes like volatile transfer may, however, be involved.

The above-mentioned relationships suggest

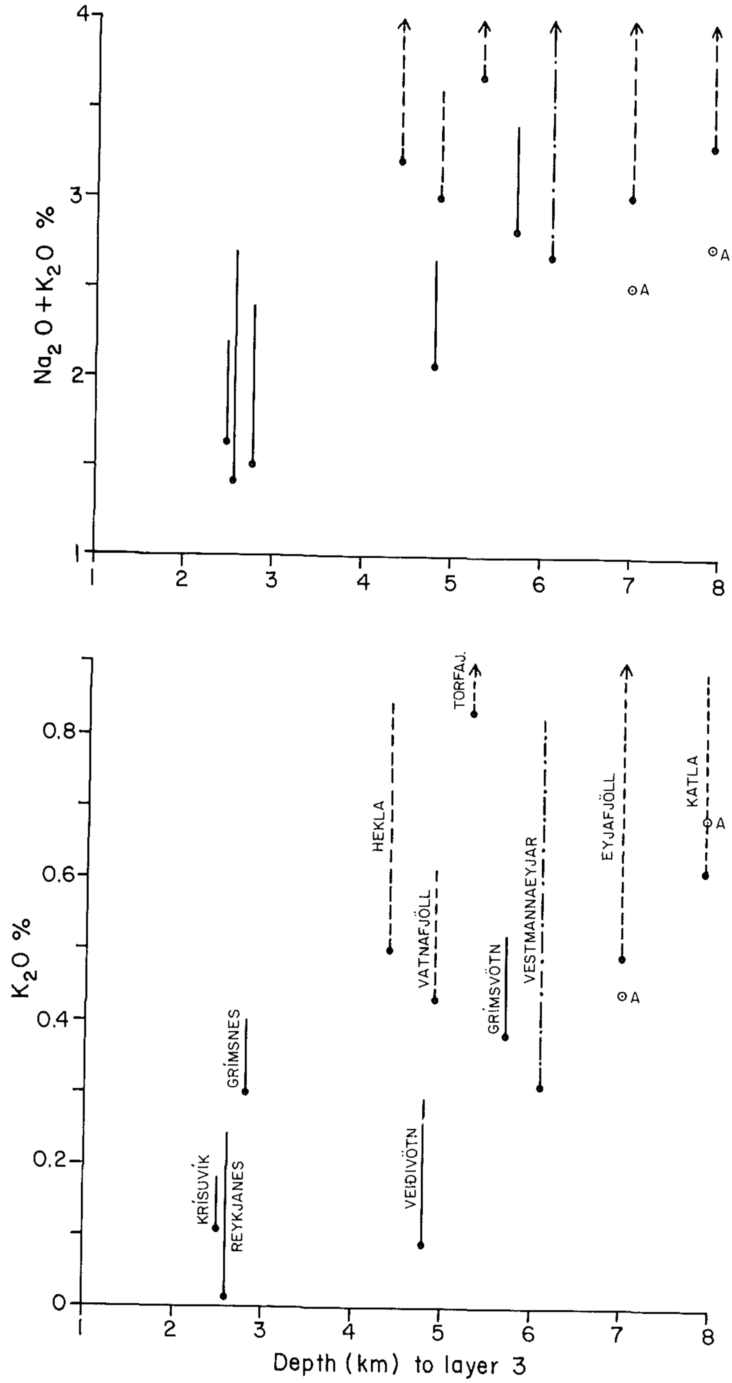


Fig. 43. Diagram showing the correlation between depth to the seismic layer 3 (Vp= 6.5 km/sec.) as measured from the surface, and the observed range of Na_2O+K_2O and K_2O content respectively, in each volcanic system. The plots of the only ultramafic compositions found in the EVZ (from Upper Pleistocene) are also shown, marked with (A). Chemical data from the Reykjanes system (Jakobsson et al. 1978), the Krísuvík system (Gunnlaugsson 1976) and the Grímsnes system (Jakobsson 1966, and unpublished) are included. The tholeiitic systems are shown with full lines, the alkalic system with dot and dash line and the transitional alkalic systems with stippled lines.

then firstly, that the most primitive compositions encountered in each volcanic system have, with the possible exception of the Vestmannaeyjar system, suffered low-pressure fractionation and secondly, that the variations within each rock suite are at least partly due to fractional crystallization.

The results of the study of crater morphology also support differentiation at shallow depth. It was suggested (p. 59) that the explosivity and therefore the content of volatiles increases with increasing content of K_2O in the magma, possibly within each rock series. This would agree with the interpretation that the most primitive magma compositions for each rock series are represented by the extrusives lowest in K_2O, and these are also lowest in volatiles as indicated above. Extruded rocks with higher content of K_2O and volatiles would then be derived from the primitive magma by differentiation in shallow magma chambers.

In this connection it will be of interest to see if there is any closer correlation beween the surface rock chemistry and the deduced crustal thickness, than already suggested by Jakobsson (1972, Fig. 8).

The thickness of the crust varies considerably in the EVZ (Pálmason 1971). Unfortunately, only few data are available as regards depth to layer 4, which is interpreted as the uppermost mantle. However, the depth to layer 3 is fairly well known, and will tentatively be used here, as there is a positive correlation between depths to layer 3 and 4 in most regions (Pálmason op. cit., e.g. Fig. 40).

Fig. 43 indicates that there is a positive correlation between the depth to the seismic layer 3 (as measured from the present land surface) and the lowest observed value of K_2O in the extrusives of each system. When Na_2O is added to K_2O an even better correlation results.

Three of the volcanic systems, Torfajökull, Hekla and Vatnafjöll, do not plot on the line joining the lowest values of alkalies in Fig. 43. The reason for this may be that the more basic compositions have not been extruded during Postglacial Time because these systems are in a mature stage, or that rocks with these compositions are hidden because of the lack of exposures in the tectonically quiet region associated with these volcanic systems. The depth to the seismic layer 3 has only been used here to give an idea of the crustal thickness. Judging from Pálmason's data (1971, Fig. 38) actual thickness may be 8—9 km for the Reykjanes system, 12 km for the Vestmannaeyjar system and 14—15 km for the Katla volcanic system.

Crustal procesess are most likely responsible for the observed correlation in Fig. 43, as the basic compositions encountered in each system are in most cases probably not primary liquids but are evolved by low-pressure fractionation. In this connection it is of special interest to note that crustal thickness is probably not the factor determining which rock series is produced. Tholeiite is produced in the Grímsvötn system at a similar crustal thickness as alkali olivine basalt in the Vestmannaeyjar system, and tholeiite in the Veidivötn system, at a similar crustal thickness as transitional alkali basalt in the Vatnafjöll system. This suggests that the parental (primary) liquid compositions of each rock series originate in the mantle.

It does not seem to be possible on the basis of the present data to give any final suggestion as to the origin of the three rock series in the EVZ. However the fact that the three rock series have been produced simultaneously in the EVZ during Postglacial Time and possibly also during the late Upper Pleistocene period as well as the fact that each volcanic system has only produced rocks belonging to one rock series, indicates that each rock series has an independent origin in the upper mantle.

SUMMARY

A detailed mapping and survey of the field relations, petrography and major element chemistry of the Postglacial basic lavas of the Eastern Volcanic Zone of Iceland has revealed the following:

1. The EVZ is composed of nine separate *volcanic systems,* which range between 28 to 98 km in length and 4 to 30 km in width. These

systems, which embrace all volcanic eruption sites in the zone, can be divided into six relatively young fissure swarms, the Veidivötn, Vestmannaeyjar, Vatnafjöll, Hekla, Grímsvötn and Katla systems, and three more mature complexes, the Eyjafjöll, Torfajökull and Tindfjöll systems. Altogether 211 subaerial basalt eruption units were identified adding up to some 175 km^3 of extrusives during Postglacial Time.

2. Each volcanic system has developed a distinct rock suite which is petrographically and chemically distinguishable from the others and can be regarded as a closed petrological system. Within each volcanic system, one or two especially productive centres can be defined which contain all the known acid and intermediate eruption sites of the system. These active centres are the main areas of magma ascent and areas outside them are possibly mainly fed by lateral magma flow.

3. The subaerial basalt eruption sites are classified according to morphology and explosivity index, a positive correlation between the explosive activity and the K_2O content of the magma being suggested.

4. It is found that the frequency of basaltic eruptions has varied simutaneously on a regional scale in the EVZ. Two main periods of volcanic activity occurred between about 0—2000 y.b.p. and 5000—8000 y.b.p., possibly due to variations in the regional stress field.

5. The petrographic survey resulted in distinction between micro- and macrophenocrysts. The microphenocrysts are formed at a shallow depth and probably at near-cotectic conditions. The macrophenocrysts are formed at a deeper level, and there are indications that approximatly half of the extruded basalt lavas of the EVZ have either lost or accumulated macrophenocrysts. These relationships indicate, that with the possible exception of the alkali olivine basalts of the VE I-type, the basalts are not primary liquids. Correlation between groundmass texture and whole rock chemistry of the lavas is demonstrated.

6. Gabbroic nodules are frequent in the extrusives. Those nodules found in the basalts appear to be formed freely floating in the magma and not by gravitational accumulation. The nodules from the basaltic andesites are broken chips of solid rock and show strong reaction relationships with the magma.

7. The nomenclature of basaltic rock is reviewed in the light of the distinct populations of rock composition found among the extrusives of the EVZ. The geochemical and petrographical data suggest that three rock series are being produced simultaneously in the EVZ as well as elsewhere in the active volcanic zones at present. These are, a tholeiitic series, a transitional alkalic series and an alkalic series. They are easily separated by use of selected chemical plots. Close similarities to the Hebridean volcanic province can be demonstrated, apart from the fact that the transitional alkalic series is not observed there.

8. It is suggested that the active volcanic zones of Iceland are made up of about 29 volcanic systems, of which 18 are tholeiitic, 7 are transitional alkalic and 4 are alkalic.

9. Picritic rocks are not observed among the Postglacial extrusives of the EVZ, but are found at a few localities in Upper Pleistocene formations. It is noted that oceanites have only been observed in tholeiitic systems of Iceland, whereas ankaramites are restricted to alkalic or transitional alkalic volcanic systems.

10. A preliminary survey of basalts of late Upper Pleistocene age within the EVZ indicates that rocks of similar composition have been produced from that time to the present.

11. It is suggested that crustal processes are responsible for the observed correlation of crustal thickness under the EVZ and the western Reykjanes Peninsula with the lowest observed values of alkalies in the extrusives of each volcanic system in these areas, and that the parental (primary) liquids to the three rock series originate independently of each other in the upper mantle.

ACKNOWLEDGEMENTS

Professor emer. A. Noe-Nygaard is thanked for financial support through a grant from the

Danish Natural Science Research Council; for providing working facilities at the Geological Museum, University of Copenhagen and for continued encouragement and interest in the project. A grant from the Icelandic Science Fund is also gratefully acknowledged.

Ib Sørensen, Head of the Chemical Laboratory, the Geological Survey of Greenland, provided 112 first-class chemical analyses.

Valuable assistance in the field by Árni Hjartarson, Einar Thórarinsson, Jóhann I. Pétursson and Thoroddur Thoroddsson is acknowledged. Jóhann I. Pétursson is responsible for much of the reconnaissance mapping of Eyjafjöll.

The norms and chemical graphs were calculated and plotted at the Regional EDB-Centre, University of Copenhagen, by Lars Skov Andersen, using programmes written by Tom Svane Petersen and Lars Skov Andersen.

Haukur Tómasson and Elsa G. Vilmundardóttir are thanked for supplying 26 samples of drillcores, mainly of the Tungná lavas from the drillcore archive of the National Energ. Auth., Reykjavík. Gunnbjörn Egilsson made the thin sections with his usual skill and care. Haraldur R. Karlsson and Jóhann I. Pétursson are thanked for assistance in the thin section analyses. Gudrún Larsen kindly supplied tephrochronological age determinations on four lavas. Jørgen G. Larsen and Karl A. Jørgensen provided information on the Tindfjöll complex. Björn Jónasson, at the National Energy Authority, supplied a sample of the 484-Lyngfell lava.

James G. Moore, and Kristján Saemundsson read an early draft of the paper and provided many helpful suggestions. Finally, George Douglas is thanked for correcting the English and reading galley proofs.

REFERENCES

Anderson, A. T., 1973: The before-eruption water content of some high-alumina basalt magmas. Bull. Volcan. 37, 530—552.

Aumento, F., 1968: The Mid-Atlantic Ridge near 45°N: II. Basalts from the area of Confederation Peak. Can. J. Earth Sci. 5,1—22.

Aumento, F. & B. D. Loncarevic, 1969: The Mid-Atlantic Ridge near 45°N. III. Bald Mountain. Can. J. Earth Sci. 6, 11—23.

Bäckström, H., 1892: Beiträge zur Kenntnis der isländischen Liparite. Geol. Fören. i Stockholm Förhandl. 13, 637—686.

Bailey, D. K. & R. Macdonald, 1970: Petrochemical variations among mildly peralkaline (comendite) obsidians from the oceans and continents. Contr. Miner. Petrol. 28, 340—351.

Bailey, E. B., C. T. Clough, W. B. Wright, J. E. Rickey & G. V. Wilson, 1924: Tertiary and Post-Tertiary geology of Mull, Lock Aline, and Oban. Mem. geol. Survey Scot., 445 pp.

Bailey, J. & I. Sørensen, 1976: X-ray fluorescene analysis. Report (mimeogr.). Geol. Centralinst. & Geol. Surv. Greenl. 105 p.

Baker, P. E., F. Buckley & J. G. Holland, 1974: Petrology and geochemistry of Easter Island. Contr. Miner. Petrol. 44, 85—100.

Baldridge, W. S., T. R. McGetchin & F. A. Frey, 1973: Magmatic evolution of Hekla, Iceland. Contr. Miner. Petrol. 42, 245—258.

Bárdarson, G., 1930: Vulkan-Ausbrüche in Island. I. Vulkan-Ausbrüche in der Gegend der Hekla im Jahre 1913. Soc. Sci. Islandica, Rit 1, 31 pp.

Beckinsale, R. D., R. J. Pankhurst, R. R. Skelhorn & J. N. Walsh, 1978: Geochemistry and petrogenesis of the Early Tertiary lava pile of the Isle of Mull, Scotland. Contr. Miner. Petrol. 66, 415—427.

Bell, J. P. & P. J. Humphries, 1972: Lakagígar fissure eruption. In: Progress in Exper. Petrology. Nat. Envir. Res. Council, Publ. Ser. D, 2, 110—112.

Björnsson, A., K. Saemundsson, P. Einarsson, E. Tryggvason & K. Grönvold, 1977: Current rifting episode in north Iceland. Nature 266, 318—323.

Björnsson, H., 1978: Könnun á jöklum með rafsegulbylgjum. (Radio-echo sounding of temperate glaciers). Nátt.fraed. 47, 184—194.

Borgen, B. I., 1967: Analytical procedures used in Geochemical Laboratory of the Survey. Rapp. Grønlands Geol. Unders. nr. 10, 44 pp.

Brooks, C. K., 1976: The Fe_2O_3/FeO ratio of basalt analyses: An appeal for a standardized procedure. Bull. geol. Soc. Denmark 25, 117—120.

Carmichael, I. S. E., 1964: The petrology of Thingmúli, a Tertiary volcano in Eastern Iceland. J. Petrol. 5, 435—460.

Carmichael, I. S. E., F. J. Turner & J. Verhoogen, 1974: Igneous petrology. New York: McGraw-Hill Book Company, 739 pp.

Carswell, D. A. 1978: Pers. comm.

Coombs, D. S., 1963: Trends and affinities of basaltic magmas and pyroxenes as illustrated on the diopside-olivine-silica diagram. Spec. Pap. Am. Soc. Miner. 1, 227—250.

Drever, H. I. & R. Johnston, 1957: Crystal growth of fosteritic olivine in magmas and melts. Trans. R. Soc. Edin. 63, 2, 289—314.

Einarsson, P., 1974: Seismic activity recorded in Surtsey during summer 1966. Surtsey Res. Progr. Report. 7, 83—90.

— 1977: Pers. comm.

Einarsson, Tr., 1950a: Chemical analyses and differentiation of Hekla's magma. The eruption of Hekla 1947—1948, IV, 4, 34 pp. Soc. Sci. Islandica.

— 1950b: The basic mechanism of volcanic eruptions and the ultimate causes of volcanism. The eruption of Hekla 1947—1948, IV, 5, 30 pp. Soc. Sci. Islandica.

— 1977: Problems in geology and geophysics. Part II. Soc. Sci. Islandica, Greinar 6, 139 pp.

Esson, J., A. C. Dunham & T. N. Thompson, 1975: Low alkali, high calcium olivine tholeiite lavas from the Isle of Skye, Scotland. J. Petrol. 16, 488—497.

Gary, M., R. McAfee, Jr. & C. L. Wolf, 1972: Glossary of geology, Washington, D. C.: American Geological Institute, 805 pp.

Gibson, I. L., 1966: Crustal flexures and flood basalts. Tectonophys. 3, 447—456.

— 1969: A comparative account of the flood basalt volcanism of the Columbia Plateau and eastern Iceland. Bull. Volcan. 33, 419—437.

Gibson, I. L. & J. D. A. Piper, 1972: Structure of the Icelandic basalt plateau and the process of drift. Phil. Trans. R. Soc. A 271, 141—150.

Goddard, E. N. and others, 1948: Rock color chart. Rock-color Chart Comm., Geol. Soc. America, Boulder, 11 pp.

Grönvold, K., 1972: Structural and petrochemical studies in the Kerlingarfjöll region, central Iceland. Unpubl. Ph. D. thesis, Univ. of Oxford, 237 pp.

Gunnlaugsson, E., 1976: Chemistry of the Postglacial lavas in the Krísuvík area, SW-Iceland. Soc. Sci. Islandica Greinar, 5, 160—166.

Heier, K. S., B. W. Chapell, P. A. Arriens & J. W. Morgan, 1966: The geochemistry of four Icelandic basalts. Norsk Geol. Tidsskr. 46, 427—437.

Iddings, J. P., 1909: Igneous rocks, I. New York.

Imsland, P., 1978: The petrology of Iceland. Some general remarks. Nord. Volc. Inst., Rep. 78 08 (mimeogr.), 26 p.

Irvine, T. N. & W. R. A. Baragar, 1971: A guide to the chemical classification of the common volcanic rocks. Can. J. Earth Sci. 8, 523—548.

Jakobsson, S. P., 1966: The Grímsnes lavas, SW-Iceland. Acta Nat. Islandica, II, 6, 30 pp.

— 1968: The geology and petrography of the Vestmann Islands. A preliminary report. Surtsey Res. Prog. Rep. 4, 113—129.

— 1971: Palagonitiseringen af tefraen på Surtsey. Naturhist. Museum, Reykjavík (mimeogr.), 61 p.

— 1972: Chemistry and distribution pattern of Recent basaltic rocks in Iceland. Lithos 5, 365—386.

— 1974: Eldgos við Eldeyjarboda (Volcanic eruptions at Eldeyjarbodi, The Reykjanes Ridge). Nátt.fraed. 44, 22—40.

— 1977: Aldur Grímsneshrauna (The age of the Grímsnes lavas. SW-Iceland). Nátt.fraed. 76, 153—162.

— (in prep.): The geology and petrology of the Vestmannaeyjar (Westman Islands), South Iceland. Acta Nat. Islandica.

Jakobsson, S. P., A. K. Pedersen, J. G. Rønsbo & L. M. Larsen, 1973: Petrology of mugearite-hawaiite: Early extrusives in the 1973 Heimaey eruption. Lithos 5, 203—214.

Jakobsson, S. P., J. Jónsson & F. Shido, 1978: Petrology of the western Reykjanes Peninsula, Iceland. J. Petrol. 19, 669—705.

Jóhannesson, H., 1975: Structure and petrochemistry of the Reykjadalur central volcano and the surrounding areas, Midwest Iceland. Unpubl. Ph. D. thesis, Univ. of Durham, 273 p.

Johannsen, A., 1939: A descriptive petrography of the igneous rocks, Vol. I. University of Chicago Press. 318 pp.

Jónasson, B., 1974: Skaftársvaedi. Jardfraediskýrsla. Unpubl. B. Sc. thesis, Univ. of Iceland.

Jónsson, J., 1979: Eldstödvar og hraun í Skaftafellsþingi (On lava flows in Skaftafellssýsla). Nátt.-fraed. 48, 196—232.

Jørgensen, K. Aa., 1976: Geologisk beskrivelse af Thórsmörk området, S.-Island. Unpubl. Cand. scient. thesis, Univ. of Copenhagen, 233 p.

— (in press): The Thórsmörk ignimbrite: a comenditic ash-flow in Southern Iceland. J. Volc. Geotherm. Res.

Kjartansson, G., 1958: Endaslepp hraun undir Eyjafjöllum. (Lava flows deprived of their distal ends

in Eyjafjöll, South Iceland). Nátt.fraed. 28, 127—140.
— 1960, 1962, 1964: Geological map of Iceland, Scale 1:250 000, Sheets 3, 6 and 5. Museum of Nat. Hist. Reykjavík.
— 1966: Stapakenningin og Surtsey. (A comparison of tablemountains in Iceland and the volcanic island Surtsey off the south coast of Iceland). Nátt.fraed. 36, 1—34.
Kuno, H., 1960: High-alumina basalts. J. Petrol. 1, 121—145.
Kunsky, J. & Z. Roth, 1946: Tindfjallajökull. A geological and geographical study from the interior of Iceland. Bull. internat. d l'Academie tcheque des Sciences 47, 31 pp.
Kuthan, M. F., 1943: Oscilácia, vulkanismus a tektonika Reykjanesu. Sbornik prác Prírodovedeckej fak. Slov. Univ. Bratislave IV, 108 pp.
Larsen, G., 1979: Um aldur Eldgjárhrauna (Tephrochronological dating of the Eldgjá lavas in South Iceland). Nátt.fraed. 49, 1—26.
Larsen, J. G. & K. Aa. Jørgensen, (in prep.): The geology of the Tindfjallajökull complex.
Leung, I. S., 1974: Sector-zoned titanaugites: Morphology, crystal chemistry, and growth. Amer. Miner. 59, 127—138.
Lofgren, G., C. H. Donaldson, R. J. Williams, O. Mullins, Jr. & T. M. Usselman, 1974: Experimental reproduced textures and mineral chemistry of Apollo 15 quartz normative basalts. In: Proc. Fifth Lunar Sci. Conf.: Geochim. Cosmochim. Acta Suppl. 5, v. 1, 549—567.
Macdonald, G. A., 1968: Composition and origin of Hawaiian lavas. Mem. geol. Soc. Am. 116, 477—522.
Macdonald, G. A. & T. Katsura, 1964: Chemical composition of Hawaiian lavas. J. Petrol. 5, 82—133.
Mattey, D. P., I. L. Gibson, G. F. Marriner & R. N. Thompson, 1977: The diagnostic geochemistry, relative abundance, and spatial distribution of high-calcium, low-alkali, olivine tholeiite dykes in the lower Tertiary regional swarm of the Isle of Skye, N. W. Scotland. Miner. Mag. 41, 273—286.
McBirney, A. R. & R. M. Noyes, (1979): Crystallization and layering of the Skaergaard intrusion. J. Petrol. 20, 487—554.
McBirney, A. R & H. Williams, 1969: Geology and petrology of the Galapagos Islands. Mem. geol. Soc. Am. 118, 197 pp.
Miyashiro, A., 1978: Nature of alkalic volcanic rock series. Contr. Miner. Petrol. 66, 91—104.
Miyashiro, A., F. Shido & M. Ewing, 1969: Diversity and origin of abyssal tholeiite from the Mid-Atlantic Ridge near 24° and 30° north latitude. Contr. Miner. Petrol. 23, 38—52.
Moore, J. G., 1970: Water content of basalt erupted on the ocean floor. Contr. Miner. Petrol. 28, 272—279.
Nielsen, N., 1929: Islandske vulkanformer. Naturens Verden 13, 1—21.
— 1933: Contributions to the physiography of Iceland. Det Kgl. Danske Vidensk. Selskabs Skrifter. Naturvid. Mathem. Afd., 9. Raekke, IV. 286 pp.
Noe-Nygaard, A., 1950: Hágöngur. A partically subglacial volcano in SW-Vatnajökull. Medd. Dansk. geol. Foren. 11, 513—521.
— 1951: Materials from the eruption in Grímsvötn, Vatnajökull in 1934. Folia Geograph. Dan. 1, 4, 20 pp.
— 1952a: Eldgígur at Hágöngur, a prehistoric, subaeric volcano at the SW-edge of Vatnajökull. Medd. Dansk geol. Foren. 12, 223—226.
— 1952b: A group of liparite occurrences in Vatnajökull, Iceland. Folia geograph. Dan. I, 3, 59 pp.
— 1966: Chemical composition of tholeiitic basalts from the Wyville-Thompson Ridge belt. Nature 212, 272—273.
Noll, H., 1967: Maare und maar-ähnliche Explosionskrater in Iceland. Sondveröff. Geol. Inst. Univ. Köln 11, 117 pp.
O'Hara, M. J., 1976: Unlikelihood of primary basalt magma containing several phenocrysts species in small amounts. In: Progress in Exper. Petrology. Nat. Envir. Res. Council, Publ. Ser. D, 6, 196—200.
O'Nions, R. K., R. J. Pankhurst, I. B. Fridleifsson & S. P. Jakobsson, 1973: Strontium isotopes and rare earth elements in basalts from the Heimaey and Surtsey volcanic eruptions. Nature 243, 213—214.
Pálmason, G., 1971: Crustal structure of Iceland from explosion seismology. Soc. Sci. Islandica Rit 60, 187 pp.
Peacock, M. A., 1925: A contribution to the petrography of Iceland: Being a description of the Mackenzie collection of 1810. Trans. Geol. Soc. Glasgow 17, 271—333.
— 1931: Classification of igneous rock series. J. Geol. 39, 54—67.
Rittmann, A., 1960: Vulkane und ihre Tätigkeit. 2. Aufl. Stuttgart.
Robson, G. R. 1957: The volcanic geology of Vestur-Skaftafellssýsla, Iceland. Unpubl. Ph. D. thesis, Univ. of Durham, 259 p.
Saemundsson, K., 1967: Vulkanismus und Tektonik des Hengill-Gebietes in südwest-Island. Acta Nat. Islandica II, 7, 105 pp.
— and others 1971: Námafjall-Krafla. Áfangaskýrsla um rannsókn jarðhitasvæðanna. Orkustofnun (mimeogr.), 114 p.
— 1972: Jardfraediglefsur um Torfajökulssvaedid

(Notes on the geology of the Torfajökull central volcano). Nátt.fraed. 42, 81—99.
— 1974: Evolution of the axial rifting zone in northern Iceland and the Tjörnes Fracture Zone. Bull. geol. Soc. Am. 85, 495—504.
— 1978: Fissure swarms and central volcanoes of the neovolcanic zones of Iceland. Geol. J. Spec. Iss., No. 10, 415—432.
Sapper, K., 1908: Ueber einige isländische Vulkanspalten und Vulkanreihen. Neu. Jahrb. J. Mineral., Geol. & Paläontol., Beil.-Band 26, 1—43.
Schau, M. & E. Gasparini, 1974: Heterogenous glass from a Recent tephra sheet. Geol. Surv. Can. Pap. 74, 1, Part B, 190—193.
Shibata, T., 1976: Phenocryst- bulk rock composition relations of abyssal tholeiites and their petrogenetic significance. Geochim. Cosmochim. Acta 40, 1407—1417.
Sigbjarnarson, G., 1972: Vatnafraedi Thórisvatnssvaedis. Reykjavík: Orkustofnun ROD (mimeogr.) 63 p.
— 1973: Katla and Askja. Jökull 23, 45—51.
Sigurdsson, H., 1968: Petrology of acid xenoliths from Surtsey. Geol. Mag. 105, 440—453.
— 1970: The petrology and chemistry of the Setberg volcanic region and of the intermediate and acid rocks of Iceland. Unpubl. Ph. D. thesis, Univ. of Durham. 308 p.
Sigurdsson, H., J.-G. Schilling & P. S. Meyer, 1978: Skagi and Langjökull volcanic zones in Iceland, 1, petrology and structure. J. Geophys. Res. 83, 3971—3982.
Sigurdsson, H. & S. R. J. Sparks, 1978: Lateral magma flow within rifted Icelandic crust. Nature 274, 126—130.
Sigvaldason, G. E., 1963: Influence of geothermal activity on the chemistry of three glacier rivers in southern Iceland. Jökull 13, 10—17.
— 1974a: The petrology of Hekla and origin of silicic rocks in Iceland. The Erupt. of Hekla 1947—1948, 4, 1, 44 pp. Soc. Sci. Islandica.
— 1974b: Basalts from the centre of the assumed Icelandic mantle plume. J. Petrol. 15, 497—524.
Smith, R. L. & H. R. Shaw, 1975: Igneous-related geothermal systems. In: White, D. F. & Williams, D. L. (ed.), Assessment of geothermal resources of the United Stated-1975. U. S. Geol. Survey Circ. 726, 58—83.
Steinthórsson, S., 1964: The ankaramites of Hvammsmúli, Eyjafjöll, southern Iceland. Acta Nat. Islandica II, 4, 32 pp.
— 1966: (Surtsey) Petrography and chemistry. Surtsey Res. Progr. Rep. II, 77—85.
— 1967: Petrography and chemistry of the Surtsey rocks. Proceed. Surtsey Res. Confer., Reykjavík, June 25th—28th, 1967.
— 1978: Tephra layers in a drill core from the Vatnajökull Ice Cap. Jökull 27, 2—27.
Sørensen, H., 1950: An examination of the plagioclases of some Hekla lavas. Medd. dansk geol. Foren. 11, 522—542.
Thompson, R. N., 1973: One — atomsphere melting behaviour and nomenclature of terrestrial lavas. Contr. Miner. Petrol. 141, 197—204.
Thompson, R. N., J. Esson & A. C. Dunham, 1972: Major element chemical variation in the Eocene lavas of the Isle of Skye, Scotland, J. Petrol. 13, 219—253.
Thorarinsson, S., 1944: Tefrokronologiska Studier på Island: Thjórsárdalur och dess Förödelse. Köbenhavn: E. Munksgaard, 217 pp.
— 1950: Jökulhlaup og eldgos á jökulvatnasvaedi Jökulsár á Fjöllum. Nátt.fraed. 20, 113—133.
— 1954: The tephra-fall from Hekla on March 29th 1947. The Erupt. of Hekla 1947—1948 II, 3, 68 pp. Soc. Sci. Islandica.
— 1955: Myndir úr jardfraedi Islands III. Eldgjá (The geology of Iceland II. Eldgjá). Nátt.fraed. 25, 148—153.
— 1960: The Postglacial volcanism. The Postglacial history of the Mývatn area and the area between Mývatn and Jökulsá á Fjöllum. In: On the geology and geophysics of Iceland. Int. Geol. Congr. XXI. Sess. Guide to excursions No. A2, 33—45 and 60—69.
— 1965: Nedansjávargos vid Ísland (Submarine eruptions off the coast of Iceland). Nátt.fraed. 35, 49—74.
— 1967a: The eruption of Hekla in historical times. The Eruption of Hekla 1947—1948 I, 183 pp. Soc. Sci. Islandica.
— 1967b: Hekla and Katla. The share of acid and intermediate lava and tephra in the volcanic products through the geological history of Iceland. In: Björnsson, S. (ed.), Iceland and mid-ocean ridges. Soc.Sci. Islandica, Rit 38, 190—199.
— 1968: Sídustu thættir Eyjaelda. (The last phases of the Surtsey eruption). Nátt.fraed. 38, 113—135.
— 1969: The Lakagígar eruption of 1783. Bull. Volcan. 38, 910—929.
— 1971: Aldur ljósu gjóskulaganna úr Heklu samkvæmt leidréttu geislakolstímatali. (The age of the light Hekla tephra layers according to corrected C^{14} datings). Nátt.fraed. 41, 99—105.
— 1974: Vötnin stríd. Saga Skeidarárhlaupa og Grímsvatnagosa. 254 pp. Reykjavík.
— 1975: Katla og annáll Kötlugosa. Árbók Ferdafélags Íslands 1975, 124—149, Reykjavík.
Thorarinsson, S., Th. Einarsson, G. E. Sigvaldason & G.

Elísson, 1964: The submarine eruption off the Westman Islands 1963—64. Bull. Volcan. 27, 1—11.

Thorarinsson, S. & G. E. Sigvaldason, 1962: The eruption of Askja 1961: A preliminary report, Am. J. Sci. 260, 641—651.

— 1972a: The Hekla eruption of 1970. Bull. Volcan. 36, 1—20.

— 1972b: Tröllagígar og Tröllahraun. (The Tröllagígar eruption 1862—64). Jökull 22, 12—26.

Thorarinsson, S., S. Steinthórsson, Th. Einarsson, H. Kristmannsdóttir & N. Óskarsson, 1973: The eruption on Heimaey, Iceland. Nature 241, 272—275.

Thorarinsson, S., K. Saemundsson & R. S. Williams, 1974: ERTS-1 image of Vatnajökull: Analysis of glaciological, structural and volcanic features. Jökull 23, 7—17.

Thoroddsen, Th., 1905—1906: Island. Grundriss der Geographie und Geologie. Ergänzungshäfte 152 und 153 zu Peterm. Mitt. 358 pp. Gotha.

— 1913—1915: Ferdabók. Skýrslur um rannsóknir á Íslandi 1882—1898, I—IV. Kaupmannahöfn.

— 1925: Die Geschichte der isländischen Vulkane. Kgl. Danske Vidensk. Selsk. Skr., Naturvid. og Matem. Afd., 8. Raekke, IX, 458 pp. København.

Tilley, C. E. 1950: Some aspects of magmatic evolution. Q. Jl. Geol. Soc. Lond. 106, 37—61.

Tilley C. E. & I. D. Muir, 1962: The Hebridean Plateau Magma Type. Trans. Edinb. geol. Soc. 19, 208—215.

Tilley, C. E., H. S. Yoder & J. F. Schairer, 1964: New relations on melting of basalts. Carn. Inst. Wash. Year Book 1963. 92—97.

— 1967: Melting relations of volcanic rock series. Carn. Inst. Wash. Year Book 1965, 260—269.

Tómasson, J., 1967a: On the origin of sedimentary water beneath Vestmannaeyjar. Jökull 17, 300—311.

— 1967b: Hekla's magma. In: Björnsson, S. (ed.), Iceland and mid-ocean ridges. Soc. Sci. Islandica, Rit 38, 180—189.

Tryggvason, E., 1968: Measurements and surface deformation in Iceland by precision leveling. J. Geophys. Res. 73, 7039—7050.

Tryggvason, T., 1943: Das Skjaldbreid-Gebiet auf Island. Eine petrographische Studie. Bull. Geol. Inst. Uppsala 30, 273—320.

— 1965: Petrographic studies on the eruption products of Hekla 1947—1948. The eruption of Hekla 1947—1948, IV, 6, 13 pp. Soc. Sci. Islandica.

Tyrrell, G. W., 1946: The principles of petrology. 8th edition. Methuen, London, 349 pp.

Vance, J. A., 1969: On synneusis. Contr. Miner. Petrol. 24, 7—29.

Vilmundardóttir, E., 1977: Tungnárhraun. Jardfraediskýrsla. Nat. Energ Authority, OS ROD 7702, (mimeogr.), 156 p.

Wager, L. R. & G. M. Brown, 1967: Layered igneous rocks. San Francisco: W. H. Freeman & Company.

Wager, L. R., G. M. Brown & W. J. Wadsworth, 1960: Types of igneous cumulates. J. Petrol. 1, 73—85.

Walker, G. P. L., 1963: The Breiddalur central volcano, eastern Iceland. Q. Jl. geol. Soc. London. 119, 29—63.

— 1974: The structure of eastern Iceland, In: Kristjánsson, L. (ed.), Geodynamics of Iceland and the North Atlantic area, 177—188. Dordrecth: Reidel Publ. Comp.

Watkins, N. P., B. M. Gunn & R. Coy-yll, 1970: Major and trace element variations during the initial cooling of an Icelandic lava. Am. J. Sci. 268, 24—49.

Wetzel, R., E. Wenk, W. Stern & H. Schwander, 1978: Beiträge zur Petrographie Islands. Vulkaninstitut I. Friedlaender, Zürich, No. 10, 128 pp.

Williams, H., F. J. Turner & C. M. Gilbert, 1954: Petrography. An introduction to the study of rocks in thin sections. San Fransisco: W. H. Freeman & Company.

Wood, D. A., I. L. Gibson & R. N. Thompson, 1976: Element mobility during zeolite facies metamorphism of Tertiary basalts of Eastern Iceland. Contr. Miner. Petrol. 55, 241—254.

Yoder, H. S. & C. E. Tilley, 1962: Origin of basalt magmas: An experimental study of natural and synthetic rock systems. J. Petrol. 3, 342—532.

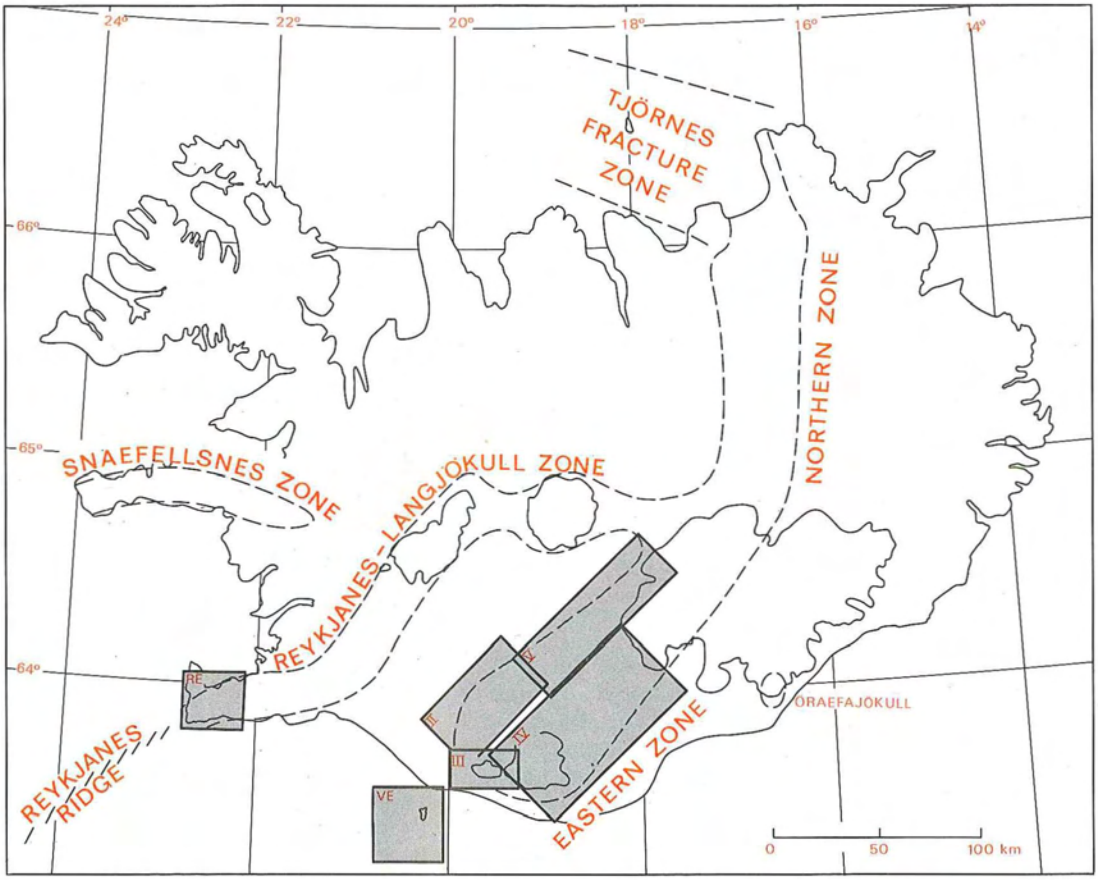


Plate I. Map of Iceland showing the active volcanic zones and the position of plates II, III, IV and V. "VE" indicates the coverage of the geological map of Vestmannaeyjar published by Jakobsson (1971). "RE" indicates the coverage of the geological map which appeared in Jakobsson, Jónsson & Shido (1978).

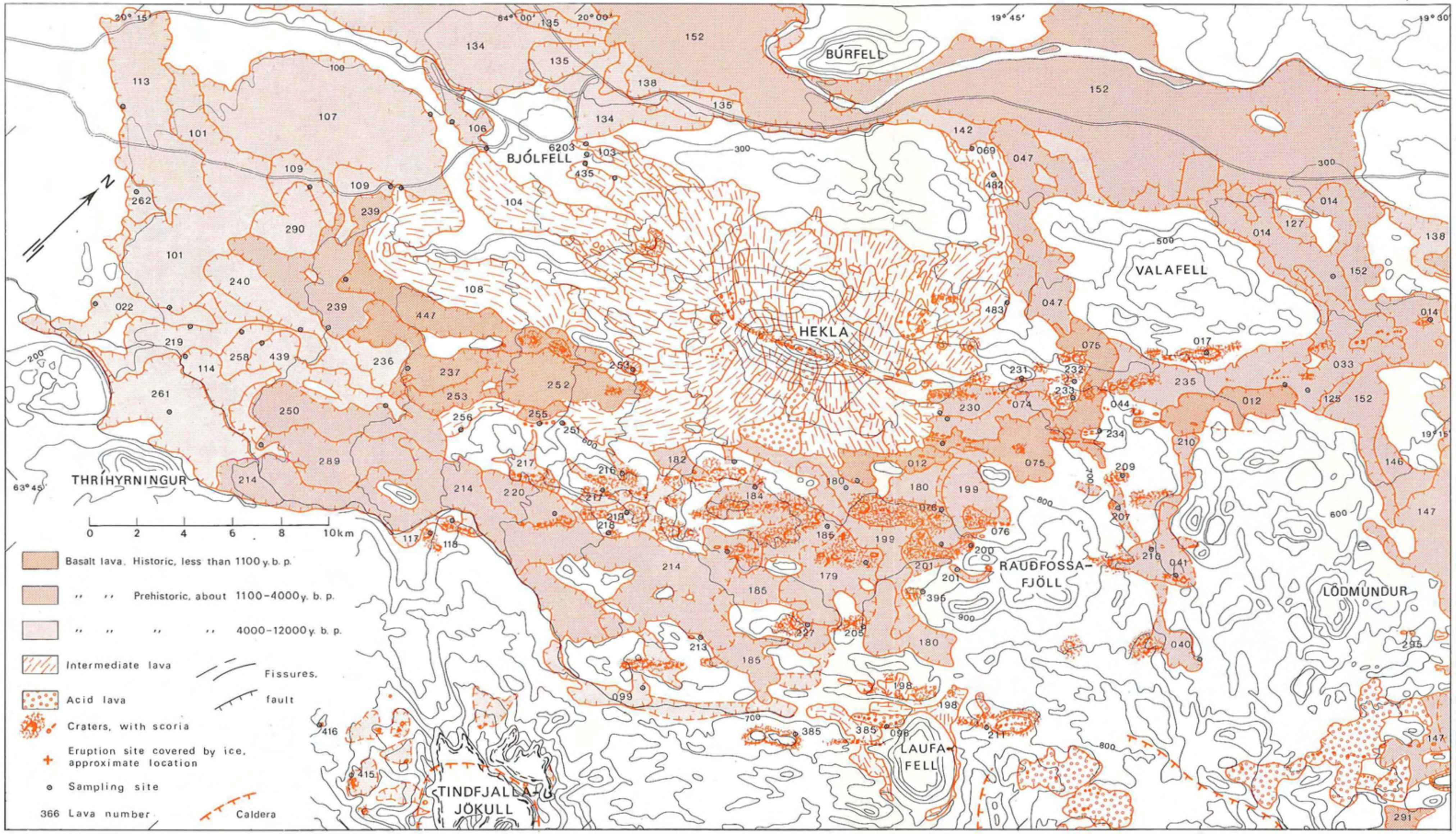


Plate II. The Hekla and Vatnafjöll volcanic systems. The basalts are transitional alkali basalts and make up, along with the andesitic and acid rocks, transitional rock suites. The Tindfjöll complex with its old transitional basaltic lavas is seen in the southern part of the map. Part of the Torfajökull complex is seen to the northeast, only about four basaltic lavas have erupted in Postglacial Time, others are intermediate and acid lavas. To the north and northeast are seen some of the Tungná lavas of the Veidivötn system. Mapped and compiled by S. P. Jakobsson during 1970—1977.

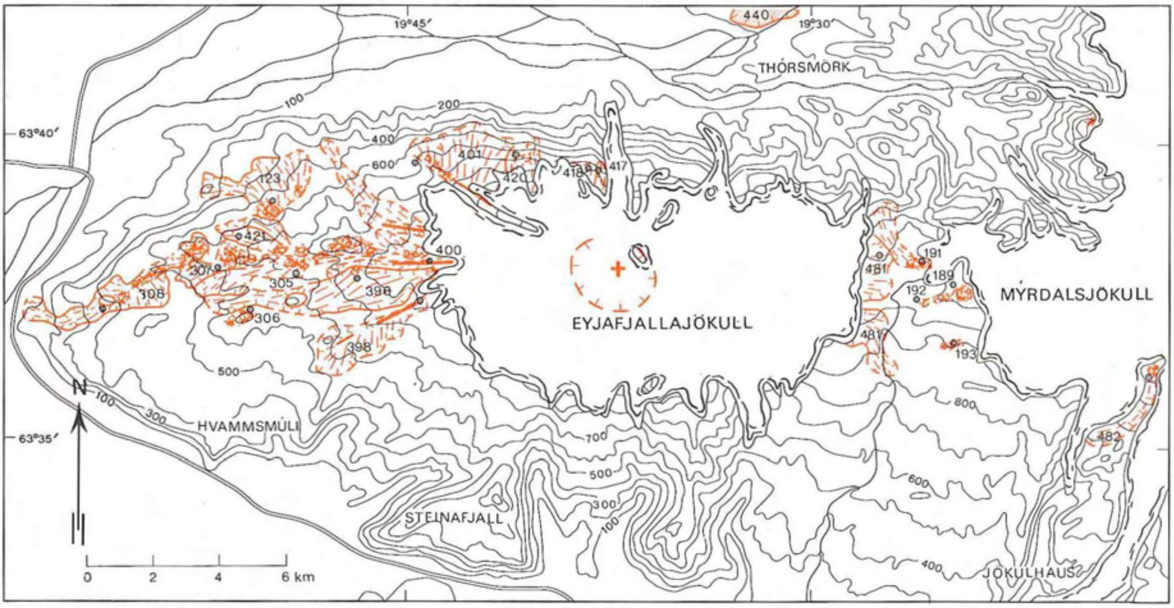


Plate III. The Eyjafjöll complex. Two basaltic lavas are identified, seventeen andesitic lavas and one acid lava. The extrusives belong to the transitional rock series. Legend as in Plate II. Reconnaissance mapping by S. P. Jakobsson and J. Í. Pétursson during 1974—1976.

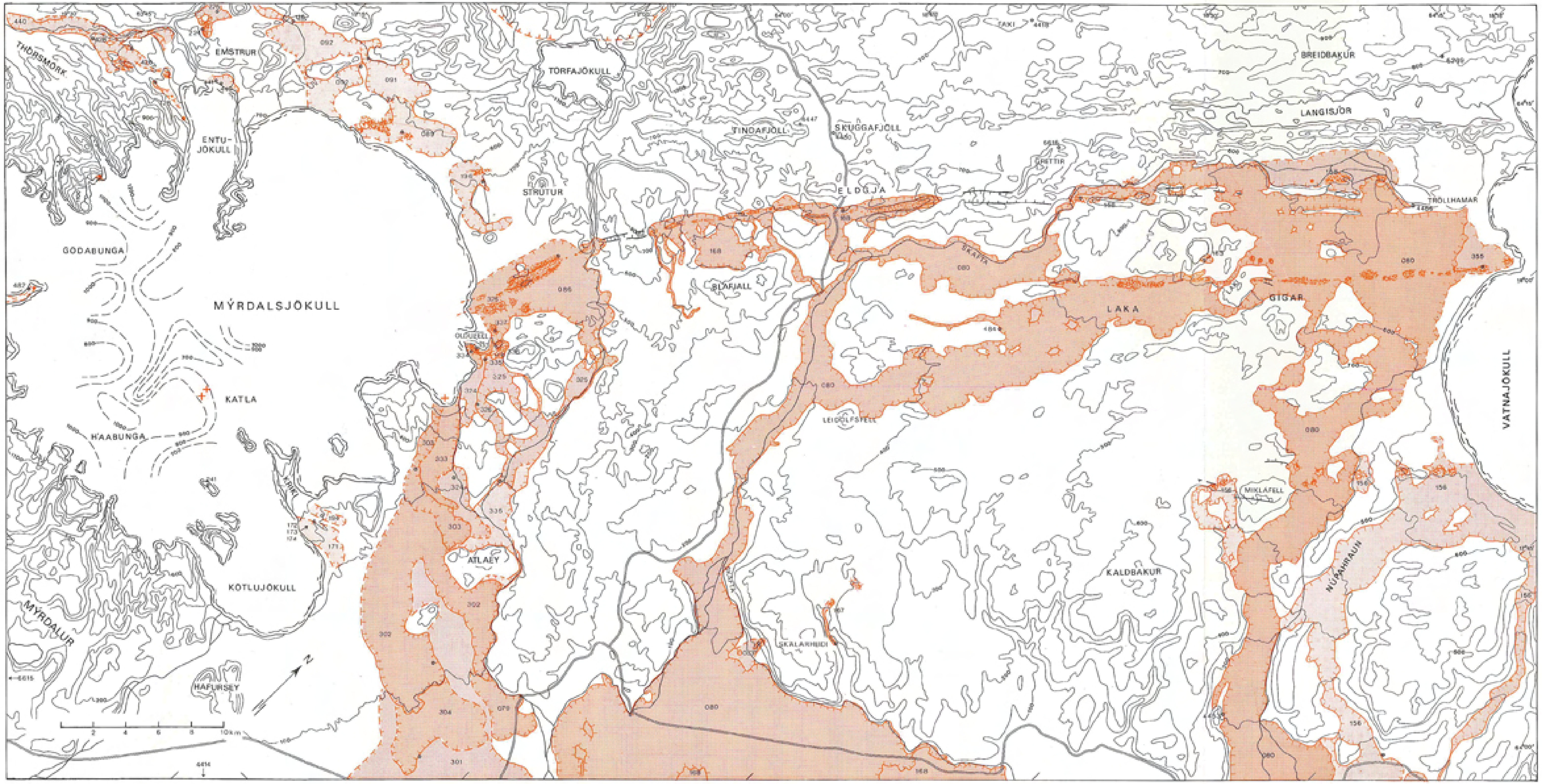


Plate IV. The Katla and Grímsvötn volcanic systems. The basalts of the Katla system are transitional alkali basalts. The Grímsvötn system is only known to have extruded tholeiites. Only a part of the Grímsvötn system is shown in the eastern half of the map, as most of the system is supposedly hidden by Vatnajökull. Legend as in Plate II. Mapped and compiled by S. P. Jakobsson during 1970—1977.

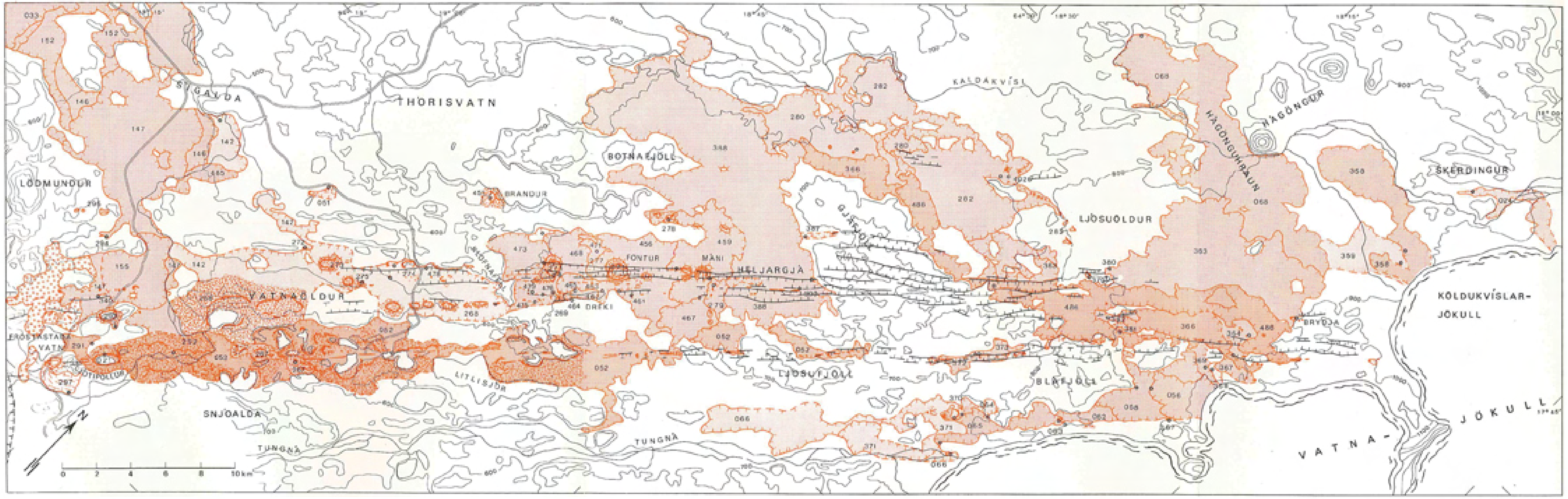


Plate V. The Veidivötn volcanic system. Only tholeiitic lavas have been erupted in Postglacial Time. The lavas in the area to the southwest of Klofnafell have not been distinguished. In the southwest are seen some of the Torfajökull lavas. Legend as in Plate II. Mapped and compiled by S. P. Jakobsson during 1973—1977.