Titill
Outline of the petrology of Iceland.

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8. Outline of the petrology of Iceland

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

INTRODUCTION

Until in the early nineteen sixties the petrology of Iceland was generally thought to be fairly simple and monotonous. The bulk of the igneous rocks was believed to be basaltic, in the main tholeiitic, with only a few per cent being rhyolitic. Intermediate rocks were considered very rare, and the chemical variation within the two above mentioned groups negligible.

However, within the last decade, mainly because of the development of ideas on sea-floor spreading and hot mantle plumes, a vast number of papers dealing with the geochemistry and petrology of Icelandic rocks has been produced, adding to the complexity of the picture, and indeed showing that the petrology of Iceland is probably more diverse and variable than in any other area of the North Atlantic ridge system.

Volcanism seems to have been more vigorous in this part of the North Atlantic than elsewhere, since the opening of the basin by sea-floor spreading in the early Tertiary. Approximately 90% of Iceland

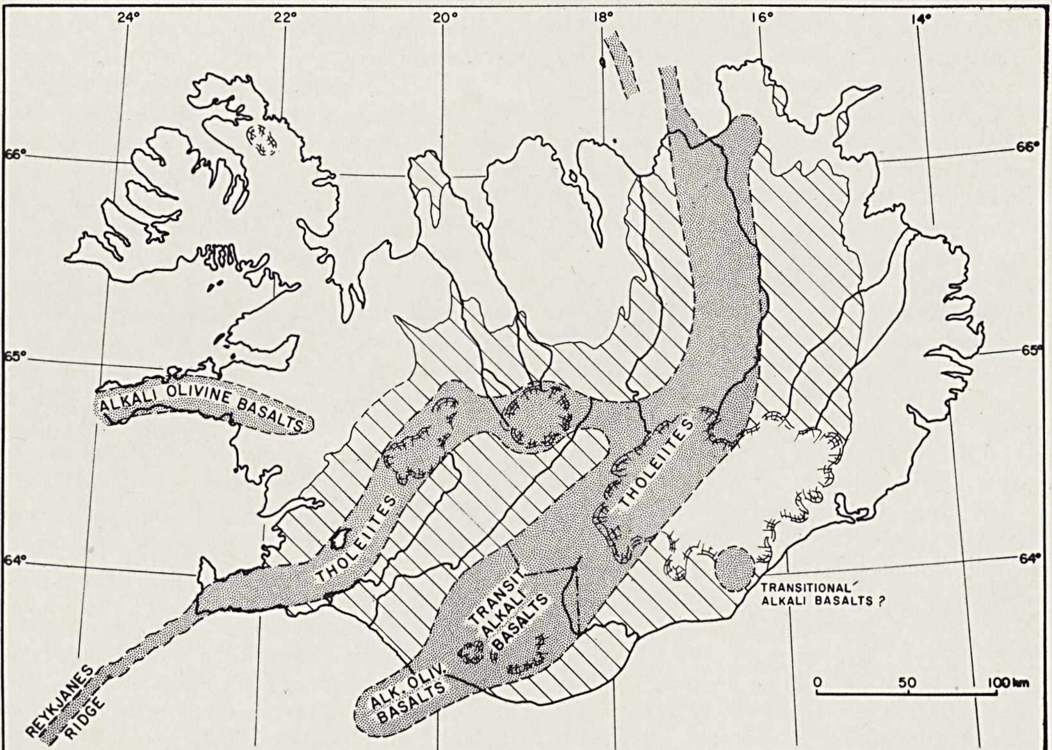

Fig. 1. Map of Iceland showing the Postglacial petrological zones, (shaded), Plio-Pleistocene formations (oblique lines) and Tertiary formations (white).

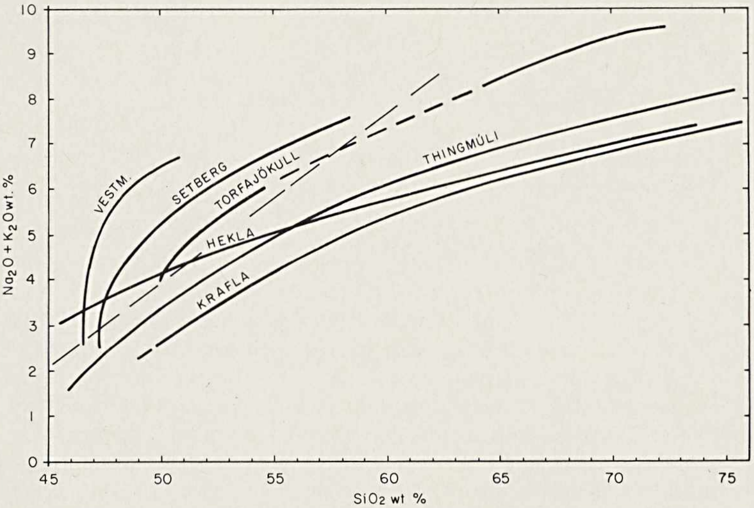

Fig. 2. Alkali:silica diagram indicating the chemical trends of six Icelandic volcanic systems, chosen to represent the three rock series. Tholeiitic series: Krafla and Thingmúli. Transitional alkalic series: Hekla and Torfajökull. Alkalic series: Vestmannaeyjar and Setberg II. The broken line is the Hawaiian division line.

above sea level is made up of volcanic rocks (including near-surface intrusions), only about 10% being consolidated sediments. These sediments are mainly interbedded tuffaceous layers of short transport and moraines and will not be dealt with here. Metamorphic rocks, conventionally speaking, are not found except ice-rafted examples. However, the zeolitic facies of burial metamorphism is reached in the deepest sections of the Tertiary lava pile in eastern and southeastern Iceland, where probably some 1000—1800 m have been eroded away since the cessation of volcanism in these areas.

THE VOLCANIC SYSTEMS

The presence of rather well-defined volcanic units, here called volcanic systems, both in the Tertiary and Pleistocene series, as well as in the active volcanic zones (Fig. 1), is now generally acknowledged. A volcanic system is a spatial grouping of eruption sites, including upper crustal feeder dykes, active within a relatively short period of time and with certain limited tectonic, petrographic and geochemical characteristics. The term volcanic system may refer to a volcanic fissure swarm or a central volcano, more commonly to both where they are associated into one structural unit.

Usually, a centrally situated complex is built up in the system, where the discharge of magma is highest and where a caldera and a high-temperature area may develop. In many volcanic systems the volcanism exhibits a compositional zoning. Acidic volcanism is confined to the central complex, rocks of intermediate composition occupy a broader zone around the acid center, and only basalt is erupted in the more distal parts of the system. All these features are indicative of shallow magma reservoir(s) under the central area of the system.

The surface dimensions of volcanic systems in the active volcanic zones vary between 17×6 km and 100×18 km. Present data on the volcanic zones (Fig. 1) indicate that these zones actually consist of about 26—28 volcanic systems. The mapped active systems of southwest and south Iceland are shown in Figs. 6 and 7.

The division into volcanic systems is of great importance in understanding the petrogenesis of Icelandic rocks. The volcanism is considered to operate within such a closed system for a limited period of between several hundred thousand to a million years and to develop a distinct rock suite.

THE THREE ROCK SERIES OF ICELAND

Available data on the petrology of Iceland indicate that three main rock series have developed in Iceland, a tholeiitic series, a transitional alkalic series and an alkalic series.

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%, and the rocks plot below the division line in the alkali:silica diagram of Fig. 2. The tholeiitic series is made up of the following main rock types: oceanite, olivine tholeiite, tholeiite, basaltic ice-

TABLE 1.

Major element compositions of the main extrusive rock-types of Iceland.

	THOLEIITIC SERIES				TRANSITIONAL ALKALIC SERIES				ALKALIC SERIES		
	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.
SiO_2:	46.21	49.30	60.59	73.23	47.08	47.08	60.52	73.60	46.56	48.46	58.64
TiO_2:	0.41	2.28	1.25	0.35	2.33	4.63	1.10	0.20	2.02	3.00	1.41
Al_2O_3:	13.69	13.51	15.07	12.25	12.25	12.71	14.98	12.04	15.93	16.40	17.12
Fe_2O_3:	1.37	2.34	2.31	3.46	2.46	4.24	2.02	1.26	1.61	3.27	1.93
FeO:	7.16	12.23	5.73	0.81	9.40	11.23	6.89	1.87	10.32	10.10	6.42
MnO:	0.15	0.24	0.19	0.11	0.19	0.22	0.20	0.07	0.20	0.26	0.26
MgO:	18.15	6.34	1.73	0.13	11.70	5.06	1.44	0.05	9.00	3.82	1.16
CaO:	10.99	10.71	4.94	1.87	11.40	9.91	4.69	0.38	10.51	7.71	4.92
Na_2O:	1.32	2.46	4.29	4.37	2.13	3.08	4.71	5.74	3.21	5.11	5.02
K_2O:	0.01	0.24	1.59	2.53	0.43	0.72	1.68	4.51	0.51	1.19	2.57
P_2O_5:	0.02	0.21	0.43	0.02	0.26	0.57	0.45	0.01	0.26	0.62	0.52
H_2O:	0.19	0.21	1.84	0.25	0.34	0.31	0.59	0.18	0.02	0.06	n.d.
Sum:	99.67	100.07	99.96	99.38	99.97	99.76	99.27	99.91	100.15	100.00	99.97

THOLEIITIC SERIES:

1: Oceanite (picrite basalt), Vatnsheidi lava shield, Reykjanes-Langjökull zone, Postglacial. Phenocrysts of chromite, olivine and plagioclase (Jakobsson et al. 1978).

2: Tholeiite, Grindavík fissure lava, Reykjanes-Langjökull zone, Postglacial. Phenocrysts of olivine, plagioclase and augite (Jakobsson et al. 1978).

3: Icelandite, Thingmúli central volcano, E-Iceland, Tertiary. Phenocrysts of plagioclase, olivine, ferroaugite and hypersthene (Carmichael 1964).

4: Rhyolite, Jörundur dome, Krafla central volcano, northern volcanic zone, Upper Pleistocene. Phenocrysts of plagioclase, olivine, ferroaugite, magnetite and pigeonite (Wetzel et al. 1978).

TRANSITIONAL ALKALIC SERIES:

5: Ankaramite, Eyjafjöll central volcano, eastern volcanic zone, Upper Pleistocene (intrusive?). Phenocrysts of olivine, diopsidic augite, plagioclase and magnetite (Steinthórsson 1964).

6: Transitional alkali basalt, Eldgjá lava, eastern volcanic zone, Postglacial. Phenocrysts of magnetite, plagioclase, olivine and augite (Jakobsson 1979).

7: Transitional andesite, prehistoric Hekla lava, eastern volcanic zone. Phenocrysts of magnetite, plagioclase, olivine, augite and apatite (Jakobsson 1979).

8: Comenditic rhyolite, Hrafntinnusker tholoid, eastern volcanic zone, Postglacial. Aphyric obsidian (Bailey & Macdonald 1970).

ALKALIC SERIES:

9: Alkali olivine basalt, 1964 Surtsey lava, Vestmannaeyjar. Phenocrysts of picotite, olivine and plagioclase, (Tilley et al. 1967).

10: Hawaiite, 1973 Eldfell lava, Vestmannaeyjar. Phenocrysts of plagioclase, olivine, magnetite and, kaersutite and hornblende (on nodules) (Jakobsson et al. 1973).

11: Benmoreite, Setberg alkalic suite, Snaefellsnes, Upper Pleistocene. Phenocrysts of plagioclase, olivine, augite and magnetite (Sigurdsson 1970).

landite, icelandite (andesite), dacite and rhyolite. The equivalent plutonic rocks (gabbro, etc.) have also been observed. The major element composition along with information on phenocryst phases of four typical extrusive rock types of the tholeiitic series is shown in Table 1. In this series, close parallels to the tholeiitic magma types of the classical Hebridean province can be demonstrated.

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 Fig. 2, 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 (hawaiite), andesite (mugearite), trachyte (?) and comenditic rhyolite. Equivalent plutonic rocks to some of these compositions have been observed. The major element composition of four typical rock types of the transitional alkalic series is shown in Table 1.

The alkalic series is of mild character, the rocks are nepheline normative and plot above the division line in Fig. 2. The alkalic series is made up of ankaramite (?), alkali olivine basalt, hawaiite (trachybasalt), mugearite (trachyandesite), benmoreite, trachyte (?) and alkalic rhyolite. Equivalent plutonic rocks have not been found with certainty. The major element composition of three typical members of this series is shown in Table 1. The alkalic series of Vestmannaeyjar (Fig. 7) is nearly identical to the Plateau Magma Type of the Hebridean volcanic province.

Several typical differentiation trends within these three rock series is shown with regard to their alkali:silica content in Fig. 2. The plots of Post-glacial basalts of the rock series is shown in Fig. 8.

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 which are retained, e.g. the trends in the alkali:silica diagram of Fig. 2. The occurrence and distribution of the rock series will be discussed in the following sections.

TERTIARY TO PLEISTOCENE VOLCANIC ROCKS

Tertiary

The petrology of the Tertiary rocks of Iceland (about 16—3.1 m.y. ago) appears to be fairly homogenous from a genetical point of view. Volcanism in this period was probably confined to an axial rift zone, similar to the present axial rift zone, and only rocks belonging to the tholeiitic series have been observed within the exposed Tertiary volcanic systems of which there are approximately 44. From a petrological point of view large areas are still unknown, but the central complexes of several individual volcanic systems have been studied in detail, especially the Thingmúli and Álftafjördur complexes in eastern Iceland and the Setberg I, Reykjadalur and Hafnarfjall complexes in western Iceland. These central volcanoes generally consist of basic, intermediate and acid lavas, pyroclastic rocks and a minor amount of sediments. Intrusive activity is confined to feeder dykes (dolerite), cone sheets (dolerite and acid rocks) and irregular intrusions (mainly gabbro and granophyre), a laccolith being recorded in one case.

These studies indicate the existence of a complete olivine tholeiite — tholeiite — basaltic icelandite — icelandite — (dacite) — rhyolite series of rocks. Picrite basalts are infrequent. At this point it is appropriate to note that the field terms frequently used in Iceland of olivine basalt, tholeiite and plagioclase porphyritic basalt are not genetical and apply to the macroscopical appearance, although these field types prove in most cases to be tholeiitic.

The petrochemical trends of these Tertiary central volcanoes are very similar, apart from minor differences, e.g. parellel shifts in trend lines as in the alkali: silica diagram of Fig. 2.

The mineralogy of the Tertiary volcanoes is relatively simple. In Thingmúli, where the rock suite has been suggested to be derived by a process of fractional crystallization from a basaltic parent, olivine is a ubiquitous phenocryst phase (Fo 85—65) in the basic rocks, and is also found as a groundmass constituent of the olivine tholeiite. The olivine is absent in the tholeiites and the basaltic icelandite, but reappears in the icelandites and the acid rocks (as Fo 45), a recurrence analogous to that of the olivine in the Skaergaard intrusion. Plagioclase is the only feldspar, and the groundmass constituent becomes progressivly more sodic going from the basalts towards the acid end of the series. In the basic rocks augite is rare as a phenocryst phase; in the groundmass augite and pigeonite coexist and vary in composition in a

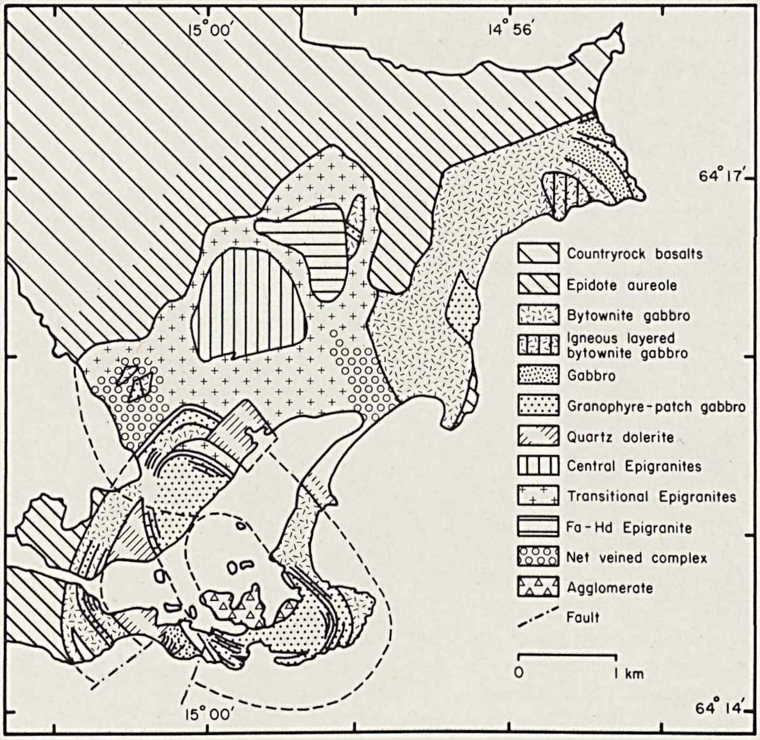

Fig. 3. Geological map of the Vesturhorn intrusion, southeast Iceland. After Roobol 1974.

similar way to those of the Skaergaard intrusion. In the icelandites (cf. Table 1, no. 3) both augite and orthopyroxene have been found as phenocrysts while in the acid rocks ferroaugite is the phenocryst phase. Of iron-titanium oxides, both magnetite and ilmenite are present. Magnetite plays a varied role in the order of crystallization; in the intermediate stages magnetite is found as a phenocryst phase and is considered to play a vital role in the course of fractionation at this stage by controlling the Ti and Fe-content of the liquids.

Several large intrusions, which are apparently not connected with central volcanoes, have been mapped in southeastern Iceland, the most notable being the Vesturhorn and Austurhorn intrusions from Upper Miocene. In Vesturhorn (Fig. 3) there are indications of more than 72 separate intrusive bodies with rock compositions ranging from gabbro through diorite to granite and granophyre. The intermediate members of the series are thought to be formed by mixing of the end members.

There is striking evidence from these intrusions that acid and basic magmas have existed side by side. Pillow-like masses of basic rock are found in and chilled against granophyre, while in other localities net-veined complexes are found, where the basic rock is veined by acid rocks, see Fig. 4. From a higher level in the crust, a number of examples are known, from Tertiary as well as from younger formations, of composite intrusions and lavas. It has been suggested that in some cases the mobility or even the uprise of the acid magma is due to the transfer of heat from the coexisting basic magma.

Layered igneous rocks are known from a few localities in Iceland. The Thorgeirsfell gabbro (Snaefellsnes) and gabbros of the Austurhorn intrusion exhibit a faint layered structure. In the Vesturhorn intrusion (Fig. 3) a block of a bytownite gabbro with size-graded layering has been described. In a Tertiary dolerite sill in Hrappsey, western Iceland, large inclusions (up to 30.000 m^2) of bytownite anorthosite showing faint layering are present, these anorthosites are thought to be cumulates formed at shallow depth from an olivine tholeiite magma.

Plio-Pleistocene and Upper Pleistocene

Volcanism probably continued without

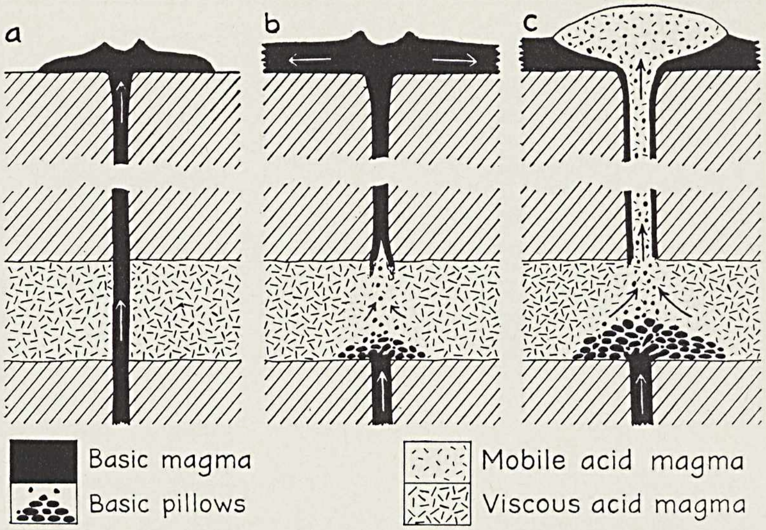

Fig. 4. Diagrammatic representation of the possible relationship between, and origin of, a net-veined complex of Austurhorn — type and a composite dyke feeding a composite lava flow. From Blake et al. 1965.

interuption from the Tertiary throughout the Plio-Pleistocene (3.1—0.7 m.y.) into the Upper Pleistocene. However, the onset of glaciations resulted in a drastical change of environmental conditions. Mountains of hyaloclastites (pyroclastic breccias and tuffs) and pillow lavas piled up subglacially. During interglacial periods, extensive lava flows were formed, as in the Tertiary era. Many large olivine tholeiite lava shields are known, particularly from the later interglacial periods, as for example Lyngdalsheidi and Skálpanes in southwestern Iceland and Vadalda and Grjótháls in central northern Iceland. As the result of volcanic activity under ice-cover the central volcanoes are usually higher than those from the Tertiary era. The best known of volcanoes dating from this period are Setberg II and Kjalarnes-Stardalur of Plio-Pleistocene age and Kerlingarfjöll and Tindfjallajökull from the Upper Pleistocene.

As is the case with the Tertiary rock formations, large areas of Plio-Pleistocene and Upper Pleistocene age have not yet been studied petrologically, although the main features are known. In the early Plio-Pleistocene only tholeiitic rocks were developed as in the Tertiary. The Kjalarnes-Stardalur central volcanoes are for example built up of a tholeiitic suite nearly identical to the Thingmúli suite previously described.

Later flank volcanic zones became active in addition to the axial zones. The temporarily active Skagi zone in western North Iceland at first produced tholeiitic rocks, but later rocks approaching the transitional series in composition were extruded. In the Snaefellsnes flank zone compositions may have changed gradually on a regional basis through time. In the Setberg area (Fig. 5) for example, a tholeiitic suite was produced from the Setberg I central volcano up to about 2.5 m.y. ago and later a transitional suite (low in Fe and Ti) was erupted from the Setberg II volcano from about 2.5 up to 0.7 m.y. ago. Finally, alkalic volcanism developed in the area from approx. 0.7 m.y. ago up to present.

Similarily, a flank zone began to develop in South Iceland south of river Tungná, perhaps some 2 m.y. ago. Rocks belonging to the transitional series developed in volcanic systems in this flank zone from that time and up to the present. In the Upper Pleistocene and Holocene rocks belonging to the alkalic series were produced in the Vestmannaeyjar volcanic system, the latest display of volcanic activity occurring on Heimaey in 1973.

In the Setberg alkalic suite, ankaramite is described as the most primitive member. This rock carries abundant phenocrysts of diopsidic augite and olivine (from Fo 89), along with plagioclase (from An 92) and dark-brown spinel. Olivine and plagioclase occur throughout the alkali basalt — hawaiite — mugearite — benmoreite suite as phenocrysts, the olivine having a compostional range of Fo 85 in the basic rocks to Fo 55 in the acid end and the plagioclase being An 81 to An 30 for the same rocks. Augite is a very scarce phenocryst phase, magnetite occurs in hawaiite, mugearites and benmoreites and apatite as phenocryst in

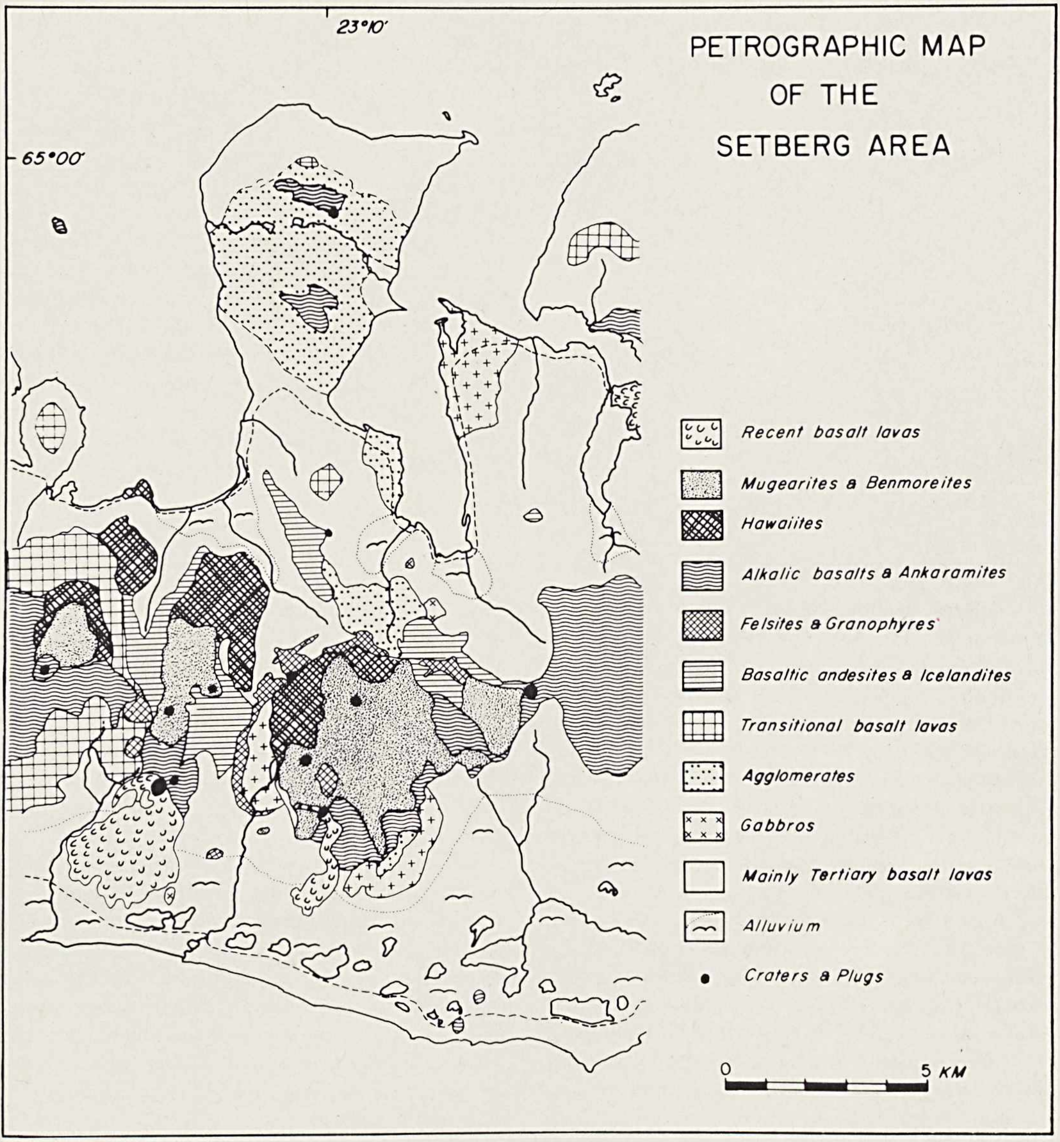

Fig. 5. Map of the Setberg area, Snaefellsnes, showing the distribution of rock types. From Sigurdsson, 1970.

mugearites. Noteworthy is the occurrence of anorthoclase as a phenocryst phase in a benmoreite. It should be noted here, that no trachyte was found associated with this series in the Setberg area. Phlogopite and hornblende is occasionally found interstitially in the groundmass in this rock series. In the alkalic rock suite of Vestmannaeyjar (mainly Postglacial), where only alkali basalts and hawaiites have developed so far, a similar mineralogy is encountered. The mineralogy of the transitional series is as yet imperfectly known.

POSTGLACIAL PETROLOGICAL ZONES

The Postglacial volcanism is a direct continuation of the Upper Pleistocene volcanism. About 26—28 volcanic systems have been active in

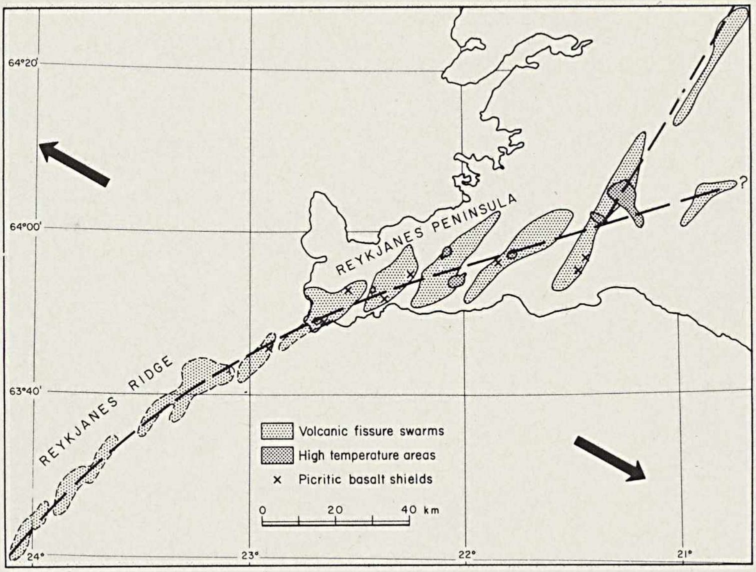

Fig. 6. The Postglacial volcanic systems of the Reykjanes-Langjökull zone and northernmost Reykjanes Ridge. Suggested location of the plate boundary is shown. Also shown is the location of high-temperature thermal areas and known picritic lava shields. From Jakobsson et al. 1978.

the Postglacial and they form the active volcanic zones which intersect Iceland from southwest to northeast (Fig. 1).

The Postglacial extrusives form distinct petrological provinces. About 18 volcanic systems have produced rocks belonging to the tholeiitic series, and these systems form what can be termed the axial volcanic rift zone of Iceland (Fig. 1). Active tectonic fissures and normal faulting with formation of shallow grabens is characteristic of these systems.

The tholeiitic systems vary appreciably with regard to size, the range of rock compositions extruded and the rate of extrusion. On the Reykjanes Peninsula (Fig. 6) three types of basaltic lavas are recognized in the comparatively small systems, i.e. picrite basalts (oceanites, cf. Table 1, no. 1) forming small lava shields, olivine tholeiites forming large lava shields and tholeiitic lavas extruded from volcanic fissures (cf. Table 1, no. 2). There is thus a distinct correlation between the morphology and the chemistry of the lavas. Petrochemically, two trends are indentifiable, being a lava shield oceanite — olivine tholeiite trend and a fissure tholeiite trend.

Studies on the western Reykjanes Peninsula suggest that observed regular temporal variations may reflect cyclic volcanic activity such that each cycle begins with the formation of oceanites. Fractional crystallization is recognized as being important in the development of the rocks, but as is so often found when a detailed study is made, other processes must also be sought to explain the compositional variation; for example variations in degree of partial melting of the source rocks and volatile transfer or other gravitational processes working in the magma at shallow level. Intermediate and acid rocks have not been found outcropping on the Reykjanes Peninsula except in the Hengill system.

In the two tholeiitic fissure swarms of the eastern volcanic zone (Fig. 7) the basalts are tholeiities of a narrow compositional range. Most of the Veidivötn basalt lavas carry abundant macrophenocrysts of plagioclase (An 88), probably cumulated in the magma at shallow depth by a floating mechanism. Although the Lakagígar swarm is for the most part covered by the Vatnajökull glacier, chemical and petrographic analyses indicate that the subglacial Grímsvötn caldera also belongs to this volcanic system. Several very voluminous basalt lavas have been extruded from these two tholeiitic swarms, such as the prehistoric Thjórsá B lava (13.5 km^3) and the well-known Lakagígar lava of 1783—1784 (13 km^3).

In the northern zone, the tholeiitic Krafla fissure swarm has been studied in detail from various points of view, mainly in connection with the present rifting and eruption episode, which has been in progress since December 1975. It has been suggested from seismic and ground deformation evidence, that magma is being fed continously into

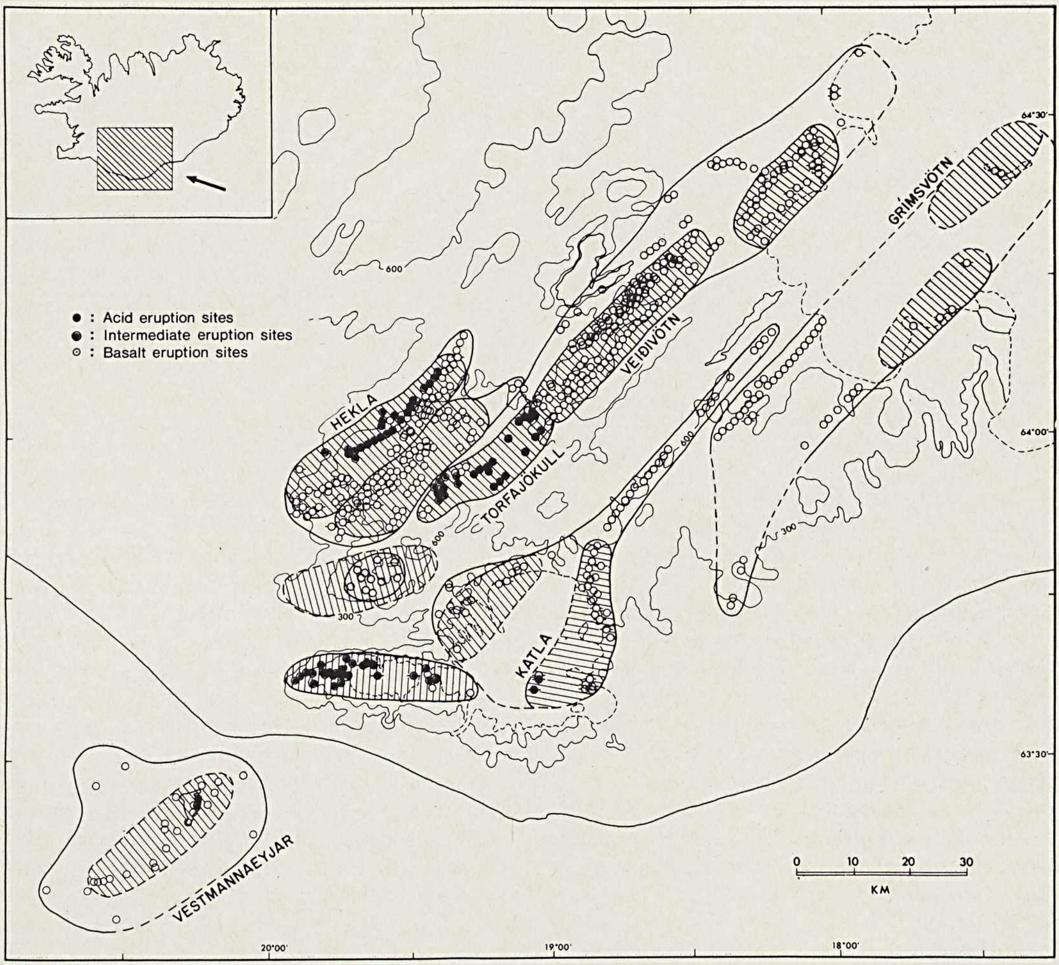

Fig. 7. The Postglacial volcanic systems of the eastern volcanic zone. Eruption sites are shown by circles and dots, divided with respect to rock groups. Particularly active areas are indicated by hatching. From Jakobsson, 1979.

a magma reservoir(s) below the centrally situated Krafla caldera, at a depth of about 3 km. When rifting and dilatation takes place, the magma is believed to be injected laterally into the rift system northwards and southwards, accompanied by deflation of the central volcano. It is estimated, that less than 1% of the tholeiite magma (MgO:5.4—7.4%) fed into the rift system has yet been erupted on surface in the three minor volcanic eruptions since 1975. The lavas are of variable composition and a mixing mechanism of two or more tholeiitic liquids is indicated.

From the study of Postglacial rocks in the flank zones, five volcanic systems producing a transitional rock series have been identified, all situated in the eastern volcanic zone (Fig. 7). The large isolated Öraefajökull volcano (Fig. 1) probably also belongs to this group. Only minor tectonic rifting or faulting is associated with the volcanism in the area of the transitional series. No ultrabasic rocks have been erupted in the eastern zone during Postglacial time, but Upper Pleistocene ankaramite intrusions (?) are known to occur in the Eyjafjöll volcano, for example Hvammsmúli (cf. Table 1, no. 5).

The Hekla central volcano has been shown to be lying within a swarm of eruption fissures which have produced mild transitional alkali basalts,

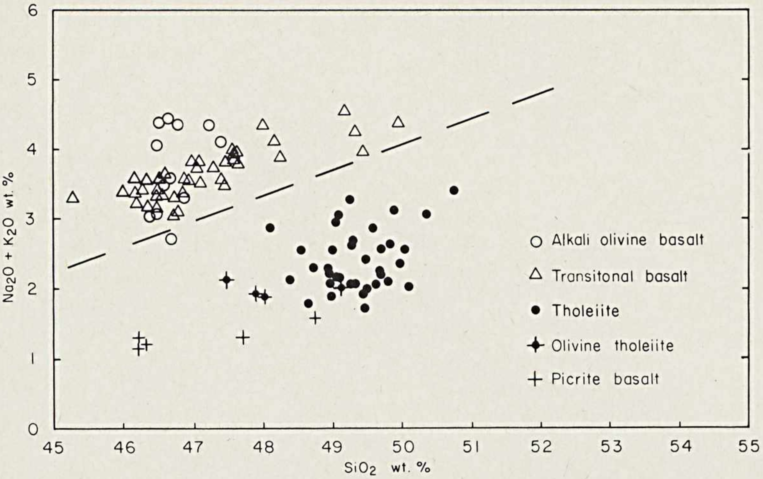

Fig. 8. Alkali:silica diagram of Postglacial basalts from the Reykjanes-Langjökull zone (Fig. 6) and the eastern volcanic zone (Fig. 7).

belonging to the same system (trend) as the intermediate and acid rocks of Hekla itself. The very high proportion (~ 40 per cent by vol.) of intermediate rocks (cf. Table 1, no. 7) produced in this system is exceptional for Postglacial volcanism.

Acid tephras and lavas are only erupted from the top crater of Hekla. It has been found that there is a positive correlation of the SiO_2 — content of the first melt erupted with the volume of tephras and lavas erupted each time, as well as with the length of the preceeding quiescent period. Opinions have differed as to the origin of the Hekla rock suite. Fractional crystallization of a basaltic parent, successive partial melting of subsided basalts at high water pressure and assimilation of acid rocks at depth have particularly been discussed as possible models.

The Torfajökull volcanic system is still somewhat loosely defined. Rhyolitic rocks of Upper Pleistocene age cover some 400 km² and the origin of these has been a matter of dispute. Measurements of Sr-isotope ratios in this area indicate that the evolved rocks of the Torfajökull complex cannot have been derived by fractional crystallization from the basalts.

Probably three alkalic volcanic systems are active in the Snaefellsnes flank zone, and one, the Vestmannaeyjar, in the eastern flank zone. Only alkali olivine basalts (cf. Table 1, no. 9) and hawaiites (cf. Table 1, no. 10) have been produced

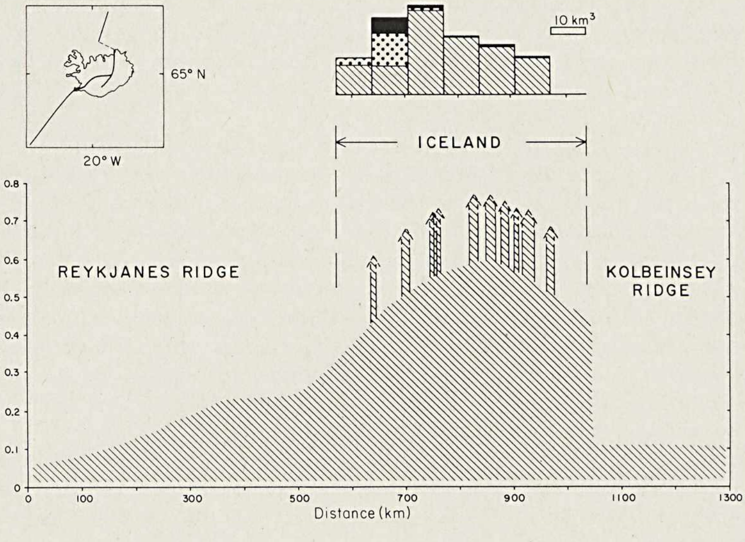

Fig. 9. Below: Diagrammatical representation of the distribution of K_2O in the axial rift tholeiites with distance along the ridge axis in the Iceland area. Columns with arrows indicate the presence of Recent central volcanoes with evolved rock compositions.
Above: Histograms indicating discharge of volcanic rocks in Postglacial time across Iceland. Oblique lines indicate tholeiites, dots alkalic basalts and black intermediate to acid rocks. The inset map with the solid line shows the location of the profile.

in the Vestmannaeyjar system. The short description on the mineralogy of the Setberg alkalic suite applies also to the Vestmannaeyjar rocks. In addition, basanitic segregation veins occur in the basalts carrying nepheline, analcime, aegirine, amphiboles and aenigmatite.

Fig. 8 shows the alkali:silica plot of analyzed Postglacial basalts from the western Reykjanes Peninsula (Fig. 6) and the eastern volcanic zone (Fig. 7).

There appears to be a relation between the distribution of the petrological zones as defined from the study of Postglacial rocks and the crustal structure of Iceland. The depth to the inferred upper mantle (layer 4) boundary is generally 8—9 km below the tholeiitic zones. Moving along the alkalic flank zones away from the tholeiitic zones (Fig. 1), the depth increases and reaches about 14 km depth in the distal ends, concordant with an overall increase in the alkalinity of the alkali basalts produced at the surface. The simplest interpretation of these relations is, that the alkali basalts are generated at greater depths and consequently higher pressures than the tholeiites, and may therefore represent different degrees of melting of similar mantle material.

An important feature of the Postglacial basalts is the compositional variation within the tholeiites of the axial zone which reaches maximum in central Iceland. Moving from typical mid-ocean ridge basalt (MORB) compositions about 400 km south of Reykjanes, the chemical transition is gradual towards middle Iceland and the maximum or minimum value encountered in the basalts in each part of the rift zone rises or falls at the same time as the scatter of values increases. In North Iceland, however, an abrupt transition across the Tjörnes Fracture Zone is indicated. Fig. 9 for example shows the variation of K_2O in the axial rift tholeiites with distance along the ridge axis in the Iceland area. The geochemical gradient across Iceland has been much discussed. Several investigators favour a multiple source hypothesis in a rising hot mantle plume to explain these relations.

Fig. 9 moreover indicates that maximum total discharge rate in this region of the Mid-Atlantic Ridge is reached just south of Central Iceland, with an output per unit length of ridge at least 4—5 times higher than just south or north of Iceland.

Gabbroic nodules

Friable and porous gabbroic nodules are common in the basic rocks, preferably in tholeiitic lavas and tephras. The gabbroic nodules are generally less than 6—8 cm in diameter, the grain size being usually between 1 and 5 mm. Those found in basalts only rarely show any reaction relation with the host rock. Plagioclase is commonly the dominating phase, in association with clinopyroxene, olivine, orthopyroxene and magnetite. Amphiboles and apatite are only rarely observed. Some of the nodules exhibit igneous layering and heteradcumulate and adcumulate textures taken to be indicative of an accumulative origin. There are strong indications that these nodules are formed freely floating. On the basis of general similarities of the host rocks, the nodules in the basalts can be suggested to be autoliths formed at shallow depth. Gabbroic nodules in andesitic

TABLE 2. Estimates on volume (km³) and relative abundance (%) of extruded rocks during Postglacial time in the eastern volcanic zone, and all the active volcanic zones.

	EASTERN VOLCANIC ZONE					POSTGLACIAL ACTIVE ZONES	
Rock type	Tholeiitic	Transitional	Alkalic	Total km³	Total %	Total km³	Total %
Basalt	107	65	3.7	176	87	390	92
Basaltic andesite*	0?	14.0	0.2	14.2	7	17	4
Andesite+	?	3.7	0	3.7	2	5	1
Dacite-rhyolite	0	8.2	0	8.2	4	11	3
	107	91	3.9	202		423	

*Hawaiite-mugearite in the alkalic series

+Benmoreite in the alkalic series

rocks are commonly found to be broken chips of solid rock which have reacted with the magma and can therefore be suggested to be xenoliths. Gabbroic nodules found in the first mugearitic extrusives of the 1973 Eldfell (Heimaey) eruption in the Vestmannaeyjar volcanic system contain hypersthene and are therefore xenolithic in the alkalic magma, although they had reacted with the magma to form hornblende and kaersutite.

No peridotitic or eclogitic nodules have been found with certainty in Icelandic rocks.

Volume of extruded rocks

In Table 2 are shown estimates of the extruded volumes of various rock types (groups) in the three rock series of the eastern volcanic zone (Fig. 7) along with estimates for all the volcanic zones. It is seen that the production of the various rock types within the three series is very different.

Compared with the five transitional alkalic and the one alkalic system, the two tholeiitic systems have by far the highest productivity of basalts. Similarly the bulk of the evolved rocks are produced in transitional alkalic systems. It appears that the ratio of evolved rocks to basalts is 1—2 order of magnitude higher in the alkalic systems than in tholeiitic areas. It may be unwise to compare these systems, since they may be in a different stage of maturity and since their tectonic environment is different and the ratio of extruded magma to underground-stored magma can not be determined. However, these differences are probably of some genetic significance. For example, partial melting models suggest, that given a constant composition of the mantle source region, olivine tholeiites correspond to a factor of five to eight times more melting than alkali olivine basalts, and indeed field data suggest that the tholeiitic systems produce about seven times more basalts than the alkalic systems per unit area.

As five of the six active transitional alkalic systems are found in the eastern zone, the percentage of evolved rocks is lower when all the volcanic zones are included, or about 8 per cent, including the basaltic andesites. These are lower values than usually calculated in Iceland. Estimates from the Tertiary formations indicate 14—40 per cent of evolved rocks, but, these values may however by misleading, since much of the field work has centered on the old central volcanoes, where the bulk of the evolved rocks is exposed.

PALAGONITIZATION AND ZEOLITE FACIES METAMORPHISM

Metamorphic rocks do not outcrop in Iceland, and extensive geophysical studies, as well as Sr and Pb isotope investigations strongly suggest that sial material does not exist under Iceland. Formerly, the common occurrence of acid xenoliths in the basic extrusives was thought to indicate the existence of such a sial layer, but more detailed

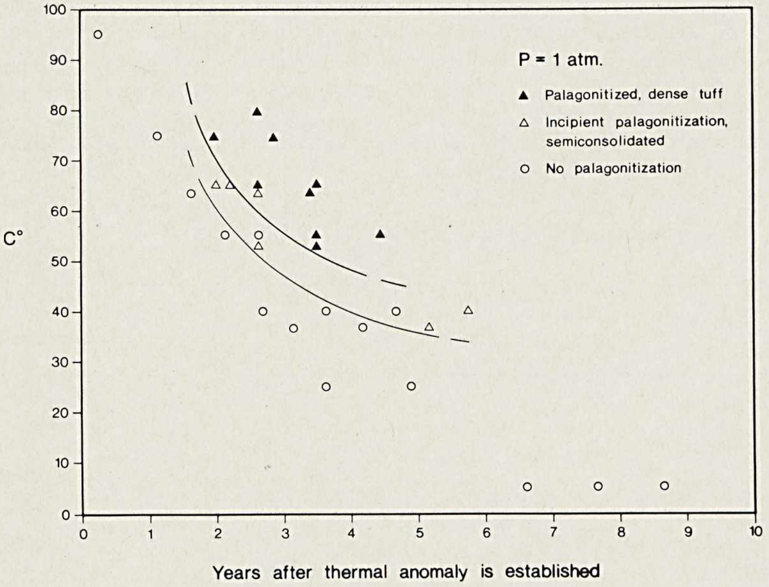

Fig. 10. The rate of palagonitization and consolidation in Surtsey tephra as a function of temperature and time. Based on surface observations and 11 localities between 1968—1976. From Jakobsson 1978.

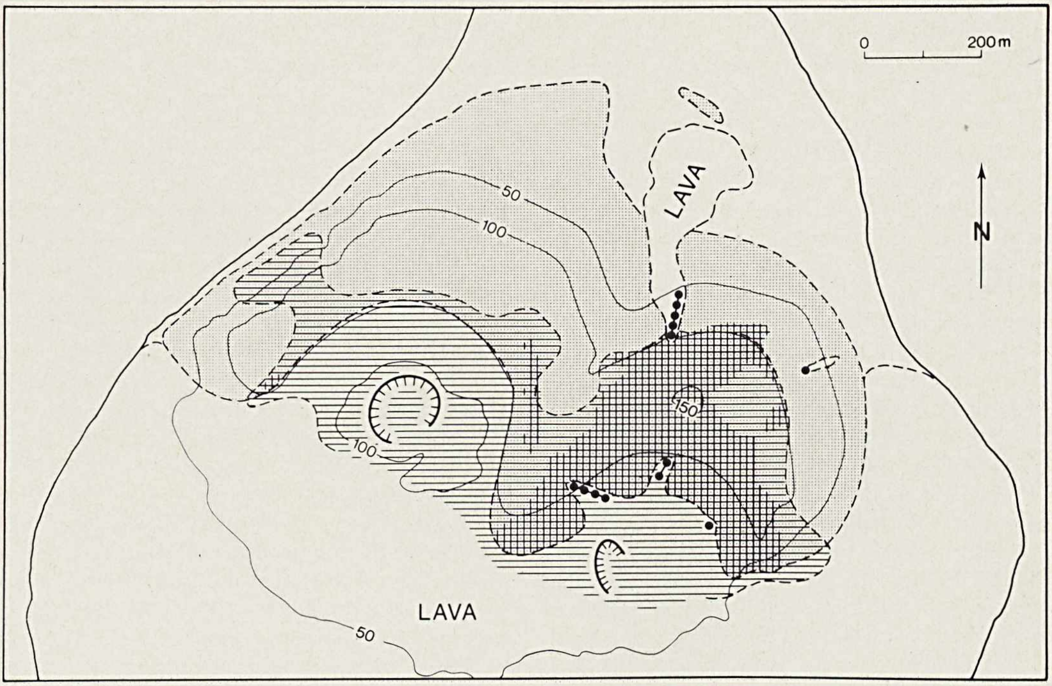

Fig. 11. Map of the northern part of the Surtsey volcanic island off the south coast of Iceland. The area of primary tepra is shown stippled. The extent of the hydrothermal area (horizontal lines) and surface exposures of the palagonitized area (crosshatching) as in Sept. 1976. From Jakobsson 1978.

studies show that the xenoliths are most probably pieces of shallow acid instrusions.

However, low-temperature alteration and leaching of glassy rocks is extensive, and the incipient marks of burial metamorphsim are seen regionally in the Tertiary lava piles of eastern, northern and western Iceland.

Hyaloclastites (Icel. *móberg*) i.e. basaltic or basaltic — andesitic rocks, which have been quenched and granulated by contact of the magma with water are widespread in Iceland. They form due to subglacial or subaquatic eruptions and constitute for example the main part of the Upper Pleistocene “Móberg Formation”. Recent examples of this formation are also known, e.g. the products of the phreatic phases of the Surtsey eruptions 1963—1967. As a result of quenching, the hyaloclastite is mainly made up of translucent brownish glass, called sideromelane.

Palagonitization

The sideromelane is unstable and leaching and alteration starts relatively quickly depending mainly on the access of water and ambient temperatures. The overall process of alteration of the sideromelane is called palagonitization, and the term palagonite is used for the vitreous,

TABLE 3. Typical electron microprobe analyses of a sideromelane grain and its palagonite rim, in weight per cent. Fe_2O_3* is total Fe as Fe_2O_3, and H_2O is assumed to add up to nearly 100% wt. The Saefell tephra, Vestmannaeyjar.

wt.%	Sideromelane	Palagonite
SiO_2	45.1	36.0
TiO_2	2.5	3.9
Al_2O_3	16.0	10.4
Fe_2O_3*	12.2	18.1
MgO	5.0	4.6
CaO	11.9	9.9
Na_2O	2.8	0.2
K_2O	0.5	0.7
Sum	96.0	83.8

transparent, but usually yellow to brown alteration product of the sideromelane.

The palagonitization starts on the surface of the glass grains and proceeds inward at a speed which is mainly dependent on moisture and temperature. In the island of Surtsey, which was created by volcanic eruptions during 1963—1967, it has been possible to follow the posteruptional process of palagonitization and consolidation of basalt tephra at temperatures between about 35° and 100°C (Fig. 10). This is a case of mild hydrothermal activity and at temperatures of about 80°—100°C, the tephra was converted to dense palagonitized tuff in only 1—2 years (Fig. 11).

Palagonitization and consolidation proceeds much more slowly at subaerial weathering conditions (up to about 20°C) and according to present data it may take several thousand years before any substantial palagonitization occurs.

Palagonitization can be termed a microsolution:precipitation mechanism. The main components to be leached out of the sideromelane are in order on a volume basis: Na_2O, CaO, Al_2O_3, K_2O, SiO_2 and MgO. Instead, H_2O enters the glass and ferrous iron is oxidized to ferric iron to give the rock the rust brown colour. Table 3 shows typical sideromelane-palagonite analyses on weight per cent basis.

The ions which are leached out of the glass form secondary minerals in the hyaloclastite, which help to cement the rock together. Most common as secondary minerals are calcite, chabasite, scolesite, analcite and opal. Smectites and other clay minerals form in the palagonite at an advanced stage of alteration ("fibropalagonite"). It appears probable that palagonitization in Iceland usually occurs at subaerial weathering conditions, and locally by mild hydrothermal activity, where feeder dykes, other intrusious and possibly pillow lavas act as heat source.

Burial metamorphism

As the lava pile is becoming thickened by continuous accumulation of lavas in a volcanic zone, geoisotherms will rise in the lava pile resulting in the alteration of the rocks. Geological mapping in eastern Iceland during the 1950's revealed that the secondary minerals formed in the lava pile, especially zeolites, have a regular distribution. They occupy near horizontal zones, which bear no relationship to the stratigraphy of the lava pile. Several zones, each with distinct mineral assemblages, have been established (Fig. 12), and these zones are inferred to be approximately paralled to the top of the lava pile at the time of zeolitization. Subsequent work has shown that a similar regional zoning of secondary (amygdale) minerals exists in the Tertiary basalt lavas of northern and western Iceland. This zonal distribution, along with studies on dyke density, has made it possible to estimate the height of the original surface of the lava pile. Up to 1800 m may have been eroded in southeastern Iceland, some 1000 m in the Eastern Fjords, but only a few hundred meters may be missing on the Northwest Peninsula.

The lowest-temperature metamorphism, the zeolitic facies, is characterized in particular by the zeolite laumontite. The regional occurrence of this mineral in the lowest part of the lava pile in eastern and southeastern Iceland (Fig. 12) therefore

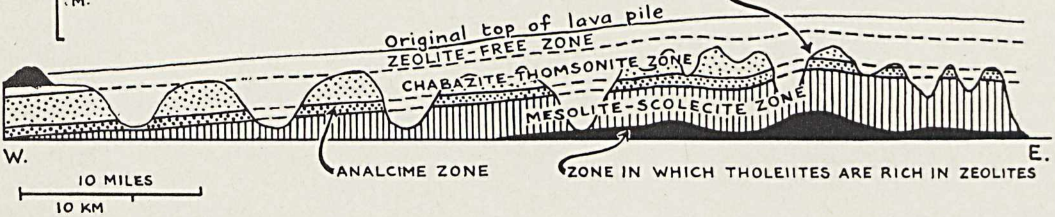

Fig. 12. Diagrammatic section across the Tertiary lava pile in eastern Iceland showing the zonal distribution of amygdale minerals. The western end of the section corresponds to sections in upper Jökuldalur and Fljótsdalur; the eastern half corresponds to exposures in the Eastern Fjordlands. After Walker 1960.

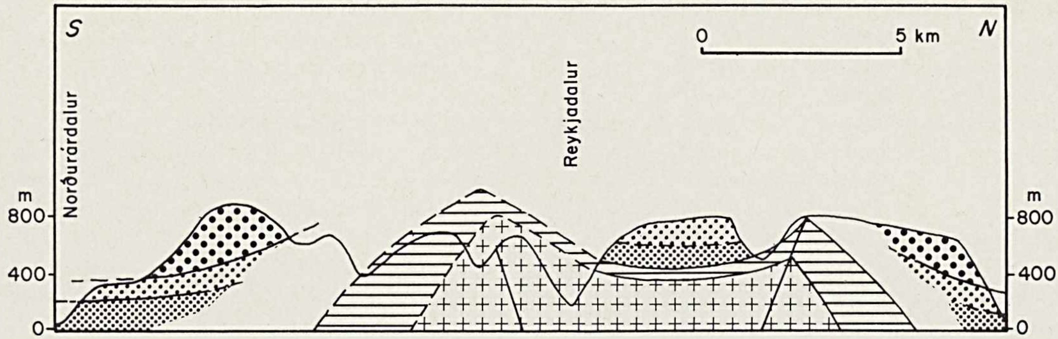

Fig. 13. A section through the Reykjadalur central volcano, western Iceland, showing the metamorphic zones around it. Large dots, chabazite-thomsonite zone; medium dots, analcime zone; small dots, mesolite-scolecite zone; horizontal lines, laumontite zone; crosses, epidote zone. From Jóhannesson 1975.

probably represents a true regional metamorphic facies.

Superimposed on these incipient regional burial metamorphism zones are local hydrothermal aureoles associated with central volcanoes. The inner aureoles may bear chlorite, epidote, calcite, quartz, laumontite, garnet and occasionally pyroxenes and amphiboles. Laumontite and calcite may be prominent in the outer zones. Fig. 13 shows one example of such a thermal dome, in this case the metamorphic zones around the Tertiary Reykjadalur central volcano, western Iceland. Here it is found that the high-grade mineralization is closely related to the intrusive activity in the volcano. True greenschist facies has only been found outcropping at one locality, the Geitafell central volcano in SE-Iceland.

ICELAND AS PART OF THE MID-ATLANTIC RIDGE

Iceland is situated in the North Atlantic where two large physiographic structures meet, the Mid-Atlantic Ridge and the Grennland-Faeroes Ridge (Fig. 14). Because of the elevated topography, high heat flow and discharge of volcanic rocks, Iceland has been defined as an anomaly on the spreading Mid-Atlantic Ridge. Iceland and similar regional highs on the mid-ocean ridges have been proposed as surface manifestations of mantle upwellings and called "hot spots" or "hot mantle plumes" where partial melts from the mantle are discharged through a pipe. The plume models are based on extensive geochemical work, mainly trace element and Sr-

Fig. 14. Map showing the Tertiary to Recent volcanic areas of the North Atlantic and the main physiographic structures. From Brooks and Jakobsson 1974.

isotopic analyses, as well as geophysical evidence and geotectonic ideas.

There is no doubt that Iceland is a pronounced anomaly with regard to the Mid-Atlantic Ridge south and north of Iceland. Extensive dredging on the ridge both north and south of Iceland has shown that MORB tholeiites are dominant on the crest of the ridge. As noted above, there is a clear gradient (Fig. 9) across Iceland with regard to many elements. No less important is the fact that the variety of rock types is much higher in Iceland. The volume of basalt types, which are rare on the abyssal ridge sections, as transitional and alkalic types, is also much higher. No intermediate or acid rocks are known with certanity from the submarine parts of the ridge in the North Atlantic, whereas in Iceland they may consititue some 8—13% of the volume in the upper part of the crust. It is still a matter of dispute whether these relations are indicative or not of the existence of a mantle plume beneath Iceland. It is, however, safe to conclude, that Iceland is a plume or hot spot in the sense that it is one of the major volcanic centers on earth, with a very high discharge rate of volcanic rocks.

In terms of sea-floor spreading the Greenland-Faeroes Ridge can be considered as a trace of the Iceland hot spot since the opening of the North-Atlantic. Petrological research in Iceland, the Faeroe Islands and in the Hebridean province indicates that the bulk of the magma erupted by the hot spot has been similar throughout the period of development of this part of the North-Atlantic.

No final conclusions on the petrogenesis of the rocks of Iceland can be presented here. Many problems of the petrology of Iceland are being actively considered at present. Discussion centers perhaps on three main problems. 1. The origin of the primitive members of the three rock series, and the possible relation between them. 2. The origin of the acid rocks and, 3. the nature of the suggested mantle plume beneath Iceland and its influence on the origin of the igneous rocks of Iceland. Some of these problems are indeed not new in petrology and are relevant outside Iceland.

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