Reviewed research article

The three igneous rock series of Iceland

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Abstract – *Volcanism in Iceland appears to have been confined to volcanic systems throughout its history. During Late-Pleistocene and Holocene times some 41 volcanic systems have been active in Iceland and its insular shelf. An examination of a scrutinized data set of 1378 major element chemical analyses of rocks from the 41 volcanic systems, confirms that three volcanic rock series have developed in Iceland, i.e. a tholeiitic, an alkalic and a transitional alkalic series. The chemical and petrographical characteristics of the three series are discussed. Each volcanic system has only developed basaltic rocks relating to one rock series. A refinement of the nomenclature of the IUGS Subcommission on the Classification of Igneous Rocks (Le Maitre, 2002) is proposed for the basalts, and for the intermediate and silicic rocks of the transitional series. Mixing and hybridization appear to be very common among the intermediate rocks. A special case is the Hekla suite where the more evolved intermediate rocks are considered to be hybrids of transitional mugearite and tholeiitic dacite. The frequency distribution of the analyzed volcanic rocks indicates that 75% are basalts, 14% intermediate rocks and 11% silicic rocks. However, there is a distinct bimodal distribution of compositions in the tholeiitic and transitional alkalic series. The tholeiitic rock series is confined to volcanic systems in the rift zones which delineate the crest of the MAR in Iceland. The alkalic and transitional alkalic systems are confined to the flank zones. The tholeiitic volcanic systems are estimated to be responsible for 80% of the volume of the extruded rocks during the time span under consideration. Alkalic volcanic systems were initiated in some parts of the volcanic zones 2–3 Ma ago. Flank zones producing transitional alkalic rocks may have been active in northeast and southeast Iceland during Late Tertiary.*

INTRODUCTION

Iceland is among the most active volcanic areas on earth. During the last 300 years, over which time records are considered fairly complete, an average of 28–30 volcanic eruptions have occurred per century (Thordarson and Larsen, 2007). The production of volcanic rocks in Iceland has been estimated to be some 87 km^3 (DRE) during the last 1100 years (Thordarson and Larsen, 2007). Approximately 85–90% of the volume of Iceland above sea level consists of igneous rocks, while some 10–15% are consolidated sediments. Due to the shallow erosional level of the volcanic pile, volcanic rocks predominate, less than 0.5% of the surface is made of intrusive and plutonic rocks (cf. Jóhannesson and Saemundsson, 1998a). The geological formations in Iceland have conveniently been divided into four formations (Saemundsson, 1980), Holocene (<0.01 Ma), Late-Pleistocene (0.01–0.78 Ma), Pliocene-Pleistocene (0.78–3.3 Ma) and Tertiary (3.3–16 Ma).

The aim of the present paper is to re-evaluate the major element geochemistry, mineralogy and nomenclature of volcanic rocks in Iceland (Jakobsson, 1972, 1979, 1980) and discuss their characteristics and distribution, especially among the younger geological formations. A general review of the geochemistry of igneous rocks in Iceland is presented by Sigmarsson *et al*. (2008).

THE VOLCANIC ZONES

The plate boundary of the Mid-Atlantic Ridge (MAR) breaks up into a complex series of rift- and transform zones as it crosses the Iceland hotspot from southwest to northeast. Figure 1 shows the overall shape of the active volcanic zones during Late-Pleistocene and Holocene in Iceland and its insular shelf. The volcanic zones are divided into nine sections, i.e. Northern Reykjanes Ridge (NRR), Western Volcanic Zone (WVZ), Hofsjökull Volcanic Zone (HVZ), Eastern Volcanic Zone (EVZ), Northern Volcanic Zone (NVZ), Tjörnes Volcanic Zone (TVZ), Snæfellsnes Volcanic Zone (SVZ), Öræfajökull Volcanic Zone (ÖVZ) and the South Iceland Seismic Zone (SISZ).

The NRR, WVZ, HVZ, EVZ, NVZ are considered to be the main rifting zones. The SVZ, the southern part of the EVZ and the ÖVZ are known as flank (lateral) zones with limited rifting activity (Jakobsson, 1972; Saemundsson, 1978; Steinthórsson *et al.* 1985). Although the HVZ is considered a part of the main rifting zone, it can also be defined as a transform-type zone, and the South Iceland Seismic Zone (Figure 1) as a nascent transform-type zone connecting the WVZ and EVZ. Individual Late Pleistocene eruptions are connected to the SISZ, but volcanic systems have not developed. The Skagi Volcanic Zone (Figure 1), which extends to the north-northwest of the WVZ (Saemundsson, 1974; Sigurdsson *et al.*, 1978), is not included here as it has been inactive since the very beginning of the Late Pleistocene (Everts, 1975).

THE VOLCANIC SYSTEMS

Volcanism in Iceland appears to have been characterized by volcanic systems throughout its geological history (Saemundsson, 1980; Thordarson and Larsen, 2007). These systems have mainly been identified on basis of either the distribution of volcanic and tectonic fissures, i.e. "fissure swarms" (Saemundsson, 1974, 1978; Jóhannesson and Saemundsson, 1998b), or on the distribution of volcanic fissures and the chemical composition of the volcanic products (Jakobsson *et al.*, 1978; Jakobsson, 1979, 1980).

A volcanic system is in this paper defined as a spatial grouping of eruption sites, including feeder dykes and possibly shallow magma chambers, and with certain petrographic and geochemical characteristics (Jakobsson, 1979; 1980). Most of the systems include a swarm of volcanic and tectonic fissures. Volcanic production is generally highest in the central region of each system and many have developed one or even two central volcanoes with associated production of intermediate and silicic rocks (Walker, 1974; Saemundsson, 1980). High-temperature hydrothermal activity is often present in the central part of each system. Each volcanic system is active within a relatively short period of time, though some systems may have been active for more than 1 Ma (Saemundsson, 1980). The silicic and intermediate volcanism is confined to the central volcanoes. These features are indicative of shallow magma reservoirs or intrusive complexes.

The volcanic systems which have been active in Iceland and its insular shelf during Late Pleistocene and Holocene are listed in Table 1. Information on the size and form of the volcanic systems (Figure 1) is considered to be reliable in the southern and western parts of Iceland (EVZ, WVZ, SFZ and ÖFZ), with the exception of ice-covered areas where boundaries have been estimated. In other parts of the volcanic zones the volcanic systems are still somewhat loosely defined. Altogether 28 terrestrial volcanic systems are considered to have been active during the Holocene. Three volcanic systems, Kerlingarfjöll, Esjufjöll and Snæfell (Table 1), which have been active during the Late Pleistocene, have apparently not erupted during the Holocene. The boundaries of the volcanic systems during Late Pleistocene are well known in the flank zones and in parts of the central rift zone, especially in the WVZ, other parts are still imperfectly known. The extent of the Late Pleistocene formation is shown in Figure 1.

On basis of morphology and magnetic anomalies, it has been suggested that there are eight separate submarine volcanic systems on the NRR (Johnson and Jakobsson, 1985). They are structurally and petrologically comparable to the systems on the Reykjanes Peninsula (WVZ) and have probably all been active during the Holocene. Similarly, morphology and magnetic anomalies indicate that there may be sev-

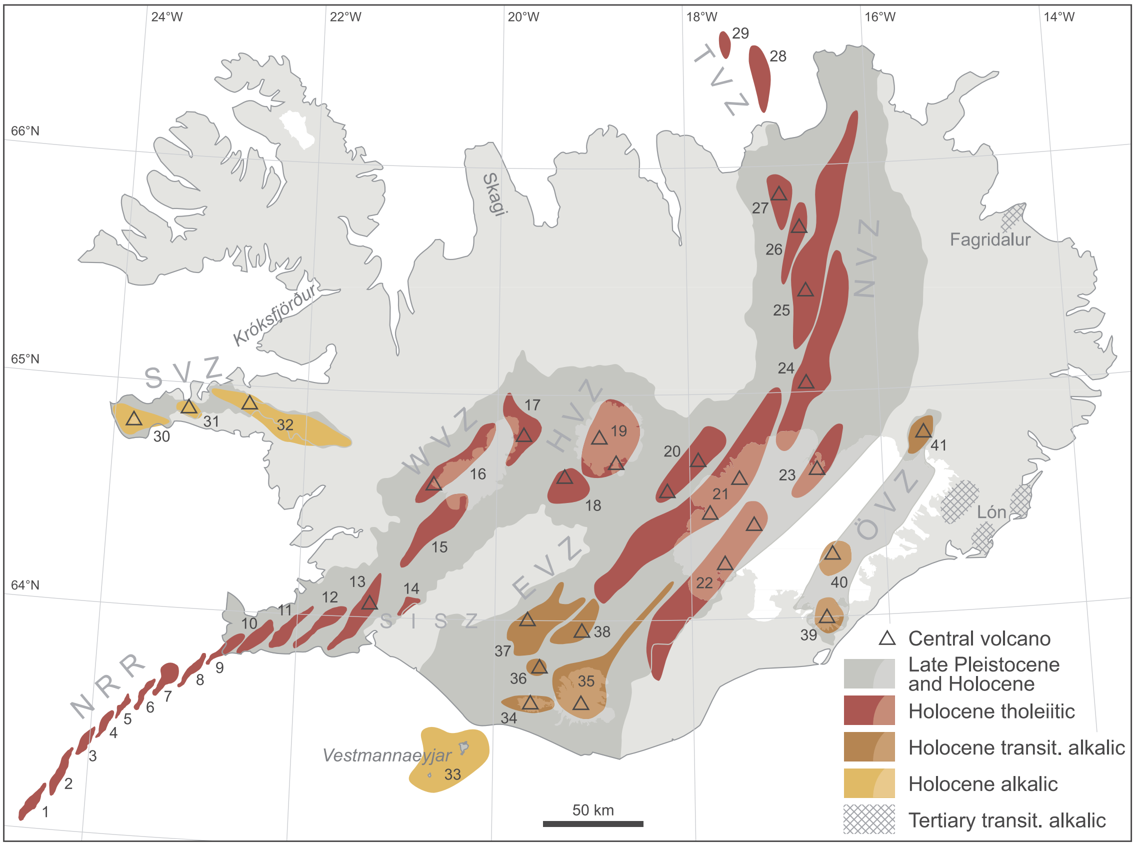

Figure 1. The volcanic zones active in Iceland and its insular shelf during Holocene and Late-Pleistocene. NRR: Northern Reykjanes Ridge, WVZ: Western Volcanic Zone, HVZ: Hofsjökull Volcanic Zone, EVZ: Eastern Volcanic Zone, NVZ: Northern Volcanic Zone, TVZ: Tjörnes Volcanic Zone, SVZ: Snæfellsnes Volcanic Zone, ÖVZ: Öræfajökull Volcanic Zone, and SISZ: South Iceland Seismic Zone. The volcanic systems active during Holocene are shown, based on the distribution of eruption sites and chemical composition of erupted rocks (Jakobsson 1979, 1980), the numbers refer to volcanic systems in Table 1. The sites of central volcanoes are indicated. Distinction is made between tholeiitic, transitional alkalic and alkalic volcanic systems. Known areas with transitional alkalic rocks in the Tertiary succession in Eastern Iceland are indicated by cross hatching. – *Virk gosbelti á Íslandi og landgrunni þess á nútíma og síðjökultíma. NRR: Norður Reykjaneshryggur, WVZ: Vesturgosbelti, HVZ: Hofsjökulsgosbelti, EVZ: Austurgosbelti, NVZ: Norðurgosbelti, TVZ: Tjörnesgosbelti, SVZ: Snæfellsnesgosbelti, ÖVZ: Öræfajökulsgosbelti, og SISZ: Suðurlandsbrotabelti. Sýnd eru virk eldstöðvakerfi á nútíma, byggt á útbreiðslu gosstöðva og samsetningu gosbergs. Tölur vísa til eldstöðvakerfa í töflu 1. Staðsetning megineldstöðva er einnig sýnd. Gerður er greinarmunur á þóleiískum, alkalískum og millibergskerfum. Þá eru merkt á kortið þekkt svæði með millibergi frá tertíer á Austurlandi.*

No.	Name	Central volcano(es)	Comments
	Tholeiitic systems		
1	Steinahóll		Submarine.
2	Gullhóll		Submarine.
3	Stóri-Brandur		Submarine.
4	Eldeyjarbodi		Submarine.
5	Grjóthryggur		Submarine.
6	Langagrunn		Submarine.
7	Geirfuglasker		Submarine, two islets.
8	Eldey		Submarine, one island, one islet.
9	Reykjanes		Partly submarine.
10	Svartsengi		
11	Krísuvík		
12	Brennisteinsfjöll		
13	Hengill	Hengill	Includes Hrómundartindur.
14	Grímsnes		
15	Skjaldbreidur		
16	Prestahnúkur	Prestahnúkur	
17	Hveravellir	Thjófadalir	
18	Kerlingarfjöll	Kerlingarfjöll	Last active >0.01 Ma ago.
19	Hofsjökull	Hofsjökull, Arnarfell	
20	Vonarskard	Vonarskard, Hágöngur	
21	Bárdarbunga	Bárdarbunga, Hamarinn	Includes Veidivötn and Tungnaáröræfi.
22	Grímsvötn	Grímsvötn, Thórdarhyrna	Includes Skaftáröræfi.
23	Kverkfjöll	Kverkfjöll	Includes Fjallgardar.
24	Askja	Askja	Includes Dyngjufjöll.
25	Fremri-Námar	Fremri-Námar	Includes Heidarspordur.
26	Krafla	Krafla	
27	Theistareykir	Theistareykir	
28	Tjörnesgrunn		Submarine, two islands.
29	Skjálfandadjúp		Submarine.
	Alkalic systems		
30	Snæfellsjökull	Snæfellsjökull	
31	Lýsuhyrna	Lýsuhyrna	
32	Ljósufjöll	Ljósufjöll	
33	Vestmannaeyjar		Partly submarine.
	Transitional alkalic systems		
34	Eyjafjallajökull	Eyjafjallajökull	
35	Katla	Mýrdalsjökull	
36	Tindfjallajökull	Tindfjallajökull	
37	Hekla	Hekla	Includes Vatnafjöll.
38	Torfajökull	Torfajökull	Includes Raudfossafjöll.
39	Öræfajökull	Öræfajökull	
40	Esjufjöll	Snæhetta	Last active >0.01 Ma ago?
41	Snæfell	Snæfell	Last active 0.1 Ma ago.

Table 1. Volcanic systems active during Holocene and/or Late-Pleistocene. Based on various sources, mainly Jakobsson *et al.* (1978), Saemundsson (1978), Jakobsson (1979; 1980), Johnson and Jakobsson (1985), Björnsson and Einarsson (1990). Jóhannesson and Saemundsson (1998b), Jakobsson *et al.* (2003), Thordarson and Larsen (2007), and Gudmundsson and Högnadóttir (2007). Compare with Figure 1. – *Virk eldstöðvakerfi á nútíma og síðjökultíma. Byggt á ýmsum heimildum. Berið saman við mynd 1.*

eral submarine volcanic systems on the insular shelf north of Iceland (Jakobsson *et al.*, 2003). Two of these systems (nos. 28 and 29 on Figure 1) are petrologically comparable to the northernmost systems on land, whereas those to the north have only erupted normal MAR type basalts (Schilling *et al.*, 1983).

Available geological field data therefore indicate that volcanic activity during Late Pleistocene and Holocene has been confined to 41 volcanic systems in Iceland and its insular shelf (Table 1 and Figure 1).

PETROLOGICAL DATA

In order to study the chemical variability and distribution of volcanic rocks in Iceland, the authors have made use of 698 high quality whole-rock chemical analyses of eruption units of Holocene and Late Pleistocene age. Of these, 502 are new, unpublished, whole-rock analyses, while 180 have been published previously. The unpublished chemical analyses are mainly from the WVZ, the NRR and the Vestmannaeyjar area of the EVZ (Figure 1), a few analyses from the TFZ have also been included (Figure 1). Additionally, H. Schiellerup and the late E. G. Vilmundardóttir, have supplied 12 unpublished chemical analyses. Petrographic, morphological and field data have been collected from nearly all of the eruption units in question.

To complete this data set, 668 high quality whole-rock chemical analyses have been selected from the publications and dissertations the list of which is available as Electronic supplementary material on the website of the Icelandic Institute of Natural History (http://www.ni.is/english/geology/-research/articles/jokull58). Petrographic and field data exist for approximately half of these eruption units. Only one chemical analysis was selected for each eruption unit except when the chemical variation of the unit exceeded about 20%. Altogether 1378 whole rock chemical analyses are therefore used in the present paper. All the analyses considered in this paper are normalized to 100 wt.%, volatile free, with total Fe as FeO. The above-mentioned 502 unpublished chemical analyses are available as Electronic supplementary material on the website of the Icelandic Institute of Natural History. Only fresh, unoxidized, crystalline rocks or coarse-grained tephras were considered in the present study. Cumulate rocks were excluded and samples collected close to segregation veins were avoided. Where petrographic or geochemical evidence indicates mixing or hybridization the analyses were excluded.

The majority of the chemical analyses are of Holocene eruption units, or 55%. Analyses of Late Pleistocene rocks have been assigned to the active volcanic systems (Figure 1) based on general geological evidence. It is considered likely that the dredge hauls from submerged parts of the volcanic zones are of Holocene age. The sampling coverage on the Northern Reykjanes Ridge is good (63 rock dredge stations; four isles) but less so on the insular shelf north of Iceland (10 rock dredge stations; two isles).

COMPOSITIONAL RANGE

The plots in Figures 2, 3 and 4 are presented to illustrate the compositional range of the volcanic rocks in Iceland. The major elements display greater variability than in any other area of the MAR in the North Atlantic (cf. Schilling *et al.*, 1983; Saunders *et al.*, 1997). Rock compositions range from basalts to rhyolites. The basalts of Iceland are in general characterized by high Ti, compared to normal MAR basalts (MORB), containing up to 4.8 wt.% TiO_2.

The present data set confirms that three volcanic rock series have developed in Iceland during Late-Pleistocene and Holocene, namely a tholeiitic, a mildly alkalic and a transitional alkalic series (Jakobs-

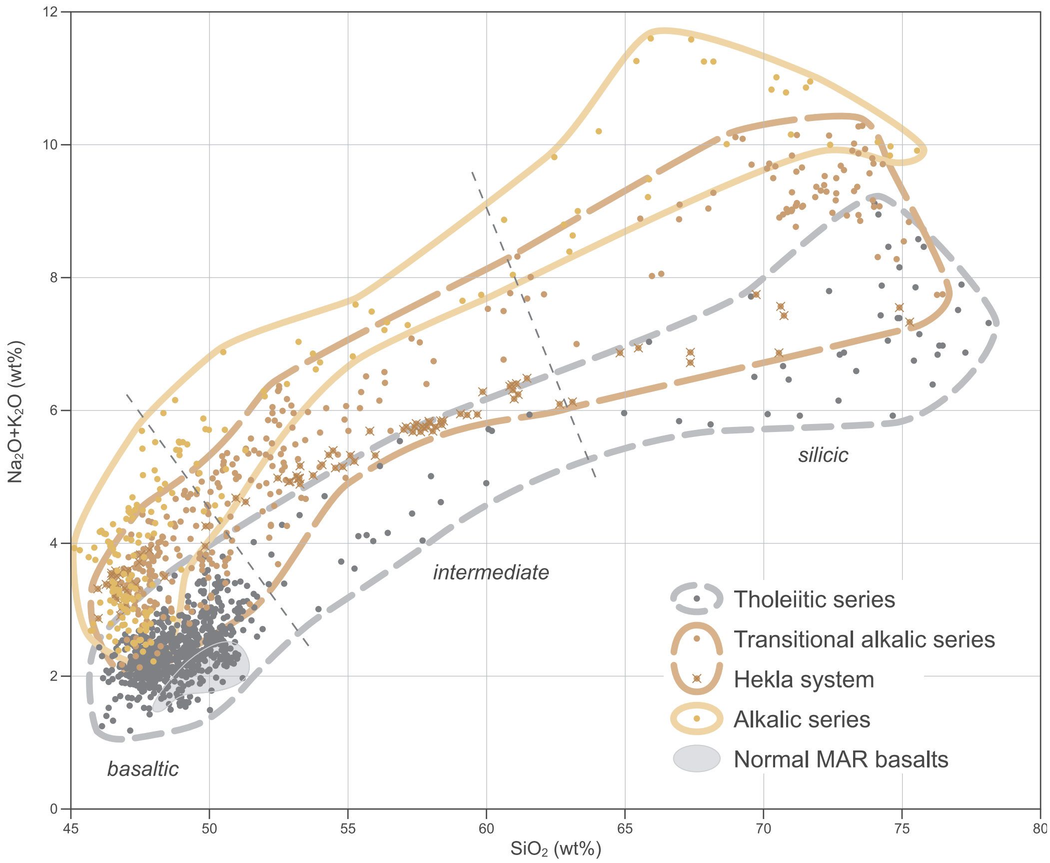

Figure 2. Plot of Na_2O+K_2O versus SiO_2 showing the compositional range of the volcanic rocks in Iceland. Distinction is made between the tholeiitic, transitional alkalic and alkalic series. The rocks of the Hekla volcanic system are marked separately. The approximate location of the division lines between the basaltic, intermediate and silicic rocks are shown. Light shaded area encloses the normal MAR basalts (Schilling *et al.*, 1983). – *Línuritið sýnir* Na_2O+K_2O *sem fall af* SiO_2 *í gosbergi á Íslandi. Greinarmunur er gerður á þóleiísku, alkalísku og millibergröðunum. Gosberg úr Heklu er merkt sérstaklega. Þverlínur skilja að mestu á milli basaltísks, ísúrs og kísilríks bergs. Grátt svæði sýnir samsetningu úthafshryggjarbasalts.*

son, 1972; 1979; 1980). The tholeiitic and the alkalic series are clearly distinguished in regard to the content of SiO_2 and total alkalies (Figure 2). The transitional alkalic series lies between the other two series, although there is an overlap at the basaltic end. The TiO_2 vs K_2O plot (Figure 3) also illustrates the differences between the three series. Figure 4 shows the pronounced Fe-enrichment trend in the Icelandic basalts and the relatively low Ca-content of the intermediate and silicic rocks, as compared with rocks produced at convergent zones. The distinction between the three rock series is reinforced by the frequency distribution pattern of the MgO content (Figure 5).

Much of the overlap between the tholeiitic and the transitional alkalic series in the plots is due to Hekla (no. 37 on Figure 1). While the basaltic to intermedi-

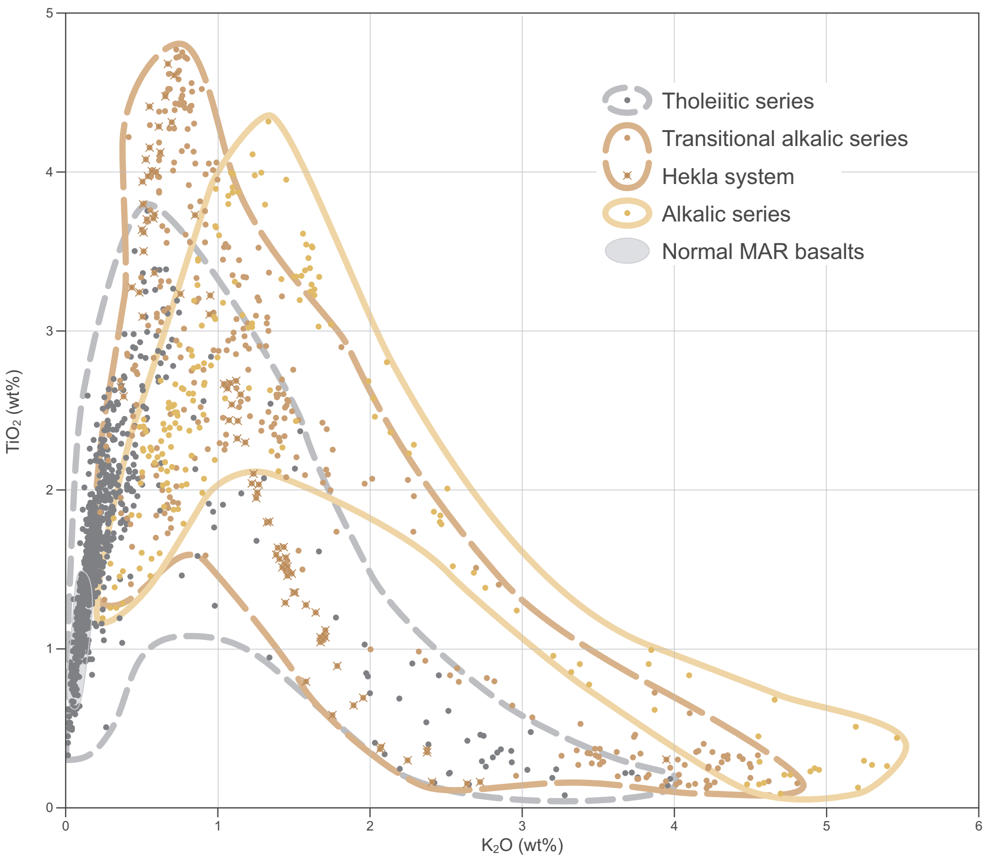

Figure 3. Plot of TiO_2 versus K_2O showing the compositional range of the volcanic rocks. Distinction is made between the tholeiitic, transitional alkalic and alkalic series. The rocks of the Hekla volcanic system are marked separately. Light shaded area encloses the normal MAR basalts. – *Línuritið sýnir TiO_2 sem fall af K_2O í gosbergi á Íslandi. Greinarmunur er gerður á þóleiísku, alkalísku og millibergröðunum. Gosberg úr Heklu er merkt sérstaklega. Grátt svæði sýnir samsetningu úthafshryggjarbasalts.*

ate rocks (46–57 wt.% SiO_2) at Hekla are comparable to the rocks of the transitional alkalic series, the intermediate to silicic rocks (57–75 wt.% SiO_2) clearly belong to the low alkali tholeiitic type (Jónasson, 2007). It has been suggested that icelandites at Hekla are hybrids of "basaltic andesites" and dacites (Sigmarsson *et al.*, 1992a). We conclude that while the basaltic to intermediate (SiO_2 <57 wt.%) rocks of Hekla are transitional alkalic, the intermediate (SiO_2 >57 wt.%) and silicic rocks clearly belong to the tholeiitic series. The few available analyses of silicic rocks from the Esjufjöll volcanic system in the Vatnajökull glacier (no. 40 on Figure 1) also clearly belong to the tholeiitic series, while the basaltic rocks are transitional alkalic. Ultrabasic nodules have been searched for in Iceland, but only mafic cumulates of gabbroic origin have been found (Genshaft and Saltykovsky, 1999).

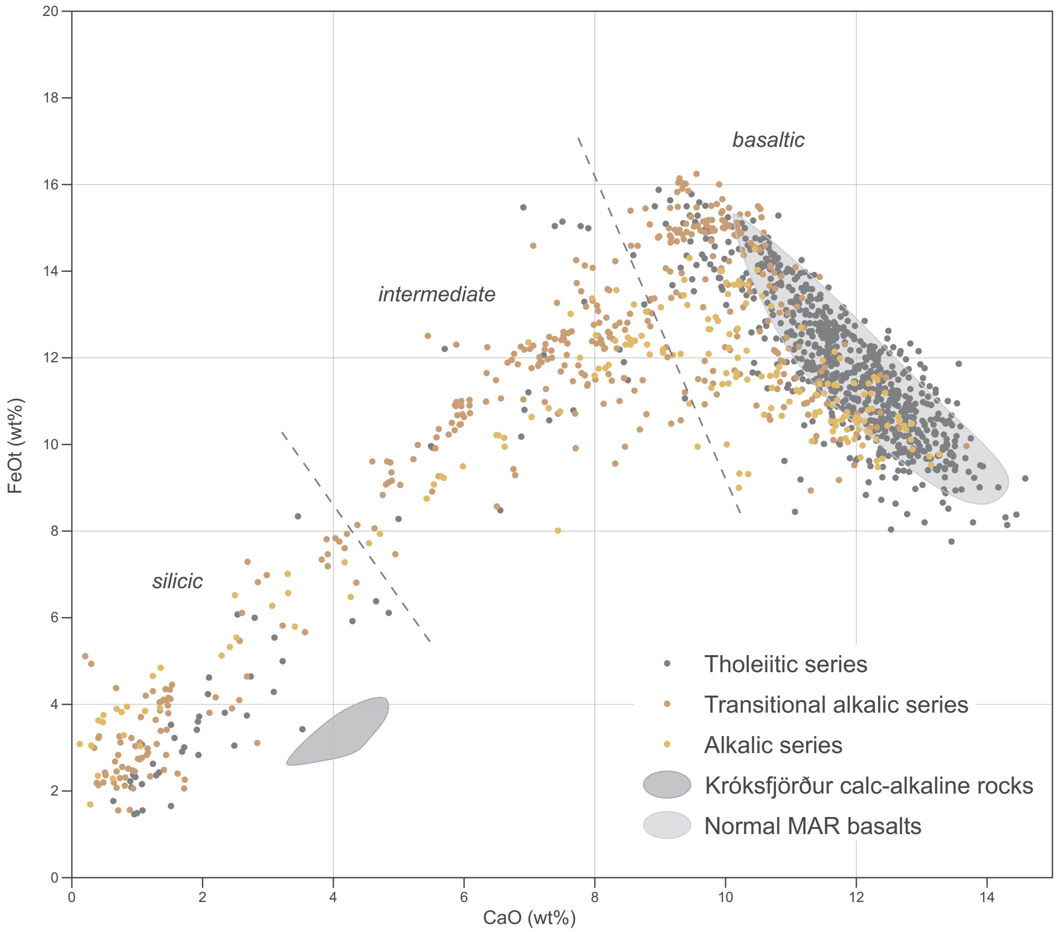

Figure 4. Plot of FeOt versus CaO showing the compositional range of the volcanic rocks in Iceland. Distinction is made between the tholeiitic, transitional alkalic and alkalic series. The rocks of the Hekla volcanic system are marked separately. Dashed lines denote the approximate division between the basaltic, intermediate and silicic rocks. Dark shaded area encloses the calc-alkaline rocks of Króksfjörður; light shaded area encloses the normal MAR basalts. – *Línuritið sýnir FeOt sem fall af CaO í gosbergi á Íslandi. Greinarmunur er gerður á þóleiísku, alkalísku og millibergröðunum. Þverlínur skilja að mestu á milli basaltísks, ísúrs og kísilríks bergs. Einnig er sýnd samsetning úthafshryggjarbasalts og kalkalkalísks bergs úr Króksfirði.*

THE CLASSIFICATION OF VOLCANIC ROCKS IN ICELAND

The IUGS Subcommission on the Classification of Igneous Rocks has recommended classifying volcanic rocks according to the "TAS" diagram (Le Maitre, 2002). While this classification is suitable in most cases it does not differentiate between the different types of basalts. We suggest a classification of the basalts primarily based on their MgO content. For intermediate and silicic rocks we follow the IUGS recommendations with the following exceptions. For the intermediate rocks of the transitional alkalic series we

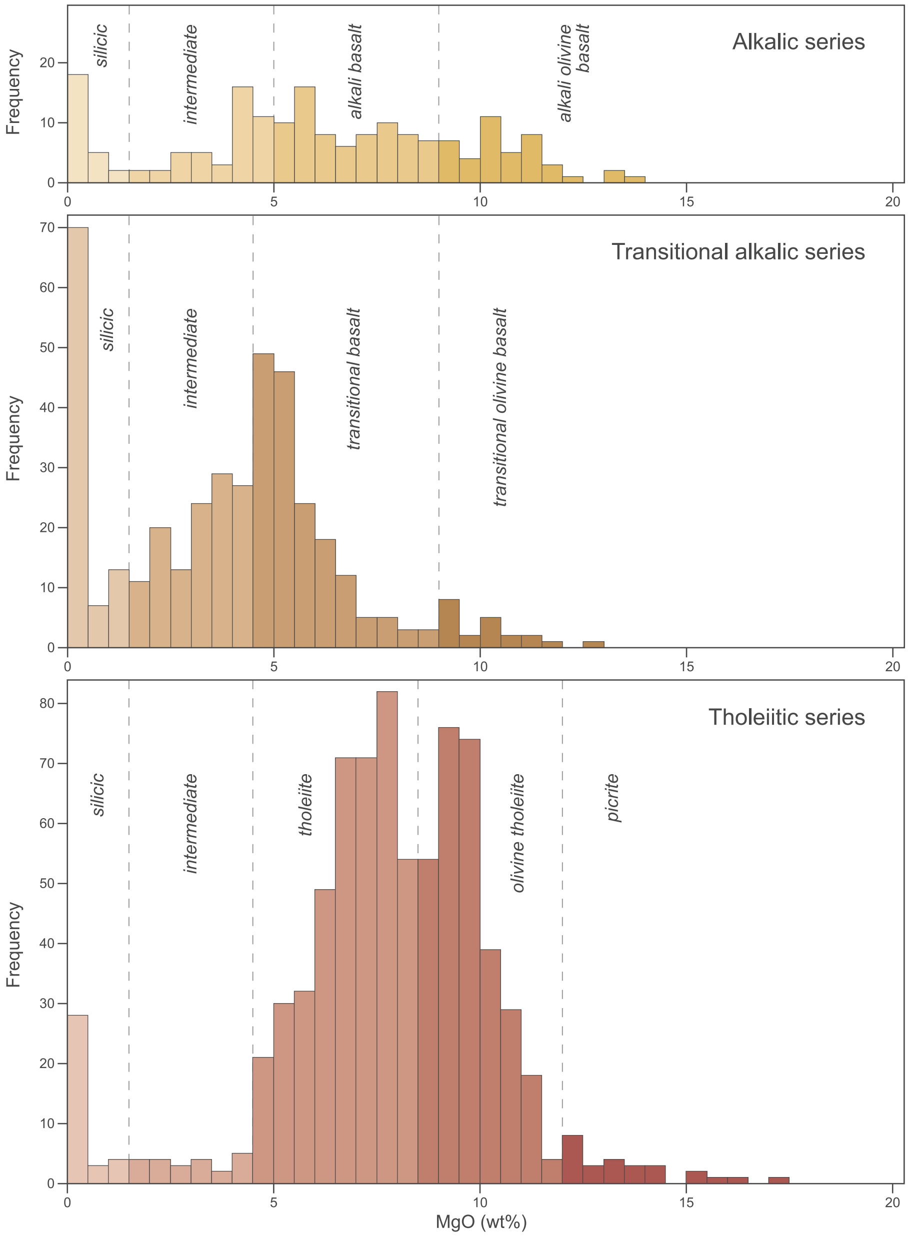

Figure 5. Frequency distribution of the 1378 analyzed rocks of the three rock series with respect to their MgO content. Suggested rock names of the basalts are shown. The approximate location of the division lines between the basaltic, intermediate and silicic rocks are shown. – *Tíðnidreifing bergefnagreininga með tilliti til MgO innihalds. Tillaga að sundurgreiningu basalts í bergröðunum þremur er sýnd. Einnig eru sýnd skil milli basaltísks, ísúrs og kísilríks bergs.*

Table 2. The volcanic rock types which make up the three igneous rock series of Iceland. Distinction is made between basaltic, intermediate and silicic compositions. *Tegundir gosbergs í bergröðunum þremur á Íslandi.*

	Tholeiitic series	**Alkalic series**	**Transitional alkalic series**
basaltic	picrite olivine tholeiite tholeiite	 alkali olivine basalt alkali basalt	 transitional olivine basalt transitional basalt
intermediate	 basaltic icelandite icelandite	hawaiite mugearite benmoreite	transitional hawaiite transitional mugearite transitional benmoreite
silicic	dacite rhyolite	trachyte alkalic rhyolite	transitional trachyte transitional rhyolite

adopt the names recommended for the alkalic series adding the prefix "transitional", even though some of the rocks plot below the division line between alkalic and tholeiitic (subalkalic) compositions. Furthermore, we believe it is appropriate to divide the rhyolites into transitional and alkalic rhyolites and rhyolites, based on alkali-content.

In Figure 5 the frequency distribution within the basaltic rocks with regard to the MgO content is shown. Although it has been stated that rock compositions are continuous, i.e. with no natural boundaries (Coombs, 1963), the MgO distribution indicates the presence of rock populations. It is suggested that the basaltic rocks of the tholeiitic series are divided into picrite, olivine tholeiite and tholeiite, with the basaltic-intermediate boundary at 4.5 wt.% MgO, which largely coincides with the 52 wt.% SiO_2 boundary (cf. Le Maitre, 2002). This is a similar classification as originally suggested by Carmichael (1964) and has since been adopted with modifications by several authors (cf. Jakobsson, 1979). Picrites have been found in eight Holocene and Late Pleistocene tholeiitic systems. Some of these eruption units may have cumulated olivine but they are included in this study since petrographic and field data indicate that picrites with between 14 and 16 wt.%, and possibly up to 18 wt.% MgO may represent true liquid compositions, deriving from the Upper Mantle (cf. Maaloe and Jakobsson, 1980; Sigurdsson, 1994).

The basaltic rocks of the alkalic series are divided into alkali olivine basalt and alkali basalt. This division of the alkalic series is supported by extensive data from Vestmannaeyjar (Jakobsson, 1979; Jakobsson and Sigurdsson, unpubl. data) which show a clear-cut division into two types of alkalic basalts and hawaiite, the boundary to the hawaiite being set at 5 wt.% MgO (Table 2; Figure 5). In regard to the basaltic compositions of the transitional alkalic series, two types seem to emerge, transitional olivine basalt and transitional basalt. The name ankaramite has commonly been used in Iceland for the high magnesia rocks of the transitional alkalic series. However, it has been suggested that the name ankaramite should not be used (Le Maitre, 2002). As a matter of fact, the analyzed ankaramites are probably in many cases cumulative, as for example in the Eyjafjallajökull system (no. 34 on Figure 1) (Wiese, 1993).

As has been pointed out by several authors (cf. Jakobsson 1972; Sigmarsson *et al.*, 1992b), there is a gradient in the chemistry of the basaltic rocks along the SVZ, the basalts becoming less alkalic to the east. The easternmost basalt lavas in the Ljósufjöll system (no. 32 on Figure 1) are not nepheline normative and have been termed transitional basalts (Sigmarsson *et al.*, 1992b). However, various chemical plots show that these lavas are an intrinsic part of the alkalic Ljósufjöll suite. There is a comparable case in the Vestmannaeyjar system in the EVZ (no. 33 on Figure 1), where some of the Surtsey lavas of 1963–1967 do not show nepheline in the norm; never the same coarse-grained rock varieties carry modal nepheline and augite zoned to aegerine-augite, reflecting their alkalic nature (Jakobsson, 1979). We therefore propose that these basalts are termed alkalic basalts.

Regarding the classification and nomenclature of intermediate rocks of the tholeiitic series, the suggestions of Carmichael (1964) have been adopted. Thus, the terms basaltic icelandite and icelandite are used instead of basaltic andesite and andesite, reflecting their high Fe-content and low Ca- and Al-contents (Figure 4), as compared to calc-alkaline andesites. The boundaries recommended by Le Maitre (2002) are retained, even though boundaries with a negative slope would be more natural.

The division lines and names of the intermediate rocks of the alkalic series are in accordance with Le Maitre (2002). We suggest, however, that hawaiite should be regarded as the most basaltic member of the intermediate rocks (Jakobsson, 1979), rather than a type of basaltic rock. The nomenclature of the intermediate rocks of the transitional alkalic series is problematic, because in many suites, the rocks straddle the boundary between the tholeiitic (subalkalic) and alkalic fields. Since most of the rocks plot above this boundary, we suggest a modification of the proposals of Jakobsson (1979), using the same terms as in the alkalic series, but adding the prefix “transitional”. Thus, the intermediate rocks of the transitional alkalic series are termed transitional hawaiite, transitional mugearite, and transitional benmoreite.

The classification and nomenclature of the silicic rocks follows the recommendation of Le Maitre (2002). Additionally, the line separating dacites and trachytes is extended into the rhyolite field, separating rhyolites of the tholeiitic series from transitional and alkalic rhyolites of the transitional alkalic and alkalic series. Thus, the silicic rocks of the tholeiitic series are dacites and rhyolites, while silicic rocks in the transitional alkalic series are transitional trachytes and transitional rhyolites. Trachytes and alkalic rhyolites constitute the silicic rocks of the alkalic series.

Some of the trachytes and rhyolites of the transitional alkalic and alkalic series are peralkaline, having an agpaitic index higher than one. The majority of these are comenditic, even though pantelleritic compositions have been reported from Pleistocene formations at Torfajökull (no. 38 on Figure 1) (McGarvie, 1984; McGarvie *et al.*, 2006). Thus, some of the trachytes can be termed comenditic trachytes and some of the alkalic rhyolites can be termed comenditic rhyolites or comendites. However, since the analyses cluster around the boundary between peralkaline and metaluminous, we feel that it is inappropriate to separate them on this basis.

MIXING AND HYBRIDIZATION

Evidence of shallow level mixing or hybridization is commonly observed in the intermediate rocks in all three series. This ranges from visible macroscopic evidence in mixed rocks, such as banding and inclusions, to microscopic evidence in hybrid rocks, such as mixed mineralogy, disequilibrium phenocrysts, dissolution textures, and zoning. In some cases, geochemical evidence in the form of mixing lines connecting end-member compositions indicates hybridization (e.g. Prestvik, 1980; Sigurdsson and Sparks, 1981; Blake, 1984; McGarvie *et al.*, 1990; Calderone *et al.*, 1990; Jónasson, 1994; Gunnarsson *et al.*, 1998; Hards *et al.*, 2000). The end-member compositions are usually evolved basalts and silicic rocks, respectively.

Some intermediate rocks, however, appear to be “true” non-mixed liquid compositions. This is the case, for example, in the hawaiite-mugearite Eldfell lava in the alkalic Vestmannaeyjar system (no. 33 on Figure 1), where there are no indications of mixing or hybridization (Jakobsson *et al.*, 1973; Furman *et al.*, 1991). At Hekla (no. 37 on Figure 1), transitional hawaiites and mugearites are related to transitional basalts in the surrounding area, while icelandites are hybrids of transitional mugearites and dacites (Sigmarsson *et al.*, 1992a). At Heidarspordur in the Fremri-Námar system (no. 25 on Figure 1), icelandites are interpreted as high temperature relatives of dacites, while basaltic icelandites in the same area are hybrids (Jónasson, 2005).

The present authors suspect that a significant proportion of the intermediate rocks in Iceland are affected by shallow level mixing, but careful petrographic and geochemical studies are needed to clarify this in each case.

THE THOLEIITIC ROCK SERIES

The tholeiitic series is generally characterized by relatively high contents of Fe and Ti and low contents of Al. The amount of normative hypersthene in the basaltic rocks is mainly between 10 and 20%, and they all plot below the Hawaiian division line (Macdonald and Katsura, 1964).

The basaltic rocks of this series comprise picrite, olivine tholeiite and tholeiite (Table 2, Figure 5). The picrites are defined as containing 12–18 wt.% MgO (Figure 5) and the SiO_2 content is always >45 wt.%. This fits the classification of LeMaitre (2002) very well. As expected, two species of monoclinic pyroxenes, augite and pigeonite, are present in the groundmass of these rocks, although pigeonites have not always been identified with certainty because of their small size (Grönvold, 1972; Nicholson, 1990; Walker, 1992; Geirsson, 1993; Martin and Sigmarsson, 2007). Chromite and olivine (with up to Fo 92) are always present as phenocrysts in the picrites and occasionally in the olivine tholeiites (Gee *et al.*, 1998; Sigurdsson *et al.*, 2000). Micro-glomerocrysts of olivine and plagioclase are fairly common in picrites and olivine tholeiites. Glomerocrysts of olivine, augite and plagioclase, which are at, or close to textural equilibrium with the groundmass, are very common in the tholeiites, for example in the Reykjanes Peninsula (Jakobsson *et al.*, 1978), indicating crystallization or equilibration of the magma at low-pressure, cotectic conditions. Accumulation of olivine phenocrysts is common in picrites, and fairly common in olivine tholeiites and tholeiites. The abundance of plagioclase macrophenocrysts (bytownite or anorthite) is very variable, generally low in the WVZ and NVZ, but common in some basalt lavas in the EVZ, especially in the Bárdarbunga system (Hansen and Grönvold, 2000; Halldórsson, 2007). Macrophenocrysts of augite are rare.

The silicic rocks of the tholeiitic series are mostly rhyolites together with a few dacites. They tend to be glassy, or very fine-grained, and are usually phenocryst-poor and often nearly aphyric. Phenocrysts of plagioclase (andesine to oligoclase) are most common. Other phenocryst phases are iron-rich augite, orthopyroxene, pigeonite, fayalite and magnetite, with apatite and zircon as frequent accessory phases. The rhyolites plot close to the thermal minimum in the "granite" system (Ab-Or-Qz), while the dacites plot within the feldspar field. They are relatively Fe-rich and Ca-poor, indicating low water pressure in the source (Jónasson, 2007; Thy *et al.*, 1990). The rare intermediate rocks of the tholeiitic series are basaltic icelandites and icelandites. Petrographic evidence for mixing and hybridization is very common. Phenocrysts include plagioclase, augite and magnetite.

Although each rock series has certain characteristics, the compositional variation within each series is perceptible as is evident from Figures 2, 3 and 4. This is because trends are often slightly different from one volcanic system to another. Figure 6A shows the trends, with regard to MgO and TiO_2, for two tholeiitic volcanic systems from different tectonic environments chosen to represent the tholeiitic rock series, the Grímsvötn system (Jakobsson, 1979; Sigmarsson *et al.*, 2000; Jónasson, 2007) in the EVZ in central Iceland (no. 22 on Figure 1), and the Krafla system (Nicholson, 1990; Nicholson *et al.*, 1991; Jónasson, 1994) in the NVZ (no. 26 on Figure1).

THE ALKALIC ROCK SERIES

The alkalic series is mildly alkalic with a sodic character, although the rocks of the volcanic systems in the SVZ are characterized by higher K content than those of Vestmannaeyjar in the EVZ. The basaltic rocks comprise alkali olivine basalts and alkali basalts (Table 2). They are nearly always nepheline normative and most of them plot above the Hawaiian division line. Nepheline has occasonally been identi-

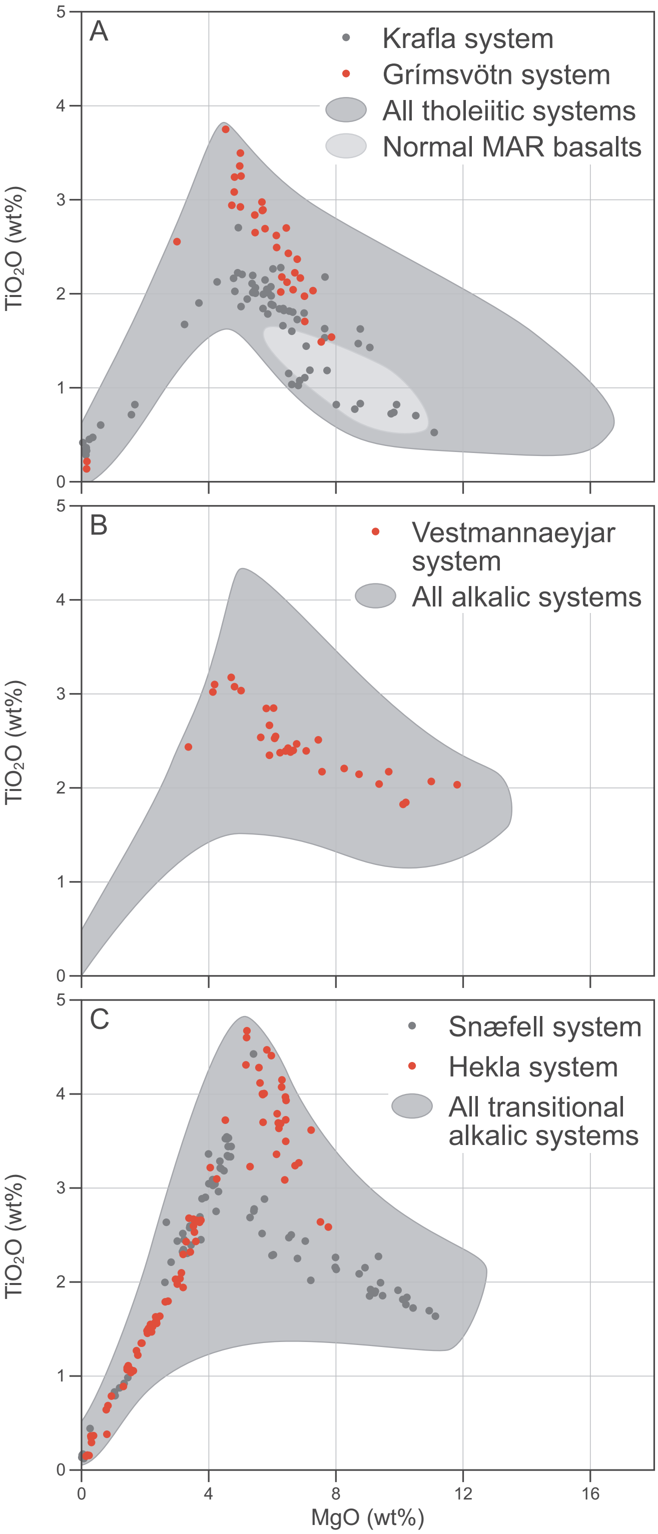

Figure 6. Plot of TiO_2 versus MgO showing the compositional range of selected volcanic systems of the three rock series. 6A: The tholeiitic series, with the Krafla and Grímsvötn rock suites highlighted. Light shaded area encloses the normal MAR basalts. 6B: The alkalic series, with the Vestmannaeyjar rock suite highlighted. 6C: The transitional alkalic series, with the Hekla and Snæfell rock suites highlighted. – *Línuritin sýna TiO_2 sem fall af MgO í völdum eldstöðvakerfum úr bergröðunum þremur. 6A: Krafla og Grímsvötn í þóleiísku bergröðinni. Ljósgrátt svæði sýnir samsetningu úthafshryggjarbasalts. 6B: Vestmannaeyjar í alkalísku bergröðinni. 6C: Hekla og Snæfell í millibergröðinni.*

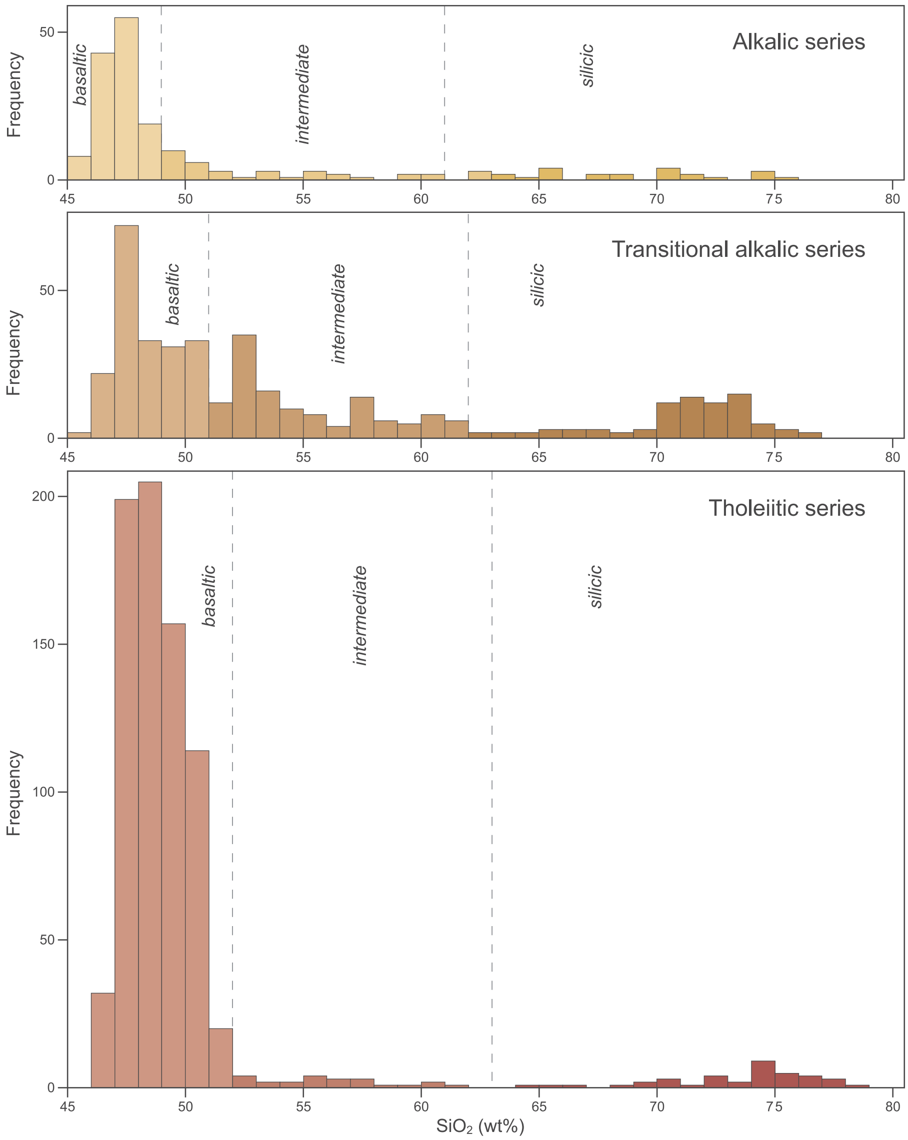

Figure 7. Frequency distribution of the 1378 analyzed rocks of the three rock series with respect to their SiO_2 content. The approximate location of the division lines between the basaltic, intermediate and silicic rocks are shown. *–Tíðnidreifing bergefnagreininga í bergröðunum þremur með tilliti til innihalds SiO_2. Sýnd eru skil milli basaltísks, ísúrs og kísilríks bergs.*

fied in residual pockets (Jakobsson, 1979), and alkali feldspar forms an interstitial phase in coarse-grained varieties (Sigurdsson, 1970). The only groundmass pyroxene is augite which often is titaniferous. In coarse-grained rocks the augite is commonly zoned to aegerine-augite (Jakobsson, 1979). The basaltic rocks are quite variable in their petrography, especially in the Snæfellsnes Peninsula where cumulation of macro-phenocrysts of olivine, plagioclase and augite has been observed (Hardarson, 1993).

The silicic rocks of the alkalic series are trachytes and alkalic rhyolites. Some of them can be classified as peralkaline and comenditic. They are usually glassy or fine-grained with phenocrysts of anorthoclase, oligoclase or sanidine. Other reported phenocryst phases are augite, hedenbergite, ilmenite, magnetite, amphibole and quartz. The main difference between the alkalic and the tholeiitic silicic rocks is in the alkali contents. Furthermore, the alkalic silicic rocks are even poorer in Ca than the tholeiitic rocks. The trachytes of the alkalic series have the highest alkali contents seen in whole-rock analyses from Iceland. They plot close to the alkali feldspar temperature minimum in the "granite" system (Jónasson, 2007).

The intermediate rocks of the alkalic series are hawaiites, mugearites and benmoreites. They are generally very fine-grained with trachytic texture, containing phenocrysts of plagioclase, olivine, clinopyroxene and oxides. Mixing and hybridization have been observed in the intermediate rocks of the SVZ (e.g. Flude *et al.*, 2007).

The trend of the Vestmannaeyjar system (no. 33 on Figure 1) with regard to MgO and TiO_2 is shown in Figure 6B as compared to the alkalic volcanic rocks in the Snæfellsnes Volcanic Zone (Jakobsson, 1979; Hardarson, 1993; Sigurdsson, 1970).

THE TRANSITIONAL ROCK SERIES

The transitional alkalic series is a hypersthene normative alkalic series. The basalts are characterized by a high content of Fe and Ti and they generally plot above the Hawaiian division line like the basalts of the alkalic series. We distinguish two types of basalts in this series, transitional olivine basalt and transitional basalt (Figure 5), which both are usually fine-grained. Low calcium pyroxenes have not been reported from the groundmass of the transitional basalts (Gunnarsson, 1987; Wiese, 1993; Hards, 1995; Hards *et al.*, 2000), which reflects the alkaline character of this series. The rocks are generally poor in macrophenocrysts with the exception of the Eyjafjöll system where cumulate rocks with macrophenocrysts of augite are abundant (Steinthórsson, 1964; Wiese, 1993). As in the tholeiites, micro-glomerocrysts of olivine, augite and plagioclase, which are close to tectural equilibrium with the groundmass, are common (Jakobsson, 1979; Wiese, 1993; Hards, 1995).

The silicic rocks of the transitional alkalic series are mainly transitional rhyolites together with rare transitional trachytes. Some of the transitional rhyolites can be classified as peralkaline comendites. They are generally very fine-grained or glassy. Phenocrysts are mainly plagioclase (oligoclase to andesine) or anorthoclase. Other phenocrysts include augite, hedenbergite, magnetite, ilmenite, hornblende (edenitic-ferroedenitic), biotite and fayalite. Apatite, pyrrhotite and zircon are common accessory phases.

The intermediate rocks of the transitional alkalic series are transitional hawaiites, transitional mugearites and transitional benmoreites. Indications of mixing in these rocks are relatively common. These rocks are rare, compared with the silicic and basaltic rocks, except at Hekla, which has produced abundant transitional mugearite and mixed icelandites.

In Figure 6C are shown the trends for two volcanic systems chosen to represent this series, Hekla in the EVZ (Jakobsson, 1979; Gunnarsson, 1987; Sigmarsson *et al.*, 1992a), and the Late Pleistocene Snæfell in the ÖVZ (no. 41 on Figure 1) (Hards, 1995; Hards *et al.*, 2000).

FREQUENCY DISTRIBUTION OF ROCK TYPES

Published estimates of the relative abundance of igneous rocks in Iceland vary significantly. Various estimates have been published based on detailed geological mapping of localized sections of the Tertiary rock series (e.g. Walker 1966) and of individual central volcanoes which give very high numbers for the silicic rocks (up to 28%), which probably are only representative for certain central volcanoes and not for the volcanic pile as a whole. The production of volcanic rocks during the last 1100 years has been calculated by Thordarson and Larsen (2007), who estimate that basaltic rocks account for 79% of the volume, intermediate rocks 16% and silicic rocks 5%. The high number for the intermediate rocks is mainly due to the high production of these rocks in the Hekla central volcano.

For comparison the frequency distribution of the 1378 chemical analyses of Late Pleistocene and Holocene rocks used in this paper is shown in Figure 7. Using the suggested boundaries, 75% of the analyses are basalts, 14% intermediate rocks and 11% silicic rocks, which is fairly close to the above-mentioned calculation of Thordarson and Larsen (2007) for the last 1100 years. Figure 7 indicates a distinct bimodal distribution of compositions within the tholeiitic and transitional alkalic rock series (Jónasson, 2007; Gunnarsson *et al.*, 1998), which is not apparent in the alkalic series. The bimodal character of individual rock suites within all three series has been noted by several workers, for example in Kerlingarfjöll (Grönvold, 1972); Krafla (Jónasson, 1994); Katla (Lacasse *et al.*, 2007) Snæfell central volcano (Hards *et al.*, 2000); and in Ljósufjöll (Flude *et al.*, 2007). For location of these volcanic systems the reader is referred to Figure 1.

The tholeiitic volcanic systems of the main rift zones have produced most of the erupted material; in our estimate (unpubl. data) they account for about 80% of the volume of extruded rocks during Late Pleistocene and Holocene in Iceland. The alkalic systems account for 8% and the transitional alkalic systems for some 12% of the extruded rocks. It should be noted that the productivity of the volcanic systems has been very variable during the above-mentioned time period, probably due to differences in the stage of maturity of each system (Jakobsson, 1980).

REGIONAL DISTRIBUTION

The tholeiitic series in Iceland is confined to volcanic systems in the rift zones (Table 1) which delineate the crest of the MAR during Holocene and Late-Pleistocene (Figure 1). The alkalic and transitional alkalic series are confined to volcanic systems in the flank zones. An important conclusion of the present survey is that during the time span under consideration, each volcanic system has without exception only developed basaltic rocks of one rock series. The evolved rocks belong to the same rock series as the respective basalts, with two exceptions, Hekla (no. 37 on Figure 1) and Esjufjöll (no. 40 on Figure 1). As discussed above, this is interpreted as being due to mixing or hybridization of basaltic magma in these systems with silicic magma from the tholeiitic series.

The present alkalic flank zones were only established recently. In the central part of SVZ (Figure 1), rocks apparently belonging to the transitional alkalic series were produced from about 2.5 to 0.7 Ma ago (Sigurdsson, 1970). During Late Pleistocene and Holocene alkalic volcanism has charcterized the three volcanic systems in the SVZ (Sigurdsson, 1970; Hardarson, 1993). A flank zone also began to develop in a southwest extension of the tholeiitic EVZ (Figure 1), more than 2 Ma ago (Sigurdsson, 1970; Kristjánsson *et al.*, 1998). It is suggested that the Late-Pleistocene transitional alkalic Öræfajökull system (no. 39 on Figure 1) overlies an earlier tholeitic system which possibly was active in Early Pleistocene (c.f. Prestvik, 1985; Helgason and Duncan, 2001).

The basalts of the Tertiary series in Iceland (about 16–3.3 Ma) are generally remarkably homogeneous in composition (Hardarson and Fitton, 1997). Volcanism was mostly confined to an axial rift zone and in western and northern Iceland only rocks belonging to the tholeiitic series have been observed in the Tertiary series. The Skagi Volcanic Zone, which is to the north-northeast of the WVZ (Figure 1), was mainly active 2.5–1 Ma ago. Initially this small volcanic zone produced tholeiitic rocks, but towards the end rocks approaching transitional basalt compositions were erupted (Everts, 1975; Sigurdsson *et al.*, 1978).

The Tertiary series in eastern Iceland is also dominated by tholeiitic rocks. However, the basalt lavas directly overlying the Fagridalur central volcano in northeast Iceland (Figure 1) show transitional alkalic characteristics and are thought to have formed close to a transform zone 13–14 Ma ago (Geirsson, 1993). In the Lón district in southeast Iceland (Figure 1), both extrusive and intrusive transitional alkalic rocks formed about 5–7 Ma ago (Torfason, 1979; Mattson *et al*., 1986; Furman *et al*., 1992; Jakobsson and Fridleifsson, 1990). It therefore appears likely that a volcanic flank zone was active during the late Tertiary in the Lón district.

Lacasse and Garbe-Schönberg (2001) linked a number of silicic tephra layers in marine sediments from the North-Atlantic and Arctic oceanic beds to alkalic off rift (flank zone) volcanism in Iceland. Datings of these tephra layers indicate three distinct eruption episodes at 5.3–4.6, 3.6–3.5, and 1.8–0 Ma. It appears plausible that the older marine tephras may have their origin in the postulated late Tertiary volcanic flank zone mentioned above. The ages of the youngest tephra layers coincide with the above-mentioned age span in the SVZ, EVZ in south Iceland, and in the ÖVZ.

A few calc-alkaline dacites have been described (Figure 4), belonging to the Tertiary Króksfjördur central volcano in NW Iceland (Figure 1) (Jónasson *et al*., 1992). These dacites constitute a minor part of an otherwise tholeiitic volcano. We regard this as an anomalous occurrence, not warranting the definition of a new rock series for Iceland.

PETROGENETIC CONSTRAINTS

The bimodal character of most volcanic systems may indicate a dual petrogenetic mechanism: A primary mantle-derived basaltic system, sometimes extending into intermediate compositions, and a secondary crust-derived silicic system, deriving heat and starting materials from the basaltic system. Mixing and hybridization is responsible for generating a large part of the intermediate rocks.

In a recent review of the origin of Icelandic basalts, Sigmarsson and Steinthórsson (2007) discuss the effects of variable proportions of melts from at least three different mantle components, a depleted upper mantle source, enriched mantle plume, and recycled oceanic crust. Crustal contamination may be important in the more evolved basalts.

The crustal thickness in Iceland varies from less than 20 km in the southwestern part of the WVZ and the northern end of the NVZ to about 40 km in eastern central Iceland (Darbyshire *et al*., 2000). It is noteworthy that there is no apparent correlation between the distribution of the rock series and the crustal thickness. Each volcanic system has, during Late-Pleistocene and Holocene times, produced basaltic rocks belonging to only one series, often within narrow compositional limits. This may indicate that the systems have roots deep in the crust or possibly in the upper mantle (Jakobsson, 1980).

In a recent review of the petrogenesis of silicic rocks (Jónasson, 2007), the importance of near-solidus differentiation processes was discussed, suggesting that silicic magmas originate from intrusive complexes beneath central volcanoes, rather than long-lived magma chambers. The source material may be cooling basaltic or gabbroic intrusions, heated crustal rocks or a combination of both. Similar concepts have recently been proposed for the origin of silicic rocks at Torfajökull (Gunnarsson *et al*., 1998; Martin and Sigmarsson, 2007), Katla (Lacasse *et al*., 2007) and Ljósufjöll (Flude *et al*., 2007). On a different note, Martin and Sigmarsson (2007) suggest that silicic rocks of Ljósufjöll and Snæfellsjökull formed by fractional crystallization. Similarly, Selbekk and Trönnes (2007) interpret extreme end member mineral compositions of the tephra from the Plinian eruption of Öræfajökull in 1362 AD as indicating protracted fractional crystallization.

COMPARISON WITH OTHER IGNEOUS PROVINCES

Oceanic basalts can be divided into Mid Ocean Ridge Basalts (MORB) and Ocean Island Basalts (OIB). MORBs are generated at mid oceanic ridges and are tholeiitic. OIBs are mostly alkaline, but when they are erupted on or near ocean-ridges (such as on Iceland and the Galapagos Islands) or on especially robust plumes (as in Hawaii) they can also be tholeiitic (Hofmann, 2003). Being a mid-ocean ridge overlying a hotspot, basalts from Iceland could be both MORB-like and OIB-like. Most of the basaltic volcanism in Iceland is OIB-like, though MORB-like basalts have formed. Olivine tholeiites and picrites of the Theistareykir system (no. 27 on Figure 1) and Krafla system (no. 26 on Figure 1) in the NVZ for example are very similar in composition to the rocks of the "normal segments" of the MAR (Schilling *et al.*, 1983; Maclennan *et al.*, 2001).

Our survey comprises what Schilling *et al.* (1983) define as a plume segment (Iceland) and transitional ridge segment (Iceland shelf). For comparative purposes, the narrow compositional range of two normal MAR segments to the south and north of Iceland (Figure 1), the Reykjanes Ridge at 54°N to 61°N and the Kolbeinsey Ridge at 66°N to 70°N, are shown in Figures 2, 3, 4 and 6.

Alkali basalts similar to the basalts of the Vestmannaeyjar system have been found at 45°N on the Mid-Atlantic Ridge (Aumento, 1968), and the basalts of the Bald Mountain at 45°N have similar chemistry to those of Hekla (Aumento and Loncarevic, 1969). Transitional basalts comparable to those in Iceland are found on many oceanic islands. On the Galapagos Islands they have been termed ferrobasalts (McBirney, 1993). Similarly, the Easter Island basalts are close in composition to the Katla basalts (Baker *et al.*, 1974).

Iceland is part of the North Atlantic Igneous Province, which extends from the British Isles to Baffin Island and has been active since 62 Ma ago (Saunders *et al.*, 1997). The consanguinity of the volcanic rocks of Iceland and the British Tertiary Igneous Province has been observed by various authors (e.g. Noe-Nygaard, 1966; Jakobsson, 1980; Saunders *et al.*, 1997). The major element chemistry of the Vestmannaeyjar alkali basalts is for instance nearly identical to the alkali olivine basalt type on Mull, and the Grímsvötn and Bárdarbunga tholeiites almost identical to the tholeiitic type (Thompson *et al.*, 1972; Saunders *et al.*, 1997). Furthermore, the tholeiites of the Reykjanes Peninsula are similar to the low-alkali, high calcium type of Skye (Thompson *et al.*, 1972).

CONCLUSIONS

A survey of available major element chemical analyses of fresh volcanic rocks of Holocene and Late-Pleistocene age, provides convincing evidence for the existence of three igneous rock series in Iceland, i.e. a tholeiitic series, an alkalic series and a transitional alkalic series.

A refinement of the recommendations by the IUGS Subcommission on the Classification of Igneous Rocks (Le Maitre, 2002) is suggested regarding the Icelandic basalts in all series, and the intermediate and silicic rocks of the transitional series. The tholeiitic series is thus made up of picrite, olivine tholeiite, tholeiite, basaltic icelandite, icelandite, dacite and rhyolite. The alkalic series is made up of alkali olivine basalt, alkali basalt, hawaiite, mugearite, benmoreite, trachyte and alkali rhyolite. The transitional alkalic series is made up of transitional olivine basalt, transitional basalt, transitional hawaiite, transitional mugearite, transitional benmoreite, transitional trachyte and transitional rhyolite.

A significant proportion of the intermediate rocks in all three series may be the result of mixing or hybridization, although some intermediate rocks appear to be non-mixed liquid compositions. The Hekla suite presents a special case, where the transitional mugearites are related to the transitional basalts in the surrounding area, while icelandites are hybrids of transitional mugearites and tholeiitic dacites.

The frequency distribution of the analyzed rocks indicates that 75% of the rocks are basalts, 14% intermediate rocks and 11% silicic rocks, which compares reasonably with a recent estimate of the production of volcanic rocks during the last 1100 years in Iceland. A general bimodal distribution is evident within both the tholeiitic and transitional alkalic rock series. In addition, several individual volcanic systems show bimodal distribution.

During Holocene and Late-Pleistocene time, 29 volcanic systems in Iceland and on its insular shelf have produced rocks which belong to the tholeiitic rock series, four volcanic systems have produced rocks which belong to the alkalic rock series, and eight volcanic systems have produced rocks belonging to the transitional alkalic rock series.

An important conclusion is that each volcanic system has without exception only developed basaltic rocks of one rock series. Many individual volcanic systems have distinct chemical characteristics. The tholeiitic systems delineate the axial zone of the

MAR, whereas the alkalic and transitional alkalic systems are confined to the flank zones.

The alkalic flank zones in west, south and southeast Iceland were initiated about 2–3 Ma ago. However, in the Tertiary series in northeast and southeast Iceland (Figure 1) there is evidence of flank zones which were active some 13–14 Ma and 5–7 Ma ago respectively, producing rocks belonging to the transitional series. The calc-alkaline dacites from an otherwise tholeiitic volcano in the Tertiary series of NW-Iceland are considered an anomalous occurrence.

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ÁGRIP

Bergraðirnar þrjár á Íslandi

Eldvirkni á Íslandi virðist frá upphafi hafa verið bundin við eldstöðvakerfi. Um 41 eldstöðvakerfi hefur verið virkt á Íslandi og landgrunni þess á nútíma og síðjökultíma. Athugun á 1378 aðalefnagreiningum á bergi úr þessum eldstöðvakerfum staðfestir að þrjár bergraðir gosbergs hafa myndast á Íslandi: þóleiísk bergröð, alkalísk bergröð og millibergröð. Efnafræðilegum og bergfræðilegum einkennum bergraðanna er lýst. Hvert eldstöðvakerfi hefur eingöngu myndað basalt sem tilheyrir einni ákveðinni bergröð. Notast er við flokkunarkerfi alþjóða jarðfræðisambandsins (IUGS) í megindráttum, en lagt er til að notuð verði ítarlegri sundurgreining á basalti og tillaga er gerð um nöfn á ísúru og kísilríku bergi millibergraðarinnar. Í ísúru bergi má oft greina að tvenns konar bergkvika hefur blandast saman. Tíðnidreifing bergefnagreininganna sýnir að 75% þeirra er basaltískt berg, 14% ísúrt berg og 11% kísilríkt berg. Áberandi tvískipting efnasamsetninga sést í þóleiísku bergröðinni og millibergröðinni. Þóleiíska bergröðin er bundin við eldstöðvakerfi í rekbeltunum sem mynda meginás Miðatlantshafshryggjarins. Alkalíska bergröðin og millibergröðin finnast hins vegar í hliðarbeltum. Um 80% gosbergs sem myndast hefur á umræddum tíma tilheyrir þóleiísku bergröðinni. Fyrir 2–3 milljónum ára mynduðust eldstöðvakerfi af millibergraðargerð til hliðar við rekbeltin, og hliðarbeltin urðu þannig til. Berg úr millibergröðinni virðist einnig hafa myndast í hliðarbeltum á norðausturlandi og suðausturlandi á síðtertíer.

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