

Silicic volcanism in Iceland: Composition and distribution within the active volcanic zones

Kristján Jónasson*

Icelandic Institute of Natural History, Hlemmur 3, P.O. Box 5320, IS-125 Reykjavík, Iceland

Received 25 October 2005; received in revised form 4 August 2006; accepted 5 September 2006

Abstract

Silicic volcanic rocks within the active volcanic zones of Iceland are mainly confined to central volcanoes. The volcanic zones of Iceland can be divided into rift zones and flank zones. Each of these zones contains several central volcanoes, most of which have produced minor amounts of silicic rocks. The silicic rocks occur as lavas and domes or as tephra layers, welded tuffs and ignimbrites, formed both in effusive and explosive eruptions. They tend to be glassy or very fine-grained, containing small amounts of phenocrysts. Plagioclase (andesine–oligoclase), anorthoclase or occasionally sanidine coexist with minerals such as augite, fayalite, pigeonite, orthopyroxene and magnetite. Quartz phenocrysts are exceedingly rare. Zoning of phenocrysts is limited and the pattern is variable. A set of 90 samples representing all active central volcanoes that have erupted silicic rocks was analysed for major- and trace-elements. The silicic rocks can be classified as dacites, trachytes, low-alkali rhyolites and alkalic rhyolites. Some of the trachytes and alkalic rhyolites are peralkaline (mostly comenditic). Trachytes and alkalic rhyolites are only found within the flank zones, while dacites and low-alkali rhyolites are mostly confined to the rift zones. The Icelandic rhyolites plot close to the thermal minimum in the “granite” system, while dacites and trachytes plot within the plagioclase field and towards the alkali feldspar temperature minimum. The silicic rocks are relatively Fe-rich and Ca-poor indicating low water pressure in the source. Trace element concentrations follow similar patterns in most central volcanoes. Exceptions are Torfajökull where silicic rocks display a negative correlation of Ba to Th and unusually high Th-contents, and the western flank zone where Ba-concentrations are highly variable. The ratios of different high field-strength elements are generally similar within each central volcano or region, which probably reflects different ratios in the source materials. Isotope systematics indicate that the silicic rocks are derived from older basaltic rocks similar to those from the same volcano, and that meteoric water has played a role in the genesis of the silicic rocks. Traditionally, the petrogenesis of silicic rocks in Iceland has been explained by various models of fractional crystallization or partial melting. The available data seems to be better explained by near-solidus differentiation than by near-liquidus differentiation. The silicic minimum melts can be extracted from the rigid framework of the near-solidus source by the process of solidification front instability or by deformation-assisted melt segregation. The source of the silicic rocks is within the intrusive complex beneath a central volcano rather than in a large, long-lived magma chamber.

© 2006 Elsevier Ltd. All rights reserved.

Keywords: Silicic; Volcanic; Iceland; Petrography; Geochemistry; Petrogenesis; Near-solidus differentiation

* Tel.: +354 5900500; fax: +354 5900595.

E-mail address: kristjan@ni.is.

1. Introduction

Silicic rocks are relatively rare within the oceanic crust. There are exceptions though, Iceland being one of them, where significant amounts of silicic material have formed. It is thought that the continental crust formed from oceanic crust, mostly at destructive plate margins, but also to some extent by the interaction of spreading ridges and mantle plumes, especially during the early history of the Earth (e.g. Taylor and McLennan, 1985; Johannes and Holtz, 1996). Examining the generation of silicic rocks in Iceland may therefore give important information on the geochemical processes of continent formation (Marsh et al., 1991; Sigmarsson et al., 1991; Jónasson, 1994).

This paper focusses on silicic rocks within the active volcanic zones in Iceland. These are defined as areas with rocks belonging the Brunhes magnetic epoch (<0.8 Ma) at the surface. Following an overview of the occurrence and petrography of the silicic rocks, geochemical analyses of rocks from all central volcanoes within the active volcanic zones is presented. Finally, different petrogenetic models are discussed.

2. Distribution

The active volcanic zones of Iceland are commonly defined as the areas where rocks belonging to the Brunhes magnetic epoch (<0.8 Ma) occur at the surface (e.g. Samundsson, 1980). The volcanic zones can be divided into rift zones and flank zones. The rift zones are the sites of active rifting and represent the continuation of the crest of the Mid-Atlantic rift across Iceland. Few signs of active rifting are observed in the flank zones. The Icelandic rift zones are arbitrarily divided into a western part extending from the Reykjanes Peninsula in the southwest to the Langjökull and Hofsjökull ice caps and an eastern part extending from central south Iceland to the northeast and north. Flank zones (or off-rift zones) occur in three areas in the western, southern and eastern parts of Iceland (Fig. 1).

Within the volcanic zones, several volcanic systems have been defined based mainly on the petrology of erupted products (Jakobsson, 1972, 1979). The volcanic systems of the rift zones produce rocks of the tholeiitic series. The volcanic systems of the western flank zone and the Vestmannaeyjar system in the southern flank zone produce rocks

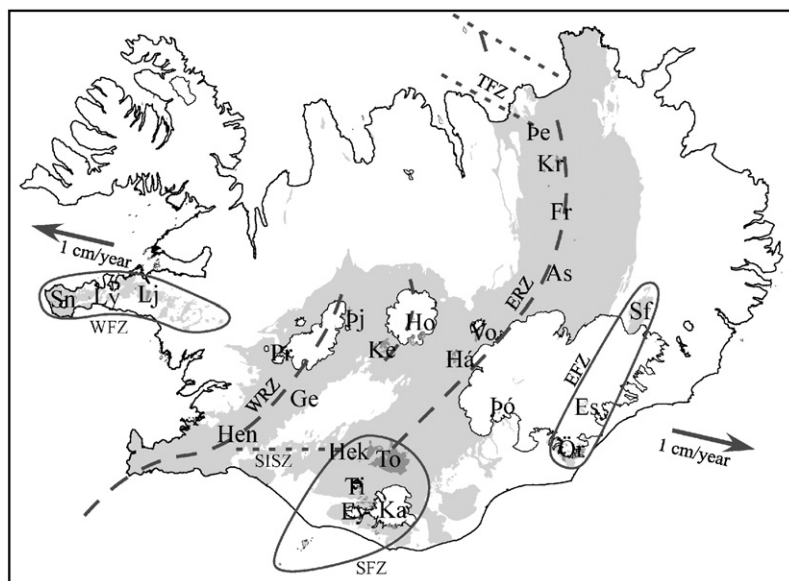


Fig. 1. Map of Iceland showing the location of central volcanoes known to have produced silicic rocks during the Brunhes magnetic epoch (<0.8 Ma). Shaded areas indicate Brunhes-age rocks. Dashed lines indicate the crest of the western and eastern rift-zones (WRZ and ERZ). The western, southern and eastern flank zones are delineated (WFZ, SFZ and EFZ) and the main transform zones are indicated (South Iceland Seismic Zone and Tjörnes Fracture Zone). Plate motion is shown by arrows. The central volcanoes in the rift zones are: Hengill (Hen), Geysir (Ge), Prestahnúkur (Pr), Þjófadalur (Þj), Kerlingarfjöll (Ke), Hofsjökull (Ho), Þórðarhyrna (Þó), Hágöng (Há), Vonarskarð (Vo), Askja (As), Fremri Námur (Fr), Krafla (Kr) and Þeistareykir (Þe). The central volcanoes in the western flank zone are: Snæfellsjökull (Sn), Lýsuskarð (Lý) and Ljósufjöll (Lj). In the southern flank zone the central volcanoes are: Hekla (Hek), Torfajökull (To), Tindfjallajökull (Ti), Eyjafjallajökull (Ey) and Katla (Ka). The central volcanoes in the eastern flank zone are: Örafjökull (Ör), Esjufjöll (Es) and Snæfell (Sf).

of the alkalic series, while other systems in the flank zones produce rocks of the transitional alkalic series (Jakobsson, 1972). Most of these volcanic systems contain one or more central volcanoes. Central volcanoes are defined by frequent eruptions from a central area (Walker, 1963; Sæmundsson, 1978). High temperature geothermal systems are associated with most of the central volcanoes and differentiated rocks are mostly confined to them. In the flank zones, the central volcanoes are cone-shaped stratovolcanoes, or areas of significant topographic buildup, whereas active rifting within the rift zones tends to reduce the topographic prominence of central volcanoes. Many of the central volcanoes in Iceland have a caldera or even several nested calderas (Sæmundsson, 1980).

Various estimates have been made of the relative abundance of silicic rocks in Iceland, ranging from a few percent up to 15% (e.g. Walker, 1966; Jakobsson, 1972). It is very difficult to estimate this accurately due to spatial and temporal variability, but in general an abundance of less than 10% seems probable. Intermediate rocks are rare and have in many cases been shown to be formed by hybridization or mixing (e.g. Sigurðsson and Sparks, 1981; McGarvie et al., 1990; Sigmarsson et al., 1992; Jónasson, 1994). It can therefore be stated that the volcanic rocks of Iceland are compositionally bimodal with a “Daly gap” separating basaltic and silicic compositions.

The silicic rocks are mainly found within central volcanoes both in the rift zones and in the flank zones. Most of these central volcanoes have only produced minor amounts of silicic rocks in a few formations. Exceptions to this are Torfajökull and Kerlingarfjöll, where silicic rocks are particularly prominent. The following account of the distribution of silicic rocks is based on references mentioned in the text and geological maps (e.g. Jóhannesson and Sæmundsson, 1998) coupled with the authors own observations.

2.1. Silicic rocks in the rift zones

Silicic volcanic rocks have not been found on the Reykjanes Peninsula in southwest Iceland, though xenoliths of silicic rocks have been found in one basaltic lava flow (Jónsson, 1965). On the western rim of the Hengill (Hen in Fig. 1) central volcano there is an outcrop of rhyolite together with small outcrops of intermediate rocks (Harðardóttir, 1983; Sæmundsson, 1967). A few outcrops of rhyolite are found in the Geysir (Ge) central volcano. Most notable is the Laugarfell rhyolite at the western edge of the Geysir geothermal area. In addition, three separate outcrops of rhyolite occur beneath the Bjarnarfell table mountain. The rhyolites at Geysir are of early Brunhes age (<0.8 Ma) (S. Jakobsson, 2006, personal communication). No Holocene eruptions have been attributed to this central volcano which is thought to be inactive (Sæmundsson, 1992). At the southwestern end of Langjökull, a large rhyolite dome, Prestahnúkur, occurs in an active central volcano of the same name (Pr). In Þjófadalur (or Hveravellir) (Þj), at the northeastern end of Langjökull, several small outcrops of silicic rocks are found. They include two small occurrences of rhyolite, a dacite and several outcrops of silicic and intermediate tuffs and cone sheets.

The Kerlingarfjöll central volcano (Ke) contains numerous rhyolite domes and a few formations of intermediate rocks (Grönvold, 1972). A large central volcano is situated underneath the Hofsjökull ice cap (Ho). It has a large caldera and on its eastern rim there are two nunataks composed of rhyolite. At the southeastern margin of Hofsjökull, rhyolites are found on both sides of the Múlajökull glacier.

At the Þórðarhryna central volcano (Þó), beneath the Vatnajökull ice cap, three rhyolite nunataks are found. Silicic rocks are not known in the Grímsvötn, Bárðarbunga and Kverkfjöll central volcanoes, also situated beneath the Vatnajökull ice cap. At the northwestern margin of Vatnajökull there are two central volcanoes, Hágöngur (Há) and Vonarskarð (Vo). At Hágöngur there are two large rhyolite domes, with smaller outcrops of rhyolite around them. At the southwestern rim of the Vonarskarð caldera there is a rhyolite dome and along the northwestern rim, there are several smaller occurrences of silicic rocks.

Large Plinian eruptions have occurred twice in postglacial time at the Askja central volcano (As), the first one at the very beginning of the Holocene (Sigvaldason, 2002). The second one occurred in 1875 and produced 0.2 km³ (dense rock equivalent) of rhyolitic pumice (Sigurðsson and Sparks, 1981; Macdonald et al., 1987). In the northern part of Askja an early postglacial dacite lava is found. At the Krafla central volcano (Kr), silicic rocks have been produced in two main phases (Jónasson, 1994). An earlier phase, probably related to the formation of a caldera (ca. 201 ka; Lacasse and Garbe-Schönberg, 2001), produced a small rhyolite dome before the eruption of a large composite welded tuff (Calderone et al., 1990). In the second phase, three large rhyolite domes were formed. In addition to these two main phases, small amounts of silicic rocks have been formed in a few eruptions (Jónasson, 1994; Nicholson et al., 1991). Small outcrops of rhyolite are found at the central volcanoes of Fremri Námur (Fr) and Þeistareykir (Þe). At Heiðarsporður, between the Krafla and Fremri Námur central volcano a dacite lava is found, seemingly unrelated to

any central volcano (Jónasson, 2005). A small outcrop of rhyolite is found at Hrúthálsar, northeast of Askja. Hrúthálsar have recently been suggested to be a central volcano (Sæmundsson et al., 2005).

2.2. Silicic rocks in the flank zones

Three central volcanoes are found in the Western flank zone; Snæfellsjökull (Sn), Lýsuskarð (Lý) and Ljósufjöll (Lj). Several trachyte lavas are found on the flanks of Snæfellsjökull (Harðarson, 1993). To the east of the volcano, a relatively young rhyolite dome occurs (Mælifell) and on the western slope of the volcano an older rhyolite formation is found. Three explosive eruptions at Snæfellsjökull in postglacial time have produced trachytic ash layers (Jóhannesson et al., 1981). A small outcrop of rhyolite occurs in the Lýsuskarð volcano (Sigurðsson, 1970). Rhyolite and trachyte lavas have formed at Ljósufjöll (Sigurðsson, 1970).

Five large central volcanoes occur in the southern flank zone, all of which have produced silicic rocks. By far the most voluminous occurrence of silicic volcanic rocks in Iceland is in the Torfajökull (To) central volcano. It is dominated by extensive subglacial rhyolite formations; postglacial lavas and domes are also found (McGarvie et al., 1990; Macdonald et al., 1990; Marsh et al., 1991; Gunnarsson et al., 1998). Intrusions of tholeiitic basalt magma during fissure eruptions in the Veiðivötn area to the northeast most likely triggered silicic eruptions in Torfajökull in postglacial times (Mørk, 1984; Blake, 1984). The Hekla central volcano quite regularly erupts explosively. Given a certain repose period, the eruptions start with silicic pumice, gradually giving way to intermediate compositions (Thorarinsson, 1967; Sigvaldason, 1974; Sigmarsson et al., 1992). Several postglacial silicic ash layers are known and on the southeastern flank there is a dacite lava (Einarsson, 1950). A large explosive eruption at the Tindfjallajökull (Ti) central volcano produced an ignimbrite in the Þórmörk area (Jørgensen, 1980), at about 54.5 ka (Lacasse and Garbe-Schönberg, 2001) and left a caldera within Tindfjallajökull. Additionally, rhyolite domes have formed to the northeast and west of the caldera and silicic breccias and hyaloclastites occur within the caldera. A trachyte lava is found on the northwestern flank of Eyjafjallajökull (Ey) (Wiese, 1993). The Katla (or Mýrdalsjökull) central volcano (Ka) is one of the most active volcanoes in Iceland. While the eruptive products are mostly basaltic, a significant amount of silicic material has also been erupted. Several rhyolite domes occur just outside a caldera situated beneath the ice-cap. Silicic pumice has been formed in many eruptions (Larsen et al., 2001) and at 11.9 ka a large explosive eruption produced a welded tuff layer to the southwest and an extensive ash layer (Lacasse et al., 1995). Silicic volcanic rocks have not been found in the Vestman Islands volcanic system, though xenoliths of silicic rocks have been found in Surtsey (Sigurðsson, 1968).

In the eastern flank zone there are three central volcanoes, Öraefajökull (Ör), Esjufjöll (Es) and Snæfell (Sf). Öraefajökull is the largest stratovolcano in Iceland. Several rhyolite formations are found both in the summit area and on its flanks (Prestvik, 1982; Prestvik et al., 2001). The largest explosive eruption in historic time in Iceland occurred at Öraefajökull in 1362 AD when more than 1 km³ (dense rock equivalent) of silicic tephra was erupted (Thorarinsson, 1958). Rhyolite and obsidian have been found in nunataks in the Esjufjöll area and a few rhyolite domes and plugs are present in the Snæfell central volcano (Hards et al., 2000).

The larger amounts of silicic rocks can be seen to occur in central volcanoes where there has been considerable topographic buildup (e.g. Öraefajökull, Mýrdalsjökull, Tindfjallajökull, Snæfellsjökull), where the rift zone changes direction or is shifted (e.g. Hekla and Torfajökull where the South-Iceland seismic zone connects with the eastern rift zone; Hágöng, Vonarskarð, Kerlingarfjöll and Hofsjökull in Central Iceland where the western rift zone converges with the eastern rift zone) and in areas with relatively thick crust. Crustal thickness in Iceland (Allen et al., 2002; Kaban et al., 2002; Darbyshire et al., 2000) varies from 15–20 km beneath the Reykjanes Peninsula and the northern end of the eastern rift-zone to over 40 km in central and southeastern Iceland. Silicic rocks are rare where the crust is relatively thin (e.g. on the Reykjanes Peninsula).

3. Petrography

In Iceland, silicic volcanic rocks occur as lavas and domes, or as tephra layers, welded tuffs and ignimbrites. They have formed both in effusive and explosive eruptions. Many central volcanoes have produced silicic volcanic rocks in both types of eruptions. Inclusions of basaltic material as rock fragments or xenocrysts, and evidence of mixing or hybridization with basaltic magma are common in rocks formed in explosive eruptions. This is less pronounced in rocks formed in effusive eruptions. Otherwise, the petrological and geochemical characteristics of silicic rocks from each central volcano are similar, regardless of the eruption mechanism, indicating that they have been generated in

similar processes, unrelated to eruption style. The mode of eruption may be related to whether mafic magma is injected (Sparks et al., 1977), or to factors such as eruption rate and conduit width (Eichelberger, 1995). This will determine whether the silicic magma is able to release its volatile content passively during ascent, leading to an effusive eruption. Otherwise the eruption will be explosive. A number of silicic formations in the volcanic zones have been erupted subglacially (Furnes et al., 1980; Tuffen et al., 2001).

Silicic volcanic rocks in Iceland tend to be glassy or very fine-grained. They commonly contain less than 1% phenocrysts, rarely more than 10%. Phenocrysts of feldspar are ubiquitous and often make up about 90% of the total phenocryst content. The feldspars are mainly plagioclase (andesine–oligoclase), anorthoclase and occasionally sanidine. Augite is a common mafic mineral, with or without fayalite, pigeonite or orthopyroxene. Hornblende and biotite are occasionally found. The FeTi oxides, magnetite and ilmenite, are often found. Zircon and apatite are common accessory phases. Quartz is exceedingly rare as a phenocryst phase.

The rhyolites in the rift-zones usually are rather phenocryst-poor and often nearly aphyric. The feldspar is plagioclase (andesine to oligoclase). Few studies have focussed on the mineral chemistry of these rocks. In the Krafla central volcano, plagioclase of andesine composition (An_{34-45}) occurs with augite, pigeonite, fayalite and magnetite (Jónasson, 1994). Apatite and zircon are accessory phases. At the Tertiary Thingmuli central volcano which probably formed within a rift zone setting, plagioclase (An_{30-35}) was reported together with ferroaugite, fayalitic olivine and magnetite (Carmichael, 1964, 1967). Plagioclase (An_{48-49}), augite, orthopyroxene, magnetite and accessory apatite were reported in pumice from the 1875 eruption in Askja (Sigurðsson and Sparks, 1981).

The rhyolites in the southern and eastern flank zones, where transitional-series rocks are found, range from aphyric to porphyritic. The feldspar is either plagioclase or anorthoclase. At Torfajökull, plagioclase of oligoclase–andesine composition (An_{10-40}) or anorthoclase ($<Or_{31}$) occur with augite, magnetite, ilmenite, hornblende (edenitic–ferroedenitic), biotite and fayalite, with apatite, pyrrhotite and zircon as accessory phases (Gunnarsson et al., 1998; Macdonald et al., 1990). In the Þórsmörk ignimbrite which originates in the Tindfjallajökull central volcano, anorthoclase coexists with ferro-hedenbergite, fayalite, ilmenite and magnetite, with zircon as an accessory phase (Jørgensen, 1980). At Snæfell, anorthoclase (Or_{35}) has been reported together with augite or hedenbergite (Hards et al., 2000). Oligoclase, anorthoclase, fayalite, augite to hedenbergite, magnetite and accessory zircon have been described at Öraefajökull (Prestvik, 1985). In the silicic products of the Hekla central volcano, plagioclase (An_{30-60}), fayalite, magnetite and augite have been reported (Sigvaldason, 1974).

For rhyolites from the Lýsuskarð volcano in the western flank zone, where rocks of the alkalic series are found, Sigurðsson (1971) reported sanidine (Or_{30-47}), some of which would classify as anorthoclase, quartz, clinopyroxene and iron-oxides in three glassy acid rocks from the area.

The zoning of phenocrysts in the silicic rocks is small and the pattern is variable. Usually both normal and reverse zoning can be observed in the same rock and resorption is common.

4. Geochemistry

While the geochemistry of silicic rocks from a few active central volcanoes is well documented, very little data exist for others. In this study 90 samples were chosen for chemical analysis. They were analysed for major and trace elements at Bristol University using ICP-AES and ICP-MS. The samples were dissolved in HF prior to analysis, therefore no SiO_2 values were obtained. A representative set of 16 samples was analysed for major elements (including SiO_2) at GEUS, Copenhagen, using XRF (Table 1). Samples are included from all central volcanoes that have erupted silicic rocks during the Brunhes magnetic epoch (<0.8 Ma). The majority of the samples are from lavas and domes formed in effusive eruptions. These formations are generally better preserved and less altered than tephra layers and ignimbrites formed in explosive eruptions. Furthermore, they usually show less evidence of mixing with basaltic material. Studies of silicic rocks from several central volcanoes indicate that in general there is no significant difference in composition between rocks formed in different types of eruptions, except for the degree of mixing with basaltic material (e.g. Jónasson, 1994). A notable exception is the Hekla central volcano where rhyolites are only formed in explosive eruptions whereas silicic lavafloes consist of dacite (Sigmarsson et al., 1992). An overview of large-volume explosive silicic eruptions in Iceland is given in Lacasse and Garbe-Schönberg (2001).

According to the classification system of the International Union of Geological Sciences (LeMaitre, 2002), silicic rocks in Iceland classify as rhyolites, dacites and trachytes. Rhyolite is by far the most common, dacites and trachytes are relatively rare. The rhyolites can be tentatively separated into two groups: low-alkali rhyolites and alkalic rhyolites

Table 1
Major and trace element composition of representative samples of silicic volcanic rocks from Iceland

S. nr.	21969	6651	21687	45	21839	20520	826	10478	678	21715	21702	4535	6188	3532	3638	22049
	Kr	Fr	Há	Þó	Ke	Pr	Sn	Lj	Hek	To	To	To	Ey	Ka	Ör	Sf
SiO ₂	74.31	74.40	76.27	74.40	73.04	76.46	66.79	66.75	68.81	68.41	72.39	70.20	68.89	70.13	72.28	72.82
TiO ₂	0.29	0.24	0.22	0.14	0.22	0.08	0.27	0.26	0.34	0.35	0.26	0.33	0.32	0.37	0.26	0.13
Al ₂ O ₃	11.88	12.37	11.69	12.83	12.99	12.18	15.86	15.45	14.25	14.92	12.14	14.25	14.50	13.45	13.58	13.33
Fe ₂ O ₃	0.26	0.59	1.39	0.17	0.53	0.19	3.17	2.63	0.87	0.92	1.15	1.06	1.96	0.46	0.76	1.53
FeO	2.63	1.80	1.06	1.30	1.88	1.31	0.14	1.55	3.04	2.57	1.93	1.50	2.42	3.40	1.36	0.80
MnO	0.09	0.08	0.07	0.04	0.08	0.05	0.14	0.21	0.13	0.11	0.07	0.07	0.14	0.15	0.07	0.07
MgO	0.14	0.12	0.06	0.16	0.10	0.05	0.23	0.11	0.29	0.45	0.14	0.34	0.22	0.29	0.30	0.06
CaO	1.66	1.28	0.97	0.94	0.93	0.99	1.04	0.85	2.39	1.44	0.34	0.92	1.13	1.34	0.94	0.39
Na ₂ O	4.34	4.76	4.95	4.56	5.38	4.59	5.87	6.14	5.06	5.93	5.70	5.53	6.57	5.74	5.02	6.03
K ₂ O	2.69	2.99	2.50	3.89	3.63	3.25	5.22	5.35	2.32	4.11	4.43	4.49	3.48	3.44	4.17	4.18
P ₂ O ₅	0.01	0.01	0.00	0.02	0.00	0.02	0.05	0.04	0.05	0.07	0.00	0.03	0.06	0.04	0.01	0.02
LOI	0.54	0.47	0.20	0.66	0.44	0.57	0.46	0.58	1.72	0.42	0.63	0.61	0.08	0.50	0.82	0.03
Sum	98.84	99.11	99.38	99.11	99.21	99.74	99.23	99.91	99.25	99.68	99.18	99.32	99.77	99.29	99.56	99.39
Li	37	26	35	35	31	42	15	11	27	29	53	35	33	27	32	26
Be	3	3	4	4	6	5	4	3	4	7	11	6	6	6	6	5
Rb	76.5	73.9	61.0	86.6	83.1	79.5	115.1	96.5	49.6	92.7	122.8	115.4	73.8	78.2	101.2	105.7
Sr	90.7	86.0	77.8	60.0	64.4	82.2	61.4	2.0	196.3	103.6	13.6	59.5	86.9	127.5	54.0	8.6
Cs	0.7	0.8	0.5	0.9	1.0	0.8	1.4	0.9	0.7	1.0	1.3	1.0	0.3	0.7	1.0	0.7
Ba	590	609	503	613	855	657	1258	75	553	454	187	451	696	726	739	696
Th	7.82	8.69	9.84	12.94	12.79	12.47	14.55	14.89	8.72	15.26	21.33	17.84	9.88	11.81	13.98	10.95
U	2.17	2.43	2.35	3.34	3.61	3.41	3.59	4.20	2.83	4.53	6.21	5.22	2.48	3.80	4.03	2.22
Sc	6	5	1	3	3	2	7	5	10	3	1	2	3	4	3	1
Cr	2	1	3	1	1	1	7	2	13	5	1	2	6	1	3	1
Co	2	0	3	1	1	0	1	2	3	2	0	2	1	1	1	0
Ni	2	0	0	1	1	1	2	1	1	1	0	1	0	2	1	1
Cu	16	8	9	7	7	8	13	3	21	6	5	7	6	5	10	3
Zn	88	108	151	49	131	97	91	117	121	96	146	80	152	122	68	113
Ga	40	29	32	52	71	30	37	27	31	31	29	30	37	41	32	39
Ge	2	1	2	2	4	2	2	2	2	3	2	1	2	2	1	2
Sn	6	7	10	5	8	8	4	5	6	9	13	11	9	9	8	5
Tl	0.1	0.1	0.1	0.2	0.1	0.1	0.1	0.1	0.1	0.0	0.2	0.1	0.0	0.0	0.2	0.0
Pb	5.69	5.39	7.26	7.05	7.33	7.92	5.81	5.81	6.64	9.24	12.07	9.88	8.30	6.88	8.26	3.36
Y	110.6	104.8	177.8	56.1	120.7	115.0	60.0	54.3	87.4	57.0	132.9	74.1	69.6	96.4	85.0	95.5
Zr	440.9	407.3	387.2	240.8	536.9	213.9	651.2	1150.5	393.2	702.3	1270.1	598.5	830.3	1003.7	475.9	479.0
Nb	52.4	73.7	79.0	33.5	143.4	68.9	152.7	209.6	70.2	103.9	165.8	128.5	107.7	113.7	73.5	93.3
Hf	14.05	12.98	13.20	9.73	18.02	9.94	15.72	23.15	12.12	18.57	37.08	15.92	24.18	27.03	12.33	14.13
Ta	3	5	5	2	9	4	9	13	4	6	12	9	6	6	5	7
W	1	2	1	1	1	1	1	2	1	1	2	2	1	1	2	1

La	52.16	63.89	80.56	57.20	94.91	71.28	109.29	93.49	73.42	85.07	130.23	105.60	78.03	101.47	82.51	93.49
Ce	113.30	140.06	184.19	117.79	209.03	151.30	210.63	239.03	150.95	167.43	261.52	207.34	181.92	214.91	169.78	198.18
Pr	13.68	16.47	22.16	11.84	23.08	16.95	20.57	22.98	17.16	18.24	27.86	21.04	19.14	24.33	17.59	21.70
Nd	58.74	73.32	99.99	49.49	92.29	68.16	75.46	90.57	73.19	68.12	108.98	77.66	80.89	99.45	73.46	93.30
Sm	14.21	16.42	24.30	9.84	20.45	16.23	13.33	15.33	15.87	13.28	22.12	15.47	19.54	19.73	14.62	19.21
Eu	2.74	2.58	4.45	1.47	3.29	2.64	2.84	0.98	3.19	2.11	1.82	1.70	3.90	4.03	1.96	2.39
Gd	20.03	23.38	33.86	14.99	27.30	20.95	30.23	23.89	21.89	25.11	27.69	27.65	27.25	26.52	26.27	30.42
Tb	2.41	2.90	4.73	1.73	3.31	2.85	1.83	2.05	2.38	2.07	3.81	2.22	2.96	3.08	2.21	2.95
Dy	16.03	17.78	28.83	9.63	20.54	18.45	10.27	11.90	14.42	12.12	21.61	13.14	17.01	17.48	14.23	16.96
Ho	3.19	3.32	5.34	1.72	3.98	3.43	1.77	2.03	2.50	2.00	4.08	2.23	2.74	3.16	2.45	2.84
Er	9.87	10.01	16.61	4.89	12.35	9.94	5.81	6.61	7.40	6.63	11.13	6.77	8.17	9.01	7.90	8.75
Tm	1.54	1.53	2.50	0.90	1.74	1.62	0.98	1.00	1.13	0.99	1.85	1.03	1.11	1.30	1.18	1.34
Yb	10.52	10.23	16.54	5.10	11.40	10.27	5.95	7.24	7.71	6.50	11.55	6.65	8.41	8.38	7.54	8.69
Lu	1.76	1.54	2.58	0.72	1.79	1.50	1.14	1.11	1.29	0.91	1.67	0.89	1.36	1.37	1.09	1.34

Major elements were analysed at the Denmark and Greenland Geological Survey (GEUS) by Jørgen Kystol, using X-ray fluorescence (XRF). Trace elements were analysed at the University of Bristol by Tony Kemp, using inductively coupled plasma mass spectrometry (ICP-MS). Oxide concentrations are shown in wt%; trace element concentrations are in ppm. Sample numbers refer to Icelandic Institute of Natural History collection numbers. Letters below sample numbers refer to central volcanoes (Fig. 1). Sample list: 21969: Obsidian, Hlíðarfjall, Krafla; 6651: Pitchstone, Ketilhyrna, Fremri Námur; 21687: Rhyolite, S-Háganga, Hágöngur; 45: Obsidian, Pálsfjall, Þórðarhyrna; 21839: Obsidian, Ögmundur, Kerlingarfjöll; 20520: Obsidian, Prestahnúkur, Prestahnúkur; 826: Trachyte, Sandfell, Snæfellsjökull; 10478: Trachyte, Ljósufjöll, Ljósufjöll; 678: Pumice, H-3, Hekla; 21715: Rhyolite, Laugahraun, Torfajökull; 21702: Obsidian, Hrafninnusker, Torfajökull; 4535: Obsidian, Markarfljót, Torfajökull; 6188: Rhyolite, Grýttindar, Eyjafjallajökull; 3532: Obsidian, Kriki, Katla; 3638: Obsidian, Vatnafjöll, Öreafjökull; 22049: Rhyolite, Snæfell, Snæfell. A complete set of analytical data and a more detailed sample list is available from the author.

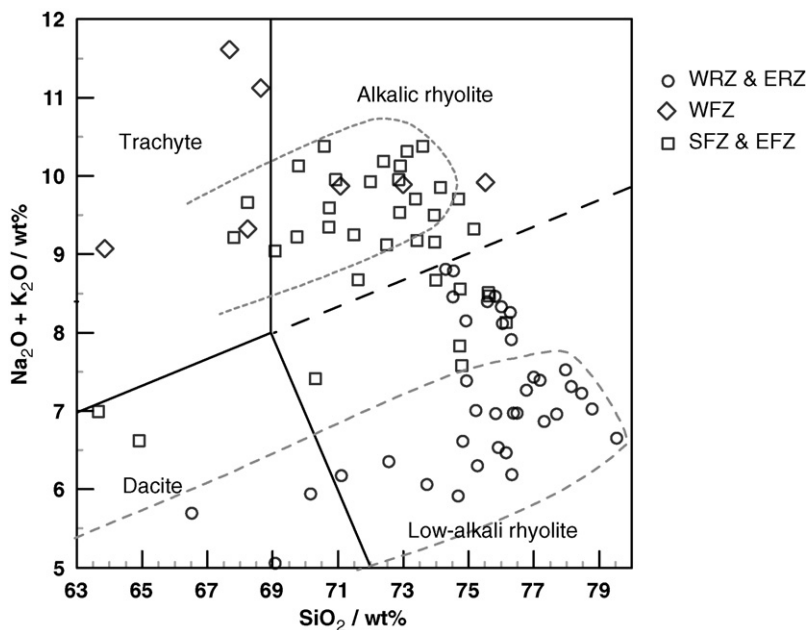


Fig. 2. Total alkalis vs. silica (TAS-diagram) in silicic rocks from Iceland. The analyses were done using ICP-AES at the University of Bristol. The SiO_2 -concentrations are calculated as 100 wt%—the sum of the concentration of other elements. Comparison with analyses made in Copenhagen (Table 1) show that SiO_2 -concentrations may be overestimated by 0–2 wt%. A few trachytes and dacites thus plot within the rhyolite field, but this does not have any significant affect on the interpretation of the results. Silicic rocks from the rift-zones are dacites and low-alkali rhyolites; most of them plot within the lower dashed area. Those that are richer in alkalis are from the Kerlingarfjöll, Þórðarhryna and Geysir central volcanoes. Silicic rocks from the flank-zones are mostly trachytes and alkalic rhyolites. The upper dashed area encloses samples from Torfajökull. Silicic rocks from flank zones that plot in the dacite and low-alkali rhyolite fields include all samples from Hekla and Esjufjöll, in addition to some samples from Öraefajökull. The highest alkali contents are found in trachytes from Snæfellsjökull and Ljósufjöll.

(Fig. 2). Alkalic rhyolites and trachytes have only been found in the flank zones, while low-alkali rhyolites and dacites are mostly confined to the rift zones. Some of the trachytes and alkalic rhyolites are peralkaline and many of them have an agpaite index close to 1.0 (molar $\text{Na}_2\text{O} + \text{K}_2\text{O}/\text{Al}_2\text{O}_3$). Peralkaline rhyolites and trachytes have been found in the central volcanoes of the western flank zone, at Torfajökull, Tindfjallajökull and Eyjafjallajökull in the southern flank zone, and in Öraefajökull and Snæfell in the eastern flank zone. The peralkaline rocks are mostly comenditic (Baker, 1974), though pantelleritic rhyolite has been reported from Torfajökull (McGarvie, 1984). Peraluminous silicic rocks have not been found.

Silicic rocks from most central volcanoes in the rift-zones plot within the lower stippled area in Fig. 2. The exceptions are silicic rocks from the Kerlingarfjöll, Þórðarhryna and Geysir central volcanoes which have slightly higher alkali contents, but still fall in the low-alkali rhyolite field. The upper stippled area encloses rocks from the Torfajökull central volcano. Silicic rocks in the flank zones mostly plot in the same area, with some important exceptions. The silicic rocks from the Hekla and Esjufjöll central volcanoes are low-alkali rhyolites and dacites, and the silicic rocks from the Öraefajökull central volcano straddle the border between low-alkali and alkalic rhyolites. The highest alkali contents are seen in trachytes from the western flank zone.

On average, more than 90 wt% of the CIPW-normative mineral assemblage is made up of quartz, orthoclase, albite and anorthite. Fig. 3a shows the composition of the samples presented in Table 1 plotted in the “granite” system (Ab–Or–Qz). The Icelandic rhyolites plot close to the thermal minimum (minimum melt composition) in this system. Dacites and trachytes plot towards higher temperatures within the plagioclase volume and towards the alkali feldspar temperature minimum (approximately $\text{Ab}_{70}\text{Or}_{30}$; Johannes and Holtz, 1996), respectively. The difference in alkali contents displayed in Fig. 2 is reflected in this diagram, with Or-contents increasing with increasing alkali content. The compilation of data by Lacasse and Garbe-Schönberg (2001, Figs. 5–7) compares well with these results. When plotted in the feldspar system (Ab–Or–An) the samples plot within a remarkably small area close to the alkali feldspar temperature minimum (Fig. 3b).

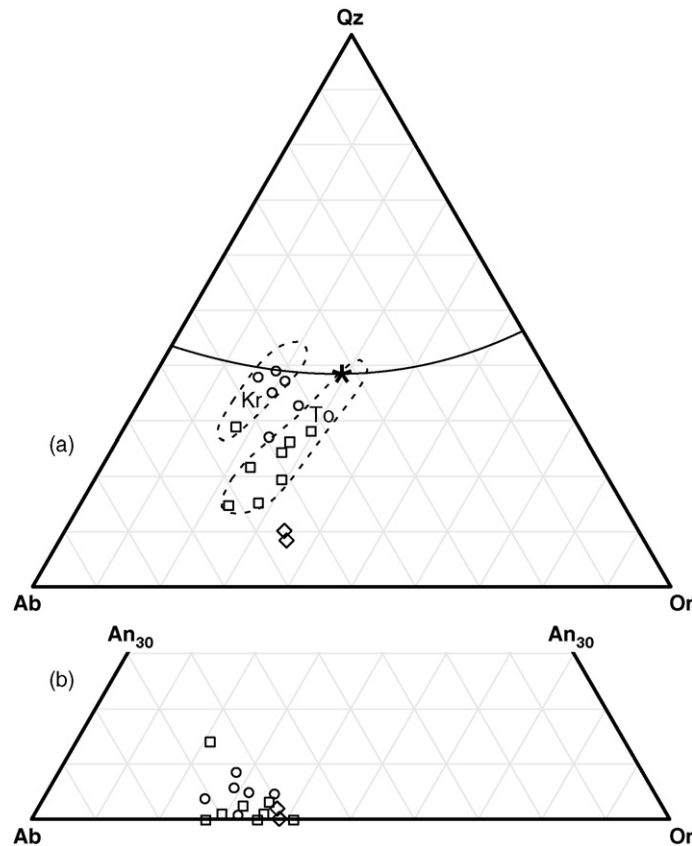


Fig. 3. The CIPW-normative composition of representative samples of silicic rocks from Iceland. The analyses were done using XRF at GEUS in Copenhagen. Symbols as in Fig. 2. (a) The “granite” system (Qz–Ab–Or). The fields labeled Kr and To indicate the projected composition of rocks and glasses from the Krafla and Torfajökull central volcanoes (Lacasse and Garbe-Schönberg, 2001). Silicic rocks from Kerlingarfjöll plot between these two and rocks from the WFZ plot to the lower right of Torfajökull. Otherwise, the silicic rocks from the rift zones and the flank zones follow the pattern of Krafla and Torfajökull, respectively. The solid line and the star indicate the quartz–feldspar cotectic and the minimum melt composition at 1 kbar, H₂O-saturated conditions (Tuttle and Bowen, 1958). The alkali feldspar temperature minimum on the Ab–Or join is at approximately Ab₇₀Or₃₀. The effects of total pressure, H₂O-activity and other components on this system is reviewed by Johannes and Holtz (1996). (b) The feldspar triangle (An–Ab–Or).

Silicic rocks in Iceland are relatively Fe-rich and Ca-poor compared to silicic rocks in general (Warshaw and Smith, 1988). The alkalic rhyolites and trachytes in the flank zones are even poorer in Ca than the low-alkali rhyolites and dacites of the rift zones (Fig. 4). These characteristics (high Fe, low Ca) have been taken to indicate low pressures of formation and specifically low water-pressure in the source, both of which increase the stability of plagioclase relative to pyroxene (e.g. Helz, 1976; Spulber and Rutherford, 1983; Thy et al., 1990). They have also been taken to indicate relatively low oxygen fugacity during formation. An exception to this is the occurrence of calc-alkaline dacites in the Tertiary Króksfjörður central volcano in northwest Iceland, which are Fe-poor and Ca-rich (Jónasson et al., 1992), but these are outside the scope of this paper. Concentrations of TiO₂, MgO and MnO are minor in the silicic rocks of Iceland and P₂O₅ is present in trace amounts.

Trace-element concentrations in the silicic rocks follow similar patterns in most central volcanoes. One of the most incompatible elements in basaltic and silicic rocks is Th, which is also generally considered resistant to alteration. Basaltic rocks in Iceland generally have low concentrations of Th (<2.5 ppm; Hemond et al., 1993). Concentrations of Th in silicic volcanic rocks in Iceland, as measured in this study, range from 5 to 15 ppm, except for silicic rocks at Torfajökull which range from 15 to 22 ppm and silicic rocks from the WFZ which range from 9 to 20 ppm. Other highly incompatible elements (e.g. Be, K, Rb, Cs, Nb, La, Ce, Pb and U) generally display a similar variation and correlate well with Th (Fig. 5a).

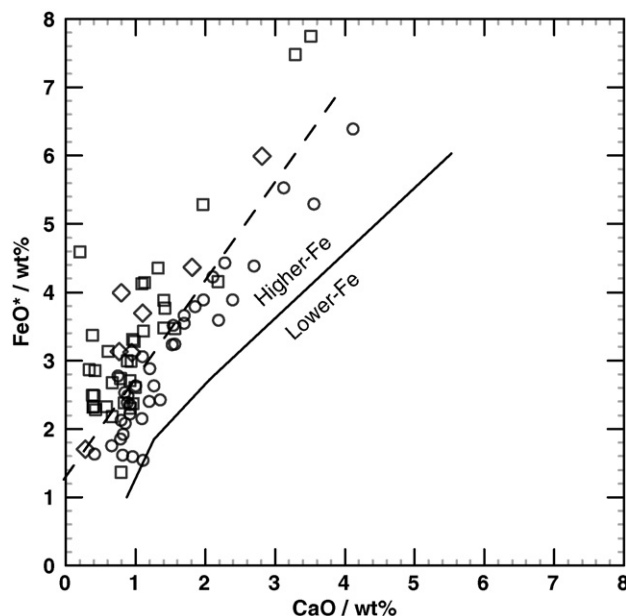


Fig. 4. Total Fe as FeO vs. CaO in silicic rocks from Iceland. The analyses were done using ICP-AES at the University of Bristol. Symbols as in Fig. 2. The solid line separates higher-Fe types from lower-Fe types (Warshaw and Smith, 1988). The silicic rocks from Iceland are all of the higher Fe-type. Rocks from the flank zones tend to have even higher Fe contents and lower Ca contents than rocks from the rift zones, although there is significant overlap. The dashed line largely separates these two groups.

Trace elements that are compatible in mafic minerals (e.g. Sc, Cr, Co and Ni) show low to very low concentrations in the silicic rocks. Sr correlates negatively with Th within each central volcano. Elements like Zn, Ga, Y, Zr, Hf and Yb correlate poorly with Th. For the majority of central volcanoes, Ba correlates positively with Th (Fig. 5b). There are two important exceptions to this. Silicic rocks from the WFZ have either very high or very low concentrations of Ba. At Torfajökull Ba has a strong negative correlation with Th. While Ba is incompatible in most minerals, it is compatible in K-feldspar. This indicates that in most cases K-feldspar has not played any role in the genesis of the silicic rocks, except for Torfajökull and the WFZ.

The most striking feature of REE-patterns for silicic rocks from Iceland (Fig. 6) is the similarity in the shape of the patterns. This may be taken to indicate a similar process of formation for all of them. There are slight differences, though, in the slopes and absolute concentrations in rocks from different volcanoes. This can be seen, for example, in the ratios La/Sm and Ce/Yb (Fig. 5c). Similar differences can be observed in other trace element ratios, e.g. Y/Nb (Fig. 5d). These ratios are generally similar within each central volcano or region, which probably reflects different ratios in the source materials. A more detailed investigation of several individual regions and possible source materials would be required for a further examination of this.

Isotopic analyses were not obtained for this study, but the available data can be summarized as follows: The isotopic ratios of Sr, Nd and Pb are generally similar to ratios in basaltic rocks from the same volcano (e.g. Sigmarsson et al., 1992; Hemond et al., 1993; Stecher et al., 1999; Hards et al., 2000; Prestvik et al., 2001). Several studies have shown that $\delta^{18}\text{O}$ -values are generally lower in silicic rocks than in basaltic rocks from the same volcano (e.g. Nicholson et al., 1991; Muehlenbachs, 1973; Gautason and Muehlenbachs, 1998), indicating involvement of meteoric water. In some cases, however, $\delta^{18}\text{O}$ -values are identical in silicic and basaltic rocks (Sigmarsson et al., 1992 (Hekla); Prestvik et al., 2001 (Öræfajökull)). Studies of Th isotopes and Th/U-ratios in rocks from Hekla, Krafla and Askja indicate that the silicic melts are generated from older (at least 50,000–140,000 years) basaltic rocks (Sigmarsson et al., 1991).

5. Petrogenesis

The origin of silicic rocks in Iceland has been discussed in a number of papers. Generally, interpretations are based on one of two themes. One suggests that the silicic rocks are formed by fractional crystallization of basaltic magma (e.g.

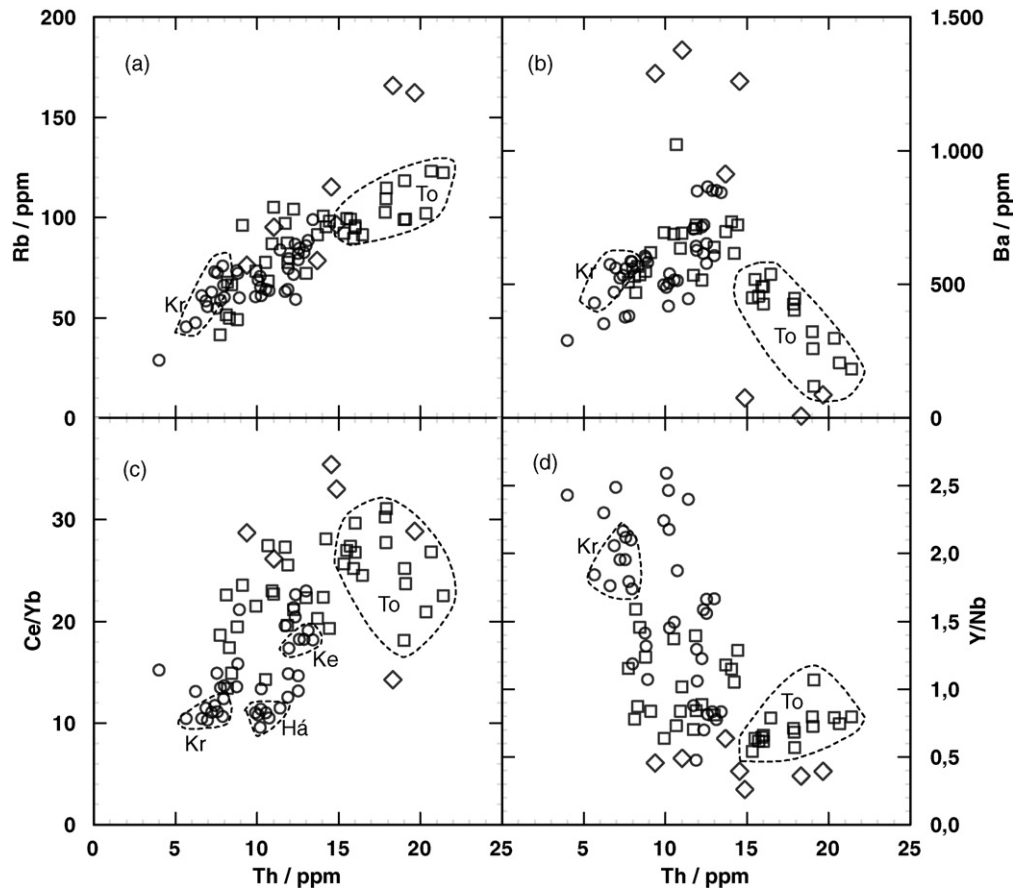


Fig. 5. Trace element composition in silicic rocks from Iceland. The analyses were done using ICP-MS at the University of Bristol. Symbols as in Fig. 2. Field markings refer to central volcanoes (Fig. 1). (a) Rb vs. Th. Similar variations are seen for several other incompatible elements. (b) Ba vs. Th. For the majority of central volcanoes, Ba correlates positively with Th. A negative correlation is seen in Torfajökull rocks and samples from the western flank zone show highly variable Ba-concentrations. (c) Ce/Yb concentration ratio vs. Th. Rocks from a certain central volcano generally have similar ratios and plot within a limited area. The different ratios probably reflect different ratios in source compositions in different central volcanoes or regions. Basaltic rocks in Iceland have Ce/Yb ratios between 2 and 20 and Th-concentrations below 2.5 ppm. (d) Y/Nb concentration ratio vs. Th. See text for discussion.

Carmichael, 1964; Macdonald et al., 1987, 1990; Nicholson et al., 1991; Furman et al., 1992; Prestvik et al., 2001), whereas the other suggests partial melting of crustal rocks (e.g. O’Nions and Grönvold, 1973; Sigvaldason, 1974; Óskarsson et al., 1982; Condomines et al., 1983; Sigmarsson et al., 1991, 1992; Marsh et al., 1991; Jónasson, 1994; Gunnarsson et al., 1998). Both are forms of crystal-liquid differentiation, the main difference being whether the process is seen as a retrograde process or a prograde one. Several variations on these themes have been proposed to explain the existing data. Assimilation of crustal rocks or melts and recharging magma chambers have been invoked to explain discrepancies from the results of a simple fractional crystallization model. Difference in source rocks, temperature, pressure, activity of water, mixing and repeated melting have been used to the same effect for partial melting models. Since so many variations exist on either theme, they may be difficult to refute. That is, they are not easily testable. For example, the isotope ratios of O and Th have been used to show that hydrated older crust is involved in the generation of silicic rocks, but this has been interpreted to result from fractional crystallization of basaltic magma coupled with assimilation (Nicholson et al., 1991), or from partial melting of metabasic rocks (Sigmarsson et al., 1991, 1992).

It may be possible to look at this problem in a different way. One way could be to attempt testing whether silicic rocks in Iceland could be formed by near-solidus differentiation or near-liquidus differentiation (Jónasson, 1994, 2005). Near-solidus differentiation (Marsh et al., 1991) involves the removal of melt from a near-solidus (mostly crystals) source. The source may be cooling gabbroic intrusions, heated crustal rocks, or a combination of both (Gunnarsson

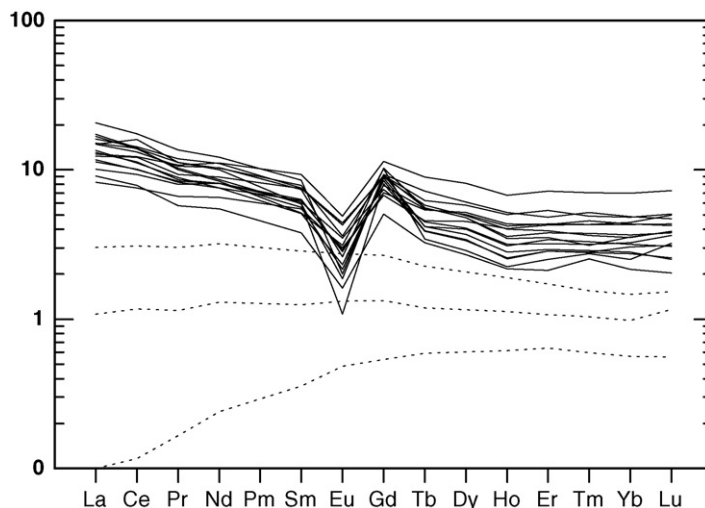


Fig. 6. REE patterns of silicic rocks from Iceland. The analyses were done using ICP-MS at the University of Bristol. The values are normalized to E-MORB values (Sun and McDonough, 1989). The solid lines show the patterns of the 16 samples presented in Table 1. Considering that this is a representative set of samples of silicic rocks from Iceland, their patterns are remarkably similar. The dashed lines show the patterns of depleted and enriched olivine tholeiites and an evolved tholeiite from Iceland for comparison (BTHO, RSG35 and SAL79; Hemond et al., 1993). The latter two are probably more representative for the types of basaltic rocks found beneath central volcanoes. See text for discussion.

et al., 1998). Given sufficient time to attain near-equilibrium conditions, the resulting composition of silicic magma can be modelled as equilibrium crystallization or batch melting, that is near-equilibrium of a small amount of silicic melt with a large amount of crystals. It should be kept in mind though, that high rates of cooling or heating will inhibit equilibration with the bulk of the crystals and in that case a simple fractional crystallization model would be more appropriate. (Martin and Sigmarsson, 2005). Near-liquidus differentiation involves the gradual removal of crystals from a near-liquidus (mostly liquid) source leading to more and more differentiated liquids (i.e. classic magma chamber models). The resulting composition of silicic magma can be modelled in terms of removal of fractional amounts of crystals in equilibrium with an evolving melt. The geochemical effects of these two alternatives can be modelled as equilibrium crystallization versus fractional crystallization, which lead to slightly different results and may therefore be testable, or at least give an indication of which type of process better explains the data. Another significant difference between these two alternatives is that near-liquidus differentiation is a gradual process leading to a liquid line of descent while near-solidus differentiation occurs in discrete discontinuous steps.

It should be noted that near-liquidus differentiation includes fractional crystallization by gravity settling or wall-rock crystallization in a magma chamber, possibly coupled with magma recharge or assimilation of country rocks, while near-solidus differentiation includes partial melting of crustal rocks as well as generation of silicic (granophyric) segregations by equilibrium crystallization in gabbroic intrusions. Therefore, looking at the problem in this way is not necessarily in disagreement with earlier interpretations and may not seem to be a very different approach. There is, however, a fundamental difference between near-liquidus and near-solidus differentiation, which is the environment in which these processes take place. Near-liquidus differentiation takes place within a large, mostly liquid, primarily basaltic magma chamber, while near-solidus differentiation takes place within a mostly solid intrusive domain with a mixture of rock types. The following discussion will look at some of the different types of existing data in this context.

The composition of volcanic rocks in Iceland is strongly bimodal, i.e. basaltic compositions predominate, with up to 15% silicic compositions, but intermediate compositions are quite rare. This is more compatible with near-solidus differentiation, with discrete steps of evolution instead of a gradual process like near-liquidus differentiation. In other words, the volcanic rocks of Iceland display bimodal composition reflecting bimodal differentiation (Marsh, 2002), the petrogenetic processes forming silicic rocks being separated from the processes forming basaltic rocks.

The Icelandic rhyolites plot close to the thermal minimum in the “granite” system (Fig. 3a). The dacites and trachytes plot towards higher temperatures within the plagioclase volume or towards the alkali feldspar minimum. Even though the projected composition of some of the rhyolites in the “granite” system indicates that they lie on a quartz–feldspar cotectic, quartz is generally not found as a phenocryst phase (Carmichael, 1963). With near-liquidus

differentiation, gradual cooling leads to crystallization and there is no obvious reason why quartz should not have crystallized in some rhyolites having formed in such a process. Pressure has a significant effect on the position of the quartz–plagioclase cotectic, the plagioclase volume expanding at the expense of the quartz volume with decreasing pressure (e.g. Nekvasil, 1988; Johannes and Holtz, 1996). The ascent of a silicic magma would therefore lead to resorption of quartz and crystallization of plagioclase. Rhyolites formed by near-liquidus differentiation would be expected to occasionally contain small amounts of resorbed quartz, unless they always ascend slowly enough to resorb all of the earlier formed quartz. If the rhyolites formed by near-solidus differentiation and separated crystal free from the source they would be expected to crystallize plagioclase during ascent, but quartz would only be able to crystallize if the silicic magma were held at constant pressure with decreasing temperature for some time. The lack of quartz phenocrysts therefore fits better with near-solidus differentiation.

The zoning of phenocrysts in the silicic rocks is small and the zoning pattern variable. Usually both normal and reverse zoning can be observed in the same rock and resorption is common. The gradual process of near-liquidus differentiation would be expected to result in the predominance of normal zoning in phenocrysts, especially plagioclase. This is however, not what is observed in the silicic rocks, which typically show only weak reverse as well as normal zonation and neither type being predominant.

Experimentalists have shown that silicic melts with the major-element characteristics displayed in Icelandic silicic rocks can be formed by near-solidus differentiation (equilibrium crystallization or melting) at temperatures of around 900 °C if water pressure is less than 1 kb. Higher water pressures lead to the production of rocks with a lower Fe content (e.g. Helz, 1976; Spulber and Rutherford, 1983; Thy et al., 1990). Such rocks have been found in the Tertiary Króksfjörður central volcano where calc-alkaline dacites have formed by dehydration melting at amphibolite facies conditions relatively deep in the crust (Jónasson et al., 1992). This is an exception though, other silicic rocks in Iceland have formed at lower water pressure at shallower levels. Dacites from the Hekla central volcano have been inferred to have formed by fluid absent melting of amphibolite at 950 °C and 3 kb (Sigmarsson et al., 1992), though their geochemical characteristics are quite different from the calc-alkaline rocks from Króksfjörður and closer to other silicic rocks in Iceland. The high K₂O-concentrations seen in some of the rhyolites from the flank zones were not reproduced in the melting experiments, but this was suggested to be directly related to the composition of the starting materials (Thy et al., 1990). Therefore, using more K-rich basalts as starting material would lead to higher K₂O-concentrations in the rhyolites.

Trace-element patterns resulting from near-liquidus differentiation may differ significantly from those resulting from near-solidus differentiation. The crystals removed during near-liquidus differentiation have been in equilibrium with a series of evolving melts. A large part of the removed crystals have equilibrated with basaltic melts, some have equilibrated with intermediate melts and some with silicic melts. Given sufficient time, the bulk of the crystals left behind during near-solidus differentiation were close to equilibrium with a silicic melt only. Partition coefficients for many elements are markedly different in basaltic and silicic melts because of the highly polymerized nature of silicic melts (Mahood and Hildreth, 1983; Nash and Crecraft, 1985; Michael, 1988; Sisson, 1991). This is especially true for many of the high-field-strength elements (including the REE) where partition coefficients are generally much higher in silicic melts than in basaltic melts. Near-liquidus differentiation would therefore lead to greater and more even enrichment of these elements in the resulting silicic melts, and less fractionation between different elements. The large variation in reported partition coefficients for silicic systems makes quantitative modelling difficult, but qualitatively trace-element patterns in silicic rocks from Iceland are more consistent with near-solidus differentiation (e.g. Jónasson, 1994, 2005).

When the REE patterns of silicic rocks are compared with the pattern of an average basalt (Fig. 6), it can be seen that while the light REE are enriched by a factor of about 10, the middle to heavy REE are only enriched by a factor of about 4. The middle to heavy REE generally behave as incompatible elements when the equilibrium liquid is basaltic to intermediate. When the equilibrium liquid is silicic the middle to heavy REE are more compatible in the crystals, especially clinopyroxene. Several studies have found that about 90% fractional crystallization of a tholeiitic basalt would be required to produce rhyolite melts (e.g. Macdonald et al., 1990; Jónasson, 1994). During most of this differentiation process, the equilibrium liquid is basaltic to intermediate. Therefore, the middle to heavy REE would be expected to be more enriched in the silicic rocks (enrichment factor closer to 10), leading to a flatter REE pattern. With near-solidus differentiation the crystals only equilibrate with a silicic liquid and the enrichment of middle to heavy REE will therefore be less pronounced than during near-liquidus fractionation. Thus, the REE patterns fit better with near-solidus differentiation.

The variations in Ba-concentrations in silicic rocks from the western flank zone and the Torfajökull central volcano indicate involvement of K-feldspar, either through assimilation of Ba-rich K-feldspar from older silicic rocks or through near-liquidus fractionation of lower viscosity fluorine- and alkali-rich silicic melts.

The results of different studies of the isotope geochemistry of silicic and basaltic rocks in Iceland lead to the conclusion that the silicic rocks are generated from basaltic rocks similar to those produced by the same volcano, but these basaltic rocks are significantly older than the silicic melts, and meteoric water has been added to the equation. This agrees well with near-solidus differentiation within an intrusive domain below the volcano. The intrusive domain would consist of hydrothermally altered lavas and volcanoclastic sediments, in most cases earlier products of the same volcano, together with gabbroic intrusions possibly containing silicic (granophyric) segregations. Parts of this domain are likely to have sustained temperatures of 900–950 °C, favorable for generating silicic melts. The large time difference indicated by studies of Th isotopes and Th/U-ratios would be difficult to accommodate in any near-liquidus differentiation scenario.

Taken together, these various arguments indicate that the origin of silicic rocks in Iceland is better explained by models of near-solidus differentiation than models of near-liquidus differentiation, though stopping short of refuting near-liquidus differentiation altogether. Near-liquidus differentiation processes may have contributed to modifying the geochemistry of silicic rocks from the western flank zone and the Torfajökull central volcano.

6. Melt segregation

Assuming that silicic melts are formed by some form of near-solidus differentiation it is appropriate to examine how they can be extracted from their source and subsequently erupted.

It is well established that there is a several orders of magnitude difference between the viscosity of basaltic and silicic melts (Shaw, 1972; Johannes and Holtz, 1996). Compared with silicic rocks in general, the Icelandic rocks cooled from relatively dry, relatively metaluminous silicic melts. Such melts would be highly polymerized and have a very high viscosity, even compared to other silicic melts. High contents of components such as H₂O or especially F can reduce this somewhat. Higher fluorine content in the more alkalic flank-zone rhyolites (Sigvaldason and Óskarsson, 1986) may induce lower viscosity in the melt producing these rocks.

The high viscosity of silicic melts has several important consequences. The separation of crystals and melt becomes much more difficult. The settling rate of crystals becomes so slow that crystal settling by gravity becomes unrealistic (McKenzie, 1985). Furthermore diffusion rates for many elements are greatly reduced, slowing down the crystallization rate. High viscosity also makes convection more difficult and with low diffusion rates, wall-rock crystallization will be difficult on a large scale. It is possible, however, to segregate highly viscous melts from a near-solidus mixture of melt and crystals. If the solid portion of the source forms a rigid framework, it can behave as brittle material. This would allow mechanical deformation to squeeze out the interstitial melt. The “critical melt fraction” below which crustal rocks display brittle behaviour is thought to be less than 50%. Such processes have been proposed for explaining the formation of granophyric veins and pods within gabbroic intrusions. Deformation causes fracturing in the near-solidus crust, drawing interstitial melt into the fractures. The deformation may occur because of internal forces within cooling intrusions by solidification front instability (Marsh, 2002), or because of external forces producing shear deformation as in deformation-assisted melt segregation (Jónasson, 1994, 2005).

The distribution of silicic rocks within the volcanic zones lends some support to the deformation-assisted melt segregation model. The deformation could be the result of inflation-deflation events in central volcanoes, subsidence due to edifice load forming ring fractures and calderas, or differential movement within large- or small-scale shear zones.

7. Conclusions

It has been discussed that silicic rocks in Iceland are not likely to have formed by near-liquidus processes (evolution from basaltic melt by separation of crystals at temperatures close to the liquidus temperatures of the melts), but rather by near-solidus processes (as near-minimum melts in basaltic or gabbroic rocks).

Because of the high viscosity of these relatively dry, relatively metaluminous melts it can be difficult to segregate the near-minimum melts from the source rocks. It is hypothesized here that this happens by deformation-induced melt segregation. Relatively rapid tectonic movements cause the silicic melt to be squeezed out of the source rock and into

veins and dykes. These tectonic movements could be rapid inflation or deflation within central volcanoes or rapid movement in shear zones which are formed where the rift zones change direction or are shifted.

The source of the silicic rocks would therefore be within an intrusive complex beneath a central volcano rather than in a large, long-lived magma chamber. The silicic melts may collect in holding reservoirs, but in most cases without significant further differentiation.

Acknowledgements

The author is grateful to the Icelandic Research Council (Rannís), for financial support, the European Union TMR programme for providing access to the Geochemical Facility at the University of Bristol, Dr. Paul-Martin Holm for providing the XRF analyses at GEUS, Copenhagen and the Icelandic Institute of Natural History for supporting the project. Insightful and constructive reviews of an early version of the manuscript by Dr. S. Jakobsson and Prof. S. Steinþórsson are much appreciated, as are the reviews of Dr. Olgeir Sigmarsson and an anonymous reviewer.

References

- Allen, R.M., Nolet, G., Morgan, W.J., Vogfjörð, K., Nettles, M., Ekström, G., Bergsson, B.H., Erlendsson, P., Foulger, G.R., Jakobsdóttir, S., Julian, B.R., Pritchard, M., Ragnarsson, S., Stefánsson, R., 2002. Plume-driven plumbing and crustal formation in Iceland. *J. Geophys. Res.*, 107, 10.1029/2001JB000584.
- Baker, P.E., 1974. Peralkaline acid volcanic rocks of oceanic islands. *Bull. Volcanol.* 38, 737–754.
- Blake, S., 1984. Magma mixing and hybridization processes at the alkalic, silicic, Torfajökull central volcano triggered by tholeiitic *Veidivötn* fissuring, south Iceland. *J. Volcanol. Geotherm. Res.* 22, 1–31.
- Calderone, G.M., Grönvold, K., Óskarsson, N., 1990. The welded air-fall tuff layer at Krafla, northern Iceland: a composite eruption triggered by injection of basaltic magma. *J. Volcanol. Geotherm. Res.* 44, 303–314.
- Carmichael, I.S.E., 1963. The crystallization of feldspar in volcanic acid liquids. *Quart. J. Geol. Soc. Lond.* 119, 95–131.
- Carmichael, I.S.E., 1964. The petrology of Thingmuli, a Tertiary volcano in eastern Iceland. *J. Petrol.* 5, 435–460.
- Carmichael, I.S.E., 1967. The mineralogy of Thingmuli, a Tertiary volcano in eastern Iceland. *Am. Mineral.* 52, 1815–1841.
- Condoin, M., Grönvold, K., Hooker, P.J., Muehlenbachs, K., O’Nions, R.K., Óskarsson, N., Oxburgh, E.R., 1983. Helium, oxygen, strontium and neodymium isotopic relationships in Icelandic volcanics. *Earth Planet. Sci. Lett.* 66, 125–136.
- Darbyshire, F.A., White, R.S., Priestley, K.F., 2000. Structure of the crust and uppermost mantle of Iceland from a combined seismic and gravity study. *Earth Planet. Sci. Lett.* 181, 409–428.
- Eichelberger, J.C., 1995. Silicic volcanism: ascent of viscous magmas from crustal reservoirs. *Annu. Rev. Earth Planet. Sci.* 23, 41–63.
- Einarsson, T., 1950. Chemical analyses and differentiation of Hekla’s magma. *Soc. Sci. Islandica. The Eruption of Hekla 1947–1948.* IV.
- Furman, T., Frey, F.A., Meyer, P.S., 1992. Petrogenesis of evolved basalts and rhyolites at Austurhorn, southeastern Iceland: the role of fractional crystallization. *J. Petrol.* 33, 1405–1445.
- Furnes, H., Friðleifsson, I.B., Atkins, F.B., 1980. Subglacial volcanics—on the formation of acid hyaloclastites. *J. Volcanol. Geotherm. Res.* 8, 95–110.
- Gautason, B., Muehlenbachs, K., 1998. Oxygen isotopic fluxes associated with high-temperature processes in the rift zones of Iceland. *Chem. Geol.* 145, 275–286.
- Grönvold, K., 1972. Structural and petrochemical studies in Kerlingarfjöll region, central Iceland. Unpublished Ph.D. thesis, Oxford, England.
- Gunnarsson, B., Marsh, B.D., Taylor, H.P., 1998. Generation of Icelandic rhyolites: silicic lavas from the Torfajökull central volcano. *J. Volcanol. Geotherm. Res.* 83, 1–45.
- Harðardóttir, V., 1983. The petrology of the Hengill volcanic system, southern Iceland. Unpublished M.Sc. thesis, McGill University, Montreal, Canada.
- Harðarson, B.S., 1993. Alkalic rocks in Iceland with special reference to the Snæfellsjökull volcanic system. Unpublished Ph.D. thesis, University of Edinburgh.
- Hards, V.L., Kempton, P.D., Thompson, R.N., Greenwood, P.B., 2000. The magmatic evolution of the Snæfell volcanic centre; an example of volcanism during incipient rifting in Iceland. *J. Volcanol. Geotherm. Res.* 99, 97–121.
- Helz, R.T., 1976. Phase relations of basalts in their melting range at $P_{H_2O} = 5$ kb as a function of oxygen fugacity, Part II. Melt compositions. *J. Petrol.* 17, 139–193.
- Hemond, C., Arndt, N.T., Lichtenstein, U., Hofmann, A.W., Óskarsson, N., Steinþórsson, S., 1993. The heterogeneous Iceland plume: Nd–Sr–O isotopes and trace element constraints. *J. Geophys. Res.* 98, 15833–15850.
- Jakobsson, S.P., 1972. Chemistry and distribution pattern of recent basaltic rocks in Iceland. *Lithos* 5, 365–386.
- Jakobsson, S.P., 1979. Petrology of Recent basalts of the Eastern Volcanic Zone, Iceland. *Acta Nat. Islandica* 26, 1–103.
- Johannes, W., Holtz, F., 1996. *Petrogenesis and Experimental Petrology of Granitic Rocks.* Springer-Verlag, Germany.
- Jóhannesson, H., Flores, R.M., Jónsson, J., 1981. A short account of the Holocene tephrochronology of the Snæfellsjökull central volcano, Western Iceland. *Jökull* 31, 23–30.
- Jóhannesson, H., Sæmundsson, K., 1998. Geological Map of Iceland. 1:500 000. Bedrock Geology, second ed. Icelandic Institute of Natural History, Reykjavík.

- Jónasson, K., 1994. Rhyolite volcanism in the Krafla central volcano, north-east Iceland. *Bull. Volcanol.* 56, 516–528.
- Jónasson, K., 2005. Magmatic evolution of the Heiðarsporður ridge, NE-Iceland. *J. Volcanol. Geotherm. Res.* 147, 109–124.
- Jónasson, K., Holm, P.M., Pedersen, A.K., 1992. Petrogenesis of silicic rocks from the Króksfjörður central volcano, NW Iceland. *J. Petrol.* 33, 1345–1369.
- Jónsson, J., 1965. Forn eldvörp í Selhrauni (in Icelandic). *Náttúrufræðingurinn* 35, 1–48.
- Jørgensen, K.A., 1980. The Thorsmörk ignimbrite: an unusual comenditic pyroclastic flow in southern Iceland. *J. Volcanol. Geotherm. Res.* 8, 7–22.
- Kaban, M.K., Flóvenz, Ó.G., Pálmason, G., 2002. Nature of the crust-mantle transition zone and the thermal state of the upper mantle beneath Iceland from gravity modelling. *Geophys. J. Int.* 149, 281–299.
- Lacasse, C., Garbe-Schönberg, C.-D., 2001. Explosive silicic volcanism in Iceland and the Jan Mayen area during the last 6 Ma: sources and timing of major eruptions. *J. Volcanol. Geotherm. Res.* 107, 113–147.
- Lacasse, C., Sigurðsson, H., Jóhannesson, H., Paterne, M., Carey, S., 1995. Source of Ash Zone 1 in the North Atlantic. *Bull. Volcanol.* 57, 18–32.
- Larsen, G., Newton, A.J., Dugmore, A.J., Vilmundardóttir, E.G., 2001. Geochemistry, dispersal, volumes and chronology of Holocene silicic tephra layers from the Katla volcanic system, Iceland. *J. Quatern. Sci.* 16, 119–132.
- LeMaitre, R.W. (Ed.), 2002. Recommendations of the IUGS on the Systematics of Igneous Rocks, second ed. Blackwell Scientific, London.
- Macdonald, R., McGarvie, D.W., Pinkerton, H., Smith, R.L., Palacz, C.A., 1990. Petrogenetic evolution of the Torfajökull volcanic complex. Iceland I. Relationship between the magma types. *J. Petrol.* 31, 429–459.
- Macdonald, R., Sparks, R.S.J., Sigurðsson, H., Matthey, D.P., McGarvie, D.W., Smith, R.L., 1987. The 1875 eruption of Askja volcano, Iceland: combined fractional crystallization and selective contamination in the generation of rhyolitic magma. *Min. Mag.* 51, 183–202.
- Mahood, G., Hildreth, W., 1983. Large partition coefficients for trace elements in high-silica rhyolites. *Geochim. Cosmochim. Acta* 47, 11–30.
- Marsh, B.D., 2002. On bimodal differentiation by solidification front instability in basaltic magmas, part 1: basic mechanics. *Geochim. Cosmochim. Acta* 66, 2211–2229.
- Marsh, B.D., Gunnarsson, B., Congdon, R., Carmody, R., 1991. Hawaiian basalt and Icelandic rhyolite: indicators of differentiation and partial melting. *Geol. Rundschau* 80, 481–510.
- Martin, E., Sigmarsson, O., 2005. Trondhjemitic and granitic melts formed by fractional crystallization of an olivine tholeiite from Reykjanes Peninsula, Iceland. *Geol. Mag.* 142, 651–658.
- McGarvie, D.W., 1984. Torfajökull: a volcano dominated by magma mixing. *Geology* 12, 685–688.
- McGarvie, D.W., Macdonald, R., Pinkerton, H., Smith, R.L., 1990. Petrogenetic evolution of the Torfajökull volcanic complex, Iceland II. The role of magma mixing. *J. Petrol.* 31, 461–481.
- McKenzie, D., 1985. The extraction of magma from the crust and mantle. *Earth. Planet. Sci. Lett.* 74, 81–91.
- Michael, P.J., 1988. Partition coefficients for rare earth elements in mafic minerals of high silica rhyolites: the importance of accessory mineral inclusions. *Geochim. Cosmochim. Acta* 52, 275–282.
- Muehlenbachs, K., 1973. The oxygen isotope geochemistry of siliceous rocks from Iceland. *Geophys. Lab. Yearb.* 72, 593–597.
- Mørk, M.B.E., 1984. Magma mixing in the post-glacial Veidivötn fissure eruption, southeast Iceland: a microprobe study of mineral and glass variations. *Lithos* 17, 55–75.
- Nash, W.P., Crecraft, H.R., 1985. Partition coefficients for trace elements in silicic magmas. *Geochim. Cosmochim. Acta* 49, 2309–2322.
- Nekvasil, H., 1988. Calculated effect of anorthite component on the crystallization paths of H₂O-undersaturated haplogranitic melts. *Am. Mineral.* 73, 966–981.
- Nicholson, H., Condomines, M., Fitton, J.G., Fallick, A.E., Grönvold, K., Rogers, G., 1991. Geochemical and isotopic evidence for crustal assimilation beneath Krafla, Iceland. *J. Petrol.* 32, 1005–1020.
- O’Nions, R.K., Grönvold, K., 1973. Petrogenetic relationships of acid and basic rocks in Iceland: Sr isotopes and rare earth elements in late postglacial volcanics. *Earth Planet. Sci. Lett.* 19, 397–409.
- Óskarsson, N., Sigvaldason, G.E., Steinþórsson, S., 1982. A dynamic model of rift zone petrogenesis and the regional petrology of Iceland. *J. Petrol.* 23, 28–74.
- Prestvik, T., 1982. Petrography, chemical characteristics and nomenclature of Öraefajökull rocks. *Jökull* 32, 69–76.
- Prestvik, T., 1985. Petrology of quaternary volcanic rocks from Öraefi, southeast Iceland. Rep. 21, Geol. Inst., NTH, Trondheim.
- Prestvik, T., Goldberg, S., Karlsson, H., Grönvold, K., 2001. Anomalous strontium and lead isotope signatures in the off-rift Öraefajökull central volcano in south-east Iceland. Evidence for enriched endmember(s) of the Iceland mantle plume? *Earth Planet. Sci. Lett.* 190, 211–220.
- Shaw, H.R., 1972. Viscosities of magmatic silicate liquids: an empirical method of prediction. *Am. J. Sci.* 272, 870–893.
- Sigmarsson, O., Condomines, M., Fourcade, S., 1992. A detailed Th, Sr and O isotope study of Hekla: differentiation processes in an Icelandic Volcano. *Contrib. Mineral. Petrol.* 112, 20–34.
- Sigmarsson, O., Hémond, C., Condomines, M., Fourcade, S., Óskarsson, N., 1991. Origin of silicic magma in Iceland revealed by Th isotopes. *Geology* 19, 621–624.
- Sigurðsson, H., 1968. Petrology of acid xenoliths from Surtsey. *Geol. Mag.* 105, 440–453.
- Sigurðsson, H., 1970. The petrology and chemistry of the Setberg volcanic region and of the intermediate and acid rocks of Iceland. Unpublished Ph.D. thesis, Durham, England.
- Sigurðsson, H., 1971. Feldspar relations in Icelandic alkalic rhyolites. *Min. Mag.* 38, 503–510.
- Sigurðsson, H., Sparks, R.S.J., 1981. Petrology of rhyolitic and mixed magma ejecta from the 1875 eruption of Askja, Iceland. *J. Petrol.* 22, 41–84.
- Sigvaldason, G.E., 1974. The petrology of Hekla and origin of silicic rocks in Iceland. *Soc. Sci. Islandica* V, 1–44.
- Sigvaldason, G.E., 2002. Volcanic and tectonic processes coinciding with glaciation and crustal rebound: an early Holocene rhyolitic eruption in the Dyngjufjöll volcanic centre and the formation of the Askja caldera, north Iceland. *Bull. Volcanol.* 64, 192–205.
- Sigvaldason, G.E., Óskarsson, N., 1986. Fluorine in basalts from Iceland. *Contrib. Mineral. Petrol.* 94, 263–271.

- Sisson, T.W., 1991. Pyroxene-high silica rhyolite trace element partition coefficients measured by ion microprobe. *Geochim. Cosmochim. Acta* 55, 1575–1585.
- Sparks, R.S.J., Sigurðsson, H., Wilson, L., 1977. Magma mixing: a mechanism for triggering acid explosive eruptions. *Nature* 267, 315–318.
- Spulber, S.D., Rutherford, M.J., 1983. The origin of rhyolite and plagiogranite in oceanic crust: an experimental study. *J. Petrol.* 24, 1–25.
- Stecher, O., Carlson, R.W., Gunnarsson, B., 1999. Torfajökull: a radiogenic end-member of the Iceland Pb-isotopic array. *Earth Planet. Sci. Lett.* 165, 117–127.
- Sun, S.-S., McDonough, W.F., 1989. Chemical and isotopic systematics of oceanic basalts: implications for mantle composition and processes. In: Saunders, A.D., Norry, M.J. (Eds.), *Magmatism in the Ocean Basins*, vol. 42. *Geol. Soc. London Spec. Publ.*, pp. 313–346.
- Sæmundsson, K., 1967. Vulkanismus und Tektonik des Hengill-Gebietes in Südwest-Island. *Acta Nat. Islandica*, II 7, 1–105.
- Sæmundsson, K., 1978. Fissure swarms and central volcanoes of the neovolcanic zones of Iceland. *Geol. J. Spec. Issue* 10, 415–432.
- Sæmundsson, K., 1980. Outline of the geology of Iceland. *Jökull* 29, 7–28.
- Sæmundsson, K., 1992. Geology of the Thingvallavatn area. In: Jónasson, P.M. (Ed.), *Ecology of Oligothropic, Subarctic Thingvallavatn*, vol. 64, *Oikos*, pp. 40–68.
- Sæmundsson, K., Jóhannesson, H., Grönvold, K., 2005. Hróthálsar, megineldstöð í Ódáðahrauni (in Icelandic). In: *Geoscience Society of Iceland, Spring Meeting 2005*, pp. 47–48.
- Taylor, S.R., McLennan, S.M., 1985. *The Continental Crust: Its Composition and Evolution*. Blackwell, Oxford.
- Thorarinsson, S., 1958. The Öraefajökull eruption of 1362. *Acta Nat. Islandica*, II 2, 1–99.
- Thorarinsson, S., 1967. The eruptions of Hekla in historical times. A Tephrochronological Study. *Soc. Sci. Islandica. The Eruption of Hekla 1947–1948. I*.
- Thy, P., Beard, J.S., Lofgren, G.E., 1990. Experimental constraints on the origin of Icelandic rhyolites. *J. Geol.* 98, 417–421.
- Tuffen, H.J., Gilbert, J., McGarvie, D., 2001. Products of an effusive subglacial rhyolite eruption: Bláhnúkur, Torfajökull, Iceland. *Bull. Volcanol.* 63, 179–190.
- Tuttle, O.F., Bowen, N.L., 1958. Origin of granite in the light of experimental studies in the system $\text{NaAlSi}_3\text{O}_8\text{--KAlSi}_3\text{O}_8\text{--SiO}_2\text{--H}_2\text{O}$. *Geol. Soc. Am. Mem.*, 74.
- Walker, G.P.L., 1963. The Breiðdalur central volcano, eastern Iceland. *Q. J. Geol. Soc. Lond.* 119, 29–63.
- Walker, G.P.L., 1966. Acid volcanic rocks in Iceland. *Bull. Volcanol.* 29, 375–406.
- Warshaw, C.M., Smith, R.L., 1988. Pyroxenes and fayalites in the Bandelier Tuff, New Mexico: temperatures and comparison with other rhyolites. *Am. Min.* 73, 1025–1037.
- Wiese, P.K., 1993. Geochemistry and geochronology of the Eyjafjöll volcanic system. Unpublished M.Sc. thesis, Oregon State University.