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Trondhjemitic and granitic melts formed by fractional crystallization of an olivine tholeiite from Reykjanes Peninsula, Iceland

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Abstract – A pair of samples, from host lava and an included segregation vein from the Reykjanes Peninsula, Iceland, allows the assessment of a complete fractional crystallization of an olivine tholeiite at low pressure. The final product consists of silicic glasses with bimodal composition: trondhjemitic and more rarely granitic. Compilation of data on major element compositions of Icelandic silicic rocks reveals a clear difference from those of the segregation glasses. Fractional crystallization of basalts at low pressure is therefore not the most likely mechanism for the origin of silicic magmas in Iceland. Similar conclusions have been reached in studies on O- and Th-isotope compositions. On the other hand, the trondhjemitic compositions of the glasses in the segregation vein from Reykjanes Peninsula suggest that fractional crystallization of olivine tholeiites could have played a significant role during the formation of the very early continental crust.

Keywords: Iceland, fractional crystallization, trondhjemite, segregation vein, interstitial glass.

1. Introduction

The question of how the primitive continental crust was formed is not readily answered because of the lack of rock record older than the Archaean. Today, continental crust is generated in subduction zones, principally by partial melting of the metasomatized mantle wedge yielding ordinary calc-alkaline magmas (e.g. Wyllie & Sekine, 1982; Tatsumi, 1989) and, more rarely, by direct melting of the subducted slab, which generates adakites (e.g. Defant & Drummond, 1990; Martin, 1999). Similarly, the TTG (tonalite, trondhjemite and granodiorite) association, typical of Archaean continental crust, has also been suggested to be related to subduction zones (e.g. Martin, 1986; Rapp, 1995; Martin *et al.* 2005). In a very different tectonic setting, relatively large amounts of silicic magmas are erupted in Iceland, where a mid-ocean ridge and a mantle plume interact. Such a context might have been frequent on the early and hotter Earth during the Hadean eon. Early existence of continental crust is indeed suggested by the discovery of 4.4 Ga old zircons (Mojzsis, Harrison & Pidgeon, 2001; Wilde *et al.* 2001), although very little is known about its character. The same holds for the formation of extraterrestrial 'continental crust' such as on Mars (see Sotin, 2005 for review). If the interaction of mantle plumes and mid-ocean ridges was frequent in the past, then an understanding of the origin of silicic magmas in Iceland would be relevant for an improved comprehension of the origin of these early crusts.

The origin of silicic magma in Iceland has long been debated, and the proposed models fall into three categories, as follows:

(1) Dacites and rhyolites are derived from basaltic magmas through fractional crystallization processes (e.g. Carmichael, 1964; Wood, 1978; Macdonald *et al.* 1990; Furman, Frey & Meyer, 1992).

(2) Silicic magmas result from partial melting of hydrated metabasalts (e.g. O'Nions & Gronvold, 1973; Oskarsson, Sigvaldason & Steinthorsson, 1982; Nicholson *et al.* 1991; Sigmarsson *et al.* 1991; Sigmarsson, Condomines & Fourcade, 1992; Jónasson, 1994). In this case, mantle-derived and more evolved basalts interact with water in geothermal systems and are transformed into amphibolites or lower-grade metamorphic assemblages. Subsequent dehydration melting gives rise to silicic melts.

(3) A third group of models is in many respects a combination of the two previous ones. In a first stage, fractional crystallization of basaltic magma produces silicic or intermediate intrusive rocks and, in a second stage, intrusion of hotter basaltic magmas melts the more differentiated rocks and thus produces large volumes of silicic magma (Sigurdsson, 1977; Sigurdsson & Sparks, 1981; Gunnarsson, Marsh & Taylor, 1998).

The aim of this study is to address the problem of the origin of silicic magma in Iceland from a different

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angle. It summarizes major element constraints from a detailed investigation of segregation veins in tholeiitic lava flows on a more global scale (Martin & Sigmarsson, unpub. data). In these veins, very high degrees of fractional crystallization are reached, producing interstitial silica-rich glasses. Here, we discuss the mechanisms of formation of two distinct glasses, having trondhjemitic and granitic compositions, in a single olivine tholeiite lava sheet from the Reykjanes Peninsula, and compare their compositions with those of Icelandic silicic rocks. Finally, we speculate about the implications of our results for primitive continental crust formation.

2. Geological setting

The interaction of a mid-ocean ridge and a mantle plume in Iceland results in magmatism displaying variable characteristics on the island. For instance, the influence of the Iceland mantle plume is less pronounced on the Reykjanes Peninsula where magma productivity is lower and silicic magmas are absent, compared to Central Iceland with four to five times higher productivity (Jakobsson, 1972) and several mature central volcanoes producing highly evolved silicic magmas. The Reykjanes Peninsula is characterized by picrites and olivine tholeiites forming small and large shield volcanoes, respectively, and quartz-normative tholeiites produced from fissure eruptions during post-glacial time (Jakobsson, Jonsson & Shido, 1978). The samples of this study, host lava (HRG2) and a segregation vein (HRG4), come from an olivine tholeiite lava shield of early Holocene age (Fig. 1).

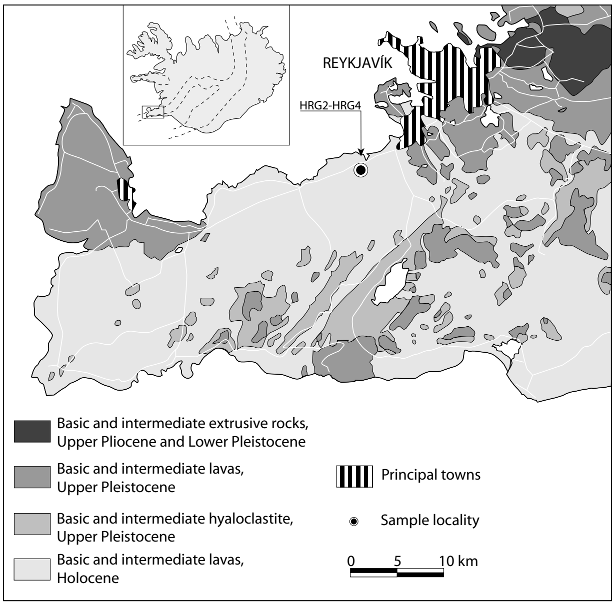

Figure 1. Simplified geological map of Reykjanes Peninsula (Iceland) showing samples location (host lava: HRG2 and segregation vein: HRG4). Modified from Jóhannesson & Saemundsson (1998).

Somewhat different models have been proposed for the formation of segregation veins in lava flows (Anderson *et al.* 1984; Goff, 1996; Marsh, 2002). Regardless of the details of vein formation, all authors agree that they result from internal differentiation of the host lava after approximately 50 % crystallization. After formation, the veins evolve as thermodynamically closed systems. This point is crucial, as it implies that the chemical composition of the magmatic liquid in the segregation veins evolved independently of that of the host lava.

3. Analytical methods

Glass compositions were measured with a CAMECA SX 100 electron microprobe (EMP). The concentrations of major elements were determined with a count time of 60 s per element, the EMP was calibrated on natural and synthetic mineral standards and raw data were corrected by an improved ZAF procedure. In order to avoid possible loss of Na during analysis, the beam was defocused with a current of 8 nA and an acceleration voltage of 15 kV. Most glass patches permitted only a beam defocusing to 2–3 μm in width, but in a few patches a larger beam (20 μm in diameter) was used, and in rare cases rasters of 15 μm × 15 μm could be analysed. The results of the three approaches are shown in Table 1. In total, 37 analysis with total oxides in the range of 98.5–101 % were obtained and are discussed here. Major element compositions of whole rock samples were measured on ULTIMA C Jobin-Yvon ICP-AES, using a purified lithium tetraborate fusion of rock powder. The ICP-AES analytical conditions are given in Cantagrel & Pin (1994) and international rock standards (BHVO-1, RGM-1 and JB-3) were used for instrument calibration.

4. Major element composition

The whole-rock compositions of both the host lava and the segregation vein are hypersthene- and olivine-normative (Table 1), illustrating their tholeiitic affinities. When compared to the host lava, the vein is MgO-poorer and FeO*-richer (FeO*/MgO equal to 1.45 and 2.44, respectively). The vein is about two times richer in K_2O with higher Na_2O concentrations and K_2O/Na_2O increases from 0.073 in the host lava to 0.1 in the segregation veins. The composition of the segregation vein falls on the extrapolation of the compositional trends defined by Jakobsson, Jonsson & Shido (1978) for Holocene basalts from Reykjanes Peninsula.

The production of the magmatic liquid forming the veins from host lava through fractional crystallization can be modelled by mass-balance (e.g. Stormer & Nicholls, 1978). Mineral compositions used for the calculation are those measured on crystals in our samples. The computed crystallizing assemblage consists of 56.5 % plagioclase ($An_{80}Ab_{20}$), 27 % clinopyroxene

Table 1. Major element composition of host lava, segregation vein and representative glass patches

			Glass				
	Host lava	Segregation vein	'K$_2$O-poor'			'K$_2$O-rich'	
Sample	HRG2	HRG4	15 × 15 μm	20 μm	3 μm	10 μm	2 μm
SiO_2	48.2	48.7	76.1	76.4	79.1	76.8	74.0
TiO_2	1.34	2.20	0.34	0.55	0.27	0.32	0.36
Al_2O_3	15.4	12.6	13.6	13.1	12.5	12.9	11.6
FeO*	11.8	15.5	1.07	2.35	0.52	1.29	4.43
MnO	0.17	0.22	–	0.02	0.01	–	0.13
MgO	8.13	6.36	–	0.01	–	–	0.30
CaO	12.9	11.5	2.35	1.93	1.78	0.24	1.28
Na_2O	1.98	2.46	5.20	5.26	5.57	2.58	2.62
K_2O	0.15	0.26	1.15	0.76	0.76	6.49	5.59
P_2O_5	0.13	0.21	n.d.	n.d.	n.d.	n.d.	n.d.
Total	100.2	99.9	99.9	100.4	100.5	100.6	100.3
Degree of crystallization (wt %)	–	44.2	87.4	80.9	80.8	97.8	97.4
Quartz	–	–	36.1	37.1	40.0	35.4	31.2
Orthoclase	0.83	1.56	6.81	4.47	4.44	38.1	33.0
Albite	16.9	21.1	44.0	44.3	46.9	21.7	22.1
Anorthite	33.0	22.9	10.4	9.54	6.81	1.16	3.54
Nepheline	–	–	–	–	–	–	–
Diopside	25.0	27.8	1.16	–	0.98	–	2.46
Hypersthene	11.5	17.1	0.80	3.47	–	1.83	7.21
Olivine	7.32	1.40	–	–	–	–	–
Apatite	0.30	0.49	–	–	–	–	–
Ilmenite	2.57	4.23	0.64	1.04	0.51	0.61	0.69
Magnetite	2.59	3.39	–	–	–	–	–

Normative composition of host lava and segregation vein is calculated assuming (Fe^{3+}/total Fe) = 0.15. No correction for Fe was applied to the glass patches due to low concentrations. For the glass analysis, raster surface and EMP beam diameters are listed. n.d. – not determined.

($Wo_{40}En_{48}Fs_{12}$), 16 % olivine (Fo_{71}), and 0.5 % FeTi-oxides ($Usp_{37}Mt_{63}$). The estimated degree of crystallization necessary to account for the segregation vein composition is thus approximately 44 %, with a sum of the squares of residuals close to 0.001.

Most of the segregation vein is crystallized (approximately 95 % of the volume), but small interstitial glass patches still remain (around 5 %). These glass patches, whose typical compositions are listed in Table 1, are highly silicic ($SiO_2 > 73$ %) and with low Al_2O_3 concentrations (~ 11–14 %). They are also characterized by a strong depletion in MgO, FeO*, TiO_2 and CaO. Surprisingly, the analyses reveal a bimodal distribution of Na_2O and K_2O. The majority of the glass analyses (32 out of a total of 37) have an average K_2O/Na_2O of about 0.2 and they are defined here as 'K_2O-poor' glasses. Based on the O'Connor (1965) classification, modified by Barker (1979), this Na-rich and K-poor silicic glass is referred to as trondhjemitic (Fig. 2). The second group of glasses is less frequent (5/37 analyses), with an average K_2O/Na_2O of about 2.5, and these are here referred to as 'K_2O-rich' glasses. According to the O'Connor–Barker classification, they have a typical granitic composition (Fig. 2).

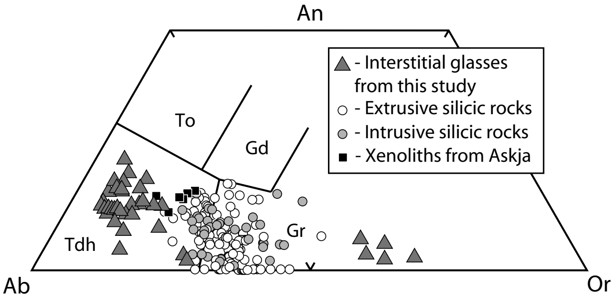

Figure 2. CIPW normative albite–anorthite–orthoclase (Ab–An–Or) classification diagram of O'Connor (1965), modified by Barker (1979), valid for > 10 % quartz normative rocks (Gr – granite, Tdh – trondhjemite, To – tonalite and Gd – granodiorite). Glasses from the segregation vein of Reykjanes Peninsula present a bimodal distribution of composition, mostly trondhjemitic and less frequently granitic. Extrusive and intrusive silicic rocks from Iceland have composition intermediate between trondhjemitic and granitic (144 samples compiled from the GEOROC database (http://georoc.mpch-mainz.gwdg.de/georoc/)). Trondhjemitic xenoliths from the 1875 eruption of Askja (Sigurdsson & Sparks, 1981) are also shown.

5. Differentiation mechanism

In both the host lava and the segregation vein, plagioclase and clinopyroxene are always normally zoned, excluding equilibrium crystallization as a realistic process for their differentiation. Fractional crystallization is a more likely differentiation mechanism for producing the segregation veins. As the differentiation takes place inside a lava flow at surface, it can be assumed to occur at a low pressure (less than a few 10^5 Pa, or bars), and in the following discussion the fractional crystallization of host lava and segregation vein liquids is taken to have proceeded close to atmospheric pressure.

Glass patches in the vein represent the last and most evolved liquids formed by the fractional crystallization of a segregation melt, which in turn has an intermediate composition due to host lava differentiation. Throughout the whole process, K_2O behaves as a strongly incompatible element (except during the very last phase of solidification, where K-feldspar crystallized). Potassium can therefore be used to estimate the degree of crystallization (1−F) necessary to generate the segregation melt and the final liquid, using the $F = (C_0/C_l)$ equation (where F is melt fraction, C_0 and C_l are concentrations of potassium in host lava and evolved melts, respectively). This gives a degree of crystallization of the host lava of 44–45 % producing the segregation melt, which is in perfect agreement with the crystallization extent estimated from major element mass-balance calculations. The same method applied to the glass compositions yields a degree of fractionation of approximately 80 % (≥ 75 %) for the 'K_2O-poor' glass and of about 97 % for the 'K_2O-rich' glass. It must be noted that in the very last stages of crystallization, during which potassium may exhibit less incompatible behaviour, the calculated values are minimum estimates of the degree of crystallization. In summary, this olivine–tholeiitic lava from the Reykjanes Peninsula, together with its segregation vein, provides a record of up to 97 % fractional crystallization at very low pressure.

6. Differentiation products

Most of the melt evolution of the basaltic lava flow can be described in the diopside–anorthite–albite (Di–An–Ab) system, due to the nature of the crystallizing minerals (≥ 80 % plagioclase and clinopyroxene), but the ultimate liquid evolution in the vein must be discussed in the quartz–albite–orthoclase (Qz–Ab–Or) system. When projected onto the Qz–Ab–Or phase diagram for 1 atmosphere pressure (Fig. 3a), the 'K_2O-rich' glasses plot close to the composition of the minimum of the granitic system proposed by Brugger, Johnston & Cashman (2003). In contrast, the 'K_2O-poor' glasses record a different behaviour and plot between the Qz and Ab corners far from the granitic minimum and straddle the quartz + feldspar + liquid cotectic valley proposed by Tuttle & Bowen (1958) and Brugger, Johnston & Cashman (2003). Several 'K_2O-poor' glasses plot well above the cotectic curve in the Qz field, since the effect of variable anorthite content of the plagioclase is not considered in the projection in Figure 3a. Indeed, variations of Ab/An ratios result in displacements of the cotectic valley and the granitic minimum projection. For instance, it is well established that at 0.2 GPa (or 2 kbar: e.g. Winkler, 1974) a decrease of the Ab/An ratio shifts the granitic minimum towards Ab-poorer values, whereas the cotectic valley moves towards the Qz corner. Increase in water pressure would have exactly the opposite effect (e.g.

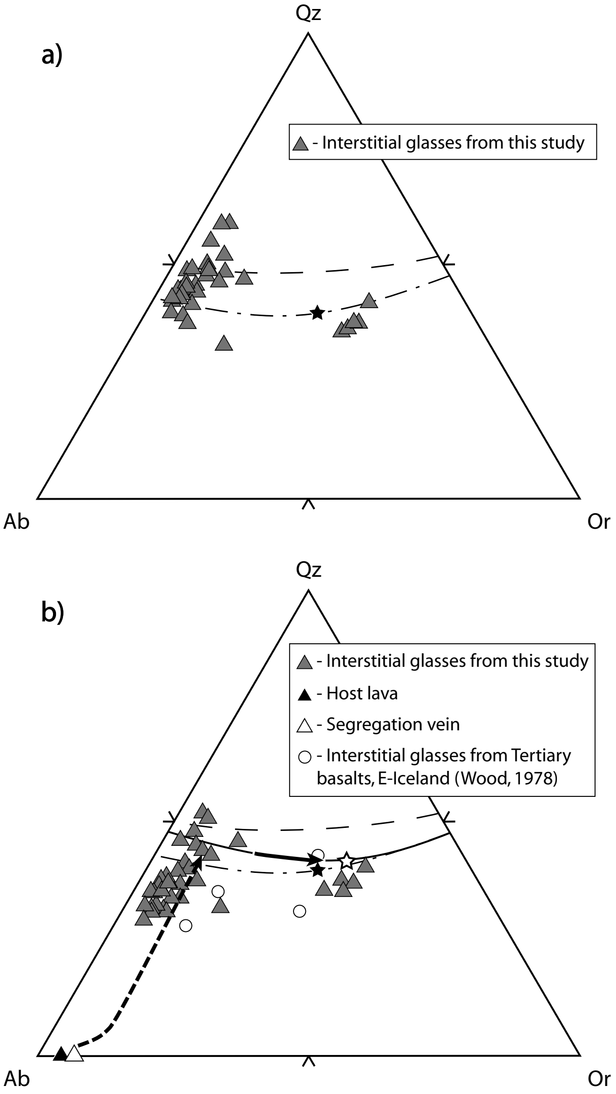

Figure 3. The one-atmosphere pressure quartz–albite–orthoclase phase diagram (CIPW-normative Qz–Ab–Or) showing: (a) the analysed glass composition from Reykjanes Peninsula, (b) recalculated compositions after corrections for the An-effect (see text for further details). Dashed curve corresponds to the experimental quartz + feldspar + liquid cotectic valley proposed by Tuttle & Bowen (1958). Dot-and-dash curve and black star represent respectively the cotectic valley and the system's minimum proposed by Brugger, Johnston & Cashman (2003). Also shown in (b) are An-corrected interstitial glasses from Tertiary basalt lavas of eastern Iceland (Wood, 1978). Continuous curve and the open star correspond to the most likely position, for the Reykjanes glasses, of the cotectic valley and the minimum of the Qz–Ab–Or system, respectively. The dashed arrow shows the liquid-line-of-descent as calculated by the *Melts* algorithm (Ghiorso & Sack, 1995) under FMQ and 1 atm pressure conditions. Solid arrow indicates the evolution from trondhjemitic liquids to granitic melts.

Johannes & Holtz, 1996). Figure 3b shows plots of the glass analyses corrected for this ‘anorthite-effect’ by assuming similar changes, from variable Ab/An at 1 atmosphere as established at 0.2 GPa, on the cotectic valley and the minimum positions in the Qz–Ab–Or phase diagram. After this correction, the ‘K_2O-poor’ glasses form a coherent evolution trend (liquid-line-of-descent) from more Ab-rich compositions to the cotectic valley, whereas the ‘K_2O-rich’ glasses still plot close to the minimum of the ternary system. It is worth noting that the compositional gap between the two glass groups exists regardless of which of the two projection schemes is used.

The *Melts* algorithm (Ghiorso & Sack, 1995) allows estimation of the theoretical evolution of liquid compositions during fractional crystallization at atmospheric pressure with the oxygen fugacity close to the FMQ buffer. It must be noted that this algorithm is mainly calibrated for basaltic to dacitic melts and that it is less accurate for granitic liquids. Consequently, the evolution calculated for more silicic liquids yields only semi-quantitative results. Models computed with the *Melts* algorithm and applied to crystallization of the Reykjanes host lava never lead to granitic but only to trondhjemitic compositions (Fig. 3b). They closely mimic the trend of the ‘K_2O-poor’ glasses from Ab-rich compositions to the cotectic valley. However, this leaves unanswered the question of how the ‘K_2O-rich’ glasses formed and why a bimodal composition is observed at the last stage of olivine tholeiite differentiation. In principle, the two types of final liquids could reflect the process of liquid immiscibility. Such immiscibility is well known in Si- and Fe-rich liquids (e.g. Philpotts, 1979) but is unknown between liquids that differ only in their alkaline and alkaline-earth metals. A more likely explanation is a two-stage evolution (Fig. 3b). The first stage consists of a liquid-line-of-descent similar to that predicted by the *Melts* algorithm. The second stage is a more local fractionation of quartz and albite-rich plagioclase from the ‘K_2O-poor’ liquid at the Or-poor end of the cotectic valley that would lead to an increased concentration of potassium and final volatiles. Volatile over-saturation in the final liquid would form a gas phase that may expel the resulting granitic glass to a different location in the final crystal framework. This would correspond to a repeated gas-filter pressing (Anderson *et al*. 1984) similar to the mechanism displacing the segregation vein liquid from the host lava.

Several arguments support the latter explanation for the formation of the final granitic liquid. The liquidus temperature, as estimated by the *Melts* algorithm, is significantly higher for the ‘K_2O-poor’ glasses compared to the ‘K_2O-rich’ ones (*c*. 1100 and 970 °C, respectively). Consequently, it appears realistic that during a cooling process, ‘K_2O-poor’ liquids formed prior to ‘K_2O-rich’ liquids. The crystallizing assemblage causing the compositional changes of the final liquid can be estimated by mass balance calculation. It consists of plagioclase $An_{20}Ab_{80}$ (56 %) + quartz (42 %) + Fe–Ti oxides (2 %) and the degree of crystallization is 89 % with a sum of the squares of residual about 0.32. Indeed, albite and quartz intergrowths (graphic texture) are frequently observed in devitrified glass patches (Fig. 4). Moreover, vesicles which could represent the gas expulsion process are observed in ‘K_2O-poor’ glasses having albite and quartz intergrowths.

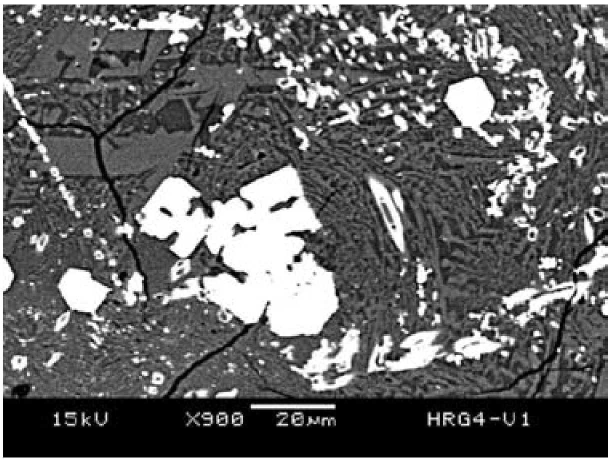

Figure 4. Scanning electron microscope (SEM) image, showing micrographic texture in a former glass patch of the segregation vein. Dark zones represent quartz, grey patches are albite and white colours reflect Fe–Ti oxide.

Taken together, the low-K_2O/Na_2O (< 0.1) olivine–tholeiitic basalt from Reykjanes Peninsula generates trondhjemitic liquids by more than 75 % (around 80 %) low-pressure fractional crystallization. Subsequently, and more exceptionally, small amounts of granitic liquid are formed. Most importantly, the silicic glasses represent bimodal compositions rather than a continuous evolution trend. Similar results can be deciphered from interstitial glass analyses in Tertiary basaltic lavas from eastern Iceland by Wood (1978), when only pristine glass analyses are considered and the anorthite effect in Qz–Ab–Or system is taken into account (Fig. 3b). The bimodality in the final silicic melt compositions is in stark contrast with observations on silicic formations in Iceland.

7. Implications for the origin of Iceland silicic rocks

Dacites and rhyolites represent between 3 and 10 % of the volcanic rocks produced in Iceland (Sigurdsson, 1977; Jakobsson, 1979). They are thought to be formed by either fractional crystallization of basalts or partial melting of hydrothermally altered basaltic crust. If they formed through a high degree of fractional crystallization at low pressure, their composition should be similar to those of the glasses in the Reykjanes segregation.

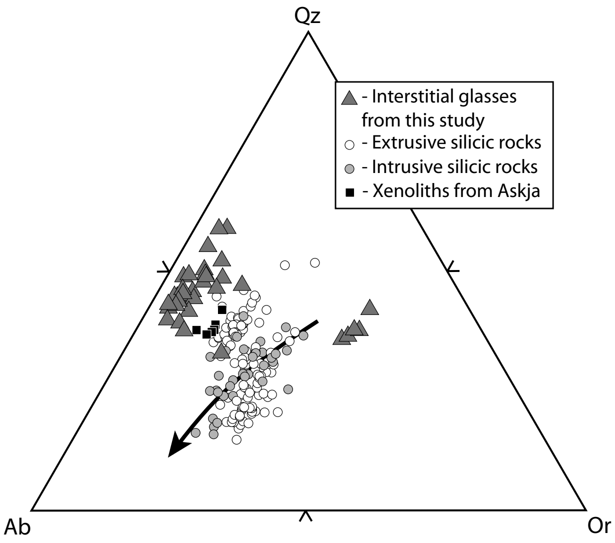

Figure 5. Comparison between glass patches from the Reykjanes Peninsula vein and silicic rocks from Iceland in the Qz–Ab–Or system. Extrusive and intrusive silicic rocks (144 samples compiled in GEOROC database (http://georoc.mpch-mainz.gwdg.de/georoc/)) as well as trondhjemitic xenoliths from Askja (Sigurdsson & Sparks, 1981) have composition intermediate between trondhjemitic and granitic glasses of this study. The arrow indicates the migration of minimum point of the system when pressure increases in a water-saturated system (Johannes & Holtz, 1996; see text for further discussion).

In Figure 5 are shown all available analyses of silicic rocks from Iceland containing more than 80 % of normative Qz + Ab + Or, like the Reykjanes glasses. It is clear that the Icelandic silicic rocks are different from the glasses analysed in this study, having compositions intermediate between the 'K_2O-poor' and 'K_2O-rich' glasses. This is further illustrated in Figure 2 where the silicic rocks from Iceland plot between trondhjemitic and granitic compositions and do not present the bimodal distribution observed in this study. Therefore, the silicic magma of Iceland is not formed by low-pressure fractional crystallization of an olivine tholeiitic magma like those erupted on the Reykjanes Peninsula.

The silicic rocks form trends towards lower Qz and higher Ab compositions in Figure 5 that concur with experimental results showing migration of the cotectic valley and the minimum point towards the Ab corner with increasing pressure (e.g. Johannes & Holtz, 1996). Trondhjemitic xenoliths from Askja volcano in central Iceland have been suggested to represent fractional crystallization products at depth (Sigurdsson, 1977; Sigurdsson & Sparks, 1981) and their compositions are plotted in Figures 2 and 5. These intrusive rocks are not as low in potassium as the 'K_2O-poor' glasses from the segregation vein, perhaps due to the pressure effect. However, these xenoliths have a significantly different composition compared to those of other intrusive silicic rocks from Iceland (Fig. 5). Therefore, based on the Qz–Ab–Or system, the fractional crystallization of basalts is not likely to have produced the silicic magmas, regardless of the exact pressure conditions. This conclusion applies to basalts having low K_2O/Na_2O such as those erupted on the Reykjanes Peninsula. Moreover, the total absence of differentiated rocks from this southwestern periphery of Iceland, and the northern extreme of the active rift-zone, compared to their abundance in the centre of the island and much higher magma productivity there, suggests a link with the presence of the mantle plume. Indeed, the thermal influence from the plume is expected to be highest in central Iceland where basalts with the least radiogenic He isotope ratios are erupted (Breddam, Kurz & Storey, 2000), a gravity low is observed (Eysteinsson & Gunnarsson, 1995) and the crust may be too hot to significantly cool down the high flux of incoming basalts. Instead, the hot mantle plume-derived basalts are likely to induce partial crustal melting.

Partial melting of hydrothermally altered basaltic crust has been shown capable of producing the silicic magmas of Iceland. For instance, fluid-absent melting of amphibolites at 0.3 GPa produces silicic liquid with composition indistinguishable from Icelandic silicic rocks (Sigmarsson, Condomines & Fourcade, 1992). Similar liquid compositions were also obtained from melting experiments at water pressure lower than 0.1 GPa and in the total pressure range of 0.1 to 0.3 GPa (Thy, Beard & Lofgren, 1990 and references therein). Finally, strong evidence for the melting model comes from O- and Th-isotope studies that observed higher isotope ratios in basalt lavas compared to contemporaneous silicic magmas from individual volcanoes (Nicholson *et al.* 1991; Sigmarsson *et al.* 1991; Sigmarsson, Condomines & Fourcade, 1992).

8. Differences between Archaean and Icelandic trondhjemites

Partial melting of metabasalts is classically thought to be at the origin of the Archaean crust with its well-known trondhjemitic, tonalitic and granodioritic (TTG) composition. In that case, a subducted oceanic crust transformed under amphibolite facies condition melts at such a depth that garnet is stable in the melting residue (see Martin *et al.* 2005 for review). The resulting trondhjemitic melt has a strongly fractionated REE pattern with high La/Yb due to the residual garnet. However, recent high-pressure experimental results reveal that water-saturated basalt melt crystallizes garnet and amphibole upon cooling (e.g. Müntener, Kelemen & Grove, 2001), which could produce similar REE patterns as observed in the Archaean trondhjemites. The mechanism of fractional crystallization may therefore have played a significant role during the formation of these trondhjemites.

Our study clearly shows that trondhjemites are generated from basalt via fractional crystallization. However, the olivine tholeiites on the Reykjanes Peninsula all have flat REE patterns (e.g. Zindler *et al*. 1979) and a similar flat pattern is expected for trondhjemitic glasses in the segregation vein. The principal difference between Archaean and Icelandic trondhjemites is the degree of fractionation of their REE pattern. Nevertheless, the different trace element ratios (e.g. La/Yb) could be explained by fractional crystallization at higher pressure forming Archaean trondhjemites compared to the near-atmosphere conditions recorded in the segregation vein on Reykjanes Peninsula. Due to the lack of rock samples, magmatic processes during Hadean times are not well known. However, as suggested for the Moon, an important magmatic ocean stage is thought to have characterized the Earth shortly after its accretion (e.g. Warren, 1985; Boyet *et al*. 2003; Caro *et al*. 2003). The progressive cooling and crystallization of the enormous volume of such a basaltic magma ocean could well have led to high degrees of fractional crystallization producing significant volumes of trondhjemitic magma and thus contributed to the formation of the very primitive continental crust.

9. Conclusions

Evolved glasses in a segregation vein hosted by olivine tholeiite lava on the Reykjanes Peninsula reveal a bimodal composition: trondhjemitic and granitic. These glasses were formed respectively by over 75 % and 97 % fractional crystallization of basaltic liquid at low pressure. The silicic magmas of Iceland have compositions that differ from those measured in the segregation vein. Consequently, major element constraints support the conclusion drawn from trace element and isotope studies that have proposed partial melting of hydrothermally altered basalts in order to account for the relatively large volume of silicic magmas in Iceland. The similarities of the trondhjemite glasses in the segregation vein and TTG may suggest that the formation of these glasses could be a modern analogue for the differentiation processes participating in the generation of trondhjemitic continental crust on the very early Earth.

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