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H₂O-rich melt inclusions in fayalitic olivine from Hekla volcano: Implications for phase relationships in silicic systems and driving forces of explosive volcanism on Iceland

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ABSTRACT

Silicic Icelandic magmas are widely believed to contain low to moderate H₂O content prior to degassing, and that their high explosivity mostly results from the interaction of the magmas with ice or meteoric water. Here we report the compositions of glass inclusions (SiO₂=57–72 wt%, K₂O=1.3–2.6 wt%) in Fe-rich olivines (Fo_{2–42}) from the largest Holocene eruptions of Hekla volcano (H3 and H4) on Iceland, which preserved quenched melts with very high primary H₂O contents (3.3–6.2 wt%). The silicic Hekla melts originate primarily by extensive (~90%) crystal fractionation of H₂O-poor (~0.6 wt%) basalts and represent an end member in the systematics of terrestrial magmas because they originate at low *f*O₂ (Δ QFM ~ -0.1 to -0.4) and have as high H₂O contents as significantly more oxidized island-arc magmas (Δ QFM \geq 1). This demonstrates that H₂O and Δ QFM do not correlate in silicic magmas from different tectonic settings, and that *f*O₂, not H₂O content, shows a major difference between silicic ocean-island (e.g., Icelandic) and island-arc magmas. Analysis of available experimental data suggests that high H₂O activity and low *f*O₂ expand the field of olivine stability in silicic melts. Low *f*O₂ and low MgO content could also suppress crystallization of amphibole. On the basis of these results we propose that an anhydrous mineral assemblage bearing Fe-rich olivine in evolved volcanic and Skaergaard-type intrusive rocks does not imply low H₂O in magmas prior to degassing but, in contrast to the commonly held view, is an indicator of H₂O-rich silicic parental magmas crystallized at low *f*O₂. Finally, the high H₂O content in magma was a major driving force of the largest explosive eruptions of Hekla volcano and must be at least as important for driving silicic explosive volcanism on Iceland as magma–ice interaction.

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1. Introduction

Icelandic magmatism belongs primarily to the classic tholeiitic series, a possible volcanic counterpart to the Skaergaard-type layered intrusives (Hunter and Sparks, 1987). The tholeiitic melts are thought to originate with low oxygen fugacity (*f*O₂) and low H₂O content (Carmichael, 1991; Grove and Baker, 1984; Spulber and Rutherford, 1983; Toplis and Carroll, 1995; Botcharnikov et al., 2008). Although predominantly basaltic, Icelandic tholeiitic series rocks also include more silicic rocks ranging from andesites to rhyolites (e.g., Jónasson, 2007). Eruptions of the silicic magmas in Iceland are often highly

explosive, have wide tephra dispersal and are comparable to large explosive eruptions of H₂O-rich magmas in island arcs (Thordarson and Larsen, 2007). However, unlike in typical island-arc magmas, H₂O-bearing minerals, such as amphibole, are exceptionally rare in Icelandic rocks (Gunnarsson et al., 1998; Jónasson, 2007). Therefore it is widely believed that silicic magmas in Iceland have less than 3–4 wt% H₂O prior to degassing (i.e., originate at pressure less than 100 MPa) (Jónasson, 2007; Selbekk and Tronnes, 2007; Sigurdsson and Sparks, 1981), and that their high explosivity primarily results from the interaction between the magmas and ice or meteoric water (Sigurdsson, 1977; Thordarson and Larsen, 2007). However, phase relationships in silicic Icelandic magmas at different P, T, *f*O₂ and aH₂O were not studied experimentally so far. Therefore, the evidence of low to moderate H₂O content in these magmas is indirect and based on the extrapolation of the available experimental data for systems of different composition.

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In this study we use the composition of melt inclusions in fayalitic olivine and mineral equilibria in silicic rocks of Hekla volcano to quantify the amounts of H₂O prior to degassing and to estimate the P, T and f_{O_2} conditions at which the olivine-bearing assemblage of anhydrous minerals is stable in silicic Icelandic magmas.

2. Samples studied

Samples were collected from near-vent pyroclastic deposits of Hekla volcano, one of the most explosive volcanoes in Europe and one of the largest centers of silicic volcanism in Iceland (Larsen and Thorarinnsson, 1977; Thordarson and Larsen, 2007). The studied samples come from the two largest eruptions of this volcano since the last Ice Age, H3 (3000 yrs ago) and H4 (4200 yrs ago) (Larsen and Thorarinnsson, 1977). These eruptions injected huge amounts of tephra, 12 km³ (H3) and 10 km³ (H4), into the atmosphere. The tephra covered 80% of Iceland and has been found in northern Europe as far as 2000 km from its source (van den Bogaard et al., 2002).

Both H3 and H4 tephra deposits are zoned from dacitic-rhyolitic (~68–73 wt% SiO₂) compositions in the lower layers to andesitic compositions in the uppermost ones (56–57 wt% SiO₂) and likely originate by mixing of silicic and more mafic magmas shortly before and during the eruptions (Sverrisdottir, 2007). Sparse olivine phenocrysts, 0.5–1 mm in size, have been found in all samples (Figs A.1 and A.2). The olivine compositions are very homogeneous and extremely Fe- and Mn-rich in the silicic parts of the deposits (with forsterite content as low as Fo_{12–13} in H3 and Fo_{2–3} in H4 (Fig. 1 and Fig. A.2), where Fo is molar 100 Mg/(Mg+Fe) in olivine). Olivines have more variable composition in the upper andesitic parts (Fo_{12–49} in H3 and Fo_{3–35} in H4). The most Fe-rich olivines (Fo_{2–15}) are not zoned. Less Fe-rich olivines in andesitic H3 tephra (Fo_{14–31}) display a slight increase in Fo-content (2–6 mol%) toward the crystal rims. Olivines from the uppermost layer of H3 tephra have the highest Fo-content (Fo_{41–48}) and exhibit normal zoning (1–4 mol%). Magnesian olivines from H3 andesites (Fo_{42–49}) have a weak normal zoning (up to 4 mol% of Fo) and are often armored by reaction coronas of low-Ca pyroxene (Fig. A.1f). Additional phenocrysts in Hekla tephra are plagioclase (Ab_{68–82}An_{15–31}Or_{2–3}), high-Ca pyroxene (Wo_{35–40}En_{4–22}Fs_{40–58}), magnetite (Usp_{58–69}Mt_{31–42}), ilmenite (Ilm_{92–94}Hem_{6–8}) and F-apatite. Zircon and pyrrhotite occur as small inclusions in Fe-rich olivine (Fo_{2–21}) (Fig. A.1).

Melt inclusions are found in olivines across the entire compositional range (Fo_{3–42}) (Fig. 1). They are usually evenly distributed inside the olivine phenocrysts, have ellipsoid shape and consist of homogeneous glass (\pm fluid bubbles in andesitic inclusions), occasionally with small single crystals of zircon, apatite or Fe–Ti oxides trapped together with melt (Fig. A.1). The inclusions studied ranged in size from 30 to 100 μ m.

3. Analytical techniques

3.1. Electron probe

Major elements in glasses of melt inclusions and in olivine were analyzed using JEOL JXA 8200 electron microprobe (GEOMAR, Kiel, Germany) at an accelerating voltage of 15 kV and current of 6 nA for glasses, 20 nA for Fe-oxides and 100 nA for olivine. Beam size was set to 5 μ m for glasses and 1 μ m for minerals. Counting time was 20/10 s (peak/background) for Si, Al, Fe, Mg, Ca, 30/15 s for K, Ti, Cl, S and 40/20 s for Mn and F. Na concentrations were determined separately from other elements using a current of 6 nA and a beam size of 10 μ m and extrapolating the time resolved Na K_{α} intensity to

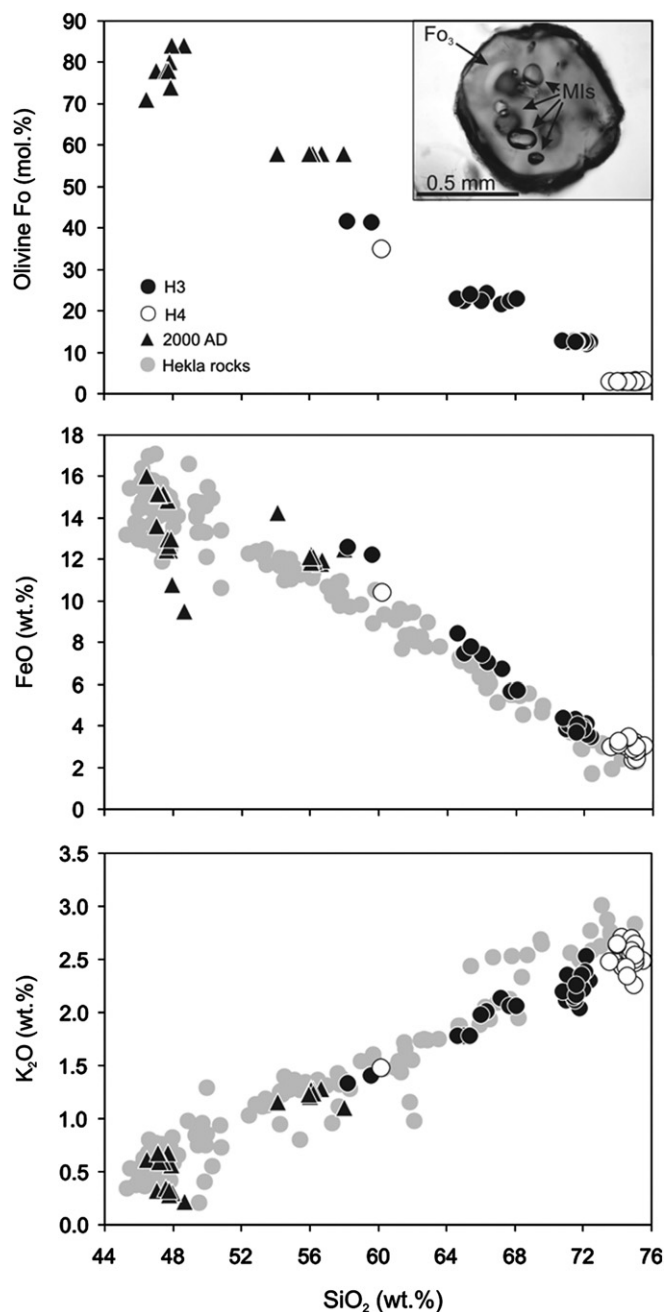


Fig. 1. Major element composition of melt inclusions and their host olivines from Hekla rocks. Melt inclusions from H3 and H4 tephra are from this study, and the inclusions from rocks of the 2000 Hekla eruption are after Mouné et al. (2007). The bulk compositions of Hekla rocks are from Jakobsson (1979), Sigmarsson et al. (1992), Meyer et al. (1985), Sverrisdottir (2007), Chekol et al. (2011). All compositions were recalculated on anhydrous basis to the sum of oxides of 100 wt%. Basaltic inclusions from work of Mouné et al. (2007) were corrected for post-entrapment crystallization of olivine (Table A.2). The inset illustrates a typical olivine phenocryst with melt inclusions (MIs) from H4 dacite.

the time 0. Natural reference samples from the Smithsonian Institute were used for calibration and monitoring of data quality (Jarosewich et al., 1980). Basaltic glass (USNM 113498/1 VG-A99) for Ti, Fe, Mg, Ca, P, rhyolitic glass (USNM 72854 VG568) for Si, Al, Na, K, scapolite (USNM R6600-1) for S and Cl, all from the Smithsonian collection of natural reference materials (Jarosewich et al., 1980), rhyolitic glass KN-18 (Mosbah et al., 1991) for F and synthetic rhodonite for Mn were used for calibration and monitoring of the measurements (Table A.1).

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