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Evolution of low-^{18}O Icelandic crust

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ABSTRACT

The Krafla central volcano in the neovolcanic zone of Iceland hosts a chemically diverse suite of magmas characterized by anomalously low δ^{18}O values. A rhyolite magma intercepted by the Iceland Deep Drilling Project (IDDP) exploratory well at 2.1 km depth provided a unique opportunity to investigate the origins of an unerupted rhyolite melt in the primarily basaltic central volcano at Krafla. Here we compare whole rock hydrogen and oxygen isotopes of this melt to those of lavas within and near the caldera of the Krafla central volcano ranging from recent fissure eruptions to Plio–Pleistocene age (including analyses of 18 new samples, plus previously published values) in order to evaluate the petrogenesis of low-^{18}O magmas within the neovolcanic zone of Iceland.

Oxygen isotope values of the IDDP-1 melt ($\delta^{18}O=+3.2\pm0.2$‰) are within the range of Krafla eruptives that have a bimodal composition of olivine-tholeiite and rhyolite ($\delta^{18}O=+1.6$‰ to +4.5‰). Lavas show significantly more variability in hydrogen isotope values ($\delta D=-161$‰ to −92‰) than the IDDP-1 melt (-121 ± 2‰), whose δD is comparable to local hydrothermal epidote (−127 to −108‰), and show significantly lower water contents than IDDP-1 (0.1–1.1 wt%, in contrast to ~1.8 wt%). Basaltic to dacitic lavas from the proximal Heidarspordur ridge volcanic zone have δ^{18}O between +3.4‰ and +4.2‰ and δD between −105‰ and −99‰.

Uniformity of oxygen isotopes in the Heidarspordur ridge lavas suggests that their magmatic compositional variations are a consequence of fractional crystallization. The δD of the glass sampled by IDDP-1 unequivocally identifies the source of silicic low-^{18}O melts like those erupted from within the caldera of the Krafla volcano as anatexis of meteoric-hydrothermally altered basalts resulting from the intrusion of mantle-derived basaltic magma. Finally, mantle-derived basalts in both the Krafla central volcano and Heidarspordur ridge (MgO > 5 wt%) have δ^{18}O values lower than the typical MORB. There is convincing evidence favoring low-^{18}O compositions in primitive Icelandic basalts as also being the result of assimilating meteoric hydrothermally altered Icelandic crust, particularly in the roots of central volcanic complexes, where high-level intrusions develop. Here hydrothermally altered basalts have a high probability of undergoing partial melting. If this is the case, we hypothesize that there should be a notable secular variation in the δ^{18}O values of upper crustal igneous products of the Iceland mantle plume over the sub-aerial extrusive geologic history of Iceland, in which progressively younger lavas exhibit decreasing δ^{18}O values. Synthesis of published oxygen isotope analyses of unaltered whole rock and mineral separates of lavas from Tertiary age to present lends support to this hypothesis.

1. Introduction

Since the pioneering work on the oxygen isotope composition of Icelandic lavas by Muehlenbachs et al. (1974) and Hattori and Muehlenbachs (1982), nearly four decades of isotopic analyses on igneous rocks from the neovolcanic zone of Iceland and their mineral cargo have demonstrated the influence of the hydrosphere on the genesis of anomalously low δ^{18}O values characteristic of Icelandic rocks (cf. Bindeman et al., 2012, 2008a, 2006; Condomines et al., 1983; Eiler et al., 2000; Elders et al., 2011; Gautason and Muehlenbachs 1998; Hémond et al., 1993, 1988; Macdonald et al., 1987; Martin and Sigmarsson, 2010; Nicholson et al., 1991; Pope et al., 2009; Rose-Koga and Sigmarsson, 2008; Sigmarsson et al., 1992, 1991; Sveinbjörnsdóttir et al., 1986). Such low δ^{18}O compositions are not unique to the neovolcanic zone of Iceland. As a consequence of low δD and δ^{18}O values characteristic of high-latitude meteoric waters and related meteoric-hydrothermal fluids, water–rock–magma interactions in the North Atlantic Igneous Province (NAIP) as a whole are characterized by significant negative departures from presumed mantle isotope values (Bindeman et al., 2008b; Brandriss et al., 1996, 1995; Fehlhaber and Bird, 1991;

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Forester and Taylor, 1976; Nevle et al., 1994; Taylor, 1968; Taylor and Epstein, 1963; Taylor and Forester, 1979; Taylor and Sheppard, 1986 as well as the studies referenced above).

Anomalously low-$\delta^{18}O$ and -δD minerals in early Tertiary mafic intrusions of the NAIP are a consequence of high-temperature meteoric-hydrothermal fluid circulation (Norton and Taylor, 1979) through systematic fracture networks within solidified intrusions and their basaltic host rocks. Glacially exposed outcrop evidence suggests that such circulation occurs at depths >5–6 km (Bird et al., 1986, 1985; Manning and Bird, 1995, 1991; Manning et al., 1993; Norton et al., 1984) and temperatures locally exceeding 600 °C (Bird et al., 1988; Manning and Bird, 1986). Additionally, gabbroic intrusions in East Greenland locally containing $>50\%$ meta-basalt xenoliths (Bernstein and Bird, 2000; Bird et al., 1985; Brandriss and Bird, 1999; Fig. 10 in Brooks, 2011) provide outcrop evidence of dehydration, partial melting, and related magmatic metasomatism producing low-^{18}O silicic melts and ultramafic restites (Brandriss et al., 1996, 1995) that may provide an analog for formation of low-^{18}O magmas in Iceland.

Despite extensive investigations in Iceland and the NAIP, the dynamics and evolution of low-^{18}O magmatism in Iceland's neovolcanic zone remain ambiguous. Uncertainty exists about what physico-chemical mechanism(s) cause crustal contamination of mantle-derived melts (e.g. assimilation of host rocks, anatexis of hydrothermally altered wallrock, mixing between mantle-derived and crustal-derived melts), how these mechanisms differ in different volcanic settings within Iceland, and whether there is an underlying low-^{18}O mantle source (Breddam, 2002; Gurenko and Chaussidon, 2002; Kokfelt et al., 2006; Macpherson et al., 2005; Peate et al., 2010, 2009; Sigmarsson and Steinthórsson, 2007; Skovgaard et al., 2001; Thirlwall et al., 2006). Resolving these issues is important for understanding the evolution of low-^{18}O crust in other environments such as Hawaii (Garcia et al., 1998, 2008), the Snake River Plain and Yellowstone hot spot (Bindeman and Valley, 2001; Boroughs et al., 2005; Watts et al., 2012) or at mid-ocean ridges (e.g. Wanless et al., 2010). Further, generation of silicic magmas through melting or assimilation of hydrothermally altered basaltic crust in the roots of Icelandic central volcanoes may be indicative of how granitic continental crust first evolved on Earth (Bindeman et al., 2012; Martin et al., 2008). Finally, the controversial presence of a low-^{18}O signature in the mantle source of Icelandic lavas potentially represents the fate of subducted oceanic lithosphere (e.g. Kokfelt et al., 2006; Skovgaard et al., 2001) as suggested by other low-^{18}O signatures in, for example, Mesozoic granites in northeastern China or mantle xenoliths obtained from kimberlite pipes in South Africa (Wei et al. (2002) and Williams et al. (2009), respectively).

Here we present new whole rock oxygen and hydrogen isotope compositions from a suite of 18 volcanic rocks from eruptions within the caldera of the Krafla central volcano and adjacent Heidarspordur volcanic ridge, both located in the neovolcanic zone of northeast Iceland (Fig. 1). The Krafla central volcano is characterized by bimodal volcanism and hydrothermal activity typical of central volcanic complexes in Iceland (Sigmarsson et al., 1991; Walker, 1966), and the hydrothermal system within the Krafla caldera was the site of the Iceland Deep Drilling Project drillhole IDDP-1, which sampled a rhyolitic glass derived from a melt that was intercepted and quenched during drilling at a depth of 2.1 km (Elders et al., 2011). In contrast, the lavas of Heidarspordur ridge are more intermediate in composition and were derived from deeply sourced fissure eruptions (Jónasson, 2005). Collectively, our analysis of these lavas and the glass sampled from the IDDP-1 melt provide a basis for better understanding sources and chemical evolution of evolved melts within the Krafla central volcano. We also explore secular variation of $\delta^{18}O$ in mafic melts resulting from crustal contamination, and propose that identification of mantle heterogeneity in $\delta^{18}O$ beneath Iceland may require more extensive investigation of older Icelandic basalts, rather than those solely located in the neovolcanic zone.

2. Background

2.1. Genesis of low-^{18}O magmas

Unaltered igneous rocks on Earth typically have $\delta^{18}O$ values between $\sim+5.5$‰ and 7‰ relative to the standard V-SMOW, with

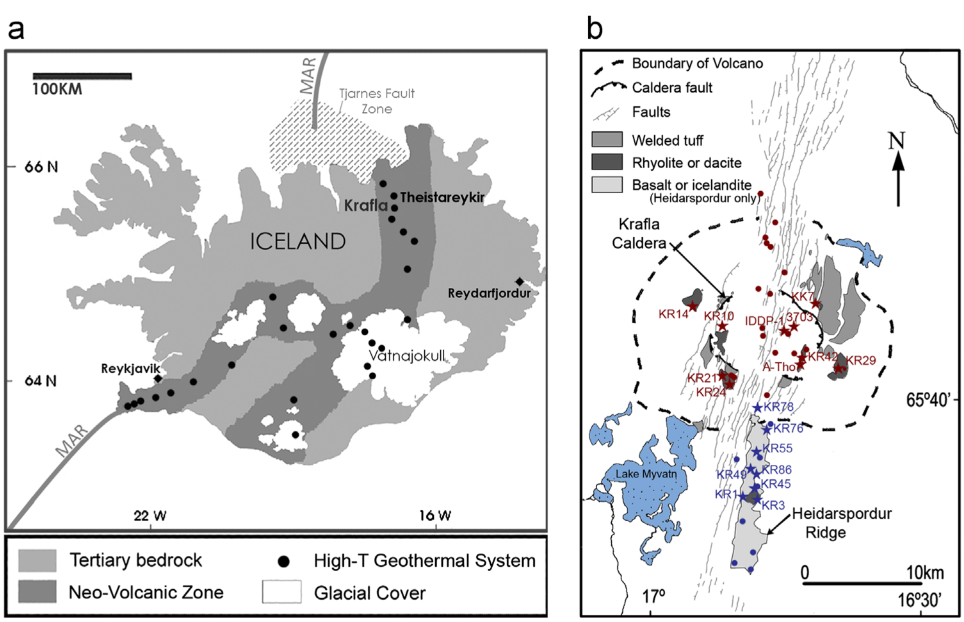

Fig. 1. Map of Krafla central volcano and Heidarspordur ridge. (a) Generalized geologic map of Iceland, showing active volcanic zone, high-temperature geothermal systems, including Krafla central volcano, and sites of the Reykjavik and Reydarfjördur IRDP drillcores. Adapted from Pope et al. (2009). MAR=Mid-Atlantic Ridge. High-T=High temperature. (b) Sample map of lavas and IDDP-1 drillhole in the Krafla central volcano and Heidarspordur ridge. Krafla=red symbols, Heidarspordur ridge=blue symbols. Sample locations: stars=this study; circles=Nicholson et al. (1991). Adapted from Arnórsson (1995) and Jónasson (2005, 1994). Basalts only mapped within the Heidarspordur ridge; aerial exposure of basaltic lavas within Krafla central volcano is not shown. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)