

# Origin of a rhyolite that intruded a geothermal well while drilling at the Krafla volcano, Iceland

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## ABSTRACT

Magma flowed into an exploratory geothermal well at 2.1 km depth being drilled in the Krafla central volcano in Iceland, creating a unique opportunity to study rhyolite magma *in situ* in a basaltic environment. The quenched magma is a partly vesicular, sparsely phyrlic, glass containing ~1.8% of dissolved volatiles. Based on calculated H<sub>2</sub>O–CO<sub>2</sub> saturation pressures, it degassed at a pressure intermediate between hydrostatic and lithostatic, and geothermometry indicates that the crystals in the melt formed at ~900 °C. The glass shows no signs of hydrothermal alteration, but its hydrogen and oxygen isotopic ratios are much lower than those of typical mantle-derived magmas, indicating that this rhyolite originated by anhydrous mantle-derived magma assimilating partially melted hydrothermally altered basalts.

## INTRODUCTION

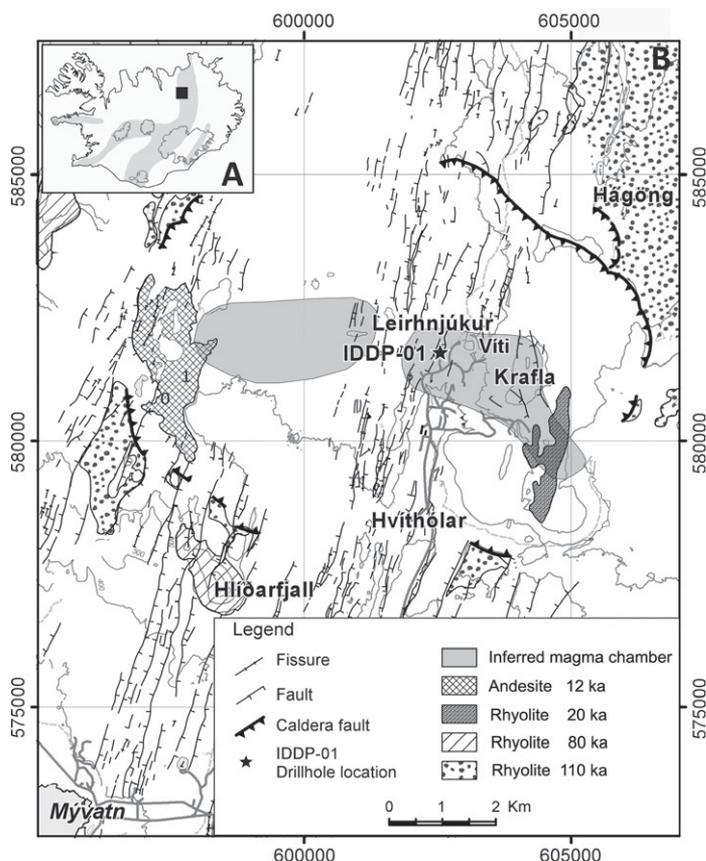
The origin of bimodal assemblages of rhyolite and basalt is controversial, and this is especially true of low  $\delta^{18}\text{O}$  volcanic rocks in Iceland. Globally, the majority of unaltered igneous rocks have  $\delta^{18}\text{O}$  values between ~5.5‰ and 7‰ (Taylor, 1968). However, there are prominent examples of lower  $\delta^{18}\text{O}$  magmas associated with the Hawaiian, Yellowstone, and Icelandic hotspots. Two dominant hypotheses for the formation of these low  $\delta^{18}\text{O}$  melts are: (1) significant oxygen isotope heterogeneity exists in mantle source regions, and (2) extensive interaction occurs between mantle-sourced melts and isotopically diverse crust. Hawaii and Yellowstone represent type examples of these two different sources. Hawaiian basalts have an average  $\delta^{18}\text{O}$  value of ~5.5‰, apparently due to the varying influence of plume and non-plume melt sources with differing  $\delta^{18}\text{O}$  contents (Harmon and Hoefs, 1995). In contrast, the low  $\delta^{18}\text{O}$  rhyolites in Yellowstone, which are depleted in  $^{18}\text{O}$  by 3‰–5‰ relative to average global values, seem to originate either by assimilation (Hildreth et al., 1991) or by complete melting of altered caldera block material (Bindeman and Valley, 2001).

Iceland is an extreme example of  $^{18}\text{O}$  depleted volcanism, averaging +4.5‰, the lowest of any ocean island basalt (Harmon and Hoefs, 1995). A combination of heterogeneous mantle sources and assimilation of hydrothermally altered crust, or ancient subducted crust, seems to be involved (Sigmarsson and Steinthórsson, 2007). Here we present data on a low  $\delta^{18}\text{O}$  rhyolite magma that flowed into a borehole while drilling in a predominantly basaltic volcano, thus providing nondegassed samples that yield unique information on the pressures, temperatures, and volatile contents. Lavas normally lose their original volatiles by degassing during

eruption, but we can use volatile contents and hydrogen isotopic ratios of the quenched magma to help solve its origin.

## KRAFLA VOLCANO

The Krafla central volcano (Fig. 1) has a 300-k.y.-long history of predominantly tholeiitic volcanic activity, most recently in A.D. 1975–1984



**Figure 1. A:** Map of Iceland's neovolcanic rift system (shaded) and location of Krafla central volcano (black square). **B:** Geological map of Krafla volcano showing faulting associated with rifting and boundary of caldera. Surface rocks are dominantly tholeiitic basalts and hyaloclastites, with lesser amounts of felsic rocks as shown (modified from Sæmundsson, 2008). Star indicates location of IDDP-1 (Iceland Deep Drilling Project well). Universal Transverse Mercator coordinates.

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(Einarsson, 1991). It is a caldera within the neovolcanic rift system, the landward extension of the Mid-Atlantic Ridge in Iceland (Elders and Friðleifsson, 2010). A magma chamber at 3–7 km depth beneath the volcano was detected during the 1975–1984 eruptions by S-wave shadowing (Einarsson, 1978). Jónasson (1994, 2007) described the bimodal nature of the eruptive rocks at Krafla and proposed that the rhyolites formed by near-solidus fractionation of melted hydrothermally altered basalts, rather than by extreme fractionation of primary basaltic magma.

### EXPLORATORY WELL

The well IDDP-1 was drilled within the Krafla caldera (Fig. 1B) as part of the Iceland Deep Drilling Project, an industry-government consortium, to test the concept of exploiting geothermal fluids at supercritical pressures and temperatures (22 MPa and 374 °C for pure water). Modeling indicated that producing supercritical fluid could yield ~10 times the power output of typical Icelandic geothermal wells (Friðleifsson and Elders, 2005).

In the main geothermal reservoir temperatures can reach 340 °C at depths as shallow as 2 km, and the basaltic rocks are altered to epidote-actinolite mineral assemblages (Arnórsson et al., 2008). Produced geothermal fluids are dilute solutions of meteoric origin, except that during, and after, the 1975–1984 eruptions HCl and CO<sub>2</sub> occurred locally (Ármansson, 2010). The IDDP-1 well was sited where the depth to the magma chamber was estimated to be ~4.5 km based on a recent magnetotelluric-transient electromagnetic survey (see Fig. DR1 in the GSA Data Repository<sup>1</sup>).

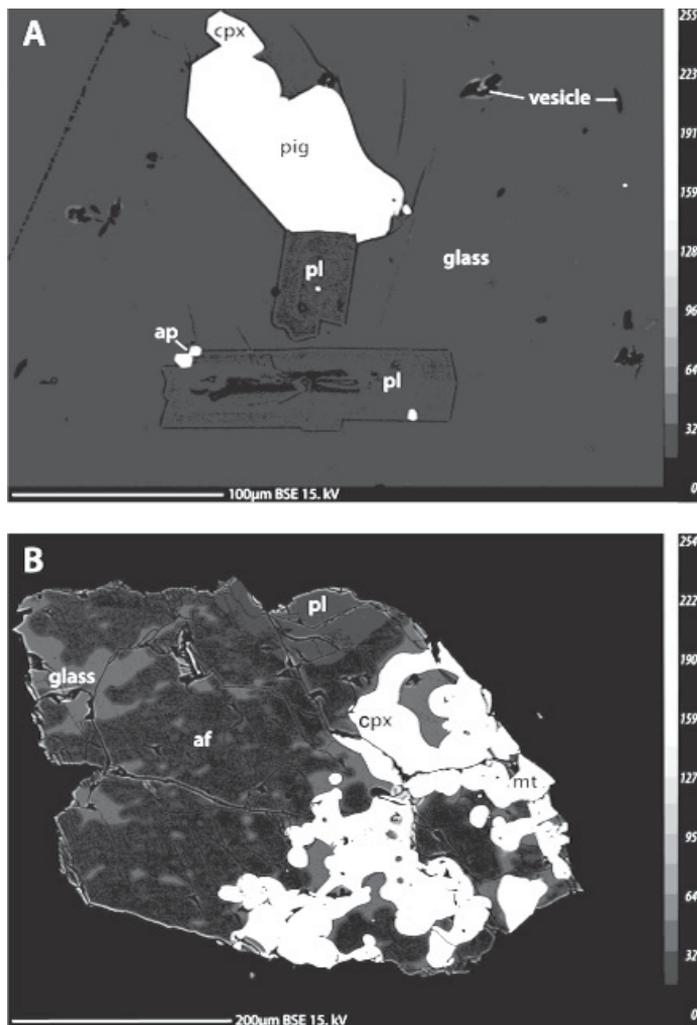
In the spring of 2009 drilling progressed normally to 2 km depth, where the deepest rocks recovered were mostly unaltered basalt dikes and irregular lenses of felsite (termed “granophyre” in Iceland, but usually lacking that texture). In the next 100 m multiple acute drilling problems occurred. In June 2009, the reason for this became apparent. At 2104 m depth, the rate of penetration suddenly increased and the torque on the drilling assembly increased, halting its rotation. When the drill string was pulled up >10 m and lowered again, the drill bit became stuck at only 2095 m and abundant samples of dark brown, bubble-poor, obsidian were recovered. An intrusion of magma had filled the lowest 9 m of the open borehole. Modeling indicates that, if the emplacement of this magma occurred during the 1974–1985 eruptions, to remain molten it must be >50 m thick (see discussion of analytical methods in the Data Repository). Drilling was terminated and the hole was completed as a production well, and cased to 2069 m.

### QUENCHED MAGMA

Samples of the glass quenched by the drilling fluids are of two kinds, an abundant, poorly vesiculated, sparsely phyrlic, black obsidian, and minor amounts of a different glass that is interstitial to felsite (Fig. 2). A few samples of the obsidian are more vesicular, occurring as white frothy pumice, some with highly stretched bubbles. Both varieties have identical phenocryst assemblages, major element compositions, and volatile contents. They are subalkaline, with high silica and low TiO<sub>2</sub> (Table 1). This obsidian contains ~1.77 wt% H<sub>2</sub>O (1σ ± 0.14, n = 14) and 85 mg kg<sup>-1</sup> of CO<sub>2</sub> (1σ ± 15, n = 12), and a high ratio of dissolved OH to total H<sub>2</sub>O (0.66), independent of the degree of vesiculation (Analytical Methods discussion; see discussion of analytical methods in the Data Repository).

This volatile content indicates that the magma was quenched at temperatures between 760 and 940 °C (Ihinger et al., 1999) and that its saturation pressure (at 900 °C) was 39 MPa ± 6 MPa (Newman and Lowenstern, 2002). This pressure exceeds the hydrostatic pressure at ~2.1 km

<sup>1</sup>GSA Data Repository item 2011088, Item DR1 (location of the well in relation to the magma chamber), Item DR2 (size of the intrusion), Item DR3 (analytical methods), Item DR4 (glass compositions), and Item DR5 (the future of the well), is available online at [www.geosociety.org/pubs/ft2011.htm](http://www.geosociety.org/pubs/ft2011.htm), or on request from [editing@geosociety.org](mailto:editing@geosociety.org) or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.



**Figure 2.** Backscattered electron images of quenched melts. **A:** Dominant rhyolite glass. **B:** Rhyolite glass in partially melted felsite. (Abbreviations: pl—plagioclase, pig—pigeonite, cpx—augite, ap—apatite, af—alkali feldspar, mt—titanomagnetite.)

TABLE 1. ANALYSES OF THE IDDP-1 GLASSES AND A NEARBY FELSITE

	Rhyolite glass average (n = 28)	Felsite interstitial glass average (n = 25)	Felsite* well K-25 2080 m (bulk rock)
SiO <sub>2</sub>	76.53	76.71	71.62
Al <sub>2</sub> O <sub>3</sub>	12.01	11.91	12.11
TiO <sub>2</sub>	0.32	0.19	0.69
Na <sub>2</sub> O	3.78	3.58	4.01
K <sub>2</sub> O	3.06	5.17	1.65
MgO	0.18	0.07	1.31
CaO	1.32	0.49	3.03
FeO	2.73	1.79	4.74
MnO	0.06	0.09	0.11

\*Analysis of a bulk rock sample of felsite from 2080 m depth in well K-25, located 80 m south of the IDDP-1 (from Jónasson, 1994, his table 1, sample 24).

(<21 MPa for cold meteoric water), and is less than the lithostatic pressure (~51 MPa, for an overburden density of 2.5 g/cm<sup>3</sup> based on the gravity data of Johnsen [1995]). It appears that drilling intersected a low-permeability zone with pressures significantly above hydrostatic, presumably formed by a recent intrusion. Fournier (1999) speculated that pressures at

a magma-hydrothermal interface might be between lithostatic and hydrostatic, but we are not aware of any previous instance where this has been directly observed.

The sparse phenocrysts include plagioclase, augite, pigeonite, and titanomagnetite, with minor amounts of apatite, and traces of zircon and pyrrhotite (Fig. 2A). Plagioclases show compositional zoning, mostly in the range  $An_{45}$ – $An_{48}$ . Crystallization temperatures were estimated using the compositions of coexisting pyroxenes (Davidson and Lindsley, 1989). Paired compositions from the cores of pyroxene crystals indicate temperatures of 930–990 °C, whereas the compositions of the rims suggest 890–910 °C, values consistent with temperature estimates from the volatile content.

A minor component among the drill cuttings recovered from 2095 m is felsite, containing small amounts of quenched interstitial melt. The felsite is composed of alkali feldspar, plagioclase, quartz, augite, and titanomagnetite. The silica content of the interstitial glass is similar to that of the rhyolite glass, but it has higher  $K_2O$  and lower  $CaO$  contents (Table 1). Rare earth elements (REE) are strongly enriched in the interstitial glass in the felsite (600–170 times chondrite) relative to those in the rhyolite (110–25 times chondrite) (Zierenberg et al., 2009), but both have similar chondrite-normalized patterns and  $Ce/Yb$  ratios (10.4–11.2) that overlap those of extrusive rhyolites at Krafla (Jónasson, 1994).

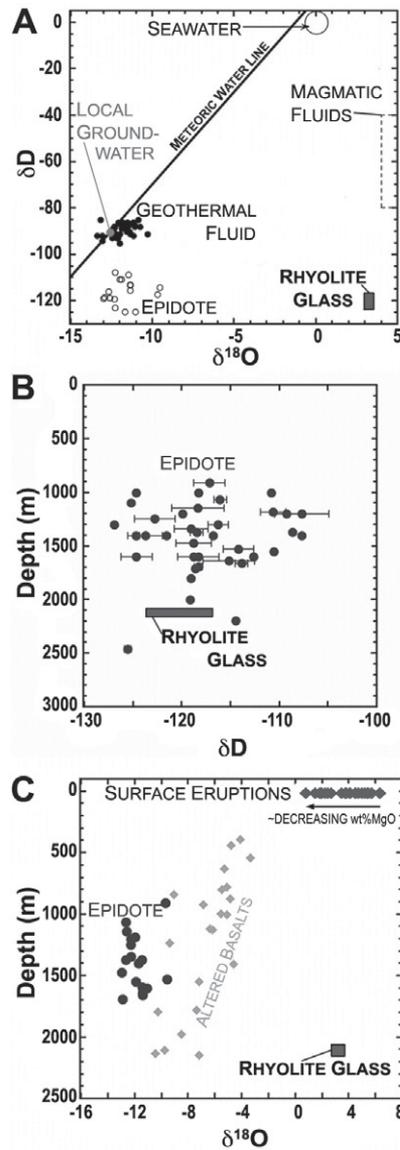
A few cutting fragments are composed of glass containing abundant crystals typical of the felsite intrusion, except that alkali feldspar occurs only as remnants of resorbed crystals (Fig. 2B). The composition of this glass is intermediate between the interstitial felsite glass and the rhyolite glass. However, all these glasses have compositions different from that of the felsite occurring in and around the IDDP-1 (Table 1), suggesting that they possibly are different fractions of evolving felsic magma, or are different stages in remelting of the felsite (see the Data Repository).

## ORIGIN OF THE RHYOLITE

Previous studies suggest Icelandic magmas could originate from three different sources: (1) upper mantle components and a geochemically enriched end member, likely from the Iceland mantle plume (Hémond et al., 1993), (2) a more depleted end member either from a mid-oceanic ridge basalt (MORB) source upper mantle (Langmuir et al., 1978) or from a second more depleted plume component (Elliott et al., 1991), and (3)  $^{18}O$  depleted hydrothermally altered Icelandic crust (Sigmarsson and Steinthórsson, 2007). Nicholson et al. (1991) established a positive correlation between  $MgO$  content and  $\delta^{18}O$  values in surface eruptions at the Krafla volcano, and attributed the low  $\delta^{18}O$  values to a combination of fractional crystallization of basalt magma and assimilation. Based on major and minor element chemistry, Jónasson (1994, 2007) suggested that rhyolites at Krafla formed by partial melting of hydrothermally altered basalt at depth.

The isotope data summarized in Figure 3 show very low values of  $\delta D$  ( $-121‰ \pm 2‰$ ;  $1\sigma = 2.10$ ,  $n = 12$ ) in the rhyolitic glass that are remarkably similar to those of hydrothermal epidotes from Krafla geothermal wells (Figs. 3A and 3B). The hydrogen isotope ratio of the IDDP-1 rhyolite could not be produced from hydration by local geothermal waters or by mantle-derived waters; instead its source is entirely hydrothermal alteration minerals.

The oxygen isotope ratio in the IDDP-1 rhyolite ( $\delta^{18}O = 3.1‰ \pm 0.06‰$ ;  $1\sigma = 0.06$ ,  $n = 4$ ) is also consistent with a contribution from partial melting of hydrothermally altered basalts. This ratio is similar to  $\delta^{18}O$  values observed in unaltered surface rhyolites at Krafla (Fig. 3C), and most of them are between 1.0‰ and 3.2‰; there is one outlier at 5.1‰ (Sveinbjörnsdóttir et al., 1986; Nicholson et al., 1991). In contrast, they are significantly higher than whole-rock  $\delta^{18}O$  values of hydrothermally altered basalt from geothermal wells (Fig. 3C; Hattori and Muehlenbachs, 1982). This suggests that, while the  $\delta D$  of the rhyolite was entirely derived from the melting of hydrothermally altered basalt, the  $\delta^{18}O$  value is a result of mixing of that source with a different, virtually anhydrous, magma. A



**Figure 3.** Average hydrogen and oxygen isotopic composition of rhyolite glass from IDDP-1 (Iceland Deep Drilling Project well) compared to geothermal epidote, and other potential sources (Pope et al., 2009a, 2009b; Sveinbjörnsdóttir et al., 1986). **A:**  $\delta^{18}O$  and  $\delta D$  of rhyolite glass, geothermal epidotes, and local groundwaters in Krafla geothermal system. Also shown are meteoric water line, seawater, and range of values generally accepted for magmatic fluids. **B:**  $\delta D$  values in rhyolite glass, compared to geothermal epidotes from Krafla wells (K-20, K-34, K-26, K-17, K-25, K-32, and K-39), as function of depth. Epidote  $\delta D$  values have a broad range, from  $-127‰$  to  $-108‰$ . Error bars represent  $1\sigma$  standard deviation. Average  $\delta D$  composition of glass is well within range of epidote values. **C:** Oxygen isotope ratios of glass, compared to epidotes from wells K-20, K-26, and K-34, as a function of depth, compared to Krafla whole-rock analyses of fresh surface lavas and subsurface altered basalts (closed diamonds).

potential source of such a melt could be an undepleted, mantle-derived magma. If such a melt, with a starting  $\delta^{18}O$  composition of 5.5‰, assimilated only 17% of its mass by melting hydrothermally altered basalts ( $\delta^{18}O = -10‰$ ), the product would be the  $\delta^{18}O$  and  $\delta D$  values observed in the IDDP-1 glass.

## MAGMA IN GEOTHERMAL WELLS

It is perhaps surprising that encounters with magma are extremely rare among the thousands of wells drilled worldwide in volcanic areas. In 2008, well K-39, ~2 km southeast of the IDDP-1 at Krafla, recovered silicic glass at ~2.5 km depth, where the temperature was 386 °C (Mortensen et al., 2010). However, only one previous instance of magma flowing into a geothermal well while drilling has been documented. In 2005 drilling in the Puna geothermal field in Hawaii encountered dacite magma at 2488 m depth (Teplow et al., 2009). That well was eventually completed as an injection well 2124 m deep, above the dacite intrusion.

## CONCLUSIONS

A serendipitous encounter with a rhyolitic magma under controlled conditions in a borehole in a predominantly basaltic milieu gave unusual insight into its origin. Formation of many bimodal basalt-rhyolite

assemblages has been attributed to extreme differentiation of mantle-derived magma, and there are hypotheses that low  $\delta^{18}\text{O}$  magmas also originate in the mantle. Our data indicate that assimilation of partially melted, hydrothermally altered, basalts was the dominant process in forming this rhyolite. Perhaps in the future, accessible magmas might become sources of very high enthalpy geothermal energy in Iceland and elsewhere (see the Data Repository).

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