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Hydrothermal alteration in the Reykjanes geothermal system: Insights from Iceland deep drilling program well RN-17

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ABSTRACT

The Reykjanes geothermal system is a seawater-recharged hydrothermal system that appears to be analogous to seafloor hydrothermal systems in terms of host rock type and low water/rock alteration. The similarities make the Reykjanes system a useful proxy for seafloor vents. At some time during the Pleistocene, the system was dominated by meteoric water recharge, and fluid composition at Reykjanes has evolved through time as a result of changing proportions of meteoric water influx as well as differing pressure and temperature conditions. The purpose of this study is to characterize secondary mineralization, degree of metasomatic alteration, and bulk composition of cuttings from well RN-17 from the Reykjanes geothermal system. The basaltic host rock includes hyaloclastite, breccia, tuff, extrusive basalt, diabase, as well as a marine sedimentary sequence. The progressive hydrothermal alteration sequence observed with increasing depth results from reaction of geothermal fluids with the basaltic host rock. An assemblage of greenschist facies alteration minerals, including actinolite, prehnite, epidote and garnet, occurs at depths as shallow as 350 m; these minerals are commonly found in Icelandic geothermal systems at temperatures above 250 °C (Bird and Spieler, 2004). This requires hydrostatic pressures that exceed the present-day depth to boiling point curve, and therefore must record alteration at higher fluid pressures, perhaps as a result of Pleistocene glaciation. Major, minor, and trace element profiles of the cuttings indicate transitional MORB to OIB composition with limited metasomatic shifts in easily mobilized elements. Changes in MgO, K_2O and loss on ignition indicate that metasomatism is strongly correlated with protolith properties. The textures of alteration minerals reveal alteration style to be strongly dependent on protolith as well. Hyaloclastites are intensely altered with calc-silicate alteration assemblages comprising calcic hydrothermal plagioclase, grandite garnet, prehnite, epidote, hydrothermal clinopyroxene, and titanite. In contrast, crystalline basalts and intrusive rocks display a range in alteration intensity from essentially unaltered to pervasive and nearly complete albitization of igneous feldspar and uralitization of clinopyroxene. Hydrothermal anorthite (An92–An98) occurs in veins in the most altered basalt cuttings and is significantly more calcic than igneous feldspar (An48–An79). Amphibole compositions change from actinolite to hornblende at depth. Hydrothermal clinopyroxene, which occurs in veins, has greater variation in Fe content and is systematically more calcic than igneous pyroxene and also lacks uralitic textures. Solid solutions of prehnite, epidote, and garnet indicate evolving equilibria with respect to aluminum and ferric iron.

1. Introduction

Hydrothermal circulation at oceanic spreading centers is a major mechanism of heat loss from the Earth's interior, and chemical interaction of oceanic crust with seawater exerts substantial influence on ocean composition (Edmond et al., 1979; Palmer and Edmond, 1989; Stein and Stein, 1994; Teagle et al., 1998). Despite significant advances in locating and sampling these systems, fundamental processes associated with mineral precipitation, isotopic exchange, and pressure–temperature gradient, remain poorly understood, in large part due to the inaccessibility of the deeper alteration zones that control fluid compositions. Constraining the parameters of fluid and mineral chemistry in hydrothermal systems is critical to our understanding of the chemical flux to the oceans (e.g. Elderfield and Greaves, 1981; Palmer and Edmond, 1989; Davis et al., 2003).

The geothermal system at Reykjanes, Iceland provides unique opportunities for studying the nature of high temperature fluid–rock interaction in a hydrothermal system at a mid-ocean ridge spreading center. The Reykjanes geothermal system is a proposed site for future Iceland Deep Drilling Project (IDDP) drilling. Samples from well RN-

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17 at Reykjanes, an initial candidate for the first Iceland Deep Drilling Project (IDDP) well, provide the source material for a study of petrology and alteration in this geothermal system.

The hydrothermal fluids of Reykjanes are a product of seawater that has been chemically modified through interaction with the basaltic host rocks (Arnórsson et al., 1978; Ólafsson and Riley, 1978; Arnórsson, 1995; Bird and Spieler, 2004; Fridleifsson and Elders, 2005). Total chloride content closely approximates seawater values, although other major elements including SiO_2, Ca, and K indicate that fluids have undergone substantial chemical modification through boiling, water–rock interaction, and perhaps evaporation (Table 1; Lonker et al., 1993; Arnórsson, 1995; Pope et al., 2009). The deuterium isotopic content is considerably lower than seawater, and suggests that the proportions of meteoric water to seawater have varied through time as a function of changes in pressure, temperature, and permeability (Ólafsson and Riley, 1978; Sveinbjörnsdóttir et al., 1986; Pope et al., 2009). Fluid inclusion studies of hydrothermal alteration minerals indicate a range of salinities from fresh to seawater values (<1000 to 35,000 ppm; Franzson et al., 2002).

The peak hydrothermal mineral assemblages observed in the upper part of the Reykjanes geothermal field indicate that the subsurface rocks experienced much hotter hydrothermal temperatures in the past (Franzson et al., 2002; Fridleifsson et al., 2005). High temperature (greenschist) mineral assemblages are observed in shallow, relatively cold regions within several wells, indicating that the geothermal system was hotter than the currently measured system (Sveinbjörnsdóttir et al., 1986). The temperatures inferred from the alteration exceed the boiling point depth curve for hydrostatic pressure. The small size of the system (~1 km^2), coupled with deuterium studies of geothermal fluids and alteration minerals, suggests a single hydrothermal system rather than overlapping systems (Björnsson et al., 1970, 1972; Arnórsson, 1995; Pope et al, 2009). It has been postulated that ice sheets overlying the geothermal system during the Pleistocene increased the hydrostatic pressure and raised the boiling point curve, resulting in higher temperatures at shallower depths (Sveinbjörnsdóttir et al., 1986; Fridleifsson et al., 2005).

Table 1
Comparison of endmember fluid compositions from Reykjanes, Krafla, seawater, and mid-ocean ridge vents.

Concentrations in ppm	RN-8[a]	Krafla[a]	MARK-1[b]	NGS[c]	Seawater[d]
Temp °C	267	300	350	273	2
pH	5.3*	6.5*	4.6*	4.7*,[e]	7.8
SiO_2	543	500	1093	1172	6.4
B	7.5	0.6	5.6	4.7[f]	4.45
Na	9594	105	11,724	11,724	10,800
K	1480	20.9	923	1009	392
Ca	1467	1.07	397	834	411
Mg	1.24	0.011	0[g]	0[g]	1290
Fe	0.238	0.048	122	49	3.4
Al	0.06	–	0.14	0.11	0.001
$\sum CO_2$	781	4267	0[g]	0[g]	114
SO_4	24.4	67.6	0[g]	0[g]	2712
H_2S	26.1	65.3	201	224	0
Cl	19648	223.4	19,818	20,527	19,800
δD	−23.1‰[h]	−88‰[i]	+3‰[j]	1‰[j]	+1.5‰[h]
$\delta^{18}O$	−1.1‰[h]	−12.4‰[i]	+2.37‰	−1.4‰[j]	+0.2‰h

*The values are the calculated pH of the reservoir water at the reported temperature.
[a] Arnórsson, 1995.
[b] Campbell et al., 1988.
[c] Von Damm et al., 1985.
[d] Quinby-Hunt and Turekian, 1983.
[e] Bowers et al., 1988.
[f] Spivack and Edmond, 1987.
[g] Endmember values extrapolated to 0 Mg, SO^4 and Alalkinity <0.
[h] Ólafsson and Riley, 1978.
[i] Darling and Ármannsson, 1989; Krafla isotopic values reflect fluctuations in meteoric water values.
[j] Shanks et al., 1995.

We have characterized the mineralogy and composition of RN-17 cuttings with petrography, X-ray Diffraction (XRD), electron microprobe, X-ray Fluorescence (XRF) and Inductively Coupled Plasma Mass Spectrometry (ICP-MS) techniques. This work has revealed the cuttings to consist of hydrothermally altered basalt with a composition that is transitional between Mid-Ocean Ridge Basalt (MORB) and Ocean Island Basalt (OIB). Alteration style is strongly dependent on protolith composition and texture, and fluid/rock interaction has resulted in systematic metasomatic alteration that is correlated with the degree of crystallization and permeability of the protolith. In this paper we will review the petrology of the RN-17 cuttings and describe in detail the alteration characteristics in the well.

2. Regional setting

The Icelandic basalt plateau rises 3000 m above the surrounding seafloor and is situated at the junction of the Mid-Atlantic Ridge and the Greenland–Iceland–Faeroe ridge. The feature results from the interaction of the spreading plate boundary defined by the Mid-Atlantic Ridge and a deep-seated mantle plume (e.g. Vink, 1984; Lawver and Müller, 1994; White and Morton, 1995; Bjarnason et al., 1996; Wolfe et al., 1997; Allen et al., 1999; Conrad et al., 2004; Parkin et al., 2007).

The Reykjanes Peninsula is constructed of young, highly permeable basaltic formations, and is tectonically active and transected by an intense NE–SW trending fault zone, the continuation of the median fault zone of the Mid-Atlantic Ridge (Björnsson et al., 1970). The Reykjanes volcanic system is the westernmost system in Iceland's western neovolcanic zone (Fig. 1). This volcanic system is characterized by oblique extensional tectonics and episodic fissure eruption volcanism (Jakobsson et al., 1978; Thordarson and Larsen, 2007). The Reykjanes Peninsula lacks central volcanoes with shallow secondary magma chambers; rather heat is provided to the geothermal system through dikes intruded at depth (Gudmundsson and Thórhallsson, 1986; Gudmundsson, 1995). The most recent volcanic eruptions at Reykjanes occurred in the late 12th and early 13th century, and were likely fed directly from fissures tapping magma reservoirs in the mantle (Gudmundsson, 2000; Thordarson and Larsen, 2007).

Significant geothermal activity occurs along the Reykjanes Peninsula with locations controlled by the complex local tectonics and the recent and ongoing volcanic activity (Jakobsson et al., 1978, Arnórsson, 1995). The field is associated with the southernmost of five volcanic fissure swarms, which are located within the active tholeiite volcanic zone of the peninsula (Jakobsson, 1972; Pálmason and Sæmundsson, 1974; Jakobsson et al., 1978; Clifton and Kattenhorn, 2006). The stratigraphy of the field is divided into two informal formations, the uppermost 1000 m of the thermal area is characterized by hyaloclastite tuffs, breccias, and tuffaceous and marine sediments; the deeper part is dominated by basaltic lavas and intrusive rocks (Fig. 2). The lateral extent of the 280 °C isotherm at 1 km depth is about 1 km^2 (Björnsson et al., 1972), and heat flow from the system is 130 ± 16 MW (Fridriksson et al., 2006).

The Reykjanes Peninsula lies less than 40 m above sea level, and the rocks within the system are highly faulted and porous. Rainwater can enter the system easily, as a result of the high permeability, and outside of the Reykjanes geothermal area a thin lens of fresh water (<30 m thick) overlies the seawater that comprises most of the groundwater (Sigurdsson, 1986). Continuous tectonic and magmatic activity facilitates the circulation of groundwater and seawater through the basaltic crust (Thorkelsson, 1928; Jónsson, 1968; Fridriksson et al., 2006). The Reykjanes thermal area sits at the center of swarms of active faults that facilitate hydrologic convection, where seawater intrusions occur below about 1500 m depth (Kadko et al., 2007). The high heat of the thermal area causes the groundwater to flow nearly to the surface, and this results in pressures that are below those of adjacent groundwaters of similar elevations outside the geothermal system (Tómasson and Kristmannsdóttir, 1972).