

## Isotopic Evidence of Hydrothermal Exchange and Seawater Ingress from Alteration Minerals in the Reykjanes Geothermal System: Results from the IDDP

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### ABSTRACT

The primary economic objective of the Iceland Deep Drilling Project (IDDP) is to find 450-600°C supercritical geothermal fluids at drillable depths. The Reykjanes geothermal system is a seawater recharged hydrothermal system, although fluid composition has evolved through time as a result of changing proportions of meteoric water influx as well as differing pressure and temperature conditions imposed by glaciation (Arnorsson, 1995; Friðleifsson et al., 2003). We have measured the Sr compositions in epidote and anhydrite as well as S and O isotopic composition of anhydrite in the Reykjanes geothermal system in order to better constrain the geometry and processes by which seawater contributes to the generation of hydrothermal fluid. Anhydrite is widespread in shallow portions of the Reykjanes system to about 1500 m, and after a depositional hiatus appears again around 2650 m depth. This may suggest either a transient incursion of cold seawater into the system at depth, or possibly a more permanent cooling at depth in the system. A zone of pyroxene hornfels facies contact metamorphism has also been observed at this depth (Marks et al., 2008), and the reappearance of anhydrite could possibly indicate heating and oxidation of previously precipitated sulfides. Analysis of the spot core successfully recovered by IDDP in November 2008 will provide an excellent opportunity to further investigate the fluid-rock interaction at depth within this well.

### 1. INTRODUCTION

The Reykjanes geothermal field, located on the landward extension of the Mid-Atlantic Ridge, is the location of a 3 km deep drill-hole developed by the Iceland Deep Drilling Project to investigate supercritical fluids as a potential energy resource and to explore geologic processes in actively spreading margins (Figure 1). In order to evaluate the nature and extent of rock-fluid interactions and the applicability of Reykjanes as a proxy to oceanic spreading margins, it is necessary to understand the source and composition of hydrothermal fluids within the system. The composition and salinity of geothermal fluids at Reykjanes resemble evolved seawater, suggesting that subsurface conditions at Reykjanes may be analogous to sea-floor black smokers. The high temperature reaction zone that is presumed to control the composition of the hydrothermal fluid is interpreted to occur deeper than the present depth of drilling, which reached just over 3 km in the well RN-17, during the initial stage of the Iceland Deep Drilling Project. 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 imposed by glaciation (Arnorsson, 1995; Friðleifsson et al., 2003). Reaction of geothermal fluids with the basaltic host rock has resulted in a progressive hydrothermal alteration sequence with increasing depth (Friðleifsson et al., 2005; Franzson et al., 2002; Lonker et al., 1993). The assemblage of greenschist facies alteration minerals implies that temperatures reached at least 250°C at depths as shallow as 350 m. This requires hydrostatic pressures that exceed the present-day boiling point to depth curve, and therefore must record alteration at higher fluid pressures during the Pleistocene.

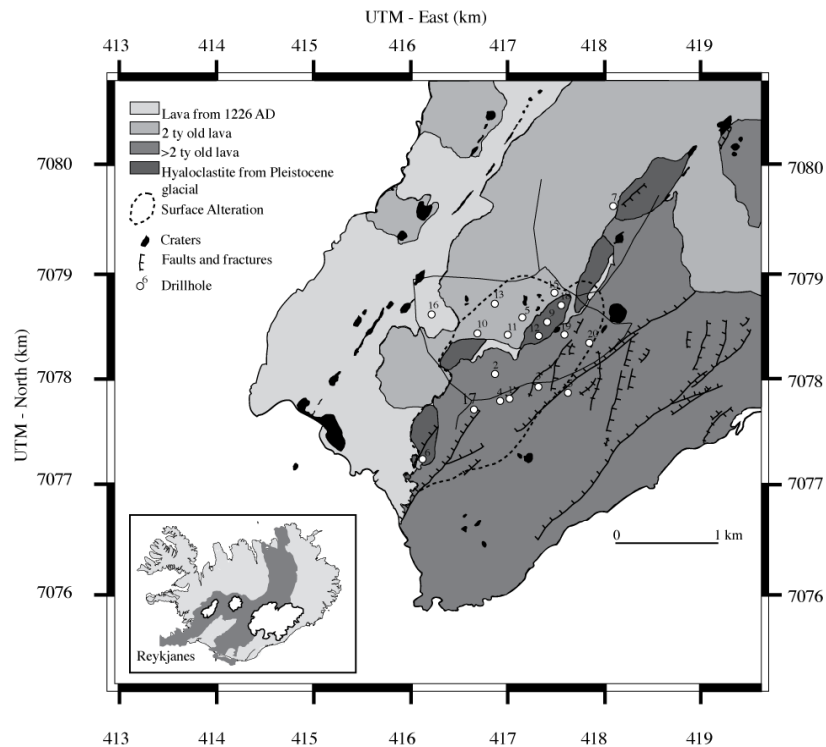
Samples of anhydrite precipitated within basaltic crust provide a unique opportunity to investigate the chemical evolution of fluids during percolation into the crust in the downwelling limb of a hydrothermal system because anhydrite contains three independent isotopic tracers of hydrothermal exchange (S, O, Sr). This combination of isotopes in a single phase provides a powerful tool for investigating fluid-rock interactions.

Anhydrite forms both when cold sulfate-rich seawater mixes with hot Ca-rich hydrothermal fluid and where seawater is heated to temperatures above approximately 150°C and anhydrite becomes insoluble. Strontium readily substitutes into the anhydrite structure and seawater-derived Sr is much more radiogenic than basalt derived Sr, therefore measurement of the Sr isotopic composition of anhydrite provides an excellent opportunity for tracing subsurface fluid mixing between seawater and geothermal fluids that have leached strontium from basalt (Humphris and Bach, 2005; Albarède et al., 1981; James and Elderfield, 1996).

### 2. METHODS

Cuttings were collected from RN-17 at 2m intervals from the entire depth of the well for lithologic logging. Cuttings were inspected with a binocular microscope as well as in 34 thin sections. Petrographic and X-ray diffraction studies were carried out on these cuttings at ISOR, the Icelandic Geosurvey.

Backscattered electron imaging (BSE) and mineral compositional analyses were performed at UC Davis on cuttings selected at 50 m intervals. Cuttings were mounted on doubly polished, carbon coated thin sections and analyzed using a Cameca SX-100 electron microprobe. Quantitative wavelength-dispersive analyses of amphibole, epidote, chlorite, garnet, and prehnite were performed at 15 keV and 10 nA beam current using an approximately 1 µm diameter beam. Feldspar analyses were performed at 15 keV and 10 nA beam current using an approximately 5 µm beam.



**Figure 1: Map of the Reykjanes Peninsula showing major faults, fractures, flows, surface alteration, and the location of IDDP well of opportunity RN-17 (map adapted from Sæmundsson and Einarsson, 1980; Friðleifsson and Albertsson, 2000; and Franzson et al., 2002).**

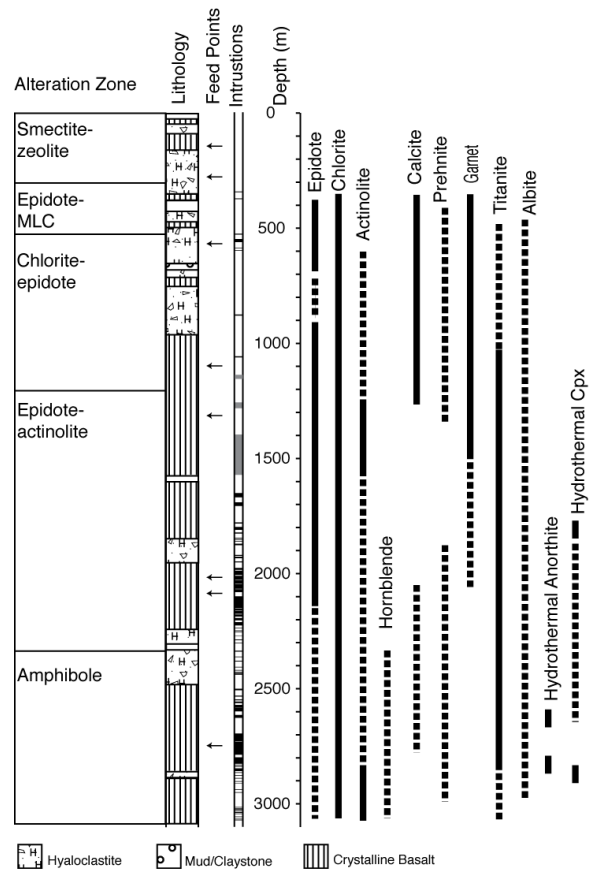
Sr isotopic measurements were made on secondary phases by laser ablation multicollector inductively coupled plasma mass spectrometry at UC Davis.

**3. RESULTS**

Well lithology is presented in Figure 2. Samples from the deepest part of Reykjanes well RN-17 include greenschist and pyroxene hornfels facies assemblages, suggesting seawater penetration into a part of the system that is close to the high temperature reaction zone. Electron microprobe studies of drill cuttings reveal intense alteration of hyaloclastites with calc-silicate alteration assemblages comprising calcic hydrothermal plagioclase, grandite garnet, prehnite, epidote, hydrothermal clinopyroxene, and titanite. In contrast, crystalline basalts and intrusives display a wide range in alteration intensity from essentially unaltered to pervasive and nearly complete replacement of feldspar and pyroxene.

Anhydrite is widespread in shallow portions of the Reykjanes system to about 1500 m, and after a depositional hiatus appears again around 2650 m depth. This may suggest either a transient incursion of cold seawater into the system at depth, or possibly a more permanent cooling at depth in the system. A zone of pyroxene hornfels facies contact metamorphism has also been observed at this depth (Figure 2), indicating temperatures as high as 600°C (Marks et al., 2008), and the reappearance of anhydrite could possibly indicate heating and oxidation of previously precipitated sulfides.

<sup>87</sup>Sr/<sup>86</sup>Sr values of individual epidote grains were typically 0.7045-0.7050, but ranged as high as 0.7073 in individual epidote grains (Figure 3). <sup>87</sup>Sr/<sup>86</sup>Sr values of anhydrite from the Reykjanes geothermal system ranged from 0.7044-0.7053, gypsum values ranged from 0.7093 to 0.7094.



**Figure 2: Lithostratigraphy, alteration zones, and distribution of secondary minerals (below the smectite zone) with depth in RN-17 (modified after Friðleifsson et al., 2005).**

#### 4. DISCUSSION

Alteration phases indicative of a transition from Epidote-Actinolite alteration to alteration at amphibolite conditions are not readily observed during routine cuttings logging, but were documented during BSE petrographic investigation and the mineral chemistry of these phases is reported in following sections. We define a new alteration zone, the Amphibole zone, based on the occurrence of the high temperature minerals hornblende-clinopyroxene-plagioclase. The zone boundary is transitional with the first occurrence of these minerals at 2350 meters, which are locally developed within the Epidote-Actinolite zone to the bottom of the hole.

##### 4.1 Effect of protolith on intensity of alteration

The nature of the protolith strongly influences the intensity of alteration in this rock dominated hydrothermal system. The hyaloclastites, tuffs, and sediments are more susceptible to alteration than the crystalline basalts as a result of their greater reactivity, greater percentage of glass, and abundant vesicles. Throughout RN-17, hyaloclastites are highly altered and host most of the hydrous calc-silicates, plus calcite and chlorite. Anhydrite and sulfide minerals are almost exclusively hosted in hyaloclastite.

In contrast, the degree of alteration in basalts is highly variable. While basalts range from essentially unaltered to thoroughly albitized and uralitized, unaltered basalts are frequently found in the same cutting interval as pervasively altered hyaloclastites. The most altered basalts host abundant amphibole up to magnesiohornblende in composition, as well as secondary orthoclase feldspar and, rarely, hydrothermal anorthite. The altered basalts are almost exclusively from cuttings intervals dominated by pillow basalts, which seem to alter more readily due to cracking, vesiculation, and a higher proportion of glass that enhances fluid ingress. Crystalline basalts are minimally altered in general. Both hyaloclastite and crystalline basalt cuttings host secondary veins, which typically comprise quartz, calcite, epidote and, rarely, hydrothermal plagioclase. The formation of calc-silicate minerals and aluminous amphiboles requires release and mobilization of aluminum during alteration (Schiffman and Day, 1995). Formation of these alteration phases in crystalline basalts therefore requires extensive alteration of plagioclase to albite. In contrast, in hyaloclastite or pillow basalts, alteration of glass can provide a local source of aluminum and may contribute to the more extensive alteration observed in these lithologies.

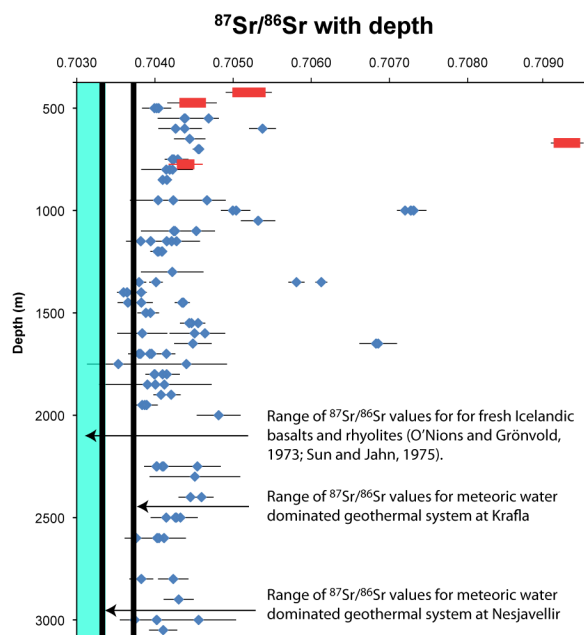
##### 4.2 Sr isotopic ratios

Epidote occurs in virtually all geothermal systems in which present or calculated paleotemperatures exceed 200-250°C (Bird et al., 1984). In the active high temperature systems in Iceland the minimum temperature for epidote has been set as 230°C. Epidote is widely distributed throughout the RN-17 samples as veins and vug fillings, replaces hyaloclastite and the interstitial matrix of basalt samples, and is also an alteration product of primary plagioclase. It occurs preferentially in the more reactive hyaloclastite and is associated with prehnite, chlorite, quartz, zeolites, calcite, amphibole, and garnet.

Anhydrite is widespread in shallow portions of the Reykjanes system, and is expected to form either when cold, sulfate-rich seawater mixes with hot, Ca-rich hydrothermal fluid or where seawater is heated to temperatures above approximately 150°C and anhydrite becomes insoluble. Strontium readily substitutes into the

anhydrite structure, and seawater-derived Sr is much more radiogenic than basalt derived Sr, therefore measurement of the Sr isotopic composition of anhydrite provides an excellent opportunity for tracing subsurface fluid mixing between seawater and hydrothermal fluids that have leached strontium from basalt (Humphris and Bach, 2005; Albarède et al., 1981; James and Elderfield, 1996).

The Sr isotopic ratios of alteration minerals are shifted from basaltic values (0.7030-0.7034; O'Nions and Grönvold, 1973; Sun and Jahn, 1975) toward seawater values (0.70916; Palmer and Edmond, 1989). Epidote samples from the Reykjanes system have significantly higher Sr isotopic ratios than analogous freshwater dominated



**Figure 3:**  $^{87}\text{Sr}/^{86}\text{Sr}$  isotopic ratios measured in epidote (blue diamonds) and anhydrite (red bars) from RN-17. Bars indicate  $2\sigma$  error.

geothermal systems at Nesjavellir and Krafla. This suggests that seawater Sr is able to penetrate deep within the geothermal system, and that seawater Sr has been able to exchange with secondary phases throughout the system. Shallow anhydrite from the Reykjanes similarly shows a shift from purely basaltic values, and in at least one set of samples from 690m reflects a purely seawater source.

#### 5. CONCLUSIONS

Samples from the Iceland Deep Drilling Program (IDDP) well of opportunity RN-17 have provided a basis for the study of the geochemistry of alteration within the Reykjanes system. We have found the intensity of alteration and secondary mineralization to be directly related to the texture of the protolith. Specifically, high porosity, glassy fragments are more susceptible to alteration, and holocrystalline basalts typically display minimal alteration. We have used electron microprobe and BSE methods to define the amphibole zone, a new alteration zone within RN-17. This zone indicates higher temperatures and pressures than had previously been suggested for the base of this well. Finally,  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios within alteration minerals are significantly shifted toward seawater values within the system, and therefore confirm the deep penetration of seawater into the Reykjanes system.

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