



Stable isotopes of hydrothermal minerals as tracers for geothermal fluids in Iceland



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ABSTRACT

The Reykjanes and Krafla geothermal systems, located within the active rift zone of Iceland, are both potential venues for exploitation of deep supercritical fluids by the Iceland Deep Drilling Project (IDDP). An essential aspect of properly characterizing geochemical and hydrologic processes occurring at supercritical depths is establishing the source, composition and evolution of geothermal fluids. Traditionally, hydrogen isotopes of thermal fluids are used to determine their source. We show that for these, and likely many other Icelandic geothermal systems, analyzing fluid δD is not sufficient alone. Rather, $\delta^{18}O$ and δD of hydrothermal minerals in conjunction with geochemical characteristics of extant geothermal fluids are necessary to characterize the source and geologic evolution of geothermal reservoir fluids. Here we review results from existing drill holes in the Reykjanes and Krafla geothermal systems to depths of ≤ 3 km, and explore the utility of using stable isotopes in alteration minerals such as epidote to assess the hydrogeology of extinct volcano-hydrothermal systems by presenting new data from the Geitafell fossil hydrothermal system in southeast Iceland.

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1. Introduction

The neo-volcanic zone of Iceland is a unique natural laboratory for studying fluid–rock interaction in magma–hydrothermal systems. There are more than twenty high-temperature ($>200^\circ C$) geothermal systems associated with central volcanoes and fissure swarms that provide an opportunity to study, in situ, geochemical interaction between basaltic rocks (magmatic products of the Iceland mantle plume and the sub-aerial extension of the Mid-Atlantic spreading ridge [MAR]) and aqueous electrolyte solutions at elevated temperatures (Arnórsson, 1978, 1995). Critical for the application of these natural laboratories toward understanding chemical mass transfer in magma–hydrothermal systems is a well-characterized source of hydrothermal fluids. The extent of chemical alteration of both the geothermal fluid and surrounding rock can only be quantified when starting rock and fluid properties are known. Further, from an economic viewpoint, fluid source is critical to understanding recharge rates for a producing geothermal field, and potential hazards such as fluid acidity or scaling of pipes during production.

In Iceland, the hydrogen isotope ratio of geothermal fluids have traditionally been used as a tracer for fluid source, based on early studies (e.g. Craig et al., 1956) indicating that there was generally no discernable difference between δD of thermal fluids and that of local meteoric water. Arnason (1977) measured the δD of meteoric waters throughout Iceland, and used the resultant contour map of his analyses to interpolate the origin of thermal waters that did not have a δD similar to the local mean values of precipitation. This interpretation requires three major assumptions: (1) δD_{WATER} remains constant with time for a given region, (2) the δD of groundwater does not change due to water–rock reactions as is observed in the $\delta^{18}O$ of groundwater and (3) input of non-meteoric fluids (such as seawater or magmatic fluids) is at most a few per cent and thus cannot significantly affect the δD of the meteorically-sourced thermal waters.

More recently, thorough investigation of two of the high-temperature geothermal regions in Iceland, facilitated through exploration activities of the Iceland Deep Drilling Project (IDDP), demonstrates that one or more of these assumptions may be invalid for any given geothermal reservoir. The IDDP, which intends to increase both the economic and scientific utility of geothermal systems within Iceland's neo-volcanic zone by sampling supercritical fluids at depths of 4–5 km has piloted two experimental deep drill holes in the Reykjanes and Krafla geothermal systems (Fig. 1; Elders and Fridleifsson, 2010; Fridleifsson and Elders, 2005). In Reykjanes, a pre-existing drill hole (RN-17) was extended

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to 3.1 km before collapse of the upper wall rock prevented further downward drilling. The Krafla geothermal system is the site of drill hole IDDP-1, which was drilled in Spring 2009. Before reaching supercritical reservoir conditions, IDDP-1 intercepted magma at a depth of 2104 m (Elders et al., 2011). Their selection as sites for the first two IDDP drill holes, and the continued interest in deep drilling in these areas, warranted a detailed analysis of the isotopic properties of alteration minerals formed through fluid–rock interaction in Reykjanes and Krafla in order to better assess the hydrogeologic character of these regions (Pope, 2011; Pope et al., 2009).

Hydrogen and oxygen isotope compositions of geothermal fluids in these systems have been monitored since the 1970s (Árnason, 1977; Arnórsson, 1978, 1995; Darling and Ármannsson, 1989; Ólafsson and Riley, 1978) and their δD values do not show a straightforward relationship to either local meteoric fluids or to an obvious distal meteoric source. This is because the hydrologic properties of both systems deviate from the assumptions Árnason (1977) required for using δD_{FLUID} as a tracer, but in different ways. Here we review and augment the isotopic results of Pope (2011) and Pope et al. (2009), and show that alone, deuterium may not be an effective independent tracer of geothermal fluids. However, by combining data on major and isotopic fluid chemistry with hydrogen and oxygen isotope properties of alteration minerals, we not only overcome uncertainties relating to fluid source of individual systems, but we can develop a spatially and temporally detailed record of variations in fluid source, composition and interaction with surrounding host rocks in discrete geothermal environments. Finally, we apply our improved understanding of what variables influence the isotopic record of fluid–mineral interaction preserved in hydrothermal epidote in active geothermal systems by presenting new isotope data from an extinct geothermal system located within the ca. 5–6 Ma old Geitafell central volcano (Fig. 1a), where direct fluid analyses are not possible.

2. Background

2.1. Reykjanes

The Reykjanes geothermal system is located on the southwest tip of the Reykjanes Peninsula, on the landward extension of the Mid-Atlantic Ridge (Fig. 1a). Like other high-temperature systems in Iceland, it is composed of highly fractured basalt lavas and hyaloclastites that have been intruded by shallow dikes and sills. Mafic intrusions are more abundant with increasing depth (Franzson et al., 2002; Kristmannsdóttir, 1983). Fracturing and faulting in the region is due to extension along a NE–SW trending graben zone, marking the sub-aerial continuation of the Reykjanes Ridge (see Arnórsson, 1995 for summary). Host rocks of the Reykjanes geothermal system have extensively reacted with hydrothermal fluids, forming common secondary minerals that include zeolites, mixed-layer clays, chlorite, prehnite, epidote and actinolite. This hydrothermal mineral assemblage displays a distinct zoning with depth, and is used to classify hydrothermal alteration into temperature- and depth- related zones (e.g. Franzson et al., 2002; Freedman et al., 2009; Fridleifsson et al., 2005). Reykjanes is a two-phase geothermal system to ~1500 m depth, in which temperatures follow the boiling point curve with depth and both liquid and vapor are present. Below ~1500 m, temperatures are approximately constant, with the highest recorded down-hole temperature at about 320 °C.

The Reykjanes geothermal system was considered to be dominated by seawater-derived hydrothermal fluids due to the elevated chloride content and total dissolved solids observed in this region relative to other high-temperature fields in Iceland, which apparently have a meteoric source (e.g. Krafla), or a mixed

meteoric-seawater source, such as the nearby Svartsengi geothermal system (Arnórsson, 1995). A seawater-derived fluid source is also likely given the system's proximity to the coast, and the highly permeable and intensely fractured host-rocks, which allow for an influx of seawater into the hydrothermal system (Arnórsson, 1995, 1978). However, hydrogen isotope values of Reykjanes fluids are as low as -23.1‰ (Fig. 2). This is inconsistent with an exclusively seawater-sourced geothermal fluid, which should have a $\delta D_{\text{FLUID}} \approx 0\text{‰}$, but is comparable to the isotopic composition of Svartsengi fluids ($\sim -24\text{‰}$), which are considered to be a mixture of ~70% seawater and 30% local meteoric water (δD is approximately -48‰) given their total dissolved solids content and salinity (Lonker et al., 1993; Ragnarsdóttir and Walther, 1984).

2.2. Krafla

The Krafla geothermal system is located within the active Krafla caldera of the Northern Volcanic Zone (Fig. 1a). Highly variable distributions of subsurface temperature and permeability distinguish three distinct well fields within the system (Arnórsson, 1995). Of the two most productive well fields (shown in Fig. 1c), Suðurhlíðar shows a classical two-phase system in which temperatures follow the boiling point curve with depth. In contrast, the Leirbotnar well field shows a temperature–depth profile that remains constant at ~205 °C for the upper kilometer, and then follows the boiling point curve below that depth. This pattern has been interpreted as the result of an inferred aquiclude that occurs at approximately 1000–1500 m depth, and separates an upper and lower zone of fluid circulation in this field (Ármannsson et al., 1987; Darling and Ármannsson, 1989). Hveragil, a topographic low that outlines a NE–SW trending fault swarm and is associated with a row of explosive craters, divides the Leirbotnar and Suðurhlíðar fields, and it is presumed the aquiclude pinches out beneath this region. Hveragil is also interpreted to overlie the primary upflow zone of the Krafla geothermal system. High downhole temperatures of Hvíthólar, a third, smaller well field, located to the south and not shown in Fig. 1c, are attributed to the ascent of hot fluids along the Krafla caldera rim, and are not considered for the purposes of this study.

The complexity of Krafla geothermal fluids is not apparent from their total dissolved solid content, which is extremely low (~700 ppm; Arnórsson, 1995) or their oxygen and hydrogen isotope chemistry, which is illustrated in Fig. 2. Both chemical characteristics present evidence of a meteoric water source that has an isotopic composition similar to local precipitation (Darling and Ármannsson, 1989), although there is a large range in both $\delta^{18}\text{O}$ and δD of fluids discharged from individual wellheads: -13.4 to -10.3‰ and -95 to -85‰ , respectively (Darling and Ármannsson, 1989; Sveinbjörnsdóttir et al., 1986). In fact, the chemistry and physical properties of individual wells reveals several additional anomalies. First, in the Upper Zone of Leirbotnar temperatures are lower than expected if fluids were a product of boiling from the Lower Zone. Instead, there must be mixing with cold groundwater recharged from another source. Second, although recharge to the deep aquifer in Leirbotnar field has a likely source in a level plateau stretching to the north and west of the field (Arnórsson, 1995; Darling and Ármannsson, 1989), there is no similarly obvious source for the Suðurhlíðar field. Krafla Mountain, located to the northeast of Hveragil, forms a hydrologic barrier between the Suðurhlíðar well field and high-elevation regions to the north that recharge the Leirbotnar field. Darling and Ármannsson (1989) suggested that recharge to Suðurhlíðar is coming from a more distant southern region, but a specific source is not clear, nor is the process by which groundwaters cross the hydrologic barriers created by faults along the southern caldera rim. Finally, due to recent and ongoing shallow magmatic activity in the Krafla region, individual wells have had large influxes of CO_2 and other magmatic gases,

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