



Lithogeochemical approaches in geothermal system characterization: An application to the Reykjanes geothermal field, Iceland



R.B. Libbey*, A.E. Williams-Jones

McGill University, Montreal, QC, Canada

ARTICLE INFO

Article history:

Received 23 July 2015

Received in revised form 16 April 2016

Accepted 2 May 2016

Keywords:

Lithogeochemistry
Metasomatism
Water-rock interaction
Resource vectoring
Mass transfer
Volume estimates

ABSTRACT

This article presents the results of a comprehensive lithogeochemical study that was conducted using downhole rock samples from the Reykjanes geothermal system in Iceland. Magmatic fractionation trends established for least-altered rocks were used to correct mass change estimates for pseudo-enrichments/-depletions due to fluid-rock interaction. Net mass changes of altered rocks in the Reykjanes geothermal system range from -26 to $+22$ g/100 g_p, and are dominated by changes in $\text{SiO}_2 > \text{CaO} > \text{MgO} > \text{Na}_2\text{O}, \text{K}_2\text{O}, \text{S} > \text{C}$. Trace elements undergoing the greatest net mass changes are $\text{Ba} > \text{Zn} > \text{Cu}, \text{Ni} > \text{Sr} > \text{Rb} > \text{As} > \text{Cd}$. The lithogeochemical data are interpreted with petrographic data and data from parallel studies of mineral chemistry (detailed in separate manuscripts). Trends in the distribution of reactive-mobile elements correspond closely to the large-scale hydrology of the Reykjanes geothermal system, as determined by measured isotherms and hydrothermal mineral zonation. A hypothesis of deep inflow to the system from the southeast is supported by lithogeochemical and mineralogical evidence and downhole temperature measurements. Whole-rock mass changes of specific components counter their documented enrichments and depletions in the Reykjanes geothermal fluid relative to the initial seawater input. Volume estimates for the Reykjanes geothermal system are made based on the redistribution of select reactive-mobile elements.

© 2016 Elsevier Ltd. All rights reserved.

1. Introduction

Despite the common application of lithogeochemistry (whole-rock chemistry) to vectoring and understanding processes in fossil ore-forming hydrothermal systems (e.g., Stanley and Madeisky, 1994; Gifkins et al., 2005; Warren et al., 2007; Piercey, 2009), this approach has been only sparingly applied to the characterization of active geothermal environments. The bulk-rock chemical signature of cuttings from a geothermal well is the product of multiple variables: the primary chemical composition of the unaltered host rock; chemical losses and gains due to water-rock interaction; alteration susceptibility of the precursor rock; pseudo-enrichment/-depletion of elements that were not leached or deposited due to overall mass change effects (i.e., closure effect signatures—a phenomenon related to constant analytical sums of 100%; Barrett and MacLean, 1994; Stanley and Madeisky, 1994); and if not mitigated, contamination from sources including drilling

mud components and metal casing/drill pipe fragments. Complications surrounding the deconvolution of these variables have prompted some authors to suggest that bulk-rock chemical studies are not well-suited for characterizing active geothermal environments (e.g., Nicholson, 1993, p. 146).

The few lithogeochemical studies that have been conducted on active geothermal systems have enhanced our understanding of metasomatic processes, however, most have only employed a limited dataset from a small number of wells and sample depths, precluding the possibility of detailed, field-wide assessments of chemical leaching and deposition (e.g., Steiner, 1953—Wairakei; Ewers and Keays, 1977—Broadlands-Ohaaki; Naboko, 1977—Kamchatka; Bamford and Christensen, 1979—Cove Fort-Sulphurdale; Goguel, 1983—Wairakei and Broadlands-Ohaaki; Cox, 1984—Ngawha and Puna; Sturchio et al., 1986—Yellowstone; Teklemariam et al., 1996—Aluto-Langano; Rychagov et al., 2000—Baranskiy; Macintosh, 2000—Broadlands-Ohaaki; Utami et al., 2006—Lahendong; Pandarinath et al., 2008—Los Azufres; Marks et al., 2010—Reykjanes; Pochee, 2010—Rotokawa; Raffone et al., 2010—Reykjanes; Ottolini et al., 2012—Reykjanes; Padilla et al., 2012—Reykjanes; Yudiantoro et al., 2012—Kamojang; Mauriohooho et al., 2014—Tauhara; Libbey

* Corresponding author at: Department of Earth and Planetary Sciences, McGill University, 3450 University Street Montreal, Quebec H3A 0E8, Canada.

E-mail address: ryan.libbey@mail.mcgill.ca (R.B. Libbey).

et al., 2015—Joaquina). The only extensive field-wide investigation of lithochemical variations in an active geothermal setting, known to the authors, was conducted on the Roosevelt Hot Springs geothermal system, Utah (Bamford et al., 1980; Christensen et al., 1980).

Lithochemical studies of geothermal systems provide complementary information to that furnished by fluid chemical studies, and can be used to reinforce understanding of element mobility, reactivity, and overall fluxes of elements in hydrothermal settings. The main perceived applications of downhole lithochemistry to geothermal exploration are in assessing the location, size, and geometry of past and present upflow, the quantification of the normative mineralogy, the estimation of system volumes, the delineation of active and fossil permeable horizons (e.g., Bamford et al., 1980; Christensen et al., 1980), and inter-well chemostratigraphy (e.g., Flower et al., 1982) to map units and offsets that cannot be determined by geological/petrographic investigation. Full implementation of the latter two applications requires a higher resolution dataset than is available in the present study. The focus herein is on the use of downhole lithochemistry as a tool for 3D mapping of geothermal upflow and estimating system volumes. This study builds on the knowledge gained from aforementioned studies by integrating mass change corrections and 3D interpolations with a large field-wide lithochemical dataset from the Reykjanes geothermal system, Iceland.

2. Chemical behavior in geothermal systems

The use of bulk-rock chemical components as tracers of fluid paths in active geothermal systems hinges on the understanding of element mobility and reactivity in hydrothermal environments (Fig. 1). A coherent discussion of this topic requires clarification of the terms “mobility”, “reactivity”, and “conservative”, as their application is inconsistent between the hydrothermal mineral deposits community and the geothermal community. The use of these terms in the present study is largely consistent with the latter, as explained below. The reader is also directed to a discussion of these concepts in Arnórsson (2000).

The *mobility* of a chemical component, as utilized herein, refers to its ability to enter an aqueous phase upon fluid-rock interaction. In empirical terms, it can be defined as the ratio of a component (originally hosted in the rock) between the coexisting fluid and the rock. In the two extreme scenarios, a component that is 100% immobile will not enter the fluid, whereas a component that is 100% mobile will be completely removed from the host rock. All elements are mobile to a certain degree, however, if measurable changes are not experimentally detectable with respect to a starting reference (e.g., if elements have only been redistributed on a sub-centimeter scale), the component is, for practical purposes, immobile (Sturchio et al., 1986; Van Baalen, 1993). Relic immobile elements from primary minerals may be incorporated into hydrothermal minerals through replacement processes (Gifkins et al., 2005).

In contrast to mobility, *reactivity* in this paper describes the ability of a component to be incorporated into the lattice of a saturated hydrothermal mineral as a major (>1 wt.%), minor (1–0.1 wt.%), or trace (<0.1 wt.%) constituent, or its ability to be removed from solution by adsorption processes. A component that is 100% *conservative* (non-reactive; a.k.a. a “tracer”) will remain in the fluid and not be incorporated into any precipitating hydrothermal minerals, whereas a component that is 100% reactive will be completely removed from the fluid as hydrothermal minerals are precipitated before the fluid leaves the system (note that the use of the term “conservative” in this manner is largely inconsistent with the mineral deposits literature, where it is generally used to describe immobility). As an example, chlorine displays a dom-

inantly conservative behavior owing to the exceptionally high solubility of chloride minerals at geothermal conditions (e.g., 45 and 78 g/100 g_{H2O} at 180°C for halite and sylvite, respectively; Tilden and Shenstone, 1884); therefore, these minerals remain highly undersaturated in the fluid under all but the most extreme conditions.

A crude measure of relative reactivity for components in active geothermal settings can be derived empirically by comparing ratios of reactive versus conservative mobile chemical components in the deep fluid to those from shallow depths or surface thermal discharges (only applicable to reactive components that are controlled by minerals with prograde solubility and those that are not significantly added to the fluid from the host rocks during upflow). Ratios are used for comparison as absolute concentrations of chemical components can change upon fluid ascent to the surface in response to phase separation and dilution. A vital assumption in the latter case is that there has been no addition of the chemical components of interest by the dilutant. The semi-quantitative definition of “reactivity” presented here differs from that used by Giggenbach (1984), in which it represents a parameter to quantify the deviation of a fluid composition from equilibrium with respect to a specific reaction (i.e., $|1 - Q/K|$, where Q is the reaction quotient, a.k.a. ion activity product, and K is the equilibrium constant), relatable to the concept of mineral saturation indices (e.g., Reed and Spycher, 1984).

Although the term *compatibility* is used in some texts to refer to both aqueous and magmatic element partitioning processes (e.g., Arnórsson et al., 1983), in this paper it refers only to the partitioning of a component between coexisting melt and minerals. It should be noted that some parameters controlling element behavior in an igneous melt, notably ionic potential (a measure of charge density, $Z/r(\text{Å})$), are the same as those controlling their behavior in aqueous fluids. The concepts of ion partitioning and crystal lattice substitutions put forth by Goldschmidt (1937) are thus foundational to understanding element mobility and reactivity in geothermal systems.

3. Geologic setting

The Reykjanes geothermal system is a basalt-hosted, seawater-dominated active hydrothermal system situated at the tip of the Reykjanes peninsula in southwest Iceland. It is one of the smallest high-temperature fields in Iceland, with surface manifestations and altered ground covering an area of ~1 km² (Fig. 2). The most recent volcanic eruptions around the Reykjanes geothermal field occurred in the late 12th to early 13th centuries and are thought to have taken place along fissures that tapped mantle magma reservoirs (Gudmundsson, 2000; Thordarson et al., 2007). The subsurface stratigraphy can be divided into two informal units. The uppermost 1 km of the system is dominated by hyaloclastite tuff, breccias, pillow basalts, and tuffaceous and marine sediments. The deeper parts of the system are composed primarily of basaltic lavas and diabase dikes (Marks et al., 2010). Altered and hydrothermally-cemented tuffaceous and sedimentary successions at depths of 400–800 m act as a semi-permeable cap-rock to the hydrothermal system (Friðleifsson et al., 2011, 2014). A low resistivity anomaly at 10 km below the surface of the Reykjanes geothermal system has been interpreted as a dense sheeted-dike complex or a large cooling gabbroic intrusion, and likely serves as the heat engine that drives the shallower hydrothermal system (Friðleifsson et al., 2011).

The present-day fluid in the Reykjanes geothermal system is heated seawater that has been modified due to interaction with basalt at high temperature. As Cl⁻ is a conservative anion in typical geothermal systems, the total chloride content of the unboiled Reykjanes geothermal fluid (~1.9 wt.% Cl⁻) is similar to that of

Download English Version:

<https://daneshyari.com/en/article/8088806>

Download Persian Version:

<https://daneshyari.com/article/8088806>

[Daneshyari.com](https://daneshyari.com)