



Chemical transport in geothermal systems in Iceland Evidence from hydrothermal alteration

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ABSTRACT

This study focuses on the chemical changes in basaltic rocks in fossil low- and high-temperature hydrothermal systems in Iceland. The method used takes into account the amount of dilution caused by vesicle and vein fillings in the rocks. The amount of dilution allows a calculation of the primary concentration of the immobile element Zr, and by multiplying the composition of the altered rock by the ratio of Zr (protolith)/Zr (altered rock) one can compute the mass addition caused by the dilution of the void fillings, and also make a direct comparison with the likely protoliths from the same areas. The samples were divided into three groups; two from Tertiary fossil high-temperature systems (Hafnarfjall, Geitafell), and the third group from a low temperature, zeolite-altered plateau basalt succession. The results show that hydrothermally altered rocks are enriched in Si, Al, Fe, Mg and Mn, and that Na, K and Ca are mobile but show either depletion or enrichment. The elements that are immobile include Zr, Y, Nb and probably Ti. The two high-temperature systems show quite similar chemical alteration trends, an observation which may apply to Icelandic fresh water high-temperature systems in general. The geochemical data show that the major changes in the altered rocks from Icelandic geothermal systems may be attributed to addition of elements during deposition of pore-filling alteration minerals. A comparison with seawater-dominated basalt-hosted hydrothermal systems shows much greater mass flux within the seawater systems, even though both systems have similar alteration assemblages. The secondary mineral assemblages seem to be controlled predominantly by the thermal stability of the alteration phases and secondarily by the composition of the hydrothermal fluids.

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1. Introduction

The location of Iceland as a subaerial part of the Mid-Atlantic Ridge, with a wealth of geothermal activity, makes it a unique area for the study of water–rock interaction. Temperatures of fluid–rock interaction range from about 2 to 3 °C in the groundwater systems to probable supercritical values in the high-temperature geothermal areas (Elders and Fridleifsson, 2005). The rocks that host the geothermal reservoirs are of igneous origin, with basaltic compositions constituting about 90% of the volume with the remainder having more evolved compositions. The abundant geothermal resources are economically important and widely utilized, and have consequently been extensively studied from geochemical, structural, geophysical and geological points of view (e.g., Arnorsson et al., 1983; Bodvarsson, 1983; Marty et al., 1991; Schiffman and Fridleifsson, 1991; Lonker et al., 1993; Riedel et al., 2001). The geothermal resources range from low-temperature systems, in which shallow groundwater has gained heat in response to the prevalent regional geothermal gradient, to high-temperature

systems in which the high thermal gradient is due to shallow crustal magmatic activity. The latter type is mostly confined to active volcanic centres. However, fossil high temperature geothermal systems are exposed by erosion allowing three dimensional access to the subsurface portions of the hydrothermal systems (e.g. Fridleifsson, 1983, 1984). The majority of the hydrothermal systems in Iceland have waters derived from local meteoric water, although seawater-dominated hydrothermal fluids occur in some near coastal geothermal systems (Sveinbjornsdottir et al., 1986). The general similarity of both source fluids and host rocks throughout much of Iceland allows comparison among hydrothermal systems.

Rock properties play an important role in the petrophysical parameters of the individual systems and an increasing emphasis has been placed on the study of reservoir characteristics. During the last 13 years, Orkustofnun (the National Energy Authority of Iceland), with the financial support of Orkuveita Reykjavíkur (Reykjavik Energy), has worked on a project with the main aim of defining the reservoir characteristics of the rocks in the geothermal systems in Iceland. While active geothermal systems have the advantage of allowing direct comparison of rock alteration to fluid composition, this comparison only relates to a single stage, i.e., the present, in the evolution of the system. In contrast, sampling of fossil geothermal fields allows

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examination of the time integrated history of rock alteration, including determination of the temporal evolution of mineralogy and porosity.

The sampling strategy utilized in this study emphasized variably eroded fossil geothermal systems, focussing on areas that had been previously mapped with respect to their geological structures and hydrothermal alteration. The assumption is that rocks in these fossil systems are close analogues of those in presently-active geothermal reservoirs. Approximately 500 samples were collected for these studies, a large proportion of which have been analyzed for total and effective porosity, permeability, chemical composition, and petrographic characteristics. This extensive data set has been especially useful in determining the interrelationship between porosity and permeability of Icelandic rocks (e.g., Sigurdsson and Stefansson, 1994; Sigurdsson et al., 2000; Stefansson et al., 1997), and the relationship of these physical properties to the degree of hydrothermal alteration (e.g., Gudmundsson et al., 1995; Franzson et al., 1997, 2000; Franzson, 1999).

The main emphasis of this paper is to elucidate the nature of chemical transport in Icelandic geothermal systems by correlating the bulk composition of rock samples with their petrographical characteristics. Using the petrographically determined percentage infilling in the rocks, we will show that it is possible to assess the amount of chemical dilution that has taken place. This allows the deduction of the primary concentration of the immobile elements in the altered rocks, and by correlating these with the relatively fresh volcanic rocks equivalents, we assess the chemical change that has taken place during the hydrothermal alteration. Furthermore, using the “isocon” method (Grant, 1986) for determining mass transport, we also evaluate the chemical enrichment-immobility-depletion of various chemical components within individual samples.

2. Geological setting

This study is based on data from approximately 130 basaltic rock samples and focuses on three locations (Fig. 1) as described below:

a) The Hvalfjordur basalt succession consists of ca. 4–3 myr old plateau basalts which have been subjected only to zeolitic alteration (chabazite–thomsonite to mesolite–scolecite, e.g., as described from Eastern Iceland by Neuhoff et al., 1999). The Hvalfjordur area

has been mapped in considerable detail and the rocks are well characterized chemically (Franzson, 1979). Twenty two samples of basaltic lava flows were taken from this area.

- b) Hafnarfjall central volcano is a 5.5–4 myr old, deeply eroded central volcano that has been mapped with respect to its structure, geochemical evolution, and locally, its hydrothermal alteration (Franzson, 1979). The volcanic products range from basalts to rhyolites which have been subjected to variable degrees of hydrothermal alteration. Forty five samples are included in this study, and off these twenty seven are lava flows, five very scoraceous or tuffaceous tops of lava flows and twenty intrusions (mostly fine grained dykes or sills).
- c) Geitafell central volcano was formed about 6 myr ago, is deeply eroded, and has been mapped in detail, both with respect to volcanic evolution and hydrothermal history (Fridleifsson, 1983). An investigation has also been completed on the geochemical evolution of the volcano (Thorlacius, 1991). Fifty five basalt samples are included in the study, where thirty are lavas, five very tuffaceous or scoraceous lava tops and twenty intrusions (mostly fine grained dykes or sills).

The three study areas are all Tertiary in age, and differ from younger volcanic successions that host active geothermal systems principally by their lack of hyaloclastite formations, which occur almost exclusively in formations younger than the onset of glaciation at 3.3 myr (c.f. Fig. 1). These older hydrothermal systems were subjected to an initial phase of low-temperature alteration, followed by the main phase of high-temperature alteration, and subsequently overprinted by low-temperature alteration formed during the demise of the central volcanic complex and succeeding erosion. It has been demonstrated by extensive petrographic observations that mineral deposition during the high temperature alteration regime in Icelandic hydrothermal systems generally reduces rock permeability and the last low-temperature alteration episode does not greatly affect the bulk rock composition. Petrography can provide important constraints on the relative timing of alteration events. For example, minor late-stage zeolite deposition, present in some of our samples, has been tentatively interpreted as due to deposition from fluids trapped in relatively impermeable rock. In general calcite does not occur within the epidote–amphibole zone in presently-active high-temperature systems where temperatures exceed 290 °C. However, in the fossil

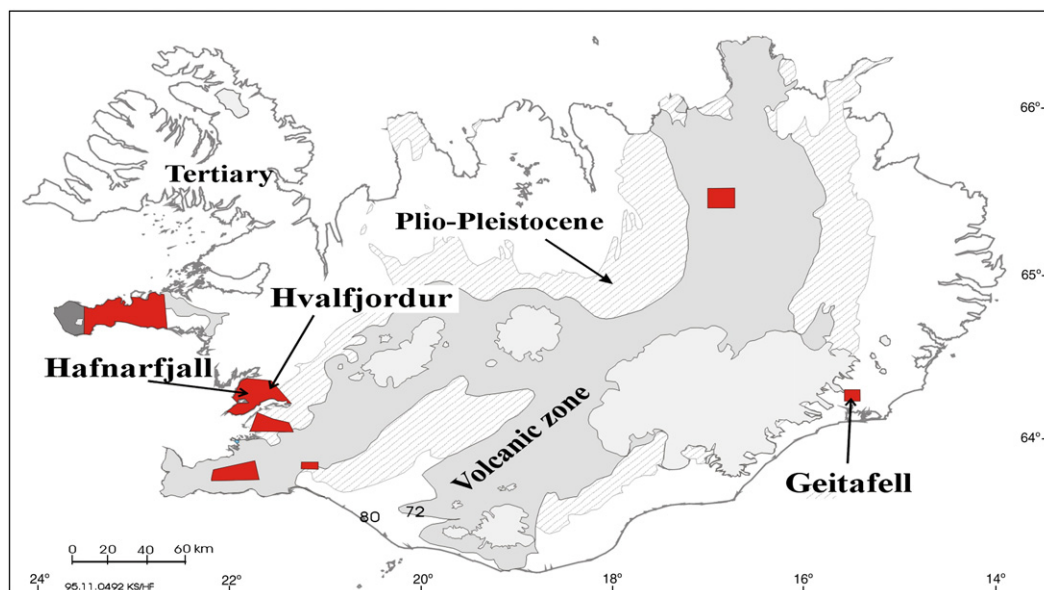


Fig. 1. A simplified geological map of Iceland showing the Tertiary, Plio-Pleistocene and the volcanic zones. The areas sampled for the petrophysical study are dark shaded, and the locations focussed on in this study (Hafnarfjall, Hvalfjordur and Geitafell) are also marked.

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