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Iceland Deep Drilling Project (IDDP): Arsenic Distribution and Mobility in Active and Fossil Geothermal Systems in Iceland

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ABSTRACT

Arsenic is a trace element in Icelandic basalts that can be concentrated in hydrothermal fluids (~0.15 ppm As) due to water-rock reactions in geothermal systems. Arsenic concentrations above 0.01 ppm As in domestic water are a health concern and, as a mobile element in hydrothermal systems, arsenic has the potential to contaminate surface waters as a result of geothermal development. Therefore, understanding the behavior of arsenic in hydrothermal fluids is important to minimizing the environmental impacts of geothermal energy development in Iceland and elsewhere.

Reactions between host rock and geothermal fluids ultimately control arsenic concentration and mobility within the active volcanic zone of Iceland. Iron-sulfides and titano-magnetite are believed to control arsenic mobility and distribution in Icelandic geothermal systems, but the amount of arsenic in Icelandic rocks, its distribution in different minerals, and the effect of hydrothermal alteration on arsenic distribution are poorly constrained.

Fossil geothermal systems preserve spatial relationships and so allow comparison of arsenic behavior in rocks with different chemistry and/or permeability that have experienced the same geothermal conditions. Fossil geothermal systems provide an excellent opportunity for comparative analysis with active geothermal systems accessed through geothermal drilling projects, such as the Iceland Deep Drilling Project (IDDP). Considered together, active and fossil systems will help us more completely evaluate arsenic mobility in geothermal environments.

We analyzed arsenic in 50 drill hole cutting samples from the seawater-dominated geothermal system at Reykjanes, 30 representative samples from fossil geothermal systems exposed at Geitafell and Vesturhorn in eastern Iceland, and one representative sample of recent volcanic eruption products from Krafla. Samples were analyzed for bulk rock trace element concentrations by ICP-MS and ICP-OES. Results indicate that sulfide mineralization accompanying hydrothermal alteration locally concentrates arsenic by a factor of 2-10 to produce basaltic rocks with 2 to possibly 19 ppm As. However, bulk rock arsenic and sulfur contents are not linearly related, suggesting that other factors in addition to sulfide abundance control arsenic concentration. This study also shows that hydrothermal arsenic enrichment is of the same magnitude as but geochemically distinct from arsenic enrichment in silicic rocks that occurs during magmatic differentiation.

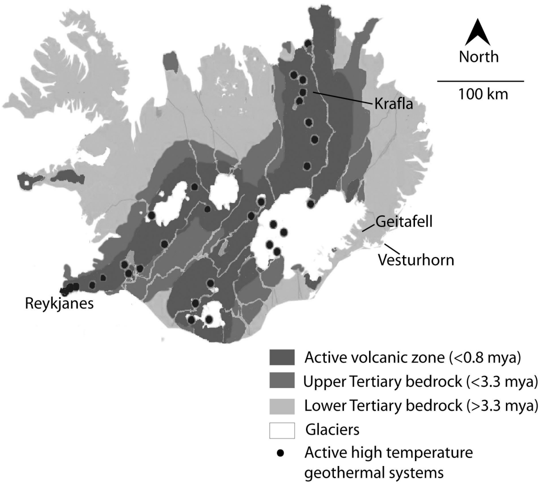

Figure 1: Map of Iceland with locations of studied hydrothermal systems.

1. INTRODUCTION

Arsenic is a trace constituent of geothermal fluids that is commonly elevated in these fluids ten to several hundred times above the World Health Organization safe drinking water level of 0.01 ppm (Smedley and Kinniburgh 2002; WHO 2008). Fluids transmit arsenic to the surface environment and boiling, cooling and fluid mixing at shallow depths result in arsenic deposition. However, the geothermal system's host rocks are the primary source of arsenic and water-rock reactions at depth control the arsenic concentration of ascending fluid (Aiuppa et al. 2006; Ballantyne and Moore 1988; Cleverly et al. 2003). Therefore, quantifying arsenic content and distribution in host rocks is necessary to understanding arsenic transport in geothermal systems.

In this study, we use a suite of rocks from active and fossil geothermal systems in Iceland that are representative of different parts of a basalt-hosted geothermal system to investigate arsenic's distribution, concentration, and its mineralogical and geochemical associations. Iceland is an informative location to study arsenic behavior in basalt-hosted geothermal systems because Iceland, located over a section of the Mid-Atlantic Ridge (MAR), is predominately basaltic, and contains many active and fossil geothermal systems (Figure 1). In active systems, we have access to rocks and, in the fossil systems, we have access to rocks that experienced supercritical or near supercritical conditions and can see the spatial relationships of intrusions, veins, and alteration zones. This sample suite provides a point of comparison for drilling projects, such as the Iceland Deep Drilling Project, that explore the high temperature and pressure regions of geothermal systems.

Basalt-hosted geothermal systems occur along most of the mid-oceanic ridges and the entire ocean cycles through these systems on the scale of every 10 million years (Elderfield and Schultz 1996). Therefore, although basalts only contain a few parts per million arsenic, arsenic behavior in basalt-hosted geothermal systems is an important part of global arsenic cycling (Baur and Onishi 1978).

2. BACKGROUND

2.1 Arsenic Mineralogy

Arsenic is a third period semi-metal, and in mineral and fluid systems it has behavior intermediate between transition metals, such as iron, copper, nickel, and more strongly electronegative non-metals, such as sulfur and phosphorous. Arsenic's electron configuration, $[Ar]3d^{10}4s^24p_x^14p_y^14p_z^1$, has five valence electrons available for bonding and three half-full 4p orbitals for additional electron occupation. This configuration produces formal valence states from -3 to +5; however, arsenite (As^{+3}) and arsenate (As^{+5}) dominate aqueous systems and arsenic bonding in minerals is dominantly covalent (O'Day 2006).

Arsenic is a chalcophile element and readily bonds with sulfur, as do most transition metals. Arsenic has an electronegatively (2.0) between that of sulfur (2.5) and the transition metals (~1.8) and so can substitute in sulfides for sulfur, producing sulfarsenides or arsenides, or for the metal, producing sulfosalts (Klein 2002; Krauskopf and Bird 1995). In addition to occurring in nominal arsenic minerals, arsenic is a common impurity in other sulfides. Although the majority of pyrite probably contains <0.5 wt. % As, pyrite can contain up to ~8 wt. % As in ore deposits (Savage et al. 2000; Smedley and Kinniburgh 2002). Pyrite and other sulfides are significant arsenic sources where they are unstable and sinks where they are stable.

Primary sulfides are minor constituents of basaltic rocks and thus, in unaltered basalts, the major silicates (feldspars, pyroxenes, amphiboles, and olivine) and oxides (iron and titanium oxides) control arsenic distribution and mobility (Best 2003). In contrast to sulfides, silicates usually contain <1 ppm As, and during crystallization of a mafic melt, arsenic is concentrated in residual melts (Baur and Onishi 1978; Best 2003). Arsenic enrichment due to its incompatibility in silicates has been observed on the outcrop scale within layered mafic intrusions (e.g. Skaergaard intrusion, East Greenland; Esson et al. 1966; Wager and Brown 1967) and is suggested by average arsenic contents of intrusive and extrusive rocks. Globally, granites contain an average 1.5 ppm As whereas associated silicic volcanics average 5 ppm As (Onishi and Sandell 1955). In addition to silicates, mafic rocks usually contain 5-10 wt. % normative iron and iron-titanium oxides (Best 2003). Arsenic is incorporated much more readily into these oxides than into silicates. Magnetite (Fe_3O_4) has been found to contain 2.7– 41 ppm As (Baur and Onishi 1978; Esson et al. 1966).

In addition to the sulfides, silicates, and oxides, Onishi and Sandell (1955) and Esson et al. (1966) argued that a significant fraction of the arsenic in basalts and gabbros is in easily soluble, fine-grained interstitial material, such as late-forming salts on the surfaces of major minerals. Onishi and Sandell (1955) found that 97%, 63%, and 56% of the arsenic was extracted, respectively, from a basalt, a granite, and a porphyritic basalt by a series of acid washes that produced minimal visible alteration of the major minerals. Additionally, reaction of a variety of volcanic rocks with distilled water at ~350°C by Ellis and Mahon (1964) indicated that arsenic was easily mobilized. Esson et al. (1966) measured arsenic in mineral separates and in the fine dust produced when the rocks where crushed for mineral separation. They found that major minerals could account for ~50% of the whole rock arsenic total. Arsenic was more concentrated in the dust than in any of the minerals, including the oxides, and when added to the mineral measurements produced reasonable totals. Together, these studies suggest that geothermal fluids can easily mobilize a significant portion of the arsenic in basalts.

2.2 Arsenic Aqueous and Sorption Geochemistry

In geothermal fluids, arsenic occurs as oxyanions and to a lesser extent as arsenic-bisulfide species of As^{+3} or As^{+5}. In the reducing, high temperature, and high pressure conditions of geothermal reservoirs, the neutral oxyanion $H_3As(O)_3$ is the dominant species (Ballantyne and Moore 1988; Heinrich and Eadington 1986; Pokrovski et al. 2002). In hot springs, As^{+3} is oxidized to As^{+5}, arsenic-sulfide and negatively charged oxyanions are more common, and arsenic sulfides become stable (Ballantyne and Moore 1988; Heinrich and Eadington 1986; Langer et al. 2001). Where charged oxyanions are stable they may be sorbed to iron oxides and hydroxides. In surface and likely in shallow geothermal environments, sorption is a major control on arsenic mobility and amorphous iron (hydro)oxides are important arsenic sinks (Ballantyne and Moore 1988; O'Day 2006). However, arsenic incorporation into stable minerals may be a more important control on arsenic transport within high temperature geothermal systems.

2.3 Icelandic Geothermal Systems and Hydrothermal Alteration

Iceland contains about twenty active high temperature (> 150-200°C) geothermal systems and numerous low temperature systems (Arnórsson 1995). The high temperature systems are concentrated within the active volcanic zone (Figure 1). Fossil geothermal systems are abundant in the Tertiary bedrock outside of the volcanic zone and often the interiors of these systems have been dramatically exposed by glacial erosion.

The geothermal fluids form from heated local groundwater and, especially in younger volcanic systems, volatiles degassed from the cooling intrusive. The primary groundwater is usually meteoric but may contain a seawater component in coastal geothermal systems (e.g. Reykjanes; Figure 2). Aquifer temperatures often follow the boiling point curve, although some systems are sub-boiling below a depth that is dependent on aquifer temperature (Arnórsson 1995).

Geothermal fluid convection is controlled both by the heat source location and the host rock permeability structure. In Iceland, the heat source for a geothermal system is typically either a fissure swarm analogous to the structure of the MOR (e.g. Reykjanes) or a central volcanic complex (e.g. Krafla, Geitafell, and Vesturhorn; Arnórsson 1995; Friðleifsson 1983; Mattson et al. 1986). Central volcanic complexes may occur above larger magma reservoirs formed in thinner crust and are associated with more evolved basalts and silicic rocks (Arnórsson 1995;

Sigmarsson and Steinthórsson 2007). Caldera formation often accompanies eruptions later in the life of a central volcanic complex and associated fracturing may create zones with high vertical permeability.

Iceland is predominately basaltic, but magmatic differentiation and differences in eruptive and intrusive conditions produce rocks with a variety of chemistries and porosities, including basaltic lava flows, hyaloclasites, and shallow intrusions are common. Hyaloclasites are the eruptive products of subaqueous or subglacial eruptions and are characterized by glass-rich, brecciated lavas with very high porosities (Schmincke 1998). Iceland's dominantly basaltic bedrock undergoes greenschist to amphibolite facies alteration that is strongly temperature and depth dependent.

Hydrothermal alteration of basaltic rocks results in the replacement of glass and the primary silicates with hydrous silicates, including epidote minerals, chlorite, and zeolites (Best 2003; Franzson et al. 2008). In addition, hydrothermal solutions contain CO_2 and H_2S that is from magmatic degassing or is scavenged from the host rock. These volatiles are responsible for the calcite and sulfide precipitation that is characteristic of hydrothermal fluid alteration. Within geothermal systems, sulfide mineralization is spatially erratic but associated with evidence for boiling (Arnórsson 1995). Pyrite is the most common sulfide in active and extinct Icelandic hydrothermal systems, with pyrrhotite chalcopyrite, and sphalerite being reported less frequently (Friðleifsson 1983; Friðleifsson et al. 2005; Marks et al. in review). Alteration intensity is greatest in the most permeable parts of the host rock, including in brecciated tops of lava flows and within fault zones, producing significant differences in the degree of alteration on the meter scale (Lonker et al. 1993).

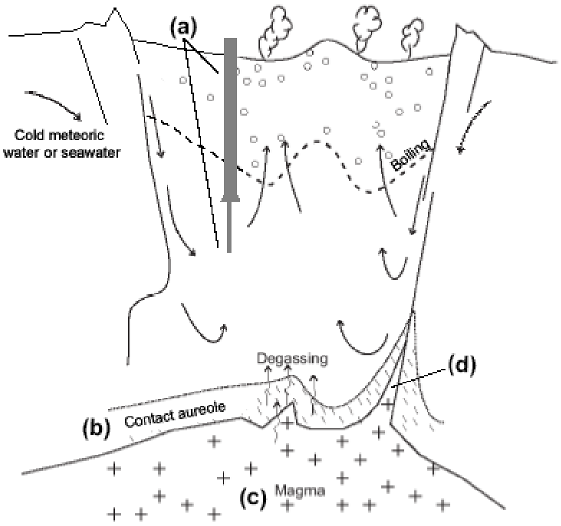

Figure 2: Model of central volcano hydrothermal system with locations of samples: (a) Reykjanes well, (b) central gabbro contact aureole, (c) central gabbro, and (d) caldera collapse gabbro. After Arnórsson et al. (2007) and Elders and Friðleifsson (this volume).

2.4 Arsenic Observed in Icelandic Geothermal Fluids and Basalts

The arsenic content of geothermal fluids and geothermally-influenced ground waters in Iceland has been well characterized and ranges between 1-10 ppb in 20-90°C groundwaters and 20-240 ppb in high temperature systems (Ólafsson and Riley 1978; Arnórsson 2003; Arnórsson 2004). Arnórsson (2003) observed that the As/B ratio in ground waters $\geq$ 90°C was less than the ratio in basalts, suggesting that some mineral phase limits arsenic fluid mobility. Arnórsson concludes that titano-magnetite is likely a mineral sink for arsenic because (a) sulfide mineralization is minimal in Icelandic basalts that experienced <100°C alteration, (b) low dissolved O_2 in ground waters limits iron hydroxide precipitation, and (c) titano-magnetite is stable in these groundwaters. In the Reykjanes geothermal system, primary titanomagnetite and secondary magnetite, titanite, and rutile are frequently observed to 3050 m depth where the aquifer temperature is at least 250º (Marks et al. in review). Thus, iron oxides are possible arsenic sinks in high and low temperature systems.

The arsenic content of Icelandic extrusive igneous rocks appears to be related to their degree of differentiation: olivine-tholeiites, contain 0.02-0.18 ppm As, tholeiites 0.36-0.38 ppm As, Icelandites 0.76-1.59 ppm As, and dacites 1.2-1.98 ppm As (Carmichael and McDonald 1961; Arnórsson 2003; Jónasson 2005). Silicic glasses, including obsidian and the chilled margins of silicic intrusions, contain 0.5-3.3 ppm As (Carmichael and McDonald 1961; Arnórsson 2003). This suite of rocks suggests that large-scale magmatic differentiation processes control the arsenic content of Icelandic rocks and can enrich arsenic up to 3 ppm. These arsenic values provide a baseline for evaluating the effects of water-rock interaction.

3. METHODS

3.1 Study Areas and Samples

In this study we analyzed a suite of rocks representative of Icelandic geothermal systems: (a) 50 geothermal well drill hole cutting samples from 350 m to 3050 m depth from Reykjanes well #17 (RN-17), (b) 30 representative samples from fossil geothermal systems exposed at Geitafell and Vesturhorn in eastern Iceland, and (c) lava from a 1984 eruption at Krafla (Figure 1, Table 1). Reykjanes is a seawater-dominated geothermal system, and RN-17 shows that the system is hosted in alternating layers of fractured crystalline basalt and hyaloclastites that are intruded by shallow mafic intrusives and have experienced up to amphibolite facies alteration in the bottom of the well (Lonker et al. 1993; Friðleifsson et al. 2005; Marks et al. this volume). Geitafell and Vesturhorn are extinct Tertiary central volcanoes that have been eroded ~2 km to expose cross-sections of their geothermal systems, including a central magma intrusion (now a gabbro body), intermediate intrusions, and variably altered dikes, hyaloclastites, and basalts (Table 1; Friðleifsson 1983; Mattson 1986). Geitafell preserves the ring fractures that accompanied caldera collapse and a small gabbro body, here called "caldera collapse gabbro," that intruded up along the ring fracture. At Vesturhorn we sampled a large felsic intrusion and its gabbro contact aureole. The Krafla geothermal system is located in an active central volcano and is a meteoric water dominated system (Arnórsson 1995).

3.2 Analyses

Minimally weathered pieces of rock were crushed into a fine powder and then ~0.3 g was microwave digested in hydrofluoric and nitric acids following U.S. Environmental Protection Agency (EPA) method 3052 (EPA 1996). Samples were evaporated to visual dryness and diluted to 50 mL volume in 2 vol. % nitric acid. Samples were analyzed for Ti, Cr, Co, Ni, Cu, Ga, As, Se, Rb, Mo, Cd, Sb, Cs, W, Tl, and Pb by ICP-MS at the University of California-Merced and for S, Ti, and Fe by ICP-OES at Stanford University. For the ICP-MS analyses, a conservative detection limit of 0.5 ppb was taken for all elements in the digested solution, which corresponds to ~0.1 ppm in the rocks. The ICP-OES detection limits where 6 and 1 ppb for Ti, and Fe, respectively.

4. RESULTS AND DISCUSSION

Rocks contained an average of 1.4 ppm As (range 0.26-19.2 ppm), 2365 ppm S, 73507 ppm Fe, 124 ppm Cr, 26 ppm Co, 47 ppm Ni, 62 ppm Cu, and 2.5 ppm Rb (Table 1). Arsenic content appears to be a function of lithology and of hydrothermal alteration intensity and mineralogy. Results are presented in Table 1 and graphically shown in Figures 3, 4, 5, and 6.

4.1 Lithology

Arsenic's incompatibility with silicates could produce significant arsenic partitioning between melt and residual solids during magmatic differentiation processes. This would result in a correlation between arsenic content and lithology. If rock-forming processes are the dominant control on arsenic distribution in Iceland, basaltic lavas should contain more arsenic than gabbros and arsenic content should increase in more evolved rocks.

The Geitafell and Vesturhorn gabbros that had experienced greenschist facies but not hydrothermal alteration had similar arsenic concentrations to layered mafic intrusions, as exemplified by the Skaergaard and Duluth intrusions. Samples AS-O6, NJO-08, and NJO-17) contained on average 0.81 ppm As (range 0.67-0.93 ppm). For the Skaergaard intrusion, Esson et al. (1966) estimated that the original magma contained ~0.38 ppm As and found that arsenic was concentrated in residual magma. Earlier crystallized layers contained arsenic contents of 0.11-0.64 ppm, while transgressive granophyres produced from the last liquid to freeze contained 0.59-1.21 ppm As. Onishi and Sandell (1955) found that Duluth gabbros contained on 0.2-1.8 ppm As (average 0.78 ppm). Given these results, 0.8 ppm As is a reasonable estimate for the "primary" arsenic content of Icelandic gabbros prior to hydrothermal alteration.

The samples that best represented unaltered basaltic lavas (Krafla, NJO-46a, NJO-46b, and NJO-47) had an average 1.2 ppm As (range 1.0-1.4). NJO-46a, NJO-46b, and NJO-47 are lavas from the flanks of the Geitafell volcano and have experienced at most zeolite facies alteration. Our basalt average agrees with the worldwide basalt average (1.5 ppm As) reported by Bauer and Onishi (1978), but is significantly more than the average for Icelandic olivine-tholeiite and tholeiites (0.08 ppm) reported by Arnórsson (2003). These differences could be the result of different digestion methods or differences in what rocks Bauer and Onishi (1978) and Arnórsson (2003) averaged together as "basalts." Given the range of arsenic contents reported elsewhere, we are not confident in estimating a primary arsenic content of Icelandic basalts from our results. Our data do not conclusively support or contradict the model that arsenic incompatibility is enough to produce measurable differences between mafic intrusive and extrusive rocks.

Lithophile trace elements (e.g. Rb andd Cs) are concentrated in more evolved rocks. A positive correlation between arsenic and lithophile trace elements (e.g. Rb, Cs) would be strong evidence for a magmatic control on arsenic concentration. Arnórsson (2003) noted increasing arsenic and rubidium content in more evolved Iceland volcanics (Figure 3). All of our samples contain rubidium concentrations within the range of olivine-tholeiites and tholeiites from Arnórsson (2003), except for samples of felsic intrusion and a dark, aphanitic dike from Vesturhorn. The felsic intrusion and to a lesser degree the dike samples fall within arsenic-rubidium trend from Arnórsson (2003). However, in the rest of the samples, arsenic increases without a corresponding increase in rubidium. This suggests that, while magmatic differentiation produces significant variation, it is not the only process controlling arsenic distribution in Icelandic basalts.

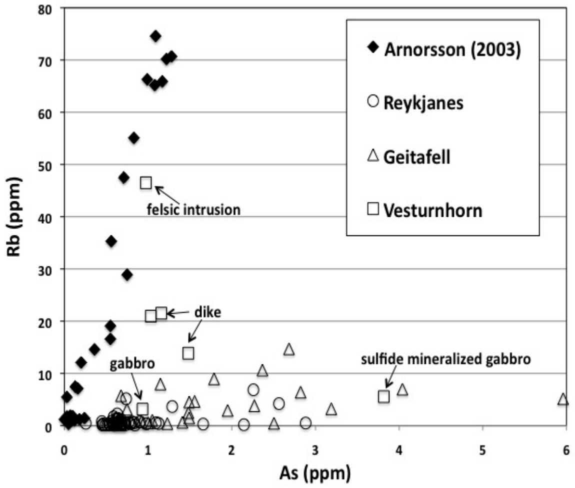

Figure 3: Rubidium as a function of arsenic in non-hydrothermally altered Icelandic extrusive igneous rocks from Arnórsson (2003) (solid diamonds) and in hydrothermally altered rocks measured in this study (open symbols, Table 1). Vesturnhorn samples (open squares) are labeled with their lithology. Sample NJO-45c from Geitafell with extreme arsenic content (As = 19.2, Rb = 8.3) is not plotted so that trends at lower arsenic values are apparent.

4.2 Hydrothermal Alteration

Hydrothermal alteration may decrease arsenic content in the rock by mobilizing arsenic in the fluid or enrich arsenic through the formation of arsenic minerals or sorption of arsenic onto mineral surfaces. Our sample suite should provide average and extreme examples of arsenic's behavior during hydrothermal alteration because the suite contains a 3000 m profile of the Reykjanes geothermal system and intensely hydrothermally altered rocks from Geitafell and Vesturhorn.

The average arsenic content of crystalline and glassy basalts from Reykjanes is 0.65. This is less than the arsenic content of Krafla basalt (1.0 ppm) and may indicate a different primary arsenic content in this system or widespread arsenic mobilization by hydrothermal fluids. In RN-17, there are two intervals, 350-650 m and 1750-1900 m, with elevated arsenic (Figure 4). These intervals overlap with the hyaloclastite units (claystone and basaltic breccia and tuff) and contain on average 1.6 ppm As. Although the hyaloclastites could have had more arsenic prior to alteration, hyaloclastites are also the most poros lithologies in the system and the units that have experienced the greatest hydrothermal alteration (Marks et al. in review).

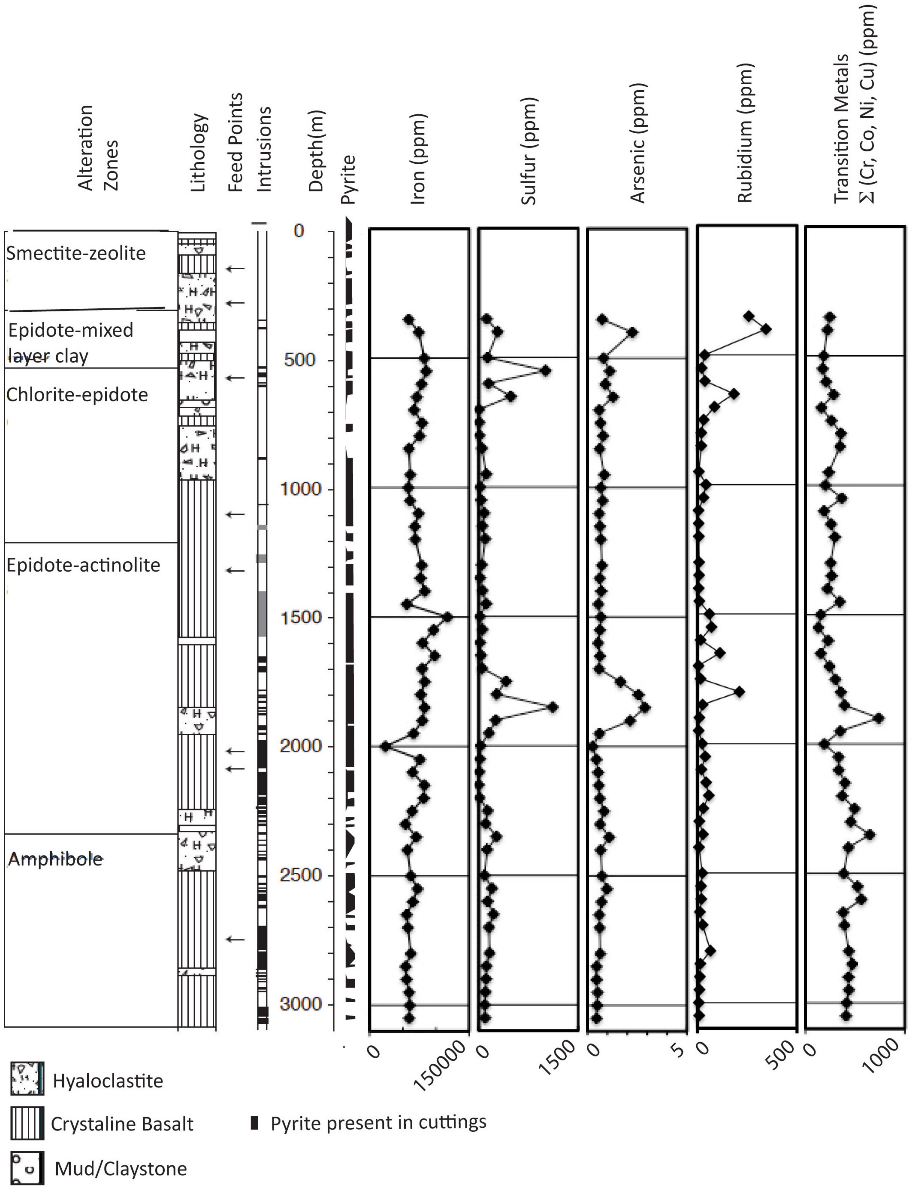

Figure 4: Profile of Reykjanes well RN-17. Alteration zones, intrusions and feed point locations, and pyrite presence from Friðleifsson et al (2005) and Marks et al. (in review).

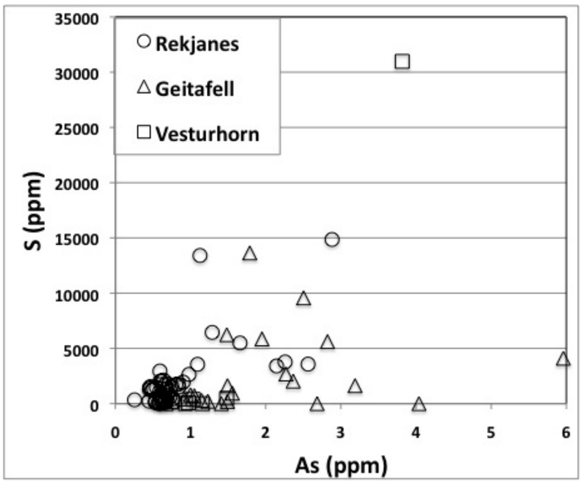

Figure 5: Sulfur as a function of arsenic. Sample NJO-45c from Geitafell with extreme arsenic content (As = 19.2, S = 2127) is not plotted so that trends at lower arsenic values are apparent.

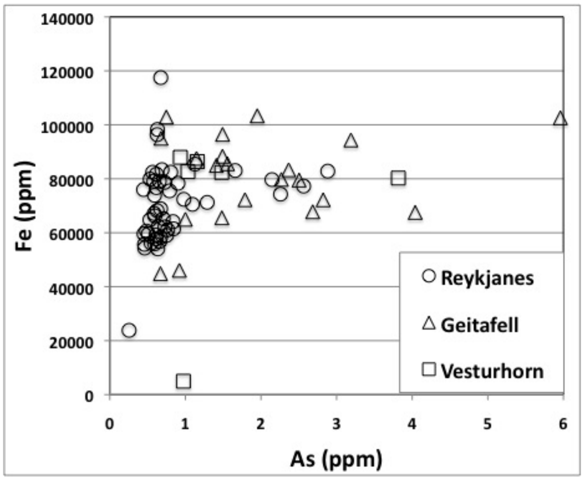

Figure 6: Iron as a function of arsenic. Sample NJO-45c from Geitafell with extreme arsenic content (As = 19.2, S = 69335) is not plotted so that trends at lower arsenic values are apparent.

Arsenic enrichment during hydrothermal alteration could be the result of arsenic incorporation into secondary iron-titanium oxides or into sulfides. Within the systems studied, arsenic appears to be correlated with the presence and abundance of sulfides based upon visual observations and bulk element chemistry (Figures 4 and 6, Table 1). Basalts from Geitafell containing abundant, macroscopic sulfides are denoted by an asterisk in Table 1 and contain on average 4.2 ppm As and 8284 ppm S. Drill cuttings from Reykjanes do not preserve the original rock texture and so visually estimating sulfide abundance is difficult; however, all drill cutting samples with ≥ 2ppm As also contain some macroscopic sulfides. Figure 5 shows that sulfur is not greatly enriched above 2500 ppm without arsenic enrichment above 1 ppm but that arsenic may be enriched at low sulfur contents. In contrast, arsenic appears independent of iron concentration (Figure 6).

In some of the high-arsenic samples, sulfur loss during oxidation of sulfides may be significant for some of the high-arsenic samples and so the measured values are not representative of the hydrothermal sulfur enrichment. The highest arsenic concentration occurs in NJO-45c, a gabbro that intruded along caldera collapse fracture at Geitafell. This sample is very weathered, and it was impossible to obtain a piece without some evidence of sulfide oxidation and iron oxide formation. Thus, the extreme arsenic concentration in this sample could be in part due to arsenic sorption on oxides during surface weathering. The low sulfur contents of 45c and 45b could be the result of sulfur loss during weathering. Further spectroscopic work will clarify this. Excluding NJO-45c, arsenic is enriched in sulfide-mineralized gabbros by a factor of 3 to 5. Similar hydrothermal enrichment has been found in the Duluth intrusion. A gabbro with evidence for hydrothermal alteration (epidote and amphibole) contained 3.6 ppm As, a factor of ~3 above the other Duluth gabbros measured (Onishi and Sandell 1955).

5. CONCLUSIONS

Hydrothermal alteration in Icelandic geothermal systems can enrich arsenic in basaltic host rocks by a factor of 3 to 6 above background levels of ~0.6-8 ppm As. This enrichment is usually associated with sulfide mineralization and within one system arsenic enrichment is associated with increased bulk sulfur content. However, between different systems the magnitude of sulfur enrichment varies. Hydrothermal alteration produces arsenic enrichment in basaltic rocks of the same magnitude as magmatic differentiation produces in silicic rocks. However, hydrothermal arsenic enrichment is limited to small regions of geothermal systems. Of the fifty RN-17 samples representing 3000 m of a geothermal system, only ten were elevated above 1 ppm As. These small regions appear to be related to host rock porosity. Therefore, models of arsenic behavior in basalt-hosted geothermal systems should consider sulfide formation and geothermal system structure.

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Table 1: Bulk rock trace element analysis. All elements in ppm and detection limit ~0.1 ppm. Asterisks (*) indicate samples with abundant macroscopic sulfides. RN-17 rock types from well logs in Friðleifsson et al. (2005). n.d. indicates below detection level.

Sample ID	Rock Type	As	S	Fe	Cr	Co	Ni	Cu	Rb
Reykjanes: cuttings from well RN-17. Listed by depth in meters.									
350	basaltic tuff	0.75	1574	59033	149.1	18.0	41.6	41.2	5.26
400	claystone	2.26	3772	74298	101.6	21.6	37.5	61.6	6.87
500	basaltic breccia	0.81	1738	82459	105.3	17.4	31.3	30.2	0.71
550	sedimentary tuff	1.13	13408	85429	69.9	20.1	31.1	52.9	0.42
600	sedimentary tuff	0.90	1948	78343	98.7	19.0	44.5	46.0	0.74
650	sedimentary tuff	1.29	6444	71245	129.1	20.4	46.8	88.6	3.66
700	sedimentary tuff	0.59	37	67133	83.9	16.1	32.3	28.4	1.70
750	basaltic breccia	0.65	72	79115	129.0	21.3	59.8	50.9	0.61
800	basaltic breccia	0.79	126	75519	177.6	22.9	68.2	65.0	0.34
850	sedimentary tuff	0.61	618	59150	203.3	21.6	77.9	44.2	0.38
950	basaltic breccia	0.84	1496	61462	112.5	22.4	45.4	55.0	0.14
1000	basaltic breccia	0.67	262	58317	110.5	17.9	38.2	34.5	0.84
1050	glassy basalt	0.77	449	61108	217.9	23.3	66.0	59.1	0.60
1100	glassy basalt	0.59	1101	73887	64.2	21.0	29.1	73.2	0.10
1150	glassy basalt	0.63	732	68207	146.9	20.2	52.1	39.1	0.11
1200	glassy basalt	0.67	1289	68888	179.4	21.2	56.5	40.2	0.13
1300	glassy basalt	0.73	608	78657	141.7	22.2	51.2	38.6	0.16
1350	glassy basalt	0.62	266	76709	146.0	20.8	54.1	42.1	0.16
1400	crystalline basalt	0.69	769	83378	107.9	21.3	46.0	46.1	0.12
1450	crystalline basalt	0.55	1472	56152	225.1	22.8	59.7	37.5	0.18
1500	crystalline basalt	0.67	230	117488	64.5	21.9	27.5	40.4	1.19
1550	crystalline basalt	0.63	744	96357	49.0	19.4	24.5	37.1	1.40
1600	crystalline basalt	0.53	249	79890	123.8	20.9	40.9	42.5	0.31
1650	crystalline basalt	0.63	465	98291	66.7	20.7	27.7	39.6	2.25
1700	crystalline basalt	0.58	661	79143	132.7	20.8	38.3	51.5	0.10
1750	crystalline basalt	1.66	5487	83057	153.8	25.0	52.0	70.9	0.30
1800	basaltic tuff	2.56	3575	77274	192.5	27.5	72.4	63.9	4.22
1850	basaltic tuff	2.88	14857	82828	206.9	36.6	69.5	79.4	0.50
1900	basaltic tuff	2.15	3407	79685	530.7	32.7	123.7	50.3	0.18
1950	crystalline basalt	0.60	2042	66246	204.6	28.1	61.0	56.1	0.12
2000	crystalline basalt	0.26	342	23837	119.7	11.5	33.0	25.0	0.46
2050	crystalline basalt	0.45	227	76001	178.3	27.5	66.9	61.1	0.77
2100	crystalline basalt	0.53	95	64804	169.6	22.9	59.9	82.5	0.39
2150	crystalline basalt	0.57	n.d.	82433	222.0	29.2	90.1	57.4	0.85
2200	crystalline basalt	0.62	133	81720	207.7	26.0	82.6	52.5	1.13
2250	glassy basalt	0.84	1765	64139	248.5	39.5	111.1	96.5	0.58
2300	glassy basalt	0.63	1357	54029	252.5	35.6	95.3	72.9	0.18
2350	glassy basalt	1.09	3557	70520	314.2	84.6	117.1	131.1	0.54
2400	glassy basalt	0.66	1684	56799	224.6	35.0	90.8	82.6	0.15
2500	crystalline basalt	0.73	1161	62186	183.6	36.7	78.1	85.9	0.48
2550	glassy basalt	0.98	2644	72381	234.5	69.4	97.6	122.7	0.35
2600	glassy basalt	0.71	1757	65243	317.7	42.3	108.5	94.5	0.38
2650	glassy basalt	0.59	2952	55891	191.6	33.2	77.4	77.2	0.24
2700	crystalline basalt	0.62	2030	57749	198.8	34.4	78.2	80.2	0.51
2800	crystalline basalt	0.64	2136	62270	231.0	36.8	83.5	85.9	1.30
2850	crystalline basalt	0.46	1524	54331	250.3	35.4	89.1	96.8	0.28
2900	glassy basalt	0.46	1458	55714	227.6	35.6	83.2	86.7	0.23

Table 1: continued.

	Sample ID	Rock Type	As	S	Fe	Cr	Co	Ni	Cu	Rb
	2950	glassy basalt	0.51	1339	59558.16	214.6979	36.0	83.6	102.9	0.19
	3000	glassy basalt	0.49	1221	60639.7	194.2973	36.5	76.1	108.3	0.13
	3050	glassy basalt	0.45	1282	59585.12	174.7776	42.3	79.8	112.7	0.17
Geitafell										
	AS-06	central gabbro	0.92	417	46065	189.4	24.1	47.2	70.5	0.8
*	NJO-01	basalt, gabbro contact aureole	2.27	2682	79764	17.2	25.0	25.1	81.0	3.8
	NJO-08	central gabbro	0.67	347	44828	262.6	21.0	55.1	17.4	0.2
	NJO-09a	mafic intrusion	3.19	1629	94353	1.1	34.4	10.8	59.0	3.2
	NJO-09b	mafic intrusion	1.49	1625	96443	1.0	35.2	10.0	61.4	4.5
	NJO-016	basalic breccia	1.49	194	88334	28.8	34.3	28.9	82.8	1.5
*	NJO-27a	basalt	1.48	6236	65552	99.4	32.5	32.0	83.7	2.5
*	NJO-27b	basalt	2.82	5617	72193	102.8	36.6	33.3	107.9	6.4
*	NJO-28	scoraeous basalt	2.50	9574	79519	7.6	16.4	11.6	19.7	0.5
	NJO-30	crystalline basalt	1.00	791	64975	105.0	26.6	30.0	61.7	0.5
*	NJO-31	basaltic breccia	2.37	2032	83317	19.4	18.5	14.7	39.1	10.6
	NJO-32a	basalt flow, chilled margin	0.68	n.d.	94990	21.6	19.9	14.7	49.6	5.7
	NJO-32b	basalt flow, interior	1.56	943	85547	27.2	20.3	16.7	51.8	4.6
*	NJO-33	scoraeous basalt	1.79	13643	72230	7.4	20.9	12.9	54.3	9.0
*	NJO-34a	basalt	5.96	4105	102582	20.2	35.8	30.5	82.6	5.2
*	NJO-34b	basalt	1.95	5855	103340	19.4	37.8	29.9	63.9	2.9
	NJO-37a	red bed	0.75	194	102889	17.4	28.5	20.2	239.9	3.1
	NJO-37b	flow host above red bed	1.05	722	----	50.5	36.8	41.3	223.3	1.0
*	NJO-45a	basaltic breccia near gabbro	4.04	n.d.	67527	15.0	12.3	9.6	23.9	7.0
*	NJO-45b	caldera collapse gabbro	2.68	n.d.	67791	4.5	12.0	5.8	15.7	14.7
*	NJO-45c	caldera collapse gabbro	19.2	2127	69335	1.7	12.2	2.8	13.0	8.3
	NJO-46a	basalt flow, chilled margin	1.15	285	87551	28.4	22.0	28.2	43.9	8.0
	NJO-46b	basalt flow, interior	1.41	n.d.	84942	33.2	23.9	30.4	51.1	0.6
	NJO-47	basalt lfow	1.23	218	----	64.4	35.6	41.5	61.6	0.4
Vesturhorn										
	NJO-17	gabbro	0.93	n.d.	87954	10.6	20.2	15.0	31.7	0.7
	NJO-19a	mafic intrusion, chilled margin	1.16	n.d.	86384	0.13	10.1	1.0	5.5	1.2
	NJO-19b	mafic intrusion, chilled margin	1.48	488	82329	n.d.	19.8	1.1	24.4	1.3
	NJO-19c	mafic intrusion, interior	1.03	389	82654	0.77	11.5	2.1	4.3	1.4
*	NJO-20	gabbro	3.82	30974	80260	0.13	7.3	2.4	12.7	1.7
	NJO-23	felsic intrusive	0.97	61	4979	0.65	0.2	0.2	1.3	46.5
Krafla	Krafla	glassy basalt	1.39	1870	109848	54.1	24.3	27.6	70.1	1.4
Digestion Blank			n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	1.8	n.d.