GAS GEOCHEMISTRY OF THE HELLISHEIÐI GEOTHERMAL FIELD, SW-ICELAND

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ABSTRACT

A fluid sampling campaign has recently been carried out at the Hellisheiði geothermal field in southwest Iceland. This high-temperature field is part of the Hengill volcanic system, and is host to the largest geothermal power plant in Iceland. A geochemical assessment of the field is presented based on the analysis of 19 wet-steam well discharges. Emphasis is placed on the chemical and physical processes that account for the concentrations of the major reactive gases (CO_2, H_2S, H_2 and CH_4). Aquifer chemical compositions were calculated from analysis of discharged water- and steam-phases and discharge enthalpies using the WATCH speciation program and phase segregation model. Under this model, discharge enthalpies in excess of that of vapor-saturated liquid at the aquifer temperature are accounted for by retention of liquid in the formation at a single pressure. The calculated concentrations of volatile components in initial aquifer fluids are observed to be very sensitive to the selected phase segregation pressure. Carbon dioxide concentrations are kept in close equilibrium with calcite. The concentrations of H_2S and H_2 species show a close approach to equilibrium with a mineral assemblage consisting of pyrite, pyrrhotite, epidote and prehnite. The field-scale distributions of the main geothermal gases are used constrain the locations of two separate upflow zones identified within the geothermal area. Additionally, chloride and nitrogen suggest the presence of a recharge zone in the northern part of the geothermal field directed towards the south.

INTRODUCTION

Due to the relatively high abundance and reactivity of the main geothermal gases (CO_2, H_2S, H_2 and to a lesser extent, CH_4), these components have long been used by reservoir scientists to characterize the physical nature of and manage production from hydrothermal systems (e.g. Ármansson et al., 1982; Gudmundsson and Arnórsson, 2002) The sources of these components are believed to be solidifying magma bodies, while nitrogen and argon are transmitted by recharging meteoric waters that have equilibrated with the atmosphere. The concentrations of these gases in aquifer fluids are greatly affected by physical properties such as enhanced boiling and recharge, but are generally believed to be kept in close equilibrium with specific hydrothermal mineral assemblages.

This study describes a major fluid sampling campaign undertaken at the Hellisheiði geothermal field in southwest Iceland, from which 213 MW_e is currently being generated. An additional 90 MW_e and 400 MW_{th} is scheduled to come online in 2011. The main objectives of this study are to utilize geochemical behavior of geothermal gases to investigate the physical nature of the Hellisheiði geothermal system and provide a baseline for future geochemical monitoring efforts.

GEOLOGIC BACKGROUND

The Hellisheiði geothermal field is one of four sub-fields making up the greater Hengill geothermal area, along with Nesjavellir, Bitra and Hverahlíð. The Hengill geothermal area is located on the North American-Eurasian plate boundary, at a triple junction where an axial rift zone (the Western Volcanic Zone, WVZ) and an oblique spreading ridge (the Reykjanes Peninsula Volcanic Zone) meet a seismically active transform zone (the South Iceland Seismic Zone). The main structural component of Hengill is a 40-80 km long NNE/SSW-striking fissure/fault swarm sub-parallel to the rifting axis of the WVZ which constitutes a 3-5 km wide graben bounded on the west by two major faults with a total throw of about 300 m (e.g. Franzson et al., 2010). The fissure swarm was last active in 1789, with extensive rifting and subsidence, but without any extrusive volcanic activity (Sæmundsson, 1992). The main bedrock type is hyaloclastite, a sub-glacially formed tholeiitic basalt, with minor amounts of subaerial lava flows and intrusive rocks. Postglacial volcanism at Hengill has been confined to
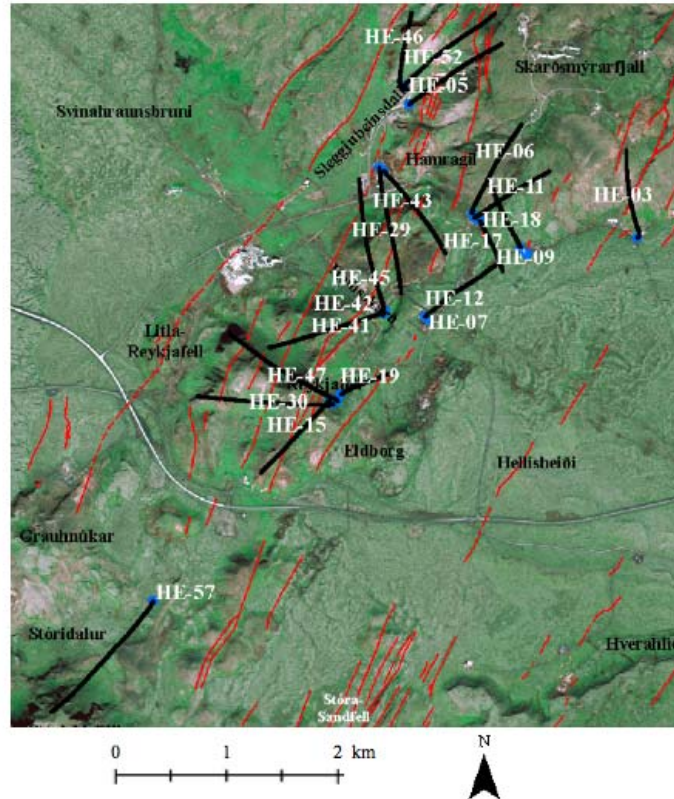
Figure 1: Locations and names of wells sampled in this study. Blue dots represent location of well head, black lines the paths of directionally drilled wells. Red lines represent surface fault traces.

three fissure eruptions dated at ~10,300, ~5,700 and ~1,800 years b.p., respectively (Sinton et al., 2005). While the interaction between dilationary rifting of the fissure swarm and the transform component related to the SISZ is not very well understood, these transverse faults are clearly important to the geothermal system as a whole, as extrusive and intrusive volcanic production is highest and overall geothermal activity is more intense on the southern and northern margin of the zone where these faults intersect the fissure swarm (Árnason and Magnúson, 2001). The model proposed by Árnason et al. (2010) implies that basaltic dikes and intrusions that make up a ductile, conductive layer at >3 km depth act as the heat source for the geothermal system.

METHODOLOGY

Two main steps are required to determine the chemical composition of aquifer fluids of geothermal systems: 1) Chemical analysis of well discharge fluids 2) Calculation of aquifer fluid compositions based on a model for boiling and potential causes for observed discharge enthalpy.

Sampling and Analysis

The primary data used in this study were obtained from 18 samples of well wet-steam discharges obtained between March and September 2010, and is supplemented by data presented in past studies of the area (Stefánsson et al., 2010; Remoroza, 2010). A map showing the locations of sampled wells is shown in Figure 1 (above). Surface well discharges of water and steam were collected using a Webre separator at the wellhead. Carbon dioxide and H_2S were analyzed in both phases by titration. Non-condensible gases (H_2, N_2, O_2, Ar and CH_4) were analyzed in the vapor phase by gas chromatography. Samples for major cation determination were filtered, acidified and analyzed by ICP-AES. Samples for major anion determination were filtered into PP bottles and analyzed by ion chromatography; sulphate was analyzed separately in samples treated with $Zn(CH_3COO)_2$. For detailed description of the methods discussed below the reader is referred to Scott (2011) and Arnórsson et al. (2006). For complete liquid and vapor phase chemical analyses, see Scott (2011).

Modeling of Aquifer Fluid Compositions

Several assumptions must be made in order to translate chemical compositions of well discharge fluids into geothermal reservoir fluid compositions. Since most well discharges exhibit "excess" discharge enthalpy (higher than that of vapor saturated liquid at the aquifer temperature), a model

accounting for the elevated steam-to-water ratio at discharge is required in order to calculate the chemical composition of initial aquifer fluids. As will be described below, the enthalpies of well discharges can be best explained by the retention of liquid in the aquifer, or reservoir phase segregation.

Phase segregation modeling

In geothermal fluids already near or on the boiling point curve, as in two-phase systems, intensive boiling will follow immediately upon entering the production zone of a discharging well. Phase segregation may occur at some point as the two-phase fluid flows through the geothermal reservoir towards the production zone of a well as the result of the higher permeability of the vapor phase under reservoir conditions relative to the fluid phase. The partial or total retention of liquid water in a two-phase flow can be explained by adhesion of water molecules to mineral grain surfaces due to capillary forces. The higher relative permeability of vapor has been observed in experimental studies for porous media (Horne et al., 2000) and artificial fractures (Chen et al., 2004; Chen and Horne, 2005).

Phase segregation is not the only process which can produce "excess" enthalpies. Enhanced vaporization of aquifer fluid can result from conductive heat flow from the rock after the lowering of fluid temperatures caused by depressurization boiling (e.g. D'Amore and Celati, 1983). Under this model, the total well discharge composition remains the same as that of the initial reservoir fluid. The relative contribution of the two processes can be qualitatively assessed by plotting the liquid phase and total discharge concentrations of a conservative aqueous solute against discharge enthalpy, as in Figure 2 (Glover et al., 1981).
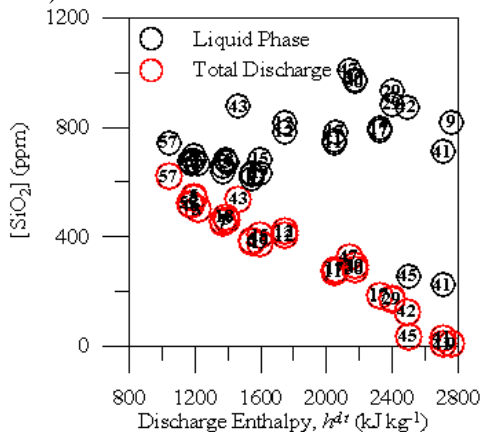

Figure 2: The concentration of SiO_2 (ppm) in the liquid phase (black circles) and total discharge (red circles) as a function of discharge enthalpy (kJ kg^{-1}). Number inside circles represent well no.

If excess enthalpy discharges result from phase segregation, the concentration of an aqueous solute in the total discharge will decrease as discharge enthalpy increases, approaching zero as discharge enthalpy approaches that of dry steam. The clear trend evident in Figure 2 strongly suggests that the observed discharge enthalpies can best be explained by the phase segregation model.

Various theoretical approaches have been developed to calculate the concentration of aquifer components upon phase segregation (e.g. Arnórsson et al., 1990; Arnórsson et al., 2007; Arnórsson et al., 2009); these mathematical models have been revised, and are described in detail in Scott (2011). The main assumption required by these models is the selection of a pressure within the intermediate zone between aquifer and wellhead at which phase segregation occurs. Previous studies calculated aquifer fluid compositions at a single selected phase segregation pressure (i.e. 10 bars-a). In Scott (2011), a method to calculate an approximate 'mid-point' phase segregation pressure was defined. However, due to the significant uncertainty associated with the selection of phase segregation pressure, the main approach used in this study is to investigate the sensitivity of aquifer fluid compositions to phase segregation pressure.

The WATCH program (Arnórsson et al., 1982a; Bjarnason, 1994) version 2.4 was used to calculate the aquifer fluid composition from data on surface well discharges and the boiling model outlined above. The calculations assume a closed-system model between the input temperature and the specified reference point, where fluid chemical composition and speciation is calculated. In order to model the open-system behavior associated with steam gain and fluid loss, a two-step method has been developed to model phase segregation in WATCH. (i.e. Gudmundsson and Arnórsson, 2002; Giroud, 2008; Angcoy, 2010; Remoroza, 2010; Karingithi et al; 2010). The first step consists of calculating the liquid and vapor compositions immediately after phase segregation, assuming conservation of enthalpy and chemical components between the point of discharge and the selected phase segregation pressure. Since phase segregation is assumed to occur at a single pressure, the concentrations of chemical components in the two phases are assumed to be equal immediately before and immediately after phase segregation. Thus, the second step consists of calculating the compositions of the initial aquifer fluid, assuming conservation of enthalpy and chemical components between an aquifer fluid assumed to be at saturated liquid enthalpy and the two-phase fluid immediately before phase

segregation. The calculation procedure used in this study is described in greater detail in Scott (2011).

For most well discharges, aquifer fluid temperatures were determined assuming equilibrium with quartz according to the solubility data obtained by Gunnarsson and Arnórsson (2000). While initial aquifer fluid temperatures determined at the 'mid-point' phase segregation pressure generally match temperatures measured downhole within 5-10°C, the degree of uncertainty is considerably greater in wells for which initial temperatures >300°C were calculated. For wells in which a steam-uncontaminated liquid phase could not be obtained due to the fact that the discharged fluid consisted of nearly dry steam, a Na/K geothermometer calibrated for use in Hellisheiði wells was used (Arnórsson, 2010, unpublished work). Since the liquid phase for HE-42 was used to model all of these wells, the major cation and anion chemistry of these wells should be ignored.

Equilibrium vapor fraction

The formation of a vapor fraction in the initial aquifer fluid can result from sufficient conductive heat transfer from the rock reservoir to the aquifer fluid to allow some of the saturated liquid water to evaporate. Since volatiles strongly partition into the vapor phase when even a slight vapor fraction is present, if the concentration of a volatile species in the liquid phase is assumed to be fixed by mineral buffers, the presence of a vapor phase allows the two-phase mixture to contain much higher concentration of that volatile. The 'equilibrium' vapor fraction can be estimated by comparing calculated reactive gas concentrations (usually H_2 and H_2S) in the initial aquifer fluid with theoretically-derived reactive gas concentrations assuming equilibrium with hydrothermal mineral assemblages (e.g. Arnórsson et al., 2010). In Scott (2010), a new method for determining equilibrium vapor fraction is described, taking into consideration the revisions made in the phase segregation model. This new method reveals that the calculated equilibrium vapor fraction is very sensitive to selected reference temperature and selected phase segregation pressure. Due to its stronger tendency to partition into the vapor phase, H_2 is a more reliable indicator of equilibrium vapor fraction than H_2S. However, calculated equilibrium vapor fractions should be interpreted primarily as order-of-magnitude indicators rather than absolute values.

Thermodynamic Data

The thermodynamic database plays an important role for both the speciation calculations performed by WATCH and in the interpretation of the saturation state of the aquifer with respect to different reactions that could potentially control the composition of aquifer fluids. The thermodynamic data base used for speciation calculations is that described in Arnórsson et al. (1982) with slight modifications described in Scott (2011). The saturation state of the aquifer was assessed for hydrothermal alteration minerals, and several potential mineral pair and mineral assemblages were evaluated for their potential to control select activity ratios and gas species concentrations in the initial aquifer fluid. The reactions considered, equations describing the temperature dependence of their equilibrium constants, as well as the thermodynamic data used to generate these equations can be obtained in Scott (2011), for both the individual alteration minerals and the mineral pairs/assemblages, respectively.

RESULTS AND DISCUSSIONS

The calculated initial aquifer fluid chemical compositions and key physical parameters associated with the phase segregation assumptions of all of the samples used in this study are presented in Scott (2010), assuming approximate 'mid-point' phase segregation pressure for all 'excess' enthalpy well discharges.

Evaluation of Phase Segregation Model

As described in great detail in Scott (2010), the calculated concentrations of chemical components in an initial aquifer fluid are sensitive to assumed phase segregation pressure to varying degrees, depending on the enthalpy of the well discharge. As an example of this, Figure 3 displays the calculated concentration of SiO_2 in the initial aquifer fluid for different phase segregation pressures for selected "representative" wells exhibiting varying degrees of 'excess' enthalpy: a low enthalpy, well (HE-18, 1385 kJ kg^{-1}) a medium enthalpy well (HE-19, 1599 kJ kg^{-1}), four high enthalpy wells, two with enthalpies below 2200 kJ kg^{-1} (HE-47 and HE-30) and two around 2400-2500 kJ kg^{-1} (HE-29 and HE-42), and one nearly dry-steam well (HE-41, 2704 kJ kg^{-1}).
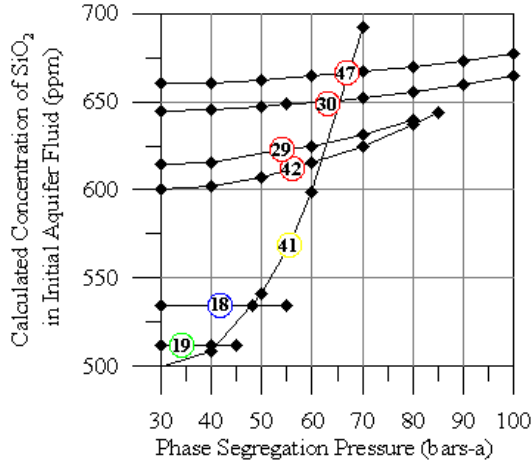
Figure 3: Calculated concentration of SiO$_2$ in initial aquifer fluid as a function of selected phase segregation pressure. Mid-point phase segregation pressures are indicated by hollow red, green and blue circles representing high ($h^{d,t} > 2000$ kJ kg^{-1}) medium ($h^{d,t} = 1500$-2000 kJ kg^{-1}) and low ($h^{d,t} = h^{f,l}$-1500 kJ kg^{-1}) 'excess' enthalpy discharges, respectively. Yellow circles represent nearly dry-steam well discharges. Black markers designate selected phase segregation pressures with which initial aquifer fluid compositions were calculated.

Figure 3 shows that for discharge enthalpies below 2400 kJ kg^{-1}, the assumed phase segregation pressure makes an insignificant difference to the calculated concentration of SiO$_2$. Even for wells with discharge enthalpies above 2400 kJ kg^{-1}, variation in the selected phase segregation pressure can change calculated SiO$_2$ concentration by no more than ~10%, impacting the calculated quartz equilibrium temperature by less than 10°C. However, for the nearly dry-steam well, the calculated concentration of SiO$_2$ is extremely dependent on selected phase segregation pressure, to the point that it renders any meaningful interpretation of the non-volatile chemistry of an initial aquifer fluid impossible.

In contrast to what was described for non-volatile components, the calculated concentrations of gaseous components in initial aquifer fluids are very sensitive to the assumed phase segregation pressure even at relatively low 'excess' enthalpies. Additionally, model calculations for the less-soluble gases (H$_2$, CH$_4$, N$_2$) are more sensitive to assumed phase segregation pressure than the more soluble gases. Similar to what was done for Figure 3, Figure 4 (below) shows the calculated concentration of H$_2$ in the initial aquifer fluid as a function of selected phase

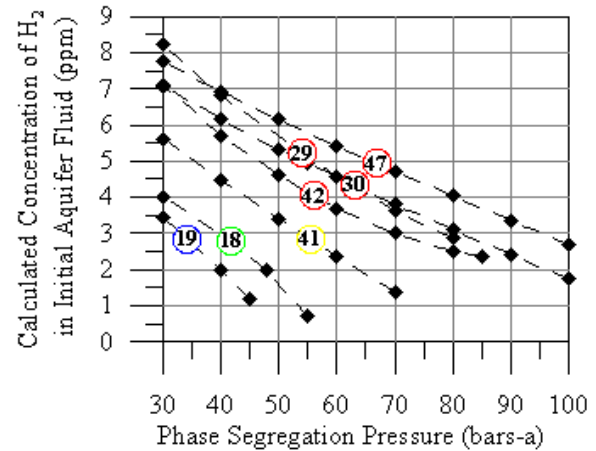segregation pressure for the same exemplary well discharges.

Figure 4: Calculated concentration of H$_2$ in initial aquifer fluid as a function of selected phase segregation pressure. Symbology same as above.

At assumed phase segregation pressures closer to the initial aquifer fluid pressure, the calculated concentration of the volatile component in the initial aquifer fluid is lower. Fundamentally, this is due to the fact that the steam phase at the point of liquid retention has a greater concentration of gaseous components at vapor pressures closer to that of the aquifer. The calculated concentration at the 'mid-point' phase segregation pressure is approximately in the middle of the possible range of calculated values.

Since the differential relative permeabilities of the liquid and vapor phases are typically described as a function of liquid saturation, it is of interest to investigate the correspondence of model calculations with these experimental studies. Calculations indicate that the level of liquid saturation prior to phase segregation (assuming mid-point phase segregation pressure) approximately corresponds to a point where many studies predict that liquid water would be immobile, around 0.2-0.3. Some degree of phase segregation is likely to occur throughout most of the pressure range encountered in the production zone of a geothermal well, and it is fundamentally inaccurate to assume that phase segregation occurs at a single pressure. However, this is currently an unavoidable assumption required to calculate initial aquifer fluid compositions.

Mineral-Solution Equilibria

Although a geothermal system as a whole is an open system, with continual inflow and outflow of mass and heat, aquifers are believed to behave locally as

closed systems, allowing the chemical composition of fluids in the geothermal reservoir to approach equilibrium with respect to several alteration minerals.

Figure 5 depicts the saturation indices (SI) of the initial aquifer fluid with respect to the main calcium-bearing minerals: calcite, wollastonite, clinozoisite, epidote and prehnite. In general, calculated initial aquifer fluid compositions demonstrate a close approach to equilibrium with respect to calcite and wollastonite, with all modeled aquifer compositions falling within 1 SI unit of equilibrium. Systematic oversaturation is observed for the Ca-Al silicates clinozoisite, epidote and prehnite. The margin of uncertainty associated with selection of phase segregation pressure can not account for the systematic oversaturation. This systematic oversaturation is at least partially an artifact of a inaccurate thermodynamic database, specifically, for the Fe-hydroxy and Al-hydroxy species. The slight systematic oversaturation observed in fluid compositions does not negate the role of these minerals in controlling aquifer fluid compositions; mineral precipitation kinetics could be somewhat slower and the response to slight oversaturation not as pronounced. The role of epidote, clinozoisite and prehnite in the process of water-rock interaction is evidenced by their abundance in well cuttings, as well as by the fairly close correspondence of observed gas concentrations in the initial aquifer fluid to equilibrium concentrations based on mineral assemblages that could buffer these gases, discussed in detail below.

The saturation indices of Fe-bearing sulfides and oxides, pyrite, pyrrhotite and magnetite, are shown in Figure 6. Saturation indices for these minerals are also affected by faulty thermodynamic data for Fe^{2+}. The role of iron-bearing minerals in the process of water-rock interaction is evidenced by the close approach of calculated reactive gas concentrations to equilibrium concentrations predicted by assemblages which include these minerals.
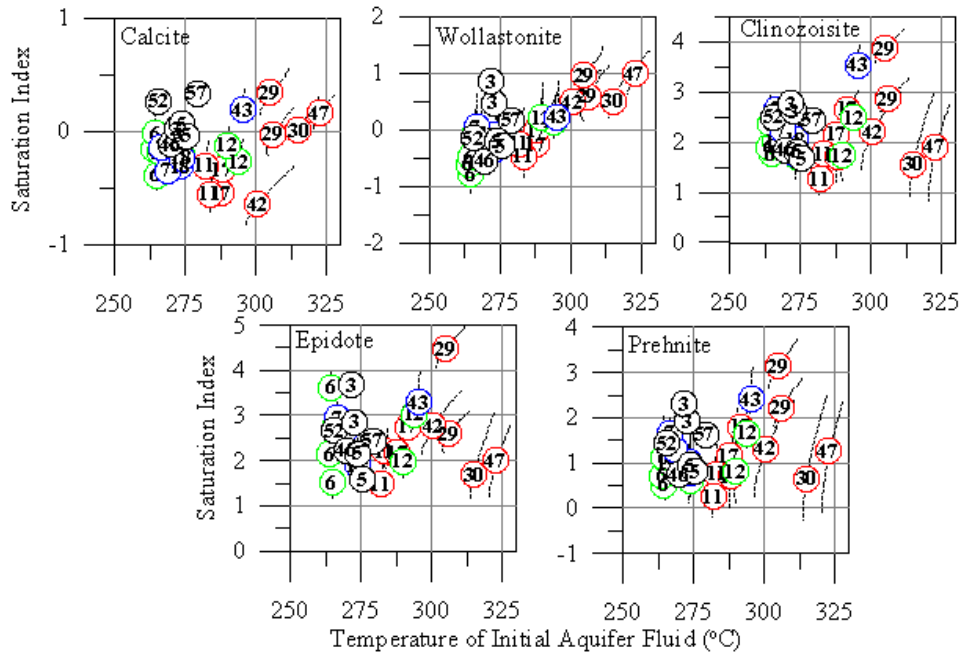

Figure 5: Saturation indices of main calcium bearing minerals: calcite, wollastonite, clinozoisite, epidote and prehnite. Symbology same as above, with black circles representing liquid enthalpy well discharges and dashed lines representing potential variation in calculated value due to different assumed phase segregation pressure.
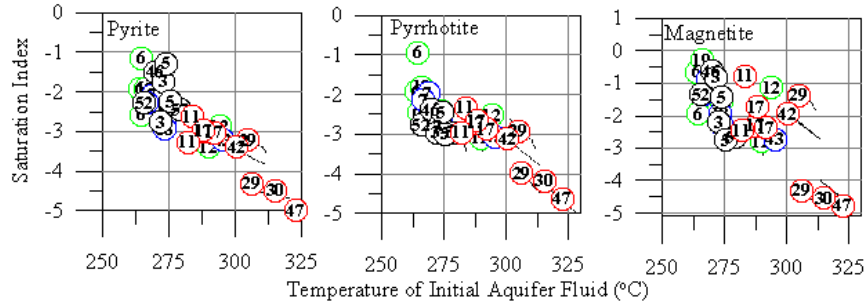
Figure 6: Saturation indices of main iron-bearing minerals versus initial aquifer fluid temperature. Clockwise from upper left: pyrite, pyrrhotite, magnetite. Symbology same as above.

Mineral Assemblage-Gas Equilibria

Previous studies have conclusively established that reactive gas concentrations are controlled by equilibrium with respect to selected mineral buffers (e.g. Arnórsson et al., 2010; Karingithi et al., 2010). What is somewhat less certain is which specific mineral assemblages exercise this control in an individual geothermal reservoir. One difficulty in making this determination is that the equilibrium gas concentrations predicted by different possible mineral buffers fall with the range of uncertainty inherent in the process of fluid sampling, analysis and aquifer fluid calculation. Additionally, different mineral assemblages have been identified to control reactive gas concentrations in geothermal fields of different geological settings.

The equilibrium curves of the mineral assemblages that could potentially fix the concentrations of the main reactive gases H_2S, H_2 and CO_2 are plotted in Figure 7, below.
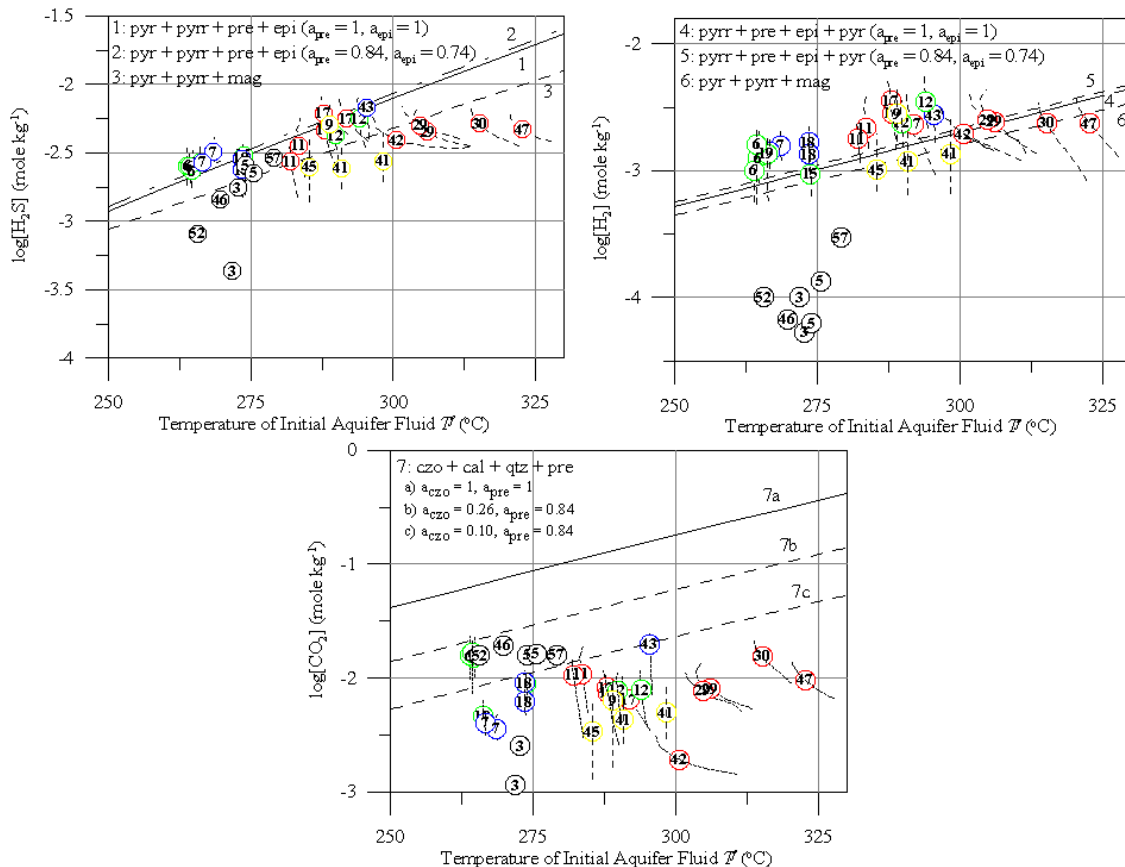

Figure 7: Calculated concentration of H_2S, H_2 and CO_2 in initial aquifer fluid compared with equilibrium concentrations according to hydrothermal mineral assemblages. Symbology same as above.

The dashed lines in Figure 7 indicate the total variability in calculated gas concentrations as a result of assuming different phase segregation pressure is approximately 0.25-0.5 log units for the high excess enthalpy and 'dry-steam' wells; this difference is greater than the difference between the equilibrium concentrations given by the pyr + pyrr + pre + epi and pyr + pyrr + mag mineral assemblages. Stefánsson et al., (2011) concluded that the pyr + pyrr + pre + epi mineral assemblage is most likely to fix reservoir H_2S concentrations, due to the instability of magnetite in the geothermal field. While many of the wells considered in this study show gas concentrations that correspond closely with this mineral assemblage, many other wells have concentrations that are considerably lower than that predicted by this mineral assemblage. Many of the wells whose H_2S concentrations correspond closely with the pyr + pyrr + pre + epi mineral assemblage exhibit H_2 concentrations elevated relative to equilibrium with this mineral assemblage. Additionally, for the high excess enthalpy and dry steam wells with H_2S concentrations that are lower than expected by this mineral assemblage, H_2 concentrations correspond fairly closely with the same mineral assemblage.

If the apparently low H_2S concentrations in these aquifer fluids were due to partial degassing of a liquid enthalpy aquifer fluid, H_2 would be expected to be more even depleted relative to equilibrium due to its lower solubility. However, the presence of even a small equilibrium vapor fraction would allow H_2 concentrations to become elevated in the initial aquifer fluid relative to equilibrium to a much greater extent than that for H_2S, since H_2 partitions much more strongly into the vapor phase. Upon extended exposure to production, both H_2 and H_2S would become depleted, but H_2S concentrations would appear to deviate more than H_2 from the equilibrium concentration. Since H_2 would be initially elevated, partial degassing may actually reduce its total concentration to a position close to equilibrium assuming a saturated liquid aquifer fluid. Using hydrogen by the methodology outlined in Scott (2011), a field average equilibrium vapor fraction of 0.19% by mass was calculated assuming 'mid-point' phase segregation. Almost all samples showed an hydrogen-derived vapor fraction of less than 0.5% by mass. The only wells in which a negative equilibrium vapor fraction was derived from H_2 also showed the most negative H_2S-derived vapor fractions (HE-30, HE-41, HE-43, HE-45 and HE-47). Thus, these well discharges seem to provide the strongest indication of degassing of an initial aquifer fluid; however, overestimation in the selected reference temperature could also partially explain the negative equilibrium vapor fraction.

All of the carbon dioxide concentrations observed in Figure 7 fall well below the equilibrium curve based on the czo + cal + qtz + pre mineral buffer, even if clinozoisite activities as low as 0.1 are considered. This observation led Arnórsson et al. (2010) to conclude that CO_2 in Hellisheiði was flux-dominated. Recall the close approach to saturation with respect to calcite exhibited by nearly all wells (Figure 5). This fact seems to indicate that CO_2 concentrations are controlled by equilibrium with calcite, rather than the proposed mineral assemblage. However, there are important aspects to the field-scale distribution of CO_2 that will be discussed in greater detail below.

Field-scale distribution of gaseous components

Beyond considering the potential chemical equilibria that could fix reactive gas concentrations in aqueous solution, the distribution of gaseous components on the scale of the field may be indicative of physical processes that control the behavior of the geothermal system as a whole, such as boiling, upflow, outflow and recharge. The distribution of the main reactive gases (CO_2, H_2S and H_2) as well as N_2 are displayed in Figure 8 (below). These figures were generated using interpolation schemes available in ArcMap – see Scott (2011) for further description of the methodology used to produce these figures. The upper-left and –right corners of these maps should be ignored due to nonexistent sample density.
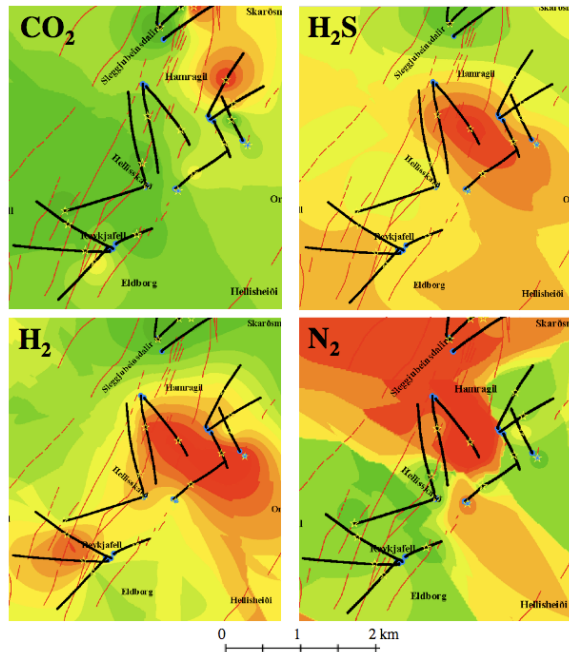
Figure 8: Distribution of CO_2, H_2S, H_2 and N_2 throughout the Hellisheiði geothermal field, assuming 'mid-point' phase segregation pressure for excess enthalpy wells. Red indicates higher concentrations, green lower.

Two local maxima were identified in CO_2 concentrations: one at the southern end of Skarðsmýrarfjall below Hamragil and another further to the south underlying Reykjafell. Calculated CO_2 rapidly declines to the south and the southeast of the former. A CO_2 minima can be found in Helliskarð area. Interestingly, the liquid enthalpy well discharges in the northern and southern margins of the sampled area all show elevated CO_2 concentrations relative to the average for the field; however, a liquid enthalpy discharge on the far eastern part of the field shows low CO_2.

The field scale distribution of H_2S is somewhat similar to that of CO_2, although the differences between the two gases are significant and intriguing. The CO_2 maximum identified below the southern margin of Skarðsmýrarfjall is found slightly more to the south for H_2S. For the well discharges to the east of Hamragil which exhibit elevated in CO_2, H_2S is fairly low. Similar to CO_2, there is a second local H_2S maximum to the south. Another similarity between CO_2 and H_2S is the depletion observed in the Helliskarð area, which is most distinct in the directionally drilled HE-41 and HE-45, but less so in vertically-drilled HE-42. The starkest H_2S minima in the area can be found in the liquid enthalpy wells to the north; in contrast to these, H_2S is fairly high in the liquid enthalpy wells to the south and east.

The broad trends described for H_2S are also observed in the H_2 distribution, with maxima being identified in approximately the same area and depletion in the Helliskarð area. In some contrast to H_2S and especially CO_2, hydrogen was observed to be very low in all of the liquid enthalpy wells.

The distribution of the three main reactive gases appears to suggest the presence of two separate upflow zones within the main sampled area of the geothermal field - one south of Skarðsmýrarfjall and a second underlying Reykjafell. These upflow zones can also be identified from downhole temperature measurements. In the conceptual model used to produce the numerical model of Gunnarsson et al. (2010), the heat source is believed to extend between these two areas along the axis of the fissure swarm throughout the Helliskarð area. The wells in this area exhibit relatively low gas concentrations, but are also some of the most highly productive wells in the field, in terms of the enthalpies of produced fluids. These high enthalpies can perhaps best be explained by geologic factors. Relatively low injected fluid losses during drilling of these wells indicated that wide fractures were not present. Fluid flow seems to be confined to a network of relatively narrow fractures through porous hyaloclastite. These conditions may be more conducive to the extensive phase segregation necessary to account for the observed discharge enthalpies. Further evidence for two separate heat sources is from downhole temperature measurements, which indicate higher downhole temperatures in the vicinity of the gas maxima than the Helliskarð area.

The differences between the distributions of CO_2 and that of H_2S and H_2 in the northern part of the field are significant. While carbon dioxide concentrations were highest at the southern end of Skarðsmýrarfjall beneath Hamragil, the H_2S and H_2 maximum lie slightly further to the south. It was previously concluded that aquifer fluids are kept in close equilibrium with respect to calcite. Geothermal waters initially at equilibrium with calcite become supersaturated upon adiabatic boiling to temperatures 10-40°C below the initial aquifer fluid temperature. Upon boiling and rapid degassing of CO_2 and H_2S, the ensuing pH increase causes an increase in the activity of HCO_3^-, resulting in the attainment of calcite supersaturation despite a decrease in the total carbonate carbon of the liquid phase (i.e. Arnórsson et al., 1978). Low CO_2 in well discharges in areas where other geothermal gases are elevated could be an indication of boiling in the formation, whereas well discharges that retain high CO_2 might reveal that extensive boiling in the formation is not present. Based on this interpretation, the northerly upflow

zone coincides with the high H_2S and H_2 anomalies, where the highest equilibrium vapor fractions are also calculated. Also, this explanation accounts for why the liquid enthalpy wells exhibit high initial aquifer CO_2 concentrations; since it is fairly certain these wells are not tapping into upflowing fluids, it is possible that they receive CO_2–rich outflowing fluids at depth and due to lower reservoir temperatures or mixing with colder, recharging fluids, the onset of boiling in these wells is in the wells themselves where calcite precipitation is less extensive.

Since the source of nitrogen in geothermal waters is the equilibration of recharging meteoric waters with the atmosphere or the transmission of air bubbles contained within in descending fluids, elevated nitrogen is suggestive of vigorous recharge and decreased nitrogen is suggestive of degassing and boiling (reference). Nitrogen is clearly at maximum in the northern part of the field, in the same areas where H_2S and H_2 are found to be lowest. Additionally, relatively high N_2 is observed in the other liquid enthalpy wells.

Another chemical component that can be indicative of recharge is chloride. Since chloride remains in solution after dissolution from rock, areas of the geothermal field that have undergone extensive water-rock interaction will show elevated chloride, while areas that are affected by recharge of dilute meteoric waters will show low chloride. Figure 9 presents the distribution of chloride throughout the geothermal area; again, the northwest and southeast parts of this figure should be ignored due to low (non-existent) sample density.
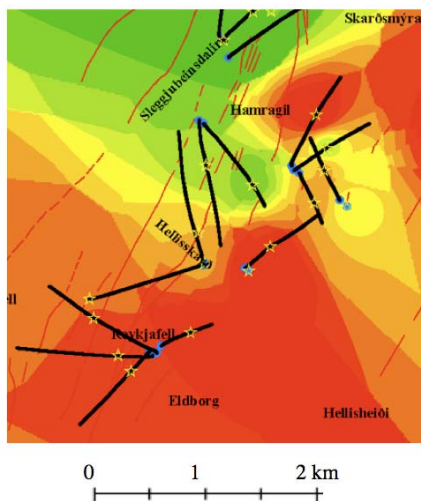

Figure 9: Distribution of chloride throughout the Hellisheiði geothermal field. Symbology same as Figure 1.

Generally, Figure 9 reveals a low Cl anomaly in the area of the liquid enthalpy wells in the north that extends to the south in HE-43 and HE-29. The highest Cl content was found in the area of the CO_2 maximum described above, but this maximum declines rapidly to the south. For the nearly dry-steam wells in the Helliskarð area, recall that the liquid phase of HE-42 was used to model aquifer compositions in WATCH; based on the latter well as well as HE-12 and HE-17, chloride in this area can be expected to be fairly high. Chloride is also elevated in the area of the gas maximum identified in the south. It is also relatively high for liquid enthalpy wells to the south and east.

The trends described in nitrogen and chloride are consistent enough to suggest that a recharge zone is present with dilute meteoric waters being conducted from the north to the south. However, it is also interesting to consider unpublished data obtained from a tracer test conducted in March 2010. A concentrated sodium benzoate solution was injected in HE-08, a vertically drilled well located on the same platform as HE-46 and HE-52. A monitoring regime was set up that included these two wells as well as HE-05 and HE-31, the latter of which is located directly to the south of HE-08. However, the only well in which the tracer was detected was HE-46, and modeling of tracer flow parameters using the TRACINV software indicated that 30-40% of the tracer was recovered in HE-46, suggesting a very strong connection between the two wells. This information would seem to suggest a strong outflow from the south the north, likely occurring along a major fault line at depth. There is nothing that would theoretically prevent both recharge and outflow to be occurring along a single flow path on the surface. The natural state model of Gunnarsson et al. (2010) shows that a very strong outflow is occurring from SW towards the NE along the axis of the fissure swarm at relatively shallow depth (~sea level) while a deep recharge from the NE towards the SW was occurring at greater depths (~1.5-2 km b.s.l.).

It is difficult to discern if recharge is occurring from the SW towards the NE (HE-57 towards HE-15 and HE-30); although nitrogen is elevated in HE-57, chloride is fairly high as well. The same is true for a possible recharge zone from the east towards the west, as chloride was found to be high in HE-03. Gunnarsson et al. (2010) suggested that some recharge in the southern part of the field may be occurring from the west towards the east, although this generally isn't very strong. Reinjection is currently taking place at Gráhnukar in the southern part of the field located to the SW of HE-30 and HE-15. Although the obvious intention of reinjection in

this location is to recharge the highly-productive wells to the north and NE, the evidence described above may suggest that recharge in this direction is not strong enough to counter outflow directed from the north towards the south. If injected fluids are mixing with outflowing fluids, the effect of relatively cool injected fluids would also account for the relatively high N_2 and Cl in HE-57 and the fact that the enthalpy of this well has recently been revised downward by approximately 150 kJ kg^{-1}.

CONCLUSION

The processes of phase segregation, dominantly caused by the retention of liquid onto mineral grain surfaces, best accounts for the observed discharge enthalpies of wet-steam wells in the Hellisheiði field. Once a phase segregation pressure has been specified, the chemical composition and speciation of initial aquifer fluids can be determined using WATCH. The main weaknesses of the method result from the fact that phase segregation likely takes place to some degree across a range a pressures, and the concentration of gaseous components in initial aquifer fluids is very sensitive to assumed phase segregation pressure. The approach taken by this study was to calculate initial aquifer fluids chemical compositions assuming a range of different phase segregation pressures.

Generally, the calculated chemical compositions of initial aquifer fluids show close approach to equilibrium with main hydrothermal alteration minerals, especially calcite. The concentrations of H_2S and H_2 are controlled a mineral assemblage consisting of pyrite, pyrrhotite, prehnite and epidote. The concentrations of CO_2 are held in equilibrium with calcite – lower than equilibrium concentrations may be indicative of boiling in the formation. The average equilibrium vapor fraction for the field is approximately 0.2% by mass, as determined using H_2.

The distribution of the main reactive gases provides evidence for two separate heat sources in the sampled area the Hellisheiði system, which correspond to the two centers of maximum in gas content. The approximate locations of these heat sources are: 1) on the southern margin of Skarðsmýrarfjall, likely to the southeast of Hamragil, and 2) underlying Reykjafell. The relatively low gas concentrations and lower measured downhole temperatures in the center of the fissure swarm suggest that the heat source may not extend through this area; however, the low gas concentrations may also be partially explained by degassing of an aquifer fluid as a result of the high permeability of the reservoir rock or even faulty phase segregation assumptions. Secondly, the

distributions of the conservative components nitrogen and chloride indicate that recharge is taking place from the north towards the south. Recharge zones from the east towards the west and well as from the south towards the north were not identified, but the evidence at the present time does not preclude their existence. Continued monitoring of both gaseous and non-volatile components will be essential to clarifying the physical processes active in the field and evaluating the response of the reservoir to increased production load.

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