Proceedings World Geothermal Congress 2020+1
Reykjavik, Iceland, April - October 2021

Characterising Geothermal Fluids of the Askja and Kverkfjöll Volcanic Systems, Iceland

Eemu Ranta*, Andri Stefánsson, Jóhann Gunnarsson-Robin, Ríkey Kjartansdóttir and Sæmundur A. Halldórsson

Nordic Volcanological Center, Institute of Earth Sciences, University of Iceland. Sturlugata 7, 101 Reykjavík, Iceland.

*Contact: eemu@hi.is

Keywords: volcanic geothermal systems, geothermal fluids, hydrothermal geochemistry, Askja, Kverkfjöll

ABSTRACT

Askja and Kverkfjöll are neighbouring and active volcanic systems in the Northern Rift Zone (NRZ) in central Iceland. Both host relatively unexplored volcanic geothermal systems. Here, we present data on geothermal water and vapour composition from the two geothermal areas with the objective of characterising the geothermal reservoir fluids, volatile element sources and the effects of shallow secondary processes on geothermal activity at the surface. Askja is a productive and bimodal (basaltic and rhyolitic) rift volcano, centered on the axis of the NRZ. Its geothermal activity is currently mainly constrained to the shores of the Öskjuvatn lake (1052 m.a.s.l.) that fills a caldera associated with a VEI 5 eruption in 1875. At the bottom of the phreatic explosion crater Víti, a small acid lake (pH = 2.4, T = 20°C) with a diameter of 150 m is heated by hot springs seeping from the lake floor. Several, mostly diffusive, fumaroles are active along the SE inner walls of Víti. A circumneutral hot spring (pH = 6.4, T = 52°C) is found on the southern side of Víti, on the shore of the Öskjuvatn lake. Kverkfjöll sits on the flank of the NRZ and has a small volcanic output compared to the rift volcanoes. Only basaltic eruptions are known, but none from the last millennium. A vigorous geothermal system is manifested on the surface as a large geothermal area, located along a fault on the NW outer rim of the ice-filled NE caldera at a high altitude (1550-1700 m.a.s.l.). The area hosts dozens of individual fumaroles, hot springs and mud pools as well as two ice-dammed geothermal lakes. Two geothermally heated rivers Volga (pH = 7.8, T = 20°C) and Hveragil (pH = 8.5, T = 44°C) are found at lower altitudes. The vapour-dominated acid geothermal area on the top of Kverkfjöll and the mildly alkaline hot rivers probably reflect large fractions of the vapour and liquid phases, respectively, formed by boiling of a parental one-phase fluid at shallow depths.

1. INTRODUCTION

High-temperature volcanic geothermal systems in Iceland are typically associated with active central volcanoes and caldera structures. In such settings, shallow (2-5 km) magmatic intrusions provide the heat sources that drive hydrothermal circulation along faults and through porous, volcanic bed rock. However, individual geothermal areas differ fundamentally in their surface manifestations, subsurface hydrology, chemistry and fluid sources (Ármannsson et al. 2016, Stefánsson 2017). In this study, we present new water and gas chemical data for non-thermal and thermal waters and fumarole gases from the Askja and Kverkfjöll volcanic systems, located in the Northern Rift Zone (NRZ) of Iceland (Fig. 1). Our aim is two-fold: (1) To provide an up-to-date review of the geothermal activity at these relatively sparsely studied geothermal areas, and (2) identify and quantify the volatile sources and their relative contributions to the geothermal fluids found at both locations.

2. GEOLOGICAL SETTING

The Northern Rift Zone (NRZ) of Iceland (Fig. 1a) is a subaerial portion of the divergent plate boundary that separates the Eurasian and North American tectonic plates. The NRZ hosts five active central volcanoes named, from north to south, Þeistareykir, Krafla, Fremrinámar, Askja and Kverkfjöll, all five hosting high-temperature geothermal areas (Ármannsson 2016). Kverkfjöll is a mature volcanic system at the SE end of the NRZ. It comprises a central stratovolcano, partly covered by the Vatnajökull ice cap, and a connecting fissure swarm (Fig. 1b). Kverkfjöll is considered to be an active volcano and has had dozens of basaltic eruptions during the Holocene (Óladóttir et al. 2011). No historical eruptions are known. A vigorous geothermal system at Kverkfjöll is manifested on the surface at several locations around the 3x8 km large and 100 m deep, ice-filled NE caldera (Fig. 1d). A large vapour-dominated geothermal area is centered along a fault on the NW caldera rim at 1550-1700 m elevation. This area is divided by Oddsson (2016) into the three separate areas Efri and Neðri Hveradalur valleys, and Hveratagl, that together host dozens of individual fumaroles, boiling pots, mud pools and several ice caves, as well as two ice-dammed geothermal lakes Galtarlón and Gengissig (Thórarinsson 1953, Ólafsson 2000, Oddsson 2016) (Fig. 1d). Hydrothermal explosions have occurred at Gengissig and its vicinity in 1959, 1968 and 2013 (Montanaro et al. 2015 and references therein). Two geothermally heated rivers Volga and Hveragil flow down the southern and eastern caldera rims, respectively, (Fig. 1d) with temperatures of up to 26°C and 61.5°C (Ólafsson et al. 2000). Hveragil is characterised by up to 0.5 m thick, layered travertine deposits along its banks. Minor geothermal activity has been occasionally observed as hot vapour or heated grounds on the high slopes of the steep NE cliffs of the caldera and close to the highest top Jörfi (1933 m.a.s.l.) (Thórarinsson 1953, Ólafsson et al. 2000), but are considered to be subordinate compared to the other geothermal manifestations (Oddsson 2016). Oddsson (2016) concluded that the total geothermal heat output of Kverkfjöll amounts to 265±72 MW spread over a geothermal area of 2-2.5 km^2.

Askja is a bimodal and productive volcanic system with a fissure swarm and a central volcano, where both deep (16 km) and shallow (3 km) magma reservoirs have been suggested to exist beneath its complex caldera structure (Sturkell et al. 2006). The latest of its three nested calderas is occupied by the 10.7 km^2 large and up to 217 m deep Lake Öskjuvatn at (c. 1052 m.a.s.l), that was formed following a rhyolitic VEI 5 eruption in 1875 (Hartley and Thorvaldson 2012). The main geothermal activity at Askja is at present found in three areas around Lake Öskjuvatn (Jónasson and Einarsson 2009): around Víti and Bátshraun in the NE, at Suðurbotnar to the SE and at Mývetningahraun and below Þorvaldstindur in the SW (Fig. 1c). The Suðurbotnar geothermal area was partly covered by a large landslide in July 2014 (Gylfadóttir et al. 2017). The geothermal activity extends to the Öskjuvatn lake, at least to a depth of 80 m (Ólafsson 1980), but its full extent and distribution on the lake floor are not well known. Öskjuvatn might also receive chemical input from weathering of relatively new eruptive products from several lava flows from the 1920's that reached the lake floor (Ólafsson 1980). Several relatively recent hydrothermal explosion craters, high temperature altered geothermal grounds and steaming holes are found at Sigurðarskarð, 5 km north of the northern rim of the Öskjuvatn caldera (Jónasson and Einarsson 2009). A hydrothermal explosion crater Víti, formed in connection to the 1875 eruption, today hosts an acid lake and several moderately active fumaroles.

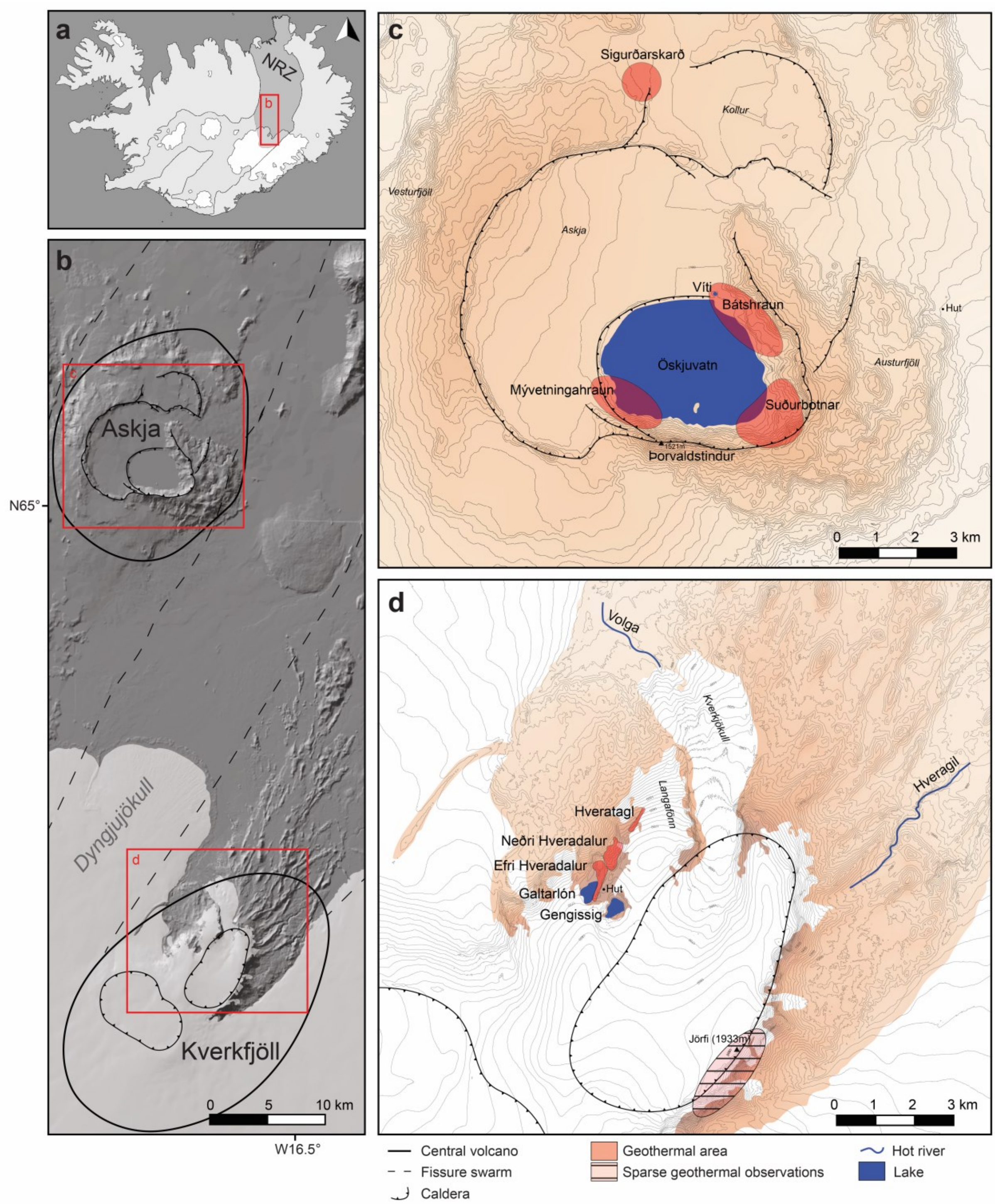

Figure 1: Maps. (a) Map of Iceland. The active rift zones are indicated by a grey shading and the Northern Rift Zone (NRZ) by dark grey shading (b) Map showing the Kverkfjöll and Askja central volcanoes and connecting fissure swarms in the southern end of the NRZ, (c) Geothermal areas of Askja. Geothermal activity is mainly found in the most recently formed Öskjuvatn caldera. Outlines of the geothermal areas are drawn after Jónasson and Einarsson (2009). (d) Geothermal areas of Kverkfjöll. Geothermal activity is concentrated along the flanks of the NE caldera of Kverkfjöll. Outlines of the geothermal areas are drawn after Ólafsson et al (2000) and Oddsson (2016).

3. METHODS

Easy access to Askja and Kverkfjöll is mostly limited to the summer months, when the highland roads are open. Access to Hveradalur at Kverkfjöll is further restricted by weather and glacier conditions. From the north, the easiest route to Hveradalur is a 3 hour hike across the Kverkjökull glacier. From the south, the Vatnajökull ice cap can to be ascended and crossed by a suitable vehicle to reach the mountain hut by Gengissig. Fumarole samples were collected during two visits to Víti (Askja) in August 2017 and August 2018, to Hveratagl (Kverkfjöll) in August 2017 and to Neðri and Efri Hveradalur (Kverkfjöll) in June 2019. Water samples at Askja and Kverkfjöll were collected in August-September 2018.

Full gas discharge was collected in evacuated gas bulbs (100 to 350 ml) including 10-35 ml of 50% KOH solution, following methodology described in Arnórsson et al. (2006). Thermal and non-thermal waters were filtered on-site through 25 µm cellulose acetate filters and collected in plastic (PP) tubes that were washed three times with the sample. Sample splits for ICP-OES analysis were acidified on site to 0.5% HNO_3 (Suprapur®). Water chemistry was determined by ICP-OES at the Institute of Earth Sciences (IES), University of Iceland, except for ΣCO_2 concentrations, which were determined within 3 days of sampling by a modified alkali titration method (Arnórsson et al. 2006). F concentrations were measured with selective electrode. The concentrations of non-condensable gases (H_2, N_2, O_2, Ar, CH_4) were determined by gas chromatography at IES. Water concentrations in the gas samples were estimated gravimetrically. The H_2S concentration was determined by Hg-acetate titration from the condensed steam fraction. The CO_2 concentrations were determined by a modified alkali titration (Arnórsson et al. 2006).

3. RESULTS

3.1 Water chemistry

The water chemistry of non-thermal and thermal waters at Kverkfjöll and Askja in Figs. 2a-c together with complementary data from Ólafsson (1980) for Askja and from Ólafsson et al. (2000) for Kverkfjöll. The non-thermal waters collected at both localities are characterised by low total dissolved solid concentrations and low ΣCO_2 (23-53 ppm) and SO_4^{2-} (0.9-17.9 ppm) content (Fig. 2b). At Kverkfjöll, the Hveragil river water has low SO_4^{2-} contents (17.4-43.7 ppm) coupled to very high ΣCO_2 content (up to 583 ppm) as well as elevated pH (7.2-8.9) and temperature (18.7-61.5 °C). The B, Cl (Fig. 1a), SiO_2 (Fig. 2c) and ΣCO_2 concentrations of the Hveragil all show good linear correlations with temperature.

Lake Öskjuvatn water (pH = 7.0, T = 12.5°C) has high SO_4^{2-} content (462 ppm) and relatively high concentrations of ΣCO_2 (163 ppm), SiO_2 (94 ppm) and Cl (46 ppm). The Víti crater lake water is acidic (pH = 2.5, T = 20°C), has low concentrations of ΣCO_2 (below detection limit) and Cl (1.6-4.7 ppm) but high concentrations of SO_4^{2-} (494 ppm) and SiO_2 (155 ppm). A circumneutral hot spring (pH = 6.4, T = 52°C) on the outer southern rim of the Víti crater has high concentrations of ΣCO_2 (628 ppm), SO_4^{2-} (822 ppm), Cl (141 ppm) and SiO_2 (142 ppm).

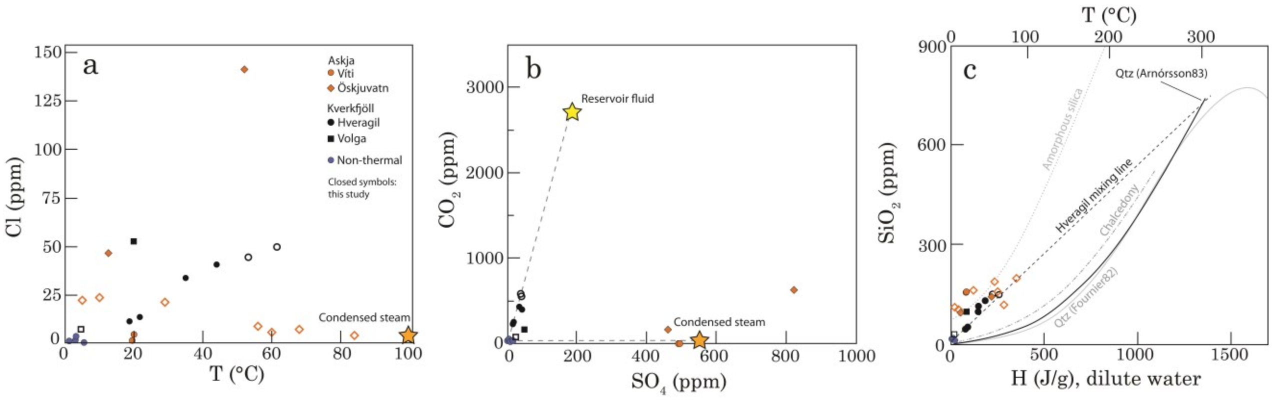

Figure 2: Water chemistry. (a) Cl vs. temperature (b) CO2 vs. SO4. The condensed steam composition was taken from Stefánsson et al. (2016) and the reservoir fluid composition was calculated using the silica-enthalpy mixing model (see section 4.2) (c) SiO_2 vs. enthalpy mixing model. The quartz solubility model of Arnórsson et al. (1983) was used together with the silica-enthalpy mixing model of Truesdell and Fournier (1977) to estimate the reservoir fluid composition (section 4.2). Solubility curves for amorphous silica, chalcedony and quartz from Fournier (1977) and Fournier and Potter (1982) are plotted for reference.

3.2 Gas chemistry

The gas chemistry of fumarole discharges at Askja and Kverkfjöll is shown in Figs. 3a-c. Additional data in the figures is from Stefánsson (2017) for Askja and Kverkfjöll and from Ólafsson et al. (2000) for Kverkfjöll. The fumarole discharge at Askja has a relatively low water content (96.90-98.00 mol.%) compared to most other Icelandic geothermal areas (Stefánsson 2017) (Fig. 3a). The other gases are dominated by CO_2 (18650-28600 µmol/mol) and H_2S (790-1770 µmol/mol). CH_4 concentrations are low (0.6-3.6 µmol/mol) (Fig. 3b) and the H_2 concentrations are highly variable (8.4-635 µmol/mol).

In comparison, the fumarole discharge at Kverkfjöll is relatively wet with a water content of H_2O = 98.34-99.68 mol.% (Fig. 3a). The steam is more wet at Efri and Neðri Hveradalur compared to Hveratagl, where the fumarole discharge has up to five times higher total dry gas content (from 3177 to up to 16580 µmol/mol). Most of the dry gas is CO_2 (2450-15510 µmol/mol) and H_2S (94-631 µmol/mol) (Figs. 3b-c). The CH_4 concentrations at Kverkfjöll are higher than at Askja at 1.6-15.0 µmol/mol (Fig. 3b). Efri and Neðri Hveradalur and Hveratagl also occupy distinct fields in a CO_2 vs. CO_2/H_2S plot (Fig. 3c): The Efri Hveradalur and Gengissig gases plot along a trend with higher CO_2/H_2S ratios with increasing CO_2. Both trends converge at the composition of a fumarole at Galtarlón (Fig. 3c). The gas chemistry of Kverkfjöll is similar to fumaroles from Vonarskarð, a high temperature geothermal area NW of Vatnajökull, situated above a dormant central volcano (Stefánsson et al. 2016, Stefánsson 2017) (Figs. 3a-c).

Five gas geothermometers from Arnórsson and Gunnlaugsson (1985) were applied using the compiled Askja and Kverkfjöll gas data (Fig. 3d). Four out of five of the thermometers are largely concordant for the Kverkfjöll data, giving a mean reservoir temperature of 306°C (Fig. 3d). The CO_2 thermometer gives a higher mean temperature of 386 °C for Kverkfjöll, possibly indicating a deeper temperature. For Askja, the geothermometers give more discordant results. Temperatures of 288-328 °C are indicated by the H_2, H_2S, H_2S/H_2 and CO_2/H_2 thermometers, while the CO_2 thermometer gives a mean temperature of 426 °C (Fig. 3d).

The data for the gas samples from Hveradalur at Kverkfjöll span over three decades of data collection from eight different field campaigns in 1983, 1992, 1993, 1994, 1997, 1998, 2017 and 2019. The gas chemistry reported for the different campaigns falls within a constrained compositional range. No long-term temporal signals, such as decrease or increase of overall activity, or a change in the gas sources at Kverkfjöll can be detected in the dataset. A similar conclusion was reached by Ólafsson et al. (2000), who sampled three fumaroles at Hveradalur multiple times over a span of seven years. For Askja, a similar time series is not available. However, the gas chemistry of three fumarole samples from 1983 (Stefánsson 2017) falls within the range of the recently collected samples in this study.

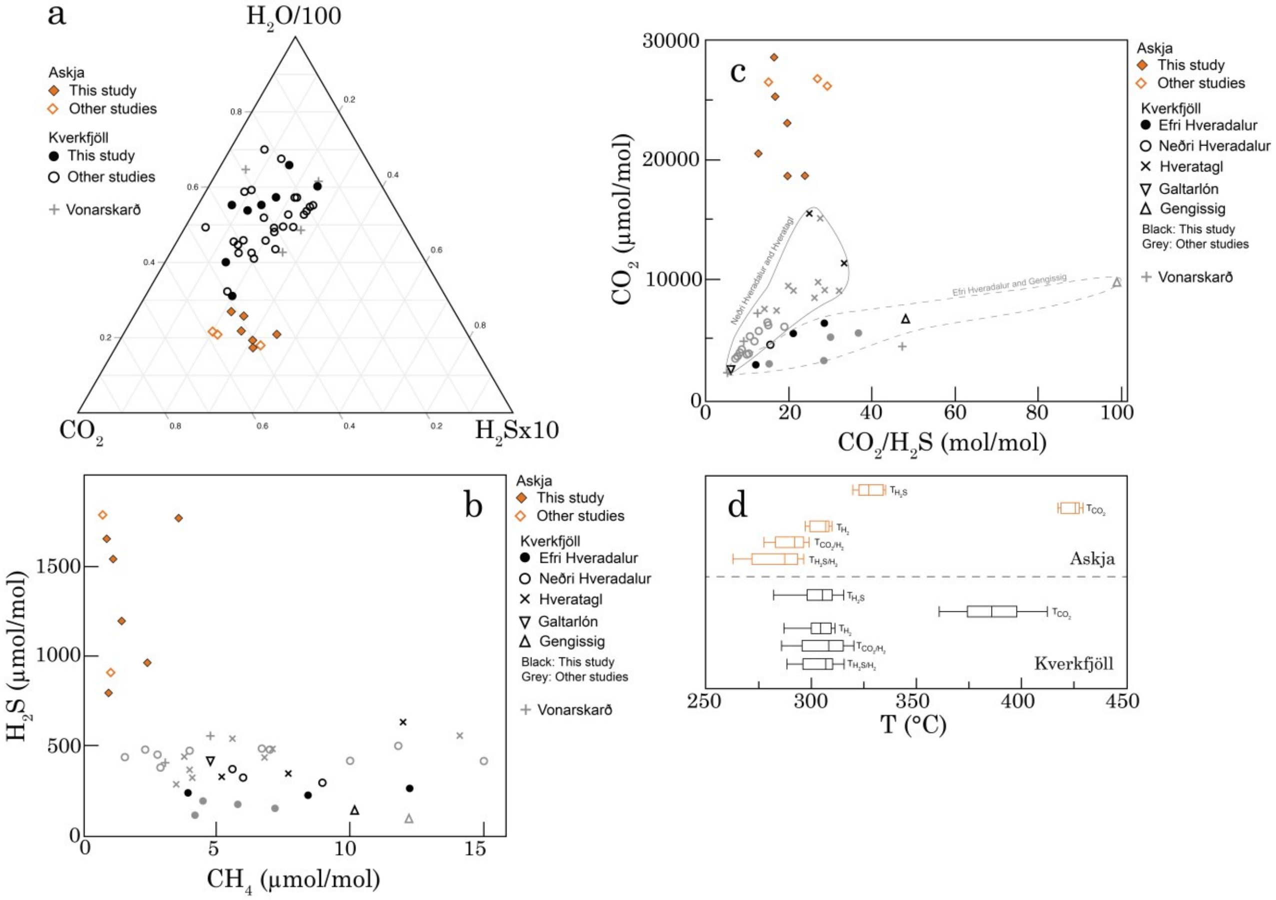

Figure 3: Gas chemistry. (a) CO_2-H_2O-H_2S ternary diagram (b) H_2S vs. CH_4 (c) CO_2 vs. CO_2/H_2S (d) Gas thermometry. The gas thermometer calibrations of Arnórsson and Gunnlaugsson (1985) were used. Additional data taken from Ólafsson et al. (2000) and Stefánsson (2017).

4 DISCUSSION

4.1 Hydrology of Kverkfjöll and Askja

Hveradalur is situated at higher altitude (1550-1700 m) than any other Icelandic geothermal area. The location implies that the heat source for the geothermal system lies approximately beneath the NE caldera of Kverkfjöll. Fluid pathways to the unusually high altitude are probably provided by steep caldera faults, supported by the SSW-NNE lineament of the Hveradalur area. Water for the hydrothermal circulation cell is supplied by both meteoric and glacial melt water (Ólafsson et al. 2000). Above a depth of c. 500-600 m below ground level, the rising one-phase reservoir fluid boils and separates into liquid and water phases (Arnórsson et al. 2007). The steep topography of the Kverkfjöll central volcano results in a steeply dipping groundwater table, that flows out along numerous rivers on the flanks of the mountain massif. This allows the liquid fraction of the boiled reservoir fluid to flow out at roughly the elevation of boiling (1000-1300 m.a.s.l.) into the Hveragil and Volga rivers on opposite sides of the NE caldera. The vapour phase rises above the ground water table, probably along steep caldera faults, to make an exit at Hveradalur. This leads to an almost perfect separation of the liquid and gas phases into Hveragil and Hveradalur, respectively (Fig. 4b). Sampling the waters at Hveragil and the steam at Hveradalur can be seen as a natural analogue to sampling of two-phase wells drilled into geothermal reservoirs. Therefore, Kverkfjöll offers a rare opportunity to model the reservoir fluid compositions at a natural site (see section 4.2).

Similar circumstances do not exist at Askja, where the groundwater table is relatively flat and marked by the surface of Lake Öskjuvatn at 1050 m.a.s.l.. Here, the rising hot one-phase fluid boils at > 300 m below the floor of Lake Öskjuvatn. Above this depth, the vapour phase rises towards the surface along caldera faults and either escapes in fumaroles or condensates and dissolves into shallow groundwater. The boiled reservoir fraction dissipates laterally and mixes with local groundwater before reaching the surface. No limiting condition at Askja, such as the topographic gradient in Kverkfjöll, blocks the back-flow of steam-heated water to the aquifer to form a mixed local groundwater reservoir (Fig. 4a). Hence, Lake Öskjuvatn and adjacent springs all seem to reflect various mixtures of non-thermal water, condensed steam and boiled reservoir water and contrasts with the solute-poor chemistry of a close-by cold stream (Figs. 2a-c).

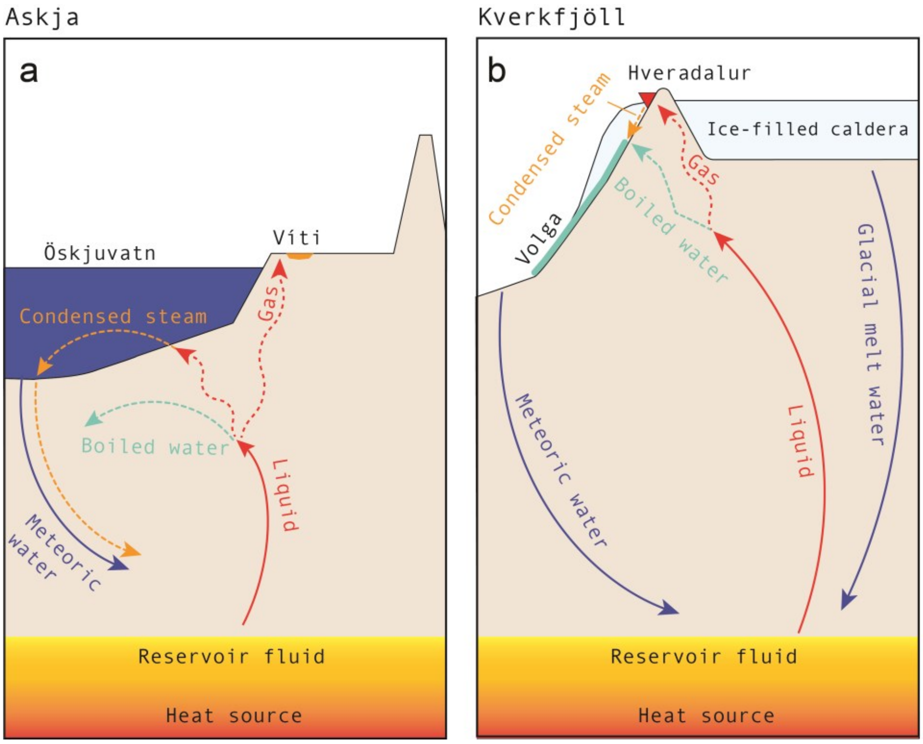

Figure 4: Conceptual models representing the geothermal fluid circulation at (a) Askja, and (b) Kverkfjöll.

4.2 Constraining fluid sources

The good linear correlations of Cl, ΣCO_2 and SiO_2 with temperature (Figs. 2a,c) shown by the Hveragil water samples indicates two-component mixing of non-thermal water with a geothermal component, with limited secondary modifications affecting the water chemistry. The geothermal component must be alkaline with high Cl, SiO_2 and ΣCO_2, but low SO_4^{2-}concentrations. Such chemistry is associated with the liquid fraction of a primary one-phase reservoir fluid that undergone phase separation through decompression boiling (Arnórsson et al. 2007), i.e. boiled reservoir water (c.f. Stefánsson et al. 2016). In contrast, condensation of geothermal vapour creates a condensed steam component that is acidic, poor in ΣCO_2, Cl and SiO_2 and rich in SO_4^{2-} (Stefánsson et al. 2016). The Volga river water (pH = 7.8, T = 20°C) has elevated Cl, ΣCO_2 and SO_4^{2-} signals (Figs. 2a-b) that imply mixing of non-thermal water with both condensed steam and boiled reservoir water. A small boiled reservoir water component can also be sensed in a tributary to the Lindaá river in the form of slightly elevated ΣCO_2, SiO_2 and Cl concentrations compared to other cold-water streams.

Using the silica-enthalpy mixing model of Truesdell and Fournier (1977) it is possible to model the primary reservoir fluid composition of Kverkfjöll by using known Hveragil water chemistry, local non-thermal water chemistry and the enthalpy of water, assuming that, (1) Hveragil reflects pure two-component mixing of reservoir fluid and non-thermal water, (2) the reservoir fluid is dilute, (3) the SiO_2 solubility is buffered by quartz (here the quartz solubility model of Arnórsson et al. (1983) is applied), (4) that no post-mixing process has altered the SiO_2 concentrations, and that (5) no conductive cooling has occurred after mixing. In order to satisfy the fifth condition, the mixing trajectory was projected through samples with the highest enthalpy/silica ratios. The mixing trajectory crosses the quartz-solubility curve at c. 290-300 °C, which reflects the temperature of the source reservoir fluid and is similar to temperatures attained from gas thermometry. The ratio of non-thermal/boiled reservoir water can be estimated to about 4.63 for the highest-temperature sample (T = 61.5 °C for sample H-4 in Ólafsson et al. 2000). Multiplying the concentrations of the chemical components of H-4 by a factor of 4.63, the reservoir fluid composition can therefore be estimated to about B = 1.0 ppm, Cl = 230 ppm, SiO_2 = 680 ppm, ΣCO_2 = 2700 ppm and SO_4^{2-} = 185 ppm.

A similar mixing model does not apply for Askja, because conditions (1) and (5) are not met. This is reflected by high SO_4^{2-} contents of the Öskjuvatn spring samples (Fig. 2b) and by the poorly defined mixing trajectory in Fig. 2c.

5 CONCLUSIONS

Based on new gas and water chemical data presented here, along with reanalysis of previously collected data, conceptual models over the geothermal fluid flow systems at Askja and Kverkfjöll were constructed. At both sites, the geothermal fluids exploit existing caldera faults as pathways to the surface. An important difference between the two geothermal areas is the topographic gradient surrounding the upflow zones of the geothermal fluids. At Kverkfjöll, the vapour phase exits at high altitude at Hveradalur and a steep topographic gradient allows the boiled reservoir water to flow laterally out of the ground to the two hot rivers Hveragil and Volga. In contrast, the topography around the geothermal upflow zone at Askja is relatively flat. Therefore, the boiled reservoir water does not reach the surface directly and is largely mixed into the local aquifer. As a result, the Lake Öskjuvatn water and surrounding springs have a considerable geothermal component, representing various mixtures of boiled reservoir water, condensed steam and meteoric water.

The alkaline, carbonate-rich Hveragil river represents a rare natural example of a binary mixture between non-thermal and boiled reservoir water. Its chemistry was used to model the chemical composition of the Kverkfjöll reservoir fluid, applying the silica-enthalpy mixing model of Truesdell and Fournier (1977). The reservoir fluid chemistry was estimated to have B = 1.0 ppm, Cl = 230 ppm, SiO_2 = 680 ppm, ΣCO_2 = 2700 ppm and SO_4^{2-} = 185 ppm.

The fumarole discharge at Askja is more gas-rich compared to Kverkfjöll. No temporal changes in the gas chemistry were found in the Kverkfjöll data that spans three decades, indicating that the geothermal system is relatively stable.

REFERENCES

Ármannsson, H.: The fluid geochemistry of Icelandic high temperature geothermal areas, *Applied Geochemistry*, **66**, (2016) 14-64

Arnórsson, S., Gunnlaugsson, E., and Svavarsson, H.: The chemistry of geothermal waters in Iceland. III, Chemical geothermometry in geothermal investigations. *Geochimica et Cosmochimica Acta*, **47(3)**, (1983), 567-577

Arnórsson, S., and Gunnlaugsson, E.: New gas geothermometers for geothermal exploration—calibration and application, *Geochimica et Cosmochimica Acta*, **49(6)**, (1985), 1307-1325

Arnórsson, S., Bjarnason, J.Ö., Giroud, N., Gunnarsson, I., and Stefánsson, A.: Sampling and analysis of geothermal fluids. *Geofluids*, **6(3)**, (2006), 203-216

Arnórsson, S., Stefánsson, A., and Bjarnason, J.O.: Fluid-fluid interactions in geothermal systems, *Reviews in Mineralogy and Geochemistry*, **65(1)**, (2007), 259-312

Fournier, R.O.: Chemical geothermometers and mixing models for geothermal systems, *Geothermics*, **5(1-4)**, (1977), 41-50

Fournier, R.O., and Potter, R.W.: Revised and expanded silica (quartz) geothermometer. *Geothermal Resources Council Bulletin*, **11(10)**, (1982)

Gylfadóttir, S.S., Kim, J., Helgason, J. K., Brynjólfsson, S., Höskuldsson, Á., Jóhannesson, T., Harbitz, C.B., and Løvholt, F.: The 2014 Lake Askja rockslide-induced tsunami: Optimization of numerical tsunami model using observed data, *Journal of Geophysical Research: Oceans*, **122(5)**, (2017), 4110-4122

Hartley, M. E., and Thordarson, T: Formation of Öskjuvatn caldera at Askja, North Iceland: Mechanism of caldera collapse and implications for the lateral flow hypothesis, *Journal of Volcanology and Geothermal Research*, **227**, (2012), 85-101

Jónasson, K., and Einarsson, S.: Jarðminjar á háhitasvæðum Íslands: jarðfræði, landmótun og yfirborðsummerki jarðhita. Icelandic Institute of Natural History, internal report, NÍ-09012, 151 pp, (2009)

Montanaro, C., Scheu, B., Gudmundsson, M.T., Vogfjörd, K., Reynolds, H.I., Dürig, T., Strehlow, K., Rott, S., Reuschlé, T., and Dingwell, D.B.: Multidisciplinary constraints of hydrothermal explosions based on the 2013 Gengissig lake events, Kverkfjöll volcano, Iceland, *Earth and Planetary Science Letters*, **434**, (2016), 308-319

Oddsson, B.: Heat transfer in volcanic settings: Application to lava-ice interaction and geothermal areas, PhD dissertation, Faculty of Earth Science, University of Iceland, (2016), 106 pp

Óladóttir, B.A., Larsen, G., and Sigmarsson, O.: Holocene volcanic activity at Grímsvötn, Bárdarbunga and Kverkfjöll subglacial centres beneath Vatnajökull, Iceland, *Bulletin of Volcanology*, **73(9)**, (2011), 1187-1208

Ólafsson, J.: Temperature structure and water chemistry of the caldera Lake Öskjuvatn, Iceland, *Limnology and Oceanography*, **25(5)**, (1980), 779-788.

Ólafsson, M., Torfason, H., and Grönvold, K.: Surface exploration and monitoring of geothermal activity in the Kverkfjöll geothermal area, central Iceland. *Proceedings of the World Geothermal Congress*, Kyushu-Tohohu, Japan**, 28**, (2000), 1539-1545

Stefánsson, A., Keller, N.S., Robin, J.G., Kaasalainen, H., Björnsdóttir, S., Pétursdóttir, S., Jóhannesson, H., and Hreggvidsson, G.Ó.: Quantifying mixing, boiling, degassing, oxidation and reactivity of thermal waters at Vonarskard, Iceland, *Journal of Volcanology and Geothermal Research*, **309**, (2016), 53-62

Stefánsson, A.: Gas chemistry of Icelandic thermal fluids. *Journal of Volcanology and Geothermal Research*, **346**, (2017), 81-94

Sturkell, E., Sigmundsson, F., and Slunga, R.: 1983–2003 decaying rate of deflation at Askja caldera: pressure decrease in an extensive magma plumbing system at a spreading plate boundary. Bulletin of Volcanology, **68(7-8)**, (2006), 727-735

Thórarinsson, S.: The Grímsvötn Expedition June-July 1953, *Jökull*, **3**, (1953), 6-22

Truesdell, A.H., and Fournier, R.O.: Procedure for estimating the temperature of a hot-water component in a mixed water by using a plot of dissolved silica versus enthalpy. *USGS Journal of Research*, **5**, (1977), 49-52