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Geochemical Reconnaissance of Fluids from the Krafla and Nesjavellir Thermal Areas, Iceland: Baseline Studies in Support of the IDDP

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ABSTRACT

Reconnaissance studies of the fluid chemistries of the Krafla and Nesjavellir systems have been undertaken to provide some insights into the nature of fluid components in these systems, and the reservoir processes that may be affecting them. The preliminary work reported here is being used to steer a more extensive project incorporating IDDP well discharges. With this, we aim to build an interpretive framework for understanding the role of supercritical (IDDP) fluid contributions in the evolution of the fluid chemistries in these (and similar) systems.

High temperatures and production enthalpies characterise the deeper reservoir environments in both systems. Three end-member compositional components have been identified in both systems, including meteoric, geothermal, and mantle (i.e., magmatic fluid) components.

At Nesjavellir, the well discharges from NG-5 and NG-10 show the largest magmatic fraction whereas those from NJ-11 show the largest geothermal component fraction. At Krafla, the fluid evolution is somewhat more complex, with discharges from KJ-34 and KJ-19 showing the largest magmatic component. Both systems show evidence of extensive vapour loss which has depleted the fluids of its geothermal and meteoric signatures.

1. INTRODUCTION

A reconnaissance geochemical study of the Krafla and Nesjavellir geothermal systems (Iceland) conducted in the lead-up to IDDP (Icelandic Deep Drilling Project) project drilling reveals compositional differences in fluids from these two systems which are consistent with their differing regional and tectonic settings, and their respective magmatic (source) fluid contributions. High temperatures and discharge enthalpies in both systems are indicative of natural 2-phase (i.e., vapour-liquid) conditions in the source regions at depth. Krafla shows evidence of compartmentalisation of its reservoir fluids, with localised natural and production-induced reservoir processes (i.e., boiling/condensation) leading to the development of isolated fluid-chemical domains. Nesjavellir thermal fluids, on the other hand, appear to be more uniformly sourced from beneath the Hengill volcano to the south, with outflow and mixing toward the Kyrdalur eruptive fissure system to the north.

Here we present results from initial work completed in 2003, which provides a basis for more detailed studies as the IDDP progresses.

2. PREVIOUS WORK

Both hydrothermal systems have been extensively studied since exploration for geothermal power production commenced in the 1960's.

Nesjavellir is situated on the northern flank of Hengill Volcano in SW Iceland (Figure 1). The volcano is at least 300,000 years old, and last erupted ca. 2000 years ago. Features of the Hengill massif and the geothermal area were described by Arnason et al., (and references therein, 1969). A comprehensive conceptual model of the hydrothermal system was proposed by Stefansson (1985), and reservoir simulations matching predicted and observed production performance through time have been discussed by Bodvarsson et al. (1988) and more recently by Steingrimsson et al. (2000).

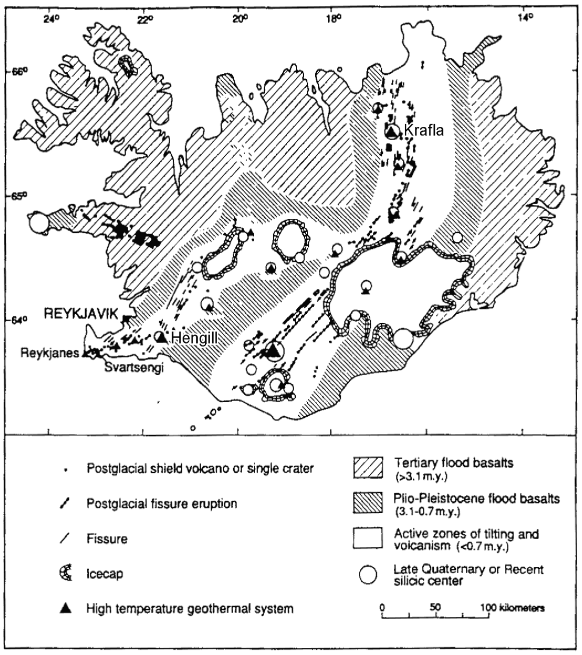

Figure 1: Schematic geological map of Iceland, showing the location of the Reykjanes, Hengill and Krafla geothermal areas (after Sæmundsson, 1978).

Fluid flow is primarily along NE-SW trending faults. The current source upwelling is believed to lie beneath the Hengill massif. Reservoir temperatures exceeded 380°C in well NJ-11, which is thought to have tapped lithostatically over-pressured gases along one of the 2000 year old Kyrdalur eruptive fissures, possibly reflecting a recent intrusive event. The system is in part naturally 2-phase (vapour-liquid), and most wells reflect this with high wellhead enthalpies (>1500 kJ/kg).

Little has been published on the chemistry of the Nesjavellir fluids. Some 22 exploration/production wells have been drilled in the system (Figure 2), and the fluids are known to be dilute, neutral-to-alkaline chloride fluids with geo-indicated temperatures generally ranging between 280 to 300°C (unpublished IDDP documentation). Four permeable aquifers have been used to model the system (Bodvarsson et al., 1988), from which 120 MW_e and 300 MW for space heating are currently being produced.

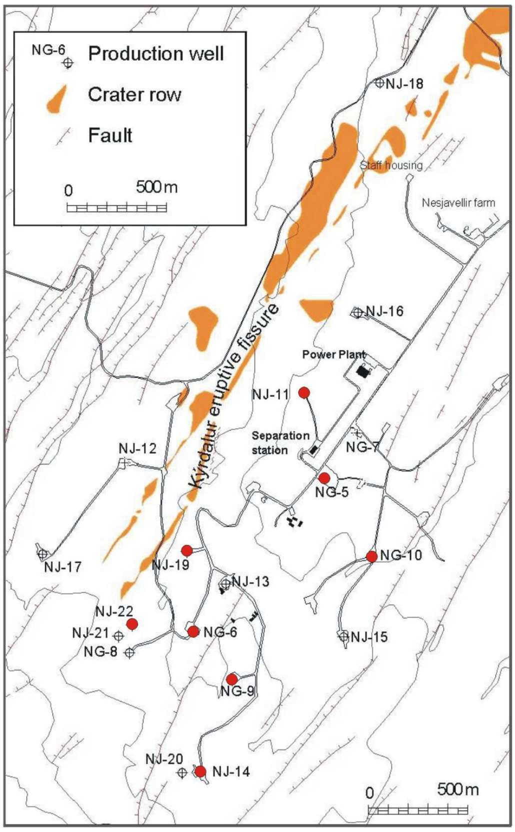

Figure 2: Nesjavellir bore field. Red symbols denote wells sampled for this study.

The Krafla system is located in the NE of the country (Figure 1), within a volcanically active caldera complex which last erupted between 1975-1984. The regional geology has been extensively reported by Saemundsson (1978), and is dominated by NE trending fissures swarms. Lavas are predominantly basaltic, although dacitic compositions are also reported (Stefansson, 1981), and intrusive rocks have been retrieved in drill core from the hydrothermal system. A magma chamber ranging between 3-7 km depth beneath the caldera has been identified by seismic attenuation studies (Einarsson, 1978). A zone of high permeability is associated with the NE-trending Hveragil Fissure system, and appears to be a main upflow feature for source fluids in the system (Armannsson et al., 1989).

40 production wells have been drilled at Krafla, with installed electrical generation capacity of 60 MW_e. Fluid chemistry of the production fluids is well characterised, principally by Armannson et al. (1982, 1987, 1989), Arnorsson (1995) and more recently summarised by Gudmundsson and Arnorsson (2002). The system is compartmentalised into at least three sub-fields (Figure 3), Hvitholar to the south, Sudurhlidar and Leirbotnar which lie south and north of the Hveragil fracture system respectively. Apart from the three drill sub-fields a fourth undrilled sub-field, the Leirhnukur field lies to the northwest of the Leirbotnar field.

Darling and Armansson (1989) applied water stable isotope systematics to the Krafla and Namafjall systems, and determined that waters in the Krafla system are essentially locally derived. Approximately 10 km to the south of Krafla caldera, but along strike with the fissure system that feeds magma into the Krafla volcanic system, lies the Namafjall hydrothermal area. This field is hydrologically distinct from that at Krafla, but the hydrothermal system was also affected by the 1975-84 volcanic activity.

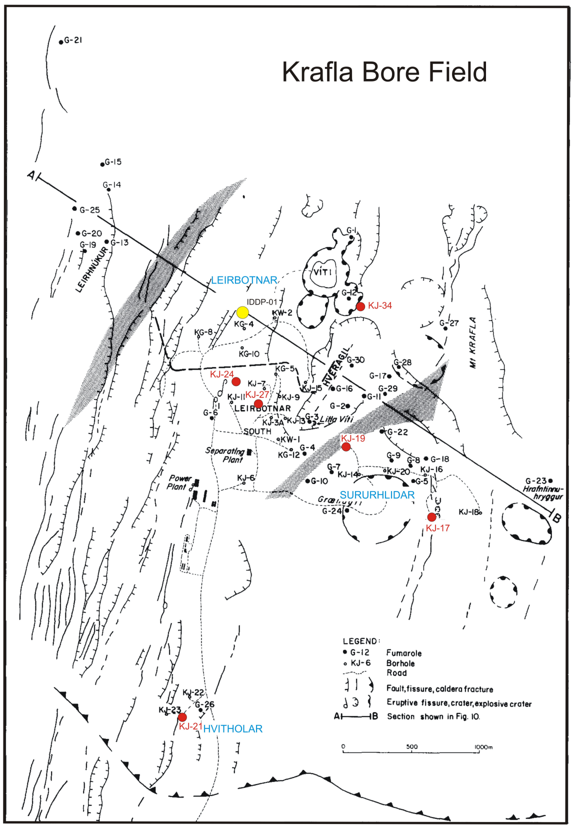

Figure 3: Krafla Bore Field. Wells sampled in 2003 are shown in red and the three subfields (Leirbotnar, Sudurhlidar and Hvitholar) are highlighted in blue. Known permeability barriers are shown in grey (adapted from Armansson et al., 1989), and the location of the IDDP wellsite is shown in yellow.

3. SAMPLING AND ANALYSIS

Samples were obtained in October 2003 from 2-phase production line discharges using a Webre separator. Sampling strategy focused on achieving as broad a spatial distribution of well sites as possible, as well as obtaining representative samples from any “compartmentalised” portions of the respective reservoirs.

At Krafla, good coverage of the three subsystems was achieved, although only discharges sourced from less than 2000 m were available at the time of sampling, and therefore do not include any acidic discharges which have been encountered recently (Hauksson and Gudmundsson, 2008). Feedzone depths are listed in Table 1.

Excellent spatial coverage of the Nesjavellir system was achieved in the 2003 sampling.

Water and condensate samples were analysed at GNS for Na, K, Mg, Ca, Li, Fe, Al, B, SiO_2 and As (by ICP-OES), Cl and HCO_3 (by titration), SO_4 (by ion chromatography), and pH (by glass electrode). Water samples were acidified and filtered in the field immediately after sampling to alleviate problems with polymerisation of silica. Nevertheless, unrealistically low silica concentrations were obtained for the discharge from KJ-34, suggesting that polymerisation/extraction of silica was occurring at some point along the sampling train.

Table 1: Production depth intervals at Krafla

Well	***Feedzone Depths (m)***
KJ-17	1100, 1600, 1850
KJ-19	1920
KJ-21	500-700
KJ-24	600
KJ-27	1573
KJ-34	1970-1985

Non-condensable gases were analysed by gas chromatography, with He, H_2, Ar, O_2, N_2, and CH_4 detected by thermal conductivity, and CO analysed by flame ionisation detector fitted with a methaniser. Noble gases were analysed at the Center for Isotope Geochemistry, Lawrence Berkeley National Laboratory in California via high resolution mass spectrometry.

4. RESULTS AND DISCUSSION

4.1 Non-Volatile Solutes

Two notable aspects of the Icelandic systems considered here are the dilute nature and the high enthalpies of their discharges. Total discharge Cl contents are plotted against measured enthalpy in Figure 4. Both systems show inverse relationships between Cl and measured enthalpy, which is to be expected given the relative solubilities of Cl in vapour and liquid phases (e.g., Truesdell et al., 1989). In the case of Krafla wells KJ-19 and KJ-34, Cl-deficient vapour appears to be a major constituent in their discharges. Noting that none of the discharges sampled in this study produce fluids from the deeper, HCl-bearing production zones discussed recently by Hauksson and Gudmundsson (2008), it appears that the Cl-deficient vapour here is a mixture of natural 2-phase reservoir conditions, and production-induced effect (near-bore boiling).

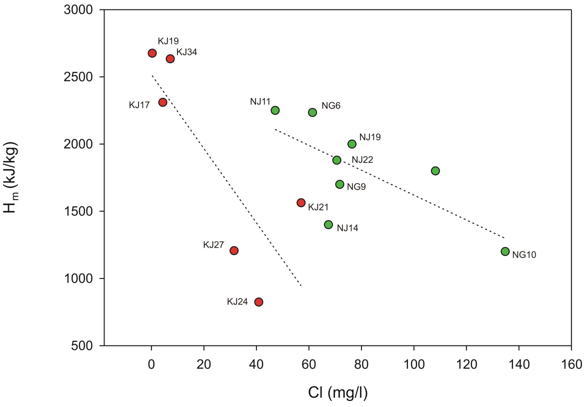

Figure 4: Measured enthalpy vs total discharge compositions of Cl.

Liquid phase Cl-enthalpy data for the Krafla fluids are plotted in Figure 5. Enthalpies here are from Na-K feldspar equilibrium temperatures (Giggenbach, 1991), with Cl liquid compositions corrected for 2-phase conditions in the reservoir. A reference mixing line is defined by the highest liquid enthalpy discharge (KJ-34), and a likely recharge fluid of 5°C and nil Cl. Given the large spatial area of the sampling, and the fact that at least 3 subsystems are represented here, it is rather unlikely that the fluids in Figure 5 necessarily share a common line of descent from a single source upwelling, but reservoir processes are considered to be similar in the 3 compartments.

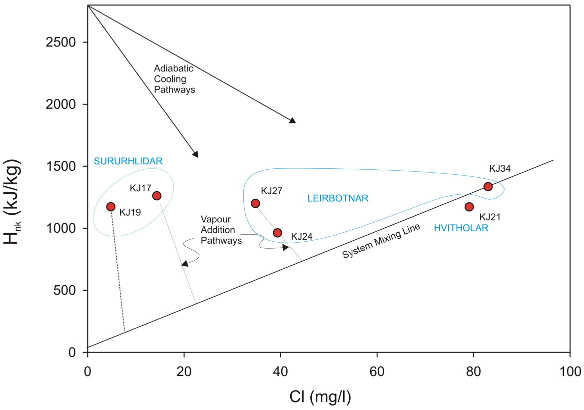

Figure 5: Liquid enthalpy at Na-K equilibrium temperature vs calculated Cl liquid phase concentration. A system mixing line is established between groundwater (~ nil Cl, and ca. 5°C) and the highest enthalpy liquid from KJ34.

This is supported by observed coherency between Cl and enthalpy within subfields. For example, discharges from KJ-19 and KJ-17 (Sudurhlidar area) are dilute, and very hot indicating steam condensation in these production aquifers. Data from KJ-24 and KJ-27 in the Leirbotnar area, on the other hand, are related through varying contributions of condensed steam, whereas the deeper reservoir fluid from KJ-34 shows an intrinsically higher Cl content, perhaps reflecting its proximity to heat source input related to Mt Krafla. Interestingly, fluids from this sector will bear the closest evolutionary lineage to supercritical fluids which will likely be produced from IDDP exploration well 1 (Figure 4).

Further to the south, shallow fluids from KJ21 most probably derive their Cl from a similar, but separately evolved source.

Total discharge Cl and H at Nesjavellir show a relationship similar to those found at Krafla (Figure 4), although maximum enthalpies do not exceed 2400 kJ/kg and Cl contents are a factor of 2-3 higher than those at Krafla. The discharge from NJ-22 has the highest calculated liquid phase enthalpy (Figure 6), and thereby provides the basis for a system mixing line. This approach indicates that fluids plotting below the system mixing line (eg. NG-5, NJ-14) have adiabatically cooled within the production reservoir, whereas those lying above the mixing line contain a condensed steam component (eg. NJ-11).

It is worth noting that two 2003 discharge compositions depart significantly from previously published results. Earlier fluids from NG-5 in 1983 (Stefansson, 1985) were amongst the most dilute in the system (~ 2 mg/l), whereas those from NG-10 were relatively enriched. The reasons for these changes are presently unclear, but probably relate to production-induced changes (cooling) in the system.

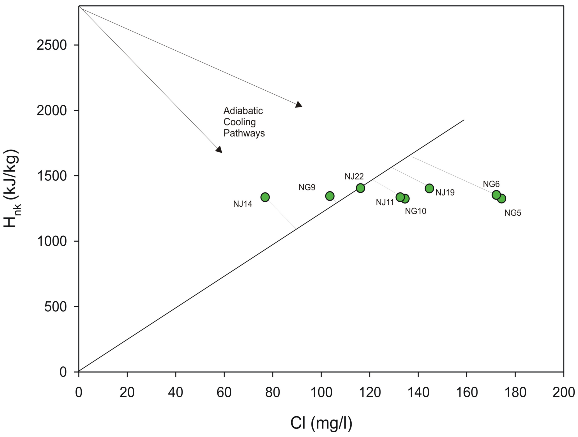

Figure 6: Liquid enthalpy at Na-K equilibrium temperature vs calculated Cl liquid phase concentration. A system mixing line is established between groundwater (~ nil Cl, and ca. 5 °C) and the highest enthalpy liquid from NJ22.

Early recorded spatial variation in Cl concentration at Nesjavellir (Fridleifsson et al., 2003) is consistent with modeling results of Steingrimsson et al. (2000) pointing to a thermal source fluid upwelling to the south of the drilled portion of the system (i.e., beneath the Hengill volcano).

The relationship between Cl and B in Icelandic systems has been discussed previously by Arnorsson and Andresdottir (1995), and B isotope systematics in Icelandic systems have been assessed by Aggarwal et al. (2000). Both studies have identified rocks being the principle source of B in Icelandic systems, although marine B and Cl are both found in low concentrations in surface waters close to the coasts.

As discussed above for Cl, total discharge B contents in Nesjavellir fluids vary inversely with discharge enthalpy, suggesting that B in the discharges is also variably diluted by B-deficient steam. In contrast, at Krafla B shows a weak but positive correlation with discharge enthalpy (Arnorsson and Andresdottir, 1995; and this study).

The differing behavior of B in the two systems is readily apparent when B concentrations are normalised to Cl (Figure 7). Nesjavellir fluids exhibit relatively constant B/Cl ratios with varying Cl contents, consistent with a single, common source for both constituents in the reservoir fluid (Figure 7). Krafla B/Cl ratios, on the other hand, vary by more than a factor of 10 across the system, with the highest ratios being found in waters with low Cl concentrations.

Calculated reservoir liquid-phase B compositions range between 0.2-4.7 mg/l at Krafla, and 1.0-2.7 mg/l at Nesjavellir systems. Applying vapour-liquid partitioning ratios of Glover (1988), it is clear that even at large reservoir vapour fractions in a closed system, the observed enrichments cannot occur through closed system vapour addition alone. Rather, and in addition to vapour transport, a likely explanation for the observed B enrichment is through addition of high temperature (i.e., magmatic) vapour into the hydrothermal environment (e.g., Quisefit et al., 1989). This idea, previously proposed to explain B anomalies at Ohaaki, New Zealand (Christenson et al., 2002), is consistent with a proposed magmatic source for HCl bearing fluids in the deeper reservoir environments of this system (Armannsson, 2010).

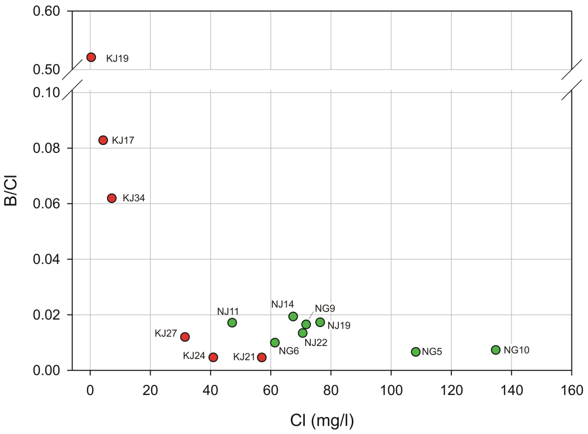

Figure 7: Cl vs B/Cl plot for Krafla and Nesjavellir fluids.

$\delta^{18}O$-δ^2H relations for the fluids from the two systems are shown in Figure 8 where they are compared to the local (Reykjavik) precipitation slope of (I.A.E.A, 1981):

$$\delta^2H = 7.02*\delta^{18}O - 0.75.$$

As reported by Darling and Armannsson (1989), most of the Krafla waters plot close to the meteoric water line, suggesting that the system has been subject to sizable water-rock ratios. There is a subtle trend of $\delta^{18}O$ enrichment with production depth, with the discharge from KJ-34 being some 3 per mille enriched over local meteoric water. This enrichment could be the result of direct input of either magmatic water into this portion of the reservoir, or magmatic (i.e., isotopically heavy) CO_2, or extensive, boiling-induced enrichment through loss of isotopically light water vapour.

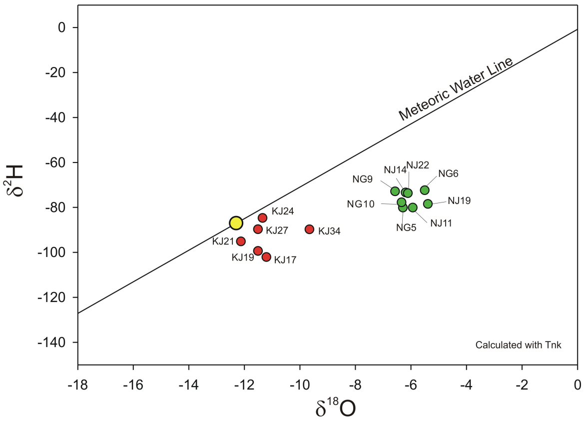

Figure 8: $\delta^{18}O$ vs δ^2H for reservoir fluids. Yellow symbol represents the ground water signature from the Krafla area.

There is no clear trend defined for δ^2H, although it is notable that the high enthalpy discharges from KJ-19 and KJ-17 are ^2H-depleted, possibly reflecting localised condensation of vapour in this portion of the reservoir, consistent with enthalpy-chloride relations discussed above.

The Nesjavellir discharges show a narrower range in their $\delta^{18}O$-δ^2H signatures, and are significantly more $\delta^{18}O$ enriched over their Krafla counterparts. In terms of water-rock ratios, this may suggest a lower through-put of water through the system than proposed for Krafla (Darling and Armannsson, 1989), although further work is required on the isotopic composition of the reservoir rocks to prove this.

4.2 Gas Characteristics

There is direct correspondence between total discharge CO_2 contents and discharge enthalpy observed in the Krafla wells, but not in those at Nesjavellir (Figure 9). Krafla discharges KJ-34 and KJ-19 are substantially enriched (> a factor of 5) in CO_2 over all other discharges in that field. Notably, these wells are situated closest to the Hveragil Fissure system, which has previously been suggested by Armannsson et al. (1989) to serve as a conduit for magmatic degassing in the system, drawing the conclusion that the elevated CO_2 in these wells is probably a source-fluid effect. In comparison, the high enthalpy discharge from KJ17, which is located ca. 750 m southeast of KJ-19 in the Sudurhlidar subfield, is only mildly CO_2-enriched, consistent with this being a localised (boiling-induced) exploitation effect.

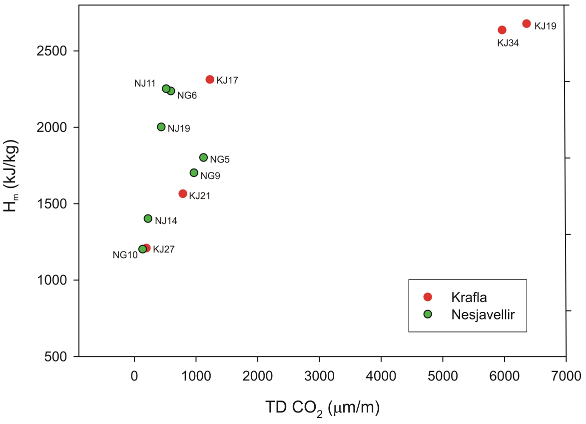

Figure 9: Total discharge CO_2 vs measured enthalpy.

At Nesjavellir, the highest CO_2 contents were produced from wells NG-5 and NG-9, whereas the highest discharge enthalpies derived from wells NJ-11 and NG-6, suggesting that localised, production-induced gas depletion is the dominant factor controlling gas contents in these reservoir environments.

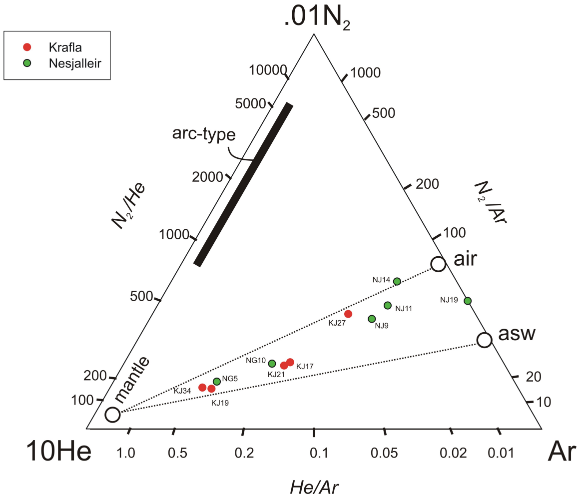

Figure 10: Relative compositions of Ar, N_2 and He for Nesjavellir and Krafla fluids.

Relative He, N_2 and Ar contents in steam from the Krafla and Nesjavellir wells point to strong mantle source signatures in both systems (Figure 10). Two component mixing between MORB and atmospheric end members is evident in both systems, consistent with Iceland's position on the mid-Atlantic Ridge. KJ-34 and KJ-19 are most-enriched in the mantle component, consistent with their aforementioned highly elevated CO_2 contents, and KJ-27 being most enriched in atmospheric gas.

At Nesjavellir, well discharges from NG-5 and NG-10 are significantly enriched in mantle component over any of the other Nesjavellir discharges. Relative contents of CO_2-N_2-Ar also show two component mixing between atmospheric and MORB end-members (Figure 11). Krafla discharges from KJ-19 and KJ-34, with CO_2/N_2 ratios ranging between 300 and 500, are once again most "mantle-like" with KJ-27 showing the highest relative content of atmospheric gases (CO_2/N_2 ~ 8). Nesjavellir discharges are comparatively lower in CO_2 than those from Krafla, and are more uniform in their composition, with the most MORB-like compositions found from NG-5, NJ-19 and NJ-9.

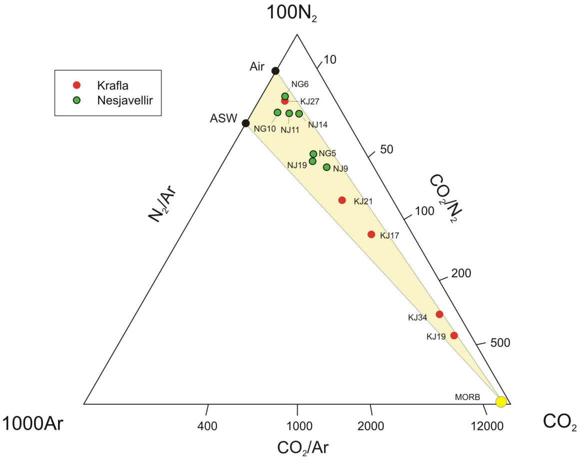

Figure 11: Relative composition of CO_2, N_2 and Ar in the Nesjavellir and Krafla discharges.

Relative contents of He, CH_4 and CO_2 provide further insights into the origins of the fluids in the two systems. In Figure 12, the Nesjavellir and Krafla discharge compositions are compared to the average MORB value (Marty & Zimmerman, 1999), which again serves as a proxy for the magmatic source fluid for both systems. As CH_4 is known to form in relatively reducing geothermal environments, either abiogenically (Geptner et al., 2005) or thermogenically (Giggenbach, 1997), geothermal source fluids for both systems would lie somewhere near to the tie line connecting the MORB composition with the CH_4 vertex. Parent geothermal component fluid compositions are thereby estimated from the intersection of vapour-loss pathway trajectories with the MORB-CH_4 tie line (Figure 12).

A compositional pathway for evolving reservoir liquid phase is shown for the adiabatic cooling of Nesjavellir NJ-11, from 300 °C to 260°C. With cooling, the liquid phase composition shifts towards the CO_2 vertex. This fact, along with the positions of samples from both systems lying along these trajectories, point to two important factors in the evolution of fluid composition in these systems. First, there is the evidence of a distinctive third end-member component in the discharges, here referred to as the geothermal component. In this regard, the Nesjavellir fluids appear to have a more evolved geothermal component than those from Krafla. Secondly, reservoir boiling has an important influence on the evolutionary development of fluid compositions in both systems.

Discharges whose compositions are not easily explained by these processes include KJ27, NG5 and NG10, all of which are depleted in CO_2 compared to their counterparts. The reasons for this are not clear at the present time, but owing to the reactivity of CO_2 in hydrothermal environments (eg. Giggenbach, 1980), it is feasible that these compositions may be showing local effects of water-rock interaction.

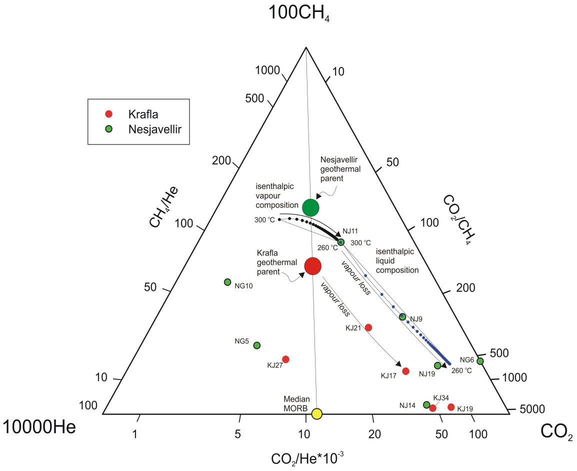

Figure 12: Relative CO_2-CH_4-He compositions of the Nesjavellir and Krafla discharges.

Two notable aspects of the relative contents of ^{3}He, ^{4}He and CO_2 are shown in Figure 13. First, consistent with the findings of Poreda & Arnorsson (1992), the $^3He/^4He$ signatures recorded for the Krafla and Nesjavellir systems are distinctly different, with Krafla discharges showing typical MORB ratios of around $8R_a$ and Nesjavellir closer to $14R_a$ (where R_a = air $^3He/^4He$).

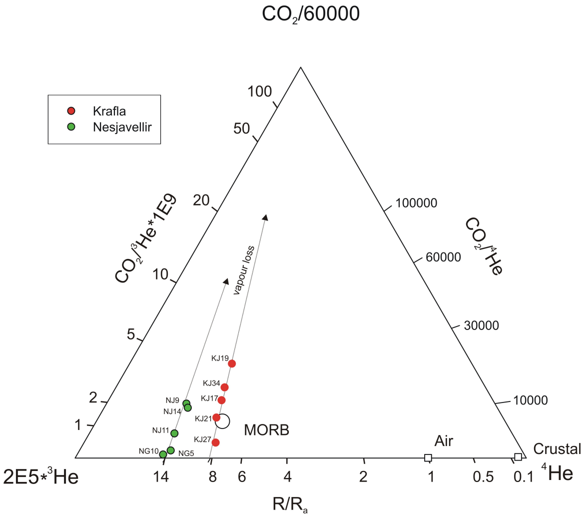

Figure 13: Relative variations in ^{3}He, ^{4}He and CO_2 for Nesjavellir and Krafla fluids.

The differences are attributable to the varying influence of the Icelandic mantle plume in the two areas, with Krafla lying well to the north of the main plume signatures (e.g., Breddam et al., 2000). Secondly, both systems show variations in CO_2 enrichment at relatively constant R/R_a values. This can be explained by vapour loss from the reservoir fluids, with CO_2/He ratios increasing with boiling owing to the lower aqueous solubility of He over CO_2.

5. CONCLUSIONS

Chemical signatures for 3 end-member fluid components are discernable at both Nesjavellir and Krafla. These include meteoric water, a magmatic (mantle-derived) vapour, and a geothermal reservoir fluid. At Krafla, fluids with the largest indicated magmatic component are found in the northern Leirbotnar (KJ-34) and Sudurhlidar subsystems (KJ-17 and KJ-19). Interestingly, these wells also exhibit the greatest effects of vapour loss, which is consistent with the 2-phase conditions encountered in their respective reservoir environments.

At Nesjavellir, NG-5 and NG-10 discharge appear to exhibit the largest magmatic component fraction in the discharges, while also being relatively depleted in CO_2, probably through water-rock interaction in the hydrothermal system.

Further application of stable isotope systematics for B-, C-, S-, H-, and N-bearing gases will further help to characterise the location and proximity of the magmatic heat sources in these systems, and their potential for producing supercritical fluids.

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