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History of Chemical Composition of Geothermal Fluids in Krafla, Northeast Iceland, with Special Emphasis on the Liquid Phase

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ABSTRACT

There are no surface springs in the Krafla area so the first studies on the liquid phase were carried out when the first two exploration wells were drilled in 1974. These revealed a dilute geothermal fluid with sulphate dominating over chloride but with a significant carbonate contribution. Sodium was the major cation and the quartz temperature close to the measured temperature. The area has later been divided into several subareas but the production wells that followed were like the exploration wells drilled in the Leirbotnar subarea and showed similar characteristics. Gas from magma entered the system during the Krafla fires 1975-1984, mainly in the Leirbotnar subarea. Drilling was moved to Suðurhlíðar and Hvíthólar where the effects of the gas did not interfere. The Leirbotnar system has been divided into an upper liquid dominated part at a temperature at c.a. 200°C, and a lower two phase part at c.a. 300°C. The Suðurhlíðar system follows the boiling point curve closely and is rwo phase to vapour dominated at depth. The Hvíthólar system follows the boiling point curve to about 1000 m depth but its lower part is cooler. The Suðurhlíðar fluid is very dilute but in most cases chloride dominates over sulphate or is of a similar concentration. In Hvíthólar the the chloride concentration is greater than that of sulphate but the converse is true of the lower part fluid. In 1990 to 2000 a relative increase in sulphate concentration and an accompanying decrease in chloride concentration was observed in several wells often with a decrease in quartz temperature. This was ascribed to a cold inflow into the area. This change appears to have levelled out. During the Krafla fires bursts of corrosive fluids of low pH and high chloride were intermittently observed in some wells. Since 2000 some deeper wells have been drilled, at least two of which have hit magma. In these wells chloride is the main anion and pH is low where a liquid phase has been obtained and the gas has contained HCl which has formed hydrochloric acid upon contact with liquid water and thus proved corrosive.

1. INTRODUCTION

The Krafla high-temperature geothermal system lies in the northern part of the neo-volcanic zone in Iceland, within the caldera of the Krafla central volcano formed about 10^5 years ago (Sæmundsson 1991). Volcanic activity is extensive, the last eruptive period lasting from 1975 to 1984 during which 9 eruptions took place. Geothermal exploration started in 1970. The first wells were drilled in 1974, when a decision was made to build a 60 MW_e power plant concurrent with drilling. The construction was completed in 1977, the plant commissioned in 1978 with sufficient steam to produce 7 MW_e due to problems related to the volcanic activity. Drilling was moved to two new fields which had been less affected and in 1984 the full capacity of one of the 30 MW turbines was reached. The reservoir recovered and in 1999 the power station reached the full 60 MW_e. Permits have been obtained for a 40 MW_e power station and 8 wells have been drilled, 3 in previously untapped fields. One well has been drilled for the Iceland Deep Drilling Project (Fridleifsson et al. 2014).

The area (Figure 1) has been divided into the sub-fields Leirbotnar (Lower Leirbotnar, Vítismóar), Sudurhlídar, Vesturhlídar, Sandabotnar, Hvíthólar, Vestursvædi, Leirhnúkur. In the Leirbotnar field the system comprises an upper zone down to 1000-1400 m depth, which is liquid dominated with a temperature of 190-220°C and sulphate the major anion, and a lower two phase zone at about 300°C (on the boiling point curve) with chloride the main fluid anion. Hvíthólar is a two phase system following the boiling curve to about 1000 m depth with chloride the main anion but is cooler and liquid dominated below that with sulphate the main anion. A two phase fluid (boiling point curve) from a reservoir at about 300°C with chloride the main fluid anion is observed in Sandabotnar. In Sudurhlídar and Vesturhlídar the boiling point curve is followed and a two phase fluid of about 300°C is delivered whose main anion is chloride. All these groups contain dilute waters of close to neutral pH. Ármannsson (2001) calculated the possible mineral matrix at 205°C and 295°C at water-tock ratio 10 from reaction of Krafla rock with local groundwater and addition of volcanic gas and obtained a matrix containing albite, clinochlore, epidote, hematite, muscovite, paragonite, pyrite, quartz and rhodonite at 205°C but albite, anhydrite, clinochlore, epidote, hematite, muscovite, paragonite, pyrite, quartz and rhodonite at 295°C. Gudmundsson and Arnórsson (2005) calculated aquifer fluid compositions and aqueous species distribution for 22 samples collected from producing wells in the Krafla and Námafjall geothermal areas and found the minerals involved to be albite, calcite, chlorite, epidote, K-feldspar(adularia), prehnite, pyrite, pyrrhotite, quartz and wairakite.T he characteristics of the fluid from the Leirhnúkur area well are similar to those of the Sudurhlídar and Vesturhlídar wells. No well has discharged from the Vestursvædi area which seems cool and unproductive.

Three separate upflow channels for geothermal fluids have been identified, the major one associated with the Hveragil fissure. The recharge is essentially local in origin according to isotopic ratios (Darling and Ármannsson 1989) although the Suðurhlídar, Hvíthólar and Sandabotnar sub-fields may be recharged from far south of the field. The objective of this study is an attempt to relate the variability in chemical composition between fields, between wells and with time to the above history and different depths of feed zones.

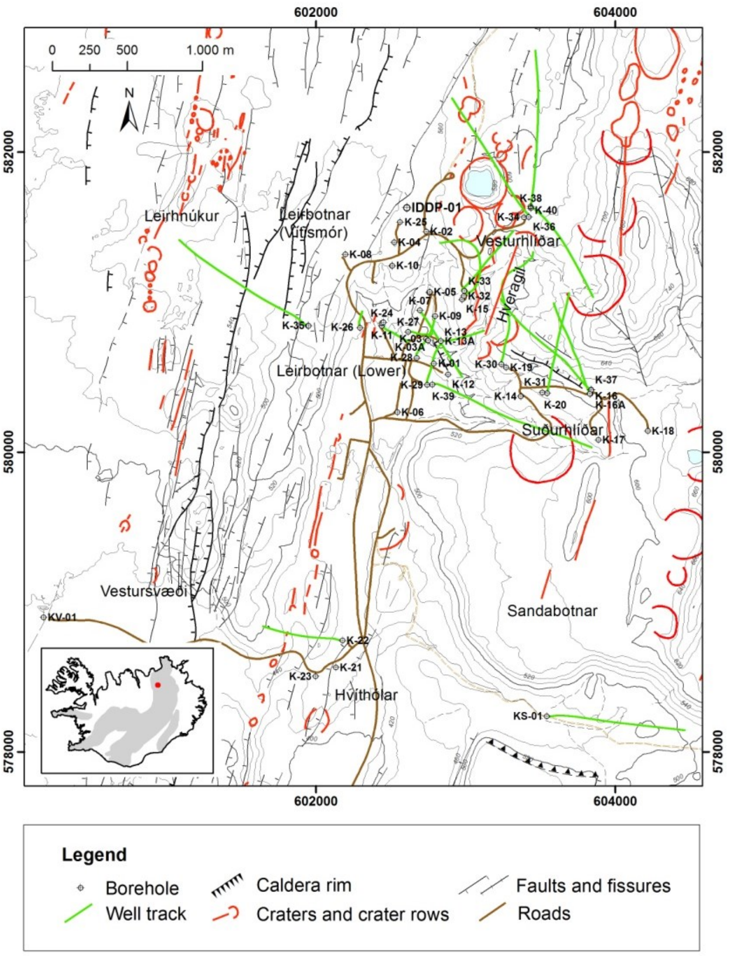

Figure 1. Map of the Krafla area showing tectonic features, the different wellfields and individual wells

2. ACID FLUIDS

Two types of acid fluids are mostly observed in geothermal steam, acid sulphate fluids and acid chloride fluids. Acid sulphate fluids are more common in relatively cool liquid-dominated systems (Moya et al. 2005, Villa et al. 2000, Moore et al. 2002, Sugiaman et al. 2004, Reyes 1990, 1991, Bowyer et al. 2008) whereas acid chloride fluids are more prevalent in hot vapour dominated systems. (Truesdell et al. 1989, D'Amore et al. 1990, Bell 1989, Hirtz et al. 1991, Izquiredo et al. 2000) . The first obvious manifestations of acidity in Krafla well fluids were found in a stream formed after a blowout of well K-4 in 1976 in which a pH of 1.86 was observed (Gíslason and Arnórsson 1976). The composition of the stream water suggested sulphuric acid but later computations with comparison with later nearby acid wells K-10 and K-25 and nearby shallow well K-2 suggested that the acidity was due to hydrochloric acid but the sulphate originated from shallower inflows (Ármannsson and Gíslason 1992). The acidity has been associated with magmatic activity in the Krafla volcanic system 1975-1984 which manifested itself in excess gas in the geothermal system and deposition of iron sulphides, iron silicates, iron oxides and silica (Ármannsson et al. 1982, 1989).

Truesdell et al. (1989) proposed a mechanism involving the existence of a deep brine from which the HCl rich steam was boiling at depth. Evidence for this brine was found in the flow of a saline liquid from nearby well K-7 whose liquid fraction concentration of Cl increased from 78.7 mg/kg to 5295 mg/kg from March 19 to March 29 1977 without a significant increase in its. This was interpreted as being from a deep inflow into the well which at most other times was blocked (Truesdell et al. 1989). The fluid from well K-26 was specifically reported on by Fridleifsson et al. (2006). There fluids turned out to be acid and the chloride concentration relatively high for Krafla fluids but gas concentrations were moderate. The same pattern has been followed in subsequent wells where fluids have shown acid character (e.g. K-27, K-29, K-33) (Ármannsson et al. 2013). Well K-36 drilled in 2007 turned out to be very powerful with a relatively low total gas concentration especially the CO_2 concentration whereas the H_2S concentration was relatively high and consequently the CO_2/H_2S ratio was low, but the well was soon damaged due to acid fluids and deposits.

Additional information has been obtained from well K-35, drilled in 2007 with acid fluids at depth close to Leirhnúkur, also from well K-38 which extends far to the north of Víti and contains acid fluids, and well K-39 drilled in 2008 which encountered magma at 2.5 km depth in the Sudurhlídar area i.e. a considerably shallower depth than previously envisaged. In Figure 2, adapted from Mortensen et al. (2009), the depth to inflow of magmatic gas is shown and thus an indication of the depth of acid aquifers (in m b.s.l.) in Krafla. This figure clearly illustrates that acid fluids may be expected anywhere in the Krafla system but at the most shallow levels in the Leirbotnar area. Well IDDP-01 drilled in the Leirbotnar Vítismóar area hit magma ar 2100 m depth and has produced dry steam which turns acid upon condensation at up to 450°C (Ármannsson et al. 2014)

Thus recent information suggests that magma may be encountered at a shallower depth than previously considered possible and that that acid fluids occur over the whole area at >2000 m depth.

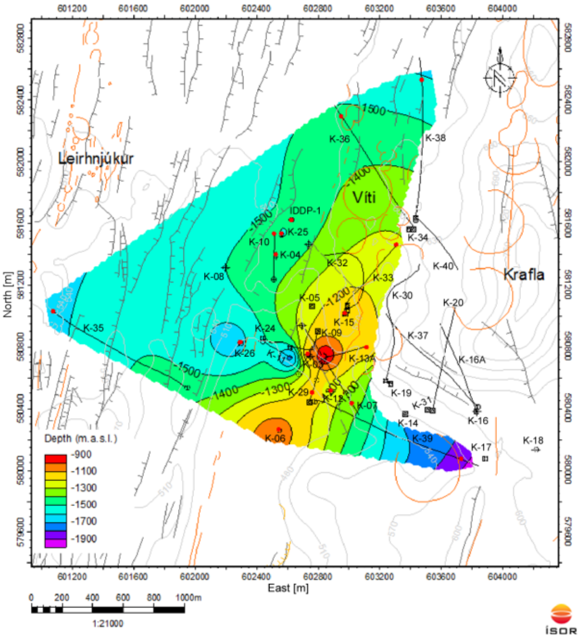

Figure 2. Map showing the inferred depth of volcanic gas inflow into the Krafla geothermal system (After Mortensen et al. 2009)

3. ORIGIN OF FLOW

Darling and Ármannsson (1989) suggested that flow in the Leirbotnar area originated locally but that in the Sudurhlídar and Hvíthólar areas from nearby high ground. Subsequent experience has led to the suggestion that the local high ground may not supply such a large flow and that deep flow from the south, i.e. the same stream that is predicted to feed the Námafjall system (Darling and Ármannsson 1989) is responsible (Hjartarson et al. 2004, Figure 3). At least a part of the geographically situated Vesturhlídar area seems to be fed by the same stream as Hvíthólar and Sudurhlídar whereas the northernmost well has a similar signature as the Leirbotnar wells. The Sandabotnar well is quite different and its isotopic composition suggests a deep inflow from

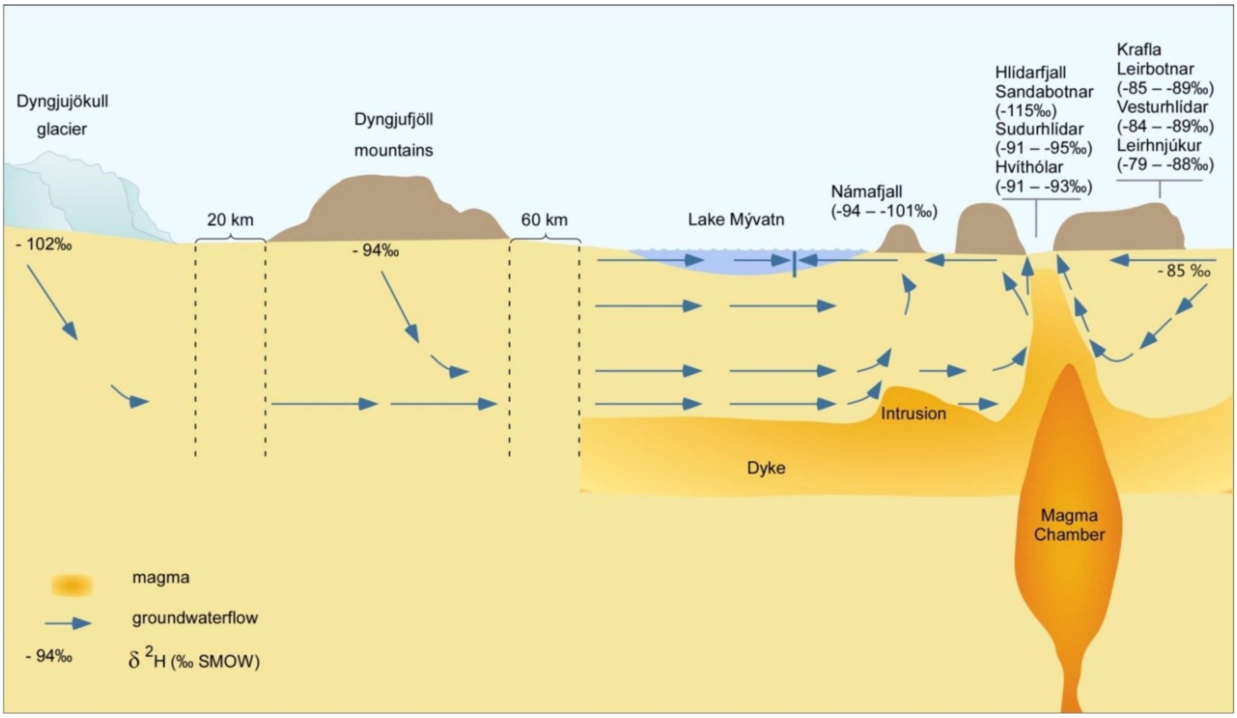

Figure 3. Proposed groundwater flow to the Námafjall and Krafla geothermal systems (After Hjartarson et al. 2004)

far south and possibly old. These three categories are listed in Table 1. It seems possible that the Hveragil fissure and related features (Figure 1) may act as a barrier between the local and southerly flows although some mixing is likely to occur

Table 3. Categories of hydrogen isotope signatures in different parts of the Krafla area

Location	δD ‰	Possible origin (Figure 3)
Leirbotnar	-80 - -90	Local
Sudurhlídar, Hvíthólar, Vesturhlídar	-90 - -100	Dyngjufjöll mountains
Sandabotnar	-115	Dyngjujökull glacier

4. VARIATIONS WITH LOCATION AND DEPTH

Ármannsson et al. (1987) divided the Krafla fluids into 7 groups according to different chemical characteristics related to geography and depth. The basic premises for the division were gas concentrations (CO_2 mg/kg, CO_2/H_2S) and chloride concentrations and ratios (Cl mg/kg, Na/Cl, F/Cl). Many wells were considered to draw mixtures from two or more groups. Gudmundsson and Arnórsson (2002) used sulphate and silica concentrations as a further criterion. Three additional geographical settings, Sandabotnar, Leirhnúkur and Vesturhlídar are considered in this paper, the chemistry criteria are δD, Cl, SO_4 as well as quartz and Na/K geothermometers and these are related to enthalpies and feed temperatures. As in earlier attempts many wells probably draw from different feeds but with the newer wells it seems that the depth factor is probably very important. Table 4 is based on recent results where available.

Generally sulphate is the dominant anion in the cooler and especially lower enthalpy wells. As suggested by Gudmundsson and Arnórsson (2002) this is probably due to the retrograde solubility of anhydrite and its saturation states in the fluids of many of the wells. Its dissolution is facilitated in lower enthalpy wells where the liquid fractions are relatively large. Chloride is mainly derived from atmospheric precipitation but may be added from magmatic sources which can be expected in the deepest hottest wells. Bicarbonate concentrations are relatively high in Sudurhlídar wells and it is the main anion in fluids from most of them.

There are some anomalies. Well K-26 which geographically would count as a Leirbotnar well has Cl > SO_4 but its lower part is probably drawing from the same flow as the Leirhnúkur well K-35. In wells K-40 and K-38 Cl $\geq$ SO_4 which is uncharacteristic of Suðurhlídar and Vesturhlídar wells. The isotope composition of the K-38 fluid furthermore suggests flow similar to that found in Leirbotnar and it might be drawing from the same flow. Well K-40 draws from relatively shallow feeds where some anhydrite dissolution might have taken place.

Table 4. Groups of Krafla fluids with respect to chemical characteristics, geographical location and thermal features

Area	Average enthalpy kJ/kg	Average feed temperature °C	T_{qz} °C	$T_{Na/K}$ °C	Cl vs SO_4 concentration	δD ‰
Hvíthólar Upper part	1580	260	270	240	Cl > SO_4	-90 - -100
Hvíthólar Lower part	1030	200	210	200	Cl $\geq$ SO_4	-90 - -100
Sandabotnar	1450	300	260	280	Cl > SO_4	-115
Sudurhlídar	2600	290	250	270	Cl > SO_4	-90 - -100
Leirbotnar Upper part	980	205	230	190	SO_4 > Cl	-80 - -90
Leirbotnar Lower part	1200	320	250	220	SO_4 > Cl	-80 - -90
Leirhnjúkur	2260	320	350	310	Cl > SO_4	-80 - -90
Vesturhlídar	2700	320	290	280	Cl > SO_4	-90 - -100

In seven of the eight groups the difference between the average feed temperature and the mean value for the two geothermometers is in the range -10 to +35 which in view of the range of feeds and the precision of the determinations can be regarded as reasonable. However in the case of Leirbotnar, lower part, the difference is +85°C which is quite significant. One characteristic of this group is low enthalpy and high temperature. There are also more wells with multiple feeds in this group than the others which may be a part of the explanation as they may play a more prominent part in the flow of the wells than anticipated.

5. VARIATIONS WITH TIME

Gudmundsson and Arnórsson (2002) have shown that there have been considerable changes in the fluid composition from the start of production of the power plant until the year 2000 and argued that the main cause was the cooling of the system citing lowering of silica and chloride concentrations and increases in sulphate concentrations. A large part of these changes took place during the early years of production while the area was suffering magmatic activity. Since the year 2000 several wells have been drilled and reinjecti on of fluids initiated. Significant changes in the above parameters have only been observed in one well, well K-32 which is a poor producer and not likely to affect the total production. Changes in Cl and SO_4 concentrations in this well and some of the recent wells in Vesturhlídar are shown in Figures 4 and 5. Well K-32 draws from several feeds some of which are shallow and relatively cool and have probably increased their share in the well's sparse flow.

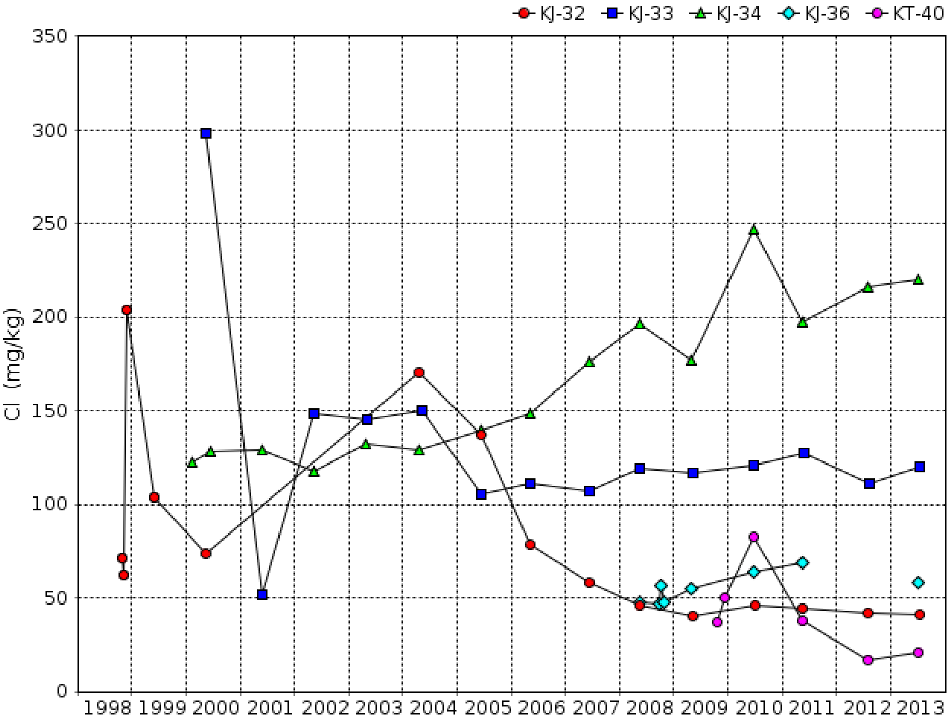

Figure 4. Chloride concentration changes in wells K-32, K-33, K-34, K-36 and K-40 1998-2013 (Hauksson 2014)

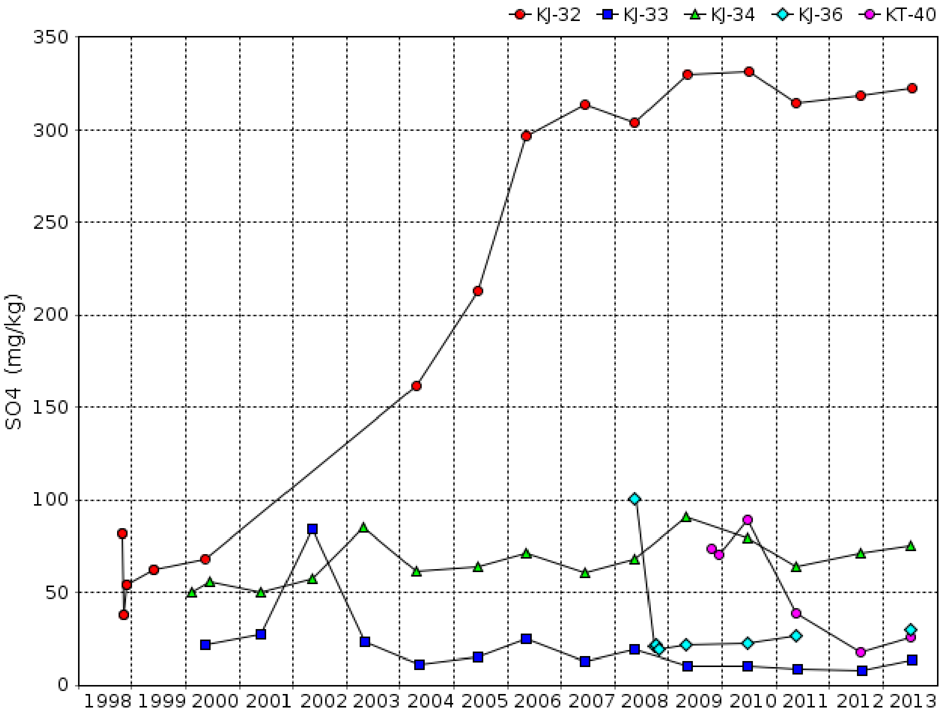

Figure 5. Sulplate concentration changes in wells K-32, K-33, K-34, K-36 and K-40 1998-2013 (Hauksson 2014)

Figure 6 shows an overview of the production from the area, amount of reinjected fluid and the average enthalpy of the producing wells from the start of production in 1977 to 2012 suggesting that enthalpy changes on the whole have been small although there has been variation within individual wells. This along with the small changes in water chemistry over the last few years suggests that the fluid has not been cooling down over the last 15 years at least.

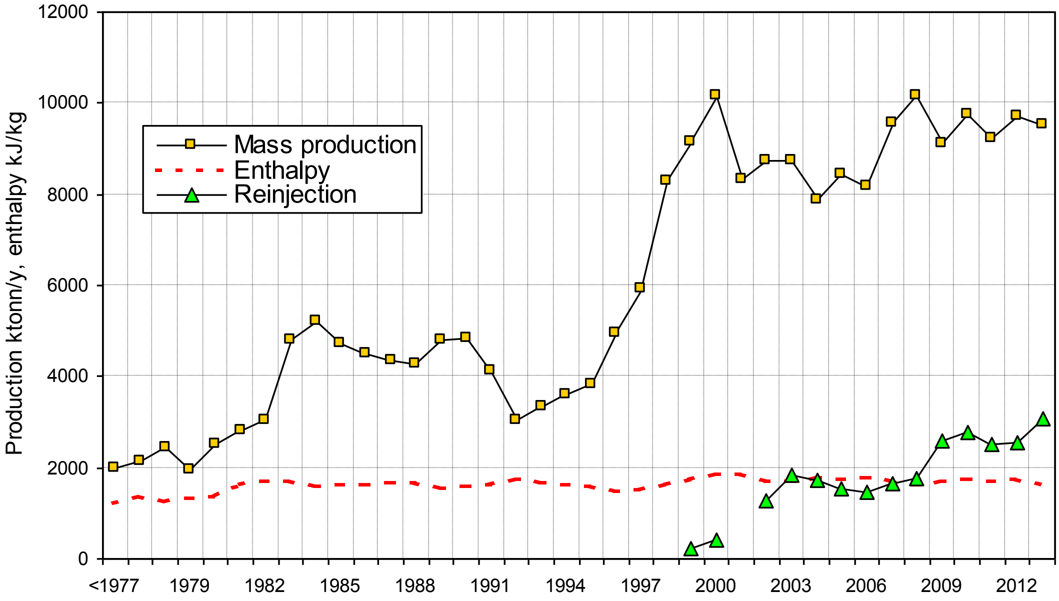

Figure 6. Krafla Power Plant. Mass production, Reinjection, Mean Enthalpy 1977-2013 (Hauksson 2014)

6. CONCLUSIONS

During the early stages of production from the Krafla field the fluids were contaminated by magmatic gas which epoecially affected the gas composition of the well fluids (Ármannsson et al. 2013). The liquid composition was also affected but to a lesser degree and since the early 1990s little change has been observed in most well fluids. Wells drilled later are mostly deeper than the earlier wells and shallow feeds generally cased off. Thus they tend to be hotter and have a higher enthalpy, and the tendency has been for the fluids to be acid and relatively chloride rich. This has caused some corrosion problems that call for measures such as wet scrubbing. The origin of the fluids is threefold. A NE-SW line through the Hveragil fissure (Figure 1) divides the fluids basically into two categories the NW lying wells issuing fluids of local origin but the SE lying wells issuing fluids of a probably more southerly origin, probably from Dyngjufjöll, and one well KS-01 in Sandabotnar fluids probably from as far south as Vatnajökull and probably quite old (Figure 3). There is likely to be considerable mixing of fluids from the first two groups. The fluids from individual wells have been divided into eight groups based on geography, depth, origin, feed temperatures and relative anion concentrations. Fluids from seven of the groups show geothermometer temperatures that are reasonably close to the estimated feed temperatures. Geothermometer temperatures for the eighth one are much lower than the estimated feed temperatures. This group contains fluids from the original production area which was most affected by the magmatic activiiy and alsom comprises several wells that draw fluids from mixtures of hot and cold feeds and the latter may be more pronounced than anticipated.

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