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The Groundwater in the Mývatn Area: Influence of Geothermal Utilization at Námfjall and Origin of the Warm Groundwater Component

Magnús Ólafsson, Thráinn Fridriksson, Thórólfur H. Hafstad, Sigrídur Sif Gylfadóttir, Finnbogi Óskarsson, and Halldór Ármannsson

ÍSOR, Iceland GeoSurvey, Orkugardur, Grensásvegur 9, IS-109, Reykjavík, Iceland

magnus.olafsson@isor.is

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ABSTRACT

The Námafjall high temperature field in North Iceland has one of the longest histories of geothermal fluid utilization in Iceland. The first wells were drilled in the early 1950s and in 1963 drilling started to provide steam for a diatomite plant and a 3 MW backpressure turbine. Later a central heating system for the Reykjahlíd village and nearby farms was constructed and in 2004 the Mývatn Nature Baths opened using hot geothermal water. The geothermal area is situated only a few km east of Lake Mývatn, which is a protected area by law since 2004. In order to study the possible influence of the geothermal water from separation stations and wells (effluent water), Landsvirkjun has undertaken an extensive monitoring programme. For the last ten years arsenic (As) and aluminium (Al) have been used as the main trace elements to monitor the possible influence. The results for arsenic show that its concentration in the groundwater east of Lake Mývatn is below Environmental limit I (<0.4 µg/L) and most often below the detection limit (<0.05 µg/L). Recent investigations based on chemical and isotopic composition of the groundwater indicate that the geothermal fraction of the warm groundwater east of Lake Mývatn may originate within the Krafla high temperature system, north of Námafjall, and not in the Námafjall system itself.

1. INTRODUCTION

The nature in the Lake Mývatn area is renowned, not least because of its biological diversity. The diversity is mainly due to the complex groundwater system in the area creating the unique living conditions in and around the lake. The groundwater is controlled mainly by the geology, and volcanic activities in the vicinity have at least three times influenced the system since the time of settlement. The high silica content of the warm groundwater contributes to a high diatomite production in Lake Mývatn and for about four decades a diatomite factory was operated in the area, but it closed in 2004. Lake Mývatn is a protected area by law since 2004 and listed as an important habitat for birds in the RAMSAR convention for wetlands (e.g. Ólafsson et al., 2013).

The Námafjall high temperature field in North Iceland has one of the longest histories of geothermal fluid utilization in Iceland. The first wells were drilled in the early 1950s for mining sulphur deposited from the geothermal steam. In 1963 drilling started to provide steam for a diatomite plant and a 3 MW backpressure turbine in Bjarnarflag. Later a central heating system for the Reykjahlíd village and nearby farms was constructed and in 2004 the Mývatn Nature Baths opened using hot geothermal water. The geothermal area is situated only few km east of Lake Mývatn, and therefore it is important to carefully monitor the effects of geothermal utilization on the Mývatn area (Gudmundsson et al., 2010).

Landsvirkjun, the National Power Company of Iceland, owns and operates the power stations and high temperature wells in Bjarnarflag and Krafla. In order to study the possible influence of the geothermal water from separation stations and wells (effluent water), Landsvirkjun has undertaken an extensive programme to monitor the chemistry of the groundwater, and also to study the origin of the thermal part of the groundwater flowing to Lake Mývatn. At present, the effluent water from Bjarnarflag is disposed of on the surface and mixes with local groundwater. The nearby Krafla power station also disposes part of its effluent water on the surface although the greater part of the effluent is reinjected into the geothermal system.

The article gives an overview of the chemical monitoring of the groundwater system which has been carried out in the Lake Mývatn area with emphasis on the origin of the warm groundwater.

2. THE GROUNDWATER SYSTEM EAST OF LAKE MÝVATN

The majority of the groundwater entering Lake Mývatn is a part of a very large groundwater system within the northeastern volcanic zone, extending from Dyngjufjöll and Vatnajökull in the south to Öxarfjördur and the Atlantic Ocean in the north. The size of the catchment area is approximately 1500 km^2. As the groundwater stream approaches the Námafjall high temperature area, part of it is heated by mixing with geothermal water from the Námafjall and Krafla geothermal systems. Model calculations show that the warm groundwater entering Ytriflói, the northern part of Lake Mývatn, amounts to approximately 11 m^3/s, whereas the cold groundwater entering Sydriflói is approximately 17 m^3/s as shown in Figure 1. This diversity in groundwater flowing to Lake Mývatn creates special living conditions for flora and fauna in the lake. The outflow from Lake Mývatns takes place in the Laxá river, one of the most famous salmon and trout fishing rivers in Iceland.

During the 1975-1984 volcanic episode (the Krafla Fires), major changes occurred within the groundwater system. In places the temperature increased by up to twenty degrees with corresponding changes to the chemistry of the groundwater.

In 1983 temperature measurements of the groundwater east of Lake Mývatn were made and a map with isothermal lines was drawn (de Zeeuw and Gislason, 1988). Recently the map was redrawn and compared with similar measurements made in 2000 (Ólafsson et al., 2013). The results are shown in Figure 2. Comparison between the two maps shows that the temperature of the groundwater has decreased and the isothermal lines have all shifted to the east in accordance with cooling of the groundwater.

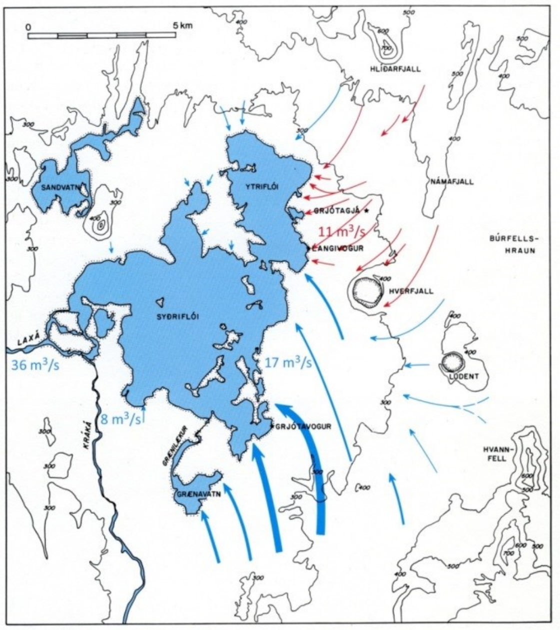

Figure 1. The main outlines of the groundwater flow to Lake Mývatn. The cold groundwater is shown with blue arrows and the warm groundwater with red arrows (Ólafsson, 1991; Thóroddsson and Sigbjarnarson, 1983; Vatnaskil, 2008).

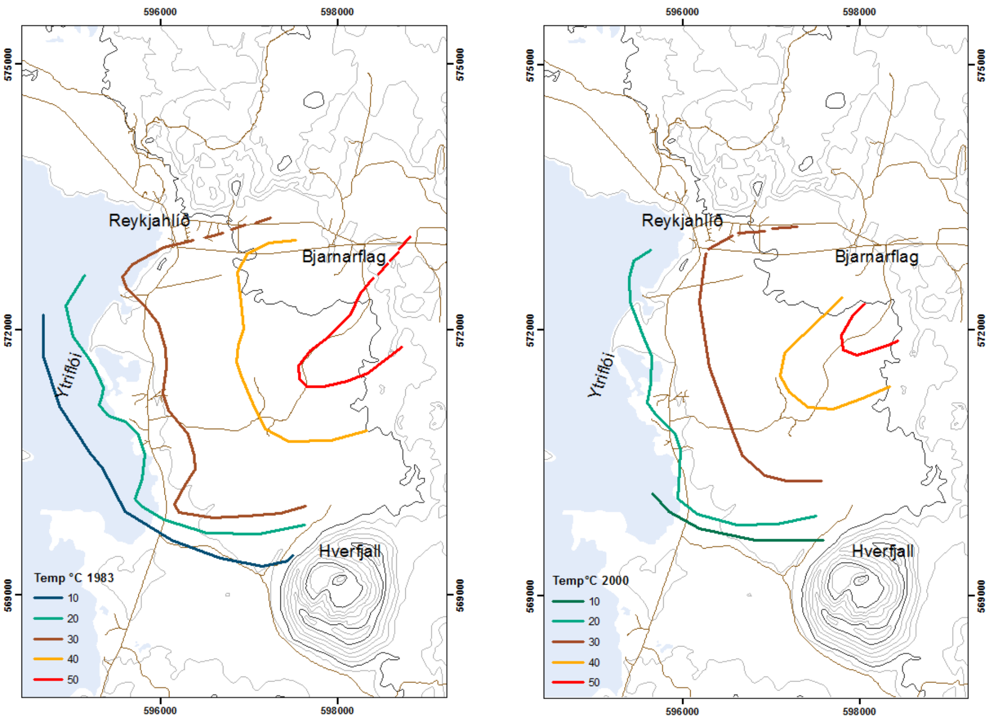

Figure 2. Temperature changes in the groundwater east of Lake Mývatn from 1983 to 2000.

As an example of the temperature and chemical changes in the groundwater due to the volcanic activity during the Krafla Fires, temperature and silica measurements in the Grjótagjá natural bathing place are shown in Figure 3. The temperature increased from about 40°C to about 60°C, which made the water unsuitable for bathing. The silica content increased from about 120 mg/l to over 180 mg/L. As shown in the figure, the temperature is gradually, but slowly, approaching the state of the groundwater prior to the Krafla Fires. The change in the silica content is much slower and is not expected to reach similar values as before the Krafla Fires for a long while yet.

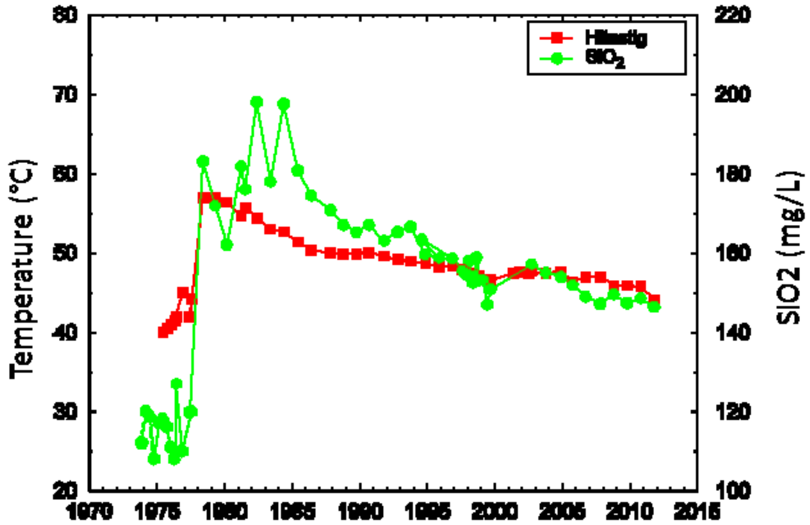

Figure 3. Measured temperature and silica content in the warm groundwater in the Grjótagjá nature bath.

3. MONITORING THE CHEMISTRY OF THE GROUNDWATER

Effluent water from the power plant at Bjarnarflag and from discharging wells has been disposed of in open cracks on the surface where it is mixed into the groundwater. The amount of the effluent water has not been measured regularly, but on the basis of mass production from the geothermal field and the enthalpy of the fluid, the total amount of effluent water has been estimated and the results are shown in Figure 4 for the time period 1977 to 2012 (Hauksson, 2013). The figure shows that the amount of effluent water (blue bars) has been variable with an average of about 830 kilotonnes per year. The amount of waste water depends on the enthalpy of the fluid from the wells. The first wells in Bjarnarflag were relatively shallow with low enthalpy whereas the newer and deeper wells are hotter with much higher enthalpy. As a result, less amount of waste water will be produced for each generated MW of electricity in the planned power station in Bjarnarflag compared to the old 3 MW generator which has been running since 1969. Moreover the steam efficiency will be much better in the new plant compared to the old plant.

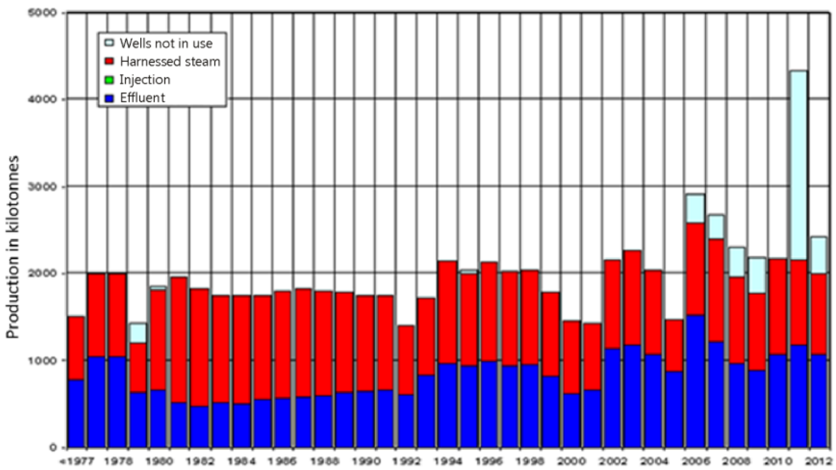

Figure 4. The total production from the geothermal system in kilotonnes. Blue bars show the amount of effluent water, red bars show the harnessed steam and light blue bars discharge from off-line wells (from Hauksson, 2013).

Regular chemical monitoring of the groundwater in the Mývatn area began in 2003 (Ármannsson and Ólafsson, 2004) approved by the Icelandic Environment Agency. Once a year, in the autumn, samples for analysis of all main and selected trace components are collected from ten locations and in the spring, samples for determination of trace elements are collected from the same locations. The main emphasis has been placed on monitoring the concentration of arsenic (As) and aluminum (Al) as these elements are in relatively high concentrations in the effluent water from the power stations in Bjarnarflag and Krafla but in very low concentrations (often below the detection limits) in the cold and warm springs in the area. The results show that the arsenic concentration of the groundwater east of Lake Mývatn is in all cases below Environmental limit I according to the Icelandic (and EU) regulation on groundwater protection (<0.4 µg/L), postulating that the concentrations will have little or no effect on aquatic organisms (Ármannsson, 2005; Ólafsson et al., 2013). In most cases, the arsenic content has been below the ICP-MS detection limit (<0.05 µg/L). The only sample locations where arsenic concentrations exceed the maximum permitted value for drinking water (0,01 mg/L) is the effluent water sampled directly from the outflow from the separation stations and in the stream Hlídardalslækur. The results of arsenic measurements from all ten monitoring location are shown in Figures 5, 6 and 7.

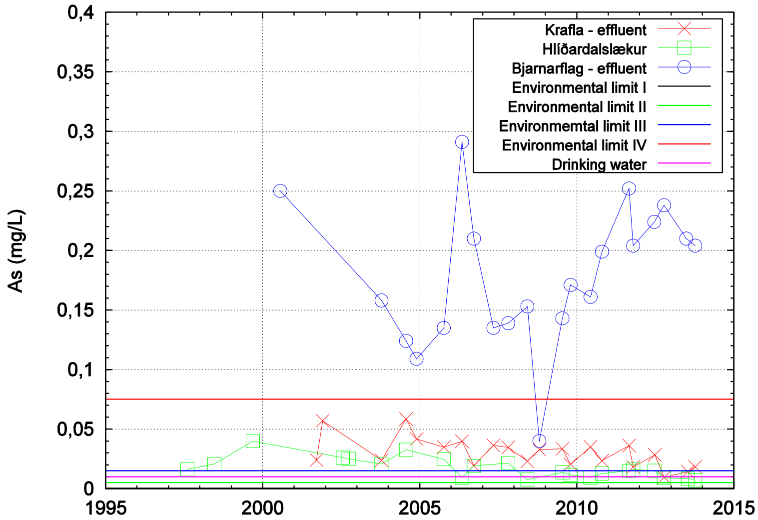

Figure 5. The concentration of arsenic in effluent water from the power stations at Bjarnarflag and Krafla and the Hlidardalslækur stream. Environmental limits I, II, III and IV are also shown.

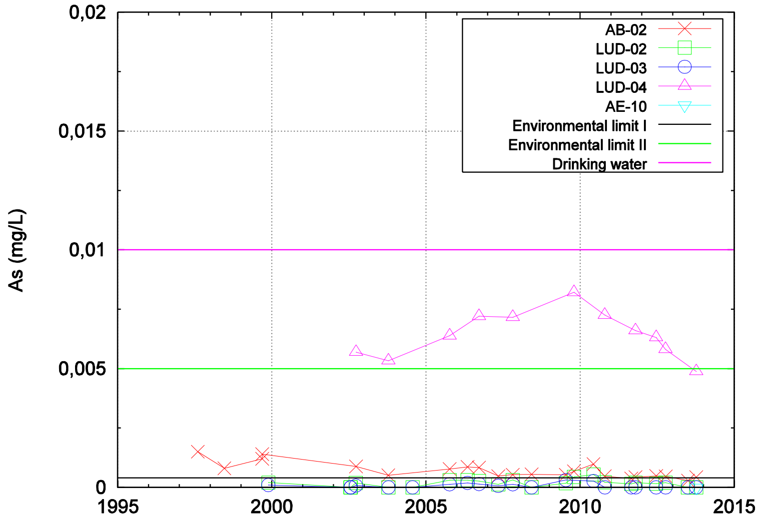

Figure 6. The concentration of arsenic from groundwater monitoring wells east of Lake Mývatn. Environmental limits I and II are shown as well as the limit for drinking water. Open symbols represent samples where As is below the detection limit (0.00005 mg/L).

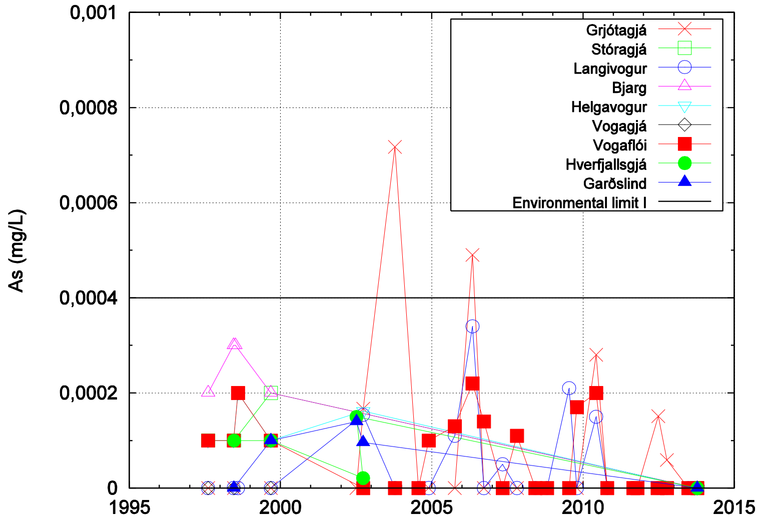

Figure 7. The concentration of arsenic in springs at the edge of Lake Mývatn. Environmental limit I is also shown.

No long-term trends toward increasing concentration of arsenic have been observed since regular monitoring of the chemical content of groundwater east of Lake Mývatn commenced in 2003. The monitoring history therefore indicates that there is no reason to expect effects caused by effluent water from the proposed Bjarnarflag power plant, especially as the current plans state that the effluent water will be reinjected into the reservoir. Several tracer tests have been performed in the area to study the flow and the dilution of effluent water from the two power stations (Ármannsson, 2005). The results suggest that the dilution is great and one such test showed that the effluent water from the Bjarnarflag power station was diluted about 100 million times by the time it reaches the Grjótagjá fissure, some 2 km away.

4. THE ORIGIN OF THE WARM GROUNDWATER

The chemistry of the groundwater east of Lake Mývatn has been extensively studied and monitored for a number of years (e.g. Kristmannsdóttir and Ármannsson, 2004). In a recent report emphasis was put on analyzing the possible origin of the geothermal component of the warm groundwater in the Mývatn area (Ólafsson et al., 2013). Three possibilities were investigated: Steam heated groundwater with steam from the Námafjall high temperature area; mixing of cold groundwater with geothermal water from Námafjall; and mixing of cold groundwater with water from the Krafla high temperature north of Námafjall. Finally it may be possible that the interaction of two, or all, of these possibilities can best explain the origin of the warm groundwater. By using the available extensive chemical database for the groundwater the possibilities mentioned above were investigated.

The main gas components of geothermal steam are CO_2 and H_2S whereas Cl is considered a conservative dissolved species in geothermal water, in the sense that Cl does not form secondary minerals. If the warm groundwater in the Mývatn area is produced by steam-heating of cold groundwater, one would expect that as the CO_2-rich but Cl-poor steam mixes with the cold water, the concentration of CO_2 in the resulting warm water should increase with increasing temperature, whereas the concentration of Cl should maintain stable or even decrease. On the other hand if the warm groundwater has its origin as a mixture of cold water and geothermal run-off or affluent water, which has higher concentrations of both CO_2 and Cl, both components should increase as the mixed-water temperature increases.

Figure 8 shows the relationships between CO_2 and temperature on one hand and Cl and temperature on the other. The data represent analyses of groundwater samples from about 30 locations in the Lake Mývatn area. The data is used to define possible mixing lines between the cold groundwater and a hypothetical geothermal fluid at 250°C. A very clear correlation is evident between Cl and temperature, indicating that the warm groundwater originates from mixing of cold groundwater and geothermal water. The correlation between CO_2 and temperature may also indicate mixing due to the higher concentration of CO_2 in geothermal fluid than in groundwater, but it cannot be excluded that some of the increased CO_2 content stems from mixing of groundwater and steam. Therefore, it is evident from the data that the heat in the warm groundwater comes mainly from mixing with geothermal water and at most partly from steam.

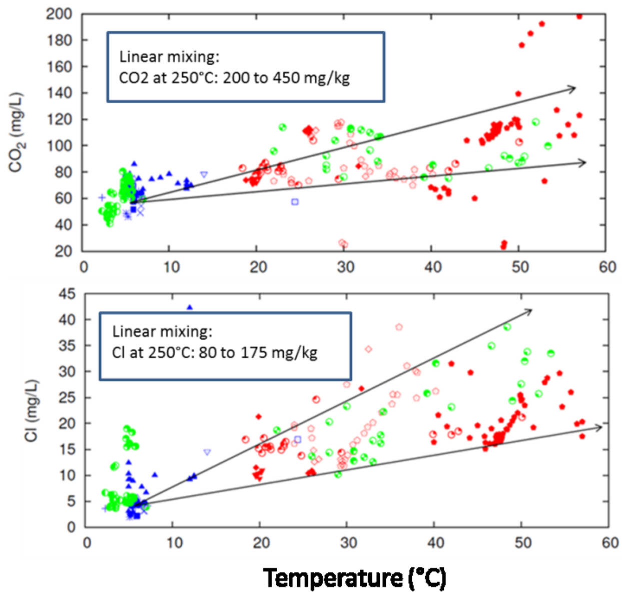

Figure 8. The concentration of CO_2 and Cl in the groundwater plotted against temperature. Concentration ranges for Cl and CO_2 in a hypothetical geothermal parent liquid at 250°C are given in the boxes.

Based on the interpretation presented above it seems evident that the warm groundwater in the Mývatn area is mainly formed by mixing of cold ground water and geothermal water and from that information one can use the chemical and isotope data to calculate the chemical composition and possible origin of the geothermal water, by further mixing calculations. In the calculations it is assumed that the heat capacity of the water is independent of temperature, which is strictly speaking not correct. For each data set two mixing lines are defined representing the highest and lowest values of the geothermal fluid. Isotopic and chemical composition of the "parent" geothermal fluid is therefore expressed as a range rather than a single value. In cases where the chemical composition or isotopic ratios of the cold groundwater are scattered it is assumed that the values for Gardslind represent the "unpolluted" cold groundwater in the area. Gardslind is one of the largest coldwater springs in the area and flows into the southeast corner of Lake Mývatn, far away from any thermal influence.

This method is not suitable for all components. Those that are in a large quantity in the host rock are not useful to specify mixing processes, especially if their concentration is governed by the temperature. The same applies for the volatile species that are easily lost from the liquid. The calculations presented here are primarily based on the concentrations of Cl and B and the deuterium ratio (δD). Both hydrogen and chloride are in very low concentrations in the rocks and chemical reactions between the rocks and the water have limited effect on the concentration of Cl and the deuterium ratio in warm water. It is also helpful that the Cl concentration is significantly higher in fluids from the Krafla high temperature area (65-75 mg/L in recent years) compared to Námafjall (about 50 mg/L) and that the deuterium content in the geothermal fluid in Námafjall is considerably lower than in the Krafla area (-94 to -101‰ as opposed to -79 to -89‰).

The upper part of Figure 9 shows the deuterium values (δD) for groundwater in the Mývatn area. This data does not show as clear signals of mixing as the concentration of Cl and CO_2 presented in Figure 8. However one can see that cold spring data at Lake Mývatn (blue symbols) are generally lower than the deuterium ratio of the warm springs (red symbols).

Boron (B) is a suitable element to trace the source of water in the same way as Cl as it is not in high concentrations in the rock and its concentration is not controlled by reactions with secondary minerals of the rock. Figure 9 shows the Cl/B mass ratio in groundwater also plotted against temperature. It shows that at low temperatures there is some scatter in the ratio but with increasing temperature it appears that the ratio approaches the value 50. The Cl/B ratios in the Krafla and Námafjall fields vary somewhat between wells, but the average value for Krafla is about 54 whereas the average ratio in Námafjall is about 30, which is lower than what is found in most groundwater samples from the Mývatn area. Therefore, the warm groundwater appears to be more related to the Krafla geothermal fluids than those of Námafjall.

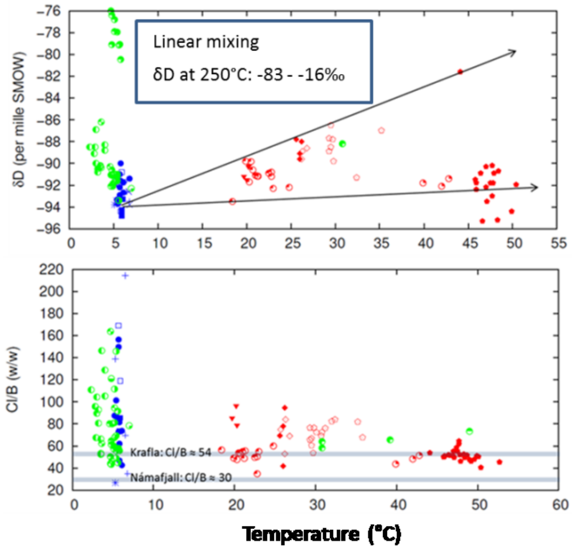

Figure 9. The deuterium ratio and the Cl/B ratio in the groundwater. Mixing lines for deuterium are shown as well as the mass ratios of Cl/B for Námafjall (30) and Krafla (54).

At first glance, these results indicate that the geothermal water that has mixed with the cold groundwater in the Mývatn area to form the warm groundwater in the area is derived from the Krafla area rather than from Námafjall. Mixing lines for deuterium and chloride suggest that the Cl concentration in the deep water which mixes with the groundwater in the Mývatn area is 60-175 mg/L and the deuterium ratio is about -85 to -16 ‰SMOW. The concentration of Cl in the deep water is slightly higher than the average concentration in the Námafjall area and closer to that seen in the western part of the Krafla area. In addition the deuterium ratio observed for the deep component according to the mixing lines is closer to that seen in the western part of the Krafla area.

5. PRODUCTION FROM THE GEOTHERMAL FIELD

Production from the Námafjall system began from well B-1 in 1963 (e.g. Gudmundsson et al., 2010; Ólafsson and Ármannsson, 2013). In 1967 power production started in a 3 MWe power station and during the first decade of operation the mass production from the geothermal system increased steadily to about 200 kg/s. During the Krafla Fires in 1977 to 1984 some wells were destroyed and the production rate fell to about 50 kg/s. After the Krafla Fires new wells were drilled to produce steam for the power plant as well as for a district heating system and the Mývatn Nature Baths and the annual mass production increased irregularly to about 90 kg/s (Figure 10). Pressure monitoring of the geothermal system has demonstrated that no decrease in pressure has been observed, at least down to 600 m, as showed in Figure 11 (Egilson, 2013) where the measured pressure in monitoring well B-5 is shown at 300 and 600 m depth with waterlevel and compared to original pressure in the system. The mass flow of steam and water for the proposed 45 MW geothermal power station in Bjarnarflag is estimated to be approximately 180 kg/s, similar to the mass flow from the system in the years 1970 to 1978 (Ólafsson et al., 2013).

6. CONCLUSIONS

On the basis of the studies conducted in the Lake Mývatn area during several decades one can envision the groundwater flow and its interaction with the high temperature areas of Námafjall and Krafla as demonstrated in a simplified model in Figure 12. The interaction between the geothermal fluids from the producing and non-producing geothermal fields and one of the largest groundwater systems in Iceland is considerable and complex. However, no measurable impact has been detected due to utilization of the geothermal fields in Bjarnarflag and Krafla whereas research show that natural changes, in particular due to volcanic eruptions, have had a significant impact on the temperature and chemistry of groundwater in the area.

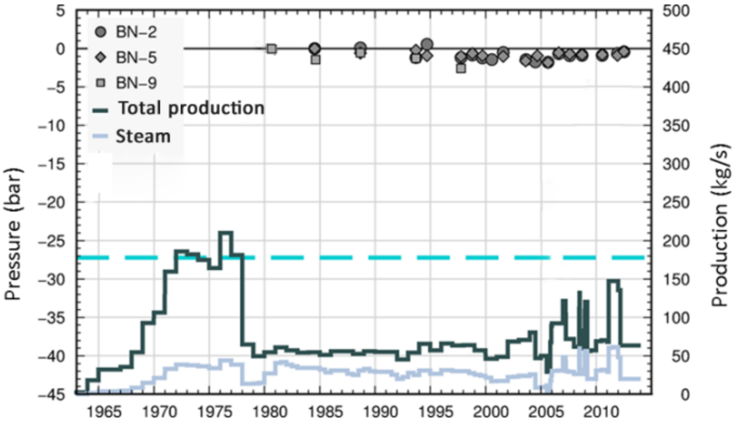

Figure 10. Annual mass production from the Námafjall geothermal system, 1963 to 2013, and pressure drawdown in monitoring wells. Also shown is the proposed mass production for a 45 MWe power station.

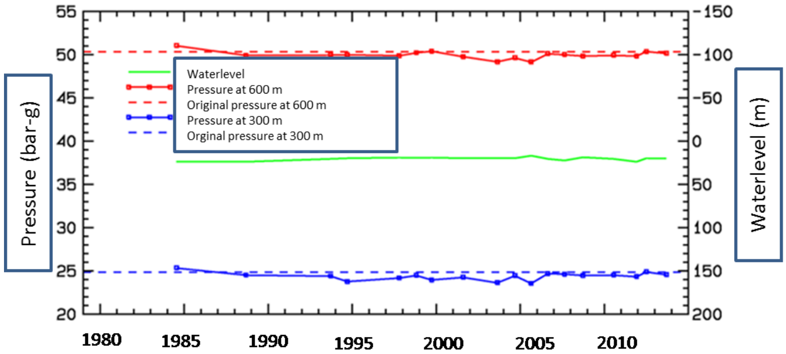

Figure 11. Measured pressure and water level at 300 and 600 m depth in monitoring well B-5 from 1980 to 2013, compared to the original pressure in the system (from Egilson et al., 2013).

Investigations based on the chemistry and the isotopic composition of the cold and warm groundwater, indicate that the warm groundwater is only partly derived by steam heating of groundwater but mainly derived by mixing of cold groundwater with geothermal water from the Krafla geothermal system.

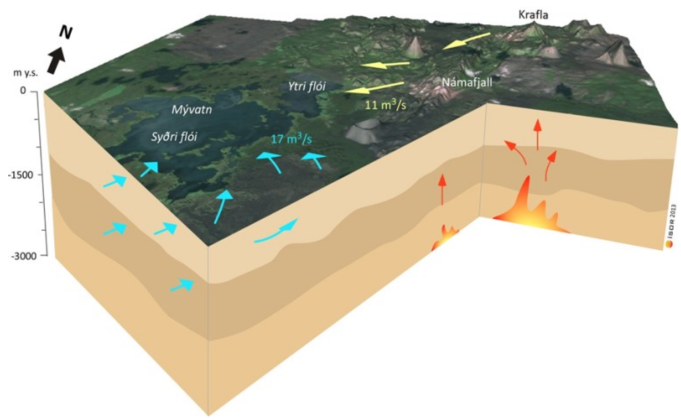

Figure 12. A simplified model of the interaction of the cold groundwater with the high temperature area of Námafjall and Krafla.

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