

## Chemical Variety of Water in Icelandic Heating Systems

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### ABSTRACT

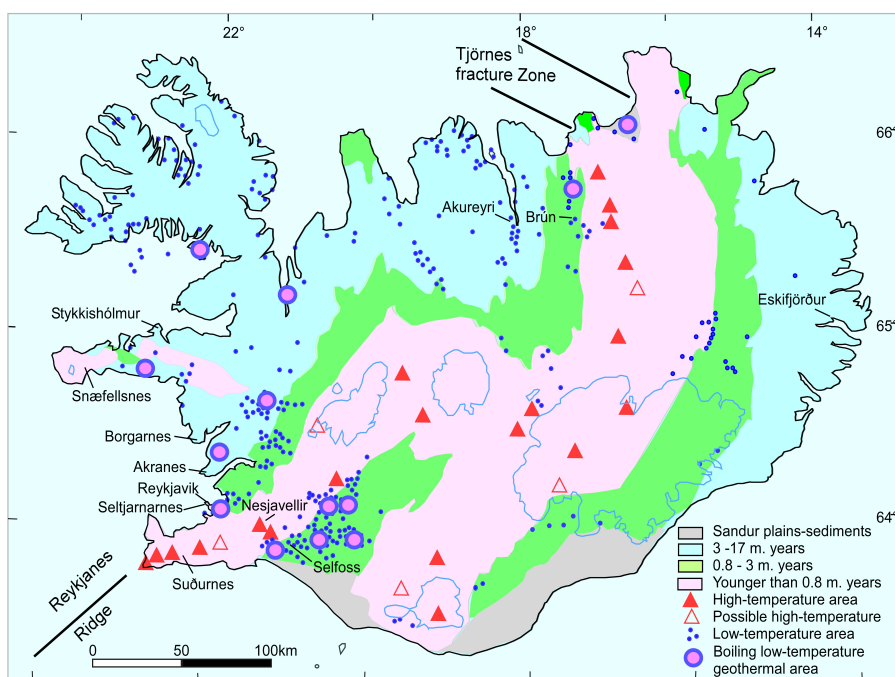
Icelandic heating systems are traditionally of very simple design; water is pumped up from the wells, distributed to the users who use the water directly for heating and as tap water without using heat exchangers. The spent water is mostly disposed of into the sewer or possibly first used for melting snow in the driveway or for the domestic hot pool. This is based on the reality that commonly the geothermal water is slightly mineralized, typically with TDS 200-400 mg/l and with a low corrosion and scaling potential. The pH is typically 9-10, devoid of oxygen and contains enough hydrogen sulfide to act as an inbuilt corrosion inhibitor by reaction with oxygen taken up from the environment. The waters are in equilibrium with silica and silica concentration rises in direct relation with temperature, but in the low and medium enthalpy systems silica scaling does not pose any problems. The waters are in equilibrium with calcium carbonate at reservoir temperatures and are highly depleted in magnesium, even at moderate temperatures. The permeability of the fields is normally high and there is ample recharge to the systems. The waters utilized in the first big heating systems in the country were typically of such a character. However there are also found geothermal waters with relatively high salinity, waters with some concentration

of oxygen, waters devoid of hydrogen sulfide and even carbonated water. Waters with extreme high pH, 10-11, are also encountered. By time and increased utilization of geothermal resources for heating there have been utilized geothermal waters with a very varied geochemical properties in the Icelandic heating systems.

### 1. INTRODUCTION

Recently a comprehensive study of the geochemistry of Icelandic groundwaters with the emphases on trace elements has been conducted (Kristmannsdóttir et al., 2005a). Within the study the chemical characteristics of waters from most heating systems in the country have been analysed and characterized and correlated to geological, geographical and meteorological conditions.

Figure 1 shows a geothermal map of Iceland with the main geological formation displayed as well as the location of the Reykjanes Ridge which is the onshore extension of the Mid Atlantic Ridge. The Tjörnes fracture zone which is a transverse zone on the Mid Atlantic Ridge where it is jumped westward towards the Kolbeinsey ridge. The geothermal fields are split into three different types of systems: high-temperature, low-temperature and boiling low-temperature fields. The classification into high-temperature or low-temperature waters depends on the reservoir temperature at 1000 m depth.



**Figure 1: A simplified geological map of Iceland showing the location of geothermal fields in Iceland The figure is based on data from Saemundsson, (1979) and Björnsson et al., (1990).**

In high-temperature geothermal fields it exceeds 200 °C, but is below 150 °C in the low-temperature fields. Due to geologic and meteorological conditions in Iceland being considerable different from most neighboring countries the properties of potable water, cold and warm, differ significantly from the water in those countries. The main differences are the high pH and alkaline nature of the waters, slight mineralization and very little environmental contamination (Kristmannsdóttir, 2004).

In most cases the geothermal water, both the boiling water and water at temperatures below boiling, can be used directly for heating in district heating systems and also as tap water. A few systems have too highly mineralized water for direct use. Water from high-temperature geothermal fields cannot be utilized directly for heating, but there cold fresh water is heated by the use of heat exchangers.

## 2. GROUNDWATER IN ICELAND

Groundwater in Iceland, both cold water and geothermal water is mostly of meteoric origin and in just a few places originated from sea-water or affected by sea-water inflow.

The dominant reservoir rocks are basaltic lavas and hyaloclastites (Figure 1) and the fluids evolved by reaction with such rocks have high pH values. Acidic igneous rocks are encountered within central volcanoes, past and present, but account only to about 10 % of the total volume of rock formations in Iceland (Saemundsson, 1979).

Iceland has a record high rate of precipitation and is geologically very young so the permeability in upper parts of the crust is generally high and a relatively rapid through flow of the shallow cold groundwater (Jónsdóttir, 2006, Björnsson et al., 1990, Sigurðsson and Einarsson, 1988).

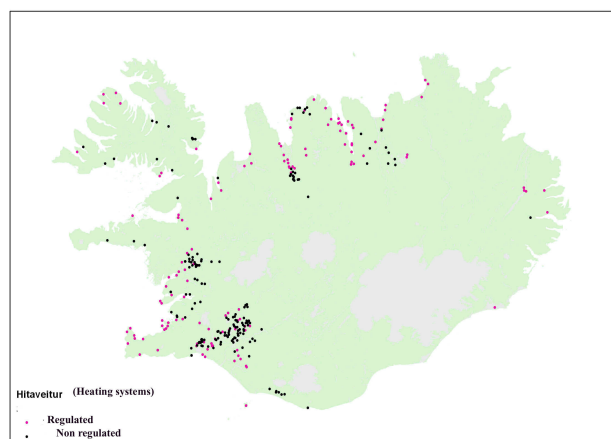
Due to rapid through flow of the cold groundwater it is slightly mineralized with TDS (total dissolved solids) generally 30-100 mg/l. The waters are generally of sodium bicarbonate type with pH 8-9. As geothermal water in Iceland is in most cases of meteoric origin the low-temperature geothermal waters are generally very slightly mineralized, typically containing 200-400 mg/L, of dissolved solids and gases. The mineralization increases by increased reservoir temperature of the geothermal fields. In the non saline high-temperature geothermal waters the total concentration of dissolved solids will exceed 1000 mg/l. There do exist a few sea-water contaminated geothermal fields with subsequently higher concentration of dissolved solids. The salinity of those waters is mostly less than 10 % of sea-water, but on the Reykjanes peninsula in Southwest Iceland and in Óxarfjörður in Northeast Iceland there are found waters with much higher salinity, even up to that of sea-water (Kristmannsdóttir and Ólafsson, 1987). The pH is typically 9-10 for the non saline low-temperature waters. The silica concentration of the waters rises in direct relation with temperature. The waters are in equilibrium with calcium carbonate and the concentration declines by increasing temperature. They are devoid of oxygen, most contain hydrogen sulfide and are highly depleted in magnesium, even at moderate temperatures. The waters are in equilibrium with silica minerals, several alkali-, iron- and aluminium silicates and metal sulfides and oxides (Arnórsson et al., 1982, 1983).

Waters reacting with acidic rocks will contain somewhat more chloride than those reacting with basaltic rocks. Such waters will also have higher concentrations of fluoride, boron, lithium and radioactive elements. Other elements as iron, manganese, copper, cobalt and zinc will be more

enriched in the basalts and therefore also in the waters reacting with such rocks. The mineral concentrations of the waters will also be highly dependent on the age and weathering and alteration state of the rocks. The recent, glassy basalts will be the more reactive than older and more altered basalts and would be expected to contain the highest concentrations of heavy metals and other trace elements. The main variation in the low temperature waters, besides differences in salinity, is encountered in the fluoride concentration, which is normally 0,5- 1,5 mg/L, but may locally be much higher (5-15 mg/L). Waters with extreme high pH, 10-11, are also encountered, especially on the borders of the active volcanic zones in South West and North East Iceland (Kristmannsdóttir, 2004).

## 3. ICELANDIC GEOTHERMAL HEATING SYSTEMS

About 86% of all houses in Iceland are heated geothermally (Ragnarsson, 2005). In most of the larger towns there are geothermal heating systems and in the rural areas there are many small systems as well (Figure 2). Due to the unique chemical properties and the ample water resources in the fields where the first big heating systems in Iceland were constructed they were designed as simple through flow systems where the water is used by directly piping into the



**Figure 2: Location of district heating systems (Hitaveitur) in Iceland (From Árni Ragnarsson, pers. comm.). The regulated ones are the official and bigger systems and the others are small and mostly privately run.**

radiators and as tap water and then discarded into the sewage systems (Gunnlaugsson et al, 2000, Pálmason, 2005, Thordarson, 1998). This was based on the reality that commonly the geothermal water is slightly mineralized, typically with TDS 200-400 mg/l and with a low corrosion and scaling potential. The concentration of silica is too low to pose any danger of scaling and as the waters are in equilibrium with calcium carbonate it will not be precipitated by proper design of the heating systems (Kristmannsdóttir et al., 2004). Later on outbuilding was conducted in places where the chemical composition was not as favourable and the resources not so ample (Pálmason, 2005, Flóvenz, et al. 1995, Kristmannsdóttir et al, 2000, 2001). In some incidences the design was still of the same simple type, demanding mitigation measures and other energy sources than geothermal energy. The use of high-temperature fields did call for an entirely different design as the waters are not fit for direct utilization. The early attempts to use them directly was a complete failure (Thórhallsson et al., 1975) and later on there has been used heated fresh water and heat-

exchangers in those systems. In most cases the design has been based on a single use of the heated water. In later years there have been built systems of different types also in the low temperature fields (e.g. Hjartarson et al., 2003, SALINEGEOHEAT, 2001, Gunnlaugsson pers. comm.).

The heated fresh water differ from the geothermal waters mainly by lower mineralization, but certain species like magnesium are in much higher concentrations which may inflict precipitation of magnesium silicates. To prevent oxygen corrosion condensed steam is commonly added to the heated waters (Kristmannsdóttir, 1990).

#### 4. CHEMISTRY OF WATERS IN THE SYSTEMS

As described in the introduction the chemical characteristics of waters from most heating systems in the country are included in the present study, both the ones using

geothermal water directly for distribution, and the ones using heated cold water, either by direct distribution and closed loop distribution.

##### 4.1. Classification of the Waters

In Figure 3 the waters are classified by a Schoeller classification diagram frequently used for the classification of groundwater. The graph shows a wide variety of water types, the most common being sodium-chloride and sodium-sulfate waters. Sodium-bicarbonate and carbonate waters are also common. Extremely alkaline waters of NaOH type are also encountered and waters classified as calcium-chloride and calcium-sulfate types are also encountered. In Figure 5 is shown classification for the waters in the Icelandic heating systems according to the Piper diagram showing a similar result as the Schoeller diagram.

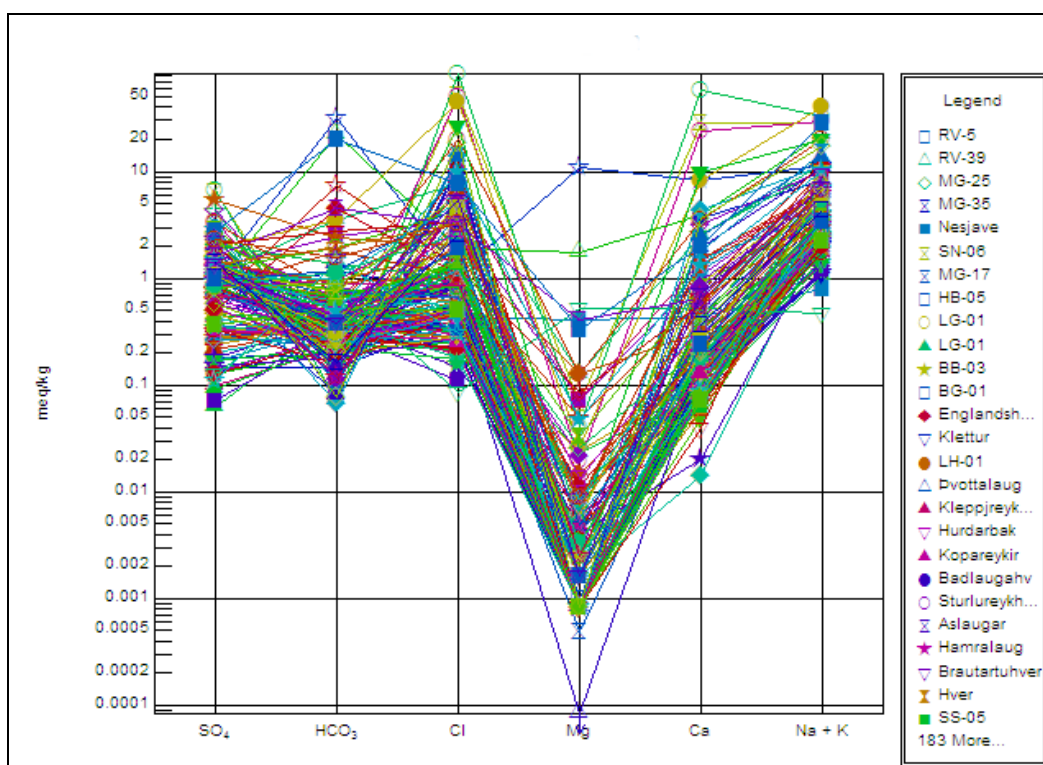


Figure 3: A Schoeller diagram of the hot water from Icelandic heating systems.

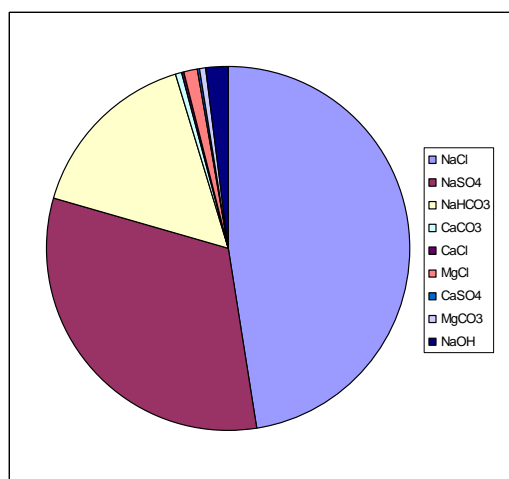
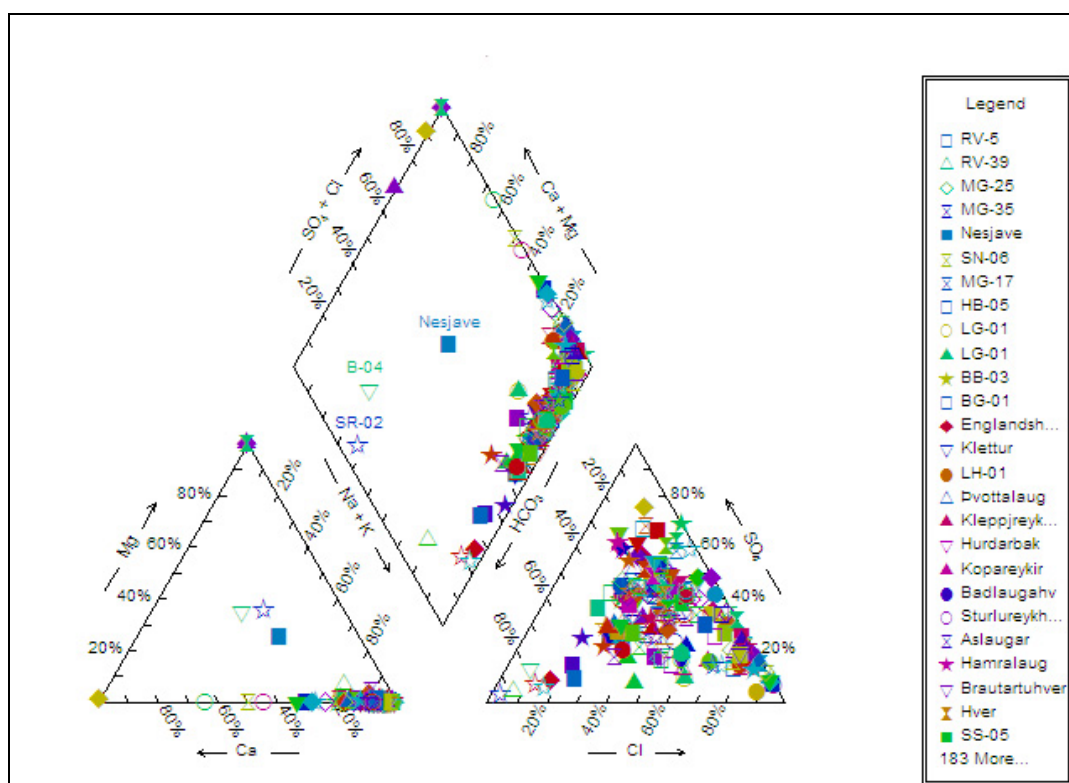


Figure 4. Relative importance of different water types in the Icelandic heating systems.

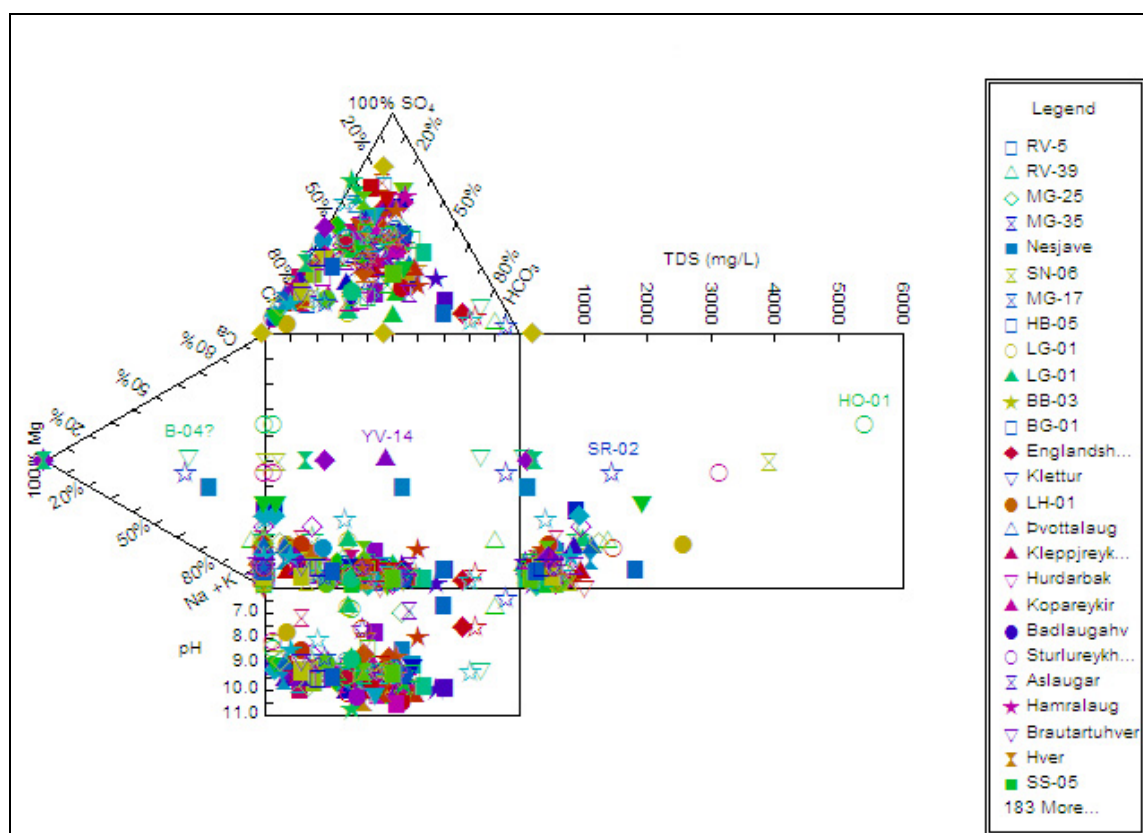




**Figure 5: A Piper diagram of the hot water from Icelandic heating systems.**

The dominance of alkali ions over calcium and very low magnesium is still more clearly displayed in this diagram. In the Durov classification diagram (Figure 6) the great

variation in pH as well as the dominance of waters with pH 9-10 is clearly shown.



**Figure 6: A Durov diagram of the hot water from Icelandic heating systems.**

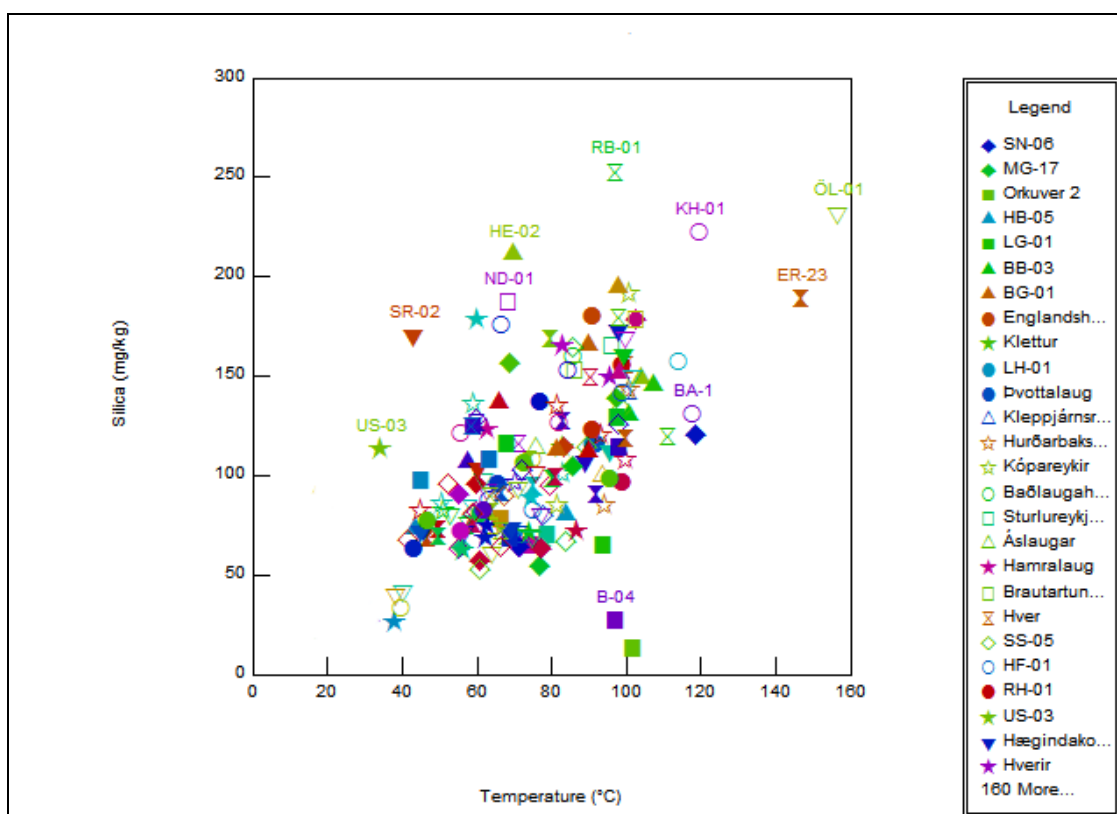


Figure 7: Silica concentration against temperature of water in the Icelandic heating systems.

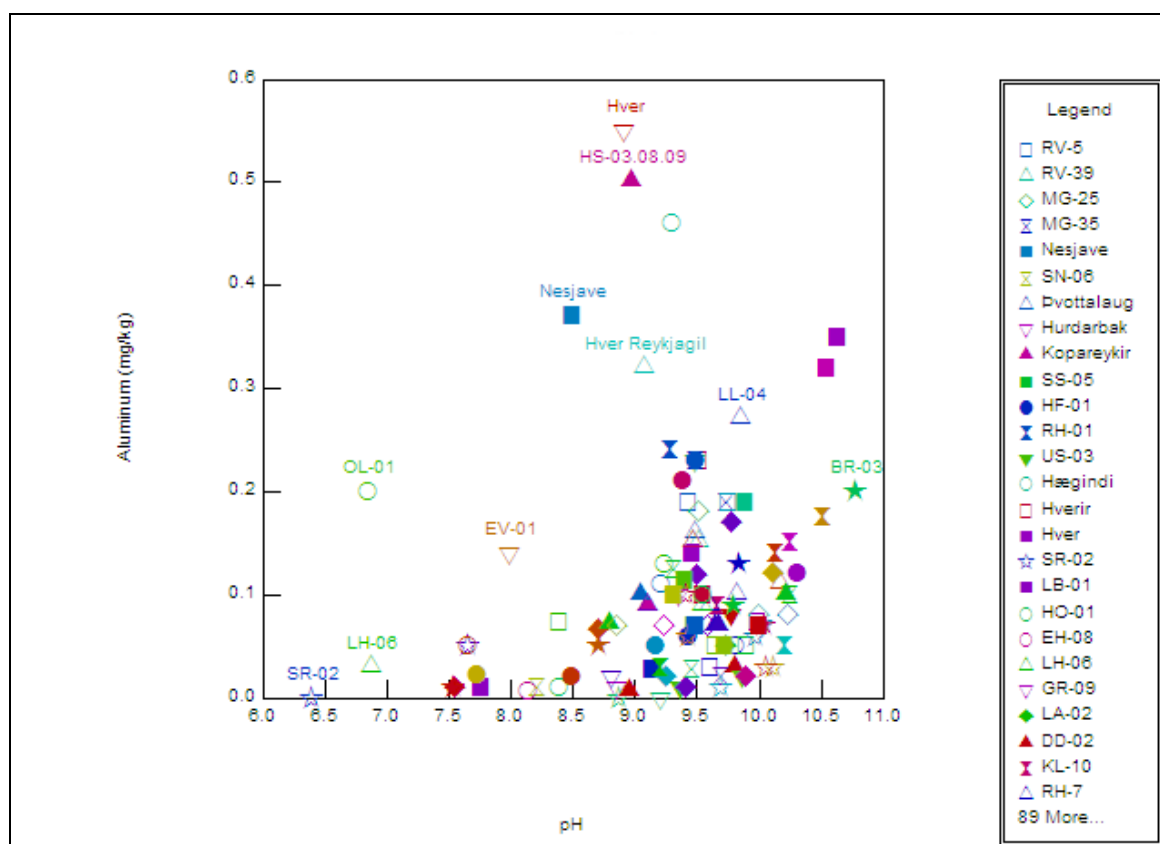


Figure 8: Concentration of aluminium against pH in water from the heating systems in Iceland.

Most waters are depleted in magnesium as is normal for geothermal water, but the heated waters have much higher magnesium concentration and may even be classified as magnesium-chloride or magnesium-carbonate waters (Figure

4). The wide range of dissolved solids (TDS) is also clearly demonstrated as well as the generally low mineralization of the waters. In Figure 7 the concentration of silica is plotted against measured temperature of the waters. There is quite a

scatter in the graph, but an almost linear correlation of increased silica by temperature may be discerned. As this is measured temperature from both springs and wells and also some heated cold water a great scatter is to be expected. In Figure 8 aluminium concentration concentration is plotted against pH for the waters. Aluminium concentrations in the waters increases rapidly by increased temperature and pH. The waters with absolute highest aluminium are boiling springs and heated water from the Nesjavellir field influenced by effluent water from the geothermal system.

#### 4.3. Origin and Age of the Waters

In figure 9 is shown the ratio of stable isotopes ( $\delta^2\text{H}$  and  $\delta^{18}\text{O}$ ) for the waters and the location of the world meteoric water line is shown for comparison (Craig, 1961). Most of the waters fall very closely on the meteoric line, but a few of the hottest ones show a distinct  $\delta^{18}\text{O}$  shift due to water-rock interaction at elevated temperatures (Sveinbjörnsdóttir et al, 1995a). Also detected in waters from the Snæfellsnes peninsula is a high deuterium excess or a negative  $\delta^{18}\text{O}$  shift, probably due to reaction with  $\text{CO}_2$  emanation from deep seated intrusions (Kristmannsdóttir et al, 2005b, Kristmannsdóttir and Sveinbjörnsdóttir in preparation).

The age of geothermal water in Iceland is from a few thousand years up to 70 thousand years (Sveinbjörnsdóttir et al., 1995b). The apparent  $^{14}\text{C}$  age of the water used for the heating systems is variable from a few thousand years to well over twenty thousand years.

#### 4.2. Examples from Main Geothermal Heating Systems

In table 1 is shown typical concentration of water from some of the large heating systems in Iceland and a few small ones with a different chemical profile. The location of sites is shown in Figure 1. The first two samples are from the heating system in the capital city of Reykjavík. The first one is from one of the geothermal fields and the second one is of water produced at the high-temperature geothermal field Nesjavellir. The geothermal water is from one of the hottest fields and contains high concentration of aluminium. The water is classified as a sodium-chloride type water. It is a typical water of meteoric origin from a boiling low-temperature geothermal field. It has a considerable concentration of hydrogen sulfide giving it an inbuilt protection against oxygen corrosion, but the concentration is not high enough to be of any health concern. The other three low-temperature geothermal fields used for the heating system in Reykjavík are colder, 75-100 °C, but with very similar water, of sodium-chloride type. In two of the fields the hydrogen sulfide concentration is twice as high as in this one and fluoride concentration is also higher. The heated water from Reykjavík also contains high concentration of aluminium and silica due to contamination from the geothermal field, but is classified as an sodium-bicarbonate water. In the heated water there is added condensed steam to elevate the pH and add hydrogen sulfide. This has the aim to prevent magnesium silicate scaling and oxygen corrosion (Kristmannsdóttir et al., 2004). The water used for the town Seltjarnarnes a suburb of the capital city is from a geothermal field within the town, one of the five low-temperature geothermal fields in the capital city area (Kristmannsdóttir and Tulinius, 2000).

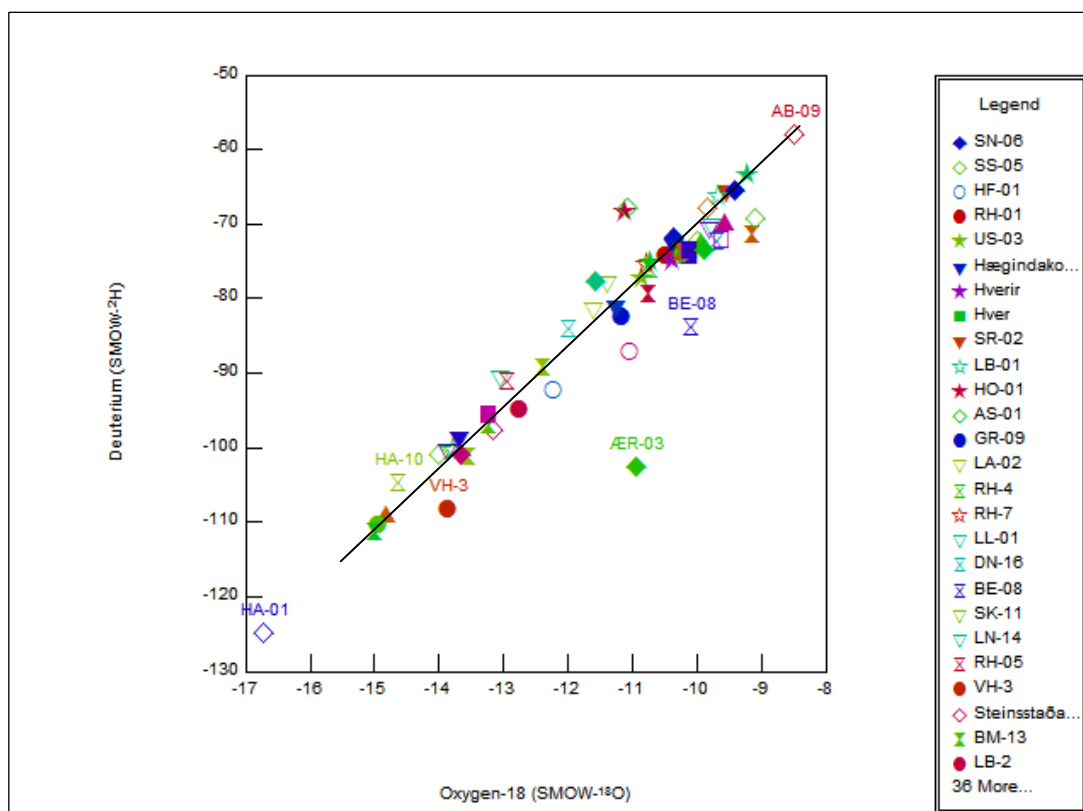


Figure 9: The ratio of stable isotopes ( $\delta^2\text{H}$  and  $\delta^{18}\text{O}$ ) in water from heating systems in Iceland. The location of the world meteoric water line is shown for comparison (Craig, 1961).

The water has 3-3.5 ‰ salinity and cannot be used directly into radiators. It is piped directly to the users in steel distribution pipes, but heat exchangers are installed in each house for the heating loop and normally also for tap water. The water from Akureyri, Iceland's next largest city, is a low salinity water of the sodium-sulfate type. It is colder than the selected sample of geothermal water from Reykjavík, less mineralized, with higher pH and contains considerably less hydrogen sulfide. The heated water from the Sudurnes hitaveita on the Reykjanes peninsula is slightly more saline than most cold groundwater, 75 mg/L of chloride. As in the case of the Nesjavellir water condensed steam is added to this water. In Selfoss SW-Iceland the water is somewhat saline and the pH is lower than in most, about 8.3. This water is a typical sodium-chloride water with the salinity partly originated from sedimentary formations formed in the end of glaciation when the sea invaded the southern coastal lowlands. The concentration of hydrogen sulfide is relatively low. The water from Stykkishólmur heating system is the most saline low-temperature geothermal water presently used for district heating purposes in Iceland, 5.4 ‰ (Kristmannsdóttir, 2004, Kristmannsdóttir et al., 2005b). The water is somewhat depleted in sulphate concentration relative to that of seawater. It is highly depleted in magnesium, but the content is still two orders of magnitude higher than in non saline geothermal waters of similar temperature. The pH of the water is 8.35-8.45, which is similar to that of salty low-temperature waters elsewhere in the country. The calcium concentration is high relative to geothermal waters elsewhere in the country indicating intensive and prolonged water-rock interaction, also supported by the high apparent  $^{14}\text{C}$  age of the water. This water is classified as calcium-chloride water. The water for the heating system for the towns Akranes and Borgarnes is piped from the largest spring in Iceland some 60 km northeast of Akranes (Georgsson et al., 1984). It is a boiling geothermal field with sodium-sulfate water with high hydrogen sulfide concentration as well as fluoride content. The Brún geothermal field is used for a heating system for the local farm houses. It is a sodium-hydrogen water type with extremely high pH of about 10.8. Waters of this type are commonly encountered at the flanks of the volcanic zones both in SW and NE Iceland. Finally there is shown in the table an example of water from a fairly new heating system in eastern Iceland where there are rather few known geothermal fields. This field was recently discovered by gradient drilling. The water is of sodium-chloride type, 76 °C, with 0.7 ‰ salinity and very low concentration of hydrogen sulfide. The system is mostly a double loop distribution system with heat-exchangers in each hose for both radiators and tap water. The return water from 60-70 % of the system is reinjected into the reservoir (Gunnlaugsson pers. comm.). The chemistry of the water is of almost identical composition as water from northern Iceland used for the heating system in the island Hrísey north of Akureyri.

## 5. DISCUSSION AND CONCLUSION

As demonstrated in the paper the chemistry of the waters from the heating systems in Iceland are far from homogenous even though there are common characteristics for most of them, as high pH and generally low mineralization, depending on the source of water and geological setting.

A great variety is displayed in chemical characteristics, the majority of the waters are classified as sodium-chloride waters, even though they are of meteoric origin. The next biggest classification group is the sodium-sulfate waters and then the sodium-bicarbonate and carbonate waters. The

different chemical properties call for different design of the systems and utilization of the waters. Still most of the heating systems are single through-flow systems where the water is mostly used directly both for heating and as tap water. In a few heating systems there are double distribution systems. In one case there is a closed loop distribution system circulating heated fresh water (SALINEGEOHEAT, 2001). The most recent heating system in Eskifjörður has a closed circulation system within the houses and reinjection of majority of the spent water. The difference in chemical character calls for a very careful selection of pipe and equipment material selection (Kristmannsdóttir et al., 2006).

The concentration of most elements in the majority of the low-temperature geothermal waters of meteoric origin used in the heating systems is within the limits required for drinking water. The main exceptions are the pH which is too high in most cases to fulfill regulations and the aluminium concentration exceeds the limit for consumption in a few of them. In the seawater contaminated waters salinity may be too high. It is also customary in Iceland to use the waters directly as tap water and commonly the geothermal water is used for cooking and even drinking. It was put into Icelandic health regulations about 15 years ago that geothermal tap water was not intended for drinking, but piped to the houses for heating and washing purposes.

It can be concluded from the study that water used in Icelandic heating systems is dominantly of alkaline, slightly mineralized type. The waters reacting with young reservoir rocks in the active volcanic zones and on their flanks have much higher pH as well as sulfide concentration than waters reacting with the older Tertiary formations. The chloride concentration in geothermal waters of meteoric origin increases by higher reservoir temperatures. There are quite a few geothermal waters with a partly seawater origin or salinity drawn from sediments formed in seawater. Those waters have lower pH and sulfide concentration than the meteoric originated ones, but significantly higher concentration of main and trace metals. Heated fresh water used in the systems based on high temperature fields has varying properties according to the type of cold groundwater in the area, but pH and sulfide concentration is controlled by addition of condensed steam.

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**Table 1. Selected analyses of water from some of the largest heating systems in Iceland. Location of the sites is shown in Figure 1.**

Location	Reykjavík	Reykja- vík heated	Seltjarn- arnes	Akureyri	Sudurnes Heated	Selfoss	Stykkis- hólmur	Borgarnes- Akranes	Eski- fjörður	Reykjad. Brún
Temp. °C	127	78	108	94	105	74	87	99	76	54
pH/°C	9.58/18	8.43/27	8.37/27	9.72/20	8.9/24	8.33/23	8.4/17	9.41/24	9.04/23	10.75/21
CO <sub>2</sub> mg/L	19	41	5.4	17	6	29	4.4	22	3.5	9.3
H <sub>2</sub> S mg/L	0.425	0.530	0.091	0.066	0.08	0.08	0.07	1.4	0.04	0.04
SiO <sub>2</sub> mg/L	139	38	95	97	13	62	72	123	51	87
B µg/L	47.9	12	0.20	0.16	-	111	80	240	460	77
Na mg/L	52.5	19.8	624	52.4	34	151	740	76	263	62.5
K mg/L	1.8	1.7	13.0	1.2	1.5	3.5	14.5	2.1	4.2	0.6
Ca mg/L	2.4	8.9	582	2.8	8.1	24.4	1170	3.1	96	2.7
Mg mg/L	0.002	4.8	0.502	<0.002	6.9	0.084	0.5	0.002	0.011	0.0003
SO <sub>4</sub> mg/L	15.6	12.6	291	39.8	11	48.8	315	54	308	18.1
Cl mg/L	28.5	14.4	1820	12.5	75	215	2960	35	393	5.8
F mg/L	0.69	0.12	0.72	0.38	0.07	0.2	1.2	2.3	2.7	1.1
Diss.sol. mg/L	264	115	3477	216	153	471.0	5430	316	1123	182
Fe µg/L	1.5	5.9	6.8	1.7	1	4.8	23	1.8	1.3	2
Al µg/L	193	385	11.3	131	3	20.2	20	130	36	245
Ti µg/L	0.04	-	0.07	0.07	-	0.08	0.58	<0.02	<0.20	0.04
Br µg/L	101.0	-	7320	43.0	-	711	9.7	109	1140	5
Cu µg/L	0.121	-	0.149	0.329	-	<0.1	<0.005	0.04	0.28	0.2
Mn µg/L	0.073	3.9	15.7	0.065	6	2.1	23	0.21	0.37	0.06
Sn µg/L	0.079	-	<0.020	<0.020	-	<0.050	0.23	<0.02	<0.20	<0.01
Sr µg/L	22.1	-	2430	19.9	-	86.1	5.3	11	575	1.1
Zn µg/L	0.65	-	0.11	2.88	-	25.7	5	0.15	0.49	0.7
δ <sup>2</sup> H‰	-64.3		-73.7	-96.6		-62.9	-68.5	-72.0	-90.4	-107.4
δ <sup>18</sup> O ‰	-9.58		-10.44	-13.33		-9.25	-11.1	-10.23	-12.57	-14.69
<sup>14</sup> C App. age	10900		17800	7400			21000	11800		10100