INTERPRETATION OF GEOCHEMICAL DATA FROM FUMAROLES AND WELLS IN THE NÁMAFJALL GEOTHERMAL FIELD, ICELAND AND FROM FUMAROLES IN THE MUTNOVSKY GEOTHERMAL FIELD, KAMCHATKA, RUSSIA

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ABSTRACT

The Námafjall area is a high-temperature geothermal area in North Iceland. In this report data from 1989, 1995 and 1999 for two production wells are used to calculate mineral equilibria and for comparison with actual temperatures, measured in the wells. Some data from fumaroles in this field are used to compare calculated gas geothermometer temperatures with measured temperatures. Gas geothermometer temperatures were also calculated for fumaroles in the Mutnovsky geothermal field (southern part of Kamchatka peninsula, Far East Russia) for comparison with available temperature data from the well`s logging. For samples from the wells there, geothermometers obtained subsurface temperatures of about 240-260°C. The gas geothermometers gave temperatures of 270-310°C (for wells) and 270-320°C (for fumaroles) in the Námafjall area. In the Mutnovsky geothermal area the H_2S and CO_2/N_2 geothermometers gave temperatures of 280-310°C, which are close to reservoir temperatures.

1. INTRODUCTION

The Námafjall high-temperature geothermal field is located in North Iceland about 5 km east of Lake Mývatn (Figure 1). Surface thermal manifestations cover some 5 km^2, being most intense on the low hyaloclastite ridge of Námafjall and just east of it (Arnórsson, 1977). The Námafjall ridge itself is about 2.5 km long and 0.5 km wide (Gudmundsson et al., 1965).

Námafjall is a boiling reservoir with reservoir temperature exceeding 300°C. The geothermal water is of meteoric origin. This field has been exploited for drying in a diatomite plant, for electrical power production in a 3MWe power plant and also for house heating in the small town of Reykjahlíd (Kristmannsdóttir, 1989).

The first wells were drilled at Námafjall in 1964 and since then twelve wells have been drilled in the geothermal area. They are all located west of Námafjall. Their depth varies from 340 to 1999 m. The
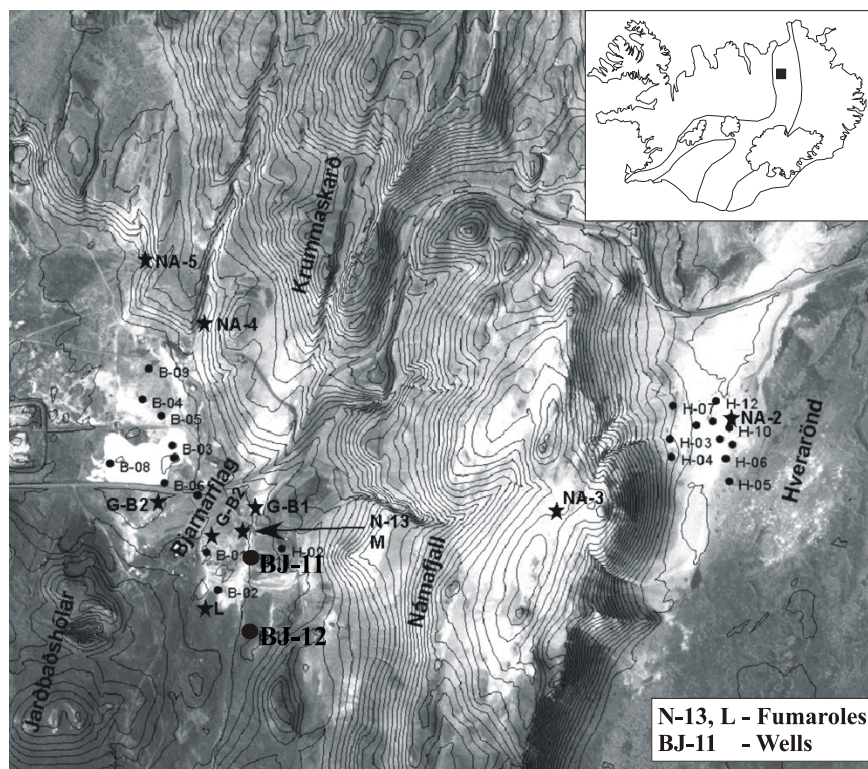
FIGURE 1: Location of the Námafjall geothermal field with sampling sites (figure made by Á. Gudmundsson)

thermal system is divided into two areas (Ólafsson and Krist-mannsdóttir, 1989) separated by a hyaloclastite ridge, Námafjall. The two areas are Hverarönd, east of Námafjall, and Bjarnarflag on the west side of Námafjall.

Production of the Námafjall geothermal field started in 1967. Now, only two production wells, BJ-11 and BJ-12 (B stands for Bjarnarflag and J for the drillrig Jötunn) remain in use. BJ-11 was drilled in 1979 to a depth of 1923 m, and BJ-12 in 1980 (1999 m). Both wells are located east of the Krummaskard fault, which marks the eastern boundary of the fissure swarm. Every year the National Power Company arranges for samples to be taken from those wells for monitoring.

2. NÁMAFJALL HIGH-TEMPERATURE GEOTHERMAL FIELD

2.1 Geological setting and geothermal activity

The Námafjall geothermal area is located in the fissure swarm 10 km south of the Krafla central volcano. In the Námafjall area many fumaroles are found, some very active, as well as mudpots and solfataras. Some of the most active natural manifestations are on the east side of Námafjall. Only basaltic rocks are exposed in the immediate vicinity of the geothermal area. They include lava flows, pillow lavas, and hyaloclastites. Other rock types have not been encountered in the drillholes.

Petrological studies in the Námafjall-Krafla area show a range of rock composition from olivine tholeiite to rhyolite (Nicholson et al., 1991). All these rock types were erupted in Postglacial times. The basalts formed by fissure eruptions, however, are predominantly quartz normative tholeiites, which appear to be of closely similar composition irrespective of the eruption site. In Postglacial times some 18 eruptions have occurred in the Krafla caldera and its nearest surroundings and about 15 in the Námafjall area (Saemundsson, 1991). Voluminous silicic eruptions did not take place in Postglacial time but subglacial eruptions within and around the Krafla caldera produced large domes or ridges during the last glacial period, among them Hlídarfjall and Hrafntinnuhryggur. Explosion craters that ejected small quantities of rhyolitic pumice exist in the Krafla caldera. The most recent formed in 1724 at the beginning of the 1724-1729 volcanic episode ("Mývatn fires"). Tephrochronological studies indicate that Postglacial volcanism in the Krafla and Námafjall areas occurred in two main periods, one in early Postglacial times,

the latter during the last 3000 years. The period of repose may have lasted more than 4000 years. In Krafla the fissure swarm has erupted six times and in Námafjall four times during the latter period of activity. Four of the eruptions are common for both areas. The Krafla fissure swarm is divided into two parallel subswarms in the Krafla and Námafjall areas. The rifting activity of the subswarms occurred alternatively on the two subswarms for a period of 4000-5000 years. The western subswarm has been almost quiet volcanically during the Postglacial period, but during the same period tectonically active. Volcanism near Krafla has been concentrated along the central and eastern part of the fissure swarm during this period whereas during the earlier period, it was dispersed over the western part as well. Most eruptions produced less than 0.5 km³ of lava. The basaltic lava from the Threngslaborgir-Lúdentsborgir crater row south of Námafjall 2100 years BP produced the exceptionally great volume of 2-3 km³ with an area extent of 220 km. The Námafjall and Krafla geothermal systems lie on the same fissure swarm (Ármannsson et al., 1987).

In 1975 volcanic activity started again in the Krafla volcanic system. The activity, which lasted till 1984, was characterized by repeated uplift and subsidence events, and occasionally magma released from the reservoir along a fissure swarm that runs through the volcano. During one volcanic episode, wells were damaged and a small volcanic eruption took place through one of the wells in the Bjarnarflag field. As a consequence, surface activity increased markedly there due to increased heat flow. The chemistry and temperature of groundwater within the Námafjall geothermal area has been greatly affected by the volcanic activity.

2.2 Chemical data

The present geochemical study is based on chemical data from the two production wells (BJ-11 and BJ-12) from Bjarnarflag (Námafjall). The samples were taken by the National Power Company in 1989, 1995 and 1999 (Hauksson and Benjamínsson, 1989, 1995, 2000). The chemical composition of these samples is shown in Table 1.

TABLE 1:   Chemical composition of thermal total flow from wells of Námafjall area
at reservoir conditions (concentrations in ppm)

	Enthalpy (kJ/kg)	pH	CO_2	H_2S	SiO_2	Na^+	K^+	Ca^{++}	Mg^{++}	SO_4^{--}	Cl^-	F^-
1989												
BJ - 11	2186	7.67	17.8	107.7	424.6	100.8	12.1	0.75	0.093	14.0	22.4	0.62
BJ - 12	2138	7.65	36.1	139.8	535.3	123.7	18.2	0.4	0.155	26.6	31.6	0.53
1995												
BJ - 11	1867	7.69	31.2	97.5	492.6	105.9	16.2	0.24	0.026	15.8	34.3	0.77
BJ - 12	1741	7.58	39.9	100.1	414.9	122.6	17.9	0.38	0.028	9.4	53.3	0.5
1999												
BJ - 11	1773	7.54	28.2	108.5	525.4	98.4	13.0	0.45	0.006	9.9	32.6	0.78
BJ - 12	1694	7.46	53.7	103.1	474.8	113.4	15.8	0.44	0.006	2.7	67.5	0.57

The reservoir water at Námafjall is low in total dissolved solids, chloride concentrations are low as well as sulphate. The major dissolved ions include bisulphide and sodium (Arnórsson, 1977). The chemistry of the various well discharges is similar, but significant differences occur in the silica and the total gas concentrations due to temperature and aquifer depth.

An increase of the Cl concentration is observed in the thermal water from the wells (1.5 times for BJ-11 and 2 times for BJ-12). A decrease of the SO_4 concentration (1.4 times for BJ-11 and 10 times for BJ-12) and of CO_2 was also observed.

2.3   Gas geothermometers

In many geothermal fields, surface manifestations consist of fumaroles and steam-heated water. The water is characteristically very low in chloride, with a pH ranging from near neutral to strongly acidic (Arnórsson, 1991). It is meaningless to apply solute geothermometers to steam-heated water. Such water has not percolated to any extent into the bedrock, so the chemical composition has not been equilibrated by temperature-dependent mineral/solution equilibria that may prevail in the reservoir, equilibria that form the basis for chemical geothermometry.

In high-temperature (> 200°C) geothermal fields, temperature-dependent gas-gas and/or mineral-gas equilibria are believed to control the concentrations (or ratios) of gases like CO_2, H_2S, H_2, N_2, NH_3 and CH_4 in geothermal reservoir water (e.g. Giggenbach, 1988; Nehring and D`Amore, 1984; Arnórsson and Gunnlaugsson, 1985).

Arnórsson and Gunnlaugsson (1985) proposed temperature functions for six geothermometers applicable to fumarolic steam. Three were based on the concentrations of CO_2, H_2S and H_2, respectively, and two on gas ratios (CO_2/H_2 and H_2/H_2S). Gas concentrations are in mmol/kg steam.

The CO_2 gas geothermometer`s temperature by Arnórsson and Gunnlaugsson (1985) is given by

$$t(°C) \;=\; -44.1 + 269.25\log(CO_2) - 76.88\,(\log(CO_2))^2 + 9.52\,(\log(CO_2))^3 \tag{1}$$

The H_2S gas geothermometer`s temperature by Arnórsson and Gunnlaugsson (1985) is given by

$$t(°C) \;=\; 173.2 + 65.04\log(H_2S) \tag{2}$$

The H_2 gas geothermometer`s temperature by Arnórsson and Gunnlaugsson (1985) is given by

$$t(°C) \;=\; 212.2 + 38.59\log(H_2) \tag{3}$$

The CO_2/H_2 gas geothermometer`s temperature by Arnórsson and Gunnlaugsson (1985), for water in the range 200-300°C and chloride < 500 ppm, is given by

$$t(°C) \;=\; 311.7 - 66.72\log(CO_2/H_2) \tag{4}$$

The CO_2/N_2 gas geothermometer`s temperature by Arnórsson (1987), for water in the range 200-300°C and chloride < 500 ppm, is given by

$$t(°C) \;=\; 148.5 + 64.35\log(CO_2/N_2) + 5.239\,(\log(CO_2/N_2))^2 - 1.832(\log(CO_2/N_2))^3 \tag{5}$$

The first empirical gas geothermometer was proposed by Tonani (1973). The relative gas concentrations were used for calculations and Pco₂ was assumed to be controlled by an external factor. D`Amore and Panichi (1980) found a relationship between the relative concentrations of $H_2S$, $H_2$, $CH_4$, $CO_2$ and reservoir temperatures. The $CO_2$-$CH_4$-$H_2$-$H_2S$ gas geothermometer`s temperature is given by

$$t(°C) \;=\; \frac{24775}{D+\delta+36.05} - 273.15 \tag{6}$$

with

$$D \;=\; 2\log(CH_4/CO_2) - 6\log(H_2/CO_2) - 3\log(H_2S/CO_2) \qquad and \qquad \delta \;=\; -7\log(P_{CO_2})$$

and $Pco_2 \;=\; 0.1$ atm. If CO_2 (% by volume) < 75
         $Pco_2 \;=\; 1.0$ atm. If CO_2 (% by volume) > 75

The H_2-CO_2 gas geothermometer`s temperature by Nehring and D`Amore (1984) is given by

$$t(°C) = 190.3 + 55.97 Q_{hc} - 0.14 Q_{hc}^2 \quad with \quad Q_{hc} = \log(H_2) + 0.5 \log(CO_2) \qquad (7)$$

Finally, the H_2S-CO_2 gas geothermometer`s temperature by Nehring and D`Amore (1984) is given by

$$t(°C) = 194.3 + 56.44 Q_{sc} + 1.53 Q_{sc}^2 \quad with \quad Q_{sc} = \log(H_2S) + 1/6 \log(CO_2) \qquad (8)$$

In this report the above gas geothermometers were used for the calculation of chemical composition from fumaroles (unpublished data of Chemical Lab. of Orkustofnun) from the Námafjall area. Table 2 shows calculated subsurface temperatures from unpublished data from different years, also using the gas geothermometers by D`Amore and Panichi (1980), and Nehring and D`Amore (1984). For comparison, Table 3 shows published data on gas geothermometers' temperatures from fumaroles in the area. As in the unpublished data, only relative gas concentrations were measured in the steam, but not the quantitative gas concentrations. Hence, only gas geothermometers' temperatures based on relative gas concentrations could be calculated. The temperatures calculated by the use of the old data from fumaroles from the Námafjall area compared closely to those from production wells BJ-11 and BJ-12. The gas geothermometers' temperatures from the wells were calculated using Equations 1-5. The chemical composition of gas components for the wells was taken from WATCH program at reference temperature 100°C.

Table 2 shows the calculated temperature of gas geothermometers from wells and fumaroles in the Námafjall area. The CO_2 geothermometer (for the wells) gives lower temperatures (210-250°C) than the CO_2/H_2 geothermometer (310-330°C), but the H_2S and H_2 geothermometers give almost the same temperatures, 270-280°C. The calculated temperatures from fumaroles (H_2S-CO_2 and CO_2/H_2 geothermometers) range from about 260-280°C and 310-330°C, respectively, whereas the CO_2-CH_4-H_2-H_2S geothermometer gives absurdly high results and is obviously not applicable for fumarolic gases.

TABLE 2: Gas geothermometer calculations based on unpublished data sampled in
different years from fumaroles in the Námafjall area compared with
gas geothermometer values from wells

	T_{CO2} (°C)	T_{H2S} (°C)	T_{H2} (°C)	$T_{CO2/H2}$ (°C)	$T_{CO2\text{-}CH4\text{-}H2\text{-}H2S}$[1] (°C)	$T_{H2S\text{-}CO2}$[2] (°C)	$T_{CO2\text{-}H2}$[2] (°C)	Years
BJ-11	207.7	278.9	274.9	327.0				1989
BJ-12	229.4	281.5	284.5	329.7				1989
BJ-11	220.8	269.6	272.5	314.6				1995
BJ-12	241.3	277.3	281.2	315.3				1995
BJ-11	216.2	274.8	276.3	324.2				1999
BJ-12	249.4	277.9	281.9	310.1				1999
NA-2					622.8	259.8	323.9	1993
NA-3					730.2	261.5	329.2	1993
NA-4					612.6	272.3	324.2	1993
NA-5					622.4	277.4	316.9	1993

1) D`Amore and Panichi (1980)       2) Nehring and D`Amore (1984)

Table 3 shows gas geothermometer values published by Ármannsson (1993). The calculated temperatures from gas geothermometers differ widely, both between different geothermometers and different fumaroles. The temperatures of the CO_2/H_2 geothermometer show values from ~ 320 to 260°C (from 1952 to 1993) and decrease over time. The temperatures of the CO_2 geothermometer vary from 250 to 310°C and increase over time.

TABLE 3:   Gas geothermometer calculations from fumaroles in the Námafjall area
from published data (Ármannsson, 1993)

	T_{CO2} (˚C)	T_{H2S} (˚C)	T_{H2} (˚C)	$T_{CO2/H2}$ (˚C)	Years
N-13	250	304	275	323	1950-52
174	276	284	290	301	1982
152	249	256	241	240	1982
143	230	244	241	254	1982
L	249	256	241	240	1984
M	242	266	249	259	1984
G-B1	301	266	233	**156**	1993
G-B2	310	230	312	269	1993
G-B3	310	266	290	229	1993

2.4 Cl-SO₄-HCO₃ triangular diagram

For the classification of the geothermal water several methods were used and their composition plotted into several basic diagrams. One was a triangular diagram, based on the relative concentrations of the three major anions (Cl^-, SO_4^{2-}, HCO_3^-). This diagram is used for the classification and characterization of the water.

Figure 2 shows that the thermal water from the entire period plotted mostly as bicarbonate-chloride water. In 1989 the water contained more than 40% bicarbonate, 45% chloride and less than 30% chloride in the case of BJ-11, whereas BJ-12 contained more than 45% bicarbonate and less chloride than BJ-11. Since then,

FIGURE 2:   The Cl-SO₄-HCO₃ triangular diagram
for waters from wells of Námafjall

sulfate has decreased in both wells. In 1995 the relative concentration of chloride increased up to 45% for well BJ-12. There was observed a small increase in chloride which continued in 1999 for both wells, and sulfate decreased accordingly.
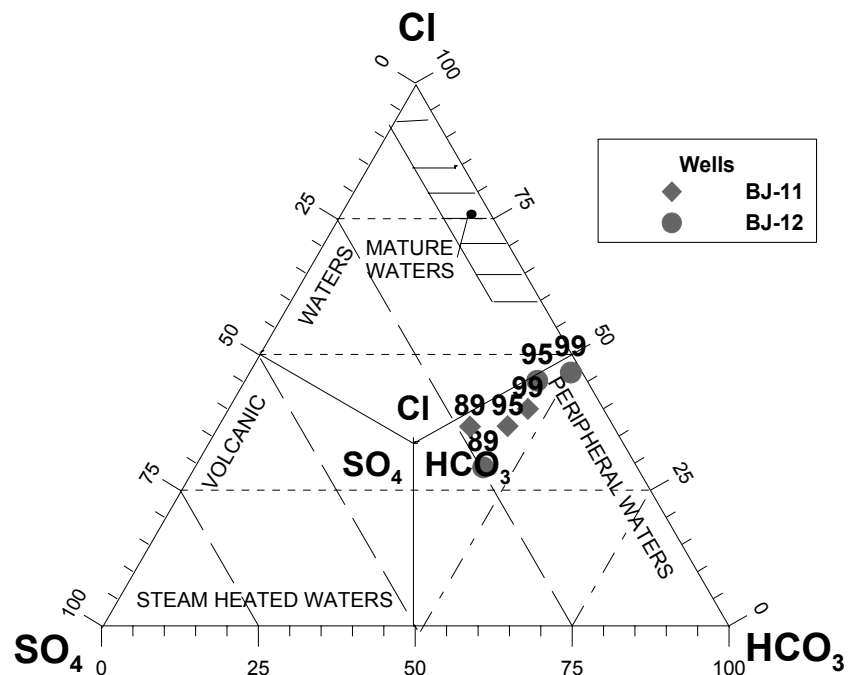
After the start of the volcanic activity in the Krafla area (1975) and the Námafjall area in 1977, some chemical changes within the groundwater system were observed, with an inflow of colder geothermal water into deeper and warmer parts of the reservoir. Probably the water in 1989 was affected by this inflow. After 1989, the chemistry starts to move a little to the Cl^- corner (mature water). However, the main changes for the thermal well water were a decrease of sulfate and no increase of chloride.

2.5 Na-K-Mg triangular diagram

Giggenbach (1988) suggested that a ternary diagram with Na/1000-K/100-√Mg at the apices could be used to classify water according to the state of equilibrium at given temperatures. Figure 3 shows the Giggenbach (1988) plot of samples from the Námafjall area in 1989, 1995 and 1999. The data from 1989 are located in the area under the line of equilibrated water. The samples from 1995 and 1999 are moving up to the K/100-corner towards the line of fully equilibrated waters. This Na-K-Mg triangular diagram gives Na/K geothermo-meter temperature values from 250 to 270˚C.
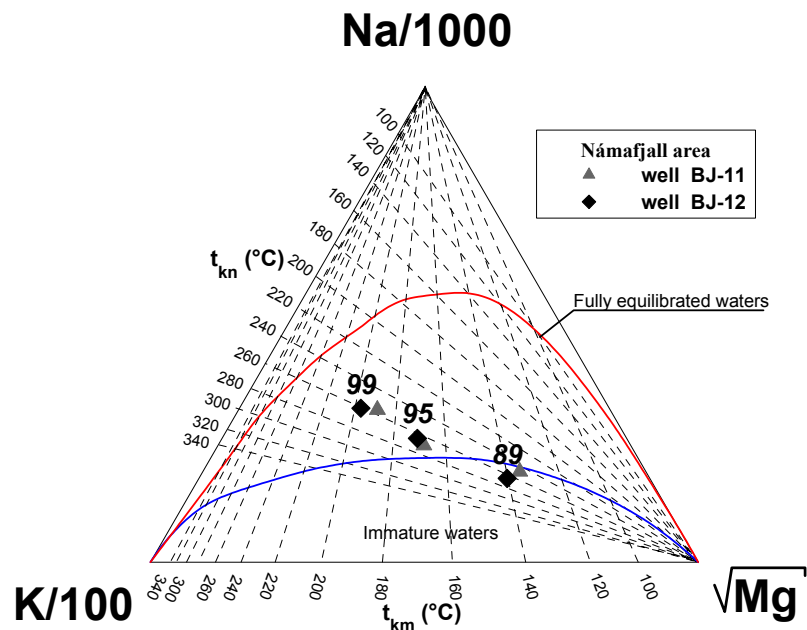
Arnórsson (1983) adapted the Na-K-Mg triangular diagram in order to correlate with Icelandic conditions. Plot of the Námafjall data in this version of the diagram is shown in Figure 4. In this case the Na/K geother-mometer temperature is 240-260˚C, and the data points for 1999 plot quite near to the border for fully equilibrated waters.

From 1989 to 1999 changes in the water indicate the effects of an inflow of colder water into the system and its gradually waning effects are similar to those reflected by the Cl-SO$_4$-HCO$_3$ diagram. There is, however, a possibility that the analytical results are not so reliable for Mg (Kristmannsdóttir, pers. comm.), which would weaken this interpretation.
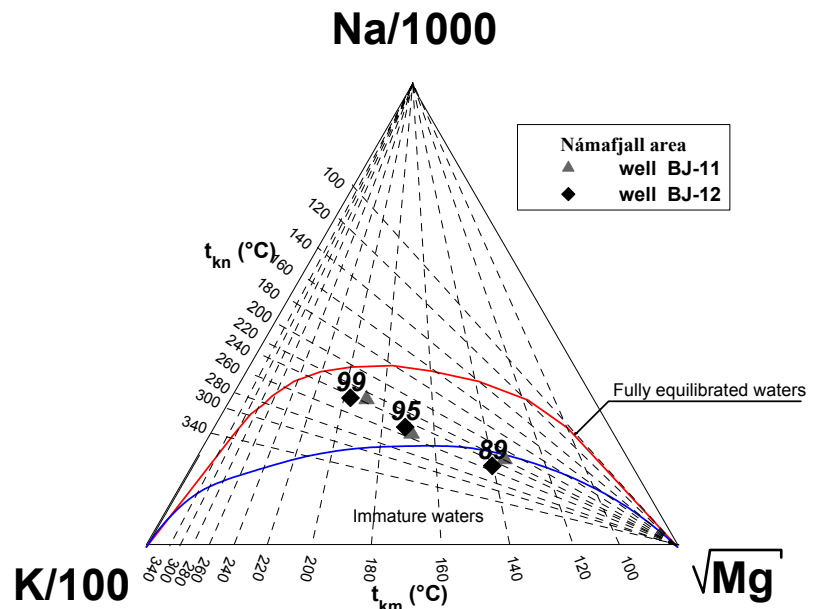

FIGURE 3: The Na-K-Mg diagram for waters from the wells of Námafjall (based on Giggenbach, 1988)

FIGURE 4: The Na-K-Mg diagram for waters from the wells of Námafjall (based on Arnórsson, 1983)

2.6 Geothermometry

Chemical geothermometers are based on the assumption that temperature-dependent mineral solute equilibrium is attained in the geothermal reservoir. In this report chemical geothermometers are used to predict subsurface temperature. Table 4 shows the results for different solute geothermometers calculated

for the Námafjall area. For most of the samples quartz geothermometers (Fournier and Potter, 1982) give higher reservoir temperatures (about 230-260°C) than Na/K (Arnórsson et al., 1983) geothermometers. But in BJ-12 (1995), the Na/K geothermometers give higher values.

TABLE 4: Calculated geothermometers' temperatures
for thermal water from wells in the Námafjall area

	T_q [1] (°C)	T_{NaK} [2] (°C)	$T_{NaK\ Gigg}$ [3] (°C)	$T_{Na-K-Ca}$ [4] (°C)
1989				
BJ - 11	234.6	221.8	246.4	247.5
BJ - 12	260.4	241.5	263.9	265.2
1995				
BJ - 11	250.2	247.5	267.4	268.7
BJ - 12	233.5	243.4	263.3	264.5
1999				
BJ - 11	259.6	231.5	254.2	255.5
BJ - 12	248.5	238.7	242.2	243.3

1) Fournier and Potter, 1982;   3) Giggenbach, 1988;
2) Arnórsson et al.,1983;   4) Fournier and Truesdell, 1973.

2.6.1 Silica geothermometers

The silica geothermometers are based on experimentally determined solubilities of chalcedony and quartz. Usually the quartz geothermometer is applied to high-temperature reservoirs like Námafjall (temperature >150-180°C). Application of the silica geothermometers is based on the fact that the activity of H_4SiO_4, is temperature dependent. The quartz temperature by Fournier and Potter (1982) is

$$t(°C) = -42.198 + 0.28831\,SiO_2 - 3.3383 \times 10^{-4}(SiO_2)^2 + 3.1665 \times 10^{-7}(SiO_2)^3 + 77.034\log(SiO_2) \quad (9)$$

2.6.2 Cation geothermometers

The Na-K geothermometers are based on equilibrium for the ion exchange reaction for the alkali feldspars, given by

$$NaAlSi_3O_8 + K^+ = KAlSi_3O_8 + Na^+ \quad (10)$$
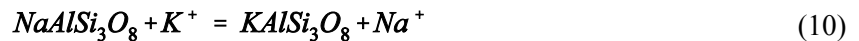
The equilibrium constant, K_{eq}, for Reaction 10 is

$$K_{eq} = \frac{[KAlSi_3O_8][Na^+]}{[NaAlSi_3O_8][K^+]} \quad (11)$$

The activities of the solid reactants are assumed to be unity and the activities of the dissolved species are about equal to their molal concentrations in aqueous solution. Equation 11 reduces to

$$K_{eq} = \frac{[Na^+]}{[K^+]} \quad (12)$$

In this report the following equations are used for calculating reservoir temperatures:

Na/K temperature in the range of temperatures 250-350°C (Arnórsson et al., 1983) given by

$$t(°C) = \frac{1319}{1.699 + \log(Na/K)} - 273.15 \tag{13}$$

Na/K temperature by Giggenbach (1988) given by

$$t(°C) = \frac{1390}{1.750 + \log(Na/K)} - 273.15 \tag{14}$$

The Na-K-Ca geothermometer (Fournier and Truesdell, 1973) takes into account a reaction involving the exchange of Na^+, K^+ and Ca^{++} with a mineral solution. The equation is

$$t(°C) = \frac{1647}{\log(Na/K) + \beta\,(\log(\sqrt{Ca}/Na) + 2.06) + 2.47} - 273.15 \tag{15}$$

where $\beta = 1/3$ for t > 100°C and $\sqrt{Ca}/Na < 1$.

2.7 Log *Q/K* diagrams

For evaluating the chemical analysis of samples from the Námafjall area, the computer program WATCH by the Icelandic water chemistry group (Bjarnason, 1994) was used. This program reads chemical analyses of water, gas and steam samples, and computes aqueous speciation, gas pressure, activity and solubility products at designated temperatures. The WATCH program allows calculations of the equilibrated fluid to be conductively cooled or adiabatically boiled from a reference temperature to some lower temperature. The ion activity products (log Q) and solubility products (log K) of selected minerals

$$SI = \frac{\log Q}{\log K} \tag{16}$$

(29 minerals) are computed. From these, the corresponding saturation indices (*SI*) can be obtained.

SI calculation allows us to interpret the equilibrium state of the reservoir fluid, predict scaling (mineral deposition) tendencies, design conditions to avoid scaling, and further, to model the chemical behaviour of the fluid at specified physical conditions in order to make the best design for the plant according to production characteristics of the fluid. Figure 5 presents the *SI* from 50-350°C for samples from wells BJ-11 and BJ-12 in 1999. The temperature at which the *SI* curves intersect the zero line determines the equilibrium temperature for each mineral. If most of the minerals cross the zero line at the same temperature, the reservoir temperature is defined.

As shown by Figure 5 for well BJ-11 there appears to be no well-defined reservoir temperature. An equilibrium temperature of about 240°C is indicated for a few minerals. Several curves intersect below the equilibrium line at about 300°C, indicating that water of this reservoir temperature is being mixed with cooler geothermal water. For BJ-12, reservoir temperatures of about 240 and 300°C are displayed and mixing of water at different equilibrium temperatures is indicated.

Most of the minerals calculated appear to be undersaturated at the estimated reservoir temperature. Albite, calcite, microcline, wollastonite and analcime in well BJ-11 cross below the line at approximately reservoir temperature (300°C), suggesting that some mixing of colder thermal water in the reservoir is present. Prehnite, zoisite, epidote are also undersaturated at all the calculated temperatures. From a temperature of 250°C, the calculated undersaturation increases sharply for some unknown reasons.
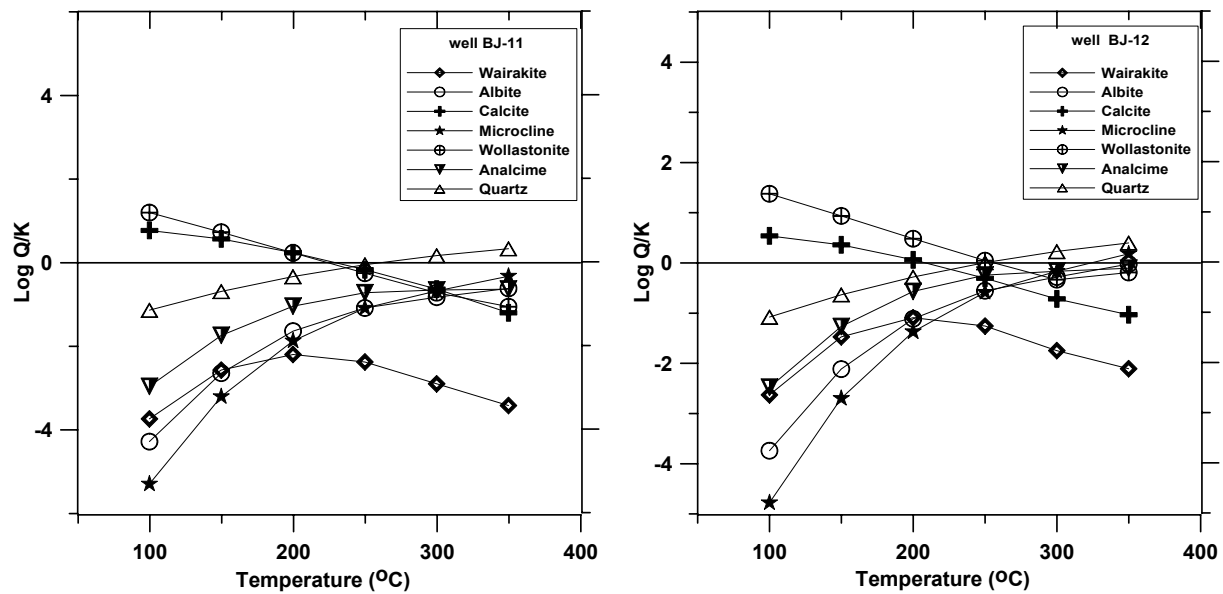
FIGURE 5:   Saturation index (log *Q/K*) vs. temperature calculated by the WATCH program
for water from wells BJ-11 and BJ-12 in the Námafjall area

For well BJ-12, the results are somewhat similar but indicate slightly higher temperatures and less mixing. At 250°C there appears to be equilibrium for some minerals. At about 300°C several curves intersect below the equilibrium line indicating mixing with a reservoir at this temperature.

3. MUTNOVSKY GEOTHERMAL FIELD

3.1 Geological setting and geothermal activity

The Mutnovsky geothermal field is a high-temperature geothermal area located 60 km to the south of Petropavlovsk-Kamchatsky in the southern part of Kamchatka peninsula (Far East Russia). It is connected with the Mutnovsky (Vilyuchinsky) center of volcano-magmatic activity. This region extends over approximately 30 km^2, consisting of active thermal manifestations associated with active volcanoes and high-temperature geothermal systems (Taran et al., 1992). It is restricted to the south by the composite construction of the Mutnovsky volcano with powerful high-temperature fumaroles, hot springs (with small mineralization of chloride-sulfate-sodium water) and steam vents at the crater and northern flank.

The Mutnovsky geothermal field is located on a high-reaching mountainous plateau at 700-900 m in immediate proximity of the active volcanoes Mutnovsky and Gorely. The system is associated with a volcanic graben in a zone crossed by deep, regional breaks sited to the northeast and below the meridion.

The Mutnovsky geothermal field is a liquid-dominated reservoir with fluid temperatures of 235-270°C (Kiryukhin and Pruess, 2000). Exploration drilling began in 1979. At present, 82 boreholes have been drilled in the area, 255-2266 m deep.

The Verkhne-Mutnovka power plant construction was proposed as early as in the middle of the 1970's, but these plans were not realised until in the 1990's. In 1999, two single flash turbines (3 MWe) and a binary cycle (6 MWe) were put into operation with a total capacity 12 MWe. Now, there are seventeen wells producing 330 kg/s of fluids with an average enthalpy of 1600 kJ/kg which are now ready for production.

3.2 Chemical data

In this report, data of the chemical composition of fumarolic gases from the Mutnovsky volcano (Taran et al., 1992), and data from temperature logs from wells in this area (Virkir-Orkint Consulting Group Ltd., 1994) are used. Two reservoirs were encountered by drilling, one of them at 500-800 m depth with temperatures of 230-240°C. The wells crossing this reservoir yielded steam or a steam/water mixture with very high enthalpy. The bottom reservoir at the depth of more than 1300 m consists of slightly mineralized chloride-sodium water (up to 1 g/l) with low gas content and high silica concentrations. Reservoir fluids contain approximately 1% non-condensable gas, dominantly CO_2 (50-95%) and N_2. Pressure conditions are close to two-phase and permeability is fracture-dominated.

3.3 Gas geothermometers

There are three individual groups of fumaroles in the Mutnovsky area. The *Active funnel* (temperatures exceed 600°C), the *Upper field* (up to 320°C) and the *Bottom field* (100-150°C) (Taran et al., 1992). Fumaroles of the *Active funnel* discharge much more sulfur. They also show maximum contents of HCl, HF and H_2. Fumaroles from the *Bottom field* also contain considerable amounts of sulfur, but CO_2-concentrations are higher. Haloid content in fumaroles of the northern area are higher as compared with those of gases in the southern area of the *Bottom field*. The *Upper field* is characterized by higher concentrations of CO_2, methane and ammonia.

For gas geothermometer calculations, fumarole data from these three parts of the Mutnovsky geothermal field were used, but unfortunately from different times. The temperatures were calculated by Equations 1-5. The results of these calculations are given in Table 5.

TABLE 5: Calculated gas geothermometer temperatures from fumaroles in the Mutnovsky area

	T_{CO2} (°C)	T_{H2S} (°C)	T_{H2} (°C)	$T_{CO2/H2}$ (°C)	$T_{CO2/N2}$ (°C)
AF 1983	303.6	309.8	282.9	260.4	252.1
UF 1984	322.4	313.8	242.2	170.1	283.3
SBF 1983	319.5	313.6	241.1	171.2	214.4
NBF 1988	321.6	316.6	230.6	150.9	286.2

The CO_2 and H_2S geothermometers give higher subsurface temperature, or ~ 300-320°C, than the H_2 and CO_2/N_2 geothermometers which compare very well and give almost the same temperatures of 240-280°C. The highest reservoir temperature in Mutnovsky is believed to be close to 300°C (Taran et. al., 1986). The highest measured temperature in the wells was about 280°C.   The calculated gas geothermometer temperatures compare well with real reservoir temperatures.

4. DISCUSSION AND COMPARISON OF THE GEOTHERMAL FIELDS

4.1 Námafjall geothermal field.

The H_2S and H_2 gas geothermometers give almost the same temperature, around 270-280°C, for both production wells. In fumaroles, the H_2S-CO_2 gas geothermometer gives similar temperatures, 260-270°C, whereas the CO_2/H_2 geothermometer gives higher temperatures, about 320°C, which is considerably higher than the real reservoir temperatures.

The Na-K-Mg triangular diagram and Cl-SO$_4$-HCO$_3$ triangular diagram both reveal the chemical changes occurring in the system from 1989 to 1999. The water chemistry of the wells in the Námafjall area from 1989 still shows effects of volcanic intrusions into the reservoir in 1977, but a gradual change is seen back to more stable conditions during the period from 1995 to 1999 as prevailed prior to the volcanic influx. Geothermometer results calculated with the WATCH computer program give a Na-K temperature of about 220-250°C. It is similar to the Na/K geothermometer temperature deduced from the Na-K-Mg triangular diagram (240-260°C).

The log *Q/K* diagram suggests that most of the minerals are undersaturated at temperatures from 100 to 350°C, but indicate mixing of the 300°C water with colder water.

4.2 Mutnovsky geothermal field.

The H$_2$ and CO$_2$/N$_2$ gas geothermometers give almost the same temperatures, 240-280°C, whereas the CO$_2$ and H$_2$S geothermometers give higher temperatures of 300-320°C.

The main difference between the two geothermal fields is that the Mutnovsky geothermal field has significally different gas chemistry such as in N$_2$ concentration which is considerable higher indicating a fast circulation of local groundwater. The fumarolic steam is also more influenced by magmatic gases like HCl, HF and H$_2$ than in the Námafjall geothermal field.

5. SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

The main aims of this project were to interpret chemical data from high-temperature geothermal fields; to predict the subsurface temperatures by calculating geothermometer and gas geothermometer temperatures from well data and from fumaroles and to compare those with real data on subsurface temperature. The main conclusions are the following:

• Few data from Kamchatka were available, therefore the main emphasis was laid on data from the Námafjall area in Iceland which has many similarities to the geothermal areas in Kamchatka.
• Significant changes occurred in the chemical composition of water from wells BJ-11 and BJ-12 (Námafjall) during 1989 to 1999. The Cl content increased whereas SO$_4$ decreased. This is interpreted as being caused by inflow of a shallow aquifer before 1989 due to the volcanic activity in the area and a recovery period up to 1995 when the chemistry gradually moved towards more mature waters.
• The reservoir temperature for the Námafjall wells, when calculated with quartz-geothermometry equations, is higher than for other geothermometers, but is slightly lower than measured aquifer temperatures.
• The CO$_2$ gas geothermometer measurements from the Mutnovsky area fumaroles give higher subsurface temperatures than those for Námafjall. The H$_2$ and CO$_2$/N$_2$-gas geothermometers show almost the same temperatures as the measured ones. Experience will show which geothermometers are the most reliable for exploration in geothermal fields in Kamchatka.
• In my opinion, when experience is gained and a long data range obtained from fumaroles in the geothermal fields in Kamchatka, we can estimate with greater certainty the changes of subsurface temperatures using gas geothermometers.
• The Institute of Volcanology has a project of monitoring the Paramushirsky geothermal system in the Kuril Islands. In this area the government plans to build a power plant (up to 15 MWe). Here data from fumaroles and wells are available. In my view, it would be useful to continue geothermal studies similar to this project for that area.

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