GEOCHEMICAL INTERPRETATION OF THERMAL FLUIDS FROM THE ARBAER LOW-TEMPERATURE FIELD, S-ICELAND

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ABSTRACT

Various physical and geological processes define the chemical properties of different geothermal fluids. Thermal waters ascending in geothermal systems may cool due to conduction of heat to the surrounding rocks; mixing with cooler water; boiling; or by more than one of these factors or a combination of them. In the same way, the origin of groundwater can make a difference to the final chemical composition. In this study, attempts are made to understand the different processes taking place in the Arbaer low-temperature geothermal field in the Southern Lowlands of Iceland, using all information available on the chemistry of the thermal fluids produced from the field. Applying different geothermometry and mixing models, it is estimated that the reservoir temperature may be as high as 170°C. The geothermal fluids are believed to originate partly from local heat-mining within the geothermal field and partly from sources far inland.

1. INTRODUCTION

Arbaer is a small geothermal field in the Quaternary rocks of the Southern Lowlands of Iceland (Figure 1). The geothermal areas in Iceland are conventionally divided into high-temperature and low-temperature areas. High-temperature areas typically reach more than 200°C at 1 km depth and they are only found within the active volcanic rift zones (Flovenz and Saemundsson, 1991). According to this classification the Arbaer field is a low-temperature area, with a maximum temperature of 140°C at 935 m depth in one of the wells. The average temperature gradient of the field is 168°C/km between 200 to 450 m where the temperature increases constantly from approximately 50°C at 200 m to 92°C at 450 m. Between 450 to 935 m, the gradient is only 95°C/km (Flovenz et al., 1985). Several wells have been drilled in the area, but so far the drilling results have been rather disappointing.

The object of the present study is to estimate the reservoir temperature and to study the possible physical processes controlling the chemistry of the geothermal fluids in the field.

2. GEOLOGY AND STRUCTURES CONTROLLING THE AQUIFERS

Quaternary regions of Iceland are characterized by a continuous succession of hyaloclastite piles from glacial times and interglacial lava flows (Saemundsson, 1979). In the Southern Lowlands the inter-glacial basalts dip a few degrees westnorthwest towards the volcanic belt, and the dip increases a little eastward, i.e. as one moves into older formations. The area is extensively faulted, NNE-SSW striking faults being most common, running approximately parallel to the volcanic belt. Younger fractures striking ENE-WSW and N-S are also relatively common in the area (Georgsson et al., 1988). In the southern part of the area recent N-S en echelon fractures occur on an E-W belt coinciding with a major transcurrent fault (Einarsson, 1989). Large earthquakes associated with movement on this fault occur about every hundred years or so. At several

FIGURE 1: Location of the Arbaer low-temperature field (Torfason, 1987)

geothermal sites in the Southern Lowlands there is conclusive evidence of movement of fractures in post-glacial times (Georgsson et al., 1988; Bjornsson et al., 1990). However, in Plio-Pleistocene strata the major aquifers tend to be horizontal and occur most commonly at the contacts of lithological units such as lavas and hyaloclastites (Fridleifsson, 1979). Flovenz and Saemundsson (1991), described the low-temperature areas in Iceland as fracture dominated systems, which draw heat from the normal heat flow, by active and localized convection in near vertical fractures. Outside these fractured zones the bedrock is quite dense and heat transfer is dominated by conduction. A temperature log from well 4n located in the northern part of the Arbaer field, illustrates very clearly the process of heat-mining (Figure 2). It is evident from Figure 2 that at a depth below 180 m, the temperature of the bedrock is much lower than should be expected from the temperature gradient of the field.
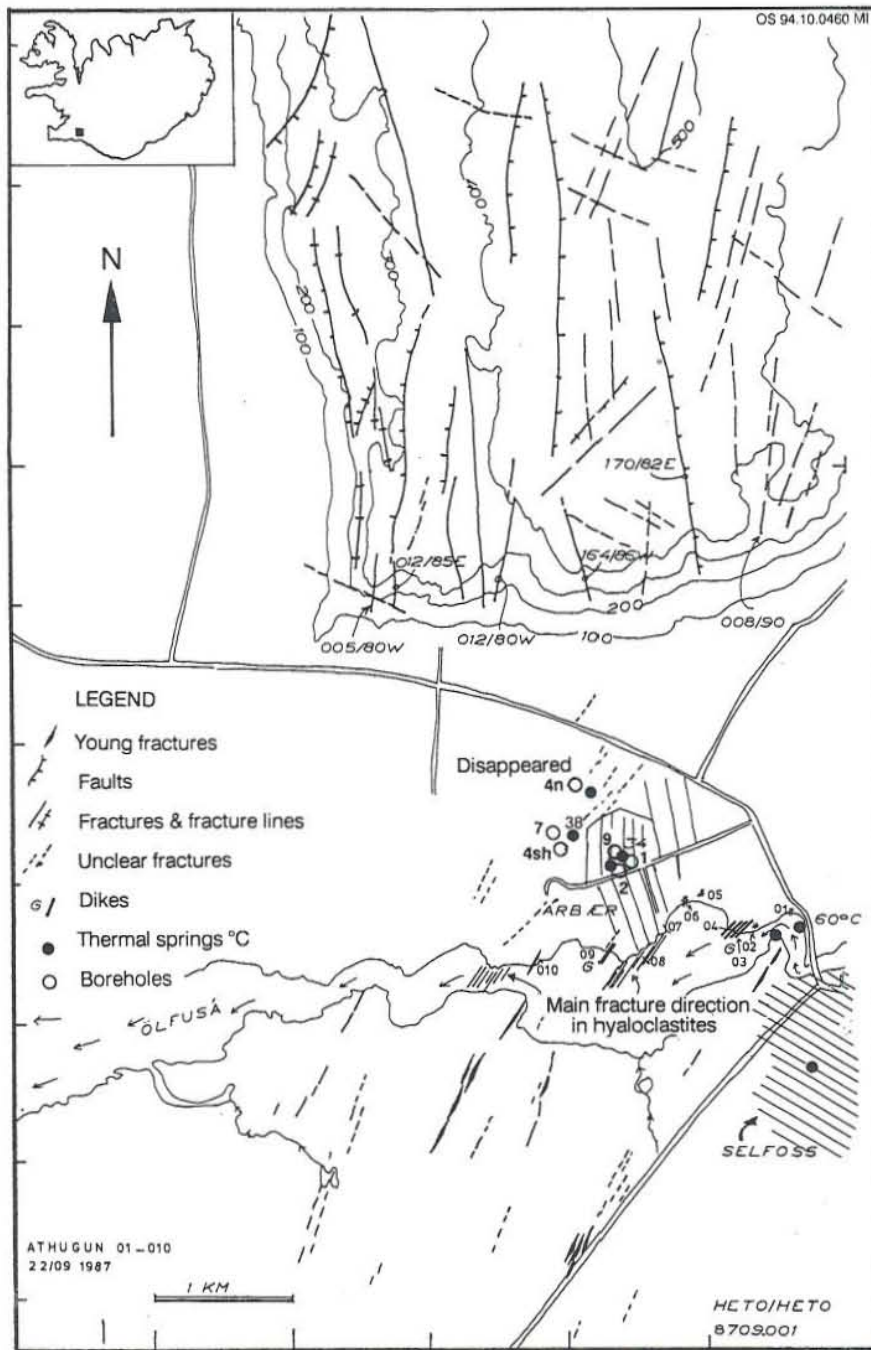
3. GEOTHERMAL EXPLORATION AND DRILLING HISTORY

Very little has been written about the Arbaer area, particularly. The following information has been obtained from two reports from Orkustofnun - The National Energy Authority (Flovenz et al., 1985 and 1990).

3.1 Surface manifestations and geological setting

In March 1980, three warm springs were located. The first was in a marsh around wells 1 and 2 (Figure 1) with a measured temperature of 34°C at 3 m depth. The second was 500 m west of the first spring with a temperature of 38°C. The third was located a few hundred meters northeast from the second, but disappeared after well 1 was drilled.

The geology in Arbaer was investigated by Eiriksson in 1973, who reported that the bedrock belongs to what is called "Hreppamyndun", which is intercalated layers of lava flows and hyaloclastites. They are tilted approximately 5-10° to the northeast, and as dykes are most likely to be at a right angle to the lava layers, they are supposed to be tilted about 10° from vertical.

FIGURE 2: Temperature profile of well 4n at Arbaer

A few faults have been located in the northern bank of the river Olfusa which point directly to the warm springs close to wells 1 and 2. The faults are tilted to the east, but to which degree is not known. Some poorly visible fractures were also located in the southern bank of the river. The general trend for these fractures is northnortheast, towards the warm springs in Arbaer.

3.2 Temperature measurements

In August 1985, near surface temperature measurements, were carried out at Arbaer, at the depth of 0.5 m with 5 m intervals. According to these, anomalies were detected at two sites; near wells 1 and 2 and 400 m west of them. Temperature measurements performed in the shallow and deep wells indicate average temperature gradient of more than 140°C/km (up to 168°C/km).

3.3 Magnetic measurements

Low-temperature geothermal activity in Iceland is commonly associated with dykes or faults. Hence, magnetic mapping was done to locate dykes in vicinity of wells 1 and 2. The measurements were carried out along 16 lines, each 480 m long, located at a right angle to the main dyke direction. The temperature anomaly around well 1 and 2 seems to be associated with a northeasterly trending dyke. The dyke is probably tilted to the east, so wells to the west of the dyke do not intersect it. The magnetic measurements showed another dyke trending north, closer to well 7. They also indicated a depth of 5-10 m to the bedrock in the area.
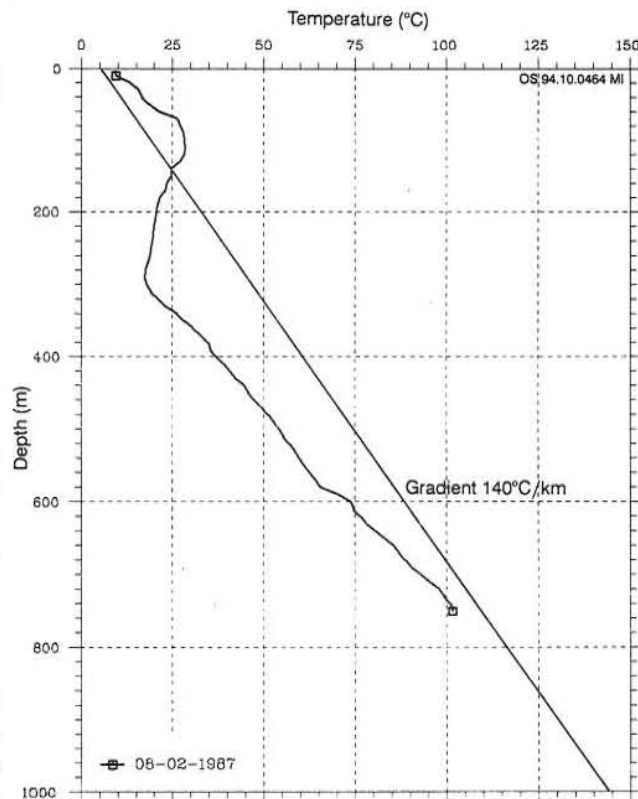
3.4 Resistivity measurements

In 1985, four head-on resistivity lines were measured. Interpretation suggested a fracture close to the western border of the field (well 7) with a northnortheastarly direction. It is believed that this fracture feeds the warm springs in this area, but it is not connected to the dykes in the neighbourhood. Weak indication of another fracture was found 100 m west of well 2, but it could be related to a dyke. A weak indication of a fracture containing water, was observed close to well 1, but this signal may also relate to the casing or the hot water pipe from the well.

3.5 Drilling history

Resistivity as well as temperature measurements, reveal a considerable geothermal reservoir at Arbaer, but drilling results have been disappointing. So far twelve wells have been drilled in the area, four deep wells and eight shallow wells. Now, only two of these wells are used with a total free flow of 5 l/s and measured temperatures of 67°C and 104°C. These are wells 2 and 9, respectively.

The first well was drilled in 1964 with a total depth of 463 m, but only 13.7 m of the uppermost part were cased. A considerable amount of 33°C water was encountered in the upper most loose layers, but at a depth of 17 m there was an increase in the temperature to 36°C followed by a slight increase in the temperature or the amount of flow down to the main aquifer at 451 m. At the end of drilling the discharge was estimated to be 5 l/s of 85°C water. According to the owner, well 1 yielded 5 l/s of 92°C in December 1976. In the summer of 1985 the measured discharge was 3 l/s of 82°C water.

Well 2 was drilled in 1971 with a total depth of 956 m. Two relatively small aquifers at 95 and 113 m and a major one between 132-138 m with a complete loss of circulation, were recorded. All these aquifers were completely sealed of by concrete, down to 224 m. In addition some small aquifers were noticed at 463, 685, 740 and 765 m. Before stimulation the discharge was 1.5 l/s of 94°C water. It is to be noticed that during the drilling, well 1 was constantly discharging about 4 l/s. Stimulation did not increase the flow but increased the temperature and it also showed a direct connection between well 1 and well 2, most likely at a depth of 315-400 and 425-465 m.

To locate the third production well (well 7), four shallow wells were drilled, in addition to the soil temperature measurements and the magnetic resistivity surveys, mentioned above. Well 7 was drilled in the hope of hitting the low resistivity structure defined by the resistivity survey. It was drilled in December 1985 and January 1986 with a total depth of 720 m. Small aquifers were observed at 47-50, 57-64 and at 104 m with a temperature of approximately 45°C. A flow of 0.5-1 l/s at 200 m, and 0.5 l/s at 293 and at 525 m was recorded. The total free flow was less than 1l/s of about 45°C. Shortly after that, in 1987, the recorded temperature was 52°C. However, in August 1994, the water had cooled to 43.6°C and the flow decreased to 0.1 l/s.

Before drilling the fourth production well (well 9), well 8 was drilled in 1986 as an observation well. Finally well 9 was drilled in 1987 with a total depth of 500 m as a replacement for well 1, which is totally closed. An aquifer of 4 l/s at 19 m, another one less than 1 l/s at 200 m, and a bigger feed zone of 10-30 l/s, below 400 m, were noticed during drilling. Temperature measurements after drilling but before casing showed downflow from the shallow aquifer at 19-23 m with 40°C hot water, to the middle aquifer at 123 m and an upflow of 83°C hot water from the deeper zone at 437 m to the same aquifer at 123 m. The well was cased down to 147 m but the cementing was unsuccessful so now water is leaking outside the casing, from the 19-23 m aquifer, into the aquifer at 123 m and the water flow inside the casing from the deeper aquifer at 437 m is cooled due to the outside downflow. So, the temperature of the water in the well decreased from 83 to 72°C on its way to the surface. Recent measurements, in August 1994, show an even lower temperature of 66.7°C. It is worth mentioning that a free flow of 5 l/s was recorded just after drilling.

4. CHEMICAL CHARACTERISTICS OF GEOTHERMAL FLUIDS

The composition of thermal fluids depends on many factors. The most important are temperature dependent reactions between host rock and fluid. Leaching also plays an important role when the amount of a particular constituent is too small to achieve an equilibrium. At the same time, mixing, boiling and cooling have a recognizable influence on the final composition of thermal fluids.

Chemical analyses of 15 samples from the Arbaer area are the data base for the present study. The chemical composition of all samples is listed in Table 1. Three of them represent cold surface water from Olfusa river and a cold spring at the foot of Ingolfsfjall and twelve represent geothermal wells of different depths taken through the last thirty years.

A first glance of the chemical composition points to dilution with respect to well depth, as total dissolved salts increase with depth, down to the major feed zones. The low TDS values also indicate the meteoric origin of thermal fluids in Arbaer.

TABLE 1: Chemical analyses of thermal and cold waters from Arbaer (ppm)

Sample no.	Well no.	T.D.S.	pH/t °C	CO2	H2S	B	SiO2	Na	K	Mg	Ca	F	Cl	SO4	Al	Fe	δ D	δ^{18}O
87-0017	2	432,2	9.32/22.8	33,1	2,28		140,9	102,9	3,04	0,026	2,71	0,888	50,29	91,37		0	-63,88	-9,16
68-3272	1	311	8.8/96	18	0,9	0,66	102	68,2	1,4	0,05	1,9	0,8	35,2	42,9				
75-0083	1		9.67/20	29,7	0,68		95											
79-3010	1	395	9.51/20	36,6	0,3	0,14	83,7	62,6	1,62	0,042	1,54	0,51	24	28,2	0,19	0,0042		
87-0018	1	232,6	9.64/22.8	33,9	0,19		72	55,05	1,15	0,011	1,45	0,447	20,89	24,9		0	-57,12	-8,59
94-0163	9	179	9.41/24.5	32	0	0,19	63,5	50,9	0,82	0,007	1,45	0,34	18	17,9				
85-0375	7	289,4	9.81/21.2	31,4	0,63		98,76	64,04	1,35	0,018	3,35	0,664	25	32,35				-8,7
87-0014	7		9.75/18.5	33,4	0,19		76,72						18,12	18,98				
87-0016	7	202,7	9.72/22.8	34,2	0,25		77,65	53,4	0,9	0,024	1,66	0,463	17,61	19,3		0	-57,24	-8,6
94-0164	7	189	9.55/24.5	33,66	0	0,21	74,9	53,3	0,74	0,004	1,63	0,42	18,4	17,7				
85-0376	4 sh.	180,5	9.86/21.2	28,1	0		53,19	45,14	0,75	0,018	2,04	0,498	16,08	17,22				-8,78
89-0004	4	117,8	9.5/22.4	40,6	0	0,04	32,5	35,8	0,44	0,043	3,13	0,192	10,76	6,02	0,023		-54,13	-8,15
9039-S.A.	Ölfusa					0,0045	14,5	7,7	0,65				5,1	3,13			-67,7	-9,7
83-9110	Ölfusa		7.67/21	23,64	0		13,92	9,33	0,76	1,76	4,18	0,083	5,81	3,01				-10,3
87-9013	cold sp.	71,3	7.95/22.8	25,8	0		14,41	10,21	0,4	0,982	7,33	0,074	9,31	2,49		0,17	-55,3	-8,46

Sulphate is the dominant anion in three of the samples from well 2 and the first samples from wells 1 and 7, but in all other samples carbonate (represented as CO_2) is the dominant anion as well as in cold water samples. Sodium is the dominant cation in all samples. There seems to be a good relation between temperature of thermal fluids and the concentration of all cations and anions. Correlation is best with F, Cl, Na, K and Ca, and to a lesser degree with Mg, B, H_2S, SO_4 and CO_2. Silica, represented as SiO_2, shows a very good correlation with temperature, as it decreases with decreasing temperature. Also, δD and δ^{18}O in thermal water decreases with decreasing temperature. The hottest thermal water from well 2 has isotope values approaching the river values. All thermal waters possess a pH higher than 9. Also, pH tends to increase with decreasing temperature. Concentrations of different constituents tend to be in the Icelandic range for low-temperature areas.

4.1 The Schoeller diagram

For a more careful study of the geothermal waters, the Schoeller diagram has been used to examine how the samples correlate to each other, and to cold water in the field. Giggenbach's (1991) triangular diagrams were used to define both the equilibrium state of thermal fluids and the most dominant cation and anion.

Truesdell (1991), suggested using the Schoeller diagram as an introduction to the water chemistry of the area and as an effective tool for showing mixing of different waters. The diagram compares the log concentrations of fluid constituents from a number of analyses, with constituents of each analysis connected with a line, and because logarithmic values are used, a wide range of concentrations can be shown. He also explained that the effect of mixing with dilute water (as well as gain or loss of steam) only displaces vertically the line representing an analysis, without changing its shape.
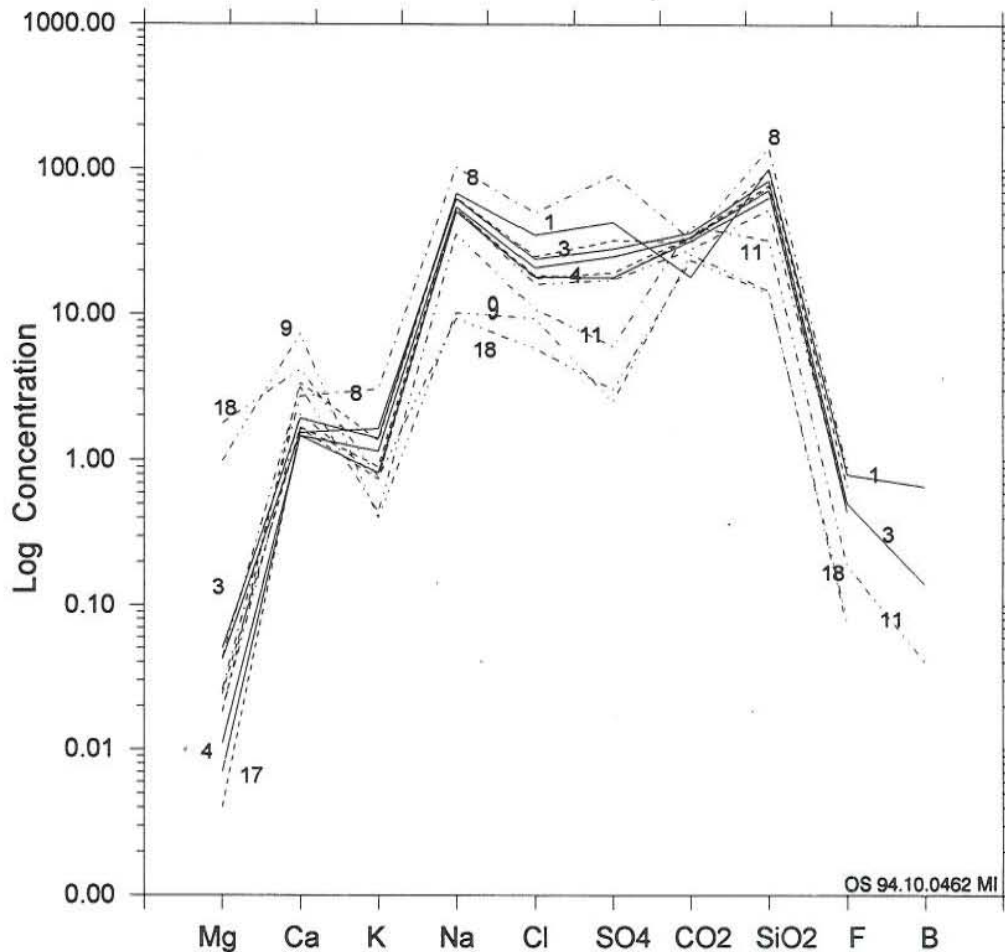
FIGURE 3:   Schoeller diagram for cold and thermal water in Arbaer

Figure 3 shows a clear graduation from the hottest thermal fluid produced from well 2 (sample no. 8), to the coldest thermal fluid produced from well 4 north of the field (no. 12), approaching the river water composition more than the cold spring to the north of the field. This is more or less true for most constituents except total carbonates, represented as CO_2, as well as calcium and magnesium. So, the Schoeller diagram suggests mixing between thermal water and more dilute water. This is probably the case of the regional groundwater coming from a far inland precipitation. Olfusa carries the same characteristics as the runoff water coming from the nearby mountain.

4.2 δD and $\delta^{18}O$ isotopes in thermal fluids

When water evaporates from the ocean under equilibrium conditions, the vapour should be depleted by about 80‰ in deuterium and 9‰ in $\delta^{18}O$ relative to the ocean water. However, this is also controlled by geographical and time variations. The deuterium concentration of the precipitation in Iceland varies significantly from one place to another. This suggests the possibility of using deuterium as a natural tracer to estimate the recharge areas of groundwater systems and to study their flow patterns. When a sample of

groundwater discharging from either a cold or a hot spring which has a deuterium value similar to the mean value of the local precipitation, this can indicate a local origin of the groundwater (Arnason, 1976). The use of deuterium as a natural tracer in groundwater studies is based on the assumption that the groundwater is derived from precipitation and that the deuterium content of the water does not change in the ground. Furthermore, the method assumes that the deuterium value of the precipitation has not changed significantly since the water fell as precipitation. Also, Arnason (1976) concluded that deuterium -$\delta^{18}O$ relations obtained from samples of hot and cold water in Iceland supports the opinion that the groundwater is almost entirely of meteoric origin. He also mentioned that the stable isotope content of the precipitation has not changed significantly during the last 8000 years, so deuterium values of groundwaters younger than 8000 years should be comparable to the values of the present deuterium map of Iceland. Comparison of deuterium content of a deep ice core with $\delta^{18}O$ content of a more recent ice core, indicates that precipitation deposited between 10.000 to 60.000 years ago was -50‰ to -100‰ lower in deuterium, than today. However, the deuterium measurements suggest that groundwaters in Iceland are younger than 8.000 years.

In Arbaer, deuterium and $\delta^{18}O$ of the hottest water indicate a far inland origin which is also very close to the values of the river water. All other samples have isotopic ratios closer to the values of local cold water, but slightly more negative. This suggests mixing with local cold water at shallow depths (Fournier, 1981; Arnorsson, 1985).

4.3 Changes to the main feed zone with time and depth

Two plots are used to evaluate chemical changes within the Arbaer geothermal field. Figure 4, indicates that most constituents in the water from well 1 have decreased with time. The sample dated 1994 is from well 9, which was drilled as a replacement to well 1, cutting the same feed zones at the same depth. Figure 5 shows that the chemical constituents of the thermal waters increase with depth to the main aquifers of the wells. Well 4 to the north of the geothermal field is closest to the local cold water recharge area and shows the lowest concentration of all chemical constituents. Figure 5 also shows that well 2 is affected by conductive cooling, as the well-head temperature is lower than expected from temperature logs for the well.
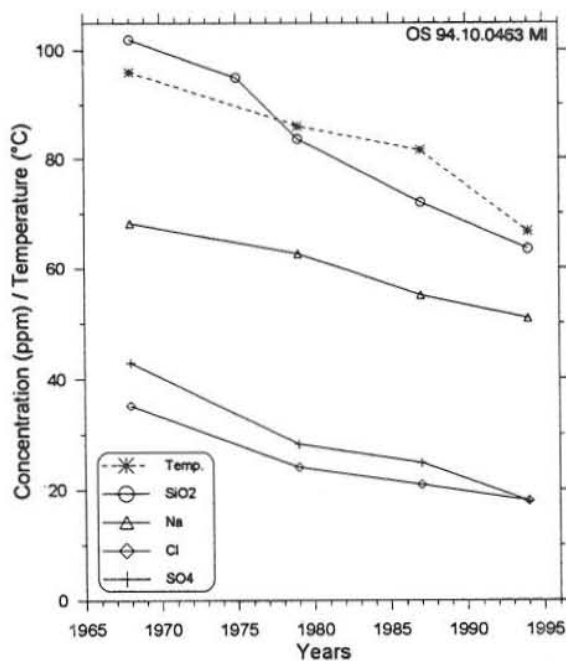

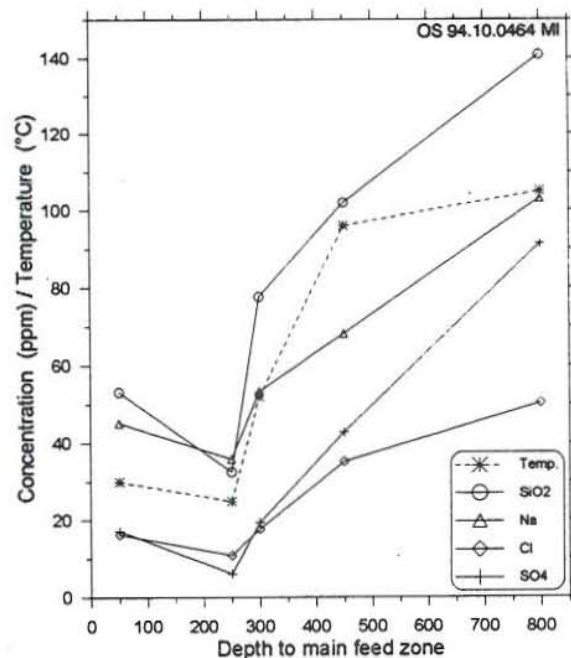
FIGURE 4:   Chemical changes with time in well 1

FIGURE 5:   Changes due to depth to main feed zone in wells

4.4 Triangular diagrams

Two different triangular diagrams were made for the chemical data from Arbaer in order to look for correlation between various constituents. The first compares the most common anions, while the second compares the cations.

The Cl-SO₄-HCO₃ diagram: This diagram was decribed by Giggenbach (1991) for an initial "eyeball" assessment of correlations among sets of various constituents. The position of a data point in such a triangular plot is obtained by first forming the sum S of the concentrations C_i (in mg/kg) of the three constituents involved.

$$S = C_{Cl} + C_{SO_4} + C_{HCO_3}$$

After that, the "%-Cl" and "%-HCO₃" are calculated. This diagram resembles the popular diagram proposed by Piper (1944) 50 years ago, for classification of natural waters. The present diagram provides an initial indication of mixing relationships or geographic groupings, e.g. Cl waters forming a central core grading into HCO₃ waters towards the margins of a thermal area. Also, high SO₄ steam-heated waters are usually encountered over the more elevated parts of a geothermal field. The degree of separation between data points for high chloride and bicarbonate waters already gives an idea of the relative degree of interaction of the CO_2 charged fluids at lower temperatures, and of the HCO₃ contents increasing with time and distance travelled underground. Figure 6 indicates that the hottest samples are sulphate waters, which with time become bicarbonate waters approaching the cold water from shallow feed zones.
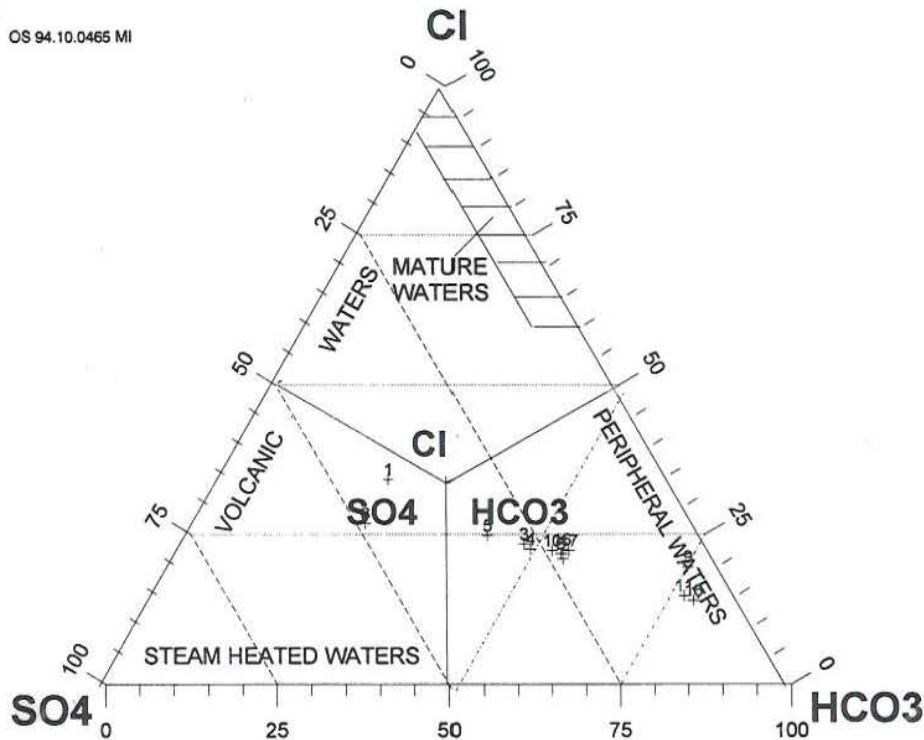

FIGURE 6: The Cl-SO₄-HCO₃ diagram for the Arbaer waters

The Na-K-Mg diagram: This diagram has been provided by Giggenbach (1988). As in the other triangular diagram, the sum is calculated to evaluate "%-Na" and "%-Mg", where C_i is in mg/kg:
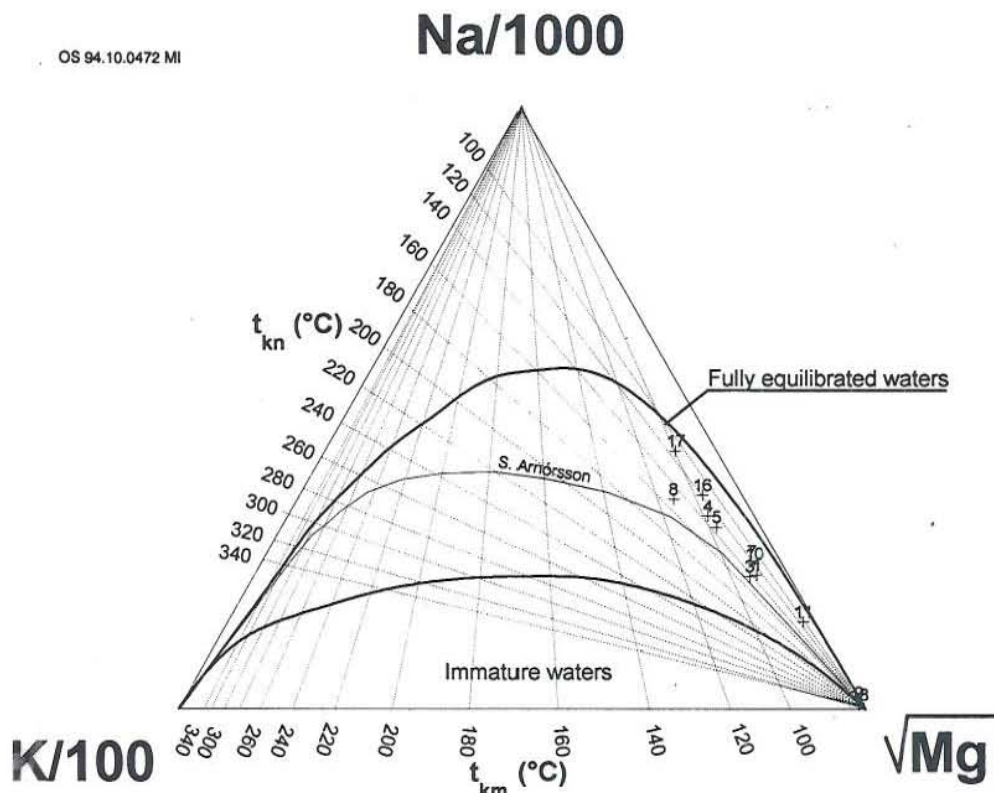
$$S = C_{Na}/1000 + C_K/100 + \sqrt{C_{Mg}}$$

FIGURE 7: The Na-K-Mg diagram for the Arbaer waters

The main advantage of this diagram is its ability to picture the position of a large number of samples simultaneously permitting delineation of mixing trends and groupings. It separates well the position of waters resulting from the two end member processes, rock dissolution and equilibration. However, applying this diagram to the Arbaer data indicates that all samples are partially equilibrated waters, and all thermal and cold waters fall near the Mg corner indicating a reservoir temperature t_{kn} between 100-150°C and t_{km} less than 120°C (Figure 7). With time samples move a little up toward the line of fully equilibrated water suggested by Giggenbach, and a little away from the line suggested by Arnorsson (1991) for fully equilibrated waters in Iceland. This shows that Giggenbach's line is more appropriate than Arnorsson's line for the Arbaer geothermal area, as Arnorsson's line indicates boiling in all thermal water samples (all points are above the line) which is difficult to explain, based on the estimated subsurface temperatures and the expected pressure of the production depth. From the experience gained in Iceland, Armannsson (pers. com.) suggested that Giggenbach's curve is more suitable for low-temperature waters than Arnorsson's curve.

5. GEOTHERMOMETRY

One of the major applications of geochemistry in the investigation of geothermal resources involves prediction of subsurface temperature using chemical geothermometers. It is useful to recognize two things. First, that in up-flow zones below hot springs or shallow drillholes, cooling of the water may occur by conduction, boiling and/or mixing with cooler water. Second, that temperatures in geothermal reservoirs are generally not homogeneous, but variable, both horizontally and vertically. So, chemical geothermometry can, at its best, be expected to reveal the temperature of the aquifer feeding the drillhole. Temperatures encountered in deep drillholes may be higher than those indicated by chemical geothermometry, particularly if they are fed by shallow aquifers (Arnorsson, 1991). Silica geothermometers and cation geothermometers, as suggested by different authors, have been used to predict the possible subsurface temperatures for the Arbaer geothermal area.

5.1 Silica geothermometers

The silica temperature is the equilibrium temperature between quartz or chalcedony and the unionized silica in the thermal fluid. Experience shows that chalcedony temperature is more reliable in low-temperature waters than quartz. In Iceland, equilibrium is attained between dissolved silica and quartz at temperatures higher than 180°C and with chalcedony at temperatures below 180°C (Arnorsson, 1975).

However, both quartz and chalcedony geothermometers were used to estimate subsurface temperatures. The following equations were used;

Quartz - no steam loss (Fournier, 1973)

$$t°C = \frac{1309}{5.19 - \log S} - 273.15 \tag{1}$$

Quartz - maximum steam loss at 100°C (Fournier, 1973)

$$t°C = \frac{1522}{5.75 - \log S} - 273.15 \tag{2}$$

Chalcedony - no steam loss (Fournier, 1977)

$$t°C = \frac{1032}{4.69 - \log S} - 273.15 \tag{3}$$

Chalcedony - maximum steam loss at 100°C (Based on Fournier, 1977)

$$t°C = \frac{1182}{5.09 - \log S} - 273.15 \tag{4}$$

Chalcedony - no steam loss (Arnorsson et al., 1983)

$$t°C = \frac{1112}{4.91 - \log S} - 273.15 \tag{5}$$

Chalcedony - maximum steam loss at 100°C (Arnorsson et al., 1983)

$$t°C = \frac{1264}{5.31 - \log S} - 273.15 \tag{6}$$

Calculations for all six silica geothermometers are shown in Table 2. Considering that the downhole temperature measured in the deepest aquifer in well 2 is about 128°C, there seems to be good agreement with chalcedony geothermometers, indicating a temperature range of 127 to 133°C. For the coldest wells, chalcedony indicates a subsurface temperature of 52 to 60°C (Table 2). The temperature range assumed by chalcedony is largest for the hottest and lowest temperatures encountered within the field, which may suggest other processes than conductive cooling, affecting thermal fluids composition, such as mixing with cold water near the surface. Relating silica geothermometers to time, we can see that they reflect a decrease in temperature with time compared to the measured temperatures. This means that the cooling observed may be due to mixing of hot and cold water.

TABLE 2:   Results of silica geothermometer calculations for the Arbaer waters

Sample no.	pH / 20°C	Enthalpy	SiO2 (ppm)	t °C (1)	t°C (2)	t°C (3)	t°C (4)	t°C (5)	t°C (6)	meas. t°C	label no
87-0017	9,374	440	140,9	157,29	149,50	132,98	128,74	129,59	126,71	105	8
68-3272	9,946	402	102	138,30	133,65	111,72	110,44	110,11	109,72	96	1
75-0083	9,67		95	134,35	130,32	107,34	106,64	106,08	106,17		2
79-3010	9,51	360	83,7	127,49	124,52	99,78	100,04	99,10	100,01	86	3
87-0018	9,692	341	72	119,63	117,84	91,17	92,49	91,12	92,94	81,5	4
94-0163	9,502	278	63,5	113,30	112,44	84,29	86,42	84,73	87,25	66,7	16
85-0375	9,833	180	98,76	136,50	132,13	109,72	108,70	108,27	108,10	43	5
87-0014	9,721		76,72	122,91	120,63	94,75	95,64	94,44	95,89		6
87-0016	9,772	218	77,65	123,53	121,16	95,44	96,24	95,08	96,46	52	7
94-0164	9,643	182	74,9	121,66	119,57	93,39	94,44	93,18	94,77	43,6	17
85-0376	9,883	126	53,19	104,72	105,06	75,01	78,20	76,08	79,51	30	10
89-0004	9,541	104	32,5	82,74	85,97	51,57	57,19	54,09	59,65	24,8	11
9039-S.A.		25,21	14,5	51,77	58,54	19,31	27,72	23,49	31,53	6	13
83-9110	7,677	14,5	13,92	50,35	57,26	17,85	26,37	22,10	30,23	3,4	18
87-9013	7,974	10	14,41	51,56	58,34	19,09	27,51	23,28	31,33	2,4	9

5.2 Cation geothermometers

Cation geothermometers are also widely used to estimate subsurface temperatures. They are based on ion exchange reactions with temperature dependent equilibrium constants. Different empirical geothermometers for the exchange of Na and K between the co-existing alkali feldspars have been proposed by different authors, but all of them lie between the albite-adularia and albite-microcline curves on a log (Na/K) versus temperature diagram. Comparing thermal waters from Arbaer with such curves indicates the use of Giggenbach's (1988) or Fournier's (1979a) Na/K geothermometer for well 2 and the first sample from well 1, but Arnorsson's et al. (1983) Na/K geothermometer for all other samples. The following five Na/K geothermometers were calculated:

Na-K (Truesdell, 1976)

$$t°C = \frac{856}{0.857 + \log Na/K} - 273.158 \tag{7}$$

Na/K (Fournier, 1979a)

$$t°C = \frac{1217}{1.483 + \log Na/K} - 273.15 \tag{8}$$

Na/K (Tonani, 1980)

$$t°C = \frac{883}{0.780 + \log Na/K} - 273.15 \tag{9}$$

Na/K (Arnorsson et al., 1983)

$$t°C = \frac{933}{0.993 + \log Na/K} - 273.15 \tag{10}$$

Na/K (Giggenbach, 1988)

$$t°C = \frac{1390}{1.750+\log Na/K} - 273.15 \tag{11}$$

Results of these cation geothermometers are shown in Table 3. There is little agreement between different geothermometers and they suggest a wide range between 85 and 150°C for the hottest water (well 2), and even wider at lower temperatures like in well 4 to the north of the field, where they range between 35 and 106°C. Although these results do not give much help, they still support the theory of mixing. Also, all Na/K geothermometers used, give a higher temperature for the third and fourth sample from well 1, which is probably due to hot water contribution from well 2 through the connection between the two wells at about 450 m depth as reported in the drilling report of well 2.

TABLE 3: Results of Na-K geothermometer calculations

Sample no.	pH/20°C	Na (ppm)	K (ppm)	Mg (ppm)	Ca (ppm)	t°C (7)	t°C (8)	t°C (9)	t°C (10)	t°C (11)	meas. t°C	label no.
87-0017	9,374	102,94	3,04	0,026	2,71	84,66	130,81	109,15	96,69	150,67	105	8
68-3272	9,946	68,2	1,4	0,05	1,9	62,46	110,68	84,68	74,90	131,20	96	1
75-0083	9,67											2
79-3010	9,51	62,6	1,62	0,042	1,54	76,27	123,26	99,89	88,47	143,38	86	3
87-0018	9,692	55,05	1,15	0,011	1,45	63,46	111,60	85,78	75,89	132,09	81,5	4
94-0613	9,502	50,9	0,82	0,007	1,45	49,13	98,35	70,04	61,75	119,18	66,7	16
85-0375	9,833	64,04	1,35	0,018	3,35	63,98	112,08	86,36	76,40	132,56	43	5
87-0014	9,721											6
87-0016	9,772	53,4	0,9	0,024	1,66	51,53	100,59	72,68	64,12	121,37	52	7
94-0164	9,643	53,3	0,74	0,004	1,63	41,46	91,17	61,64	54,16	112,16	43,6	17
85-0376	9,883	45,14	0,75	0,018	2,04	50,76	99,88	71,84	63,37	120,67	30	10
89-0004	9,541	35,8	0,44	0,043	3,13	35,44	85,48	55,05	48,19	106,59	24,8	11
9039-S.A.		7,7	0,65			169,20	202,88	203,23	178,32	219,13	6	13
83-9110	7,677	9,33	0,76	1,76	4,18	165,68	200,01	199,28	174,96	216,45	3,4	18
87-9013	7,974	10,21	0,4	0,982	7,33	104,06	147,96	130,61	115,61	167,15	2,4	9

5.3 Solution-mineral equilibria

Reed and Spycher (1984) have taken a somewhat different approach to geothermometry. Their approach involves the evaluation of the saturation state of a particular water composition with a large number of minerals as a function of temperature. If a group of minerals is close to equilibrium at one particular temperature, the conclusion is that the water has equilibrated with this group of minerals and the temperature represents the aquifer temperature. Mixed waters and waters which are not close to equilibrium with hydrothermal minerals, like surface waters, are characterized by lack of apparent equilibration for many minerals at a particular temperature.

An aqueous speciation programme WATCH (Arnorsson et al., 1982; Bjarnason, 1994) has been used to construct mineral equilibria diagrams (Figures 8, 9, 10). These diagrams indicate that the thermal waters in Arbaer are not close to equilibrium with hydrothermal minerals. This again reflects that mixing of different waters plays an important role in the chemical composition of the thermal waters in the Arbaer geothermal field. The figures also indicate an "old" equilibrium state for some of the minerals, represented by crossing of their lines at log (Q/K) less than zero. This suggests some degree of equilibrium, probably prior to mixing, in the deeper part of the geothermal system and equilibration temperature as high as 170°C. This is also

reflected by the most recent samples from the field, showing higher degree of mixing, and indicating that mixing probably increased after drilling. This is particularly the case where the casings in the wells are not efficient enough to prevent mixing of hot water with colder water at shallow depth, as in wells 1 and 9.
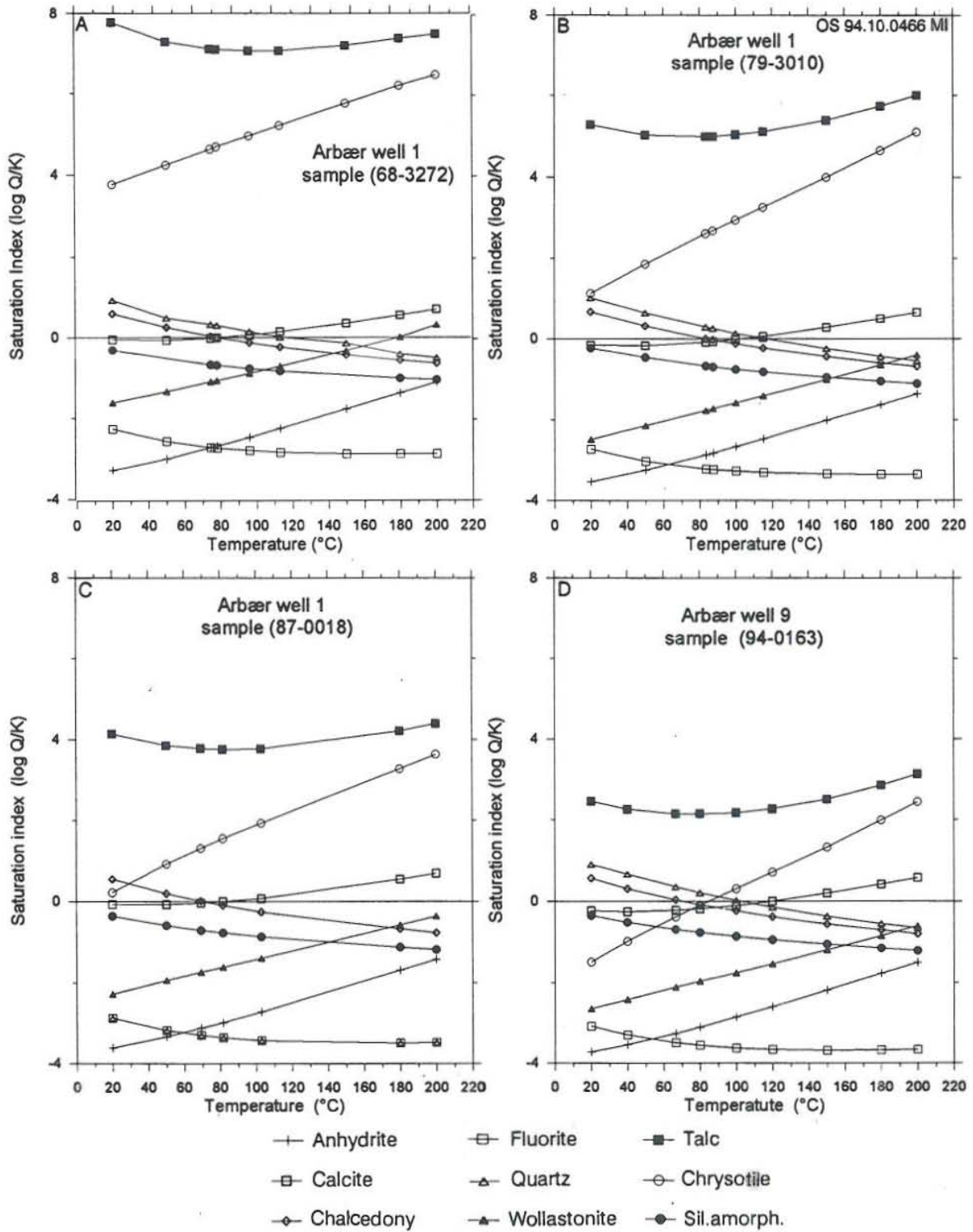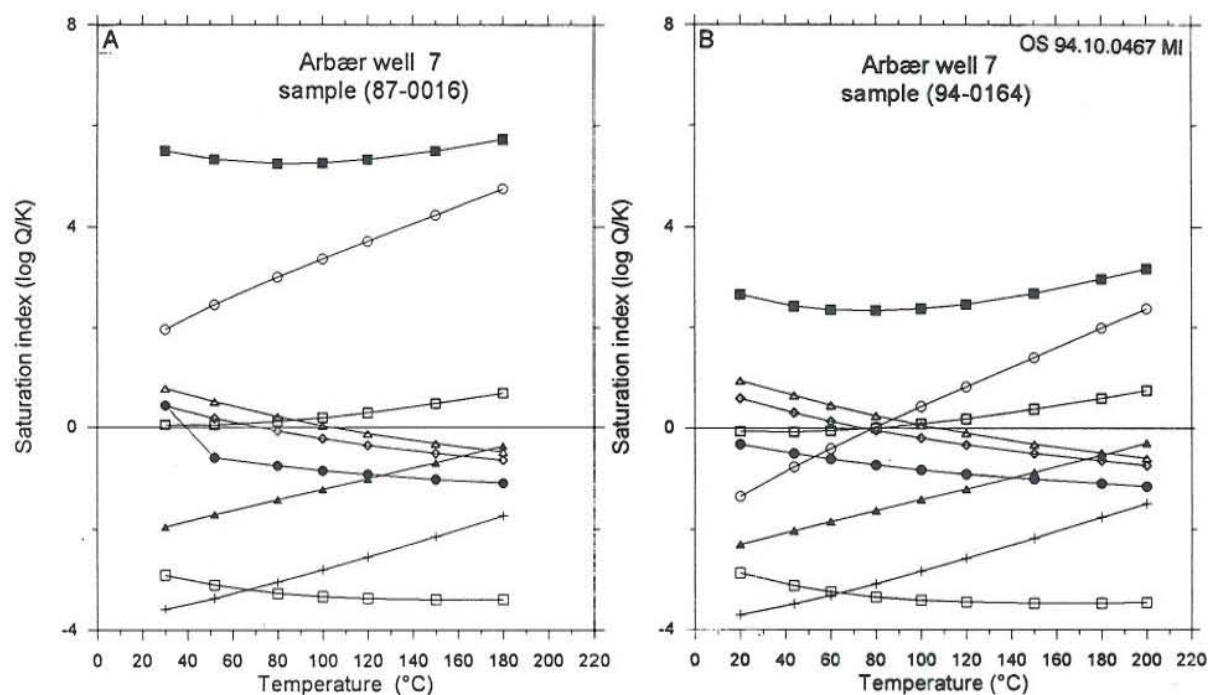

FIGURE 8: Mineral equilibria diagrams for wells 1 and 9

FIGURE 9: Mineral equilibria diagrams for well 7 (labels, see Figure 8)

Noticable chemical changes with time have a considerable effect on the equilibrium state between fluids and hydrothermal minerals. Figure 8 shows mineral equilibria diagrams for three samples from well 1 from 1968, 1979 and 1987, and one sample from well 9 from 1994 which can be considered a continuation of well 1. These few samples indicate that curves for different minerals tend to move closer to the equilibrium line (log $Q/K = 0$) with time. This is clearly demonstrated by the sample taken from well 9 in 1994, where the curves for chrysotile, calcite and chalcedony converge at approximately 80°C. This can also be seen from well 7 by the samples of 1987 and 1994 (Figure 9).

Figure 10 shows mineral equilibria diagrams for wells 2, and 4 to the north of the field and for the shallow well 4 near to well 7. Figures 8 to 10 indicate a subsurface temperature of 80 to 90°C and probably hotter water of 170-180°C deeper in the system.

6. MIXING EVALUATION

6.1 Evidence for mixing

In the previous chapters it has been pointed out on several occasions, that there is a strong evidence of mixing in the thermal waters at Arbaer. First, dilution was noticed with time for well 1 and in the shallow feed zones. Second, a disagreement between different Na/K geothermometers was observed. Third, on the Giggenbach Na-K-Mg triangular diagram, all samples fall in the mixed water area. Fourth, the mineral equilibria diagrams show no clear conversion to zero saturation index by any group of minerals at the same temperature. The final evidence for mixing, is a near linear relationship between most constituents and Cl as suggested by Arnorsson (1985) as evidence for mixing in Icelandic geothermal fields. The Arbaer data clearly indicate this linear relationship between Cl and other chemical constituents, as shown in Figure 11. Based on this evidence, it seems proper to use mixing models to estimate reservoir temperature in the Arbaer field, as well as to gain better understanding of the processes which may take place within the geothermal system.
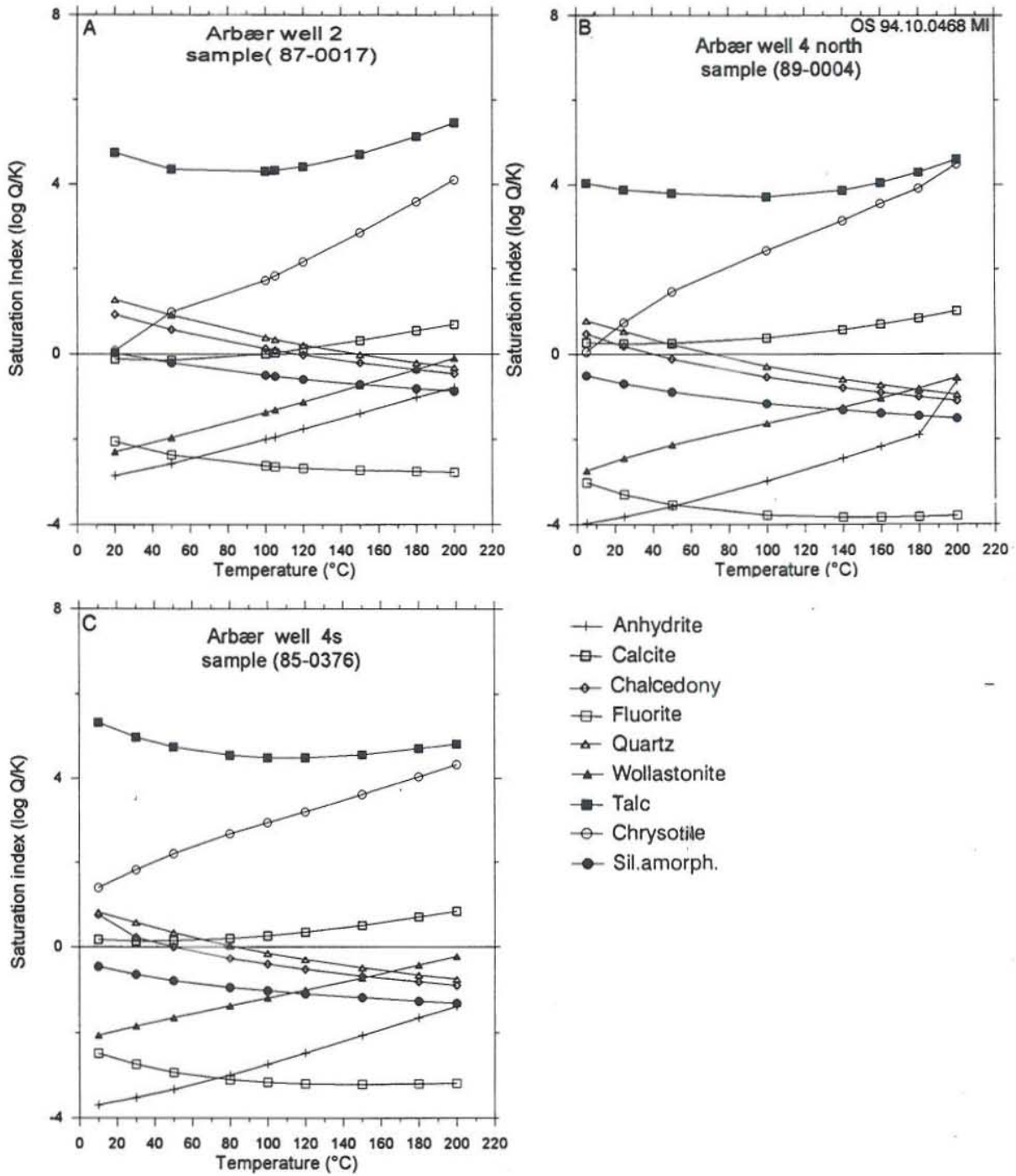
FIGURE 10:   Mineral equilibria diagrams for wells 2, 4n and 4s

6.2 Mixing models

Two mixing models were applied, the silica-enthalpy mixing model by Truesdell and Fournier (1977) and the enthalpy-chloride mixing model of Fournier (1979b).
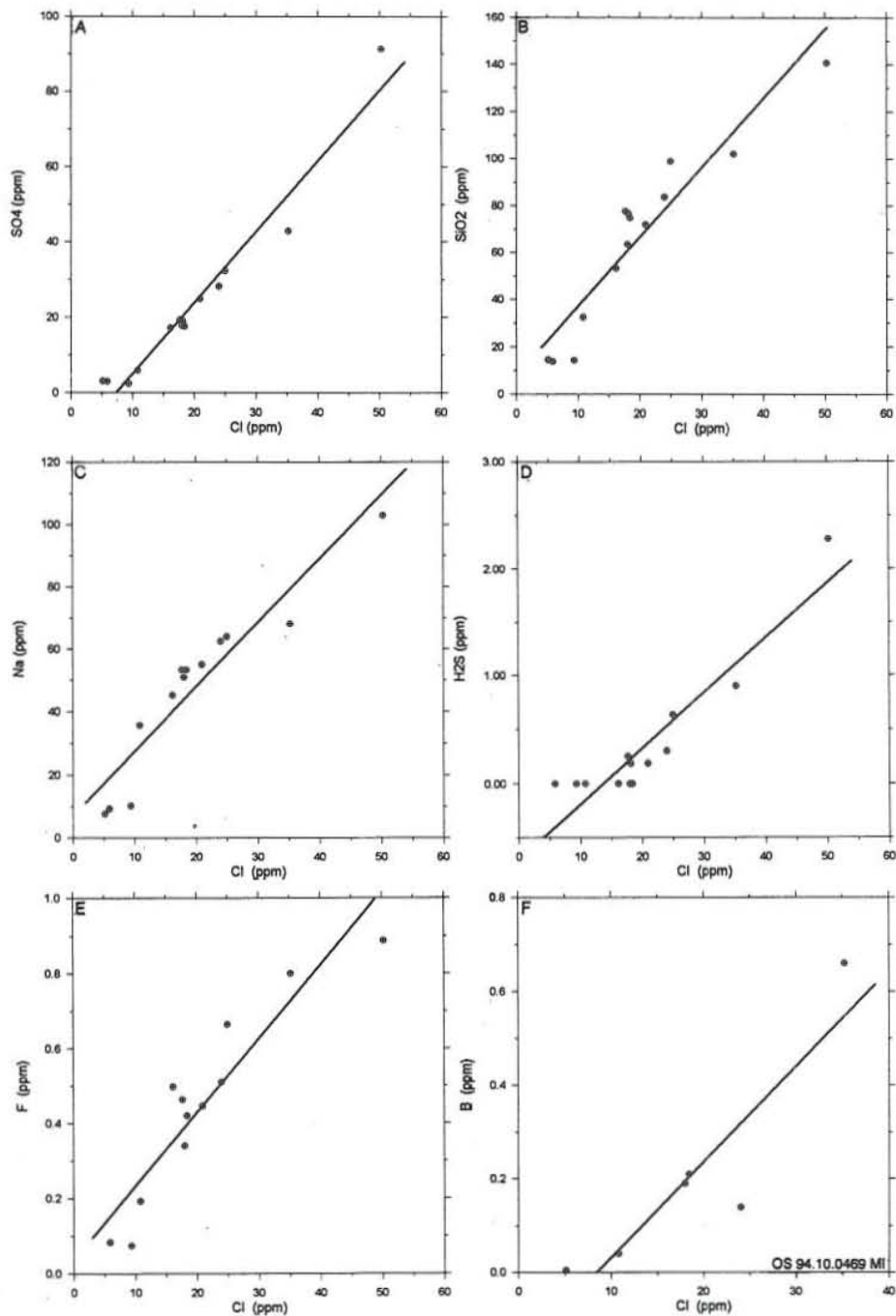
FIGURE 11: Linear relationships between Cl and some other constituents in the Arbaer waters

Silica-enthalpy mixing model: Truesdell and Fournier (1977) used a plot of dissolved silica vs. enthalpy of the liquid water to estimate the temperature of the hot water component of the mixed water. Enthalpy is used as a coordinate rather than temperature. This is because the combined heat contents of two waters at different temperatures are conserved when those waters are mixed (neglecting small heat of dilution effects), but the combined temperatures are not.

Figure 12 shows the results of the silica-enthalpy mixing model applied to the Arbaer data. The reservoir temperature is expected to be below 180°C, so chalcedony is expected to control the silica content of the thermal fluids. The chalcedony solubility curve used in Figure 12 is the curve proposed by Arnorsson et al. (1983) for Icelandic thermal fluids. Two main mixing lines are proposed. The first mixing line connects well 2, well 7, shallow well 4 near well 7 and the cold water intersecting the chalcedony curve at an enthalpy of 700 kJ/kg (>160°C). The second mixing line connects well 1, well 4 to the north and the cold water intersecting with the chalcedony curve at an enthalpy of 440 kJ/kg (>110°C).
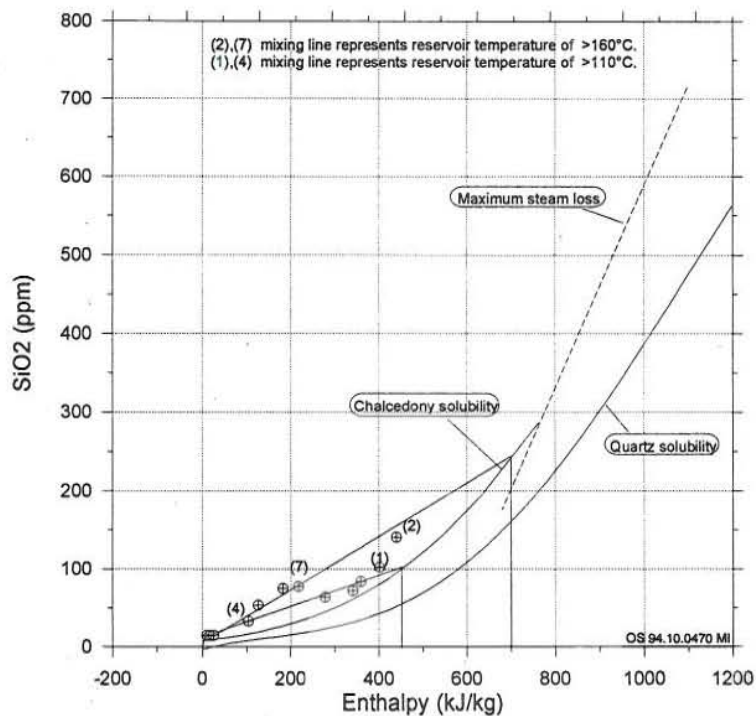
FIGURE 12: Silica-enthalpy mixing model for the Arbaer waters

Chloride-enthalpy mixing model: Fournier (1979b) discussed the use of enthalpy-chloride diagrams in the prediction of underground conditions in hot spring systems. In many places all the hot-spring waters that reach the surface are mixed waters or have equilibrated chemically at shallow or intermediate reservoirs or quifers, so a consideration of the enthalpy and chloride relations may overcome this difficulty.

This diagram depends mainly on the fact that the range of chloride concentrations of hot springs appear to result mainly from different amounts of boiling, so this range in concentrations can give information about the minimum temperature of the reservoir feeding the springs.
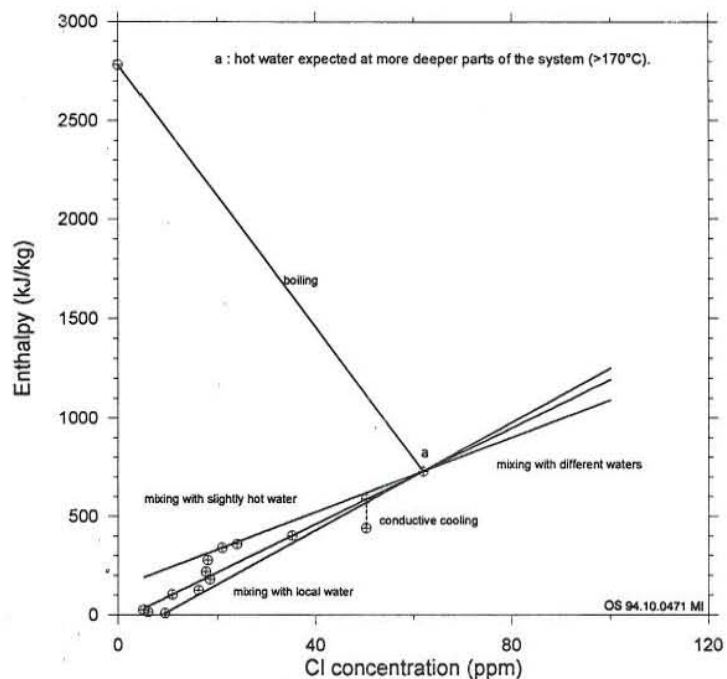

FIGURE 13: Chloride-enthalpy mixing model for Arbaer

Figure 13 shows the enthalpy-chloride mixing model for Arbaer data. The model indicates a hot end member with a minimum temperature of 170°C at deeper parts of the reservoir. Most data points fall between two mixing lines with two different end members. The first line represents mixing of either the cold local groundwater, representing the local precipitation, or the river water of Olfusa at Selfoss, which in the same time carries the characteristics of the far inland precipitation. The second line suggests a mixing between

waters from well 1 and a warm water component which probably has the same characteristics as the cold water but a higher enthalpy.

The enthalpy-chloride mixing model indicates that thermal water can be found at different depths within the geothermal field. These waters are probably mixed waters of different origins and different temperatures. The model also suggests, as does the silica-enthalpy mixing model, that deep down in the reservoir hot unmixed water might be present. The temperature of this water could be as high as 170°C, with silica content as high as 240 mg/l and Cl content of about 60 mg/l.

7. CONCLUSIONS

The main aim of this report was to predict subsurface temperatures of the Arbaer geothermal field in S-Iceland and to gain some understanding of the chemical processes taking place within the geothermal system. The following are the main conclusions of the study:

1.   Generally, all chemical constituents in waters from the wells decrease with time. That applies to most of the wells, except well 2, where shallow feed zones are well cemented.

2.   Mixing is the main process controlling the chemical composition of thermal fluids at all depths. Geothermometers suggest a subsurface temperature of 160°C in the deeper part of the system. Mixing models suggest a subsurface temperature of 160-170°C.

3.   Thermal water is expected at different depths carrying the characteristics of each particular depth, so thermal water temperature is varying depending on the depth. When thermal fluids ascend through natural up-flow zones or wells, they start to mix with fluids of lower temperature.

4.   Hydrogen and oxygen isotopes suggest a far inland meteoric origin for fluids from the deeper parts of the system, as in well 2. In the shallow feed zones, hydrogen and oxygen isotopes tend to approach local precipitation, represented by a local cold spring.

5.   Arbaer has been described by Flovenz et al. (1990) as a localized circulation geothermal system, where cold water descends through young fractures, heats up and rises as it mines the heat almost directly under the geothermal system itself. This model requires some degree of homogeneity of the chemical composition of water and temperature caused by a local convection. This homogeneity is not found in the entire depth interval of different wells, so the heat mining model can only be applied to the upper most 500 m, while Arnason's (1976) description for groundwater systems can be applied to the deeper parts of the geothermal field. This theory is also confirmed by the drilling records from well 1, where no changes in temperature were noticed in the depth interval 17-451 m, where the main hot zone was crossed. Temperature profile in well 4 to the north (Figure 2) shows evidence for the heat mining model in the upper part of the system.

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