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EXPLORATION OF GEOTHERMAL FLUIDS IN THE REYKHOLT AREA, BORGARFJÖRDUR, W-ICELAND

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ABSTRACT

The Reykholt geothermal system in Borgarfjördur is the largest low-temperature thermal system in Iceland. The natural discharge of boiling water is 400 l/s. This system comprises the largest low-temperature geothermal area in Iceland and all the largest ones in Borgarfjördur, including the Deildartunga-Kleppjárnsreykir, Hurdarbak-Sídumúli and Vellir fields. After studying the chemistry of the fluid, the ratio of Cl/B in the range of Icelandic basalt and the $\delta D/\delta O^{18}$ values both represent the origin of thermal fluid as meteoric. These meteoric waters originate from the Arnarvatnsheidi highlands percolating through faults and permeable rocks. The faults are intersected by active fractures in the lowlands. The fluids then flow along the fractures to the surface in the form of hot springs, usually in lines. The Giggenbach Cl-SO_4-HCO_3 triangular diagram classifies the thermal fluid (with the exception of a few carbonate localities) as sulphate water. The change in chemical composition and temperature with time is negligible. There is no evidence of mixing with cold ground water in the area and the mineral equilibria are consistent, as reflected from the saturation index diagrams and also from the cation geothermometer temperature results. The geothermometers give quite reliable results for the reservoir temperature in the investigated area. These are in the range 70-150°C for the chalcedony geothermometer.

1. INTRODUCTION

The Borgarfjördur region covers the area around the bay of Borgarfjördur up to the highlands, to the north of the Reykjavík area. This region has been divided into five separate geothermal systems. The systems have been named after their centres, i.e. Reykholt, Baer, Brautartunga, England and Húsafell (Georgsson et al., 1984).

Each system comprises a few to numerous hot springs which are often located along lines. One thermal field can include more than one line of hot springs. The Reykholt thermal system is the largest system in Borgarfjördur. The thermal water is of meteoric origin and has fallen as precipitation on the Arnarvatnsheidi highlands (Figure 1), percolated down to a depth of 1-3 km and is heated by regional heat flow. It flows laterally for about 50 km to the southwest, driven by hydrostatic gradient. The main

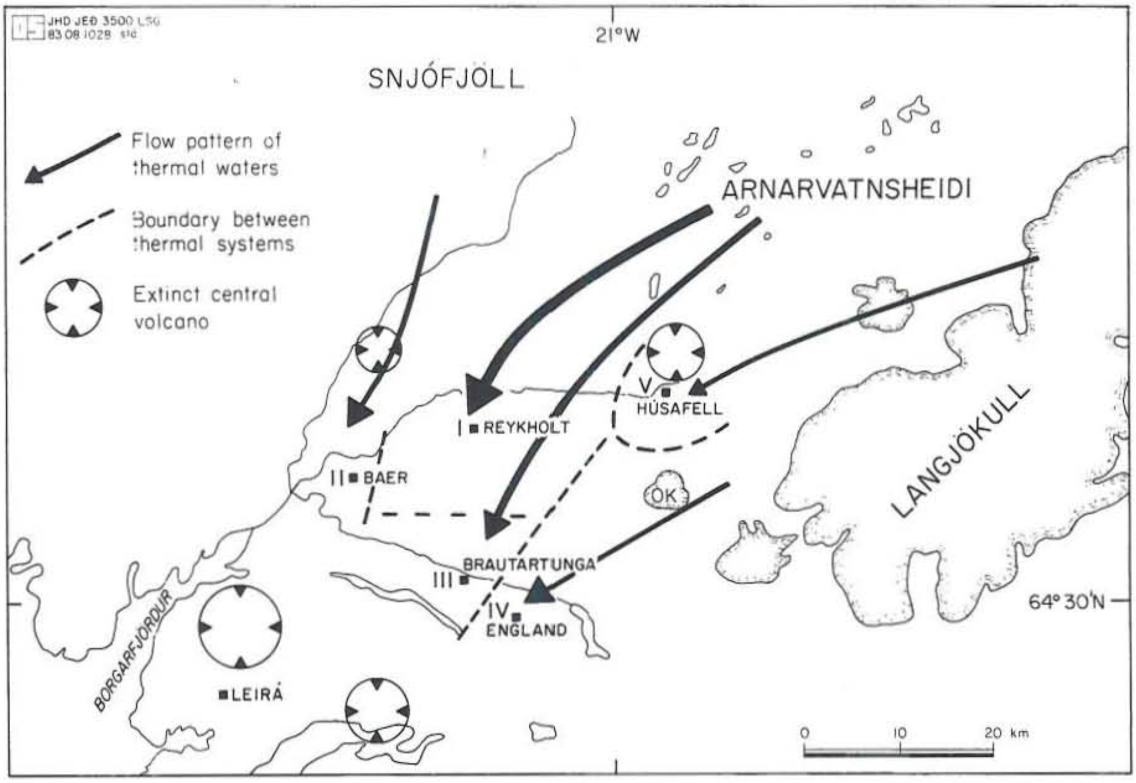


FIGURE 1: The source of the water of the Reykholt thermal system (Georgsson et al., 1984)

aquifers are associated with northeasterly trending faults and occasionally dykes. In the lowlands they are intersected by open northwesterly to northerly trending fractures which enable the hot water to flow to the surface.

The Reykholt thermal system covers an area of 250-300 km^2 in the valley of the upper Borgarfjördur regions (Georgsson et al., 1984). The natural discharge is about 400 l/s of boiling water. It is the largest low- temperature system in Iceland. The highest reservoir temperature is at the Haegindi and Kópareykir thermal fields and exceeds 130°C. The temperature decreases in all directions from the centre.

This study is based on the analysis of fluid samples and the interpretation of previous and new analytical data to study

- the changes in the chemical composition and properties of the thermal fluids with time;
- the reservoir temperature by the use of different geothermometers;
- the recharge and upflow zones of the geothermal field.

Geochemical techniques were applied to study the geothermal systems in order to provide information on conditions at depth and processes. This information was not obtainable by geological or geophysical techniques during the early, pre-drilling stage. The constituents in the fluids that give information are of two major groups:

a) Chemically inert, non-reactive constituents like noble gases (He and Ar), followed by comparatively conservative constituents like Cl, B, Li, Rb, Cs and N_2.

b) Chemically reactive species, responding to changes in their environment in a controlled and well-understood manner and used as geoindicators. They are Na, K, Ca, Mg and SiO_2, taking part in temperature dependant interactions with the Al. This group also consists of H_2, H_2S, CH_4 and CO_2 involved in temperature and pressure dependant redox reactions among themselves or with a redox system (Fe^{++}/Fe^{+++}) of the rock phase. The boundaries between the two groups are

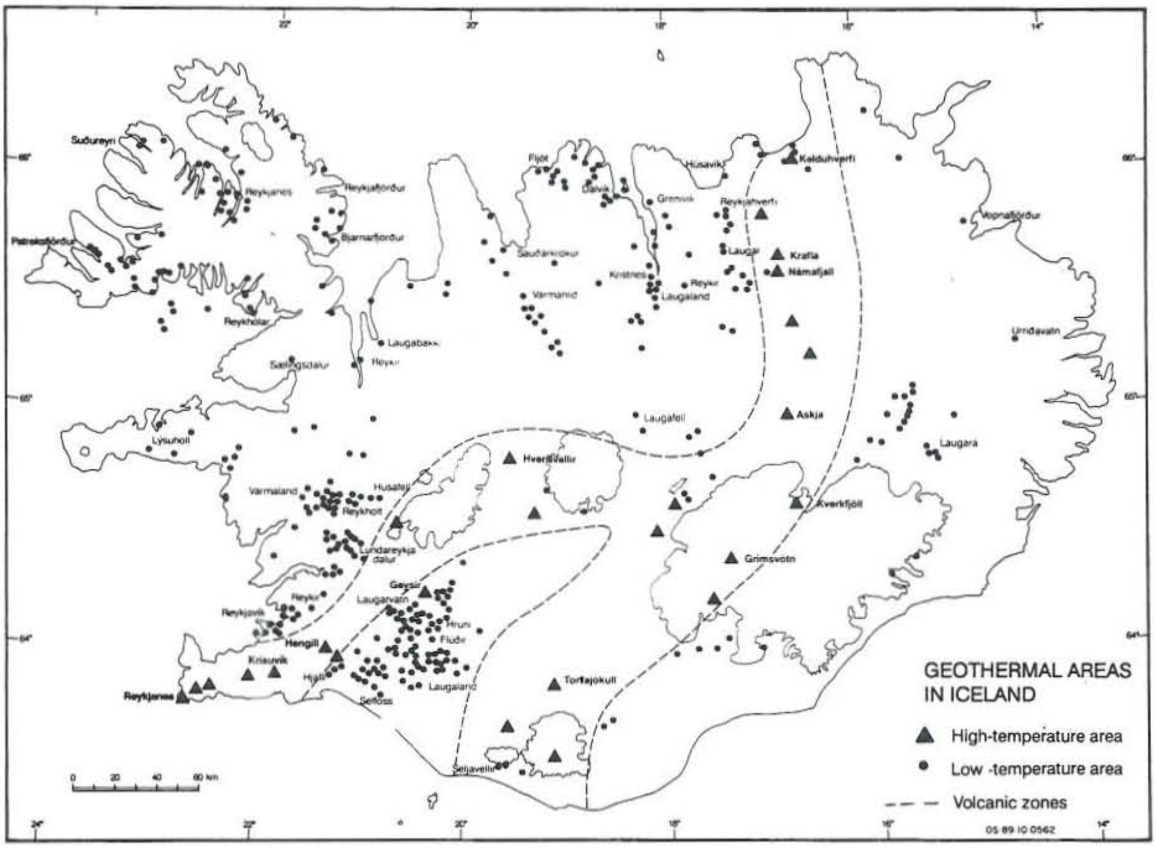


FIGURE 2: Geothermal areas in Iceland

not rigid. Each constituent of a geothermal system behaves in its own way and if used, provides unique information. On the basis of this information, the geothermal reservoir potential is exploited for direct and indirect use as a source of energy.

2. GEOLOGY

Iceland is a part of the oceanic lithosphere. The Mid-Atlantic Ridge crosses through it from southwest to northeast where the active spreading axis appears as a zone of active rifting and volcanism (Figure 2). The geothermal areas in Iceland are divided into high-temperature and low-temperature areas (Bödvarsson and Pálmason, 1961). The low-temperature areas are found outside the volcanic zone. The temperature within these geothermal systems is generally lower than 150°C at 1 km depth. They are quite abundant on the west side of the volcanic rift zones (Figure 2). The low-temperature areas are fracture dominated, and derive their heat from the hot crust by active and localized convection in near vertical fractures and regional heat flow (Bödvarsson, 1982; Björnsson et al., 1990). Away from these fractured zones, the bedrock is impermeable and heat transfer is dominated by conduction. At shallow depths the source of heat is convection, so in low-temperature areas the fluid escapes to the surface through narrow fractures as hot springs, so there must also be a recharge to the system. The recharge is either from the general groundwater flow or from the surface through some parts of the fracture system. The low-temperature areas are in Plio-Pleistocene and Tertiary volcanic formations. Due to the oceanic climate, there is heavy precipitation on the island. Some of the precipitation perculates deep into the bedrock in the highland areas and flows laterally along faults and permeable horizons for distances of tens of km before it appears on the surface along dykes or faults in the lowlands. The water extracts heat from the regional heat flow during its passage through the strata, but mostly from localized highly permeable and fractured locations.

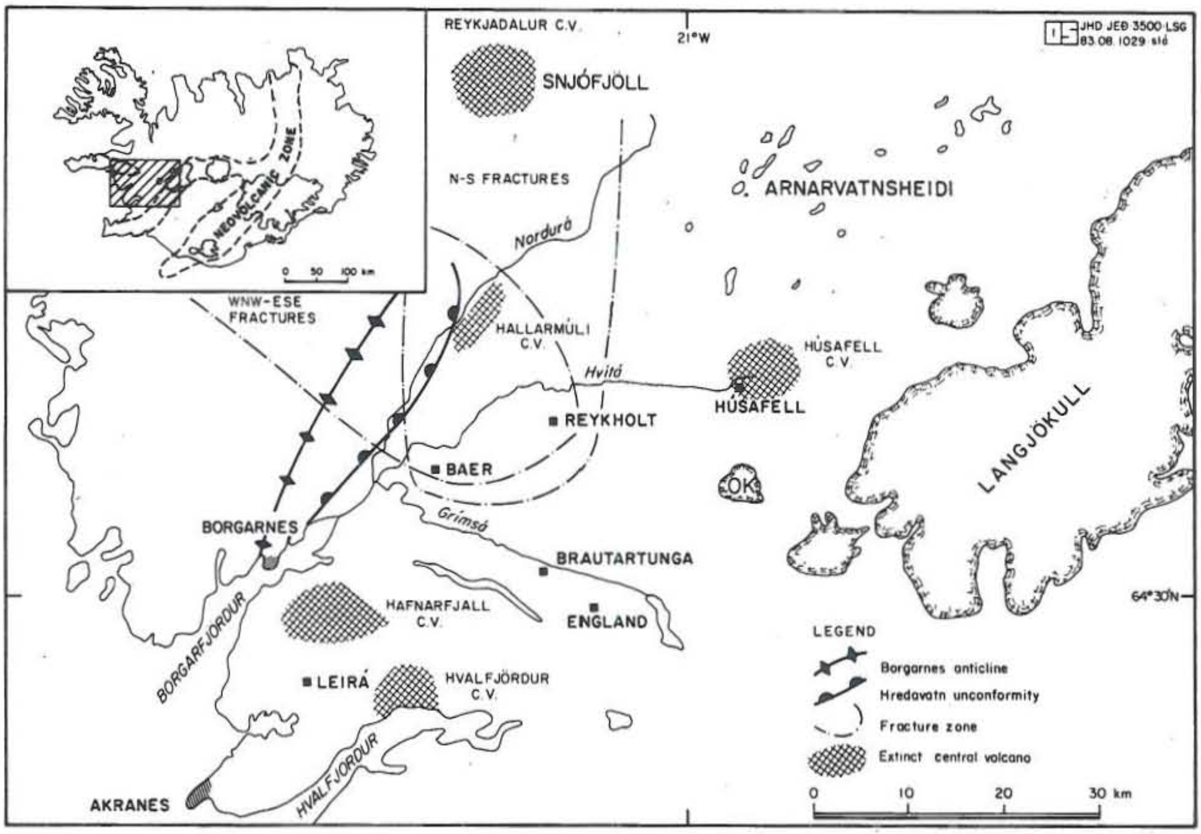


FIGURE 3: The main tectonic features of the Borgarfjördur region (Georgsson et al., 1984)

The basement of the Borgarfjörður region consists of late Tertiary basaltic lava flows. The axis of the Borgarnes anticline (Saemundsson, 1979) runs NE-SW and marks the western margin of the geothermal manifestations (Figure 3). There are a great variety of faults and joints in the region. The NE-SW trending faults correspond to the fissure swarms of the active rift zone. These are accompanied by dyke swarms.

The hot springs of the major thermal fields in Borgarfjördur are aligned along young fractures with a northwesterly or northerly trend (Figure 4). Most of the hot springs are found at the intersection between the fractures and northeasterly trending faults and dykes (Georgsson et al., 1984). The resistivity survey suggests that the northeasterly trending faults operate as main channels for regional flow from the highlands towards the thermal fields. In the lowlands these aquifers are intersected by open fractures and the water flows to the surface. The best example is the Deildartunga hot spring (Georgsson et al., 1978). The spring is located at the intersection of a fracture trending N20°W and a dyke trending N30°E (Figure 4). A similar situation is in the Vellir field (Georgsson et al., 1985). Here two northeasterly trending faults, the Snaeldubeinsstadir and Logaland faults, seem to control the flow of water towards the Vellir line. A northerly trending fracture intersects the faults and the two main hot springs, Badlaugahver and Vellir, are at the intersections (Figure 5). The fracture is exposed in the unconsolidated marine sediments in the river bed. The central segment of the Vellir line coincides with the fracture but the southern segment coincides with the Logaland fault.

The Sturlureykir line has a different aquifer. There the hot springs break out on a northwesterly trending fracture associated with the Sturlureykir fault. The fracture is intersected by a northeasterly trending fault 100 m northwest of the hot springs and a dyke 50 m further northwest. Not only do the northeasterly faults serve as the main channels for the system and the fractures open the way for the water to the surface, but the associated seismicity of the area keeps them open, as it counteracts low temperature zeolitization and then hydrothermal sealing, which otherwise would gradually fill the channels.

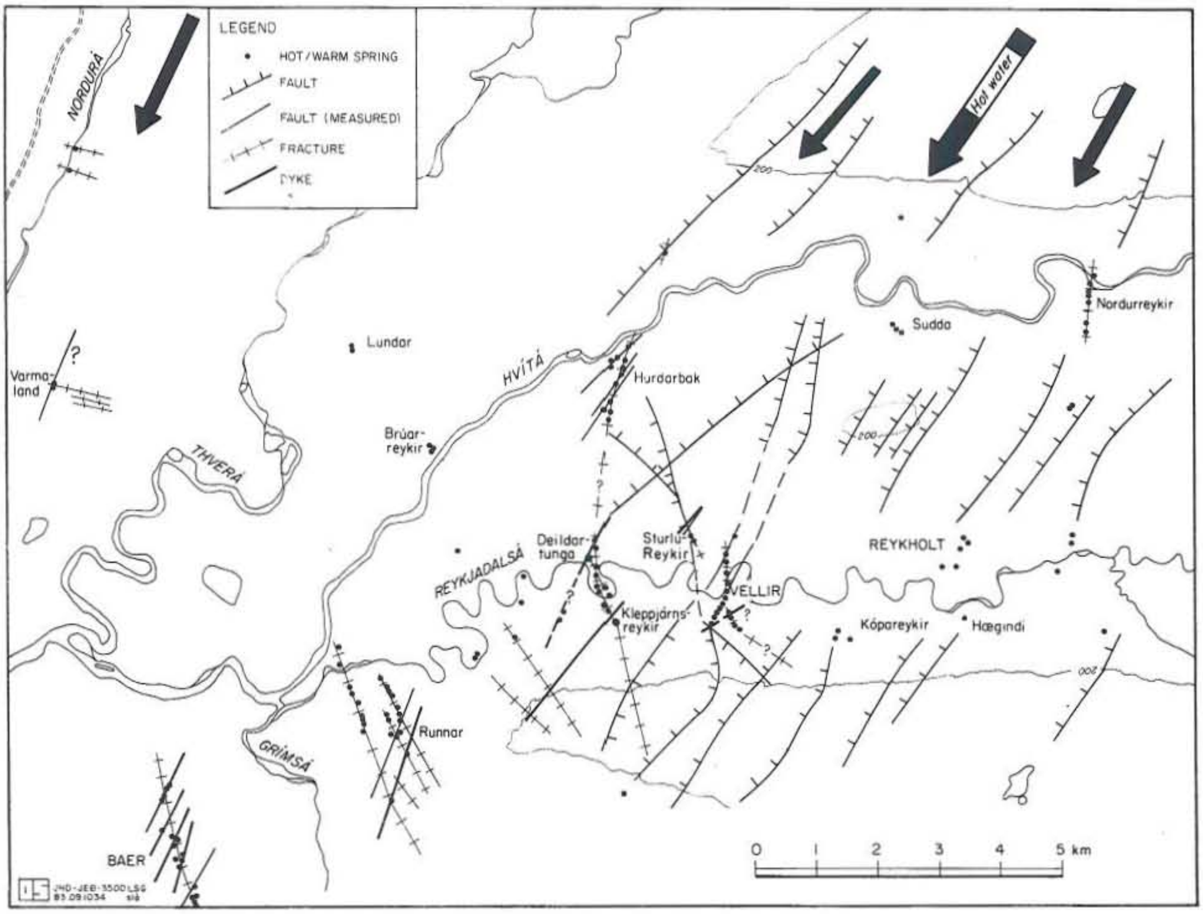


FIGURE 4: The tectonic features of the Reykholtsdalur thermal system (Georgsson et al., 1984)

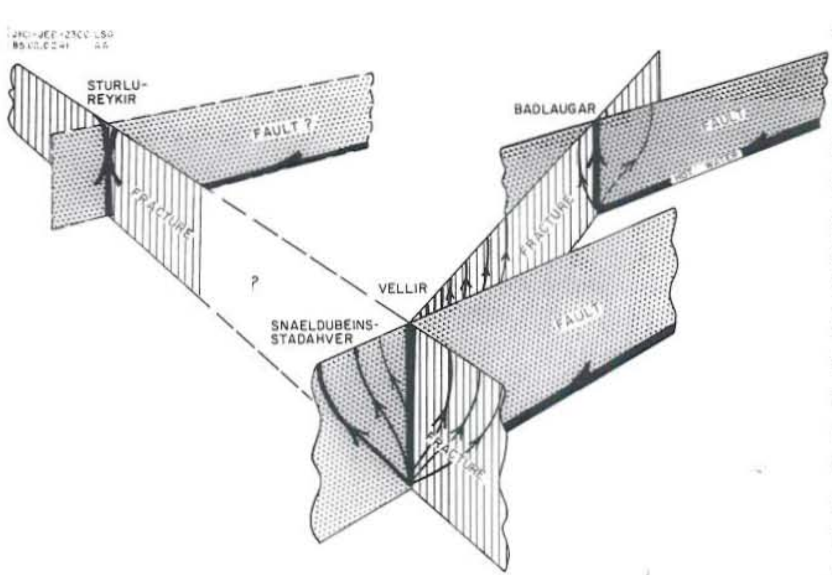


FIGURE 5: The main structural features of the Vellir thermal field in Borgarfjördur (Georgsson et al., 1985)

The faults are formed in a stress field characterised by lateral shear forces. The faults of the fractured zone can be divided into three groups, based on their trend and age. The trends are NW-SE, N-S and NE-SW. The fractured zone was active about 8-13 m.y. ago, but minor movements have continued up to Postglacial times. The dykes and faults are usually subvertical and those oriented parallel to the strike of the lava usually transect the lava at right angles.

3. METHODOLOGY

3.1 Collection of analytical data

The present study is mostly based on existing analytical data of the geothermal fluids from the selected area. The data of hot springs and geothermal wells used in this study have been collected and analysed at irregular intervals since 1944 (Orkustofnun database). After compilation of the old data, a comparison was made with new analytical results from a few representative samples from the area. The new samples were collected from Reykholt well 2, Úlfsstadir low-temperature well, Haegindi, Deildartunga and Hýrumelur (Nordurreykir) hot springs.

3.2 Chemical analysis

The fluid samples were collected in fractions in different containers and treated accordingly (Ólafsson, 1988): Ru (raw and untreated) for the analysis of SiO_2. If SiO_2 concentration is more than 100 ppm, then Rd (raw and diluted), Fu (filtered and untreated) for the analysis of anions, Fa (filtered and acidified) for the cation analysis, Fp (filtered and precipitated) for the analysis of SO_4. The samples for analysis of volatile components were collected in air tight double valve glass bulbs.

The fluid temperature was measured and for H_2S determination, a sample was added to a 5N NaOH solution and analysed in the field. The remaining analyses were made in the geochemical laboratory of Orkustofnun. The analytical methods applied for these samples are summarized in Table 1.

TABLE 1: Analytical techniques for the geothermal fluids

Element	Sample fraction	Technique applied	Method used
Na, K	Fa	Atomic absorption spectroscopy	Flame, Cs added
Ca, Mg	Fa	Atomic absorption spectroscopy	Flame, La added
Fe	Fa	Atomic absorption spectroscopy	Flame
Al	Fa	Atomic absorption spectroscopy	Graphite furnace
SiO_2	Rd	Spectrophotometry	Ammonium molybdate
B	Fu	Spectrophotometry	Azomethine-H
SO_4	Fu	Titration / Ion chromatography	Barium perchlorate (Thorin titration) / conductivity detectors
Cl	Fu	Ion chromatography	Conductivity detectors
F	Fu	Potentiometry	Orion 96-09 combination, fluoride electrode
CO_2	Ru	Titration	HCl / glass electrode
H_2S	Ru	Titration	Dithizone

This study is based on 93 fluid samples of geothermal wells and hot springs. The data are compiled and arranged location and time wise (Table 2). The idea behind this, is to study the changes in the fluid composition at different locations over time. The data were run on the WATCH program to study speciation and equilibration with selected minerals.

3.3 WATCH program

The WATCH program (Arnórsson et al., 1982, 1983a, 1983b; Bjarnason, 1994) was used to calculate the speciation, ionic balance, geothermometer (quartz, chalcedony and Na/K) values and the log

TABLE 2: Analytical data of geothermal fluids of the Reykholt area, Borgarfjördur, W-Iceland (concentrations in mg/l)

No.	Location	Date	No.	Temp. (°C)	pH	°C/pH	SiO_2	Na	K	Ca	Mg	CO_2	SO_4	H_2S	Cl	F	TDS	B
1	Húsafell - well	15.9.1996	96-0280	75	9.43	21.6	82.8	91.1	1.53	4.69	0.006	30.7	77.7	0.23	35	13.8	332	0.42
2	Húsafell - hot spring in Teitsgil	25.9.1986	86-0141	59.8	9.35	21.4	73.92	79.48	1.54	5.06	0.04	30.6	65.1	0	31.94	12.63	302.9	0
3	Húsafell- well 1 Selgil	25.9.1986	86-0140	76	9.49	21.3	81.25	86.94	1.68	4.61	0	30.6	68.79	1.05	35.09	14.33	327.1	0
4	Húsafell - hot spring	27.6.1979	79-3023	56	8.81	20	64.4	68.5	1.67	5.12	0.122	25.7	61.9	0.19	29.5	12	312	0.38
5	Húsafell - hot spring	15.9.1967	67-3303	62	9	62	88	74.3	1.3	5.5	0.07	15.7	65.4	0	32	16	309	0.42
6	Hýrumelur -Norðurreykir	15.8.1997	97-0469	96	9.66	21.9	140.55	79.3	2.32	2.39	0.003	22.15	60.7	0.31	33.9	1.929		0.41
7	Nordurreykir - Spunahús, Heimahver	23.7.1983	83-0188	99	9.5	0	144.6	80.6	2.53	2.3	0.01	0	62.4	0	33.06	1.85	400.9	0
8	Nordurreykir - Spunahús, Adalhver	17.11.1983	83-0279	96	9.52	22	143.57	83.39	2.74	2.48	0.005	26.28	63.49	0.15	32.07	1.924	376.8	0
9	Nordurreykir - Spunahús, Adalhver	23.7.1983	83-0187	96	9.6	0	145.3	80.92	2.54	2.28	0	0	62	0	33.68	1.85	381.3	0
10	Nordureykir - Strokkur	4.7.1978	78-0029	101	9.45	25	142	78.2	2.66	2.31	0	31.9	64	0.2	34.2	2.08	383	0
11	Nordurreykir	15.9.1967	67-3302	100	9.1	100	149	75.2	2.6	2.6	0.04	14.4	66.1	0.4	34.2	1.9	370	0.98
12	Nordureykir, Strokkur	15.7.1965	65-0008	100.5	9.5		131	73	2.8	1.61	0.12	32.6	62.8	0	33.70	2	375.5	3.2
13	Nordurreykir, spring 1A	15.7.1965	65-0009	97	9.45		127	67.2	2.3	1.69	0.26	39.6	70.4	0	33.20	1.75	368	2.6
14	Nordurreykir, spring 1A	15.7.1965	65-0010	99	9.45		121	69.2	2.5	1.54	0.3	36.6	65.8	0	34.10	1.75	377.5	3
15	Nordurreykir, Dynkur	15.7.1965	65-0011	99	9.45		123	69.1	2.3	1.29	0.12	34.7	64.6	0	33.30	1.75	364.5	2.9
16	Nordurreykir, v/ Spunahús	15.7.1965	65-0012	91.5	9.45		127	69.2	2.8	1.79	0.2	34.7	63	0	35.20	1.75	383	3.2
17	Nordurreykir, v/ Spunahús	15.7.1965	65-0013	99	9.5		134	68.7	2.3	1.68	0.3	37.4	62.3	0	33.80	1.75	377.5	4.7
18	Nordurreykir, v/ Spunahús	15.7.1965	65-0015	99	9.45		126	66.5	2.5	1.78	0.27	31.68	63.8	0	33.30	1.75	373	4
19	Deildartunguhver	15.8.1997	97-0468	99	9.64	21.8	121.88	73.6	1.99	2.91	0.003	22.46	51.9	0.19	35.6	2.372		0.3
20	Deildartunguhver	27.6.1979	79-3025	100	9.2	20	127.6	71.7	2.54	3.1	0.06	22.8	56.2	0.53	36	2.59	390	0.26
21	Deildartunguhver	4.7.1978	780031	101	9.36	25	135	74.4	2.6	3.1	0.01	26.1	56.6	0.41	36	2.68	359	
22	Deildartunguhver (Sláturhver)	4.7.1978	780032	100	9.38	25	127	72.3	2.4	3.1	0.01	23.5	57	0.61	34.7	2.51	346	
23	Grófarhver (Kársnes)	4.7.1978	780033	100.5	9.36	25	156	76.6	2.8	2.2	0.01	29.7	58.4	1.1	35.9	2.92	388	
24	Deildartunguhver	15.9.1967	67-3305	99	9.1	99	143	75.3	2.2	3.4	0.03	13.5	71	1.8	32.7	2.5	358	0.29
25	Deildartunguhver 1	15.7.1965	65-0026	99	9.45		125	62	2	2.3	0.23	29	55.8		35.20	2.5	341	2
26	Deildartunguhver 11	15.7.1965	65-0027	99	9.35		125	63.2	2.5	1.9	0.22	31.2	52.7		35.10	2.75	354	2
27	Deildartunguhver 111	15.7.1965	65-0028	99	9.5		122	63.9	2.3	2.1	0.1	33.5	56		35.20	2.75	342	2
28	Deildartunga - Kársnes	15.7.1965	65-0030	95	9.45		140	64.5	1.3	2.1	0.13	31.2	60.1		35.20	2.75	368	1.9
29	Deildartunguhver	25.5.1960	220	100	9.2		142	86.5	2	2.8	1.2		60.8		36.9	2.6	365	
30	Deildartunga	26.5.1960	249	100	9.1		138	77	2.9	3.6	0		58		36	2.6	353	
31	Deildartunga	15.11.1949		100	9.47		112						54		37			
32	Deildartunga - Árhver	1944	248	100	9		127	78.5	4.2	5	0.7		60		48	1.3	361	
33	Kleppjárnsreykjahver	4.7.1978	780028	100.5	9.53	25	140	73.1	2.3	3	0.01	23.8	56.3	0.68	35.9	2.52	356	
34	Kleppjárnsreykir	15.9.1967	67-3295	99	9.1	99	103	66.6	2.3	4.8	0.12	12.6	54.6	2.2	32.8	1.8	343	0.83
35	Kleppjárnsreykjahver	15.7.1965	65-0033	100	9.5		127	61.9	2.8	2.5	0.1	34.7	54.7		36.00	2.25	344	1.8

TABLE 2: Continued

No.	Location	Date	No.	Temp. (°C)	pH	°C/pH	SiO_2	Na	K	Ca	Mg	CO_2	SO_4	H_2S	Cl	F	TDS	B
36	Kleppjárnsreykjahver	15.7.1965	65-0034	98	9.55		125	61	2	2.1	0.14	36	57.2		36.20	2.5	358	ud
37	Kleppjárnsreykir	14.5.1959	226	100	9.47		140						58.3		36.8	2.4	371.2	
38	Kleppjárnsreykir	15.11.1949		98	9.4		112						50		37			
39	Hver at Logaland	6.11.1987	87-0232	100	9.41	22.4	155.2	80.9	3.1	2.52	0.053	28.6	49.61	2.23	35.15	3.169	380.1	0
40	Árhver	14.2.1979	790021	100	9.48	17	166.5	81	2.8	2.9	0.09	29.9	57.2	1.84	33.4	3.22	388	
41	Snældubeinsstadahver	14.2.1979	790022	101	9.35	18	167	78.7	2.8	2.6	0.01	33.1	56.8	2.13	33	3.24	367	
42	Logaland	15.9.1967	67-3296	100	9.1	100	132	75	2.8	3.2	0.06	18.4	58.5	2.8	25.9	2.8	382	0.56
43	Logaland	14.5.1959	229	100	9.32		161						59.3		36	3	400.8	
44	Árhver - Vellir	1944	247	101	9.1		145								40		410	
45	Sturlureykjahver	14.2.1979	790025	96.5	9.48	19	165	80.2	2.8	2.6	0	24	58.7	1.87	34.3	3.03	377	
46	Sturlureykir	15.9.1967	67-3304	95	9.1	95	163	74.3	2.6	2.8	0.03	11.2	68.5	2.4	29.7	2.6	383	0.38
47	Sturlureykir	13.5.1959	233	100	9.4		160.4						59.4		47	2.9	404	
48	Sturlureykir	15.11.1949		100	9.4		128						56		39			
49	Kópareykir	15.11.1979		97	9.15		155						60		39			
50	Kópareykir	4.7.1978	780034	101	9.12	25	191	80.8	4	2.2	0.01	36.9	59.1	3.98	36	4.43	427	
51	Kópareykir, S	15.9.1967	67-3297	100	9	100	153	78.1	3.7	2.8	0.05	29.6	60.4	2.9	35.4	3.9	438	0.85
52	Kópareykir N	15.7.1965*	65-0006	98	9.25		174	72.6	4	1.6	0	49.7	58.4		34.20	4.5	423	2
53	Kópareykir S	15.7.1965*	65-0007	94.5	9.15		178	73.7	3.3	1.5	0.22	53.2	59.7		32.30	4.25	419	2.4
54	Kópareykir	14.5.1959	227	100	9.2		183.6						62.7		35	4.5	436.4	
55	Sudda	15.2.1979	790030	70	9.29	21	178	78.9	2.7	2.3	0.05	35.6	62.7	0.24	28.2	2.57	383	
56	Sudda	21.5.1959	239	66	9.05		151.5						56.1		31.4	2.5	378	
57	Hamralaug in Ásgard's land	15.2.1979	790031	63	9.61	21	123	72.2	1.9	3.3	0.01	19.1	54.5	0.44	34.4	2.2	305	
58	Hamrar	14.5.1959	221	71.5	9.47		123.6						53.8		37	2.1	340	
59	Áslaugar (Stóraáslaugar)	15.2.1979	79-0029	76	9.88	21	113.5	48.1	0.89	1.72	0	24	17.1	0.17	11.8	1.34	235	0
60	Stóriás	15.9.1967	67-3301	77	9.1	77	107	45	0.8	1.9	0.04	13.5	54.5	0.7	12	0.4	235	0.44
61	Haegindi	15.8.1997	97-0467	98.3	9.43	21.4	172.7	83	3.54	2.51	0.005	36.83	55	1.8	33.7	2.396		0.33
62	Haegindakotshver	15.9.1967	67-3298	99	9.1	99	164	77.7	3.5	2.7	0.07	14.4	58.5	2.2	27.9	2.2	416	0.41
63	Haegindakotshver	15.7.1965*	65-0005	98	9.3		162	71.5	4.3	1.8	0.18	45.8	58.2		32.20	2.5	410	2.4
64	Haegindi	13.5.1959	223	100	9.12		174						58.3		33.2	2.6	422.4	
65	Runnar Thvottalaug	4.7.1978	780027	92	9.49	25	116	77	2	3.3	0.01	22.2	58	0.2	49.6	2.26	350	
66	Klettur	15.9.1967	67-3293	83	9.3	83	114	73.2	1.6	4.3	0.05	8.1	57.5	0.7	42.9	1.8	330	0.37
67	Runnar	15.9.1967	67-3294	83	9.1	83	116	73.6	2	3.8	0.03	8.1	61.4	0.6	49.9	1.7	343	0.47
68	Runnar 1	15.7.1965*	65-0016	82	9.45		103	67.4	2.3	2.3	0.07	27.7	58		49.70	1.75	347	1

TABLE 2: Continued

No.	Location	Date	No.	Temp. (°C)	pH	°C/pH	SiO_2	Na	K	Ca	Mg	CO_2	SO_4	H_2S	Cl	F	TDS	B
69	Runnar 111	15.7.1965*	65-0018	53	9.45		95	61	3.8	2.3	0.1	36.5	47.3		42.20	1.75	314	0.82
70	Klettur, east of homedrive	15.7.1965*	65-0019	82	9.5		101	63	1.8	2.1	0.23	29.1	52.7		43.20	1.75	321	1.38
71	Klettur, spring south of	15.7.1965*	65-0020	74	9.5		100	63.2	1.3	2.2	0.23	25.1	53.3		43.30	2.25	325	1.7
72	Klettur, spring in S wetland	15.7.1965*	65-0021	68	9.4		104	67.4	1.8	3.1	0.3	29.9	56		51.80	1.5	371	1.17
73	Klettur, Hermann Jónasson	15.7.1965*	65-0022	67	9.5		90	67.2	1.5	3.2	0.33	26.8	53.3		49.20	2.25	370	1.65
74	Stóri-Kroppur	15.9.1950		83	9.07		93						51		41	1.1		
75	Reykholt-well 2	15.8.1997	97-0465	99.1	9.35	21.4	162.3	75.5	3.28	2.06	0.001	31.9	54	1.18	31.4	2.08		0.3
76	Reykholt well 2	17.11.1983	83-0280		9.4	22	167.84	82.85	4.07	2.11	0	32.49	61.3	1.04	32.89	2.17	406.3	0
77	Reykholt, Skrifla-spring	27.6.1979	79-3024	100	9.15	20	188.2	79.7	4.32	2.22	0.008	27.2	63.9	1.09	35.1	2.49	456	0.34
78	Reykholt, well 1	15.9.1967	67-3299	98	9.1	98	198	75.8	3.6	1.3	0.04	18	60.4	0.1	32.3	2	430	1.08
79	Reykholt, Skrifla	15.9.1967	67-3300	100	9	100	196	77.9	4.1	2.6	0.04	14.8	62.4	1.7	34	2.3	424	1.12
80	Reykholt, Skrifla spring	15.7.1965*	65-0001	90	9.35		165	73	3.3	1.3	0.13	42.2	59.1		38.70	2.75	419.3	2.5
81	Reykholt, Skrifla	15.7.1965*	65-0002	100	9.5		178	70.8	3.8	1.4	0.13	34.3	57.4		34.20	2.25	429.3	1.9
82	Reykholt, Dynkur	15.7.1965*	65-0003	96	9.55		186	71.3	3.3	1.2	0.16	38.7	57.4		34.30	2.5	406	2.4
83	Reykholt, well at garage	15.7.1965*	65-0004	99	9.45		197	70.5	3.3	0.8	0.47	45.7	51.8		31.20	2.25	411	2.3
84	Reykholt, Dynkur	13.5.1959	230	100	9.47		181.6						59.6		35.7	2.4	428.4	
85	Reykholt, Skrifla	15.11.1949		100	9.4		125						52		39			
86	Hurdarbakshver	4.7.1978	780030	101	9.36	25	143	75.3	2.4	2.7	0.01	33	58.2	0.4	34	2.65	368.8	
87	Hurdarbak	15.9.1967	67-3306	99	9.1	99	133	75.3	2.3	3.1	0.04	16.2	69.4	1.2	32.9	2.3	368	0.33
88	Hurdarbak, at washing house	15.7.1965*	65-0023	99	9.35		122	65.1	2.5	1.7	0.3	39.1	58.4		33.00	2.75	364	2.22
89	Hurdarbak in wetland	15.7.1965	65-0024	98	9.3		126	64	2.5	1.8	0.3	37.4	58		33.30	2.75	371	2.22
90	Hurdarbak in wetland	15.7.1965	65-0025	91	9.4		132	64.9	2.5	2	0.2	36.5	57.6		33.20	2.75	367	1.9
91	Hurdarbak	13.5.1959	222	99	9.4		140.8						58.4		34.4	2.5	378.8	
92	Úlfsstadir	15.8.1997	97-0466	50	9.48	21.4	107.02	72	1.31	0.96	0.007	39.2	43.9	0.04	25.4	3.215		0.23
93	Úlfsstadalaug	14.2.1979	79-0023	45	9.07	21	102	63.7	1.57	1.69	0.08	40.5	46.5	0.34	22.8	2.19	182	
				Fe	Al		$\delta^{18}O$ (‰)	δD (‰)										
6	Hýrumelur-(Nordurreykir)	15.8.1997	97-0469	0.0019	0.234		-10.36	-75.0										
92	Úlfsstadir	15.8.1997	97-0466	0.0075	0.006		-10.83	-77.4										
75	Reykholt-well 2	15.8.1997	97-0465	0.011	0.238		-10.48	-74.2										
61	Haegindi	15.8.1997	97-0467	0.0047	0.463		-10.34	-72.8										
19	Deildartunguhver	15.8.1997	97-0468	0.0017	0.137		-10.31	-72.3										

solubility products (log K/Q values) of minerals in the deep water of the samples.

a. The ionic balance is a good tool to check the analytical results. The value is very low if analyses are accurate and high if the analytical results are not accurate. The values in the range of ±10 are counted to be low enough in dilute waters for further interpretations.
b. The deep water temperatures calculated from various geothermometers (quartz, chalcedony and Na/K) were obtained by using the chalcedony temperature as a reference temperature. As the Reykholt geothermal field is a low-temperature area, the use of chalcedony as a reference temperature is assumed to give the most suitable results.
c. The log solubility product of minerals was calculated for the five samples collected during this study. As these samples are representative for the Reykholt area they were run on the WATCH program, in the temperature range 50-200°C. The mineral equilibrium in a low- temperature area like Reykholt, almost always lies in this temperature range.

3.4 Origin of fluid

Several chemical elements and their ratios as well as stable isotope ratios are used to classify ground waters as well as geothermal fluids and to trace the origin of such fluids.

3.4.1 Cl/B ratio

The source of Cl and B in geothermal water is sea water spray/aerosols, sea water infiltration in the bedrock or leaching of rock by the water. Rock leaching, which seems to be stoichiometric with respect to Cl and B, causes lowering of the Cl/B ratio. The Cl/B ratio in Icelandic basalt lies in the range of 50-150. The Cl/B ratios in sea water spray is the same as sea water i.e. 4350 (Arnórsson et al, 1989). The study of this ratio can yield valuable information on the origin of the water.

3.4.2 $\delta D/\delta^{18}O$

Deuterium is used as a natural tracer to locate the recharge area of groundwater systems and to study their flow patterns. The meteoric water in different geothermal areas will have different isotopic ratios. The mean annual isotopic composition of precipitation is related to the mean annual temperature. The lower the temperature, the lower the content of heavy isotopes. Altitude, latitude and continental effect all affect the isotope concentrations in the rainfalls. At higher altitude and latitude the rainfalls are isotopically lighter than in the lowlands. The standard for δO^{18} and δD in water is SMOW (Standard Mean Ocean Water) and it is equal to $\delta O^{18} = 0$ and $\delta D = 0$.

3.5 Cl-SO_4-HCO_3 triangular diagram

The Cl-SO_4-HCO_3 triangular diagram (Giggenbach, 1991) classifies geothermal water on the basis of major anions, i.e. Cl, SO_4 and HCO_3. The source of Cl is seawater and rock dissolution, while for SO_4, a small amount comes from seawater; a large amount is usually derived from the oxidation of sulfide in volcanic steam. Carbonates are present at the periphery of high temperature systems. CO_2 is obtained by the degassing of volcanic formations like deep-seated intrusions. In cold water, carbonates originate from biological sources. High concentrations of sulphate and carbonates thus obtained give erroneous geothermometer results. In some old magmatic systems, equilibrium with alteration minerals is established in the presence of excess sulphate in the water and the water acidity is not increased. The Giggenbach diagram is obtained by the summation of the concentration of all the three constituents

$$S = C_{Cl} + C_{SO4} + C_{HCO3} \tag{1}$$

and calculating the percentage of individual constituent

$$\%Cl = 100\frac{C_{Cl}}{S} \tag{2}$$

$$\%SO_4 = 100\frac{C_{SO4}}{S} \tag{3}$$

$$\%HCO_3 = 100\frac{C_{HCO3}}{S} \tag{4}$$

3.6 Geothermometers

Geothermometry is used for the determination of subsurface or reservoir temperature by assuming equilibrium between specific minerals and the geothermal fluids at depth. They are of two types, qualitative and quantitative. The qualitative geothermometers are based on the distribution and relative concentrations of various elements in the water. For example, B and NH_4 are high in geothermal waters originating from sedimentary rocks. High contents of HCO_3, Hg and H_2S or sulphate in near surface waters are indicators of high temperature at depth (Tonani, 1970). High Cl/F and Cl/SO_4 ratios are sometimes indicative of high temperature systems. The variations in CO_2/NH_3, CO_2/H_2 and CO_2/H_2S indicate zones close to deep hot water (Mahon, 1970). According to Sigvaldason and Cuellar (1970), the presence of H_2 gas in a thermal system is a good indication of high temperature. Brondi et al. (1973) suggested that the presence of high concentration of Li is good evidence of high temperature at relatively shallow depths. According to Friedman and Denton (1976), the variation in He contents can be used as an indicator of high subsurface temperature. Decreasing and very low concentrations of Mg is an indicator of thermal water.

The quantitative geothermometers are divided into two groups, i.e. chemical and isotopic geothermometers. The isotopic geothermometers are mostly used for high-temperature waters. The chemical geothermometers are sustained by the evidence of equilibria between deep solutions and different mineral phases, the silica minerals and feldspars. There are several chemical geothermometers used to predict reservoir temperature in geothermal systems. They include a silica geothermometer based on the solubility of quartz and chalcedony developed by Fournier and Rowe (1966), Arnórsson (1975), Fournier and Potter (1982), Arnórsson et al. (1983b) and Arnórsson (1985); Na-K geothermometers by Fournier (1979), Arnórsson et al. (1983b); Arnórsson (1985) and Giggenbach (1988); Na-K-Ca geothermometer by Fournier and Truesdell (1973) and Arnórsson (1985). These geothermometers are based on the assumption that specific temperature dependant mineral solute equilibria are attained in the geothermal reservoir. These geothermometers often give different reservoir temperatures for the same fluid. This may be due to lack of equilibrium between the respective species and hydrothermal minerals or due to mixing of cold water during the upflow. It may also be that the geothermometer in question is not usable for the area studied.

3.6.1 SiO_2 geothermometer

The silica geothermometers are of two types i.e. the quartz geothermometer, usually used for high temperature (>180°C) and the chalcedony geothermometer used for the determination of low (<180°C) reservoir temperatures. The rates of dissolution and precipitation of quartz and amorphous silica change as logarithmic functions of absolute temperature, with moderately fast rates at very high temperatures and extremely slow rates at low temperatures (Rimstidt and Barnes, 1980). In a geothermal reservoir after prolonged water-rock interaction at constant temperature the silica polymerizes and precipitates during fast upward movement to the earth surface. The solubility of silica is also affected by variations in pH when pH is greater than 7.5.

3.6.2 The Na-K-Mg geothermometer

The Na-K-Mg diagram (Giggenbach, 1988) gives an indication of the suitability of water for the application of ionic solute geoindicators. It is based on the temperature dependence of the two reactions.

$$K\text{-}feldspar + Na^{+} = Na\text{-}feldspar + K^{+} \tag{5}$$

$$2\,albite + 0.8\,K\text{-}feldspar + 1.6\,water + Mg^{2+} = 0.8\,mica + 0.2\,chlorite + 5.4\,silica + 2Na^{+} \tag{6}$$

$$2.8\,K\text{-}feldspar + 1.6\,water + 2\,Mg^{2+} = 0.8\,mica + 0.2\,chlorite + 5.4\,silica + 2\,K^{+} \tag{7}$$

This diagram classifies waters as fully equilibrated with rock at given temperatures, partially equilibrated and immature waters. The temperatures and compositions at which full equilibrium is shown may change significantly due to many Na/K geothermometers for the given mineralogy and fluid. The position of full equilibrium also changes as the assumed K. √Mg geothermometer equation changes and is most uncertain at low temperatures (Fournier, 1991). In geothermal waters the Mg concentration decreases with increasing temperature. As geothermal water flows from high-temperature rock formations to some low-temperature environment, it picks up a significant amount of Mg from the surrounding rocks and, thus, leads to a major ambiguity in the application of the Fournier and Potter (1979) Mg correction. So low-temperature waters require Mg correction. Similar correction is also used for high-temperature waters, which pick up Mg during upflow and show the lower reservoir temperature. The coordinates for this triangular diagram are calculated as follows.

$$S = \frac{C_{Na}}{1000} + \frac{C_K}{100} + \sqrt{C_{Mg}} \tag{8}$$

$$\%\,Na = \frac{C_{Na}}{10S} \tag{9}$$

$$\%\,K = \frac{C_K}{S} \tag{10}$$

$$\%\,Mg = 100\frac{\sqrt{Mg}}{S} \tag{11}$$

This diagram gives Na-K (t_{kn}) and K-Mg (t_{km}) geothermometer values. The temperature drop in t_{kn} is minor but is major in t_{km}. This trend shows much greater speed for the K-Mg geothermometer adjusting to a change in temperature than the K-Na system. The shift in K-Mg temperature is a function of the time taken by the water to rise from the deep reservoir to the surface.

3.7 The log Q/K diagram

Log Q/K values are obtained from the log solubility products of minerals in deep waters, where Q is the calculated ion activity product in the water and K is the equilibrium constant.

$$\text{Saturation index } (SI) = \log Q - \log K \qquad (12)$$

The SI value plotted against temperature for each mineral gives an estimation of the equilibrium state of the fluid. The SI higher than zero shows supersaturation, less than zero shows undersaturation and equal to zero shows equilibrium. The point at which several minerals cross the saturation line is near to the reservoir temperature. The saturation index (log Q/K) was obtained for minerals assumed to be relevant for the system such as albite, calcite, microclines, chalcedony and quartz.

3.8 The mixing models

The Schoeller diagram shows mixing for a large number of constituents by plotting the log of concentration versus elements. The constituents are connected with a line. The effect of mixing with dilute water is to move the line vertically without changing its shape. Slopes of lines between constituents represent concentration ratios. The thermal waters have higher concentrations of Li, Na, K, F, Cl, SO_4 and B. The cold waters have higher Mg and Ca and may have almost the same HCO_3 as the thermal waters. The thermal waters are particularly low in Mg and Ca. The linear or near linear relationship between the constituents and Cl as suggested by Arnórsson (1985) is evidence for mixing in Icelandic geothermal fields.

4. RESULT AND DISCUSSIONS

Existing data of 88 geothermal springs and well samples and recent data of three geothermal springs and two wells have been used for this study (Table 2). The main localities in Reykholt area from which the geothermal fluids have been collected are: Nordurreykir, Úlfsstadir, Sudda, Reykholt, Haegindi, Kópareykir, Sturlureykir, Árhver, Deildartunga, Kleppjárnsreykir, Hurdarbak and Runnar. The compiled data was passed through different stages for classification and identification:

1. Ionic balance;
2. Origin of fluids;
3. Cl-SO_4-HCO_3 triangular diagram;
4. Geothermometer temperatures;
5. Na-K-Mg triangular diagram;
6. Saturation index diagrams;
7. Mixing models;
8. Concentration versus time diagrams;
9. Concentration versus location diagrams.

4.1 Ionic balance

The analytical data was run on the WATCH program to calculate speciation, saturation index and to check the accuracy of the results. The ionic balance value calculated by this program gives information about the quality of the analysis. These values were found to be accurate for samples collected and analysed after 1978 except for SO_4, and comparatively good for samples collected and analysed during 1965, but very poor for data obtained in 1967. From 1960 to 1964, the ionic balance is again very poor and beyond this back to 1944, no cations were analysed so no ionic balance values obtained (Table 3). The inaccuracy of the analysis is reflected in the concentration versus time graphs in the forthcoming diagrams.

TABLE 3: Ionic balance and geothermometer values for the data presented in Table 2

No.	Date	Sample No.	Ionic bal.	T_{Quartz} (°C)	$T_{chalcedony}$ (°C)	$T_{Na/K}$ (°C)	No.	Date	Sample No.	Ionic bal.	T_{Quartz} (°C)	$T_{chalcedony}$ (°C)	$T_{Na/K}$ (°C)
1	15.9.1996	96-0280	-6.29	113.3	84	64.1	49	15.11.1979			161	137	
2	25.9.1986	86-0141	-5.61	110.1	80.5	71.2	50	4.7.1978	780034	-6.95	168	145	
3	25.9.1986	86-0140	-8.02	111.3	81.8	71.1	51	15.9.1967	67-3297	-39.08	114	85	131
4	27.6.1979	79-3023	-4.63	111	81	83.6	52	15.7.1965*	65-0006	-14.27	165	141	143
5	15.9.1967	67-3303	-15.69	110.3	80.7	66.2	53	15.7.1965*	65-0007	-13.02	167	144	125
							54	14.5.1959	227		172	149	
6	15.8.1997	97-0469	-5.81	136.1	109.1	95	55	15.2.1979	790030	-1.74	162	138	105
7	23.7.1983	83-0188	-35.19	154.2	129.2	99.1	56	21.5.1959	239		160	136	140
8	17.11.1983	83-0279	2.37	142.1	115.8	102.5							
9	23.7.1983	83-0187	-32.95	153.3	128.3	99.1	57	15.2.1979	790031	-2.27	131	104	88
10	4.7.1978	78-0029	-9.36	141.5	115.1	104.9	58	14.5.1959	221		147	121	
11	15.9.1967	67-3302	-40.14	101.1	70.7	107.1							
12	15.7.1965	65-0008	-6.25	144.1	118	113.3	59	15.2.1979	79-0029	-8.7	116	87	69
13	15.7.1965	65-0009	-20.31	143.1	116.9	105	60	15.9.1967	67-3301	-38.07	106	76	67
14	15.7.1965	65-0010	-13.87	140	113.5	108.9							
15	15.7.1965	65-0011	-12.37	141.2	114.7	103.2	61	15.8.1997	97-0467	-3.56	156	131	122
16	15.7.1965	65-0012	-11.97	142.9	116.7	117.3	62	15.9.1967	67-3298	-32.72	109	79	127
17	15.7.1965	65-0013	-16.62	144.4	118.3	103.6	63	15.7.1965*	65-0005	-8.68	160	136	151
18	15.7.1965	65-0015	-13.63	142	115.7	111.8	64	13.5.1959	223		169	146	
19	15.8.1997	97-0468	-5.32	128.7	101	90.1	65	4.7.1978	780027	-9.71	129	101	88
20	27.6.1979	79-3025	3.55	143.4	117.2	107.6	66	15.9.1967	67-3293	-29.86	83	51	78
21	4.7.1978	780031	-3.29	141.9	115.1	106.8	67	15.9.1967	67-3294	-25.88	105	74	91
22	4.7.1978	780032	-3.04	137.5	110.7	103.2	68	15.7.1965*	65-0016	-13.98	133	105	105
23	4.7.1978	780033	-8.3	150.1	124.6	110	69	15.7.1965*	65-0018	-15.3	128	100	154
24	15.9.1967	67-3305	-38.77	99.1	68.5	95.6	70	15.7.1965*	65-0019	-14.7	131	103	93
25	15.7.1965	65-0026	-13.1	143	116.8	101.1	71	15.7.1965*	65-0020	-13.37	130	102	74
26	15.7.1965	65-0027	-9.72	144.1	117.9	115.7	72	15.7.1965*	65-0021	-14.05	133	106	89
27	15.7.1965	65-0028	-15.35	140.7	114.2	108.8	73	15.7.1965*	65-0022	-11.09	124	96	79
28	15.7.1965	65-0030	-15.83	149.9	124.4	73	74	15.9.1950			132	104	
29	25.5.1960	220	44.66	155.6	130.6	80.4							
30	26.5.1960	249	37.68	154.2	129.3	111.8	75	15.8.1997	97-0465	-2.42	154	129	123
31	15.11.1949			139.7	113.1		76	17.11.1983	83-0280	-0.87	155	130	133
32	1944	248	32.98	149.6	124.1	140	77	27.6.1979	79-3024	2.91	168	145	141
							78	15.9.1967	67-3299	-46.72	124	96	132
33	4.7.1978	780028	-10.18	138.7	112	99.7	79	15.9.1967	67-3300	-38.04	131	104	140
34	15.9.1967	67-3295	-31.59	76.4	44.4	125.9							
35	15.7.1965	65-0033	-17.15	143.2	117	126.2	80	15.7.1965*	65-0001	-13.07	162	138	126
36	15.7.1965	65-0034	-21.14	142.9	116.6	102.2	81	15.7.1965*	65-0002	-8.04	165	141	140
37	14.5.1959	226		152.9	127.7		82	15.7.1965*	65-0003	-13.87	166	143	128
38	15.11.1949			140.3	113.7		83	15.7.1965*	65-0004	-11.19	171	149	129
							84	13.5.1959	230		170	146	
39	6.11.1987	87-0232	15.74	150.6	125.3	113.5	85	15.11.1949			147	121	
40	14.2.1979	790021	-0.26	155.1	130.2	105.9							
41	14.2.1979	790022	-1.82	157.6	133	107.9	86	4.7.1978	780030	-7.9	145	119	100
42	15.9.1967	67-3296	-32.03	92.9	61.9	112.6	87	15.9.1967	67-3306	-37.37	94	63	99
43	14.5.1959	229		162.8	138.9		88	15.7.1965*	65-0023	-14.66	142	116	113
44	1944	247		157.5	132.9		89	15.7.1965	65-0024	-14.25	145	119	115
							90	15.7.1965	65-0025	-13.48	147	121	114
45	14.2.1979	790025	-0.31	153.8	128.8	106.8	91	13.5.1959	222		154	129	
46	15.9.1967	67-3304	-38.28	113.6	84.3	107.8							
47	13.5.1959	233		262	137.9		92	15.8.1997	97-0466	-3.03	126	98	68
48	15.11.1949			148.1	122.4		93	14.2.1979	79-0023	-0.47	132	105	84

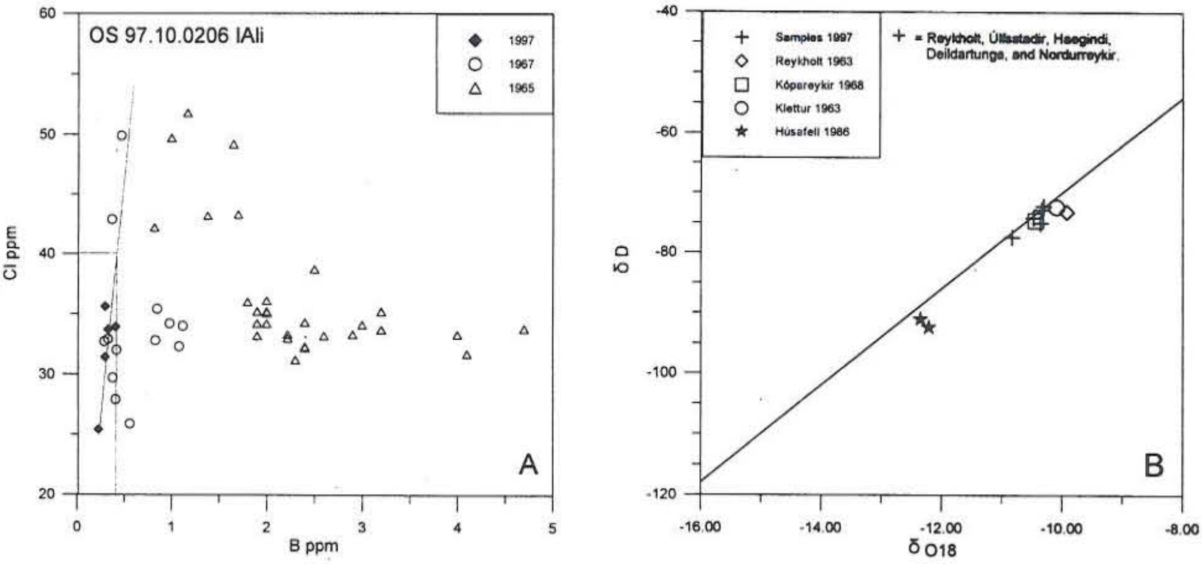


FIGURE 6: Origin diagrams for the the Reykholt water, a) Cl vs. B ratio; b) δD vs. δO^{18}

4.2 Origin of the waters

4.2.1 Cl / B ratios

The Cl vs. B ratio (Figure 6A) is one indication of the poor quality of analysis from 1965, as B has very high and scattered values. Therefore, my assumptions of Cl/B ratios are based on the data of 1997. According to this the Cl/B ratio is 101 and falls within the range for Icelandic basalt (Arnórsson, 1995). Accordingly the origin is not sea water.

4.2.2 δD / δ^{18}O ratios

The δO^{18} and δD values for Reykholt, Haegindi, Deildartunga and Hýrumelur (Nordurreykir) are nearly the same and representing the same origin and no mixing (Figure 6B). The δO^{18} and δD values for Úlfsstadir are slightly different and somewhat lower. The 1997 samples (see Table 2) show similar results as the older ones. These values do not show any mixing of cold water, but their properties are close to the fluids from Húsafell geothermal field, so there could be some mixing from Húsafell geothermal field or from the same recharge area.

4.3 Type of the water, Cl-SO_4-HCO_3 triangular diagram

Figure 7 shows that only eight samples, i.e. [Kópareykir N, Kópareykir S, Áslaugar (Stóraáslaugar), Haegindakotshver, Runnar,

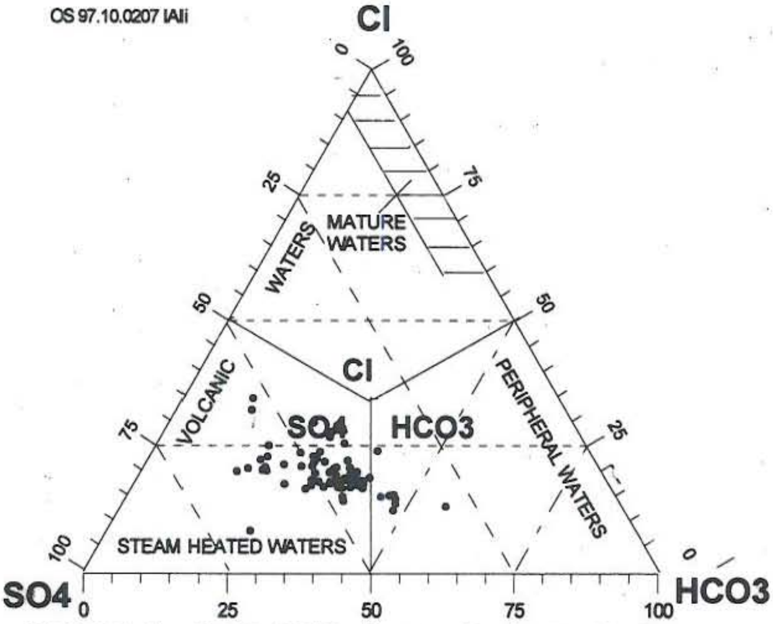


FIGURE 7: Cl-SO_4-HCO_3 diagram for the Reykholt waters

Reykholt, well at garage, Úlfsstadir and Úlfsstadalaug] plot into the carbonate region and represent carbonate or mixed groundwaters. None of the samples fall into the chloride region and the remaining samples are sulphate water, and plot in the volcanic waters region. This type of water is formed by the absorption into groundwater of high-temperature HCl containing volcanic or low-temperature H_2S containing "geothermal" vapours. Sulphate is probably formed by the oxidation of H_2S during upflow. Such phenomena are usually found at the elevated parts of the field. The samples from Runnar area are close to the chloride line. The dilute water (Arnórsson, 1983) with Cl content about 10 ppm, which have equilibrated with alteration minerals, have a much higher pH, in the range of 9-10.

4.4 Subsurface temperature

4.4.1 Geothermometers

The geothermometer values obtained from the WATCH program are listed in Table 3. According to these values, all the samples lie in the range of 76-172°C for quartz, 44-149°C for chalcedony and 67-154°C for the Na/K geothermometer. The different geothermometer temperature values for five representative samples of the area collected during this study are given in Table 4. The quartz temperature is very high as well as Giggenbach's Na/K temperature. For all the samples except Úlfsstadir the Na/K temperature of Arnórsson is about 10±5°C below the chalcedony temperature. All the samples (Table 4) lie in the range of 126-156°C for quartz, 98-131°C for chalcedony, 68-123°C for Na/K, and 144-172°C for Na/K (Giggenbach, 1988) temperature. The highest temperature is found in the Haegindi area. Probably the chalcedony geothermometer gives the most relevant temperature values in this temperature range.

TABLE 4: Different geothermometer values for the samples from 1997

Location	Log Q/K temperature (°C)	Gigg.-Na/K temperature (°C)	Watch-Na/K temperature (°C)	Watch-chalc. temperature (°C)	Watch-quartz temperature (°C)
Nordurreykir	80-140	150	95	109	136
Úlfsstadir	70-136	-	68	98	126
Reykholt	113-160	172	123	129	154
Haegindi	132-162	-	122	131	156
Deildartunga	98-131	144	90	101	129

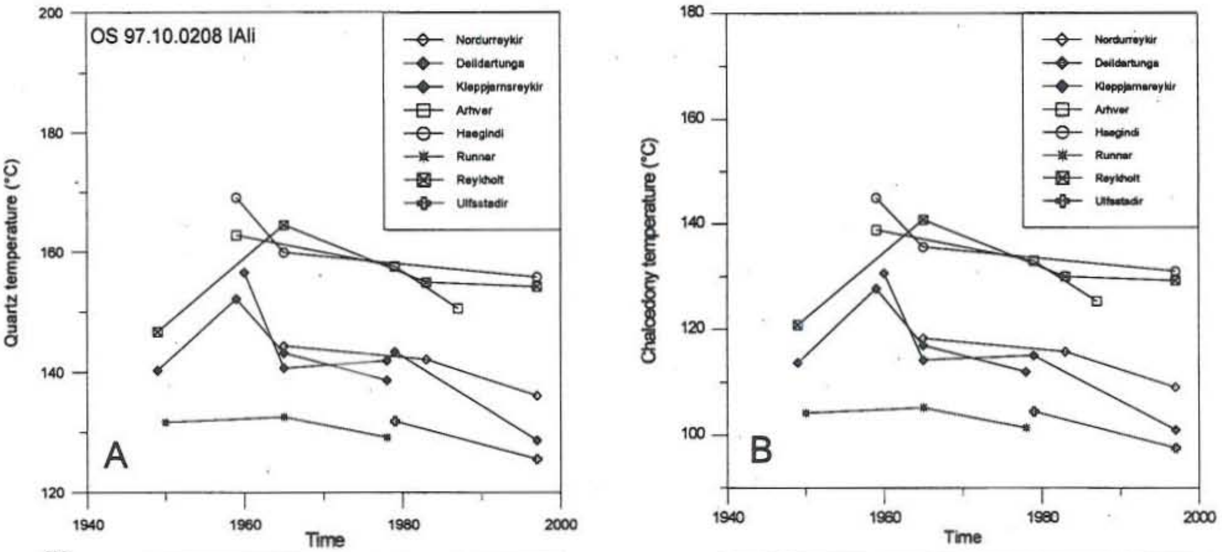
4.4.2 Change of geothermometer temperature with time

1. The quartz geothermometer is not suitable for low-temperature areas like this, but for checking the general trend, it is evident that the calculated quartz temperature has decreased with time as shown in Figure 8A.

2. The calculated chalcedony geothermometer temperature has also decreased throughout the Reykholt geothermal field area (Figure 8B).

3. The Na/K geothermometer temperature shows the same general trend as the quartz and chalcedony temperatures and has decreased in the Reykholt geothermal field (Figure 8C). This is not significant in all the fields but there is a distinct trend.

As pointed out previously, the chalcedony geothermometer is probably more relevant than the quartz



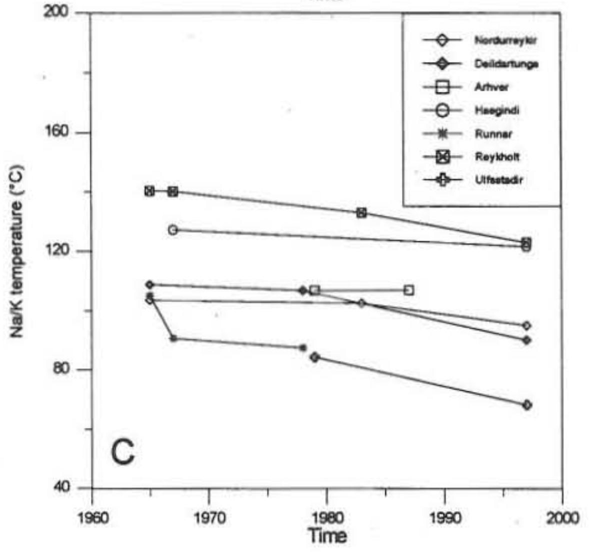


FIGURE 8: Changes in geothermometer temperature with time, a) Quartz; b) Chalcedony; c) Na/K

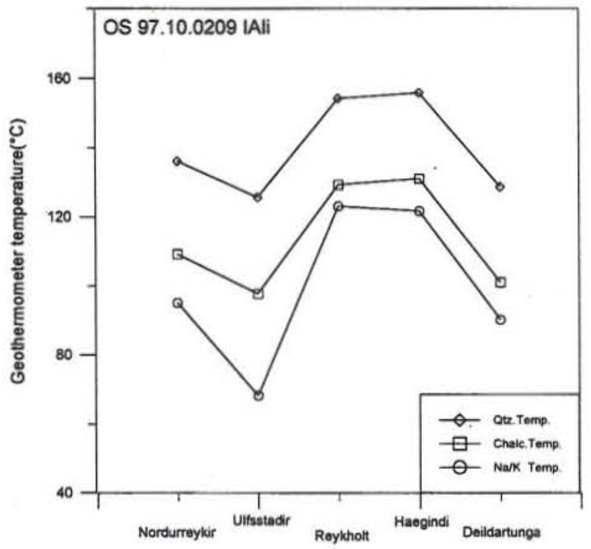


FIGURE 9: Geothermometer temperature versus location

geothermometer as reservoir temperatures are below 180°C. The Na/K geothermometer by Arnórsson is normally better adjusted for Icelandic waters than the Giggenbach Na/K geothermometer. The changes with time of these two geothermometers (chalcedony and Na/K) are considered for all the fields as shown in Figures 8B and 8C.

As there were no signs of an inflow of cold water into the fields, the temperature decline is probably due to a general decline in thermal activity. No report of the yield at different times exists, so it is not known if there is a recess in natural flow from the fields.

4.4.3 Geothermometer temperature versus location

The trend of the geothermometer temperatures is the mirror image of the concentration versus location diagram. The quartz and chalcedony geothermometer temperatures are high for the Haegindi area while Na/K geothermometer temperature is high in Reykholt. The lowest temperature is in the Úlfsstadir area (Figure 9).

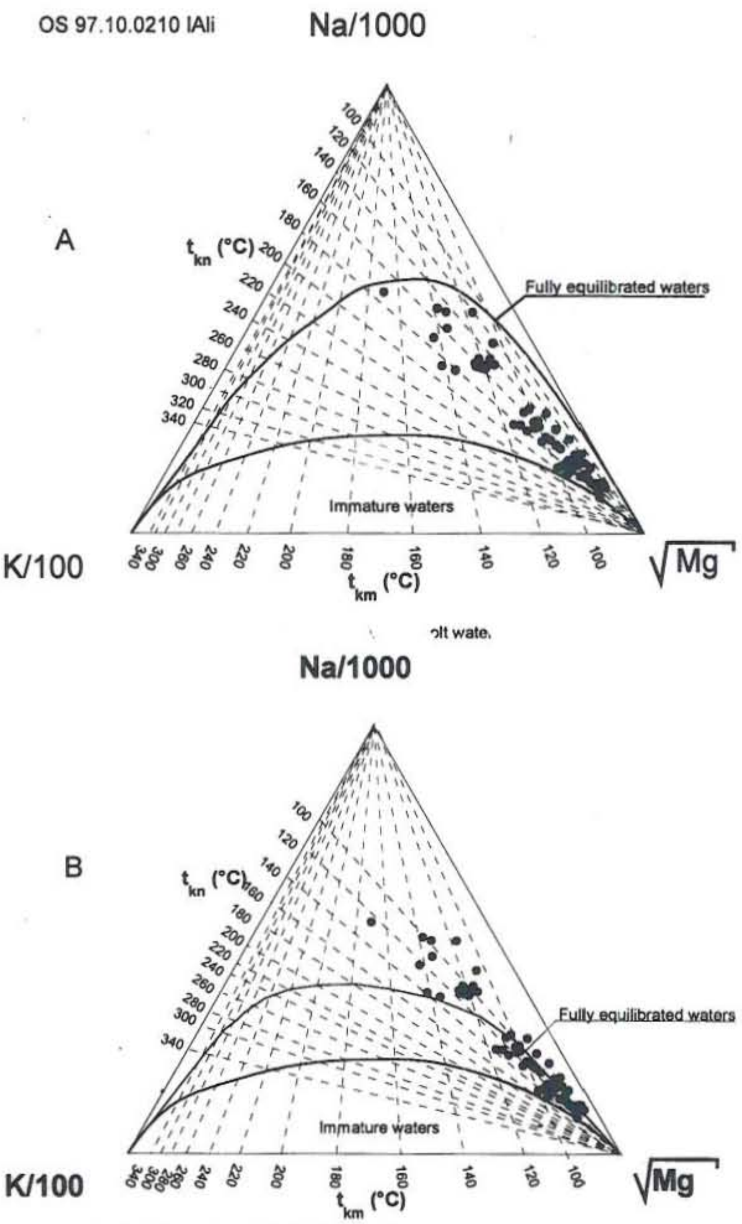


FIGURE 10: Na-K-Mg triangular diagram for the Reykholt waters, a) Based on Giggenbach (1988); b) Based on Arnórsson (1983)

4.4.4 The Na-K-Mg triangular diagram

The Giggenbach (1988) diagram (Figure 10A) shows that four samples, i.e. Reykholt well 2 (No. 97-0465), Hýrumelur (Nordurreykir) (No. 97-0469), Húsafell (No. 96-0280), and Deildartunguhver (No.97-0468) lie near to the fully equilibrated line and the rest of the samples fall in the partial equilibrium zone; none of the samples fall in the immature water section. This partial equilibrium indicates some mixing of thermal water with cold meteoric groundwater during upflow.

According to the Na-K-Mg diagram (Figure 10B) of Arnórsson et al. (1983b), most of the samples lie above the fully equilibrated line. The rest of the samples are on the line or in a partially equilibrated region and none is in the immature water section. The Na/K geothermometer temperature (80-148°C) values from this diagram are quite acceptable. On the other hand, the Na/K temperature (120-197°C) of the Giggenbach (1988) diagram is very high and is not suitable for this area. It shows that both Arnórsson and Giggenbach diagrams have limitations in one respect or another.

4.5 The log Q/K diagram

The saturation index (log *Q/K*) was calculated for minerals assumed to be relevant like albite, calcite, microclines, chalcedony and quartz for the five water samples from Reykholt, Úlfsstadir, Haegindi, Deildartunga and Hýrumelur (Nordurreykir). In all samples except Úlfsstadir, the saturation index supports the Na/K and chalcedony geothermometer temperature for all the minerals (Figures 11A-D). In Úlfsstadir, the saturation index is not clear from the diagram (Figure 11E). Here two rather distinct crossing points may be distinguished. It is probably due to low temperature of the fluid and reservoir or some mixing of different groundwaters, showing an old and a more recent equilibrium with the underground rocks. The reservoir temperature obtained from saturation index diagrams (Table 4) coincides with the Na/K and chalcedony temperatures obtained from a WATCH computer program.

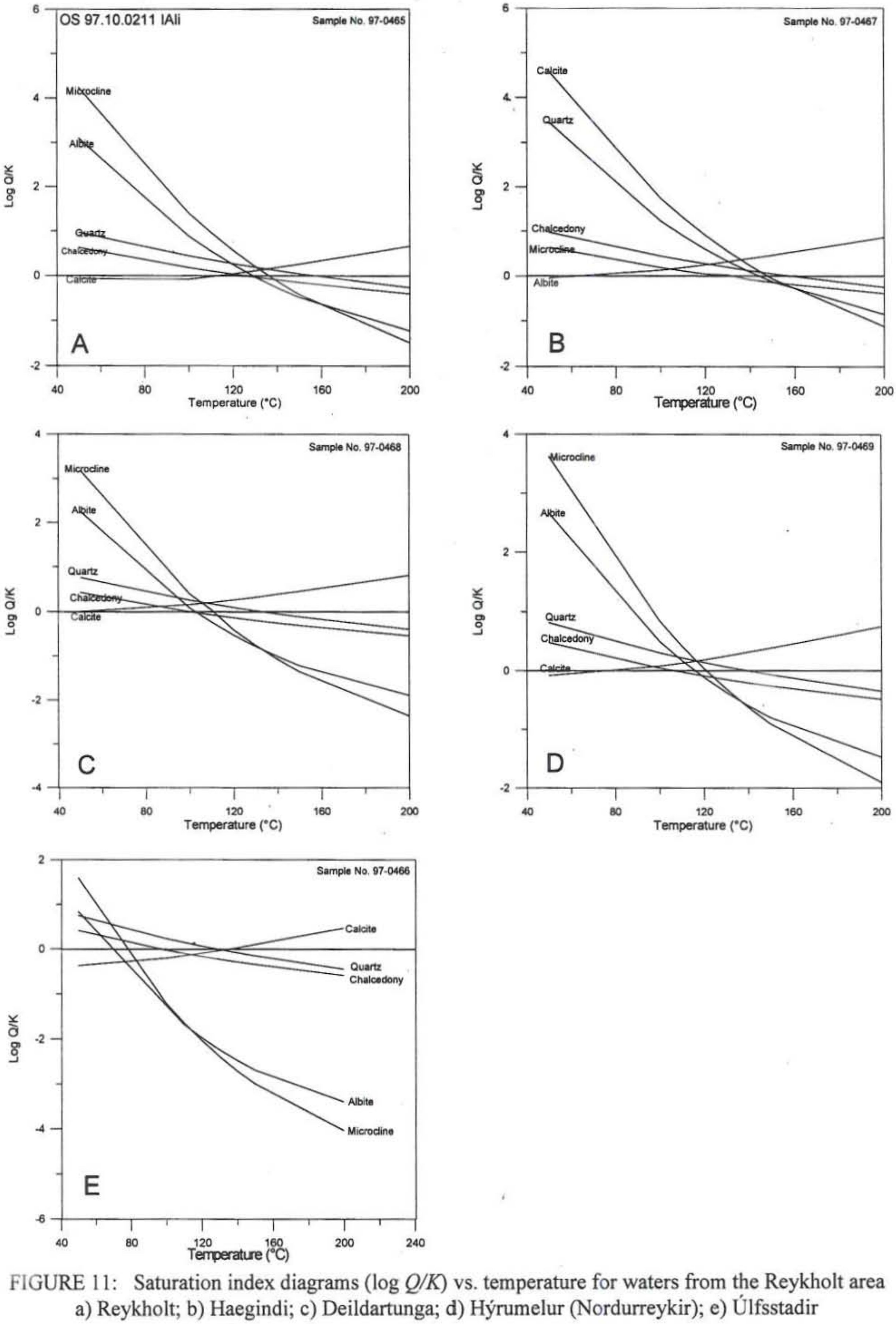


FIGURE 11: Saturation index diagrams (log Q/K) vs. temperature for waters from the Reykholt area a) Reykholt; b) Haegindi; c) Deildartunga; d) Hýrumelur (Nordurreykir); e) Úlfsstadir

4.6 Mixing evaluation

There is no evidence of mixing of the geothermal water with cold water. The saturation index diagrams (Figure 11A-D) for Reykholt, Haegindi, Deildartunga and Hýrumelur (Nordurreykir) show equilibrium temperatures, while the sample from Úlfsstadir area (Figure 11E) does not. But there is no indication of mixing of geothermal water with cold surface water.

The diagrams, SiO_2 vs. Cl, Na vs. Cl and B vs. Cl (Figures 12A and B and 6A) do not indicate a linear relationship, suggested by Arnórsson (1985) as an evidence for mixing. The Schoeller diagram (Figure 12C), shows a slightly higher log Mg concentration at Úlfsstadir as compared to other samples and this higher concentration is an indicator of mixing. Also the increasing fluoride concentration and low δD and δO^{18} values (Figure 6B) at this area indicate some mixing from the Húsafell thermal system.

4.7 Change in concentration with time

Figure 13 shows concentrations versus time for several elements. Due to poor analysis prior to 1965, there is a great scatter in concentration.

Silica: After 1965 the SiO_2 concentration decreases slightly in Nordurreykir, Deildartunga, Árhver and Reykholt areas but increases slightly in the Haegindi Kleppjárnsreykir, Sturlureykir, and Úlfsstadir areas (Figure 13A). The changes are hardly significant.

Sodium: Na decreases in the Nordurreykir, Deildartunga and Reykholt areas while increasing in Kleppjárnsreykir, Árhver, Sturlureykir, Kópareykir, Runnar and Úlfsstadir (Figure 13B). Except for Úlfsstadir the change is not significant from one sample to another, but shows a slight trend of changes.

Potassium: There is hardly any significant change in the K concentration (Figure 13C).

Calcium: No significant change seems to be in Ca (Figure 13D).

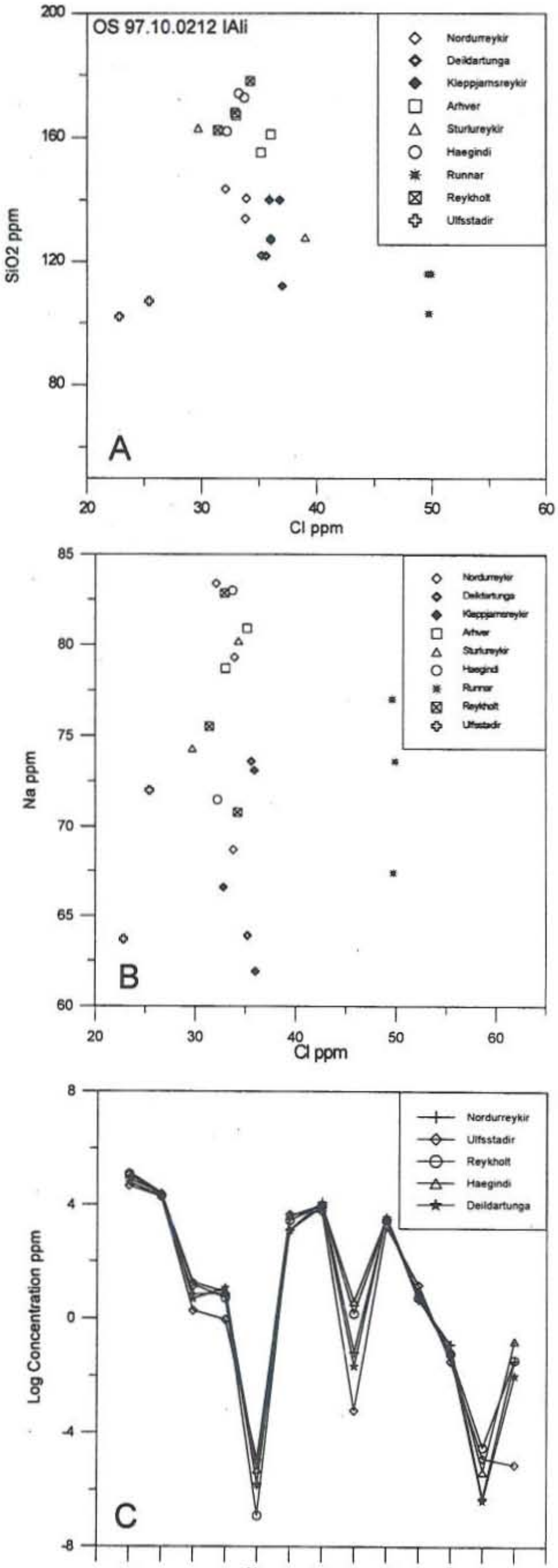


FIGURE 12: Mixing diagrams for the Reykholt area waters; a) SiO_2 vs. Cl; b) Na vs. Cl; c) Schoeller diagram

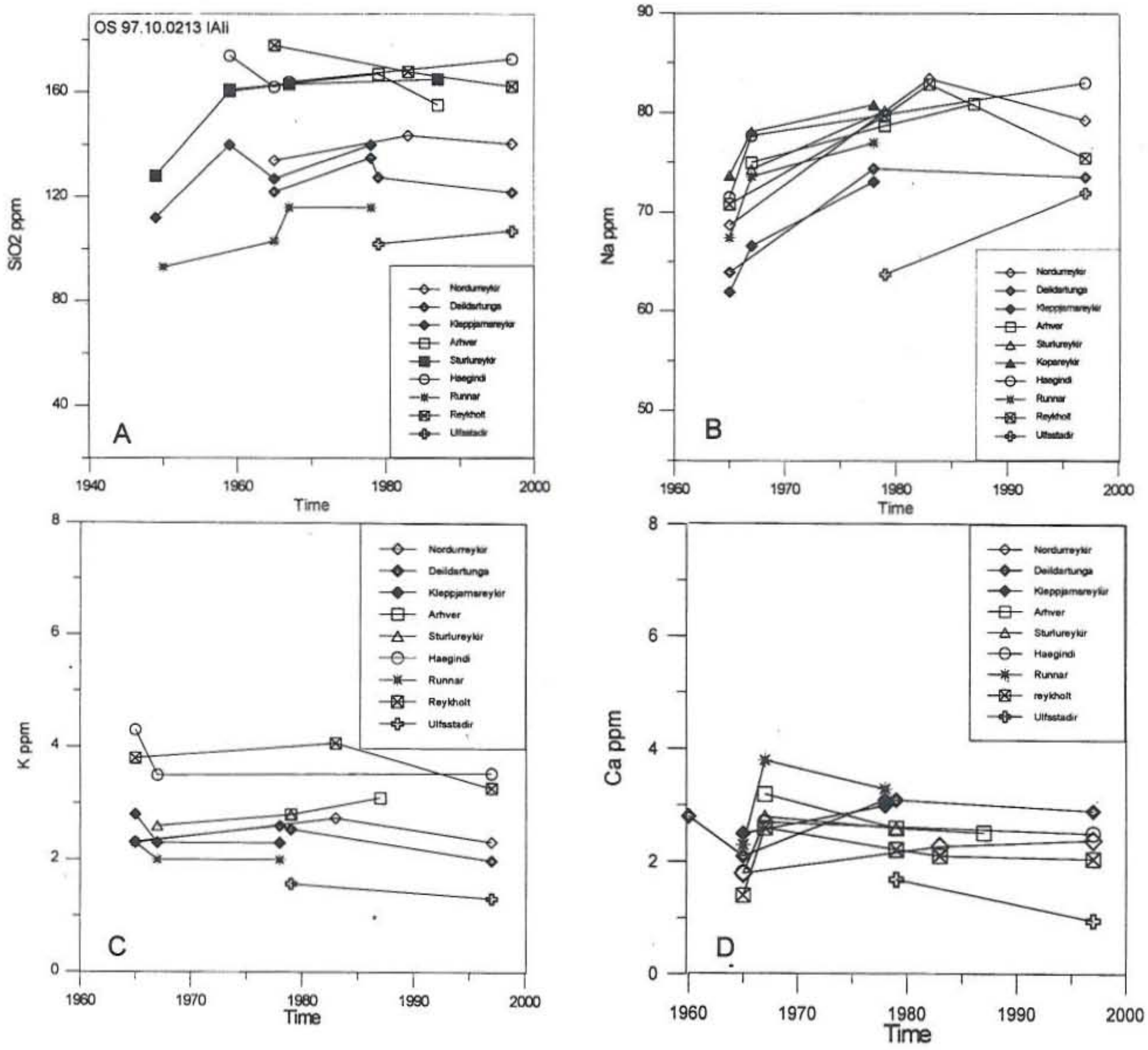


FIGURE 13: Changes in concentration with time in the Reykholt area waters;
a) SiO_2; b) Na; c) K; d) Ca

Total carbonates: In Húsafell, Deildartunga and Reykholt the concentration of CO_2 is constant, and slightly decreasing in the other fields (Figure 13E).

Sulphate: The concentration of sulphate has increased only in the Húsafell area. This geothermal field is out of the Reykholt area and is a different geothermal system. According to Figure 13F, the SO_4 concentration appears to be decreasing throughout the Reykholt geothermal system. The 1979 and 1983 results are suspicious so the decrease looks very prominent. Comparing the recent results with the 1965 and 1967 results, the change in concentration is very minute. Regarding SO_4, one has to bear in mind that if H_2S is not removed from the samples by precipitation, then each ppm of H_2S may increase SO_4 by 2.8 ppm if oxidized.

Chloride: The chloride concentration has decreased in Deildartunga, Runnar and Reykholt while it has increased in the remaining part of the Reykholt geothermal field (Figure 13G). The data before 1978 are scattered and show no clear and significant trend.

Fluoride: The concentration of F has increased in Nordurreykir, Kleppjárnsreykir, Sturlureykir, Runnar and Úlfsstadir and decreased in the Deildartunga, Árhver, Haegindi and Reykholt geothermal fields (Figure 13H). Except for Kópareykir and Úlfsstadir, near the Húsafell thermal field, changes are minor.

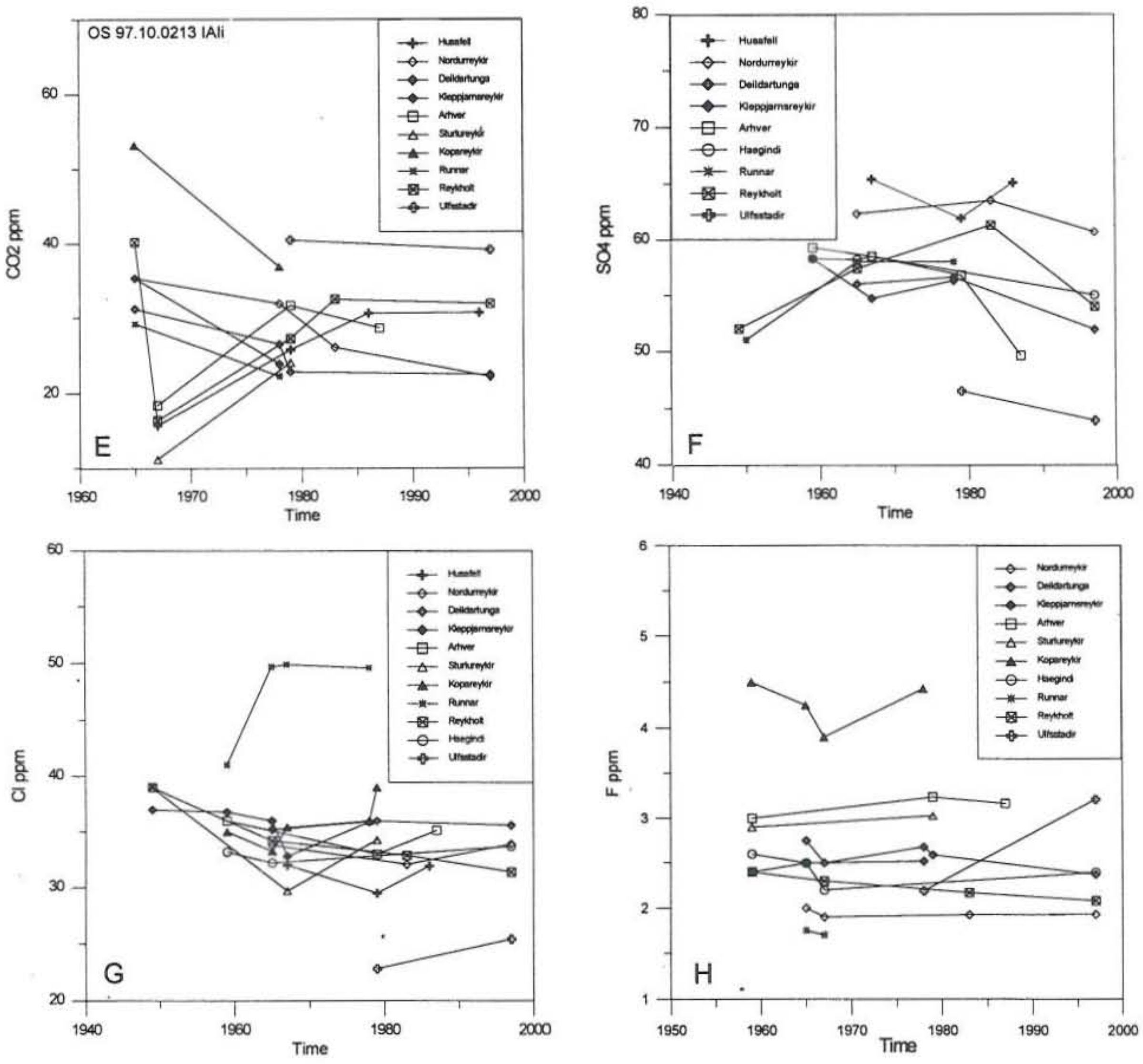


FIGURE 13: Continued; changes in concentration with time in the Reykholt area waters; e) CO_2; f) SO_4; g) Cl; h) F

4.8 Concentration versus location

During this study, five samples from geothermal springs and wells were collected. These are the representative samples of the Reykholt geothermal field. The concentrations of all the major elements is plotted against their respective locations (Figure 14A and B). The figures show that the concentration of all the elements is high in the Haegindi area and low in the Úlfsstadir area.

5. CONCLUSIONS

The main objectives of this work were to study the geochemical characteristics of geothermal water from the Reykholt geothermal area, to predict the subsurface temperature, study the changes in concentration with time and also possible mixing. To obtain this, all older data were compiled. As almost no data

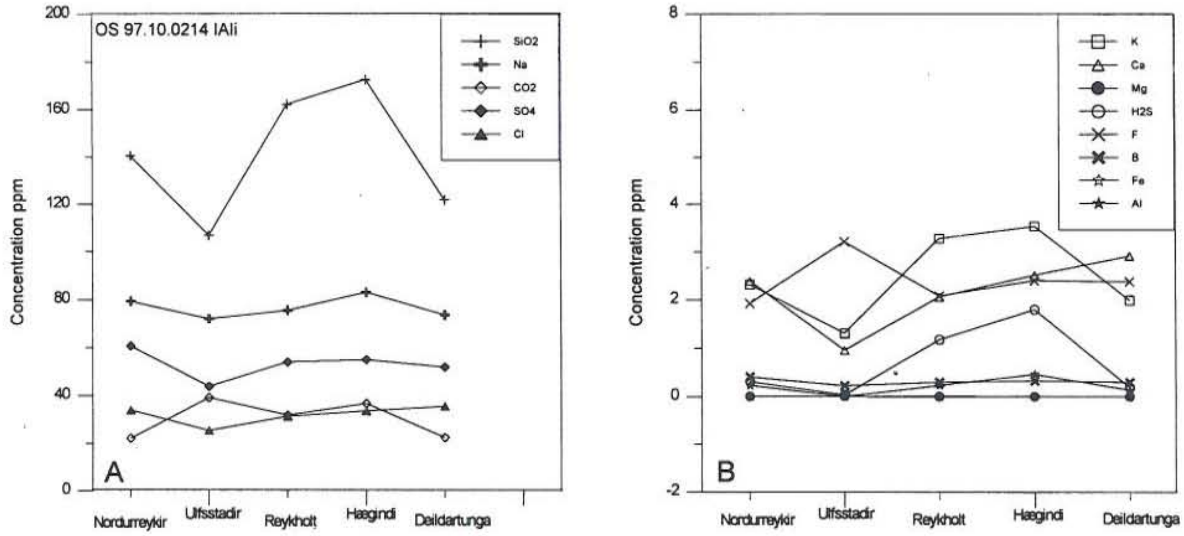


FIGURE 14: Concentration vs. location diagrams for the Reykholt area waters

existed from the last 15-18 years, five samples from selected fields were collected and analysed for comparison. The main conclusions of the study are

1. The subsurface temperature of the area is not uniform. It has a maximum at Haegindi (130°C), which is the central part of the Reykholt area and a minimum at Úlfsstadir (97°C).

2. The low ratio (95) of Cl/B and isotope values proves that the origin of the thermal fluid is mainly meteoric water and not sea water.

3. The change in the concentration of fluid composition with time is negligibly small.

4. The SO_4 concentration appears to decrease with time, but this change is most significant when compared with results from 1979 and 1983. Comparison with 1965 and 1967 data shows no prominent change. Therefore, it is concluded that the analysis of sulphate from 1979 and 1983 is not correct.

5. There is no indication of mixing of cold surface water with hot geothermal water during upflow. The Schoeller diagram, as well as the saturation index diagram (which does not show mineral equilibrium) indicates slight mixing for the Úlfsstadir area. The mixing is, however, believed to be with geothermal water from the Húsafell system, of low $\delta^{18}O$, high F and a temperature of ca. 80°C.

6. The concentration of all the elements is directly proportional to the temperature in this area except for carbon dioxide and fluoride. The concentration of these elements is at a maximum at Úlfsstadir. Carbon dioxide is at minimum at Nordurreykir and fluoride is nearly the same everywhere except at Úlfsstadir.

7. In all fields a slow cooling is suggested from the geothermometer versus time plots, where comparable data exists during the last 30 years.

8. Isotopic studies suggest that the waters originate in the Arnarvatnsheidi highlands to the northeast of the geothermal field.

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