Proceedings World Geothermal Congress 2000
Kyushu - Tohoku, Japan, May 28 - June 10, 2000

CHEMISTRY OF FUMAROLES AND HOT SPRINGS IN THE TORFAJÖKULL GEOTHERMAL AREA, SOUTH ICELAND

Magnús Ólafsson and Jón Örn Bjarnason
Orkustofnun, Grensásvegur 9, IS-108 Reykjavík, Iceland

Key Words: geothermal activity, geochemistry, geothermometry, Torfajökull, Iceland

ABSTRACT

The preliminary results of a geochemical survey of fumaroles and hot springs in the Torfajökull geothermal area, South Iceland, are presented. The total gas content in fumarole steam ranges from about 20 to roughly 25,000 mmole/kg, with carbon dioxide as the main component. Gas geothermometers indicate subsurface temperatures of about 300°C in the northern, western, and central parts of the area, and as high as 350°C in the southern and southeastern parts of the field. Mercury concentrations in steam range from 20 to 600 ng/kg, generally highest in the southeastern part. The thermal spring waters are mostly of the bicarbonate type in the southern part of the field, and of the sodium chloride type in the northern part.

1. INTRODUCTION

The Torfajökull high-temperature geothermal area is the largest thermal field in Iceland, located within a central volcanic complex in the southern part of the country (Fig. 1). This complex encompasses a large caldera subsidence with an abundance of rhyolitic rocks (Saemundsson, 1972; 1988). Surface thermal manifestations, which include extensive alteration, warm and boiling springs, mudpots, and a large number of fumaroles (Fig. 2), cover an area of some 140 km^2. The fumaroles and mudpots appear to be confined to the caldera proper, mostly at altitudes between 850 and 1000 m a.s.l., and virtually all of the boiling springs are found there as well. The most powerful fumarole (Fig. 3) is called Hvínandi (no. 607 in Fig. 4). Most of the warm springs are located on the rim of the caldera or just outside it, at an altitude of around 600 m.

The Torfajökull massif is cut by a multitude of gullies and ravines. This badlands topography is particularly striking in the southern and southeastern parts, and it makes field work rather laborious. A popular backpacking trail winds through the central part of the area, which is otherwise relatively inaccessible and almost devoid of vehicle tracks. Vegetation is sparse. The weather is frequently inclement. Winter snowfall is heavy and the snow lingers far into the summer. As a result, the field season is quite short.

Fumaroles and thermal springs in the northern, western, and central parts of the area were studied by Arnórsson et al. (1987), who reported subsurface temperatures on the basis of gas geothermometers and spring chemistry. The southern and southeastern parts of the field appear to have been little studied until now.

An extended program of geothermal exploration of the Torfajökull field was initiated in 1992 by Orkustofnun, the National Energy Authority of Iceland (Stefánsson, 1992). The project involves mapping the geology of the area, including active and fossil surface thermal manifestations. It also involves a regional resistivity survey, and a study of the chemistry of fumaroles and thermal springs. This paper presents some preliminary results of the geochemical study, including the first fumarole data from the southern and southeastern parts of the field.

2. CHEMICAL COMPOSITION OF STEAM

Samples of steam for chemical analysis were collected from fumaroles throughout the Torfajökull area. Even though only a tiny fraction of the fumaroles could be sampled, an attempt was made to cover the entire field fairly in order to obtain a representative picture. The fumarole sampling points are shown as circles on the map in Figure 4, and Table 1 displays the chemical composition of ten representative samples. These samples are indicated on the map by their respective numbers. Steam for gas analysis was collected into evacuated glass bottles containing a sodium hydroxide solution, as described by Fahlquist and Janik (1992).

The total concentration of gas in steam spans a wide range, from approximately 20 to almost 25,000 mmole/kg, with a single extreme value of nearly 400,000 mmole/kg. Carbon dioxide is the main gas constituent in most samples. It generally represents 80 to 99% of the total gas. Hydrogen sulfide and hydrogen are the other principal components, accounting for 0.1 to 10% of the total gas. The nitrogen concentration is below 1% in all samples except two. These exceptional samples may have been contaminated by atmospheric air. Methane amounts to less than 0.2% of most samples.

The highest gas concentrations, by far, are found in the southern and southeastern parts of the field. The carbon dioxide concentration, in particular, is very high in these areas. The concentrations of hydrogen sulfide and hydrogen are also generally highest in the southern and southeastern parts, but the pattern is much less pronounced than for carbon dioxide. As a result, the concentration ratios of carbon dioxide to the other gases are very much higher in the south and southeast than in other parts of the field.

The concentration of mercury in steam ranges from 20 to 600 ng/kg. On the whole, the highest concentrations are found in the southern and southeastern parts of the geothermal area. The chloride concentration does not display any clear geographical pattern. It ranges from 0.05 to 0.76 mg/kg, but five out of every six samples were found to contain less than 0.40 mg/kg. The concentration of boron in steam ranges from less than 0.03 mg/kg, which is the detection limit for the analytical method used, to roughly 0.5 mg/kg. Most of the samples with concentrations above 0.03 mg/kg were collected from the southern and southeastern parts of the field.

No clear geographical pattern emerges from the hydrogen and oxygen isotope data. Figure 5 shows a crossplot of the isotope ratios for the fumarole samples, represented by circles. Two frying-pan samples, represented by triangles, are also included in the graph. Tie-lines connect the steam and liquid phase of each. It is worth noting that the trend of the fumarole points is parallel to the tie-lines, which represent phase separation at a temperature of about 100°C. This suggests that the isotope ratio distribution may be a result of the condensation of water out of the rising steam column near the surface. The remaining steam would thus be enriched in the lighter isotopes.

3. GAS GEOTHERMOMETERS

Subsurface temperatures were estimated on the basis of gas geothermometers. Seven such geothermometers were applied to the samples reported in Table 1. The results are presented in Table 2. These are the CO_2, H_2S, H_2, CO_2/H_2, and H_2S/H_2 geothermometers of Arnórsson and Gunnlaugsson (1985), the CO_2/N_2 geothermometer of Arnórsson (1987), and the CH_4/CO_2 geothermometer of Giggenbach (1991). This last-named geothermometer rather consistently yields substantially higher subsurface temperatures than the others. This is generally attributed to the slow rate of re-equilibration of methane with carbon dioxide. This geothermometer is thus thought to reflect temperatures at greater depth in the geothermal system.

Temperatures computed from the CO_2/N_2 geothermometer of Arnórsson (1987) are shown on the map in Figure 6. The highest values, ranging up to 350°C or so, are found in the southern and southeastern parts of the area. Elsewhere, temperatures of around 300°C, or a little less, are obtained. This pattern is even more pronounced for the CO_2 geothermometer, which yields temperatures of 350°C or higher in the south and southeast, but temperatures generally below 280°C in other parts.

The H_2, H_2S, and H_2S/H_2 geothermometers all show a rather more uniform temperature distribution over the area. The H_2S geothermometer gives values of about 300°C in the southern and southeastern parts of the Torfajökull field, and 275 - 290°C elsewhere. The H_2 and H_2S/H_2 geothermometers yield temperatures close to 300°C over the entire field, with a slight trend toward higher values in the south and southeast. The H_2S geothermometer shows more scatter than the other two.

It is well known that the application of different geothermometers to data from real geothermal fields often yields somewhat divergent results. The Torfajökull area is no exception. Even so, the picture that emerges here is rather consistent. Thus the preponderance of evidence seems to indicate subsurface temperatures of 300°C over most of the field except the south and southeast, where temperatures may reach 350°C.

4. SPRING CHEMISTRY

Samples of water were collected from hot and warm springs, some of which are located within the caldera and some just outside it. These are indicated by squares on the map in Figure 4. The chemical composition of four representative samples is presented in Table 3.

The thermal spring waters are mostly of the bicarbonate type in the southern part of the Torfajökull field and primarily of the sodium chloride type in the northern part, where the chloride concentration reaches 575 mg/l (Fig. 7). Boiling pools with acid sulfate waters are found throughout the Torfajökull area. Most of these represent drowned fumaroles. Examples of alkaline springs with very low chloride content, e.g. sample 161, are also found within the caldera.

The mercury concentration in the springs ranges from less than 5 ng/l, which is the limit of the analytical method used, to 70 ng/l. There is a single extreme value of 800 ng/l.

The spring at Landmannalaugar, labelled L on the map in Figure 4, yields a chalcedony geothermometer temperature (Fournier, 1977) of 182°C, and a surface temperature of 77°C. The chalcedony temperatures of the remaining springs are lower and rather evenly distributed over the range from 85°C to about 170°C. Their surface temperatures range from 24°C to 100°C. The quartz geothermometer temperature (Fournier and Potter, 1982) for Landmannalaugar is 200°C. This geothermometer, which yields temperatures of 20 - 25°C above the chalcedony geothermometer, is probably the more appropriate one for the springs with the highest indicated temperatures.

Most of the hot spring waters seem to be close to fluorite saturation. Although unusual for Iceland, where most of the rock is basaltic, this is to be expected in the Torfajökull area, where rhyolite dominates the geology.

Figure 8 displays a crossplot of the hydrogen and oxygen isotope ratios for the water samples. Most of the thermal waters, indicated by squares, fall on the meteoric line, though some appear to be oxygen-shifted. Cold water samples, shown as diamonds, presumably represent the local precipitation.

5. CONCLUSIONS

The highest concentrations of gas in steam are found in the southern and southeastern parts of the Torfajökull geothermal area. This pattern is particularly striking for carbon dioxide. On the whole, gas geothermometer temperatures also appear to be highest in that part of the field, ranging up to 350°C or so, compared to 300°C or less in other parts of the area. The regions of the highest concentrations of mercury and boron in steam coincide with those of the highest gas geothermometer temperatures. Although some doubts may remain about the accuracy of some individual gas geothermometers as absolute indicators of subsurface temperature, we feel that the data support the conclusion that the south and the southeast constitute the hottest parts of the Torfajökull field.

REFERENCES

Arnórsson, S. (1987). Gas chemistry of the Krísuvík geothermal field, Iceland, with special reference to evaluation of steam condensation in upflow zones. *Jökull*, 37, pp. 31-47.

Arnórsson, S. and Gunnlaugsson, E. (1985). New gas geothermometers for geothermal exploration - calibration and application. *Geochim. Cosmochim. Acta* 49, pp. 1307-1325.

Arnórsson, S., Ívarsson, G., Cuff, K.E. and Saemundsson, K. (1987). Geothermal activity in the Torfajökull field, South Iceland: Summary of geochemical studies. *Jökull*, 37, pp. 1-11.

Fahlquist, L. and Janik, C.J. (1992). *Procedures for collecting and analyzing gas samples from geothermal systems*. U.S. Geological Survey Open-File Rept. 92-211, 19pp., and references therein.

Fournier, R.O. (1977). Chemical geothermometers and mixing models for geothermal systems. *Geothermics*, 5, pp. 41-50.

Fournier, R.O. and Potter, R.W. II (1982). A revised and expanded silica (quartz) geothermometer. *Geoth. Res. Council Bull.*, 10-11, pp. 3-12.

Giggenbach, W.F. (1991*). Chemical techniques in geothermal exploration*. In Application of Geochemistry in Geothermal Reservoir Development (Co-ordinator D'Amore, F.) pp. 119-144, UNITAR/UNDP Centre on Small Energy Resources, Rome.

Saemundsson, K. (1972). Notes on the geology of the Torfajökull central volcano. (In Icelandic.) *Náttúrufraedingurinn*, 42, pp. 81-99.

Saemundsson, K. (1988). *Geology of the Torfajökull wilderness*. (In Icelandic.) Árbók Ferdafélags Íslands, pp. 164-180.

Stefánsson, V. (1992). *Geothermal energy for electricity production*. (In Icelandic.) Orkustofnun Report VS-92/05, 4 pp.

Table 1. Chemical composition of steam from selected fumaroles in the Torfajökull geothermal area.

Sample	**613**	**158**	**214**	**166**	**607**	**605**	**671**	**674**	**672**	**140**
CO_2 (mmole/kg)	132	242	67	128	370	8330	2000	21100	370000	819
H_2S (mmole/kg)	10.7	4.40	3.79	10.2	21.1	38.5	14.5	0.81	15.9	20.1
H_2 (mmole/kg)	16.6	3.55	4.17	25.3	41.8	47.9	49.7	36.3	383	28.9
CH_4 (mmole/kg)	0.24	0.21	0.085	1.42	0.19	0.036	0.035	0.59	9.37	0.70
N_2 (mmole/kg)	0.54	0.90	0.33	2.26	0.58	3.67	2.11	26.4	663	2.14
Ar (mmole/kg)	0.014	0.020	0.008	0.055	0.011	0.057	0.032	0.39	8.19	0.042
B (mg/kg)	<0.03	<0.03	<0.03	0.08	<0.03	<0.03	0.04	0.04		0.065
Cl (mg/kg)	0.27	0.17	0.04	0.25	0.33	0.09	0.13	0.11		0.76
Hg (ng/kg)	40	70	100	30	20		140	90		120
δD (‰ SMOW)	-90.7	-88.7	-78.2	-76.6	-87.9	-89.3	-85.2	-103.6		-96.8
$\delta^{18}O$ (‰ SMOW)	-13.32	-13.57	-11.47	-11.68	-13.29	-13.48	-12.48	-19.13		-15.44

Table 2. Gas geothermometer temperatures for selected fumaroles in the Torfajökull area (°C).

Sample	**613**	**158**	**214**	**166**	**607**	**605**	**671**	**674**	**672**	**140**
CO_2 1)	272	290	249	271	302	404	349	452	714	323
CO_2/N_2 2)	308	310	303	268	330	354	338	335	327	318
CH_4/CO_2 3)	331	358	344	275	378	646	545	518	524	358
H_2S 1)	293	276	273	292	306	318	299	241	301	305
H_2 1)	303	289	290	307	311	312	313	310	331	308
CO_2/H_2 1)	316	289	307	322	315	278	296	263	256	300
H_2S/H_2 1)	312	300	306	320	316	308	325	371	359	310

1) : Arnórsson and Gunnlaugsson (1985); 2) : Arnórsson (1987); 3): Giggenbach (1991)

Table 3. Chemical composition of selected hot springs in the Torfajökull geothermal area (concentrations in mg/l, except where noted).

Sample	**601**	**161**	**603**	**143**
Temp. (°C)	100	96.5	91.8	69.5
pH/°C	8.96/22	8.83/21	7.24/22	6.87/14
CO_2 (t)	25.2	67.5	573	1023
H_2S	4.86	3.79	0.06	<0.03
SiO_2	200	120	111	229
B	7.93	0.066	0.83	1.78
Li	0.070	0.09	0.12	0.34
Na	356	57.4	387	365
K	14.6	4.43	9.74	39.5
Mg	0.030	0.15	0.56	8.67
Ca	15.0	1.87	5.19	27.4
F	9.61	9.53	20.7	8.57
Cl	575	3.13	115	29.2
Br	2.19	0.006	0.35	0.08
SO_4	18.9	20.6	31.1	38.3
Al	0.26	0.18	0.037	0.017
Mn	0.017	0.025	0.0035	0.026
Fe	0.16	0.014	0.058	0.40
Hg (ng/l)	< 5	65	16	15
TDS	1200	258	1020	1287
δD (‰SMOW)	-74.6	-79.8	-75.5	-75.1
$\delta^{18}O$ (‰SMOW)	-8.43	-11.26	-10.82	-10.20

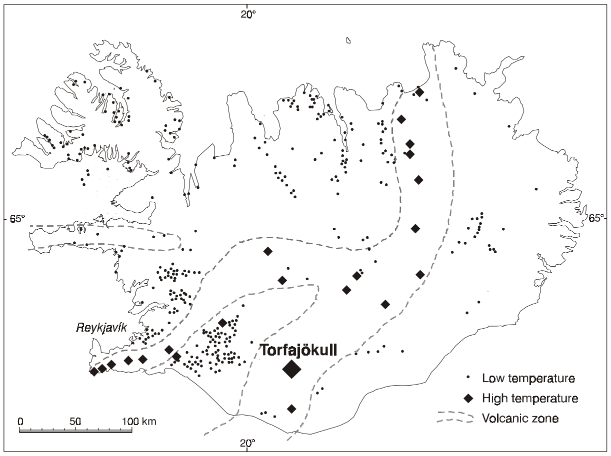

Figure 1. Geothermal areas in Iceland.

Figure 2. Geothermal activity in the Torfajökull geothermal area.

Figure 3. Hvínandi, the most powerful fumarole in the Torfajökull geothermal area.

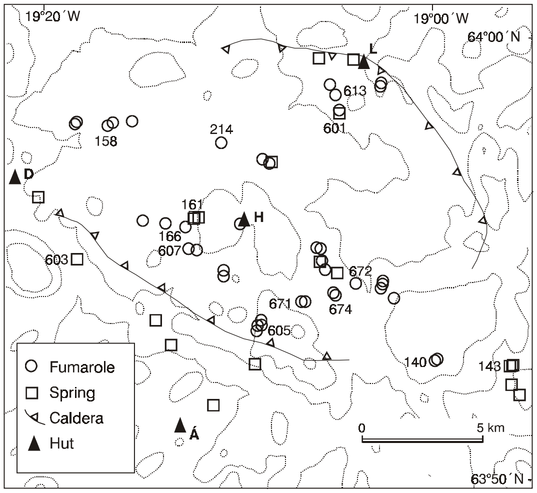

Figure 4. Location of steam and water samples.

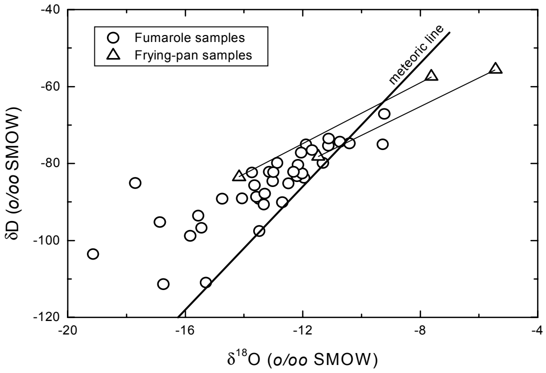

Figure 5. Hydrogen and oxygen isotope ratios in samples from fumaroles and frying-pans.

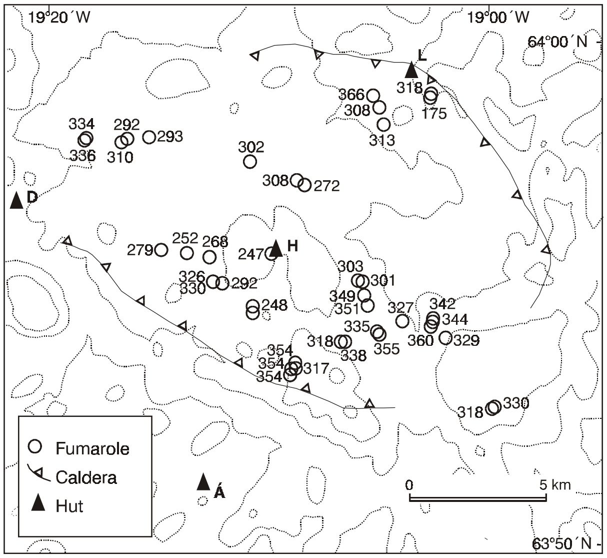

Figure 6. The CO_2/N_2 geothermometer temperatures of fumarole samples.

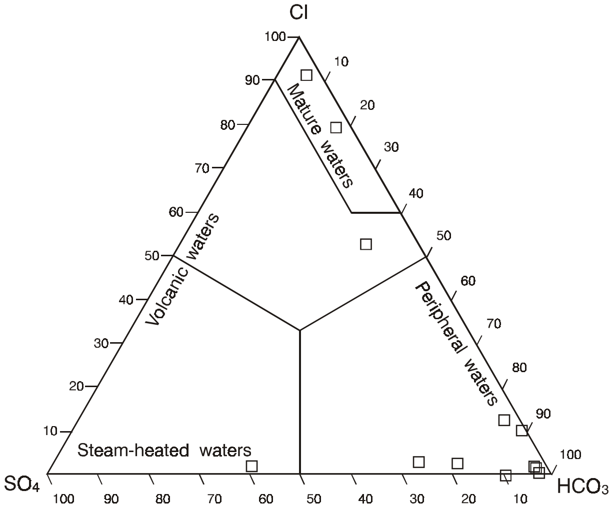

Figure 7. The SO_4-Cl-HCO_3 classification diagram for waters in the Torfajökull geothermal area.

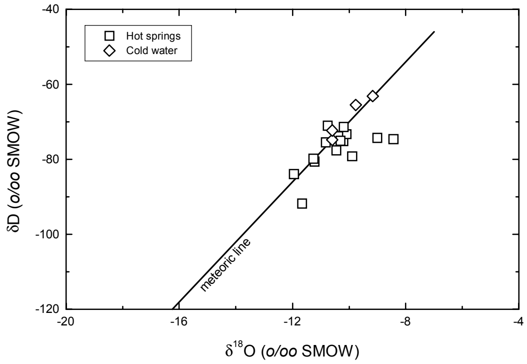

Figure 8. The hydrogen and oxygen isotope ratios in hot and cold water samples.