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GAS CHEMISTRY AND SUBSURFACE TEMPERATURE ESTIMATION IN THE HVERAGERDI HIGH-TEMPERATURE GEOTHERMAL FIELD, SW-ICELAND

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ABSTRACT

Five gas geothermometers based on the concentrations of CO_2, H_2S, H_2, CH_4, N_2 and Ar in fumaroles and wet-steam well steam are applied to estimate subsurface temperature in the Hveragerdi high-temperature geothermal field, SW-Iceland. The results for fumaroles indicate that the calculated subsurface temperatures decrease from the northern part to the southern part part of the field. The CO_2 - geothermometer gives the highest temperature values, an average of 256°C for the northern part, and 247°C for the southern part. The H_2S - geothermometer reveals aquifer temperature of 211°C for the northern part, and 203°C for the southern part. The H_2 - geothermometer gives an average subsurface temperature of 229°C for the northern part, and 184°C for the southern part, which agrees excellently with the measured temperatures in wet-steam wells. The measured borehole temperatures in the field range from 215°C to 230°C for the northern part, and from 167°C to 198°C for the southern part. The CO_2 /H_2 - geothermometer gives the lowest subsurface temperature values, an average of 203°C for the northern part, and 143°C for the southern part. The CO_2 /N_2 - geothermometer gives 249°C for the northern part and 235°C for the southern part. For data from wells, the CO_2 - geothermometer, the H_2S - geothermometer, and the H_2 - geothermometer, give an average subsurface temperature of 247°C for the northern part and 246°C for the southern part, 213°C for the northern part and 220°C for the southern part, and 217°C for the northern part and 216°C for the southern part, respectively. The CO_2 /H_2 - geothermometer indicates an average subsurface temperature of around 200°C for both the northern part and the southern part. The CO_2 /N_2 - geothermometer gives an average subsurface temperature of 180°C for the northern part and 259°C for the southern part. The discrepancy between the estimated subsurface temperatures obtained by various gas geothermometers has been explained in this paper. By integration of solute geothermometry results, mixing model studies and the gas geothermometry results, the maximum subsurface temperatures of the Hveragerdi high-temperature geothermal system may be considered to be about 240-260°C.

1. INTRODUCTION

Iceland is located on the Mid-Atlantic Ridge which traverses the island from southwest to northeast where the active spreading axis appears as a zone of active rifting and volcanism. The volcanic rift zone is characterized by active volcanoes, fissure swarms, numerous normal faults and high-temperature geothermal fields. Geothermal activity in Iceland is divided into two types on the basis of the base temperature (maximum temperature) in the uppermost 1 km . The base temperature is thus ≤150 °C in the low -temperature areas, but ≥200 °C in the high-temperature areas. Low-temperature fields are in Pli-Pleistocene and Tertiary volcanics, and the high-temperature fields are located in the active volcanic zones.

The Hveragerdi high-temperature geothermal field, located about 50 km south-west of Reykjavik, is on the southern margin of the Hengill neovolcanic area. Numerous drillholes have been sunk into the field (Figure 1). A temperature reversal is observed in most of the wells and a temperature decrease from a maximum of 230 °C in the northern part of the drilled area to about 160 °C just south of the Hveragerdi village. This temperature reversal has been explained by lateral flow from the central parts of the Hengill geothermal area.

In the Hveragerdi field, geothermal manifestations consist of fumaroles dominating in the north, and hot springs most abundant in the south. The sampling locations for samples used in this paper are shown in Figure1.

In the geothermal field, subsurface temperature estimations by water and gas chemistry from hot springs, well discharges and fumaroles have been made by Arnorsson and Gunnlaugsson (1985), Gestsdottur and Geirsson (1990), Geirsson and Arnorsson (1995), and Ivarsson (1996). However, further interpretation of available data by integration of gas and water geochemistry needs to be made. In this paper, gas chemistry of geothermal fluids from the Hveragerdi high-temperature geothermal field, SW-Iceland, were used to estimate subsurface temperatures in geothermal systems. The mixing and boiling/degassing processes in up-flow zones below hot springs and boreholes were assessed by three mixing models. The subsurface temperatures predicted by various geothermometers are evaluated by comparison with measured down-hole temperatures.

2 GAS CHEMISTRY AND SUBSURFACE TEMPERATURE ESTIMATION

2.1 Gas chemistry of steam

During the last 15 years, many fumarole steam samples have been collected in the Hveragerdi area (Figure 1). The gas composition of some of these fumarole steam samples and steam from wet-steam wells is presented in Table 1.

The concentration of various gases in fumaroles and steam from wet-steam wells are considered to be equilibrium with specific mineral buffers. Calcite, together with quartz, epidote and prehnite above about 230 °C, and various zeolites in addition to calcite may possibly be involved at lower temperatures (Arnorsson and Gunnlaugsson, 1985). Iron minerals and iron-containing aluminium silicates such as pyrite + pyrrhotite + epidote + prehnite, magnetite + epidote + prehnite and/or pyrite + epidote + prehnite + chlorite may constitute the H_2S and H_2 buffers (Giggenbach, 1980; Arnorsson and Gunnlaugsson, 1985). Five gas geothermometers based on the concentrations and ratios of H_2,H_2S and CO_2 from Arnorsson (1991) are applied in this study.

The concentrations of CO_2, H_2S, H_2 and N_2 in fumarole steam of this field are in the range 48.3-161.9, 0.33-8.91, 0.07-9.38 and 0.26-26.2 mmoles/kg steam, respectively. CH_4, Ar and O_2 are generally less than 1% of total gas. Gaseous compounds make only up about 0.02% of the total volume of the fumarole steam, considerably less than observed in most other high-temperature geothermal fields in Iceland. The gas chemistry of this field is also characterised by low concentrations of H_2S and H_2 compared to the neighbouring fields of Nesjavellir and Hengladalir (Armannsson et al., 1986; Arnorsson, 1986).

If a line is drawn arbitrarily from east to west through well 3 (Figure 1), the geothermal field can be divided into a northern part and a southern part. For each part, the average gas composition is shown in Figure 2. The concentrations of CO_2, H_2S, H_2 , CH_4, N_2 and Ar decrease significantly from north to south in this field. H_2S, H_2 , CH_4 and CO_2 concentrations change relatively more than those of N_2 and Ar owing to the former being more reactive. It is also noted that samples collected at higher altitudes in the ridges between the valleys contain less H_2 and H_2S than samples collected on the valley floors most likely due to oxidation of these reduced species above groundwater level.

2.2 Gas geothermometry results

As discussed above, the concentrations of various gases in fumarole steam and steam from wet-steam wells are considered to be in equilibrium with mineral buffers at any given temperature. The above-mentioned five gas geothermometers are used for this paper. The results are presented in Table 2.

The results for fumaroles indicate that the subsurface temperatures calculated by these gas geothermometers decrease from the northern to the southern part of this geothermal field. This is well demonstrated in Figure 3.

The CO_2 - geothermometer gives the highest temperature values, an average of 256 °C for the north, and 247 °C for the south. The H_2S - geothermometer indicates aquifer temperature of 211 °C for the north, and 203 °C for the south. The H_2 - geothermometer gives an average subsurface temperature of 229 °C for the north, and 184 °C for the south, which agrees excellently with the measured temperatures in wet-steam wells. In this field, the measured temperatures range from 215 °C to 230 °C for the northern part, and from 167 °C to 198 °C for the southern part. The CO_2 /H_2 - geothermometer gives the lowest subsurface temperature values, an average of 203 °C for the north, and 143 °C for the south. The CO_2 /N_2 - geothermometer gives 249 °C for the north and 235 °C for the south.

For data from wells, the CO_2 - geothermometer, the H_2S - geothermometer, and the H_2 - geothermometer give an average of subsurface temperature of 247 °C for the north and 246 °C for the south, 213 °C for the north and 220 °C for the south, and 217 °C for the north and 216°C for the south, respectively. The CO_2 /H_2 - geothermometer indicates an average subsurface temperature of around 200 °C both for the north and the south. The CO_2 /N_2 - geothermometer gives an average subsurface temperature of 180 °C for the north and 259 °C for the south, which is not reliable due to the danger of even a small proportion of air drawn in during upflow or sampling causing significant interference.

The discrepancy between the estimated subsurface temperatures obtained by various gas geothermometers may be explained by various causes. One is that the area is a relatively old geothermal area which means that the geothermal system has cooled down, and such system tend to be high in CO_2 and yield high CO_2 geothermometer temperatures. For the high CO_2 concentration in such systems, various explanations have been offered, one being that there is probably a steady flow of CO_2 from the magma which becomes masked in the high concentrations in new systems, but with lowered equilibrium concentrations along with a reduced steam fraction, the CO_2 concentration of the steam may become significantly higher than the equilibrium concentration. As speculated by Arnorsson and Gunnlaugsson (1985) and Zhao and Armannsson (1996), different mineral buffers may control H_2S and H_2 concentrations at different temperatures. The good results obtained by the H_2 - gas geothermometer is probably due to better defined buffers for H_2 than for others. Another explanation may be the combination of condensation and oxidation in the upflow. The low H_2S temperatures are due to loss of H_2S by oxidation, especially for the samples collected on high ground. The higher CO_2 temperatures are partially caused by condensation which leads to higher CO_2 concentration in the steam which is reflected in data from wells in whose fluid the CO_2 concentrations are lower than those of nearby fumarole steam. The CO_2 /H_2 - geothermometry temperatures are not reliable probably because of inflow of CO_2 from depth and/or due to complex effects of condensation and oxidation.

3 SOLUTE GEOTHERMOMETRY RESULTS AND MIXING MODELS

3.1 Solute geothermometry results

The silica (quartz and chalcedony), Na-K and Na-K-Ca geothermometers are used to estimate subsurface temperatures in the geothermal field based on data from hot springs and well discharges by applying the respective equations (Fournier, 1977; Fournier and Potter, 1982; Arnorsson et al., 1983; Fournier and Truesdell, 1973).

The solute geothermometry results show that the measured aquifer temperatures in wells and the four solute geothermometer temperatures compare quite well (Sun, 1998). On average, the quartz geothermometer yields 16.7 °C higher values, the Na-K geothermometer gives 4.1 °C lower values, and the Na-K-Ca geothermometer gives 2.6 °C higher values. For all well discharges in the area, regardless of their aquifer temperatures being higher or lower than 180 °C, the chalcedony geothermometer gives excellent results which is only 1.9 °C lower than the measured temperatures on average. It may be inferred that chalcedony rather than quartz predominately controls the silica-fluid equilibrium in the geothermal system.

Solute geothermometer temperatures for all the hot springs except for two steam-heated waters (Springs, numbered 272 and 263) are 165-230 °C by the quartz geothermometer, 131-216 °C by the chalcedony geothermometer, 129-173 °C by the Na-K geothermometer, and 126-188 °C by the Na-K-Ca geothermometer. The considerably large range of estimated subsurface temperatures is probably due to mixing and degassing/boiling effects. The detection and elimination of mixing and degassing/boiling effects will be discussed below.

3.2 Detection and elimination of mixing and degassing effects

Most of the hot springs sampled are believed to contain waters of mixed origin. Such mixing can be detected from the following evidence: 1) The measured temperatures for these springs are 33-146 °C less than the calculated geothermometry temperatures in all cases; 2) Linear relationships between Cl and B as well as F, SiO_2, K, Na, also between B and SiO_2, exist; 3) Most of the hot spring waters fall into the mixed waters section of the K-Na-Mg triangular diagram (Sun, 1998).

The evident mixing processes diminish the reliability of the subsurface temperatures estimated by solute geothermometers. In order to eliminate such mixing effects, three mixing models have been applied to evaluate the subsurface temperatures of the Hveragerdi geothermal system.

The silica-enthalpy warm spring model (Truesdell and Fournier, 1977) is based on the silica-enthalpy relationship of hot spring waters. It assumes that conductive cooling and changes in aqueous silica concentrations do not occur in the up-flow subsequent to mixing. Figure 4a shows the results of this model applied to the Hveragerdi data. The hot water component of the mixed hot spring waters is expected to be 220-237 °C. In Figure 4a, line a is based on the sample numbered 55 which has the highest silica concentration and assumes adiabatic cooling to 100 °C prior to mixing whereas line b assumes conductive cooling for hot spring numbered 56 of which the silica concentration is the lowest except for the two steam-heated waters, numbered 263 and 272.

The carbonate-silica mixing model (Arnorsson, 1985) is based on the relationship between silica and total carbonate concentrations in hot spring discharges to estimate subsurface temperatures. The model assumes that both aqueous silica and CO_2 concentrations are fixed by temperature dependent solute/mineral equilibrium in the reservoir, and that most of the dissolved total carbonate is in the form of carbon dioxide and temperature dependence of silica is controlled by quartz at temperatures above about 200 °C. Boiling leads to instant degassing of CO_2 but increasing silica concentration, so boiling springs fall above the curve in Figure 4b, whereas mixed unboiled waters fall below the curve as both silica and carbonate concentrations decrease. The aquifer temperature is estimated to be 207 °C by linear extrapolation of the data points to the equilibrium curve. The samples are divided into three groups by this model:1) Boiled and degassed waters above the curve; 2)Mixed waters below the curve, and 3) steam-heated waters (samples numbered 263 and 272) far away from the curve.

The chloride-enthalpy mixing model (Fournier, 1979) assumes that the concentrations of chloride in hot spring waters are fixed by boiling and mixing. The result obtained by this model for the Hveragerdi field is given in Figure 10c. In Figure 4c, the steam loss line is drawn by linking steam point (0 ppm Cl and 2778 kJ/kg enthalpy) and well discharge point with highest chloride (Well-7); line a is drawn radiating from the average enthalpy and chloride concentration point of three cold springs with temperatures of less than 10 °C in the area to the point of the boiling spring numbered 262 with lowest chloride concentration except for the above-mentioned two steam-heated waters. Line a is the mixing line that is the upper boundary for all of the estimated points except for the two noted above. The intersection point of the steam loss line and line a indicates an original hot water temperature of 260 °C. Line b sets a lower limit for the waters that seem to be mixed water. The temperature predicted from line b is 132 °C.

The mixing and boiling/degassing effects have been detected, and eliminated by the three mixing models. The original hot water temperatures are estimated to be about 210-260 °C which compares quite well with measured temperatures in wells, the solute geothermometer temperatures from well discharges, and gas geothermometer temperature from fumarole steam and steam from wet-steam wells.

4 SUMMARY

By integration of gas geothermometry results, solute geothermometry results and mixing model studies, the maximum subsurface temperatures of the Hveragerdi high-temperature geothermal system may be considered to be about 240-260 °C. By combination of hydrochemical and gas chemical studies with temperature logging data in bore holes, a conceptual model for the Hveragerdi high-temperature geothermal field can be constructed as: geothermal fluids of the Hveragerdi geothermal field come from the north and flow towards the south accompanying the temperature decrease caused by mixing processes with cold groundwaters as well as conductive cooling. Boiling/degassing occurs in the up-flow zones.

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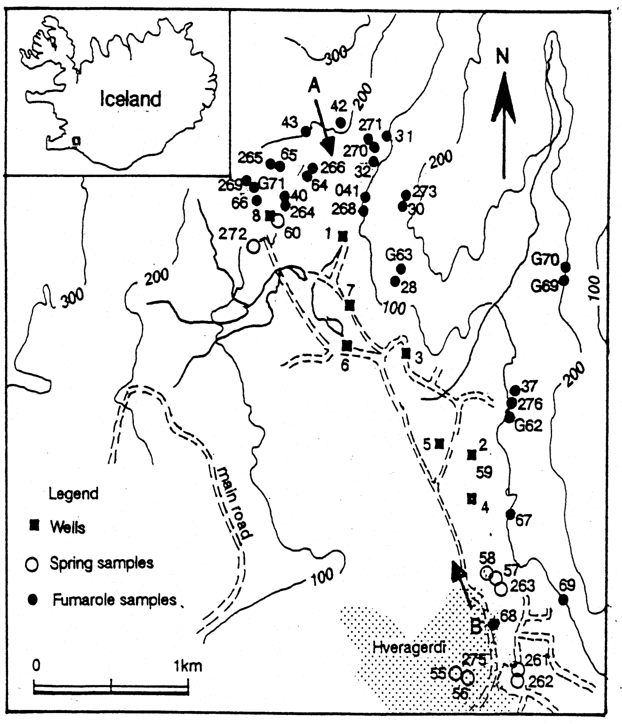

Figure 1. The Hveragerdi high-temperature geothermal field in SW-Iceland. Location of wells, fumaroles and hot springs included in this paper.

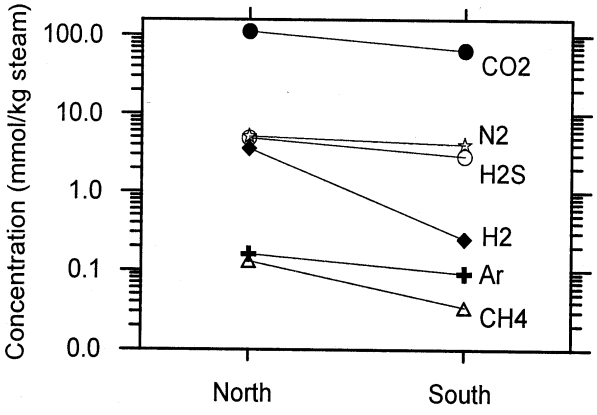

Figure 2. The variation in gas concentrations in the Hveragerdi field

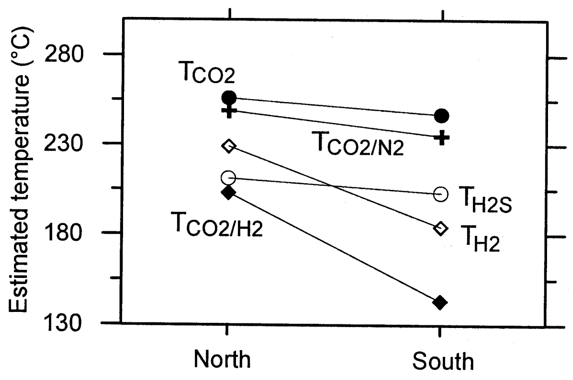

Figure 3. The variation in various gas geothermometry results in the Hveragerdi field

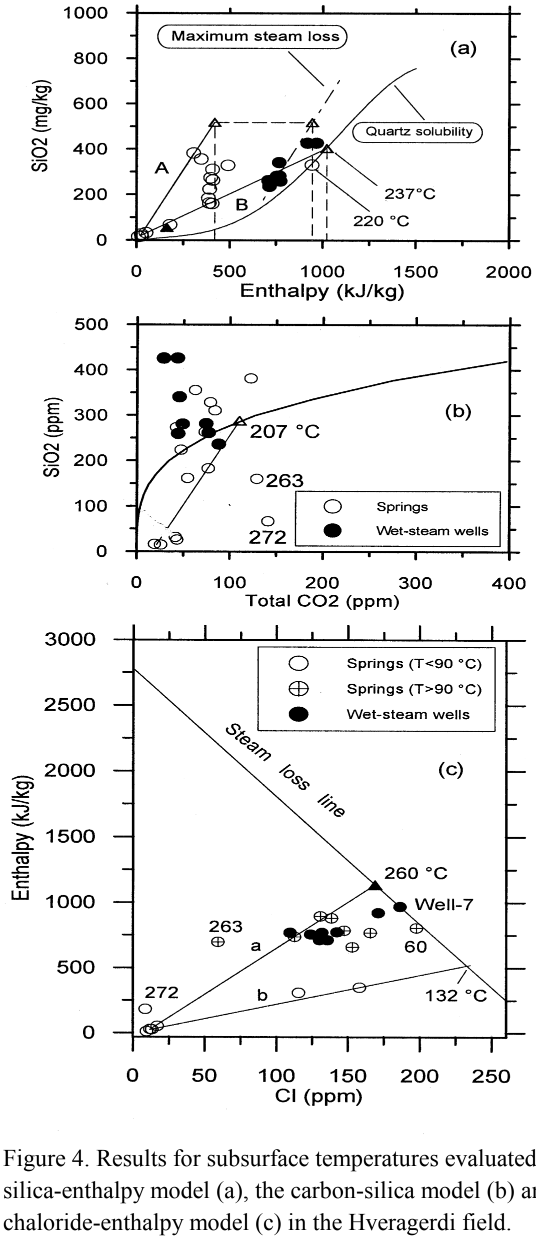

Figure 4. Results for subsurface temperatures evaluated by the silica-enthalpy model (a), the carbon-silica model (b) and the chaloride-enthalpy model (c) in the Hveragerdi field.

Table 1. Gas composition of fumaroles and steam from wet-steam wells in the Hveragerdi area (in mmoles/kg steam)

No.	CO_2	H_2S	H_2	CH_4	N_2	Ar	O_2
264	66.0	0.60	0.26	0.006	2.08	0.037	0.09
265	98.4	0.33	1.87	0.057	3.08	0.052	0.15
266	125.3	3.32	2.93	0.059	3.13	0.056	0.14
267	133.7	8.68	8.54	0.143	6.14	0.108	0.2
268	119.8	7.23	5.51	0.149	5.29	0.095	0.13
269	99.5	1.97	1.91	0.035	2.73	0.045	0.14
270	113.2	8.91	4.43	0.118	4	0.066	0.19
271	136.3	8.32	4.66	0.096	4.08	0.067	0.3
273	132.1	6.71	1.1	0.114	5.8	0.099	0.23
276	67.8	2.67	0.07	0.004	2.63	0.035	0.11
28	107.1	5.1	3.96	0.161	11.14	0.365	0.29
30	108.6	7.33	3.1	0.174	3.87	0.163	0
31	140.3	8.37	9.38	0.168	8.87	0.273	0.06
32	128.1	1.43	5.46	0.158	6.5	0.247	0.02
37	58.9	2.92	0.07		4.67	0.132	0.7
41	151.4	8.91	8.32	0.196	5.28	0.279	0
42	161.9	2.9	2.34		26.2	0.994	4.74
43	141.1	1.14	3.12	0.076	2.24	0.052	0
64	94.5	4.66	3.67	0.09	2.34	0.049	0.09
65	83.9	3.47	3.06	0.488	1.9	0.04	0.14
66	99.6	4.2	2.94	0.038	1.7	0.043	0.21
67	77.9	3.74	0.34	0.058	2.82	0.07	0.1
68	48.3	2.36	0.39	0.019	1.45	0.048	0.06
69	67.1	2.68	0.37	0.055	8.65	0.171	0.77
2	32.26	4.43	0.699	0.072	0.021		
4	51.49	3.81	1.23	0.132	4.14		
6	56.41	2.68	1.39	0.094	22.32	0.306	
7	69.82	6.04	1.27	0.150	19.12	0.980	
NLFI-1	56.96	6.31	1.29	0.150	3.87	0.07	
NLFI-2	83.51	5.98	1.26	0.170	4.16	0.07	
H-1	65.16	5.24	1.43	0.170	0		
H-2	65.99	6.37	1.85	0.150	0		
						$Ar+O_2$	
G62	64.15	2.8					
G63	100.4	5.68	4.2	0.193	6.555	0.223	
G69	124.0	6.32	1.043	0.197	0.261	0.014	
G71	93.78	4.13	0.47	0.016	2.046	0.27	

Table 2. Results of gas geothermometry of fumaroles and wet-steam wells in the Hveragerdi field

Type	Sample No.	T_{CO2}	T_{H2S}	T_{H2}	$T_{CO2/H2}$	$T_{CO2/N2}$
Fumarole	264	249	159	190	151	251
Fumarole	265	263	142	223	197	251
Fumarole	266	270	207	230	203	258
Fumarole	267	272	234	248	232	240
Fumarole	268	269	229	241	222	241
Fumarole	269	263	192	223	197	255
Fumarole	270	267	235	237	218	247
Fumarole	271	273	233	238	214	252
Fumarole	273	272	227	214	173	241
Fumarole	276	250	201	168	112	245
Fumarole	28	265	219	235	216	215
Fumarole	30	266	229	231	209	247
Fumarole	31	274	233	250	233	230
Fumarole	32	271	183	241	220	237
Fumarole	37	244	203	168	117	223
Fumarole	41	276	235	248	228	248
Fumarole	42	278	203	226	189	202
Fumarole	43	274	177	231	201	271
Fumarole	46	261	217	234	218	258
Fumarole	65	257	208	231	216	260
Fumarole	66	263	214	230	210	269
Fumarole	67	255	210	194	154	247
Fumarole	68	237	197	196	172	252
Fumarole	69	249	201	196	161	209
Fumarole	G62	248	202			
Fumarole	G63	263	222	236	220	229
Fumarole	G69	270	225	213	173	323
Fumarole	G70	270	226	212	171	246
Fumarole	G71	261	213	200	158	261
Well	2	220	215	206	201	347
Well	4	239	210	216	203	229
Well	6	243	201	218	204	175
Well	7	251	224	216	196	185
Well	NFLI-1	243	225	216	202	229
Well	NFLI-2	257	224	216	190	237
Well	H-1	248	220	218	201	
Well	H-2	248	226	223	208	