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GEOCHEMICAL STUDY OF THE GEYSIR GEOTHERMAL FIELD IN HAUKADALUR, S-ICELAND

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ABSTRACT

The Great Geysir geothermal area in Haukadalur, S-Iceland is one of Iceland's most famous tourist attractions and a treasured historical place. During the last twenty years there has been rather limited geothermal research activity in the area even though exploitation has increased considerably during that time. Considering the future protection of the field it is of utmost importance to know the relationship between the Geysir geothermal field and the reservoir that feeds exploited wells in the neighbourhood.

The present project concentrates on the geochemical properties of the field and possible changes over time and also on the environmental effects of nearby production. All available older data were compiled and two hot springs and three wells nearby were sampled and the water and gas analysed.

The geothermal waters are sodium chloride and bicarbonate waters with high contents of fluoride and boron indicating reactions with acidic volcanic rocks. The radon concentration in the fluid is found to be exceedingly high, 10-100 times higher than that encountered in most other geothermal fields in Iceland. The calculated quartz geothermometer value for water from the Geysir hot spring indicates minimum reservoir temperatures of 240 ºC. Other hot springs in the area give lower values, probably due to initiation of silica precipitation.The calculated mineral saturation indexes for the waters show that water from Geysir itself is in near equilibrium at 220-240°C, whereas water from the other hot springs shows signs of boiling, condensation and mixing. The Na-K and Na-K-Ca geothermometers give mostly lower values for the hot spring waters than the quartz geothermometer.

Only minor changes, probably mainly due to different sampling and analysing methods, are found in the chemistry of the hot spring waters during the last 30 years. However the run-off from the field appears to have declined considerably during that time.

The waters in warm springs and wells in the neighbourhood yield carbonate waters with high silica, typical for mixed waters on the borders of high-temperature geothermal fields. The chemistry and isotopic composition indicate that the fluid originates from the mixing of run-off water from the Geysir geothermal field and local cold groundwater.

The results of the project stress the need for enhanced reservoir research, increased protection and the monitoring of the effects of nearby exploitation.

1. INTRODUCTION

The Geysir geothermal area in Haukadalur is located in South Iceland, about 110 km from the capital, Reykjavik and 50 km from the sea, at approximately 100 m altitude. The geothermal area is one of the Icelandic high-temperature areas which are largely confined to the central volcanoes of the active volcanic rift zones, and draw their heat from local accumulations of igneous intrusions located at a shallow level in the crust (Saemundsson,1979). The Geysir area lies in a shallow valley and is elongated in a north-south direction. The Geysir hot spring itself lies at the bottom of the eastern slope of the rhyolitic dome Laugarfjall, which rises to 187 m (Fig. 1). A simplified map of the geology of the Geysir geothermal area is shown in Figure 1. The thermal area lies just east of the western volcanic rift zone, but during the last 10,000 years there has been no volcanic activity in the Geysir area. The geothermal system is driven by volcanic intrusions in the roots of a now extinct central volcano. Rhyolitic rocks are found in Laugarfjall and the northern and eastern slopes of Bjarnarfell mountain, indicating a complex geology at depth below the area. Acid and intermediate rocks are confined to central volcanoes in Iceland. The lowlands east and south of the Geysir area are made of interglacial basaltic lava flows. The upper part of Bjarnarfell mountain is made of basaltic breccia and hyaloclastites formed during the last glacial period. Tectonic fractures strike SW-NE, but there is some evidence of other fracture systems connected with the geothermal area, probably related to the now extinct central volcano.

In the neighborhood of the Geysir area low temperature water, of temperature 45-70 °C, has been obtained by drilling. Due to the historical and touristic value of Geysir itself and the geothermal area around it is important to reveal the connection to those areas and the influence of their exploitation. In spite of the possible danger to the area research has been very limited during the last twenty years.

The aims of this study were to obtain new geochemical data from selected sampling points and also to compile all existing geochemical data from the Geysir area in order to detect and explain possible changes in chemical composition and properties of the thermal fluids with time. Also to evaluate reservoir temperatures and equilibrium conditions by the use of chemical geothermometers and equilibrium calculations. Further to evaluate effects of mixing and boiling processes on the waters. Finally to assess possible environmental effects of the production of geothermal wells in the neighborhood and give recommendations for future protection.

2. GEOTHERMAL ACTIVITY

Thermal manifestations, mostly in the form of warm springs, are spread over an area of approximately 6 km^2. The most active hot springs lie on a fracture striking north-east. All the boiling hot springs and fumaroles within this area are located within intensively altered basalts. Warm springs are found at the foot of the cliffs on the west side of Laugarfjall rhyolitic dome and the alluvial plain to the south, as far as 4 km from the main hot springs. Warm and hot springs also occur in Haukadalur about 2 km to the north. Boiling springs, acid pools and small mud pots are found within the main hot spring area, which is only few hundred meters across and elongated NNE-SSW.

The Great Geysir in Haukadalur, as well as the almost continuously active geyser Strokkur, have attained worldwide fame for their geyser activity and a large number of travellers and scientists have visited the area. Geysir has also given the international name for the phenomenon of an erupting hot spring.The uppermost part of Geysir's plumbing system has been probed and revealed a large bowl in the sinter, 20 m in diameter and 1 m deep with at least 23 m deep and about 1m wide upflow channel in the center, becoming narrower at depth.

The oldest written accounts about the Geysir thermal area date back to the year 1294 AD when earthquakes caused great changes in the area and some hot springs disappeared and new ones were created. Once or twice each century large earthquakes occur in S-Iceland. Many records exist of changes in the hot springs during earthquake episodes (Thorkelsson, 1925). In written annals it is reported that in 1630 the Geysir in Haukadalur erupted so violently, after having been dormant for some 40 years, that the area around it trembled during the eruptions. Before the last big earthquakes of 1896, the activity of Geysir had declined so much that months could pass between eruptions. At the same time, the activity of Strokkur had increased considerably. The earthquakes revived Geysir, erupting up to a height of about 60 m, sometimes once in an hour. After 1896 the activity declined gradually. In 1935 Geysir was reactivated when a narrow ditch was dug through the rim of the silica bowl that had accumulated around its vent, lowering the water table. This ditch was gradually refilled with silica, deposited from the water. In 1981 the ditch was cleared out and eruptions could be stimulated by lowering the water level and putting in it a generous dose of soap. At present this pracice is prohibited.

Extensive deposits of silica sinter have formed around many of the alkaline hot springs. From the distribution of the thermal activity and the high fluoride content of the thermal waters, it is concluded that the hot water ascends either along permeable contacts between the Laugarfjall dome and the basalts, or that the water ascends along permeable cracks within the rhyolite itself.

The flow rate from the Geysir field has been measured several times and outflow from hot springs have also been measured. The total flow amounted in 1967 to 14 l/s, in 1984 it was 13 l/s but only 9 l/s in 1994. It is not known whether this decrease in flow is related to drilling or other activities in the area.

Drillholes have been sunk in the near vicinity in Nedridalur and Helludalur (Figure 1) which may have some effect on Geysir and the thermal area. The deepest well is 850 m deep and struck an aquifer at 386 m. The flow rate is 5 l/s and the bottom hole temperature is 173°C. There is a constant thermal gradient below the producing aquifer, equivalent to 220°C/km. The total flow of drillholes was near to 12 l/s in 1994.

3. GEOCHEMISTRY OF FLUIDS

For the present study a few representative hot springs were selected for sampling in the area as well as a few from nearby exploited drillholes. The hot springs included Geysir itself, the very active Strokkur and also a boiling spring named Smidur not showing any geyser activity (Fig. 1). A cold water sample was taken from a creek in the area, Kaldilaekur, and a gas sample was also taken from a boiling spring in the eastern part of the field. All available older data were compiled for comparison. Typical chemical composition of the hot springs and waters from nearby wells is shown in Table 1.

3.1 Classification of fluids

By classification of the water by the Cl-SO_4-HCO_3 triangular diagram (Giggenbach, 1991) in Figure 2 it is shown that the waters from Geysir, Strokkur, and Smidur hot springs fall in the bicarbonate water range, but are close to the chloride and sulphate water fields. The samples from wells (Nedridalur, Helludalur) are located near the HCO_3 corner and plot in the area of peripheral water as well as the sample from the creek Kaldilaekur.

According to the Na-K-Mg Giggenbach diagram (Figure 3) the Geysir, Strokkur and Smidur water lie near to the fully equilibrated line and the rest of the samples fall in the immature water section, near the Mg corner. The Na/K geothermometer temperature values of this diagram show 175-230°C for the hot springs.

Mass ratios like the Cl:B, Na:K, and Na:Li show a narrow range for each group of spring waters suggesting a homogeneous fluid source at depth.

Schoeller diagrams (Fig. 4) were used to display possible general changes with time or between locations. They suggest that the waters from Geysir, Strokkur, Smidur and the Nedridalur and Helludalur wells and the Kaldilaekur cold water are all very similar and come from local precipitation and has passed through similar rock types, i.e. that the water comes from the same lithology and aquifers. No apparent changes in chemistry are displayed by time in the hot springs, but considerable changes in the wells (Pasvanoglu, 1998).

High fluoride concentration is typical for the waters, which is probably due to reaction with acidic reservoir rocks. The concentration ratios of Ca/Mg, Na/K, F/Cl and Na/Cl all exceed the value of 1 which indicates contact with acidic rocks. The same applies to rather high boron, lithium and arsenic concentration as compared to Icelandic waters. The unusually low concentration of calcium in the waters is probably of the same reason. Mercury in the hot springs is similar to average concentrations in high-temperature geothermal water in Iceland. Mg concentration is very low in the boiling hot springs, as in all Icelandic thermal water, except carbonate water. In the Nedridalur and Helludalur waters Mg is relatively high due to high carbonate concentration.

The gas chemistry of the Haukadalur geothermal field is characterised by high CO_2 and low concentrations of H_2S and H_2 compared to most other high-temperature geothermal fields in Iceland. Also CH_4, Ar and O_2 are generally less than 1% of total gases (Pasvanoglu, 1998).

3. 2 Mineral equilibrium

The saturation index (log Q / K) was calculated for minerals assumed to be relevant like anhydrite, calcite, fluorite, amorphous silica, chalcedony, quartz, wairakite, albite-low, microcline, analcime and adularia for all six hot water samples using the WATCH aqueous speciation program (Arnórsson et al., 1983a, Bjarnason, 1994).

The hot spring waters of Geysir, Strokkur, and Smidur attain equilibrium with many of the minerals but all the other waters are undersaturated with the most common hydrothermal alteration minerals. For Geysir a reservoir temperature of 200-250 °C is indicated (Fig. 5), but there appears to be some mixing. The waters of Strokkur and Smidur (Fig. 6) do show indications of a lot more mixing, but a similar range in temperature. For the waters from wells in Nedridalur and Helludalur (Fig. 7) no apparent equilibrium can be defined from the graphs.

3.3. Geothermometry

Various chemical geothermometers have been calculated for the water from the hot springs and wells to evaluate subsurface temperatures of the geothermal field. For Geysir the quartz geothermometer (Fournier and Potter, 1982) gives similar value as Na-K-Ca (Fournier and Truesdell, 1973) but all other geothermometers give lower values (Pasvanoglu, 1998). For Smidur and Strokkur the quartz geothermometer gives the highest values, but somewhat lower than for Geysir, 215 and 230 °C respectively.

The relationship between the chemical geothermometry results is different for the warm water wells than for the boiling springs. Here, the Na-K temperatures (Arnórsson et al., 1983 b, Fournier, 1991, Giggenbach, 1991) are generally much higher than the quartz equilibrium temperatures in the warm water and they are also about equal to or higher than the Na-K temperatures of the boiling hot spring water.

Results of calculated gas geothermometers indicate that there is removal of H_2S by condensation and oxidation in the upflow. The estimated temperature by the gas geothermometer of D´Amore and Panichi (1980) yields temperature near 120°C, the reason is probably that oxidation and boiling occur in the upflow. However the geothermo-meters of Tonani (1973) give temperature values with an average of 260°C.

3.4 Stable isotopes

Isotope analysis of water samples show no significant changes in $\delta^{18}O$ and δD in the period 1967-1998. Figure 8 shows the relationship between δD and $\delta^{18}O$ values for the water. The results show that samples collected in the Geysir geothermal area have δD values ranging from -83.3‰ to -64.9‰ with an average $\delta D = -75.1$‰. The data points from the Geysir area show a minor scattering. Water from boiling hot springs shows distinct oxygen shift due to reaction with rocks. The deuterium levels indicate that the water is not local precipitation, as they are similar to that of precipitation in the southern part of the Langjökull ice-sheet, some 50 km to the north (Árnason, 1976). The deuterium content of the warm water is compatible with being largely local precipitation. Samples from wells ND-01 and HD-02 plot intermediate between the boiling hot spring water and the meteoric line. This as well as chemical composition indicates that the fluid originates from the mixing of run-off water from the Geysir geothermal field and local cold groundwater (Arnórsson, 1985).

3.5 Radioactivity

The discharge from the Geysir hot springs has 10-100 times higher concentrations of radon than most other springs in Iceland. Early this century Thorkelsson (1910; 1925) measured radon concentrations in gas samples from numerous hot springs in Iceland. The highest concentrations he observed were 186 and 260 nC/l gas. Radon concentrations measured in many hot springs in 1965 (Björnsson, S., 1998) confirmed the observations of Thorkelsson with 187 nC/l gas at the highest.

The origin of the high radon concentration in the field has not been fully explained, but may be caused by a reaction with a geologic formation where the long-lived mother atom ^{226}Ra has become enriched to concentrations 10-100 times the average for Icelandic rocks. The most likely locations for such enrichment are mineral scales in shallow feeders of the springs or the silica sinter precipitated from the water at the surface.

3.6 Mixing models

As pointed out above there are indications of mixing in the hot springs and especially in the water from the drillholes. Therefore several geochemical mixing models were used to clarify this and try to estimate the temperature of the hot water component. Figure 9 shows a plot of silica versus carbonate for waters in the Geysir geothermal area. A linear relationship is observed for the warm water from drillholes and cold water, which indicates that the hot water component of the mixed water has not boiled. An extrapolation of a line through the data points indicates that the temperature of the hot water component is about 229°C. Geysir, Strokkur and Smidur contain relatively little total carbonate. This low concentration of carbonate might be due to near-surface boiling with CO_2 loss before sampling.

A plot of dissolved silica vs. enthalpy of the liquid water (Truesdell and Fournier 1977) gives maximum temperatures of the hot water component of 240-250°C (Pasvanoglu, 1998). Similarily the enthalpy chloride mixing model (Fournier, 1977) gives a reservoir temperature of about 240°C.

4. CONCLUSIONS

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

The hot spring thermal water is classified as sodium bi-carbonate thermal water containing high contents of fluoride. The geothermal water in the Geysir geothermal area has concentration ratios of Ca/Mg, Na/K, F/Cl and Na/Cl that all exceed a value of 1. It has high Na and K contents, high F, B, As and Li. This is strong evidence that the water has been in contact with acidic rocks.

The minimum reservoir temperature of the Geysir field is estimated to be about 240 °C.

The Geysir hot springs have 10-100 times higher concentration of radon than most other springs in Iceland.

The waters in springs and drillholes in the neighborhood are carbonate waters with high silica, typical for mixed waters on the borders of high-temperature geothermal fields. According to mixing models the hot water component in the mixtures appears to be 230-240 °C.

The δD-$\delta^{18}O$ relationship for hot and cold water in Geysir geothermal field indicates that the groundwater is of meteoric origin. The hot spring water has similar concentrations as precipitation from the southern part of the Langjökull ice-sheet to the north, whereas that of the drillholes is closer to local precipitation.

The chemistry, isotopic composition and results from mixing models indicate strongly that the water in the wells in the neighborhood, in Nedridalur and Helludalur, is runoff water from the Geysir geothermal field. Therefore the reservoir has to be monitored closely before allowing further harnessing.

The run-off from the field appears to have declined considerably during the last 30 years.

The hydrologic setting of the Geysir geothermal area in Haukadalur has to be further investigated and the recharge and flow of the geothermal system better defined. Additional work is required to determine the geothermal potential of the area in terms of possible direct and indirect applications of the thermal energy that could be extracted from the system.

Radioactive tritium (^3H) isotope analysis is recommended in order to evaluate the hydrogeological systems, the residence time and the water's age.

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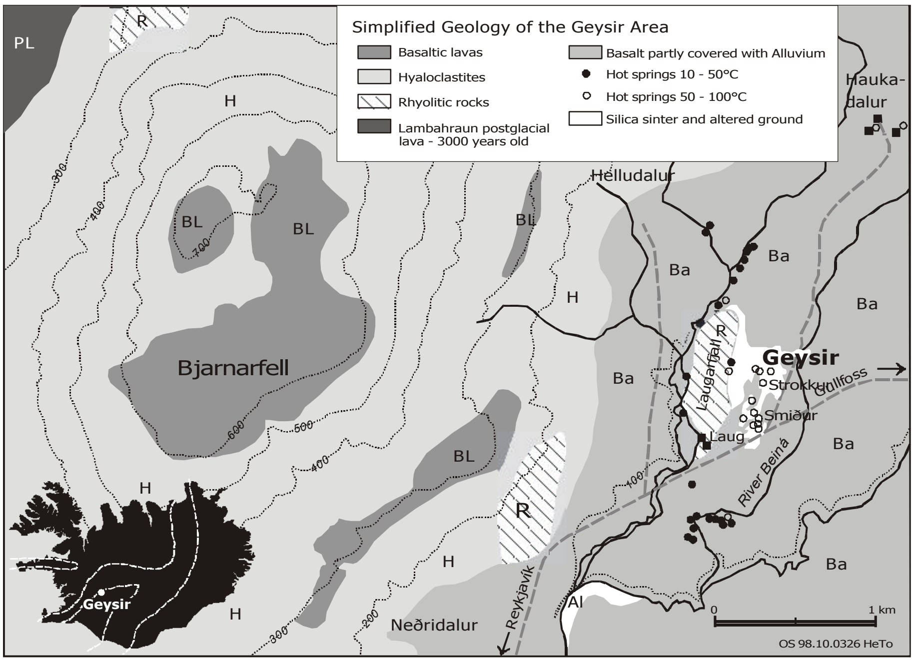

Figure 1. A simplified geological map of the Geysir geothermal area and its surroundings (Torfason, 1985)

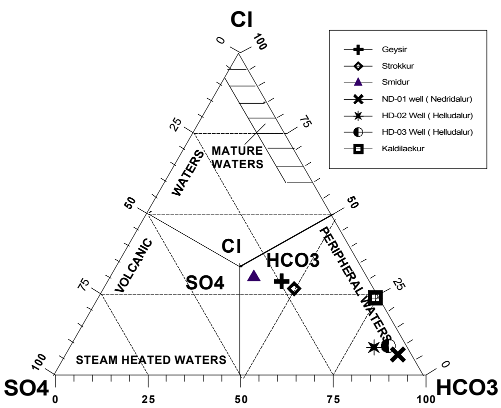

Figure 2. Triangular Cl-SO_4-HCO_3 diagram for water from the Geysir geothermal area.

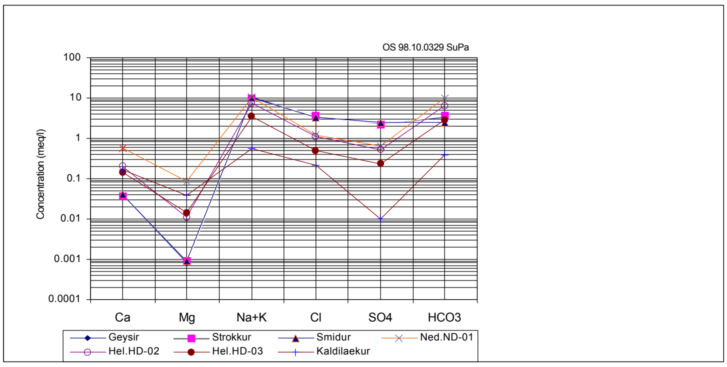

Figure 4. Schoeller diagram for samples from the Geysir geothermal field and the areas around.

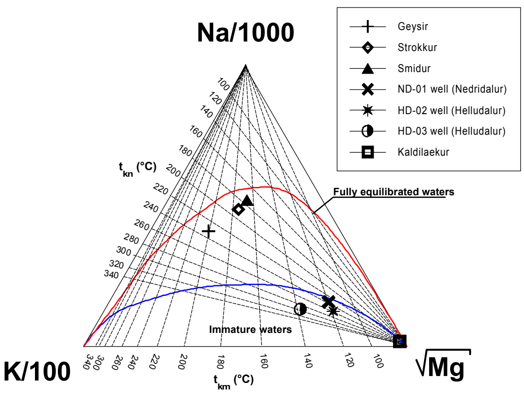

Figure 3. Na-K-Ca equilibrium diagram (Giggenbach, 1988) diagram for water from the Geysir geothermal area.

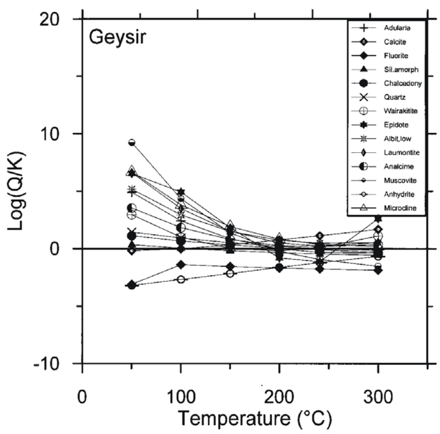

Figure 5. Mineral equilibria diagrams for water from Geysir.

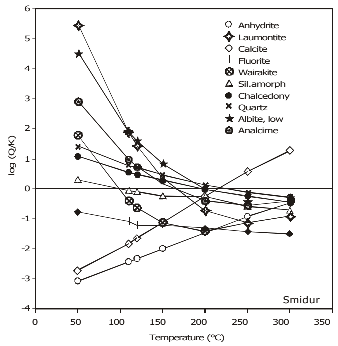

Figure 6. Mineral equilibria diagrams for water from Smiður.

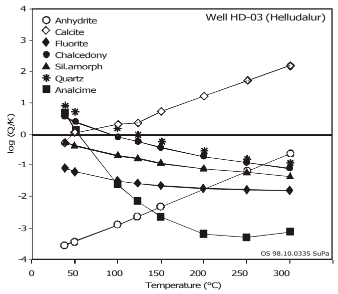

Figure 7. Mineral equilibria diagrams for waters from one of the warm wells around, Helludalur.

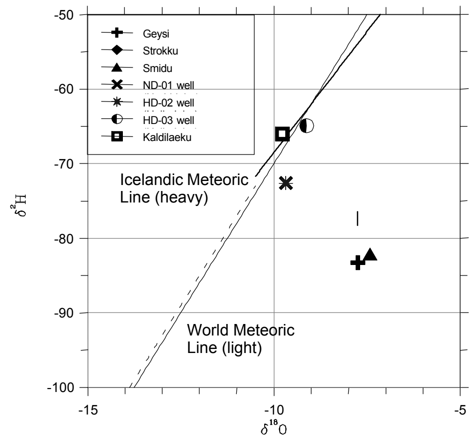

Figure 8. δD against $\delta^{18}O$ for the water from the Geysir field and the geothermal drillholes around.

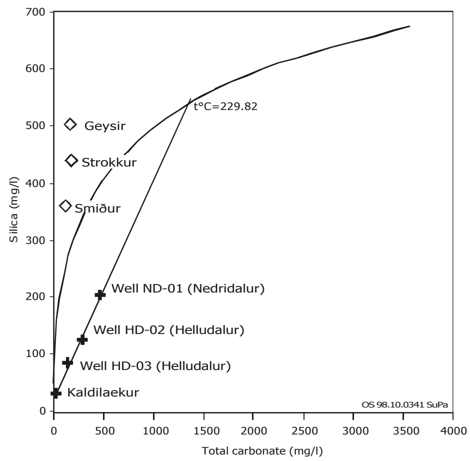

Figure 9. Silica versus total carbonate mixing model for water from the Geysir geothermal field.

Table 1. Typical composition of geothermal water from the Geysir field and nearby areas.

Place	Geysir	Strokkur	Smiður	Ned. ND-01	Hel. HD-02	Hel. HD-03	Kaldilaekur
T°C	73	100	100	69	59	38	5
pH/°C	9.28/23	9.26/22	9.17/23	7.55/22	7.56/22	8.18/22	8.01/20
SiO_2	501	448	358	182	125	84	31
Ca	0.81	0.77	0.81	11.5	4.13	2.79	3.22
Mg	0.01	0.013	0.011	1.04	1.37	0.178	0.461
Na	228	243	225	210	165	74	11.8
K	23.6	15.2	10.1	44	17	9.8	0.96
Cl	125	130	117	44	38	18	7.4
SO4	105	108	121	30	25	11	0.5
CO2	144	146	107	449	279	123	16.6
H2S	0.67	0.07	1.02	0.04	<0.03	<0.03	<0.01
F	8.31	11.4	11.3	5.23	5.25	3.16	0.07
B	0.9	1.08	0.83	0.32	0.26	0.1	0.01
Fe	0.0024	0.004	0.009	0.054	0.013	0.0028	-
Mn	0.0008	0.0007	0.0007	0.0064	0.0006	0.001	-
Al	0.36	0.55	0.11	0.005	0.01	0.005	-
Pb	0.0003	-	0.0005	0.0007	0.0005	0.0004	-
L	0.404	-	0.244	0.059	0.064	0.021	0.001