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Geochemical Interpretation of Thermal Water and Borehole Water from the Asal-Ghoubbet Region, Djibouti

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ABSTRACT

The Asal area, Djibouti, is characterized by volcanic activity with extensive faulting, hot springs and fumarole manifestations on the surface. Geologically, this area is dominated by volcanic rocks like basalts. Twenty-eight samples were collected from springs and Asal wells in 1990 from the Asal-Ghoubbet area. The purpose of this project is to interpret the chemical data obtained from these samples using the Cl-SO_4-HCO_3 and Na-K-Mg ternary diagrams for classification of the water and to estimate the temperature and origin of the reservoir fluids from the results of chemical analysis. Apparently, chalcedony controls the silica solubility and the results of original cation geothermometer calculations suggest a much higher temperature for the Na-K-Ca geothermometer than the Na/K geothermometer, for the spring waters. The high Na-K-Ca temperatures are due to the influence of cold groundwater and after the application of a magnesium correction, values much closer to those of the other geothermometers are obtained. Quartz controls the silica solubility in the fluids of the Asal wells, and the quartz geothermometer yields temperatures close to measured temperatures as do the cation geothermometers (Na-K and Na-K-Ca). The Cl/B concentration ratios suggest that the spring water composition is influenced by water-rock interaction, but that of the borehole water suggests evaporated seawater with a relatively low boron concentration. Thus, the results of this study suggest that the spring waters are mostly relatively low temperature waters whose origin is in seawater and whose composition has been modified by evaporation and water-rock interaction. The Asal well water is predominantly evaporated seawater from a reservoir with temperatures of 220-260°C.

1. INTRODUCTION

The Republic of Djibouti (surface area 23,000 km^2) is one of several African countries located on the East African rift system, whose geology is also a result of two other ridges in the Red Sea and the Gulf of Aden**.**

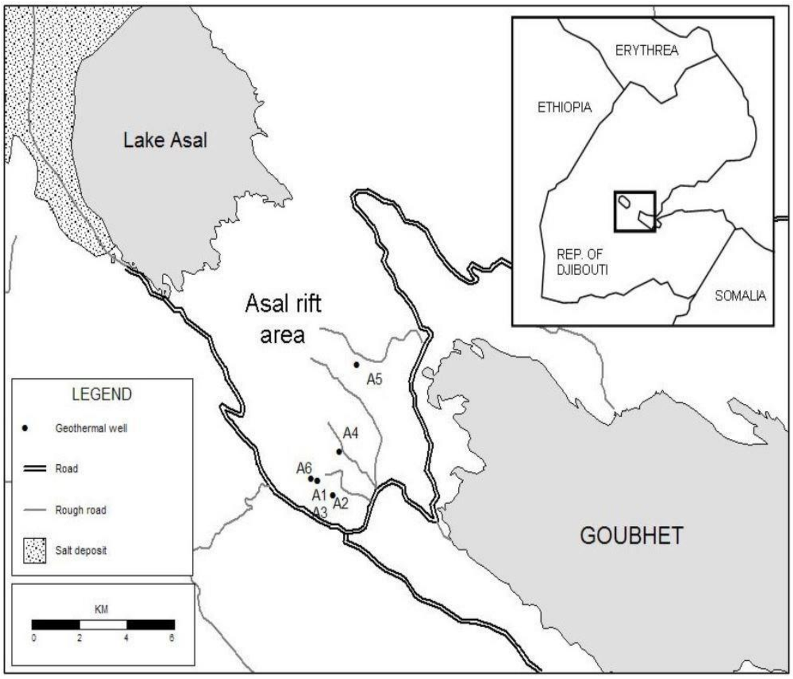

Figure 1: Asal geothermal field (from Elmi Houssein, 2005)

The Asal area (Figure 1) is located in the Afar depression at the bottom of the Gulf of Tadjourah. The first geothermal investigations in this area were undertaken in 1970 and included geological and geochemical studies, as well as geophysical exploration (Elmi Houssein and Axelsson., 2010; BRGM, 1973). The existence of a shallow crust-melting zone, important seismic activity, the presence of fumaroles and hot springs make it possible to classify this region as a zone with a high geothermal potential (Sanjuan et al., 1990, Barberi et al., 1980).

Most importantly, a high-temperature geothermal system was established in the Asal field where six deep wells have been drilled (Figure 1) (BRGM, 1973). Wells Asal 1 and 2 were drilled in 1975 by BRGM (BRGM 1975a, b, 1980, Barbut et al., 1982 and wells Asal 3 to Asal 6 in 1987/1988 by Intairdrill Ltd. supervised by Aquater (Aquater 1987, 1988, 1989 a, b). The salinity of the water of this region is high and the maximum salinity of the water from Lake Asal is 9 to 10 times greater than that of seawater.

The purpose of this study is to interpret the chemical properties of surface thermal water from the Asal area and the water from wells Asal 1, 3 and 4 using ternary diagrams to determine the water type and the maturity of the geothermal water, and also to estimate the reservoir temperature using chalcedony, quartz, Na/K and Na/K/Ca geothermometers.

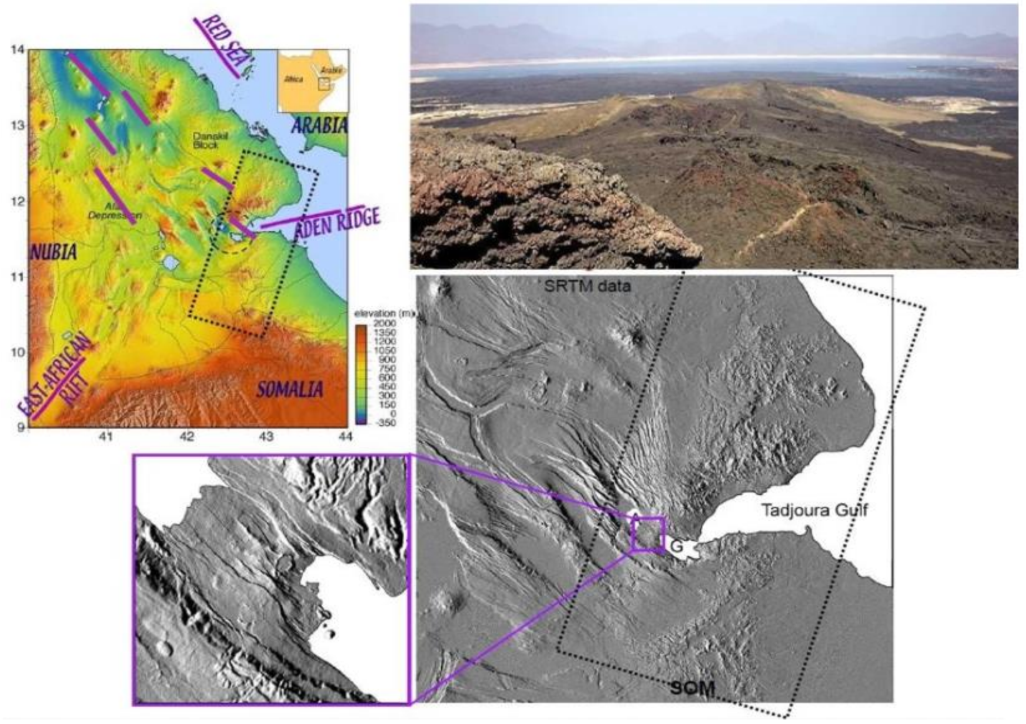

Figure 2: Location of the Asal geothermal site at the first emerged rift segment in SE Afar, where the axial volcanic ranges (in violet) meet the Aden ridge through the Gulf of Tadjourah and the Ghoubbet Bay (G) (Varet, 2014)

2. BACKGROUND OF THE ASAL GEOTHERMAL FIELD

2.1 General geological setting

Asal (alternative spelling: Assal), the most important geothermal area in Djibouti, is in an active rift zone (Figure 2) on the isthmus between Lake Asal, which is 160 m below the sea water level and the lowest point in Africa, and Ghoubet al Kharab at a distance of 120 km from Djibouti town. The Asal region has several surface manifestations, such as hot springs and fumaroles. Warm springs are abundant along the east side of Lake Asal with temperatures varying from 30°C to 90°C and the temperature of the borehole thermal water ranges from 260 to 280°C and even higher (Sanjuan et al. 1990).

This region is characterized by extensive faulting and volcanic activity (Figure 2) with the latest eruption taking place in 1978 (Árnason and Flóvenz, 1995). The external rift is manifested by large normal faults and the inner rift is characterized by vertical faults as well as by intense fracturing and recent lava flows where the Korilii (AS1) and Manda areas (AS2, AS3, AS4, AS5, AS9, and AS10) with thermal water springs are located. A major fault intersects Lake Asal where the Eadkorar (AS 6 and AS 7) and Kalou Wadi (K1, K2, K4, K5 and K6) groups of hot springs are located (Figure 3).

The main geological units in the Asal rift area are of a basaltic origin (Figure 2). The results of analysis of drill cuttings from wells drilled in the rift show that the stratigraphic column in the area is composed of, from top to bottom:

- The Asal series: basalts and hyaloclastites less than 1 Ma old,
- The Afar stratoid series: basalts with some rhyolites 1-4 Ma old, where AS6, AS7, AS8, AS11 and AS12 are located.
- The Dala Basalt: basaltic lava flows with some intercalations of rhyolites and trachyte 4-9 Ma old which is the component of the reservoir of Asal 1, Asal 3 and also Asal 4 (Elmi Houssein and Axelson, 2010).

The thermal water on the edge of the Ghoubbet (G2) is located in the basaltic series of the Gulf (1-4 Ma). Finally, Lake Asal is located in the pit that resulted from the collapse of the stratoid basalt series.

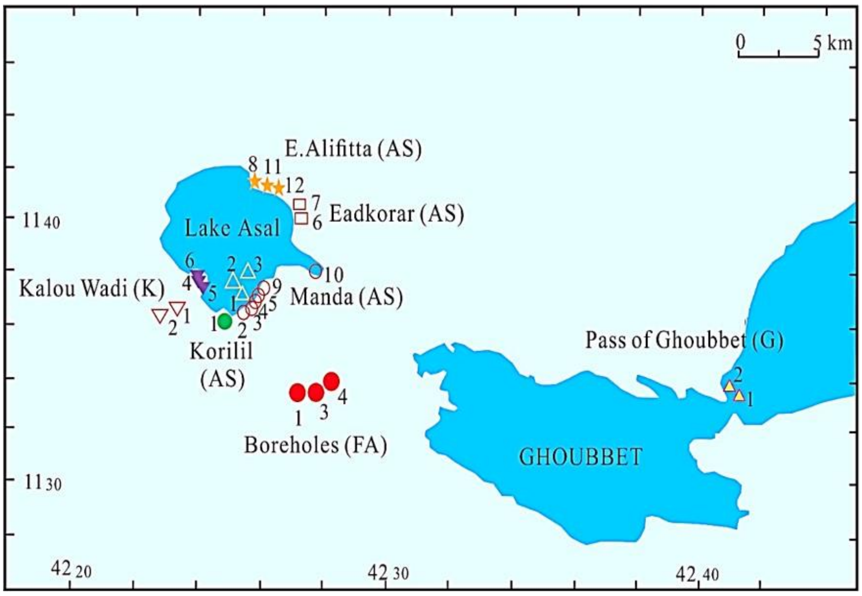

Figure 3: Map of the Asal-Ghoubbet area

2.2 Wells drilled in the Asal area

In the Asal area, six wells have been drilled (Table 1). The first two wells were drilled in 1975 by BRGM. The depth of Asal 1 was 1554 m and the second well Asal 2 (located 800 m southwest of Asal 1) 1147 m. The other wells (3, 4, and 5) were drilled by Intairdrill Ltd. and supervised by Aquater in 1987-1988. Asal 1, 3 (1361 m), and 6 (1761 m) are located in the southern zone of the Asal rift inside the half circle of hyaloclastites known as Gale le Koma (Souleiman, 2010; Elmi Houssein, 2005) where Asal 6 was drilled by ISERST (Institut supérieur d'études et de recherches scientifiques et techniques). These wells have produced extremely saline fluids (130 g/l), about 3.5 times the salinity of seawater, from between 1000 and 1300 m depth. These wells also share the same reservoir with an aquifer temperature between 260 and 280°C. Wells Asal 3 and 6 are the only two wells which are currently productive. Asal 4 and 5 are located towards the center part of the rift. Their final depths reached 2013 and 2105 m respectively, and they encountered a superficial, underground sea water flow at depths between 250 m and 280 m. Despite these greater depths, no deep reservoir was encountered although the bottom-hole temperatures reached 345°C and 359°C respectively. The characteristics of the Asal wells, such as the depth of the wells, the maximum temperature, the salinity etc. are summarized in Table 1.

Table 1: Characteristics of Asal wells (Souleiman, 2010)

Drilled wells	Beginning of drilling	End of drilling	Final depth (m)	Temperature e maximum (°C)	Total flow (ton/h)	Salinity (g/l)
Asal 1	9.3.1975	6.6.1975	1146	260	130 (WHP = 6 bar)	120
Asal 2	4.7.1975	15.9.1975	1554	235	-	-
Asal 3	11.6.1987	11.8.1987	1316	260	350 (WHP = 12.5 bar)	130
Asal 4	15.9.1987	20.12.1987	2013	345	-	-
Asal 5	7.1.1988	7.3.1987	2105	359	-	-
Asal 6	8.4.1988	10.6.1988	1761	280	150	130

From October 1989 to April 1990, the Virkir-Orkint Consulting Group Ltd. (Virkir-Orkint, 1990) made a study of the wells in the Asal area. This study was carried out to assess the effect of scaling/corrosion and to determine the optimum level of production for each well with time. With a pH of 4 to 5 and a chemical fluid composition that is basically sodium and calcium chloride, the fluid from the Asal wells is supersaturated with respect to several minerals such as silica, iron silicate and several metal sulphides. The concentration of silica was equivalent to that expected from a reservoir temperature of 260°C, which is the reservoir temperature of Asal 1 and 3.

The deposition products were varied and the scaling rate increased about six fold at a pressures below 16-bar g. The main products were:

- Sulphide at high pressures.
- Iron silicate at lower pressures (2 to 16 bar/g).
- Amorphous silica was the major deposit at a much lower pressure than the iron silicate.

During production, chemical deposition (scaling) took place in the well at differing rates with depth, the sulphide and the iron silicates are mostly deposited in the well but the silica mostly in surface equipment.

3. RESULTS AND DISCUSSION

The results of the water analysis of 28 samples (Sanjuan et al., 1990) in the Asal-Ghoubbet area, of which 22 samples were collected from springs and six samples from the Asal wells, are presented in Table 2. These results show that all the samples have a higher salinity than that of seawater like the thermal water samples from Lake Asal, except samples K1 and K2 from Kalou Wadi, which have a low salinity. Measured surface water temperature varies between 30-90°C for the thermal water and the well reservoir temperature from 260° C to more than 280° C.

Table 2: Chemical analysis of water from the Asal-Ghoubbet region (results in millimoles/liter)

Source		T (°C)	pH	Na	K	Ca	Mg	Li	Sr	Cl	SO_4	Br	B	SiO_2	$^{87}Sr/^{86}Sr$
Korilii	**AS 1**	80	-	427	11.5	77.2	18.4	0.38	0.56	640	2.63	1	0.34	1.05	0.70449
Manda	**AS 2**	40.5	7.14	682	19.5	39.2	62.6	0.2	0.3	840	19	1.55	0.53	0.42	0.70599
	AS 3	45	7.07	713	21.4	55.7	66.2	0.23	0.37	940	19	1.76	-	0.74	0.70577
	AS 4	43	7.26	680	20.5	42	56	.	.	820	-	-	-	1.04	-
	AS 5	45	7.3	670	19.2	38	56.8	0.08	.	810	-	-	0.55	1.21	-
	AS 9	38.5	7.45	675	19.9	43.1	60.6	0.12	0.19	839	30.2	1.53	0.56	1.35	0.7066
	AS 10	30	7.2	535	11.4	14	61	0.046	0.1	617	32	1.09	0.39	0.52	0.70862
Eadkorar	**AS 6**	84	-	820	52.4	242	22	1.36	0.62	1395	0.1	2.9	0.65	1.38	0.70435
	AS 7	90	-	789	46	211	25.9	1.28	1.19	1330	0.1	2.73	0.65	1.37	0.7036
Eounda Alifitta	**AS 8**	39	-	3700	138	180	500	-	-	5120	-	-	2.2	0.15	-
	AS 11	58.5	6.48	609	22.5	15.2	24.8	-	-	974	26.3	1.9	0.65	1.1	-
	AS 12	-	-	-	-	-	-	-	-	815	-	1.55	0.58	-	0.70679
Kalou Wadi	**K1**	74	-	31.9	0.315	3.2	0.1	0.0079	0.016	31.6	3.17	0.07	0.17	1.33	0.70403
	K2	35	-	24	0.345	5.64	1.11	0.0035	0.024	28.3	3.99	0.05	0.07	0.49	0.70574
	K4	-	-	710	18.4	75.2	59.7	0.37	0.37	1070	3.57	2.04	0.51	-	0.70486
	K5	-	-	600	15.3	73.5	46.8	0.37	0.48	880	3.62	1.69	0.49	-	0.70481
	K6	-	-	550	12.9	74.5	41.6	0.36	0.51	830	3.07	1.56	0.46	-	0.70456
Ghoubbet	**G1 (sea)**	-	-	497	11.2	10.2	57.5	0.37	0.096	594	27.4	1.01	0.44	0.02	0.70903
	G2	60	-	490	10	20.6	48.2	0.72	0.165	588	23.9	1.01	0.47	0.32	0.70700
Lake Asal	**S1**	-	-	3565	111	63.7	403	0.70	0.74	4600	-	8.11	-	-	0.70645
	S2	32	7.1	4120	121	61.6	472	0.67	0.60	5190	44.8	-	2.96	-	-
	S3	32	7.0	4400	132	66.8	514	0.80	0.75	5610	45.8	-	2.99	-	-
Boreholes	**FA 1**	255	-	1240	125	409	0.97	1.87	-	2200	0.22	-	0.6	8.55	0.70424
	FA 3	260	4.65	1142	120	385	0.1	2.04	2.3	2033	0.20	3.71	0.73	-	0.70439
	FA 3A	-	5.22	1115	115	356	0.1	-	-	1970	-	-	0.65	-	-
	FA 4	-	5.13	1400	136	437	0.1	2.2	1.75	2400	0.28	-	0.65	-	0.70426
	NA 3 (419m)	100	7.8	513	24.8	77.1	16.3	0.6	0.45	798	6.81	-	0.43	1.74	0.70463
	NA 4 (255m)	33	8.15	510	10.6	13.1	55.4	0.04	0.095	590	27.9	0.98	0.39	0.32	0.7088

3.1 Classification of the samples

3.1.1 The Cl-SO_4 -HCO_3 ternary diagram

The construction of this ternary diagram which includes the major anion concentrations of the waters (Cl-HCO_3-SO_4) makes it possible to classify the waters according to their origins, such as mature waters, peripheral waters, steam heated waters and volcanic waters (Giggenbach, 1988), and thus identify individual samples. The results of the analysis of the hot spring water and well samples from the Asal area show that chloride is the predominant anion (Figure 4). This allowed some of the waters to be classified as mature waters and some as volcanic waters. Thus, there is water-rock interaction resulting in relatively high chloride concentrations and some possible volcanic influence leading to relatively high sulfate concentrations.

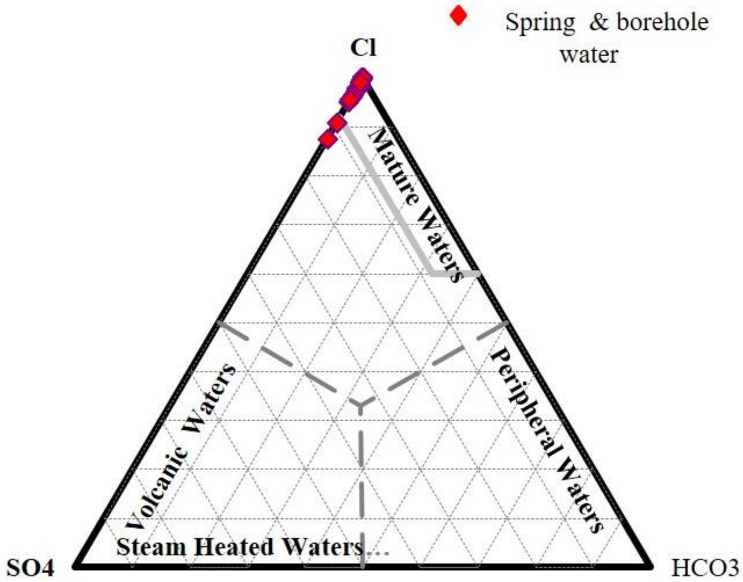

Figure 4: Classification of the thermal water and the well water using the Cl-HCO_3-SO_4 ternary diagram.

3.1. 2 The Na-K-Mg ternary diagram

The main purpose of Giggenbach's (1988) ternary diagram is to determine the reservoir temperature on the basis of the Na-K and K-Mg geothermometers, but an important aspect is its utilization to infer the equilibrium state of these ions in the water with respect to equilibration with the rock. From Figure 5 it is clear that the water from the warm and hot springs in the Asal-Ghoubbet area plot as immature waters with a relatively high magnesium concentration, suggesting a high proportion of cold groundwater. On the other hand, the fluids from the Asal wells plot close to the full equilibrium line except that from well Asal 1, which plots as a partially equilibrated water. The reservoir temperature is thus in the range 220- 260°C.

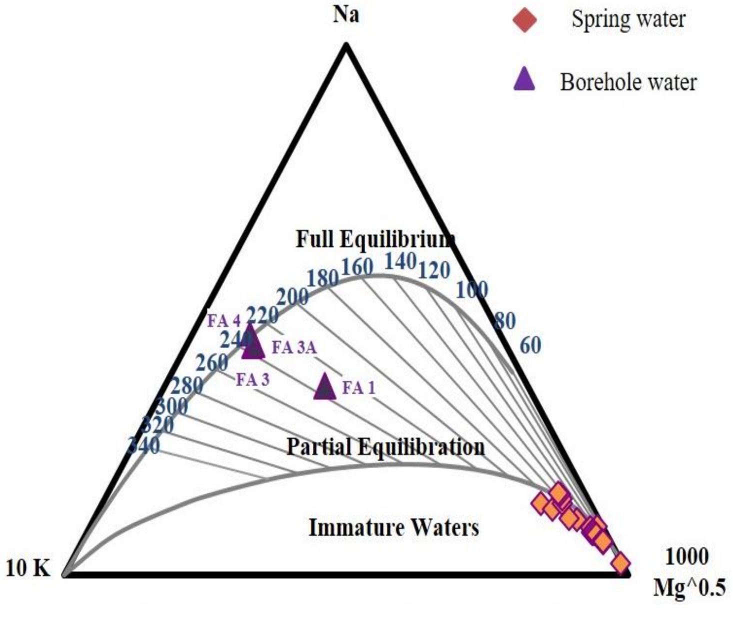

Figure 5: The Na-K-Mg ternary diagram for samples of the thermal water and well water from the study area.

3.2 Solute geothermometers

Various chemical geothermometers like quartz (Fournier and Potter, 1982), chalcedony (Arnórsson et al., 1983a), Na-K (Arnórsson et al., 1983a) and Na-K-Ca (Fournier and Truesdell, 1973) have been used to calculate the reservoir temperature in the Asal-Ghoubbet area. The results of these calculations and the surface temperature measurements are presented in Table 3. For quartz, the calculated temperature ranges between 34-261 °C, with the lowest temperatures being found for sample AS8 from Eounda Alifitta and the highest temperature for the sample from the well Asal 1. As expected, the lowest and the highest chalcedony temperatures are found for AS8 spring water (8°C) and the fluids from Asal 1 (232°C), with 0.15 mmol/l and 8.55 mmol/l silica concentration respectively. For the Na-K-Ca geothermometer, the temperature varies between 107 and 269°C and the temperature ranges between 64 and 263°C for the Na/K geothermometer. These results are also shown in the form of a diagram in Figure 6.

Table 3: Measured surface temperature and the results of reservoir temperature calculations by solute geothermometers for the samples of spring waters and borehole waters in Asal-Ghoubbet, Djibouti

Samples	**T surface (°C)**	**T Quartz**[1] **(°C)**	**T Chalcedony**[2] **(°C)**	**T Na/K**[3] **(°C)**	**T Na/K/Ca**[4] **(°C)**	**T Na/K/Ca (°C) after correction**
***Korili*i**						
AS 1	80	113	84	127	166	96
Manda						
AS 2	40.5	73	44	131	264	34
AS 3	45	97	68	135	254	37
AS 4	43	113	84	136	264	43
AS 5	45	120	92	132	264	35
AS 9	38.5	126	97	134	260	31
AS 10	30	82	52	110	269	n.a.
Eadkorar						
AS 6	84	127	99	204	217	177
AS 7	90	127	98	194	212	147
Eounda Alifitta						
AS 8	39	34	8	153	218	n.a.
AS 11	58.5	116	87	152	205	55
AS 12	-	-	-	-	-	-
Oued Kalou						
K1	74	125	97	64	107	107
K2	35	79	50	85	115	98
K4	-	-	-	124	173	43
K5	-	-	-	123	170	48
K6	-	-	-	117	164	52
Ghoubbet						
G2	60	62	34	107	166	n.a.
Lac Asal						
S1	-	-	-	138	217	n.a.
S2	32	-	-	133	216	n.a.
S3	32	-	-	135	218	n.a.
Boreholes						
FA 1	255	261	232	257	251	251
FA 3	260	-	-	263	253	253
FA 3A	-	-	-	260	252	252
FA 4	-	-	-	252	251	251
NA 3 (419m)	100	140	112	176	202	137
NA 4 (255m)	33	62	34	109	171	171

(1) Fournier and Potter, 1982 (25-900°C); (2) Arnórsson et al., 1983b; (3) Arnórsson et al., 1983a (25-250°C); (4) Fournier and Truesdell, 1973; n.a.: not applicable

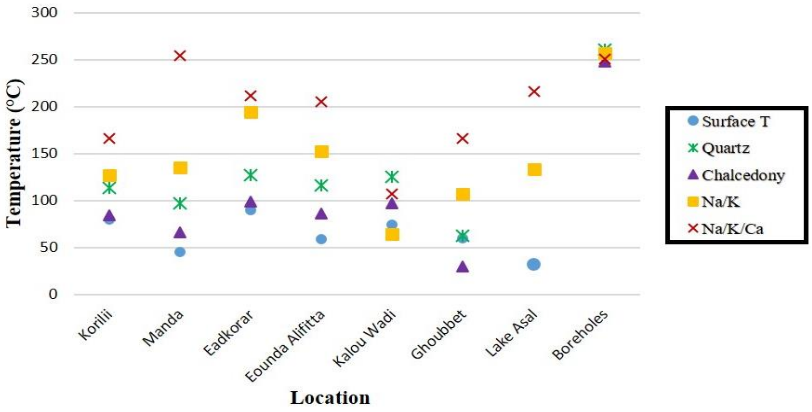

Figure 6: Results of temperature calculations with silica, Na/K and Na-K-Ca geothermometers and measured spring and well temperatures

Most of the silica geothermometer temperatures estimated for the spring samples from the AsalGhoubbet area are below 120°C and thus the silica concentration is most likely controlled by equilibrium with chalcedony. In some cases, the silica concentration might be controlled by equilibrium with quartz, either because the rock is old or because mixing with cool groundwater might have taken place. For the quartz geothermometer temperature for the Asal well water the temperature is estimated to be above 180°C and thus the silica solubility is controlled by equilibrium with quartz, and the Na/K temperature is similarly in agreement with the measured temperature. For most samples, the Na/K geothermometer suggests temperatures well below 180°C and supports the use of the chalcedony geothermometer. The Na-K-Ca geothermometer gives higher temperatures for the samples compared with the Na/K geothermometers, suggesting a lack of equilibrium with rock minerals or high Mg concentrations. According to Fournier and Potter (1979), the higher Mg^{2+} concentrations indicate that water-rock reactions have taken place at a relatively low temperature. The thermal waters from Manda and Lake Asal have high estimated Na-K-Ca temperatures and high Mg^{2+} concentrations but the measured surface temperature is eventually lower. A method of applying a magnesium correction to Na-K-Ca estimated temperature was applied when the data was plotted as shown in Appendix I (Figure 1). The results for the magnesium correction to the Na-K-Ca chemical geothermometer are demonstrated in Appendix I (Table 1).

3.3. Mixing models

The line that passes through the data points cuts the quartz solubility curve at a point of intersection (Figure 7). This point of intersection has the enthalpy value 700 kJ/kg of the hot water in the mixed water and 165°C as the temperature from steam tables. Thus, the temperature of the hot water component before mixing with cold groundwater in the Asal-Ghoubbet area is 165°C. The estimated temperature of the Asal region aquifer using this method is particularly high compared to the result of the calculated quartz geothermometer temperature presented in Table 3 and Figure 6. This may infer that most of geothermal hot spring water was mixed with cold water and there has been an infiltration of cold water into the reservoir. The liquid component of the fluid from well Asal 1, whose silica concentration and enthalpy are high or 513.8 mg/kg and 1100 kJ/kg respectively, was probably not mixed with cold water, because the temperature estimated for 1100 kJ/kg enthalpy of the hot water in mixed water using a steam table is 255°C, which is about the same as the calculated quartz temperature (260°C) and measured temperature (255°C).

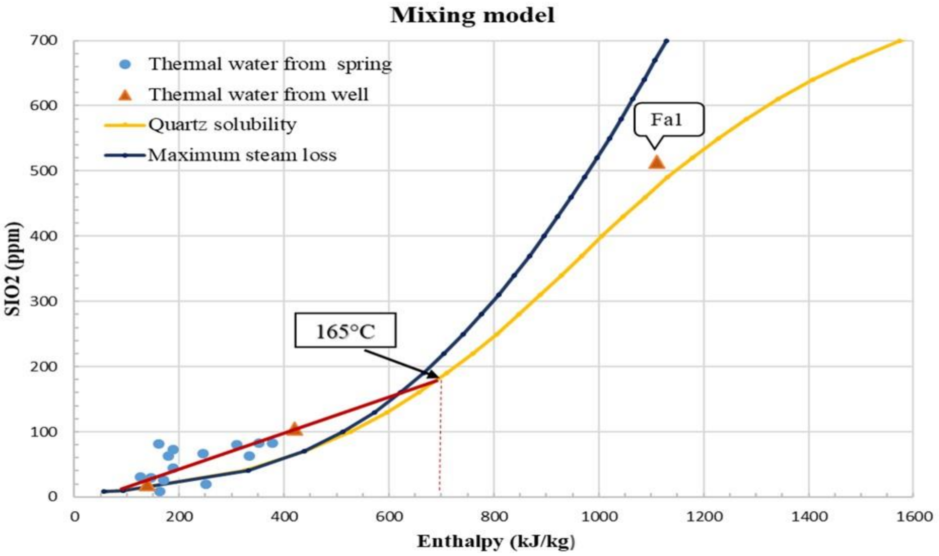

Figure 7: Silica-enthalpy mixing model for springs and borehole water from the Asal-Ghoubbet area

3.4 Origin of the water

The ratios of isotopes such as those of oxygen (^{18}O and ^{16}O) and hydrogen (^{2}H and ^{1}H,) and the correlation between Boron (B) and Chloride (Cl) are important tracers in identifying the origin of geothermal fluids.

3. 4.1 Isotopes

When isotope ratios are used to trace the origin of geothermal water, it is important to realise that although the isotope values suggest the origin, processes such as mixing, water-rock interaction, condensation and age may have to be accounted for (Óskarsson and Ármannsson, 2015). The isotope analysis of water from well Asal 3 was carried out by Virkir-Orkint (1990) and the value of $\delta^{18}O$ is 0.92‰. Fontes et al. (1979) and Fouillac et al. (1983) carried out the analysis for the oxygen and hydrogen isotope ratios of water from the Asal-Ghoubbet area and they classified the thermal springs into three groups with reference to these ratios (Sanjuan et al. 1990):

1) The Korilii group which is located on the south of the lake with the lowest mineralization and resembling seawater. The oxygen and hydrogen isotope data indicate a meteoric contribution.
2) The Northeast group from the lake (Eadkorar) involving thermal waters whose source of water is meteoric and highly saline. The higher salinity was acquired by the leaching of evaporates and the chemical composition by interaction with the reservoir rock.
3) The thermal springs of Manda are located in the central zone of the rift. The origin of the water is seawater, which reaches the lake via fissures.

Having classified the thermal water, they propose three hypotheses on the possible origin of the geothermal fluids as follows:

1) Leaching of evaporites, a mixture of seawater and current meteoric water is in equilibrium with reservoir rocks.
2) A mixture of meteoric water, seawater and a small proportion of Lake Asal water is in equilibrium with reservoir rocks.
3) Old meteoric water is in equilibrium with the reservoir rock after the leaching of the salt deposit.

The interpretation of previous results suggests that the main processes that influence the chemical composition of the Asal-Ghoubbet fluids are: infiltration of seawater, evaporation, the dissolution of evaporites and the water-basalt interaction at high temperatures.

3. 4.2 Cl/B Ratio

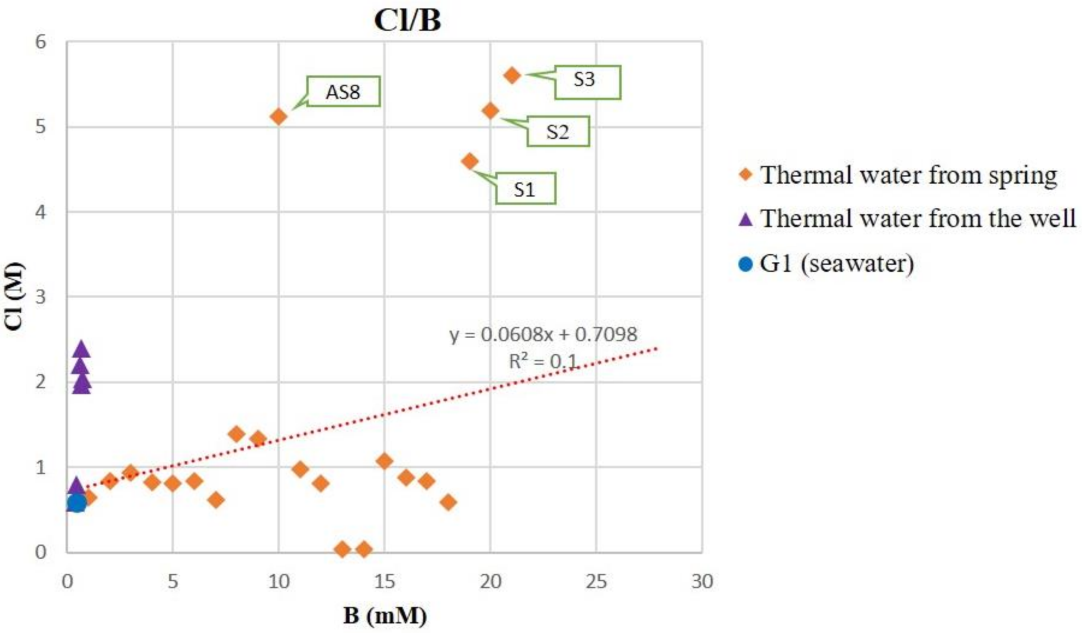

Figure 8: Relation between Cl and B for thermal water from springs and borehole water from the Asal-Ghoubbet area

The correlation between boron (B) and chloride (Cl) is used to trace the geothermal water's mixing with seawater or magmatic steam with precipitation but also the mixture of evaporated water. The reason is that the boron concentration of seawater and thus precipitation is low, but that of rocks and volcanic steam is much higher. On the other hand, the chloride concentration of seawater is high but that of rocks and volcanic steam low (Óskarsson and Ármannsson, 2015). The relation between Cl and B in Figure 8 shows that those with values close to the line are seawater that has undergone some water-rock interaction. Those with Cl values close to zero are groundwater (or surface water) samples that have also taken up some B during water-rock interaction. The blue dots with very low B values are likely to be seawater that has evaporated to a different extent but not undergone water-rock interaction. For the samples from Lake Asal (S1, S2, and S3) and AS8 with very high chloride and moderate B concentrations are likely to have taken part in some water-rock interaction and then evaporated. The samples from the well with a B concentration close to zero and a high Cl concentration compared to the seawater have probably evaporated.

4. CONCLUSIONS

Interpretation of the thermal fluid chemistry of the Asal-Ghoubbet region was carried out by examining the correlation between the major ion concentrations, boron, and silica concentrations, and enthalpy, and mixing to estimate the reservoir temperature using geothermometers and establish the origin of the water.

The chemical analysis of 28 samples of which 22 samples were collected from springs, seawater and lake water, and six samples from Asal wells was used for geochemical interpretation of the thermal water in this area.

Classification of the samples using the Cl-SO_4 -HCO_3 ternary diagram suggests that their chemical composition is derived from water-rock interaction but influenced by volcanic water with high chloride and sulfate concentrations. According to the Na-K-Mg ternary diagram, the spring waters, lake and sea water are likely to have mixed with cold groundwater or be immature waters that have not attained equilibrium with the rock as can be deduced from their high magnesium concentrations. However, the borehole waters plot as mature waters that have equilibrated with the rock at 220-260°C.

Reservoir temperature estimation using solute geothermometers indicates that the silica concentration of the spring samples is controlled by equilibrium with chalcedony because the calculated source temperature is below 120°C. Those are not controlled by equilibrium with quartz because the rock is probably not old enough or the water has mixed with cool groundwater. The Na/K geothermometer suggests temperatures well below 180°C and supports the use of the chalcedony geothermometer. On the other hand, a higher temperature estimate for the Na-K-Ca geothermometer may be caused by equilibrium with rock minerals or show immature cool waters as indicated by high Mg concentrations. For the fluids of the Asal wells, the geothermometer temperature calculated is in agreement with the measured temperature and the silica concentrations are controlled by equilibrium with quartz.

Using the silica-enthalpy mixing model, the temperature of the hot water component before mixing with cold groundwater is 165°C in this area. This temperature is higher than the temperature calculated using the quartz geothermometer. Thus, the water from the springs was mixed with cold groundwater, while water from well Asal 1 has not mixed with cold water and the estimated temperature of the hot water reservoir is 255°C.

The correlation between Cl and B concentrations suggests that most of the thermal water has undergone water-rock interaction, apart from the well waters and the evaporated seawater sample. The waters from the Lake Asal samples and AS8 from Eaounda Alifitta are probably waters that have evaporated after water-rock interaction.

Finally, the composition of the thermal waters in the Asal-Ghoubbet area was interpreted considering a combination of water-rock interaction and evaporation of the solution. The conclusion was that the waters sampled have not equilibrated with reservoir rock, except the fluids from the wells. According to Sanjuan et al. (1990), the superficial circuits are not in direct contact with the fluids of the reservoir like the fluids encountered in the Asal wells. Supposedly, there is no contact, or the contact is limited and then there is re-equilibration.

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APPENDIX I: SUGGESTED CORRECTION PROCEDURE

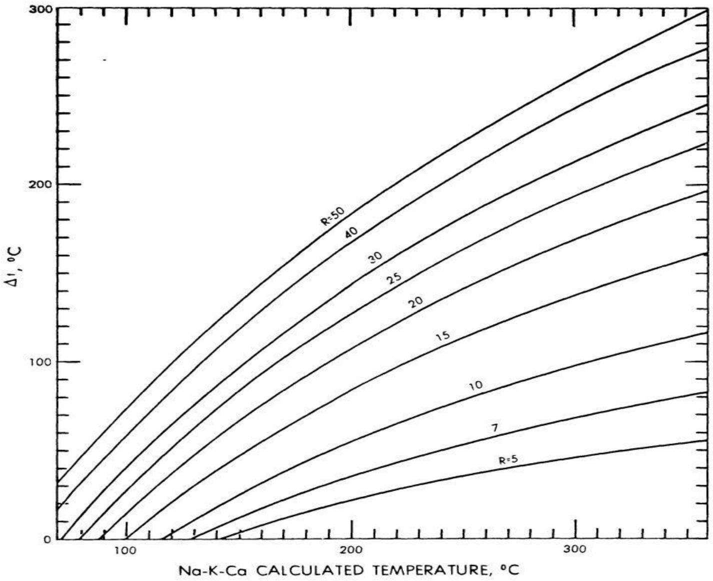

Figure 1: Magnesium correction to the Na-K-Ca chemical geothermometer

1. Calculate the Na-K-Ca temperature as described by Fournier and Truesdell (1973). Do not apply a magnesium correction if this calculated temperature is below 70°C.
2. Calculate R= {Mg/ (Mg + Ca + K)} * 100, using equivalent units of concentration.
3. If R > 50, assume that the water comes from a relatively cool underground environment at a temperature approximately equal to the measured water temperature, irrespective of high calculated Na-K-Ca temperature.
4. If the calculated Na-K-Ca temperature is greater than 70°C and R< 50, use Figs 4, 6, or 7 to calculate Δ t Mg, which is the temperature correction (in °C) to be subtracted from the Na-K-Ca calculated temperature.
5. When using a computer to calculated Δt_{Mg} the following tests should be included in the program:

a) Check if the Na-K-Ca calculated temperature is > 70°C. If yes, do not proceed further with a magnesium correction.
b) Check if R> 50. If yes, assume that the water in the aquifer is relatively cold and do not proceed further with a magnesium correction.
c) If R = 5-50, use eqn (1) to calculate Δt_{Mg}. Do not apply a magnesium correction if Δt_{Mg} is negative.
d) If 0.5 < R < 5, use eqn (2) to calculate Δt_{Mg}. Do not apply a magnesium correction if Δt_{Mg}. Do not apply a magnesium correction if Δt_{Mg} is negative, or if R < 0.5.
e) Subtract Δt_{Mg} from the calculated Na-K-Ca temperature.

Table 1: The results of the magnesium correction to the Na-K-Ca chemical geothermometer of Asal-Ghoubbet area

Samples		**T** surface **(°C)**	**T** Na/K/Ca **(°C)**	**R**	Δt_{Mg}	**T** Na/K/Ca **(°C) after correction**
Korilii	**AS 1**	80	166	15,51	70	96
Manda	**AS 2**	40,5	264	44,46	230	34
	AS 3	45	254	40,19	217	37
	AS 4	43	264	40,29	221	43
	AS 5	45	264	42,64	229	35
	AS 9	38,5	260	42,23	229	31
	AS 10	30	269	62,37	**R > 50**	n.a.
Eadkorar	**AS 6**	84	217	5,97	40	177
	AS 7	90	212	7,87	65	147
Eounda Alifitta	**AS 8**	39	218	52,30	**R > 50**	n.a.
	AS 11	58,5	205	29,18	150	55
	AS 12	-	-			
Oued Kalou	**K1**	74	107	2,54		107
	K2	35	115	14,92	17	98
	K4	-	173	34,77	130	43
	K5	-	170	31,01	122	48
	K6	-	164	29,32	112	52
Ghoubbet	**G2**	60	166	54,28	**R > 50**	n.a.
Lac Asal	**S1**	-	217	58,52	**R > 50**	n.a.
	S2	32	216	60,86	**R > 50**	n.a.
	S3	32	218	60,84	**R > 50**	n.a.
Boreholes	**FA 1**	255	251	0,15	**R < 0.5**	251
	FA 3	260	253	0,02	**R < 0.5**	253
	FA 3A	-	252	0,02	**R < 0.5**	252
	FA 4	-	251	0,01	**R < 0.5**	251
	NA 3 (419m)	100	202	11,40	65	137
	NA 4 (255m)	33	171	61,76	**R > 50**	171

n.a.: not applicable