GEOCHEMISTRY OVERVIEW OF HOT SPRINGS FROM THE LAKE ABHE AREA: REPUBLIC OF DJIBOUTI

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ABSTRACT

The Abhé Lake site is located in the south-Western region of the Republic of Djibouti near the Ethiopian border. Geologically, the area is mainly composed of stratoïd basalts with a high plateaus and sedimentary plains. Several fumerolles and hot springs are identified in Abhe lake area. The temperature of the hot springs can exceed 100°C. Chemical analyses from 20 water sample, hot spring, shallow water well, lake and borehole from the Abhé Lake area were evaluated in order to investigate spring water origin, water–rock interaction mechanisms, and estimate the thermal potential of the geothermal areas. This study presents a preliminary geochemical data interpretation of the abhé area geothermal systems. Based on their hydrochemical facies, the water bodies are categorized into four main groups. The first group is Na-Cl type of water and represents all the boreholes catching the regional volcanic aquifer. Several springs located in Hanlé plain (Agna, Oudgini…) belong also to this group. The hot springs in abhe lake area are characterised by Na-Ca-Cl type of water and form the group 2. At last the waters from sedimentary aquifers are on the one hand characterized by Na-HCO3-Cl type of the shallow water well and on the other hand are characterized by Na-SO4-Cl type of water for deep well. The Lake Abhé waters belong to the Na-HCO3 type with high salinity (155 g/l) and high pH values (>9). The use of geothermometers suggested that the investigated geothermal areas have high enthalpy fluids at depth with temperature estimated by Chemical geothermometers are mostly 160°C.

Key Word: Abhe Lake, Hot springs, geothermometers, geochemistry, Djibouti, overview.

INTRODUCTION

The Republic of Djibouti is located in the arid zone of eastern Africa. Precipitation is randomly distributed on the coast and becomes monsoon in type in the inland (summer rains). Temperatures are high and show little monthly variation. The whole country is practically covered by lava and volcanodetrital deposits from Tertiary an Quaternary ages, some of them very recent. This volcanic activity is due to the location of the area on the southern part of the Afar rift (Fontes et al. 1980). Vertical movements along the faults on the rift structure give rise to isolated basins with internal drainage (Grand Bara, Abhè, Hanlé, Gobaad, Asal). During the upper Pleistocene and until 4000 years ago, lacustrine episodes took place in these depressions (Fontes et Gasses, 1973). At present two basins are still active, both occupied by highly saline lakes. Lake Asal represents the highest potential geothermal reservoir in Djibouti. Lake Abhè is the terminal lake of the Awash River system which comes from the Ethiopian Plateau. It is a sodium-bicarbonate type water (TDS~155g/l).

In Djibouti, different geothermal zone, revealed by numerous hot springs spread, are identified (**figure 1**). The study area is one of them. Located on the south western part of the country, it is a unique landscape in the world with hundreds of chimneys of ruiniform aspect forming a travertine chain on several kilometres (**figure 2**). Several hot springs and fumaroles are observed in this zone. The temperature of the hot springs can exceed 100°C.

Previous chemical and isotopic investigations on surface, groundwater and lake system in the Hanlé-Gaggadé geothermal fields were carried out during the 1970s and 1990s. The aim of this study is to present a preliminary result carried out to the hot springs from Lake Abhè area as well as estimation of the subsurface reservoir temperatures.

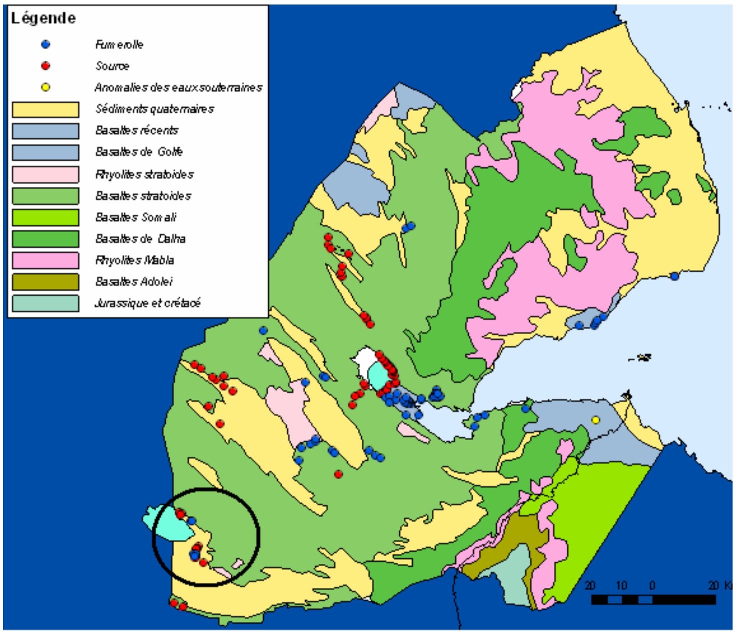

Figure 1: Gelogical map and hydrothermal manifestation in the Republic of Djibouti

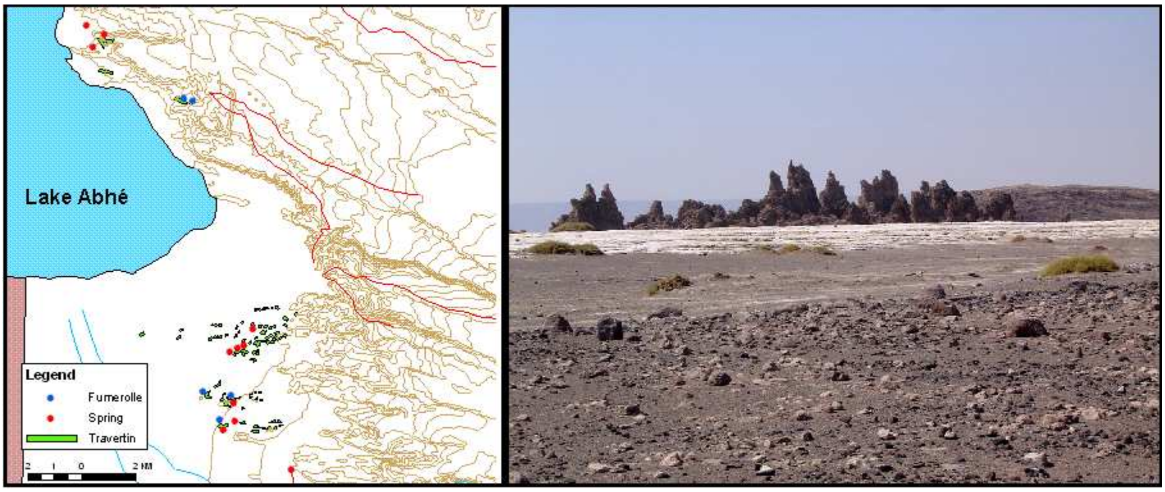

Figure 2: Location map of the thermal water from the study area. (Jalludin 2008)

GEOLOGICAL FEATURES OF THE STUDY AREA

The volcanic series overlie the basement rocks (Jurassic limestones and Cretaceous sedimentary rocks) as a result of the Red Sea, Aden gulf and East African rifts triple junction system, related to plate tectonic movements in the last 25-30 Ma. Adolei basalts characterize the first rupture movement within the Arabo-Nubian block which occurred during the later Miocene period (Figure 1). During these first movements the area is under an Ethiopian rift tectonic pattern with N-S extension faults system (Gaulier and Huchon 1991). There then followed a period of slow expansion during which the Mabla rhyolites outcrop formed (15 Ma) in a large senestral shear zone. Oldest Ethiopian structure oriented N-S to N20°E are reactivated as senestral strike-slip faults. Mabla rhyolite located in the Northern part of the country were then submitted to a diffuse extension phase with associated N160°E normal fault system. After an interval during which these rhyolites were eroded, the Dalha basalts were laid down with an angular unconformity (3.4 - 9 Ma). The Somali basalts outcrop was formed practically contemporaneously in the eastern part of the region. N160°E extension links to early movements during the emplacement of Dalha basalts. Progressively this extension turned to N20°E. Between 3.4 and 1.5 Ma, the Stratoid basalts and Gulf basalts poured out as the Gulf of Tadjourah opened (Black et al., 1974; CNRS-CNR 1973). At the early stage of the opening of the Gulf of Tadjourah the western border of Ali Sabieh horst acts as a wide dextral strike-slip zone with related N-S to N20°E extension which turned to N40°E. Recent volcanic formation are mainly located in the Asal rift and the Manda Inakir rift.

Sedimentay rocks are encountered in coastal areas, in tectonic basins in the southwestern part of the country and along the main stream beds. During the miocene-pliocene, sedimentary rocks (clays and alluviums) are interbedded in Dalha basalts. Alternative humid and arid climates went through the pliocene period with the outcrop of stratoid basalts. Limestones, clays and diatomites are interbedded in these basalts and fill tectonic basins. In the plains, the thickness of the sedimentary rocks can exceed several hundred of meters and in stream bed it remains between some meters to some tens of meters. During the quaternary period, marine sediments (coral limestones and limestones) were deposited in coastal areas. Since 100 000 years BP five phases of major extension of lakes in the tectonic basins were developped during the humid climates and has formed limestones, diatomites and clays outcrops (Gasse et al., 1980).

SAMPLING AND ANALYTICAL METHODS

For this report twenty one water samples from cold and hot springs and of lake water (**Table 1**) were used. These samples were collected in Janvier, 2009. During sampling, field measurements for pH, conductivity, spring temperature were carried out (**figure 3**). Samples were filtered through a 0.45 µm filter membrane and stored in two polyethylene bottles. One of the bottles was acidified with suprapure HNO3 for determination of cations and SiO2 analyses and the other was kept unacidified for anion analyses. The major chemical constituents were analyzed in the geochemical laboratory of the CERD. The δD and δ^{18}O values on the some sample were determined, at the "Laboratoire d'Hydrogeologie d'Avignon" (France), with standard deviations of 2 and 0.2‰, respectively. Additionally, isotopic (18O, 2H) analyses and some chemical analyses of waters from Hanlé and Gobaad area were used from previous studies. All the earlier and current analytical results were used to comment on hydrogeology and water chemistry.

Figure 3: Water sampling and field measurement

RESULTS AND DISCUSSION

Chemical results

The results of the chemical analyses of the hot spring, cold and Abhe lake waters from the study area are listed in Table 1. According to the *Piper diagram* (**figure 4**) the waters were classified into four groups. The first group is Na-Cl type of water and represents all the boreholes catching the regional volcanic aquifer. Several springs located in Hanlé plain (Agna, Oudgini…) at contact of sedimentary rocks and basalts fault scarp are also Na-Cl type and their chemistry is compatible with the chemistry of the volcanic rocks through which they flow.

The hot springs from the lake abhè area are characterised by Na-Ca-Cl type of water and form the group 2. One of the possible origins of these hot springs could be from waters of meteoric origin that circulates deep into the fault zones and rises to the surface once it is heated. The increase of the calcium contain in the water is the result of a reaction which produced at high temperature beetwen an chlorinate-alkaline water and basalts (albitisation of anorthite). The total dissolved solids of this group range from 1700 to 3400 mg/l. The temperature of the hot spring varies from 88,8 to 99,7°C.

The group 3 type is Na-HCO3-Cl and exhibit low mineralisation. It corresponds to the low depth waddi bed alluvium aquifers and is characterized by direct recharge from intermittent stream waters. The TDS range from 278 to 640 mg/l. The Abhé lake water belong to this group with high salinity (~155g/l) and high pH values 9,9.

The water catching the sedimentary aquifers are Na-SO4-Cl type of water form the group 4. This group represented by the sample koutabouya, Yoboki show moderate salinity (TDS=2200mg/l) with high SO4 contain in water. The enrichment SO4 is due to dissolution of evaporite minerals (gypsum) present in sediments lacustrine.

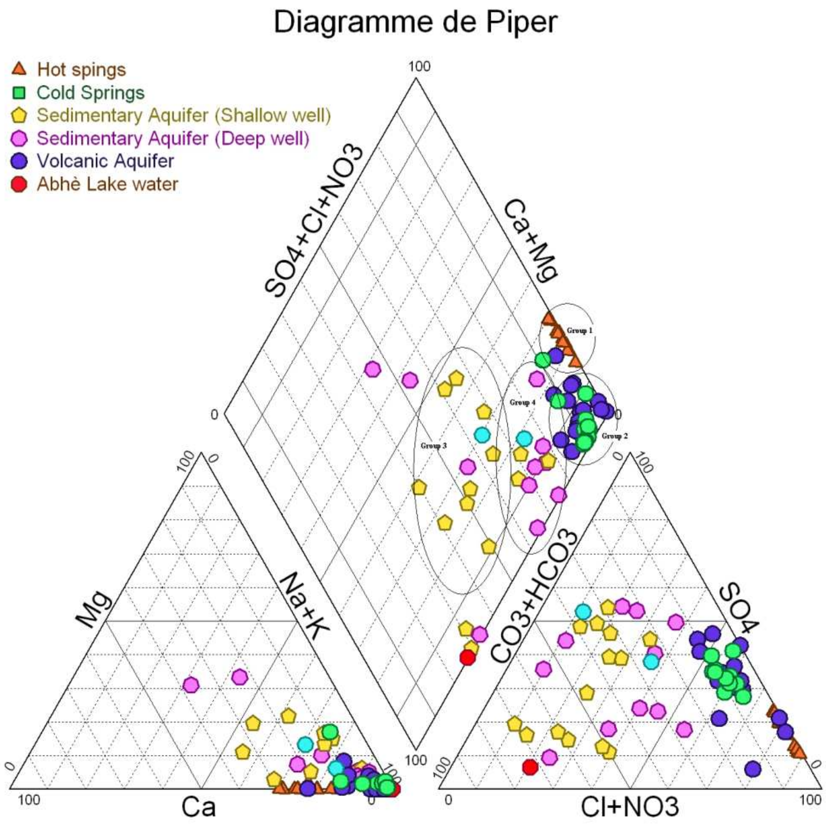

Figure 4: Distribution of the waters points from the study area in Piper diagram

The relations of the chemical constituents in the water samples from the study area are presented in Figure 5. The concentrations of the major ions were plotted against that of chloride, which is considered to be a conservative ion in thermal waters. The SO4 content increase with increase in Cl content. The Ca and HCO3 contents from the cold springs and volcanic aquifer wells seams controlled by the CaCO3 dissolution at high temperature. The Mg content for the hot spring waters is consistently low. The increase in SO4 and decrease in Mg in the hot springs can be explained by: (a) the increase in the solubility of CaSO4 with increasing temperature, and (b) the ion exchange at high temperature of Mg ions in several Ca-Mg-silicate minerals (Ellis, 1971) and subsequent re-equilibration in the solutions (Giggenbach, 1988). The increase of HCO3 could be explained by the reaction between the dissolved carbon dioxide and calcite from the rock that form HCO3.

Mineral saturation index (SI) are used to describe the extent to which a particular solution is saturated, supersaturated or undersaturated with respect to a particular mineral phase. The SI states with respect to calcite, dolomite and gypsum and other minerals were calculated for the water samples using the computer programWATQF, part of the parent code NETPATH (Plummer et al., 1994). The SI values indicate that the geothermal waters are saturated with respect to calcite and aragonite (except the lake abhe water which is supersaturated), and are undersaturated with respect to gypsum and anhydrite.

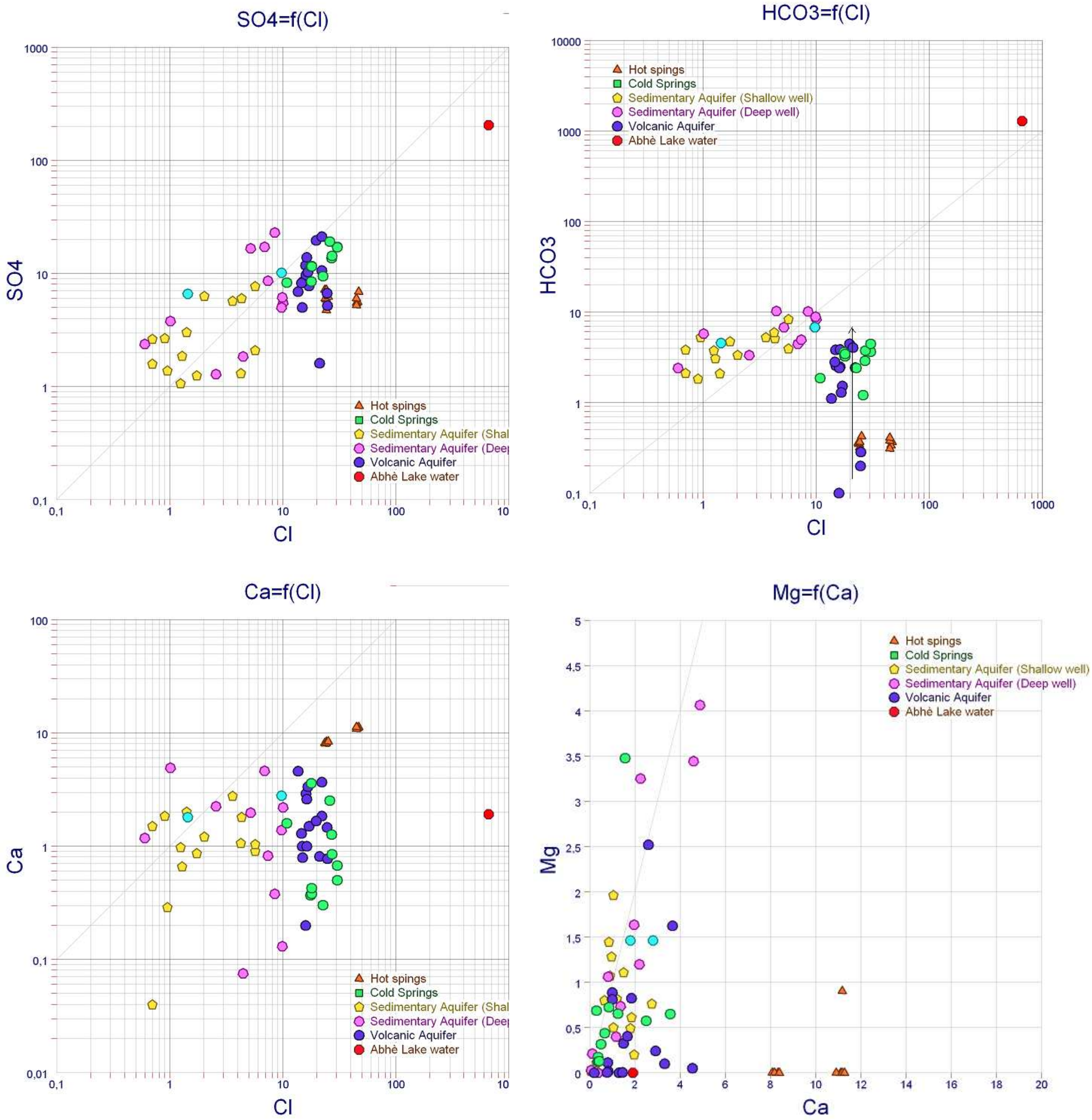

Figure 5: Plots of Ca, HCO3 and SO4 against Cl and Mg against Ca

Table 1: Chemical and physical data of the lake abhé hot springs area and Hanlé-Gobaad area cold water.

Nom	Libellé	T°C	Cond	pH	Cl	HCO3	CO3	SO4	NO3	Na	K	Ca	Mg	Li	B	SiO2	18O	2H
Asbahaltou	CS	36	3760	8,86	824,1	888,8	29,6	566,4	0,0	1426,0	12,9	5,6	0,0					
Abakara	CS	32,4	4540	8,52	1039,1	739,9	10,8	566,4	0,0	1058,0	21,5	6,8	0,0					
Agna	CS	43,7	2525	8,39	652,3	176,9	12,0	172,9	0,0	563,3	12,1	10,0	1,2	0,01		46,8	-3,27	-22,2
ALEYLOU	CS		8283		1816,0	1100,0	0,0	696,0		2012,0	35,0	9,0	3,0					
Dagirou	CS	41,5	5044	7,8	860,0	155,0	0,0	320,0	1,0	724,0	26,5	11,4	3,6	0,02		49,4		
Dahotto	CS	42	5290	7,85	890,0	216,0	0,0	330,0	1,5	806,0	31,5	8,1	4,6	0,02		40,3		
Dali	CS	42,9	6016	8,1	1060,0	220,0	0,0	400,0	1,5	904,0	54,8	6,1	3,3	0,02		58,5		
Eadara	CS	41,9	6151	8,2	1050,0	225,0	0,0	400,0	1,0	916,0	52,4	4,1	1,8	0,01		50,7		
Neinle	CS	68,3	2916	7,59	310,0	155,0	0,0	200,0	1,5	300,0	21,3	33,4	2,8	0,27		79,3	-1,90	-1,3
Oudgini	CS	43,2	4749	8,1	830,0	112,0	0,0	240,0	1,5	630,0	29,0	20,3	6,4	0,02		44,2		
S-AbP2	HS	95,6	4760	8,04	1658,0	22,6	0,0	331,0	0,0	906,2	31,6	224,0	11,0	0,265	1,059	**100,75**	-3,48	-23,74
S-AbP 3	HS	99,7	4710	8,1	1621,3	20,7	0,0	269,8	0,0	906,2	32,4	222,4	0,0	0,287		**114,7**		
S-AbP4	HS	98,6	4640	7,84	1578,0	23,2	0,0	264,0	0,0	1000,0	34,3	218,4	0,0	0,283		**111,4**		
S-AbP5	HS	88,8	4780	7,53	1584,4	25,0	0,0	288,0	0,0	1311,0	35,9	224,0	0,0	0,316	1,038	**119,54**	-2,92	-22,18
S-AbP 6	HS	97	4640	7,76	1575,8	18,9	0,0	251,5	0,0	772,8	24,6	226,0	0,0	0,249				
S-AbG1	HS	94,6	2800	8,32	861,6	19,5	0,0	228,5	0,0	460,0	17,2	166,8	0,0	0,133		**117,9**		
S-AbG3	HS	96,6	2770	8,26	848,5	21,4	0,0	288,0	0,0	743,4	16,4	163,6	0,0	0,133		**101,14**		
S-AbG5	HS	99,6	2720	8,3	848,5	21,4	0,0	282,2	1,2	529,0	16,4	162,4	0,0	0,134				
S-AbG6	HS	94,5	2720	8,5	844,2	21,4	0,0	290,9	0,0	552,0	14,4	161,6	0,0	0,129				
S-AbG7	HS	91,1	2750	8,14	835,3	22,0	0,0	345,6	0,0	644,0	13,3	163,6	0,0	0,132	0,664		-3,42	-24,78
S-AbG8	HS	96,8	2740	8,16	863,7	22,6	0,0	345,6	0,0	460,0	13,3	163,6	0,0					
S-AbG9	HS	93,9	2900	8,34	887,1	26,2	0,0	298,6	0,0	449,9	14,0	168,4	0,0		0,663		-3,03	-25,67
Abaïtou	INF		1072	8,08	150,7	361,2	0,0	62,4	22,3	223,0	9,8	21,2	23,8					
TeweoPuits	INF		720	8,43	33,7	319,1	20,4	66,3	19,8	174,7	2,0	5,8	1,3					
Checkeyti	INF		779	8,71	61,4	287,9	8,4	59,5	33,5	147,2	0,4	17,2	17,5					
Galafi	INF		1430	8,41	202,0	509,4	0,0	100,8	18,6	335,6	32,0	18,0	13,0					
Gagdé Puit	INF		495	8,06	45,7	186,7	0,0	89,3	18,0	102,1	2,0	13,2	9,7					

Teweo	INF		685	8,73	24,9	231,9	60,0	75,9	8,8	163,0	1,2	0,8	0,2					
Galafi 8	INF				202,3	509,8	0,0	201,9	0,0	335,2	31,9	35,9	25,7					
Koutabouya	SED	23	3610	8,52	302,8	622,2	9,0	1096,3	14,9	1133,9	0,0	7,6	0,0					
Gagadé	SED		1525	8,1	152,7	311,1	0,0	288,0	2,9	331,2	3,9	36,0	6,0		2,9			
Kimbire As	SED	30,8	900	7,99	71,4	205,6		303,4	0,0	227,7	5,1	24,0	10,0					
Yoboki1	SED		2370	8	184,6	413,1	0,0	792,5	164,3	598,9	7,8	39,7	19,9					
As Ela	SED		1270	7,56	127,3	319,7	0,0	273,8	1,9	252,9	3,9	54,9	9,2					
Koudi K	SED		530	8,27	44,4	229,4	0,0	50,9	10,5	81,7	3,9	19,6	15,6				-0,69	-1
LiLiya Bouri 1	SED		2030	8,6	261,6	302,6	0,0	412,1	20,5	445,5	6,3	16,4	12,9				-1,16	-0,4
LiLiya Bouri 2	SED		2770	8,16	354,5	511,3	0,0	265,1	446,4	620,7	5,1	44,1	14,6					
G2b Alo	SED		2000	8,1	345,7	414,9	0,0	242,1	11,2	443,5	6,3	27,7	9,0					
Gorabous	SED			7,85	38,0	314,0		74,5	14,0	62,0	5,5	64,0	22,0				-0,20	-0,9
Teweo 4	VOLC		2140	8,43	519,0	117,1	1,2	220,8	0,0	481,9	24,6	14,0	0,0				-2,75	-18,4
R1 bis	VOLC		2194		566,0	146,0	0,0	233,0	0,0	501,0	25,1	29,3	1,5				-2,92	-20,4
R-2	VOLC		2126		588,0	79,0	0,0	247,0	0,0	489,0	18,4	33,5	0,6				-2,86	-21,7
R-3	VOLC		3238		700,0	273,0	0,0	467,0	0,0	752,0	5,5	16,7	2,5				-2,23	-17,7
galafi1	VOLC	39,8	2200	8,9	158,0	624,0	82,0	88,0	18,1	400,0	16,6	1,5	0,4					
Koutabouya forage	VOLC	36	4500	8,1	785,0	149,0		507,0	20,0	740,0	27,0	37,0	10,0					
Gabaita	VOLC	37	2800	8,2	524,0	234,0		240,0	7,0	470,0	19,4	20,0	10,8	0,02		36,4		
Daoudouya forage	VOLC		758	7,99	124,1	210,5	0,0	84,5	26,0	153,6	8,2	33,3	16,5	0,01		35,1		
G2	VOLC				599,8	92,0	0,0	373,7	0,0	540,2	11,7	30,0	4,0					
T1	VOLC				560,8	0,0	0,0	565,6	0,0	589,3	21,8	4,0	0,0					
Hanlé1	VOLC				532,7	156,0	0,0	403,8	0,0	483,2	17,9	16,0	1,4					
Hanlé2	VOLC				481,6	67,2	0,0	333,8	0,0	367,2	7,5	91,4	0,6				-3,52	-21,9
Yoboki 3	VOLC				572,8	152,0	0,0	475,7	0,0	593,3	28,9	20,0	9,9					
Lake Abhé	LAKE	29	79100	9,94	23462	77763	31140	9768	0,0	43746	434,5	38,4	0,0	0,002	31,160		8,94	47,85

Geochemical geothermometry

Several chemical geothermometers have been developed to predict the subsurface reservoir temperatures in geothermal system (Fournier and Truesdell, 1973; D'Amore et al., 1987; Giggenbach, 1988). Dissolved silica and certain cation ratios in deep waters that have experienced prolonged interaction with rocks are usually controlled by temperature-dependent reactions between minerals and the circulating fluids (e.g. Fournier, 1973). Geothermometers represent the equilibria of these temperature-dependent reactions, and geothermometric analysis can indicate the temperature of the reservoir yielding the deep waters. These temperature variations may be due to the lack of equilibrium between solutes and minerals or due to additional processes (including mixing with cold water in the upflow).

Chemical analyses of thermal waters from the study area were used to estimate the subsurface reservoir temperatures by several solute geothermometers. Different geothermometers were applied to the thermal waters of the Lake Abhé hot springs area: chalcedony and quartz (Fournier, 1973 and 1977), Na/K (Giggenbach, 1988), Na-K-Ca (Fournier and Truesdell, 1973), Na-K-Ca-Mg (Fournier and Potter, 1979). Temperatures calculated by these geothermometers for the thermal waters discharged from springs are given in Table 2.

Tableau 2: Geothermometric temperatures (ºC) calculated using different methods

THERMOMETER								
Nom	T°thermal springs	Chalcedony	Quartz	Quartz steam loss	Na/K (Fournier & Potter 1979)	Na/K (Fournier 1979)	Na-K-Ca (Fournier 1979)	Na-K-Ca Mg corrected
S-AB-G1	94	120	146	140	157	144	132	
S-AB-G3	96	111	138	133	123	113	116	
S-AB-G5	99				144	132	125	
S-AB-G6	94				133	122	119	
S-AB-G7	91				120	110	111	
S-AB-G8	96				140	128	120	
S-AB-G9	93				146	134	124	
S-AB-P2	95	110	137	133	152	140	136	132
S-AB-P3	99	119	145	139	154	142	137	
S-AB-P4	98	117	143	138	152	139	137	
S-AB-P5	88	121	147	141	136	125	130	
S-AB-P6	97				146	134	129	
Lake Abhè	29	60	91	93	83	76	152	
Asbahaltou	36	71	101	102	75	69	110	

Results of the different solute geothermometers from de hot springs (**S-AB**) show that the subsurface reservoir temperatures varied between 110 and 157°C. Na/K and Na-K-Ca geothermometers gave the maximum reservoir temperatures (157°C). According to the chalcedony and quartz geothermometers (Fournier, 1977), the subsurface temperatures of the Lake Abhé hot springs area range between 110 and 147°C. In general, the quartz geothermometer is applied in high temperature reservoirs, and the chalcedony geothermometer in low temperature reservoirs. Chalcedony geothermometer gave temperatures close to the measured discharge temperatures (110 – 121°C), whereas quartz geothermometer gave the most reasonable subsurface temperatures (133 – 147°C) for all the investigated thermal waters.

Giggenbach (1988) is a method to discriminate mature waters, which have attained equilibrium with relevant hydrothermal minerals from immature waters and waters affected by mixing and/or re-equilibration at low temperatures along their circulation path. The graphical resolutions of this combined geothermometer for this study are illustrated in Figure 6. Most of the thermal waters in the Lake Abhé area fall into the immature fields or mixed waters (Figure 6), indicating that none of these waters have attained full equilibrium with their associated host rocks.

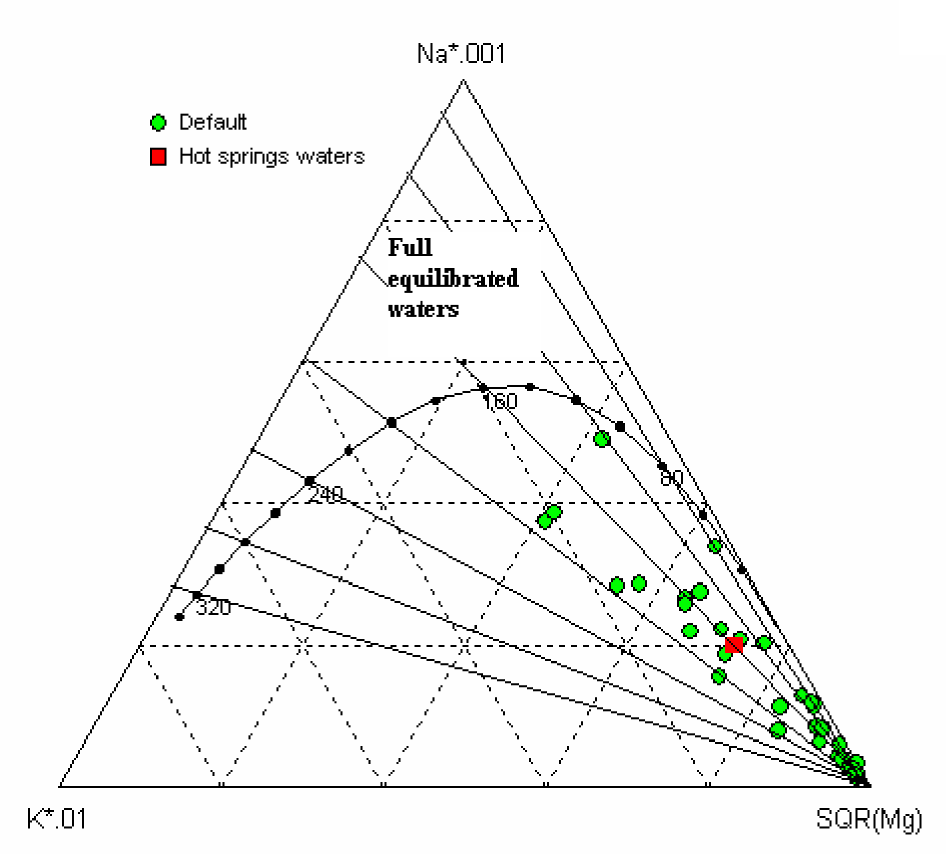

Figure 6: The Giggenbach (1988) Na-K-$Mg^{1/2}$ triangular diagram.

Stable isotope results

Stable 18O and D isotopic analyses were carried out to determine the origin of thermal waters and the geothermal reservoir recharge areas (**figure 7**). The Djibouti Local Meteoric Water Line (LMWL) is not yet available, thus the oxygen-18 and deuterium mean contents in precipitation were taken from stations of the International Atomic Energy Agency (IAEA) network near the studied area (Addis ababa).

The The Oxygen-18 and deuterium composition for 1980 and 2006 sampling ranges from -2 ‰ to 0 ‰, and from -6 ‰ to +2‰ respectively.

The Oxygen-18 and deuterium composition of thermal spring ranges from -2,92‰ to -3,48‰, and from -22,18‰ to -25,65‰ respectively.

Most of the values obtained by Fontes (1980) and Bouh (2006) fall on a range with a slope of 8 indicating that no significant evaporation occurred before or during infiltration; this fact is in agreement with the concept of a fast infiltration through fractured lavas.

The water from hot springs show and oxygen shift, indicating the occurrence of an exchange process with rocks at high temperatures. The following conclusions confirm the chemical observation. The increase of the calcium contain in the water is the result of a reaction which produced at high temperature between an chlorinate-alkaline water and basalts (albitisation of anorthite).

The Lake water show the effect of evaporation, the heavy isotope content between 1980 and 2010 is shifted. Also, the boiling sample from the lake abhé area between 1980 and 2010 show an oxygen and deuterium shift due to evaporation effect.

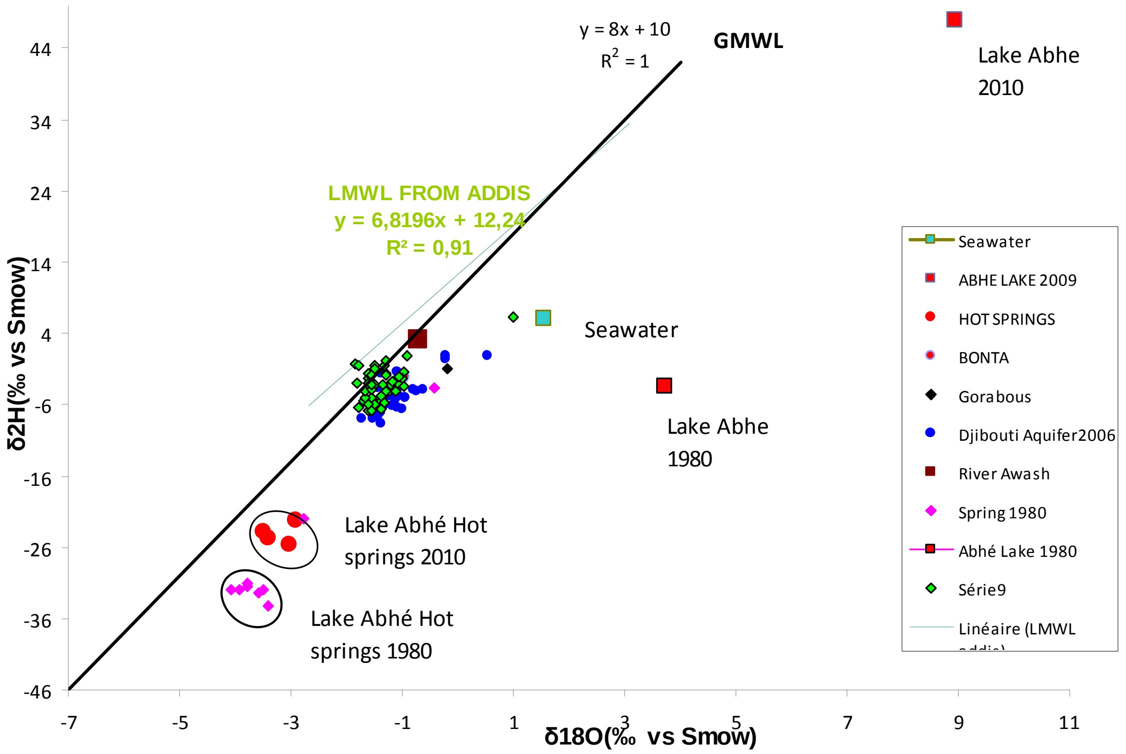

Figure 7: Plot of 18O-2H for the thermal waters from Lake Abhé, Hanlé-Gaggadé and Djibouti aquifer.

CONCLUSION

Geochemical study of thermal water from Abhè Lake area is carried out in order to investigate the origin and sources of solutes and estimate the subsurface reservoir temperatures. Four groups of type of water were found, the first are Na-Cl hydrochemical facies and represents the regional volcanic aquifer and several springs located in Hanlé plain. The hot springs from the lake abhè area are characterised by Na-Ca-Cl type of water and form the group 2. The group 3 type is Na-HCO3-Cl and corresponds to the low depth waddi bed alluvium aquifers. The Abhé lake water belong to this group with high salinity (~155g/l) and high pH values 9,9. The water catching the sedimentary aquifers are Na-SO4-Cl type of water form the group 4. The result of the geothermometer shows that the reservoir temperature can be reach up to 150 °C.

The hot springs from Abhè Lake area are depleted in 18O and 2H, indicating the occurrence of an exchange process with rocks at high temperatures.

The hydrochemical and isotopic information combined with geological and hydrological data from the study area were used to build a conceptual model with the purpose of simplifying field problems (figure 8).

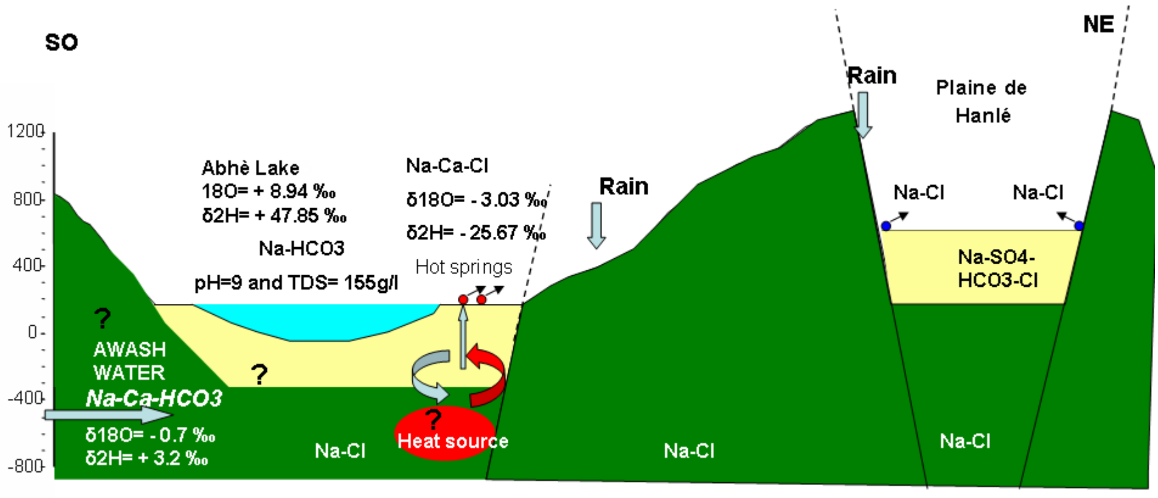

Figure 8: Conceptuel model

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