Geology, Geothermometry, Isotopes and Gas Chemistry of the Northern Algerian Geothermal System

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ABSTRACT

Algeria belongs to the north-western part of Africa, with a quite large area, providing its complex geology and vigorous tectonic activity, which generates an important geothermal potential. In fact, the northern part of Algeria is considered as a part of the Alpine-Magrebides belts. A chemical study counting 31 hot springs data-base reveals the presence of four major types of a near neutral pH water in the northern part of Algeria; Na-Cl, Na-Ca–SO_4, Ca-Mg-CO_3 and Ca-Na-CO_3. The isotopic results (δ O^{18}, δD) indicate a meteoric origin of the thermal water in the western part of Algeria, while the use of gas chemistry in the eastern part of the country has enhanced the meteoric origin of the thermal water at the most of hot springs except 2 hot springs which are enriched in He. The major numbers of the studied hot springs are of immature water rather close to the Mg corner using the Na/1000-K/100-$Mg^{1/2}$ diagram, and the estimated temperature ranges between 80°C to 160°C, while the cationic geothermometers where estimated between 100-500°C. The northern Algerian geothermal system is a non-volcanogenetic system. The water has gained depth until 3 to 7 km, through the NE-SW and E-W faults and finally mixed with high Mg shallower cold carbonated ground water.

1. INTRODUCTION

The are more than 200 hot springs in the northern part of Algeria (Fig. 1). The most important number is located at the northeastern part, with the temperature ranged between 20°C to 97°C. The aim of this study is to find out the origin of the thermal water and possible relationship whith the geological and tectonic set of the study area, relying on isotopic results and gas chemistry mixing model. Gas ratio geothermometers and several cationic geothermometers have been also used to evaluate the most suitable reservoir temperatures for the northern Algerian geothermal water.

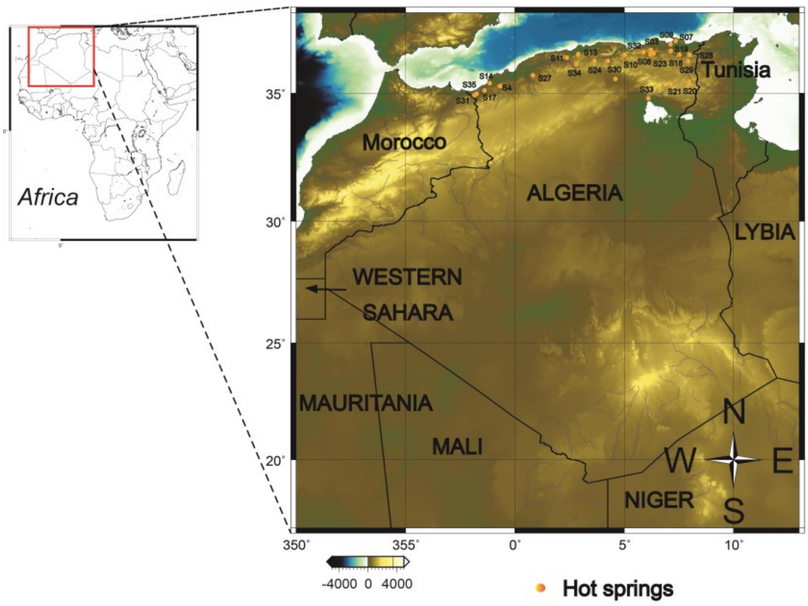

Figure 1: Localisation map of Algeria in Africa. Orange circls indicate the situation of 35 hot spring samples in northern Algeria.

2. GEOLOGICAL SETTING:

The northern part of Algeria displays complex geological features (Fig. 2). The study area belongs to the alpine-Maghrebides belt (Aubouin and Durand-Delga, 1971), it is essentially made by two main zones; the internal zones in the north and the external zones or the Tellian sector in the south, overthrusting the atlasic foreland. Between the internal zones and external zones a syn-orogenic sediment of the flysch unit are formed (Mauretanian, Massylian and Numidian). The flysch are shown as alternance of clay-sandstone and marl-limestone overthrusting the Tellian zone toward the south. The Tellian sector is divided on two zones, the autochthonous or Tellian para-autochthone considered as a part of African passive margin and allochtonous zones. The sediment of this African passive margin are mainly carbonated deposit during the lower Cretaceous to Eocene. While the Tellian Jurassic outcrops in limited places in the western part of Algeria as limestone and dolomitic sequence. To the south, the atlasic domain appears as a large scale folded zone of NE-SW direction which caracterise the late Eocene tectonic stade of deformation , affected by E-W faults (Guiraud, 1970). This area is charachterised by the presence of NE-SW Triassic diaper trend intruding Mezosoic to Eocene formation of clay and limestone. The magmatic activity has widely affected the coastal zones in the north western part of Algeria dated between 0.8 to 3.9 Ma for the alkali-basaltic volcanism (Coulon et al., 2000) and (Louni-Hacini et al., 1995), where in the north eastern part of Algeria has been shown as a granitic intrusion.

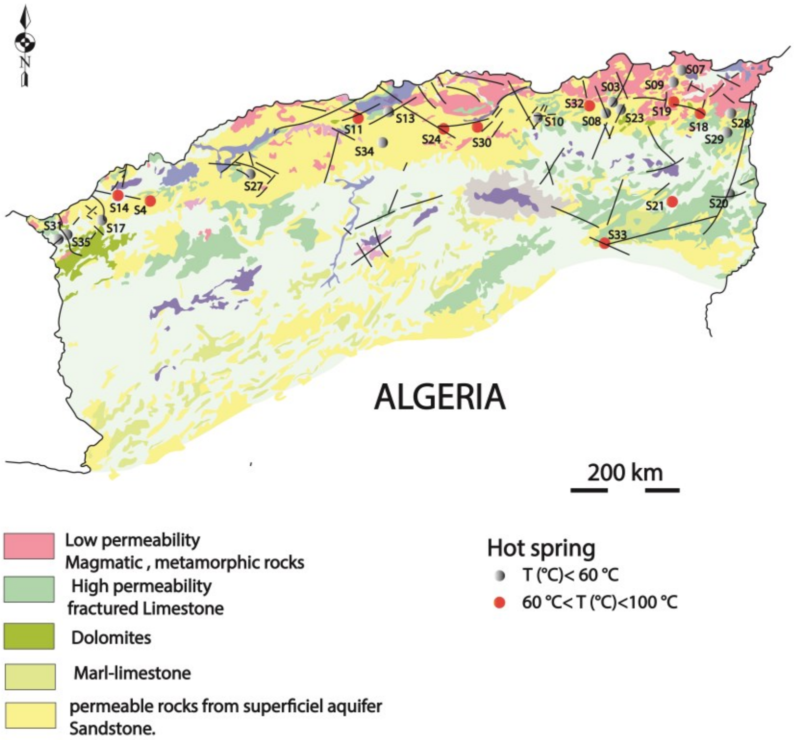

Figure 2: Hydrogeologic map of the northern part of Algeria showing hot springs location (modified from Bouchareb-Haouchine, 2012).

3. WATER CHEMISTRY:

Table 1 shows water major element chemical analysis data base of 35 collected water samples from several Algerian geothermal fields (Guigue, 1947). The studied samples show a near-neutral pH and a higher TDS value, this high salinity may reflects the high dissolved CO_2 in water and the near-surface reaction with minerals of higher Na-Cl and CO_3.

Water samples belong to four major types shown in Piper diagrams in Figure 3;

- Na-Cl waters, Na and Cl are the major species in the most studied samples. The Major number of Na-Cl water types are located in the northern eastern part of Algeria (see samples S13, S21, S24, S30, S32 in Fig. 3b-c), this likely reflects the presence of the NE-SW trending “diapir zone” of Triassic evaporites exetending from Bizerte and el kef (Tunisia) to souk Ahrass in the Eastern part of (Algeria). Therefore, those Na-Cl waters are the result of interaction of the infiltrating waters with the halite-bearing Triassic evaporites (Fourre et al., 2011). The high Na-Cl waters in the western part of Algeria are mainly due the near-surface reaction of the thermal water with shallower salt-flat water (see samples S27, S31, S14, S22, S12 in Fig.3b-c).
- Na-Ca-SO_4 waters, (see samples S11, S09, S10, S35, S25, S26 in Fig. 3a-b-c) which makes in evidence of dissolution of gypsum /or anhydrite minerals in geothermal waters hosted by Triassic formation expressed by diapirism at the eastern part of the country, while its showns as thrust-sheet bordure in the Tellian zone to ease the movement of nappes S11 in Fig. 3b.
- Ca-Na-CO_3 waters, CO_3 is the main anion species for the Tellian sector essentialy made by upper Jurassic Eocene flyschs (Mauretanian, Massylian and Numidian) and Cretaceous Tellian formation extreamly rich in carbonate. However those formation can leach Na from the flyschs alternance and Ca, CO_3 from the limestones from carbonated tellian formation in the thermal water (see samples S1, S2, S3, S4 in Fig. 3a).
- Ca-Mg-CO_3 waters, At most, the Algerian geothermal water shows a higher content of Mg up to 232 mg/l (see sample S27 in Table 1), unlikely with the high enthalpy geothermal systems which have a very low concentration of Mg around 0.01 to 0.1 mg/kg. This high Mg concentration indicate a near-surface reactions leaching the Mg from the expanded Dolomitic sequences present in Jurassic and Cretaceous in all Tellian zones from Tunisia to Morocco (See samples S20, S16, S17 in Fig.3b)

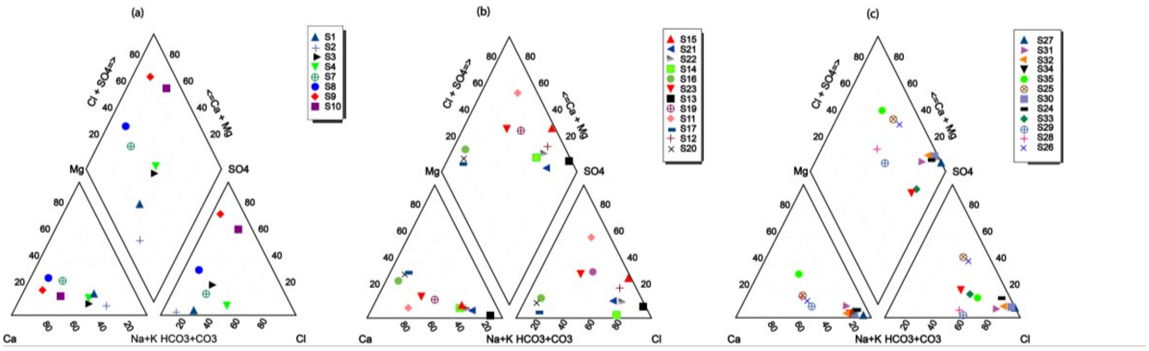

Figure 3: (a, b, c) Piper classification diagrams showing the chemistry distribution of the northern Algerian geothermal waters.

Table1: water chemical ions data (mg/l) from 35 hot spring of the northern part of Algeria, from (Guigue1947; Rezig and Marty, 1995).

Sample ID	Station ID	T(°C)	TDS	Cl^-	SO_4^-	CO_3^-	K^+	Na^+	Mg^{+2}	Ca^{+2}	CO_2	H_2S	CH4	H2	N2	O2	Ar	He	P_{CO2}
S1	**S.Leblanc**	**24**	1610	237	52.5	653	110	293	58	183									
S2	**Takitount**	**22**	2210	152	55	1084	6	615	37	212									
S3	**Ben-Haroun**	**19**	3312	550	618	887	12	693	56	46	60.6	1.05			874.7	52.4	11.1	0.108	0.1
S4	**H.Bouhnifia**	**65**	1314	372	81	330	30	251	36	170									
S5	**Ain N'Sour**	**18**	288	19	30	132	4	10	24	59									
S6	**Sidi M'Cid**	**29**	778	145	93	240	9	90	40	138									
S7	**Le Hamma**	**34**	729	120	105	233	3	74	42	131									
S8	**Dj.Lekhal)**	**31.5**	553	39	158	159	5	26	32	110	484			0.067	378	131	6.7	0.049	0.1
S9	**O.Hammimime**	**47**	2391	78	1367	200	14	103	85	502									
S10	**H.Guerguor**	**44**	3521	482	1682	167	10	347	92	601									
S11	**H.Righa**	**67**	2466	337	1075	161	15	214	31	477									
S12	**O.Ghalia**	**40**	2444	951	431	154	15	641	35	194									
S13	**H.Melouane**	**40**	29422	15850	1921	325	120	10260	79	832									
S14	**H.Bou-Hadjar**	**70**	3516	1608.1	54	463	57	845	49	330									
S15	**A.Ouaraka**	**46.5**	5609	2215	1293	68	65	1331	100	466									
S16	**H.Bradaa**	**28**	371	27.6	47.9	154		15	23	89									
S17	**Les Abdellys**	**34**	405	42.6	13	192	4	22	32	82									
S18	**H.N'Bails**	**42**	5839	2733	445	429	106	1526	77	500	570.4			0.3	337	85	7.8	0.022	10
S19	**H.Meskhoutine**	**96**	1466	327	382	183	46	205	37	202	994.9	1.4	0.46		4.1	0.11	0.11	0.00046	0.1
S20	**Youks-Les-Bains**	**34**	431	28	45	191	2	21	33	92									
S21	**H.Amamrhas**	**65**	2190	880	215	224	22	631	23	132									
S22	**H.Bou-Akkaz**	**40**	2724	1153	228	278	13	738	41	236									
S23	**H.Grous**	**38**	1160	209	294	203	7	132	34	191									
S24	**H.Ksenna**	**52**	5466	2584	664	155	37	1774	69	160									
S25	**H.Bou-Sellam**	**45**	1399	284	456	120	10	208	42	187	34.1	7.2	1.6	0.168	934.5	11	11.4	0.895	0.1
S26	**Oulad khaled**	**49**	1833	415	598	150	18	314	45	240									
S27	**A.Mentila**	**33**	59522	33015	3600	30	143	21502	232	969									
S28	**H.Zaid**	**40**	1017	333	47	228	15	167	35	163									
S29	**H.Tassa**	**41**	1992	724	25	451	26	410	36	284									
S30	**H.el Biban**	**80**	15435	8278	1002	200	60	5122	95	572	58	3.9		5	0.047	0.075	0.016	58	0.1
S31	**H.Ben Chigueur**	**33**	3075	1476	193	225	10	922	52	153									
S32	**H.Beni Guecha**	**55**	16876	8555	1163	580	83	5362	103	934									
S33	**H.Salhine**	**43**	9159	3224	1424	1424	90	2958	61	357	39.6	0.039	0.054	0.017	680.9	0.039	9.84	0.08	0.1
S34	**H.Berrouagia**	**38**	1361	319	197	197	11	432	8	64									
S35	**H.Boughara**	**45**	405	56	18	18	5	52	31	59									

4. RESERVOIR TEMPERATURE ESTIMATION

Solute geothermometers are valuable tools for estimation of the reservoir temperature, and which are based on temperature dependent mineral-fluid equilibria. In fact in the northern Algerian geothermal waters, the raised geothermal water may mix with a cold groundwater and therefore the equilibrium will not be ensured, so the reliability of some geothermometres will be rejected.

4.1 Na-K-Mg diagram

The ternary diagram of Na/1000-K/100-$Mg^{1/2}$ (Fig.4) suggested by Giggenbach (1988) is used to estimate the reservoir temperature and to select the waters most suitable for geothermometry, by recognizing the fluid maturity of waters which have attained the equilibrium with the host rock.

The major number of the northern Algerian geothermal water samples falls in the immature water field quite nigh to the $Mg^{1/2}$ corner (see samples S26, S28, S29 and S35 in Fig. 4a). It's the same case for (samples S19, S11, S14, S23, S20, S21, S15 S7, S4, S10, S9, S8, S1 shown in Fig. 4b-c). This plot may result from the mixing of fully equilibrated or partly equilibrated geothermal water with cold shallow immature groundwater and /or meteoric water, and could be also explained by the interaction with the host rock such as the high Mg dolomite-limestone rocks which constitute the main reservoir rocks of the northern Algerian geothermal waters. Thus, the use of such waters for evaluation of geothermal reservoir is so doubtful (Giggenbach, 1988), and makes the reliability of cationic geothermometers only tentative (Tarcan, 2005).

Hence, some water samples are plotted in fully equilibrated or mixed water field indicating a reservoir temperatures ranged between 80°C and 160°C (see samples S24, S33, S32, S34, S31 in Fig 4a). same resulte are given by (S2, S3, S22 and S12 in Fig 4b-c) showing an estimated temperatures between 80°C and 120°C. Those results indicate more direct feeding from the reservoir and less contribution of shallow groundwater which decrease the Mg and K in water.

More over, in all Algeria there are only two samples which indicate a fully equilibrium whith the host lithology whith an estimated reservoir temperature of 120°C (see samples S27, S13 in Fig 4a-b).

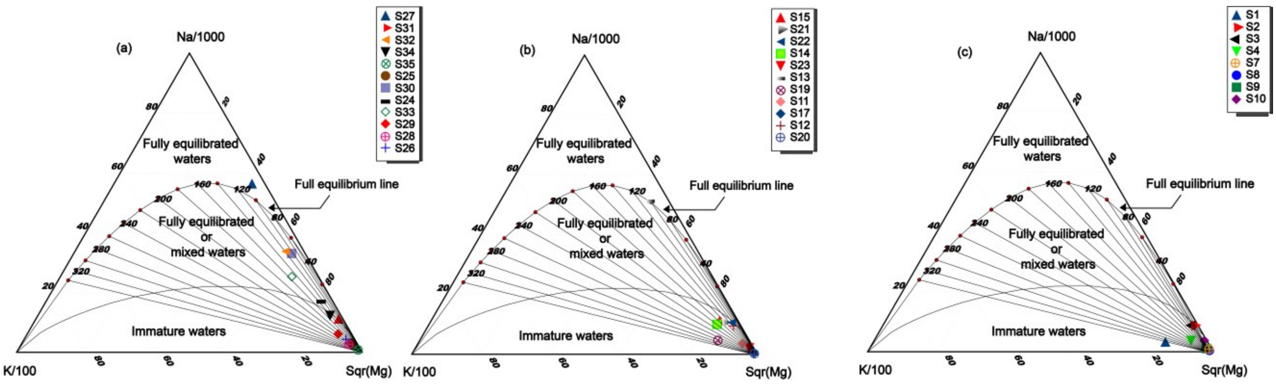

Figure 4: (a, b, c)Ternary Na-K-Mg diagram of the Northern Algerian geothermal fields water samples.

4.2 Cationic Geothermometers

The near neutral geothermal waters of the northern part of Algeria shows a higher Na/K ratio >16 (Table1), in fact the increase of this ratio decrease temperature (Ellis and Wilson, 1960) and $\sqrt{Ca}/\sqrt{Na} < 1$ which is indicative of the low temperature at depth. Thus the Na/K geothermometers give a very high temperature in case of rich sedimentary horizon (Fournier, 1989). However the Na and K are influenced by dissolution of clay minerals located at the shallower part of the geothermal fields.

The CCG (Nieva and Nieva, 1987) estimated temperature are much higher than Na-K-Ca geothermometer (without Mg correction), after Olade (1994) and Saibi and Ehara (2010), CCG method is an effective tool for temperature estimation. This low value of Na-K-Ca geothermometer is due to the calcium loss by boiling from water which leads the precipitation of aragonite confirmed by the travertine deposit around (samples S4, S19, S11 Fig 2) field in high Mg geothermal water such as Algerian geothermal waters the Na-K-Ca should be used with discrimination.

The estimated reservoir temperature given by K/Mg (Giggenbach,1988) gives very low results than measured temperature however the use of this geothermometer is unreliable. The Mg content in the northern algerian geothermal waters increases because of the interaction between water and Jurassic dolomite and/or the mixing with shallow carbonated groundwater rich in Mg. The increase of Mg content gives the low temperature.

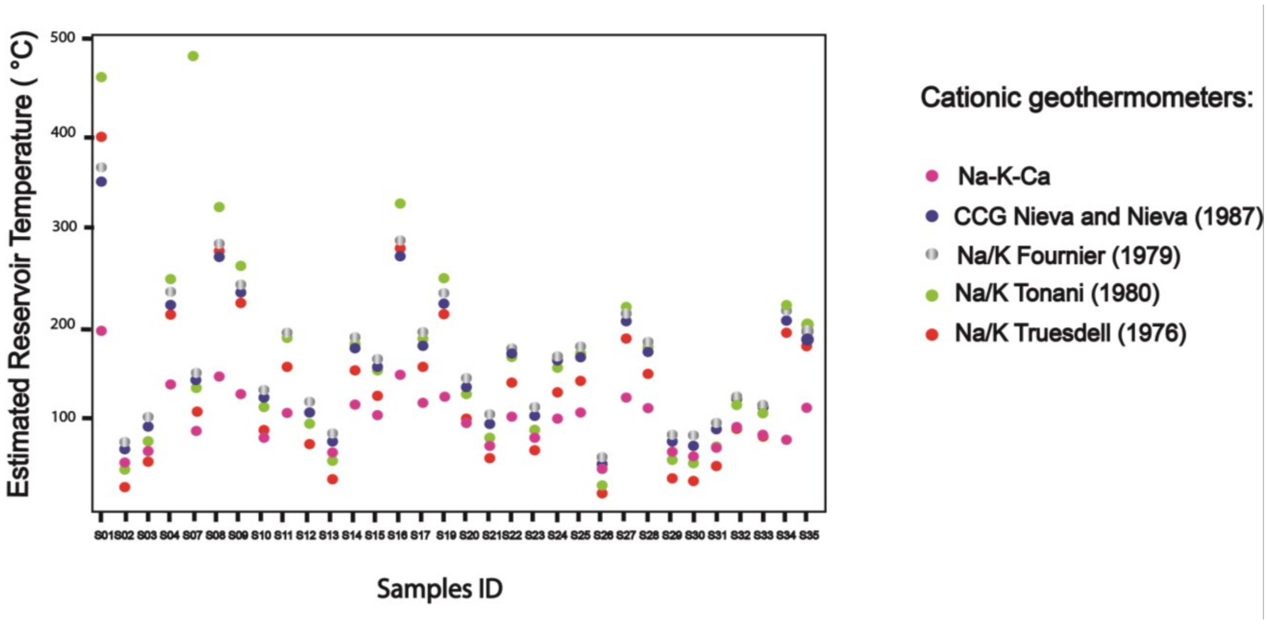

Figure 5: Estimated Reservoir Temperature based on different Cationic geothermometers. Na-K-Ca geothermometer (Fournier and Truesdell, 1973); cation composition geothermometer (CCG) (Nieva and Nieva, 1987); Na/K geothermometer (Truesdell,1976); Na/K geothermometer (Tonani,1980); Na/K geothermometer (Fournier, 1979).

5. ISOTOPES

In order to know the origin of the geothermal fluid, the isotopic signature (Craig et al., 1956; Craig, 1963) constitutes a good indicator for any magmatic or meteoric contribution in geothermal waters. Both δ^{18} O and δ D contents depend on many factors such as altitude latitude and precipitation in the study area.

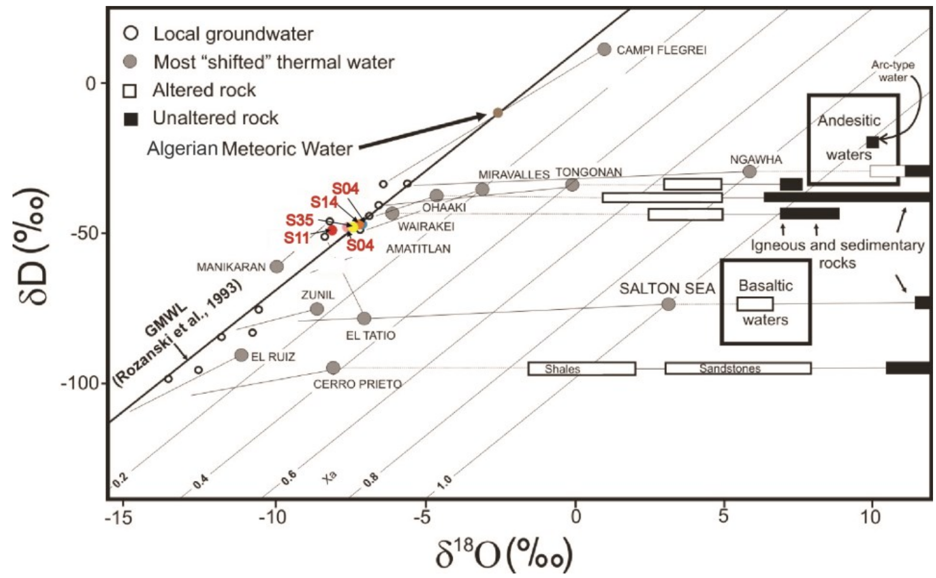

Figure 6: Plot of δ^{18}O vs. δD for thermal water showing trends and shift from different geothermal field including the north central and western Algerian geothermal fields, Giggenbach (1992). GMWL, Global Meteoric World Line is also shown.

The waters issued from the Algerian geothermal fields fall on /or close to the Meteoric line (GMWL; Rozanski et al., 1993), with equation of ($\delta D = 8.13\ \delta^{18}O + 10.8$), indicating a meteoric fed of those geothermal water.

- The δ D shifting in the northern central and western Algerian geothermal waters (see samples S04, S14, S35, S11 in Fig. 6), may likely due to the altitude of the recharge zone area as the Tlemcene Mountain up to 1300 m.a.s.l, and Saida Mountains up to 1150 m.a.s.l, and same for the Zeccar mountain that attain 1200 m.a.s.l.
- The long distance between the recharge zone area 80 km and the upflow area for S04 in Fig.6 reflects the long residence time of the geothermal fluid in the reservoir and explains the depletion of δ D of geothermal waters comparing to the meteoric water. This light isotopic value of geothermal field samples may due also to the seasonal changes; therefore Seasonal changes occur a lower isotope ratio in winter than summer (Armannsson, 2007).

- The shifting of δ^{18} O in sample S11, towards less negative value, is due to the mixing with shallow groundwater rich in CO_2 hosted by carbonated formation of the Cretaceous tellian zones.
- This δ^{18} O and δ D results reject the possible contribution of 0.8 to 3.9 Ma for the alkali-basaltic volcanism (Coulon et al.,2000) and (Louni-Hacini et al.,1995) in this geothermal manifestation of the western part of Algeria. Otherwise it enhances the thought of deep water circulation promoted by the thick Jurassic layers and supplied with the NE-SW fault bend fold.

6. GAS CHEMISTRY:

Table 1 shows the relative abundances of the major and noble gas components (N_2, O_2, CO_2, CH_4, H_2, He and Ar) in the dry gas phase at equilibrium with each geothermal water sample of northeastern Algeria of Rezig and Marty (1993). N_2=He*1000=Ar*100 (1), N_2=CH_4=H_2S (2), CH_4=H_2=H_2S (3) Ternary mixing models (Werner et al., 2008) reveals an excess of N_2 and CO_2 which involves the contribution of hydrothermal fluid from deeper source Fisher and Marty (2005), with a lower amounts of H_2 and CH_4.

In occurrence, the use of gas ratio in the northeastern Algerian geothermal water samples reveals:

- Most of the northeastern geothermal waters samples gives a higher N_2/O_2 except for (S18, S07 in Fig. 7_1), which have values near those of air and have a higher O_2 concentration. However this is likely due to the air contamination (Saibi, 2009).
- The He/Ar ratio gives a greater value than the atmospheric value of $5.7*10^{-4}$. This enrichement of crustal radiogenic He indicate a presence magmatic input (see S25 and S30 in Fig 7_1) where He/Ar ~0.2 in S30 and N_2/He ratio less or approxiamtif to 1000. This result involve the contribution of a deeper than crustal origin of helium in S30 and S25 (Giggenbach and Glover ,1992).
- N_2/Ar ratio is ranged between 37 (see samples S19, S18 in Fig. 7_1) rather close to air saturated water, to 87 (see samples S33, S03, S07 in Fig. 7_1) for free air in all studied samples. This results likely reflects the atmospheric origin of the geothermal water.

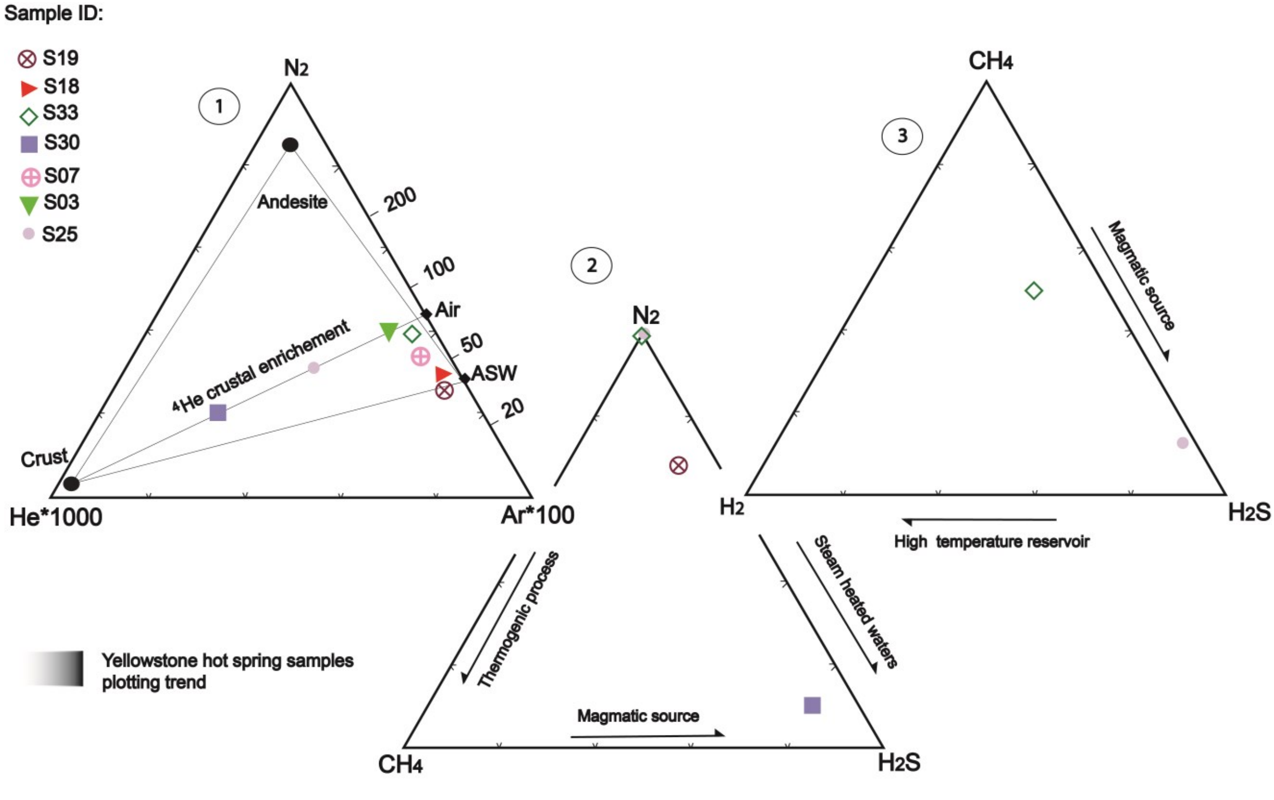

Figure 7: N_2=He*1000=Ar*100 (1), N_2=CH_4=H_2S (2), CH_4=H_2=H_2S (3) Ternary mixing models of the northeastern Algerian geothermal water (after , Werner et al., 2008).

7. GAS GEOTHERMOMETERS

The gas concentration in geothermal reservoir are eventually affected by the gas ratio. However, the use of gas-gas geothermometers is needed for estimation of geothermal reservoir.

To better estimate the reservoirs temperatures for the northeastern Algerian geothermal waters, four geothermometers CO_2-H_2S-CH_4-H_2; (D'Amore and Panichi, 1980), H_2-Ar; (Giggenbach and Goguel, 1989), CO_2-Ar and CO_2-H_2 of Giggenbach (1991) have been applied in Figure 8.

CO_2-H_2S-CH_4-H_2 (D'Amore and Panichi, 1980) is partially empirical with respect to the selection of CO_2 partial pressure (P_{CO2},) which is related to the proportion of CO_2 in the total gas content of the discharge (if CO_2<75% P_{CO2}=0.1; if CO_2>75% P_{CO2}=1.0; if CO_2> 75% &CH_4>2H_2& H_2S>2H_2; P_{CO2} =10). Therefore, the estimated reservoir temperature by these geothermometer gives temperature ranged between 199°C and 313°C respectively (see samples S33, S25 in Fig. 8) with a P_{CO2} = 0.1. those estimated temperature are considered slightly higher than resevoir temperature, because of the high CO_2 content in water due to the precipitation of carbonated minerals around hot springs area.

While, H_2-Ar geothermometer of Giggenbach and Goguel (1989) gives much lower estimated temperatures than the reservoir temperatures of the northeastern Algerian geothermal water (see samples S18, S07, S25 in Fig. 8). This is likely due to the low content of H_2 comparing to the other gas species or consomation of H_2 due to the oxidation or alteration of the evaporites mineral such anhydrite. The effect of dilution process in the northeastern geothermal water is far to be negligeable, Thus the dilution with meteoric recharge can decrease Ar content and decrease the air contamination. While this effect is less observed when applying CO_2-Ar geothermometer (Giggenbach, 1991).

Even so , the CO_2-H_2 geothermometer (Giggenbach, 1991) has evaluated much higher temperature between 217°C to 275°C (see samples S18, S33, S07, S25 in Fig. 8). Those results may likely reflect the depletion of H_2 and carbonated nature of the geothermal reservoir leading the precipitation of calcite and the increase of CO_2 in water.

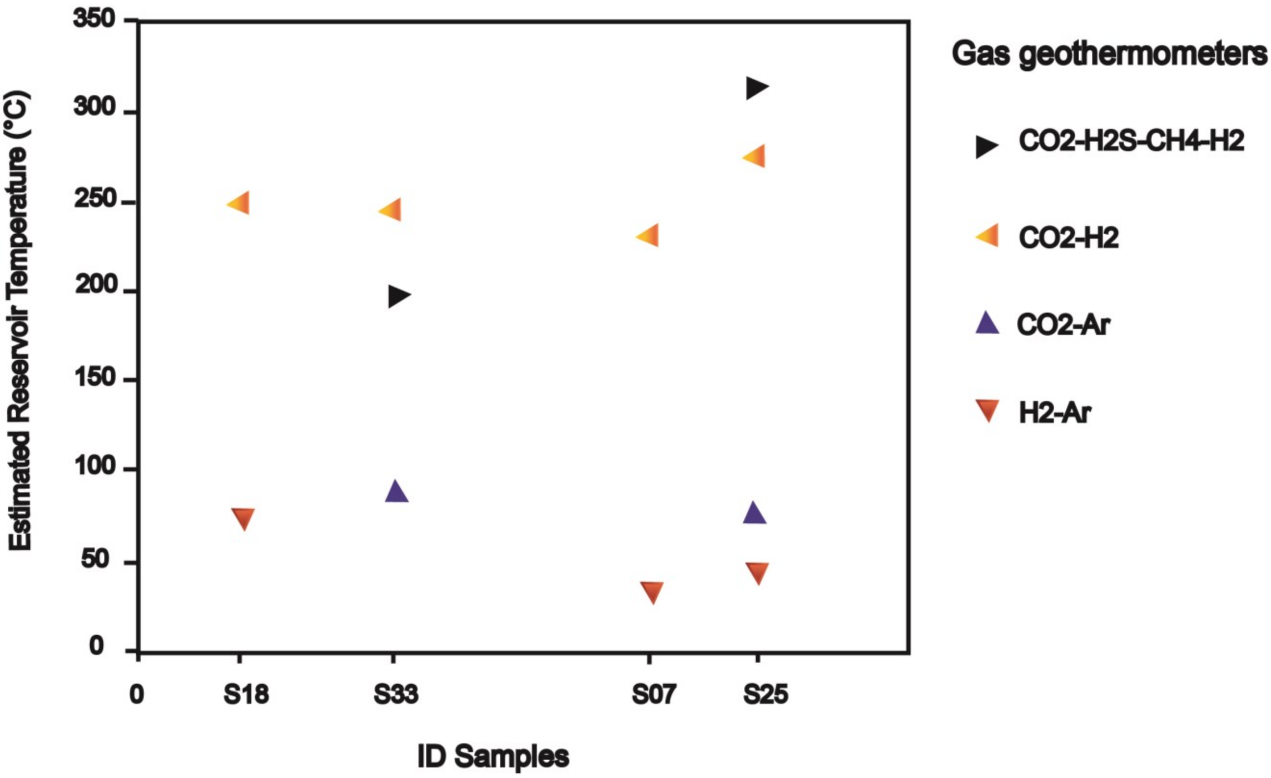

Figure 8: Estimation of reservoir temperatures using several Gas Geothermometers. CO_2-H_2S-CH_4-H_2: t °C = [24775/ (2log (CH_4/CO_2)-6log (H_2/CO_2)-3log (H_2S/CO_2)+7logP_{CO2}+36.05)]-273 (D'Amore and Panichi, 1980). H_2-Ar: t °C = 70 [2.5+log (X_{H2}/X_{Ar})] (Giggenbach and Goguel, 1989). CO_2-Ar: t °C = [0.227*t-7.53+2048/t+273]. CO_2-H_2: t °C = -28.57 *log[CO_2/H_2]+341.7. (Giggenbach, 1991).

7. CONCLUSION:

Chemical analysis of the northern Algerian hot springs makes in evidence the relationship between the water type and the geologic and tectonic setting. Four types of water were classified in the northern part of Algeria, Na-Cl and Ca-SO_4 are mainly to the Triassic evaporites sequence mineral dissolution as halite, gypsum/or anhydrite. Those waters facies are found typically in the northeastern part of Algeria due to the NE-SW Triassic diapir trend from Tunisia to Algeria. While Na-CO_3 and Ca-Mg-CO_3 caracterise the northwestern and the central part of Algeria, due to the Tellian carbonated-dolomited reservoir type.

According to the isotopic result in the western part and the gas ternary mixing model, most of the northern Algerian geothermal water are derived from meteoric origin except S25 and S30 in Fig.7_{1-2}. The gas ratio reveals the presence of magmatic input He/Ar ~0.2 in S30 and N_2/He ratio ~370, which involve the contribution of mantle in the origin of those two hot spring.

The major number of the thermal water issued from northern Algeria are of immature water which makes the use of cationic geothermometer inappropriate to estimate the reservoir temperature for those samples. While the use of Na-K-Mg geothermometer for fully and partly in quilibrated waters has evaluated the reservoir temperatures from 80°C to 160°C. The use of gas geothermometers relying in low H_2 and higher CO_2 has obtained unsatisfied results in the low to medium enthalpy Algerian geothermal field.

In the northern part of Algeria the geothermal gradient varie between 2.2°C and 4.3°C per 100 m (Bouchareb-Haouchine, 2012), the maximale reservoir temperature obtained by Na-K-Mg diagram is around 160°C. therefore, the maximal depth that the meteoric waters infiltrate ranges between 3.8 to 7 km for the northern part of Algeria.

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