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, namely Na-Cl, Na-Ca–SO4, Ca-Mg-CO3 and Ca-Na-CO3. The isotopic results (δ O18, 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-Mg1/2 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

There 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 with 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 circles 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-Magrebides 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 aitlasic 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-autochthon 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 characterised 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\textsubscript{2} in water and the near-surface reaction with minearls of higher Na-Cl and CO\textsubscript{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 extending 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\textsubscript{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\textsubscript{3} waters**, CO\textsubscript{3} is the main anion species for the Tellian sector essentially made by upper Jurassic Eocene flyschs (Mauretanian, Massylian and Numidian) and Cretaceous Tellian formation extremely rich in carbonate. However those formation can leach Na from the flyschs alternance and Ca, CO\textsubscript{3} from the limestones from carbonated tellian formation in the thermal water (see samples S1, S2, S3, S4 in Fig. 3a).

- **Ca-Mg-CO\textsubscript{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.

Table 1: water chemical ions data (mg/l) from 35 hot spring of the northern part of Algeria, from (Guigue1947; Rezig and Marty, 1995).

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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 geothermometers 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 results 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 with the host lithology with an estimated reservoir temperature of 120°C (see samples S27, S13 in Fig 4a-b).

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 √Ca/√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 δ¹⁸O and δ D contents depend on many factors such as altitude latitude and precipitation in the study area.

Figure 6: Plot of δ¹⁸O 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 (δ D = 8.13 δ¹⁸O+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).
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- The shifting of δ¹⁸O in sample S11, towards less negative value, is due to the mixing with shallow groundwater rich in CO₂ hosted by carbonated formation of the Cretaceous tellian zones.
- This δ¹⁸O 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 (N₂, O₂, CO₂, CH₄, H₂, He and Ar) in the dry gas phase at equilibrium with each geothermal water sample of northeastern Algeria of Rezig and Marty (1993). N₂=He*1000=Ar*100 (1), N₂=CH₄=H₂S (2), CH₄=H₂=H₂S (3) Ternary mixing models (Werner et al., 2008) reveals an excess of N₂ and CO₂ which involves the contribution of hydrothermal fluid from deeper source Fisher and Marty (2005), with a lower amounts of H₂ and CH₄.

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 N₂/O₂ except for (S18, S07 in Fig. 7), which have values near those of air and have a higher O₂ 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 enrichment of crustal radiogenic He indicate a presence magmatic input (see S25 and S30 in Fig 7) where He/Ar ~0.2 in S30 and N₂/He ratio less or approxiamtifi to 1000. This result involve the contribution of a deeper than crustal origin of helium in S30 and S25 (Giggenbach and Glover, 1992).
- N₂/Ar ratio is ranged between 37 (see samples S19, S18 in Fig. 7) rather close to air saturated water, to 87 (see samples S33, S03, S07 in Fig. 7) for free air in all studied samples. This results likely reflects the atmospheric origin of the geothermal water.

![Sample ID: N₂=He*1000=Ar*100 (1), N₂=CH₄=H₂S (2), CH₄=H₂=H₂S (3) Ternary mixing models of the northeastern Algerian geothermal water (after , Werner et al., 2008).](image)

Figure 7: N₂=He*1000=Ar*100 (1), N₂=CH₄=H₂S (2), CH₄=H₂=H₂S (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 CO₂-H₂S-CH₄-H₂ (D’Amore and Panichi, 1980), H₂-Ar; (Giggenbach and Goguel, 1989), CO₂-Ar and CO₂-H₂ of Giggenbach (1991) have been applied in Figure 8.
CO₂-H₂S-CH₂-H₂ (D’Amore and Panichi, 1980) is partially empirical with respect to the selection of CO₂ partial pressure (P_CO₂) which is related to the proportion of CO₂ in the total gas content of the discharge (if CO₂<75% P_CO₂=0.1; if CO₂>75% P_CO₂=1.0; if CO₂> 75% &CH₂>2H₂& H₂S>2H₂; P_CO₂ =10). Therefore, the estimated reservoir temperature by these geothermometers 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 reservoir temperature, because of the high CO₂ content in water due to the precipitation of carbonated minerals around hot springs area.

While, H₂-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 H₂ comparing to the other gas species or consumption of H₂ 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 negligible, Thus the dilution with meteoric recharge can decrease Ar content and decrease the air contamination. While this effect is less observed when applying CO₂-Ar geothermometer (Giggenbach, 1991).

Even so, the CO₂-H₂ 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 H₂ and carbonated nature of the geothermal reservoir leading the precipitation of calcite and the increase of CO₂ in water.

**Figure 8:** Estimation of reservoir temperatures using several Gas Geothermometers. CO₂-H₂S-CH₂-H₂: t °C = [24775/ (2log (CH₂/CO₂)-6log (H₂/CO₂)-3log (H₂S/CO₂)+7logP_CO₂+36.05)]-273 (D’Amore and Panichi, 1980). H₂-Ar: t °C = 70 [2.5+log (X_H₂/X_Ar)] (Giggenbach and Goguel, 1989). CO₂-Ar: t °C = [0.227*t-7.53+2048/t+273]. CO₂-H₂: t °C = -28.57 *log[ CO₂/H₂]+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-CI and Ca-SO₄ 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-CO₃ and Ca-Mg-CO₃ 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. The gas ratio reveals the presence of magmatic input He/Ar ~0.2 in S30 and N₂/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 quilated waters has evaluated the reservoir temperatures from 80°C to 160°C. The use of gas geothermometers relying in low H₂ and higher CO₂ has obtained unsatisfied results in the low to medium enthalpy Algerian geothermal field.
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In the northern part of Algeria the geothermal gradient varies between 2.2°C and 4.3°C per 100 m (Bouchareb-Haouchine, 2012), the maximal 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.

REFERENCES


