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Hydrothermal characterization of groundwater in the Tamlouka Plain and its surroundings (Northeast Algeria)

Samir Djorfi*[1], Laroussi Beloulou[1], Saadane Djorfi[1], Mohamed Djidel[2], Salima Guechi[1]

[1]*Laboratoire des Ressources Naturelles et Aménagement, Université Badji Mokhtar, Annaba, Algérie*

[2]*Laboratoire de Géologie du Sahara, Université Kasdi Merbah Ouargla, Ouargla, Algérie*

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Abstract

Located in the North East of Algeria, the Tamlouka-Ain Makhlouf Plain contains several aquifers. Some layers include locally hot water with relatively high temperature (30 to 72°C). In order to elucidate the mode of deposit and circulation of such waters and to evaluate the thermal water potential in the basin, a multidisciplinary approach that focused on geology, geophysics, hydrodynamics and hydrochemistry was used. This approach pointed out that the basin occupies an intermediate structural position between the Tellian domain, the neritic domain and the Sellaoua unit. It is also characterized by the presence of a series of horsts formed by the Lias to Miocene limestones and dolomites, on one hand, and grabens filled by alluvial formations of the Mio-Plio-Quaternary, on the other. The hydrogeological overview shows that the Mio-Plio-Quaternary formations form the excessively salty superficial aquifer whose potential is reduced. However, neritic domain limestones and dolomites providea significant aquifer potential. The hydrochemical tool shows that the hot waters are characterized by two chemical facies: the HCO_3-Ca and the SO_4-Ca types, respectively, in the West and the East. The salinity of hot thermal waters is mainly due to deep water circulation in the crystallophyllian rocks and in the carbonate formations that are in contact with the terrigenous salt formations. The silica and sodium geothermometers show that thermal waters temperature varies from 60 to 100°C and water would emerge from 1600 to 3000m deep layers through a fault system that affects the basement.

*Corresponding Author: Samir Djorfi ✉ samirdjorfi@gmail.com

Introduction

The Tamlouka-Ain Makhlouf basin is a part of the high Constantine hills; located to the east of Constantine City. It extends from 6°57'to 7°23', east longitude and from 35°59'to 36°15' north latitude. It is characterized by the presence of a number of springs of variable importance (discharge: 100l/s) including 8 hot springs: Ain Arko (AA), F8, F17 and F18 wells; located in the southwest; and Belhachani Hammam (HB), Guerfa Hammam (HG), Ghallaia1 (GH1), Ghallaia2 (GH2) and Ain Debba (AD); in the North-east. The water temperature ranges from 30 to 72°C. Actually, waters of the F8, F17, F18 and Ain Arko wells are used for the drinking water, while those of the other springs are used in agriculture and recreation.

This paper addresses, for the first time, a new approach to the structural and geochemical context of these "hot" waters through a geological, geophysical, geochemical and geothermal study. This will help to better understand the tectonic mechanisms responsible for their recharge, circulation, accumulation and emergence and to highlight their typological characteristics and chemical relationships.

Materials and methods

Physico-geographical characteristics

The study area is characterized by a flat topography except the Ain Arko hilltop in the Southwest. It is limited by Djebel Djaffa in to the West and to the North-West, Djebel Oncel to the North, the Sellaouas Chebka to the South and the Southeast. The Ain Makhlouf hills represent the eastern plain extension towards the Chenniour Wadi.

The region has a seasonally variable continental climate characterized by a hotand dry summer and a cold and wet winter. The hydrographic network is relatively dense; it consists mainly of the Charef wadi and its tributaries: Mgaisba, Mellah, Bardo, Chenniour wadis and several greeks along Djebel Oncel, Djebel Djaffa, Sellaouas Chebka and El Maida (Fig. 1).

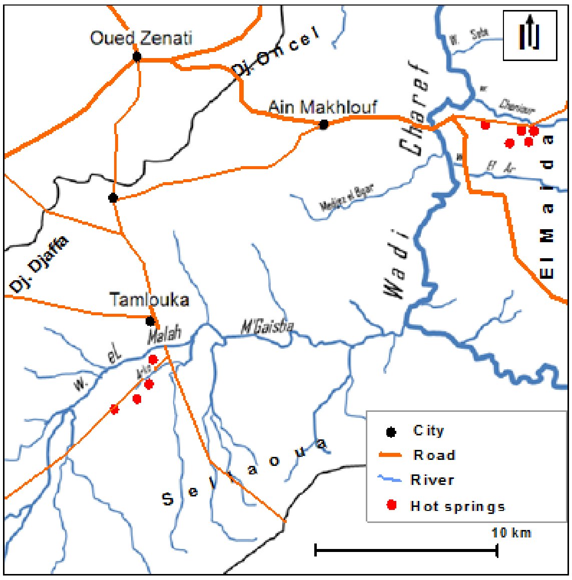

Fig. 1. Geographical location of the Tamlouka-Ain Makhlouf Basin.

Geostructural and hydrogeological framework

The Tamlouka-Ain Makhlouf basin occupies an intermediate structural position between the Numidian thrust sheet, the Tellian domain, the Neritic domain and the Sellaoua unit.

It is also characterized by the presence of a series of horsts formed by limestones and dolomites that dated from the Lias to Miocene and alluvial formations filled grabens of the Mio-Plio-Quaternary periods (Voute, 1967; Vila, 1980; Wildi, 1983). This structural situation resulted, from a topographical point of view, in the appearance of the Tamlouka plain and the Ain Makhlouf hill system. The hydrogeological overview shows that the Mio-Plio-Quaternary formations contain the superficial aquifer with reduced potential and excessive salinity (Gueroui *et al.*, 2015. In some places, the fissured (or karstified) formations exibit very good aquifer potential (Hemila *et al.*, 2002). This is the case of the Upper Jurassic limestones and dolomites, the Barremo-Albian sandstones and limestones and the Turonian, Maestrichtian and Eocene limestones. Water discharges exceeding 30 l/s are observed in the wells reaching these formations (Djidel *et al*, 1992. These formations are drained by several cold water springs such as Ain Djenane, Ain Kabrit and Ain Arbi that emerge in areas with low elevation along the rivers banks and fault crossings.

At the eastern extension of the Ain Makhlouf sector, the Miocene conglomeratic, Quaternary travertines and Quaternary limestone horizons form, locally, good ground water reservoirs that feed springs discharging at up to 10 l/s (Sebbagh *et al.*, 2014). The SW-NE sub-atlasic deep fault system conditioned the formation of Triassic diapirs and the emergence of thermo-mineral springs (Dib-Adjoul, 1985; Issaadi, 1992). It is also responsible for the limestone formations cutting into large panels, some of which remain on the surface and serve as infiltration zones, the others subside to constitute the zones of accumulation circulation for thermo-mineral waters (Fig. 2).

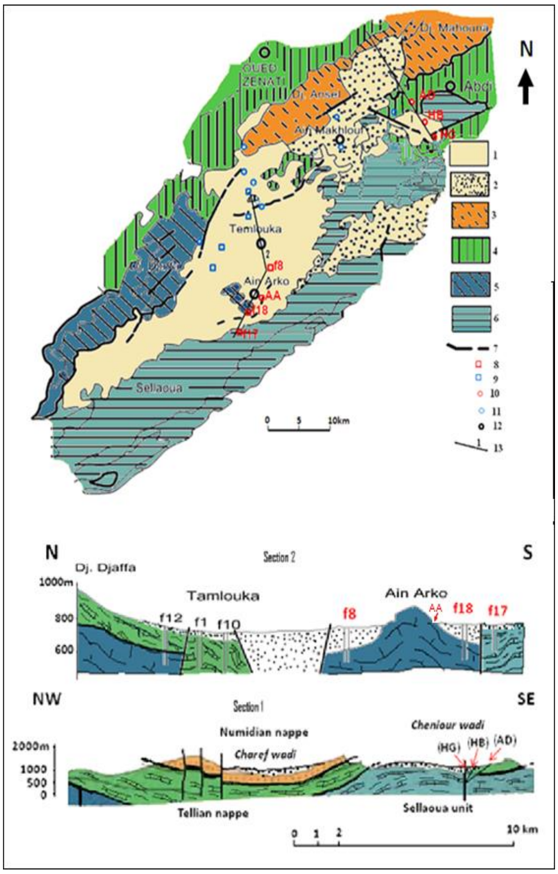

Fig. 2. Geological map and section of the study area. Key: 1- Quaternary (alluvial formations); 2-Mio-Pliocene (alluvial formations); 3-Numidian thrust sheet; Oligocene (clay and sandstone); 4-Lutetian-Aptian Tellian thrust sheet (marl and limestone); 5-Miocene-Aptian Sellaoua units (marl and limestone); 6-Upper Senonian–Upper Jurassic Neritic thrust sheet (limestone); 7-Fault and abnormal contact; 8-Hot water well; 9- Cold water well; 10-Hot spring; 11-Cold spring; 12- City; 13-geological section.

Definition of concentrations of chemical elements

Sampling strategy

The chemical composition of thermal water reflects the processes and mechanisms it was subjected to (Castany G. 1967). Water moves through the hydrothermal circuits and leaches the host-rocks resulting in an increase in the total concentration of dissolved salts and the variations in the characteristic ratios that provide information on the origin of the waters, the ground water movement paths, the influence of litho-structural conditions and possible mixtures with superficial cold waters.

To address these issues, water samples from eight points (three wells and five springs) are chemically analyzed. The F8 well, located about 3km north-east of the Ain Arko village, is a 300 m deep well that crosses a column of the 200 m thick neritic fissured crystalline limestone. The operating flow rate is 30.2l/s and the water temperature is 36°C.

The F18 well, located 700m from the Ain Arko village, is 300m deep. The well is screened at depths between 120 and 300m. The operating flow rate is 20l/s and the water temperature is 30°C. The aquifer formations are represented by the Djebel Djaffa fissured Jurassic limestones.

The F17 well, located 2km southwest of the Ain Arko village, is 300 m deep. It is screened from 110 m to 300 m. The flow rate is 20l/s and the water temperature is 31.5°C. The aquifer formations are represented by the constantinois Jurassic neritic fissured limestones. The four springs are divided into 3 groups. The first group includes GH and GL springs forming the Hammam Guerfa griffins, the second group is represented by the Hammam Belhachani (HB) emergence and the third one corresponds to the Ain Debba (AD) spring.

The samples were taken using three acid-washed polypropylene bottles (Rodier, 2009). Each sample was immediately filtered at the site using 0.45 µm cellulose acetate filters. The filtrate for trace elements and cations analyzes was stored in polyethylene 250cc flasks and immediately acidified to pH<2 by adding Merck TM ultra-pure nitric acid.

Water samples for anion analysis have not been acidified. All samples were stored in a cooler at a temperature below 4°C and transferred to the laboratory and kept in a refrigerator at the same temperature for less than a week. The water temperature (T), the pH, the electrical conductivity (CE) and the dissolved oxygen were measured in the field using a multi-parameter WTW (P3 Multi Line pH/LFSET) and an Oximeter (WTW) with a probe (CellOx 325).

Water chemicals analysis was carried out according to two methods: the atomic absorption with flame (Perkin-Elmer 1100) for the dosage of major cations and spectrophotometer Photolab Spektral brand WTW for the analysis of anions and trace elements. Water analysis results are reported in Table 1.

Table1. Concentration of major elements and silica (mg/L).

Site.	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	Cl^{-}	SO_4^{2-}	HCO_3^{-}	T°C	pH	CE (µS/cm)	SiO_2
F8	288	73	155	12	239	280	439.2	36	8.7	1300	27
F18	255	72	144	9.8	144	284.16	790	30.6	7.65	1220	25
F17	256	72	144	10	222.3	284	390	31.5	7.5	1231	26
HB	326.7	109	109	14	198	873	420.9	56	8.5	2280	40
GL	500	100	120	30	185	1150	501.4	58.1	7.8	2320	44
GH	463.2	102	105.7	32	160.9	1032.5	511.79	46	7.8	2380	37
AD	310.5	96	110	29	169.7	750	481.3	30	7.5	2286	32

Results and discussion

Geochemistry

The thermal waters emerge with temperatures ranging between 30°C in Ain Arko, Southwest and 72°C in Hammam Belhachani in the Northeast. According to Schoeller's classification, they belong to the meso and hyperthermal classes (Djorfi, 1988). The pH varies between 7 and 8.7 and the electrical conductivity, which is proportional to water salinity, ranges from 1200 to 2400µS/cm. The acquisition of such a relatively weak salinity shows that the water moves mostly in non-saliferous soils through a probable fault system affecting the carbonate formations. The Schoeller-Berkall off diagram (Fig. 3) shows that the waters of the region have two different chemical facies. The first, in the Northeast, is the SO_4-Ca type (HB, HG, GH, AD), the second, in the Southwest, is the HCO_3-Ca type (F8, F17, F18). These facies express water movement in carbonate host rocks in contact with salt soils.

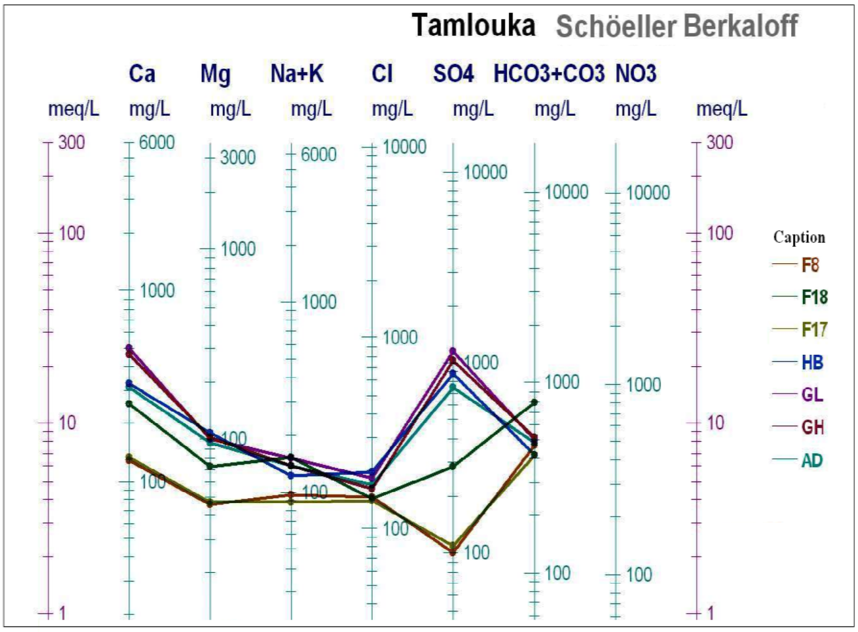

Fig. 3. Schoeller-Berkaloff diagram applied to thermal waters of Tamlouka basin.

The IIRG method (International Institute for Geothermal Research) developed by D'Amore *et al.* (1983), is the most appropriate tool for determining the lithological nature of the reservoir of thermal waters. The principle of this method is based on the use of the ratios of the major elements concentrations to the sum of cations (Σ (+)) and anions (Σ (-)), expressed in meq/l. Six dimensionless parameters (A,B,C,D,E and F) are thus defined and standardized between -100 and +100 as follows:

$$A = 100x\frac{(HCO_3 - SO_4)}{\Sigma(-)}$$

This parameter helps distinguish waters moving through calcareous soils from those crossing evaporite layers.

$$B = 100\,x\left[\frac{SO_4}{\Sigma(-)} - \frac{Na}{\Sigma(+)}\right]$$

Parameter B allows to discriminate between sulphate-rich waters moving in evaporitic soils and sodium-rich waters encountered in sedimentary marly clay soils

$$C = 100\,x\left[\frac{Na}{\Sigma(+)} + \frac{Mg}{\Sigma(-)}\right]$$

The parameter C tends to distinguish between flyschs or volcanic rocks derived water and those coming from evaporitic carbonate series or from a schisto-quartzitic basement. Both types of water have high sodium (Na +) levels however, the former has a very low chloride (Cl^-) content while the latter is characterized by a Na/Cl ratio close to 1.

$$D = 100\,x\left[\frac{Na - Mg}{\Sigma(+)}\right]$$

This parameter individualizes waters circulating in dolomitic limestones.

$$E = 100\,x\left[\frac{(Ca + Mg)}{\Sigma(+)} - \frac{HCO_3}{\Sigma(-)}\right]$$

Parameter E mainly distinguishes circulations in carbonate reservoirs from those in sulphated reservoirs.

$$F = 100\,x\left[\frac{Ca - Na - K}{\Sigma(+)}\right]$$

Parameter F reveals the potassium (K^+) content increase in the water samples.

The values make it possible to establish rectangular diagrams to be compared to reference diagrams (α, β, γ and δ) established by the authors (Fig. 4). Applied to hot waters in the Tamlouka region (Fig. 5), this method shows two intermediary different rectangular configurations between the theoretical standards of reference.

- In the Southwest, the Ain Arko region is much more adapted to the limestone formations "β" standard reference; however it is marked by the parameters "C", "E" and "F". These parameters show that there is a circulation in a sodium rich carbonated reservoir due to terrigenous salt formations during the rise towards the surface.
- In the Northwest, the Chenniour Wadi region is much more adapted to the "α" standard reference than to the others. Such a standard is characteristic of evaporitic series. Parameter C, being very significant, shows a circulation in an evaporates-rich carbonated reservoir.

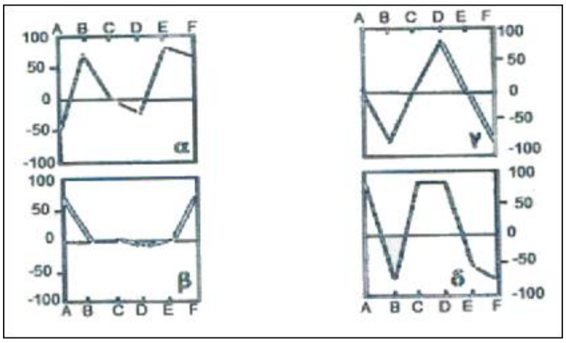

Fig. 4. IIGR reference diagram (α: evaporative sequence; β: circulation in limestone; γ: deep circulation through a crystalline basement; δ: clayey formation).

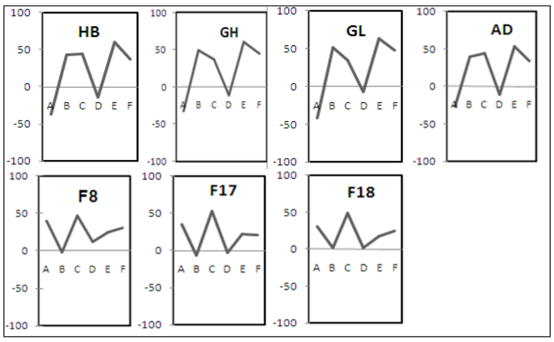

Fig. 5. IIRG diagram applied to the thermal waters of the Tamlouka basin.

The application of the IIRG diagrams makes it possible to conclude that the hot solutions have been moving in deep crystallophyllian bedrock and in carbonate formations linked, in some places, to saline terrigenous soils. This is the case of points HB, GL, GH and AD.

Moreover, the Langelier-Ludwing diagram (1942) shows the influence of salt soils on the chemistry of thermal waters of the region (Fig. 6). Thus, the increase in the sodium and potassium concentration occurs simultaneously as chloride and sulphate concentration (Fig. 6A), but in an inverse manner with that of the carbonate elements (Fig. 6B).

This trend is likely due, locally, to a Na-Ca base exchange with the clays that are deeply driven by thermal disharmony affecting the region. A similar case has been reported by Boudoukha *et al.* (2012) in the Setifian Southern Domain.

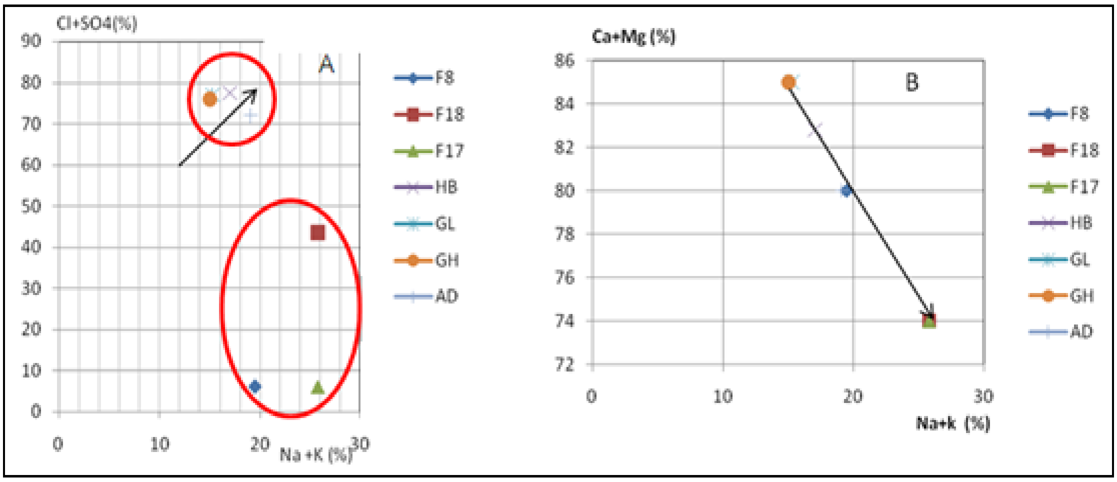

Fig. 6. Langelier-Ludwing diagrams applied to the thermal waters of the Tamlouka basin.
(A: [Cl + SO_4]vs[Na + K] relationship; B: [Ca + Mg]vs[Na + K] relationship)

The acquisition of Cl^- and Na^+ contents in groundwater is likely due to halite dissolution or a mixture with seawater. The second hypothesis is discarded as the study area is located a 100 km away from the Mediterranean Sea. On the other hand, the presence of the Tamlouka Sebkha (or salt lakes) could justify the presence of such high levels.

It is known that chloride is a highly mobile chemical species that weakly interacts with the host rock and that forms a part of the so-called conservative elements that are frequently used as tracers for hydrological cycle studies (Boudoukha *et al*, 2012). Analytical points of the Tamlouka region thermal springs, reported on a Na^+/Cl^- diagram, show a good distribution (R = 0.99) around a straight line with a slightly lower slope than that of the halite (Fig. 7). In other words, the average Na/Cl molar ratio of these samples is similar to that of halite whose ratio is 1.0. As a result, this approach tends to indicate that the thermal water salinity originates from the dissolution of salt formations.

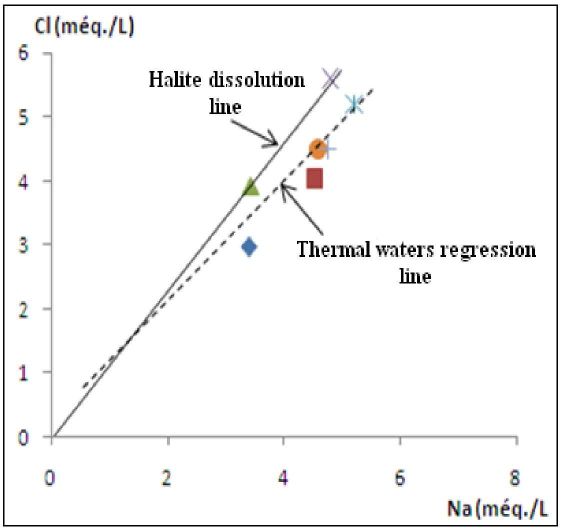

Fig. 7. Na-Cl relationship in the Tamlouka basin thermal waters.

On the other hand, good agreement between sulphate-calcium (r=0.98) and C.E - $HCO_3/(Cl+SO_4)$ supports this hypothesis (Figs. 8 and 9). The presence of sulphates in large quantities in thermal spring waters (3 to 24meq/L) could also be attributed to the anhydrite or pyrite dissolution of according to the formula proposed by Appelo and Postma (1993):

$FeS_2 + 4{,}75\ O_2 + 1{,}5\ H_2O + 4e^- \leftrightarrow Fe(OH)_3 + 2\ SO_4^{2-}$

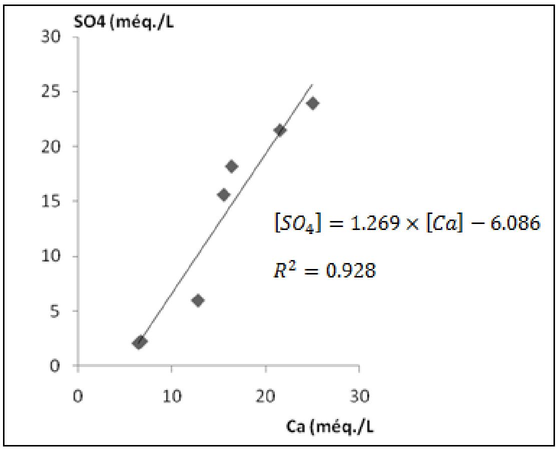

Fig. 8. Ca-SO_4 relationship in the Tamlouka basin thermal waters.

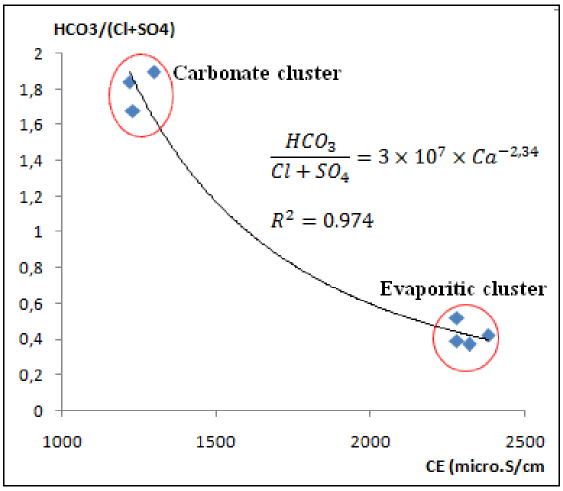

Fig. 9. Electrical conductivity and $HCO_3/(Cl+SO_4)$ relationship of the Tamlouka basin thermal waters.

It is clear that thermal waters acquire their chemical composition in depth by interaction with the carbonate rocks that are in contact with saline terrigenous sediments. This mechanism was also studied using the saturation index (IS) of some evaporitic minerals (halite, anhydrite, gypsum), carbonates (aragonite, calcite, dolomite), silica and dissolved CO_2. This simulation has been established using the Phreeqc program (Parkhurst *et al.*, 1980). The saturation indices (Table 2) show that the evaporitic minerals are undersaturated (IS<0), indicating a contact time long enough to allow their dissolution that is accelerated by the temperature of the hydrothermal fluid. The positive saturation index values of carbonate minerals indicate that the water has undergone significant changes due to CO_2 depletion (IS<0). According to Djidi *et al.* (2008), the gas depletion generally occurs during the karstic aquifers recharge or it is due to water temperature rise that generates the calcite precipitation. The second hypothesis would indicate that the contact time with the minerals is rather short.

Geothermometry

Geothermometry is a tool for estimating the geothermal reservoir depth and the temperature of last chemical or isotopic equilibrium before emergence. Usually, deep waters and gases come to the surface with their geochemical history. However, during the upward movement, hot water may be mixed with superficial cold waters that may complicate the use of chemical geothermometers leading to either overestimation or underestimation of temperatures (Lahlou *et al*, 1998). It must be noted that the upward movement of thermal waters from their original reservoirs is usually accompanied by a decrease in temperature and a change in total mineralization. According to Bouri *et al.* (2007), the use of geothermometers assumes that there is no significant chemical change in the water during the upward movement despite the various possible and often remarkable cooling. To estimate the temperature of the last thermodynamic equilibrium, the silica (quartz) geothermometer was applied which is best adapted to the Tamlouka region thermal waters. Water temperatures, originally estimated, range from 79°C in the Southwest to 100.9°C in the Northeast (Table 3). The last value, being much higher than the measured temperatures, shows an average dissipation of 40°C during the upward water movement from the reservoir to the ground surface. Such dissipation could be due to a mixture with the surface waters or to a thermal diffusion linked to the long flow path to reach the surface.

Table 2. Stability indices of the Tamlouka basin thermal waters.

Sample	Halite	Anhydrie	Gypsum	SiO_2	Calcite	Aragonite	Dolomite	CO_2 (gas)
F8	-6.53	-1.74	-1.58	-0.77	1.85	1.72	3.74	-3.13
F18	-6.34	-1.16	-0.96	-0.71	1.33	1.19	2.52	-1.79
F17	-6.58	-1.68	-1.49	-0.70	0.72	0.58	1.40	-1.91
HB	-6.39	-0.52	-0.51	-0.75	2.04	1.91	4.07	-2.91
GL	-6.40	-0.26	-0.26	-0.67	1.72	1.60	3.19	-2.00
GH	-6.48	-0.42	-0.32	-0.66	1.60	1.47	2.99	-2.06
AD	-6.39	-0.73	-0.53	-0.60	0.98	0.84	1.84	-1.86

Table 3. Aquifer depth-Thermal water temperature relationship in the Tamlouka basin.

Samples	Geothermometer	Depth Temp. (°C)	Water T (°C) at emergence	Air T (°C)	Aquifer depth (m)
F8	SiO_2	79.16	36	17.3	2173.1
F18	SiO_2	76.73	30.6	17.3	2098
F17	SiO_2	78.35	31.5	17.3	2154.75
HB	SiO_2	100.9	56	17.3	2944
AD	SiO_2	63.6	30	17.3	1638
GH	SiO_2	89.29	46	17.3	2537

Operating model

The Tamlouka basin formations present a varied lithology (limestone, dolomite, marly limestone and sandstone) that is related to the tectonic units forming the side massifs. The last ones are potential areas for deep water recharge. In the Southwest, the dolomitic limestones of Dj. Djaffa constitute the zone of excellence for aquifers recharge. Well discharge rates (whose water temperature exceeds 30°C) are about 40 l/s. In the Northwest, the contribution of Dj. Maida and Mahouna massifs is reduced due to a complicated lithology by clay and marly layers. At this level, the thermal springs emergence is due to deep faults in relation to hydrothermal circuits (Fig.10).

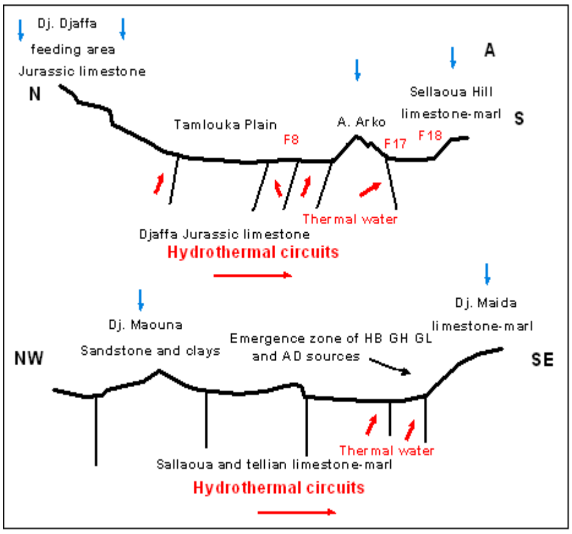

Fig. 10. Conceptual model of the the Tamlouka basin thermal waters.

Conclusion

The methodology adopted showed that the Tamlouka-Ain Makhlouf basin carbonate massifs present a horstand graben structure that is bordered by large faults that would facilitate communication between the different reservoirs and the transmission of deep thermal waters to the surface. This geothermal reservoir is located in the Jurassic carbonate formations 1600 and 3000m deep where the waters acquire their original carbonate mineralization. Furthermore, these waters contain more soluble chlorides, sodium and sulphate salts due to contact with terrigenous salt formations and base exchange with clays. During the upward movement, thermal waters cross permeable terrains and define, in the Northeast and the Southwest, the Chenniour Wadi and the Ain Arko thermal zones, respectively. These waters are characterized by different chemical facies: the SO_4-HCO_3-Ca type to the Northeast and the HCO_3-SO_4-Ca type in the Southwest. The significant levels of trace and ore elements reflecta deep circulation through the hydrothermal circuits.

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