Thermo-mineral waters of Hammam Meskoutine (north-east Algeria): Composition and origin of mineralization

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Abstract

The extreme north-eastern Algeria, in particular the Guelma city conceals thermal springs, whose waters circulating at great depths allow the rain-waters to warm up (according to the average geothermal gradient of 1°C per 33 m) and to acquire a mineralization which depends on the traversed rock. The goal of this research work was to determine mineralization origin of the thermo-mineral waters of Hammam Meskoutine (Algerian N-E). A hydro-chemical study involved analyses of a number of physical and chemical parameters of waters such as: temperature, hydrogen potential, electrolytical conductivity, Cl^-, SO_4^{2-}, HCO_3^-, Ca^{2+}, Mg^{2+}, K^+ and Na^+. The data processing on the diagram revealed two dominating chemical facies: sulphate-magnesium and bicarbonate magnesium. With a high conductivity in excess of 2300 μS·cm⁻¹, the temperature reaches 97°C. Calculation of the saturation index shows that the waters are supersaturated in carbonate minerals (calcite, dolomite and aragonite) and less saturated with evaporite minerals (halite, anhydrite, sylvite and gypsum). The reconstitution in dissolved salts reveals a dominant salt rich in calcium bicarbonates, in calcium sulphates and secondarily in magnesium salts. Geological sections used in the study zone affirm that the chemical composition of the spring waters comes from the neritic limestone dissolution and the gypso-saline complex of Hammam Meskoutine.

Key words: *chemical facies, Hammam Meskoutine, mineralization, north-east Algeria, thermo-mineral springs*

INTRODUCTION

There are over 200 thermal springs on the Algerian territory, the majority of which are located in the country North-East. The thermal water's presence is a phenomenon associated to the stratigraphic conditions and structural of its come out [VERDEIL 1982]. The circulation of thermo-mineral water in hydrothermal systems is associated to tectonic activity; they penetrate deeply the main structures. Some minerals dissolution of limestone is due to the high temperature of the water initially coming from the surface with the superheated water vapors influency [POVARA *et al.* 2008]. The waters mineralization is determined predominatingly by the chemical and mineralogical nature of the sediments that they move through. It comes direct and quickly at great depths, whose the chemical composition reflects that of the reservoir formations, which accept successive modifications characterizing the various aquifer formations travelled

[RIMI 2001]. The put in solution is as a function of the temperature, pressure and a lesser measure of the water circulation speed in the dissolution zones.

Thus, according to GUIGUE [1947], the thermal springs which are the most mineralized are in direct relation with the gypso-saline sediments of Trias so widespread in Algeria. The Guelma region is an unavoidable regional pole in thermalism terms with the thermo-mineral springs of Hammam Meskoutine.

MATERIAL AND METHODS

STUDY SITE

Hammam Meskoutine is situated South of the Guelma city extend an area of 76, 45 km^2, the zone sector is limited between latitudes from 36°36'0" to 36°27'0" N and longitudes from 7°12'0" to 7°24'0" E (Fig. 1). From a climatic point of view, the region is exposed to a semi-arid climate, with a precipitation ranging between 500 and 600 mm·year^{-1}. Larg part of this rains participate to the evapotranspiration phenomenon with a rainfall of 511 mm·year^{-1}. The annual average temperature is about 18.5°C.

SITE GEOLOGY

The study region (Fig. 2) belongs to the epi-Tellian aquifers which result of a thrust towards the south of the Djebel Debagh chain of the Grar and
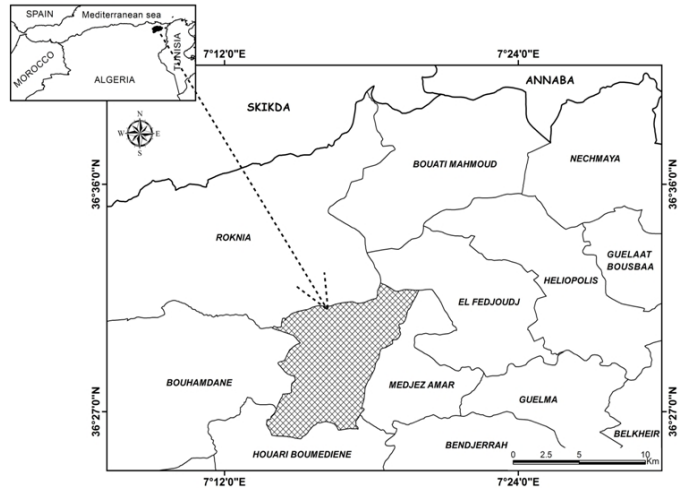

Fig. 1. Geographical situation of the study area; source: own elaboration

Kef-Hahouner, where outcrop a formed substratum of Cretaceous limestones, on which are flowing past the Tellian aquifers, consisting of black or gray marls intercalated by calcareous banks (limestone) belonging to the Cretaceous and the Tertiary. Another aquifer known by the Cretaceous Flysch generally covers the Tellian aquifers, made up of black Schists, powerful de sandstone banks and locally Pudding-stones. The depression which forms the aquifer of the Guelma valley is filled by the Plio-Quaternary alluviums. This filling constitutes the old and the current terrace of the Seybouse valley.
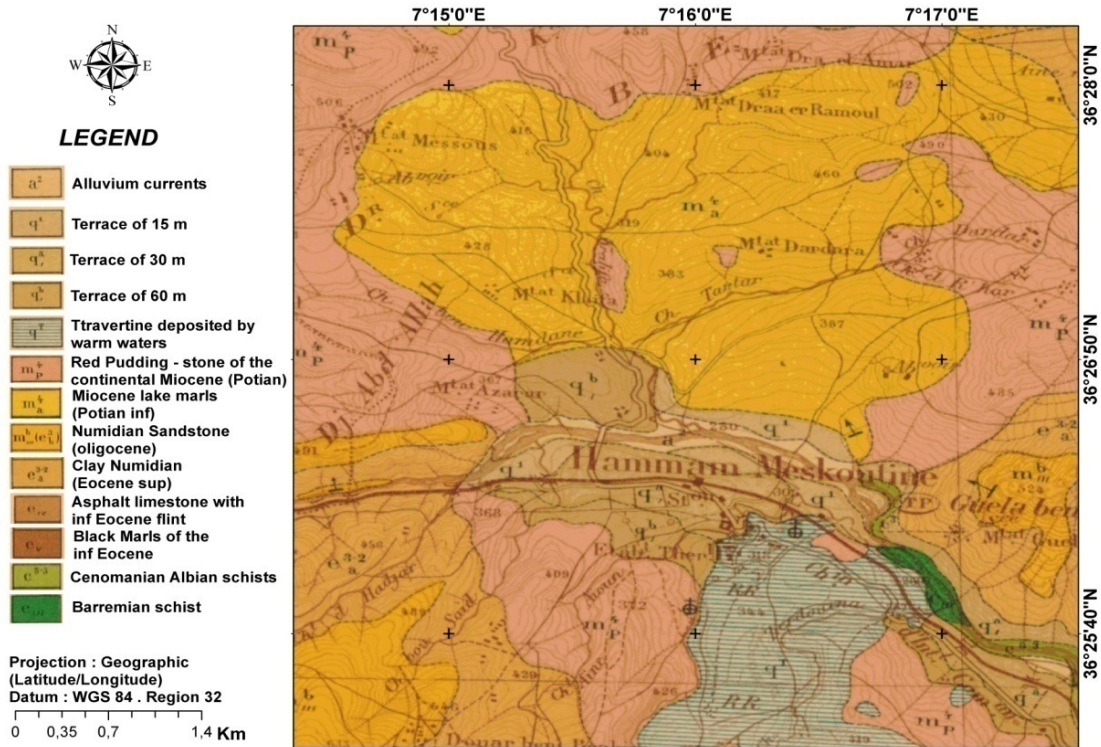

Fig. 2. Geological map of the study area; source: DELEAU [1938]

TECTONICS AND HYDROGEOLOGY OF THE STUDY AREA

The tectonic movements take three phases as follows: (i) the Siliceous levels: they are very mineralized and poorly stratified rocks resulting from silicification at the level of a grinding zone between the flint limestone from the summit of the upper Senonian and the flint limestones of the Teleno allochthonous Eocene, (ii) the massive limestones attributed to the Campanian, (iii) black dolomites thick from 250 to 300 m completely crystalline which support the whole series. The Guelma basin has experienced several filling cycles related to regional tectonics. We point out that the thermo-mineral sources are located at the intersection of the direction folds (NE-SW). In the first direction, it is the tectonics of the aquifer, in the second orientation (N-S), it is the tectonics of readjustment of the edifice and the birth of the current relief. The hydrogeology of the study area contains wide quantities of water in the southern parts that presented by thermo-mineral sources and also with an underground lake. Most of these sources are located in a travertine geological pattern in the southeastern part of the study area. At the centre of the North-West region, we find a big quantity of water included the numidian clay sheets.

THE GEOCHEMISTRY OF THE AQUIFER

The carbonate formation leads to the predominance of bicarbonates of magnesium and calcium. The excess of calcium and magnesium reminds one of a limestone reservoir $(HCO_3)_2Ca$ and sometimes dolomitic limestone $(HCO_3)_2Ca$, $(HCO_3)_2Mg$, note that, there is a chemical influence on the waters composition caused by the physicochemical characteristics of the aquifer rock.

The waters are meteoric cold at the level of the impluvium and more or less warm at the depth and also when they reach the surface. Depending on the depth of circulation (a few hundred meters or more than 1 km), the water will be more or less heated (Fig. 3).

FLUCTUATING FACTORS OF GROUNDWATER IN THE STUDY AREA

The dolomites and the cracked limestones, have alveoli and several dissolving basins. At present, the hydrostatic level is very low and only the source which appears at the down the mountain of Taya. Its flow diminishes in summer. The marls of the Cretaceous and the Lutitian, when they support a few calcareous beds, retain aquiferous horizons, but give only a small spring which dry up in summer, especially in the Cretaceous. The marl-limestone matstrichtians provides regular sources. The aquifer level by the excellence of the region, and in the lattorfian sandstones, still gives only sources of a low flow but constant. The most important are on the mountain of the southern Mourmoura. Any way to obtain these sources, still always difficult because the underlying Numidian clays carry away the aquifer sandstones and losse the water. The fluvio-continental alluvial of the upper Miocene, clumping on the marls, gives a form of an aquifer level feeding some springs north of Hammam Meskoutine. The flow of these thermo-mineral sources is not less than 500 $dm^3 \cdot s^{-1}$. Their temperatures reach 98°C. They are distributed according to their situation into two main groups: the sources of Wadi Chadakha, and the sources of the great waterfall.

SAMPLING AND ANALYTICAL TECHNIQUES

Two sampling campaigns were carried out during the year 2016 (low and high waters). It has covered ten (10) hot springs in the Hammam Meskoutine region (Fig. 4). The water collected was conserved in polyethylene bottles previously washed with distilled water and then rinsed with the water to be analyzed.

Precipitations

Infiltration

- ▧ Miocene Red Pudding -Stone
- ▦ Eocene sup Clay Numidien
- ▩ Aptian Limestone massif
- ⚲ Spring (S1.S2)
- ╱ Fault
- ┄ Drainage network
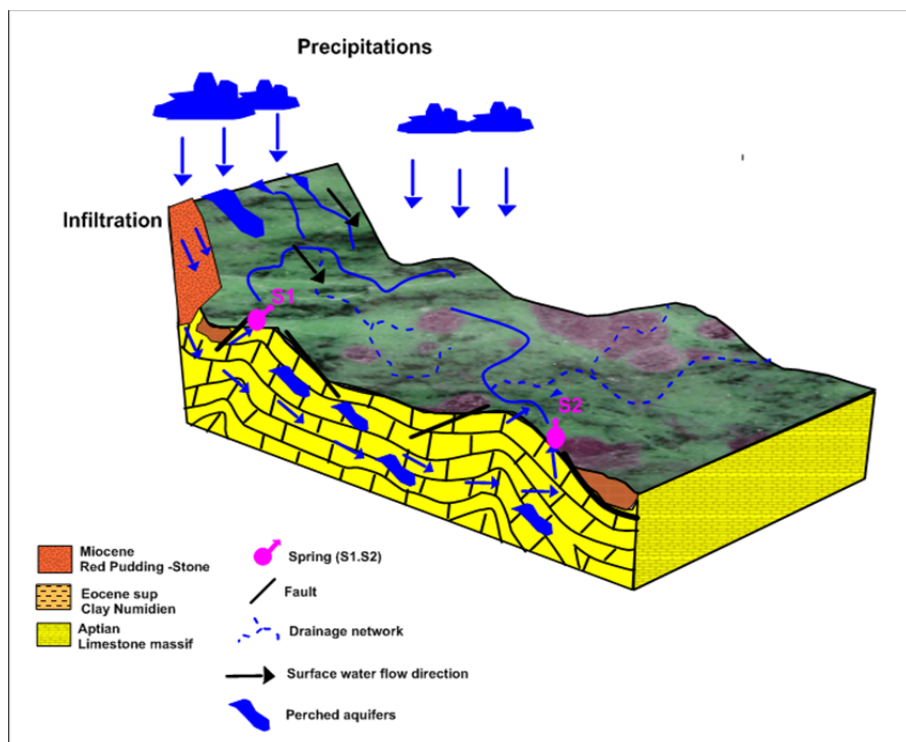- → Surface water flow direction
- ▰ Perched aquifers

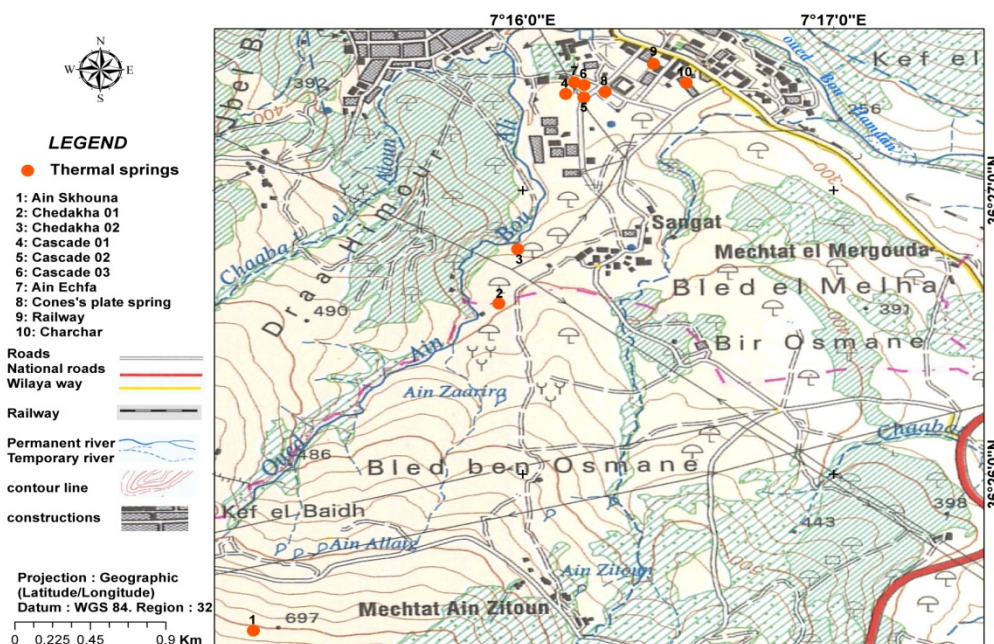Fig. 3. Conceptual model; source: own study

Fig. 4. Sampling point's location; source: own elaboration based on the map of Algeria
published by the INCT [1996]

PHYSICO-CHEMICAL ANALYSES METHODS

The geochemical characterization is carried on the measurement, in situ the physical parameters of the water using a multi parameter of the Consort type C 65. These parameters have concerned the temperature, pH and electrical conductivity (*EC*). Some parameters risk the salts precipitation; we have deemed it useful to measure on the ground the bicarbonates (HCO_3^-). By a multi parameter the content determination of the chemical elements as (Cl^-, Ca^{2+}, Mg^{2+}) has been effected by titrimetry (volumetry), (SO_4^{2-}) by spectrometry (HACH-ODYSSEY Tayland spectrophotometer) at the Laboratory of Algerian Waters situated in Skikda city and (Na^+ and K^+) by flame spectrophotometry.

The coordinates of the various water points were taken using a Global Positioning System (GPS) type Garmin wap (62 stc 79946) (Tab. 1).

The obtained data have been processed by the use of software such as Microsoft Office Excel which allows more to visualize a numerical data by graph-

ical representations. From hydro-chemical view point, the waters chemical classification method per Piper based on a datas graphical representation was used. Another datas graphical representation (inspired by Collins's graphs) allows us to reconstruct the dissolved salts that were at the origin of the waters mineralization. From a thermodynamic view point, the PHREEQC functions (software developed by Parkhurst and Appelo 1999 of United States Geological Survey (USGS – version 2.15) have studied the waters equilibrium state (mineral phases's saturation index) and put in equilibre of an aqueous phase with a solid phase or a gas (water-rock interaction).

The Hammam Meskoutine geological map at (1: 50 000 scale) has been used to confirm the dissolved salts origin in the study area.

RESULTS AND DISCUSSIONS

PHYSICAL PARAMETERS STUDY

– The temperature (T°C): The griffons's waters temperature values oscillate ranges from 41 to 96°C (low water) and (39–94°C) to high water. It is noted that all temperatures are upper than the air's annual average temperature. That explains a thermalism of low enthalpy [ARNÓRSSON 2000].

– The potential of hydrogen [pH]: the whole of the water points have pH values that vary between (6.74 and 7.58 low water) and between (6.01–7.51 in high water). The water springs with pH < 7 indicate that water has a brief contact with the rocks [BERKANI *et al.* 2016].

– Concerning the conductivity, the recorded values oscillate between (733–2200 µS·cm^{-2} in low water levels) and (810–2360 µS·cm^{-2} in high water) far ex-

Table 1. The geographic coordinates of the sampling points

Points	Name	X	Y	Z, m
1	Ain Skhouna spring (S1)	7°15'8.0401"	36°25'36.3168"	561
2	Shdakha 01 spring (S2)	7°15'55.4082"	36°26'45.4809"	331
3	Shdakha 02 spring (S3)	7°15'59.0487"	36°26'56.9568"	313
4	Cascade 01 spring (S4)	7°16'8.3560"	36°27'28.1806"	290
5	Cascade 02 spring (S5)	7°16'11.7907"	36°27'29.0742"	304
6	Cascade 03 spring (S6)	7°16'11.8528"	36°27'31.7037"	299
7	Ain Ashfa spring (S7)	7°16'9.9926"	36°27'32.2608"	294
8	Cones's Plate spring (S8)	7°16'15.9024"	36°27'30.2371"	302
9	Railway spring (S9)	7°16'25.2107"	36°27'36.1808"	272
10	Sharshar spring (S10)	7°16'31.5265"	36°27'32.1507"	278

Source: own study.

ceeding the values of non-thermo-minera's natural waters.

THE CHEMICAL PARAMETERS

Calcium [Ca^{2+}] is bound either to the dissolution of the gypseous formations $CaSO_4$, or to the dissolution of carbonate formations $CaCO_3$. The calcium content varies essentially according to the nature of the terrain traversed. We note that the highest concentration is recorded at the spring S5 (260 mg·dm^{-3} low water) and 255 mg·dm^{-3} at the spring S4 in high water (Tab. 2).

Magnesium [Mg^{2+}] present in water, the magnesium accompanies calcium, which lets suggest that they have the same origin; it comes from soluble minerals such as the gypsum, calcite and dolomite that we find in the limestones and the travertines of the Hammam Meskoutine. The affected analyses have shown that the concentration reach its maximum in the spring S7 with an order's value of 804 mg·dm^{-3} and a weak value recorded of the spring S1 (225 mg·dm^{-3}) at low water. In high water we note that the maximum is recorded of the spring S8 with a value of 254 mg·dm^{-3} and the weak value of the spring S1 (71 mg·dm^{-3}).

Sodium [Na$^+$]. The sodium contents varying between 128 and 274 mg·dm^{-3} in low water and between 114–260 mg·dm^{-3} in high water. These parameters emerge in the deposits of the limestones-marl of the lower Eocene.

Potassium [K$^+$]. The potassium concentrations are enough weak compared to the other elements [Ca^{2+}, Mg^{2+}, Na$^+$]. The lowest value is observed in the spring S3 with a dose of 58 mg·dm^{-3} in low water and 60.89 mg·dm^{-3} at the spring S9 (high water). The maximum is 188 mg·dm^{-3} at spring S2 (low water) is of the order of 141 mg·dm^{-3} at the spring S5 in high water.

Chloride [Cl$^-$]. The main source of chloride in the waters is due to the sedimentary rocks dissolution that are deposited them self in the marine environment and that have not been completely leached, and moreover at the evaporites presence. The chloride contents are generally weaks ranging from 92 to 170 mg·dm^{-3} in low water and between 35.5 and 177.5 mg·dm^{-3} in high water.

Sulphates [SO$_4^{2-}$] probably originate from the marly and gypseous formations of the lower eocene, the maximum is observed in the spring S9 with a value of 600 mg·dm^{-3} concentrated in the high terraces in low water and 280 mg·dm^{-3} for the spring S5 in the high water. The minimum is observed in the spring S1 with a value of (165.21 mg·dm^{-3} low water) and an order's value of (190 mg·dm^{-3} at the spring S1 high water).

Bicarbonates [HCO$_3^-$] in general manner, the HCO_3^- concentrations are important compared to the other anions for the majority of the analyzed waters. The highest concentration is of (900 mg·dm^{-3} low water), it is observed at the spring S7 and with the order of 440 mg·dm^{-3} at the spring S9 (high water). It emerges in travertine formations deposited by warm waters.

The major cations presenting the following order of abundance: Mg^{2+} > Ca^{2+} > Na$^+$ > K$^+$ in low flow, maintain the same abundance order during the flood period. However, we note an increase in the flood period of the content of major cations except the calcium and potassium. The most abundant anions in low water by chronological order of average concentrations are the bicarbonates followed by the sulphates and chlorides finally. In the flood period SO$_4^{2-}$ > HCO$_3^-$ > Cl$^-$.

These variations in period-flood concentrations can be imputed to the leaching of the calcareo--dolomitic soils which are responsible for the contents increasing in magnesium, the bicarbonate and sulphate, while the clays contribute to the increase in sodium content. The concentrations variability of the various parameters is relatively much weaker from one source to other, but it is very clear at the anions scale between the two companions, they are between 3 and 40% for chlorides and from 9 to 34% for sulphates (Fig. 5).
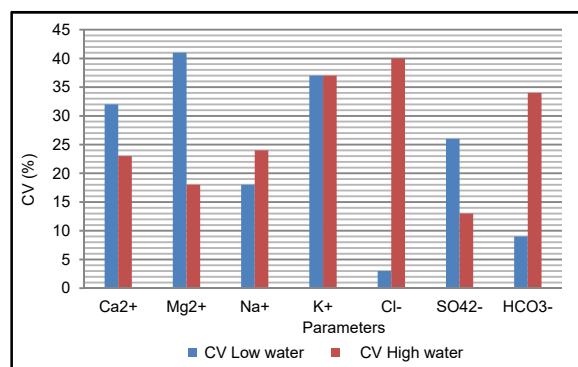
Fig. 5. Variation coefficient (*CV*) of the major elements of the Hammam Meskoutine springs; source: own study

CHEMICAL FACIES

The Hammam Meskoutine waters have a chemical composition closely related to the soils that contain them, in order to determine the water springs origin, the chemical analyzes results of these waters have been reported in the Piper's diagram (Fig. 6) Which has allowed us to deduce that thermo-mineral waters whatever the period (low or high) the waters facies are almost identical. Therefore the facies of the source waters is of the chlorinated type and calcic sulphated and magnesian type.

To determine the chemical facies of each thermal spring, we have used the Schöller Berkaloff diagram (Fig. 7). And the existance of following facies have been revealed.

Calco-magnesian bicarbonated and magnesian sulphate which are probably due to the calcareo--dolomitic soils dissolution and the leaching of evaporite formations (Fig. 8).
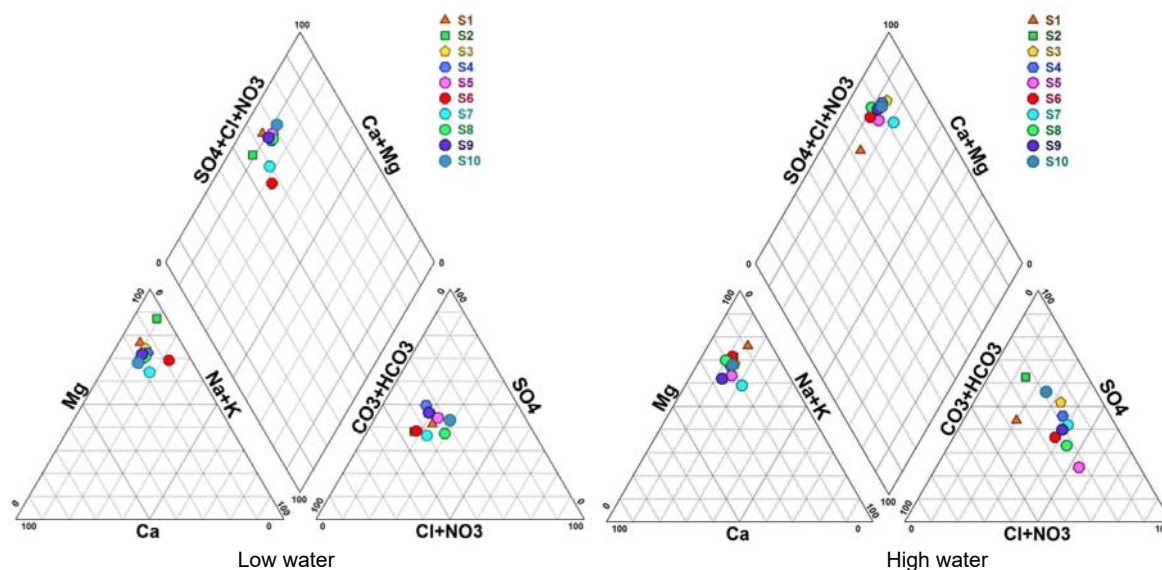
Low water

High water

Fig. 6. Piper's diagram of the Hammam Meskoutine's thermo-mineral waters; source: own study
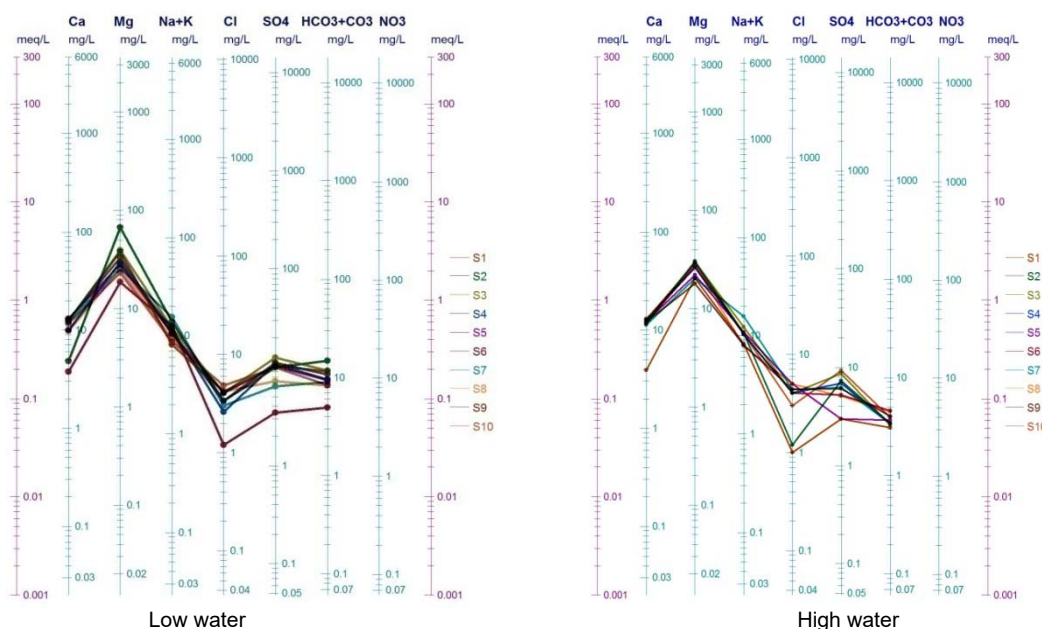

Low water

High water

Fig. 7. Schöller Berkaloff's diagram of the Hammam Meskoutine's thermomineral waters; source: own study

Table 2. Results of the physicochemical analyzes appropriate to the Hammam Meskoutine's thermo-mineral waters of year 2016 (low and high waters)

Spring name (source)	Parameters									
	T °C	pH	EC µS·cm^{-1}	Ca^{2+}	Mg^{2+}	Na$^+$	K$^+$	Cl$^-$	HCO$^-_3$	SO$_4^{2-}$
				mg·dm^{-3}						
1	2	3	4	5	6	7	8	9	10	11
Low water										
S1	41	7.08	733	75	225	231.95	97.38	42.6	300	165.21
S2	73	6.75	1992	240	310	249.32	188.76	106.5	550	307.27
S3	96	6.77	2200	194	306	184.00	58.11	149.1	500	348.01
S4	94	6.80	1754	248	452	142.99	78.22	149.1	700	500.00
S5	95	7.01	1982	255	395	195.73	78.00	120.5	650	540.00
S6	95	7.58	1850	230	280	128.70	125.30	170.3	510	475.00
S7	92	7.00	1691	96	804	273.56	79.39	120.7	900	480.00
S8	92	6.96	1965	260	340	165.52	135.31	142.0	600	490.00
S9	83	7.23	1982	250	470	231.95	82.13	142.0	720	600.00
S10	68	6.74	1980	220	360	193.10	125.15	92.3	580	520.00

cont. Tab. 2

1	2	3	4	5	6	7	8	9	10	11
High water										
S1	39	6.95	810	78	71.05	151.00	65.92	35.5	190	143.00
S2	72	7.51	2120	236	228.49	196.50	83.00	42.6	210	350.00
S3	94	6.70	2170	252	245.30	240.10	77.00	142.0	200	410.00
S4	93	6.32	2130	255	248.68	176,80	111.40	142.0	206	330.00
S5	94	7.34	2140	230	222.66	153.00	141.10	142.0	280	250.00
S6	92	6.98	2210	246	239.02	199.50	89.91	177.5	225	143.00
S7	90	6.46	2090	225	218.54	260.00	173.90	156.2	205	299.00
S8	91	6.01	2360	260	253.99	144.98	60.89	177.5	270	243.10
S9	84	6.26	2120	243	236.74	201.00	69.00	106.5	238	440.23
S10	65	6.46	1937	242	235.54	114.00	123.00	156.2	245	290.50

Source: own study.

The Hammam Meskoutine waters are thus characterized by a predominance of the bicarbonate ions on calcium ions, confirming the water interaction with a largely carbonated medium over the massif whole [BOUCHAREB-HAOUCHINE *et al* 2012]. The sulphate ions on the calcium ions, so the composition of these sources situates at the limit of the two fields (calcic sulphated waters and calcic bicarbonated).

The water saturation degree can be estimated by the saturation index calculation, which reaches the zero value when the solution is in equilibrium with a solid phase. A negative saturation index indicates a sub-saturation and a positive index shows a super-saturation towards the minerals. The thermodynamic interpretation by using the concentration simulation of major ions Cl^-, SO_4^{2-}, HCO_3^-, Ca^{2+}, Mg^{2+}, Na^+, K^+) under the effect of isothermal evaporation at 25°C by the thermodynamics software "PhreeqC" in terms of equilibrium (salts/solution) shows that the Hammam Meskoutine waters are:

– sub-saturated relative to the halite (NaCl) and sylvite (KCl) that provokes the dissolution by resulting an enrichment of the region's waters in sodium and chlorides;

– concerning gypsum ($CaSO_4·2H_2O$) and anhydrite ($CaSO_4$) the waters are supersaturated by causing precipitation in the form of gypsum and anhydrite.

The waters are supersaturated in calcite, dolomite and aragonite in all the points analysed, leading also to the carbonated elements precipitation in the form of calcite, aragonite and especially in the dolomite form (Tab. 3, Fig. 9). It is important to know the mineral saturations indexes to predict which from them can precipitate during extraction and water use [TARCAN *et al* 2000].

The dissolved salt composition illustrated in the Figs 5 and 6 shows a predominance of magnesium and calcium bicarbonates that we could attribute to the carbonated formations but with variation in secondary salts with magnesium and chlorides excess. The calcium and magnesium excess make think to a dolomitic calcareous reservoir with a strong sulphate mineralization which can prevent in the evaporites leaching, gypsum and pyrite; the sodium excess would be attributed to the leaching of the clay layers which overcome them. The chemical composition of thermo-mineral waters is particularly by interfering with the carbonated minerals which are present largely in the reservoir. Then, the dissolution of calcic carbonates and magnesians brings the water to saturation towards these minerals. However, the absence of evaporitic minerals in the aquifer reservoir, through the gypsum-saline Trias leads to sub-saturation towards of these [BOUCHAREB-HAOUCHINE *et al.* 2012].

Table 3. Saturation index of dissolved minerals in the Hammam Meskoutine's thermo-mineral waters (year 2016)

| Minerals dissolved in thermal waters		Emergencies									
		S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
Low water											
Evaporite minerals	halite	–3.79	–3.59	–3.61	–3.83	–3.75	–3.99	–3.57	–3.66	–3.76	–3.81
	anhydrite	1.61	0.99	1.55	1.37	1.64	0.39	1.24	1.48	1.68	1.63
	sylvite	–4.05	–4.08	–3.98	–3.83	–3.82	–3.89	–3.63	–4.15	–4.17	–3.80
	gypsum	1.22	0.62	1.26	1.22	1.28	0.51	1.05	1.09	1.29	1.24
Carbonated minerals	calcite	3.35	3.16	3.62	2.95	3.46	2.48	3.08	3.19	3.53	3.88
	dolomie	6.78	7.16	7.50	6.24	6.89	5.69	6.41	6.38	7.05	7.67
	aragonite	3.24	3.05	3.51	2.84	3.36	2.35	2.97	3.09	3.43	3.78
High water											
Evaporite minerals	halite	–4.24	–4.13	–3.55	–3.67	–3.73	–3.50	–3.45	–3.65	–3.75	–3.78
	anhydrite	0.55	1.43	1.74	1.64	1.46	1.22	1.52	1.48	1.66	1.29
	sylvite	–4.11	–4.32	–4.04	–3.84	–3.72	–3.79	–3.58	–3.97	–4.14	–3.50
	gypsum	0.70	1.25	1.37	1.27	1.09	0.86	1.17	1.13	1.36	1.17
Carbonated minerals	calcite	2.25	3.41	2.90	2.57	3.57	3.21	2.64	2.36	2.43	2.49
	dolomie	4.67	6.90	5.57	4.96	7.01	6.39	5.17	4.63	4.75	5.13
	aragonite	2.12	3.30	2.80	2.46	3.47	3.10	2.54	2.26	2.32	2.37

Source: own study.
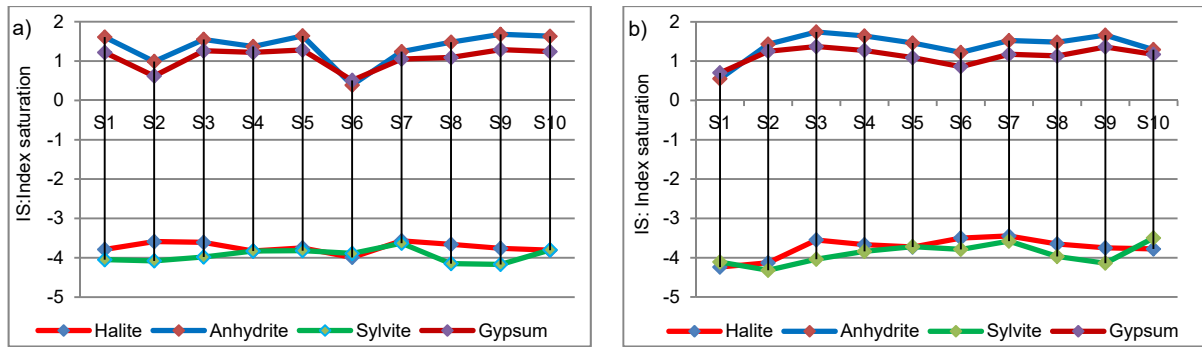
Fig. 8. State of evaporitic minerals in the Hammam Meskoutine's thermo-mineral waters: a) low water, b) high water;
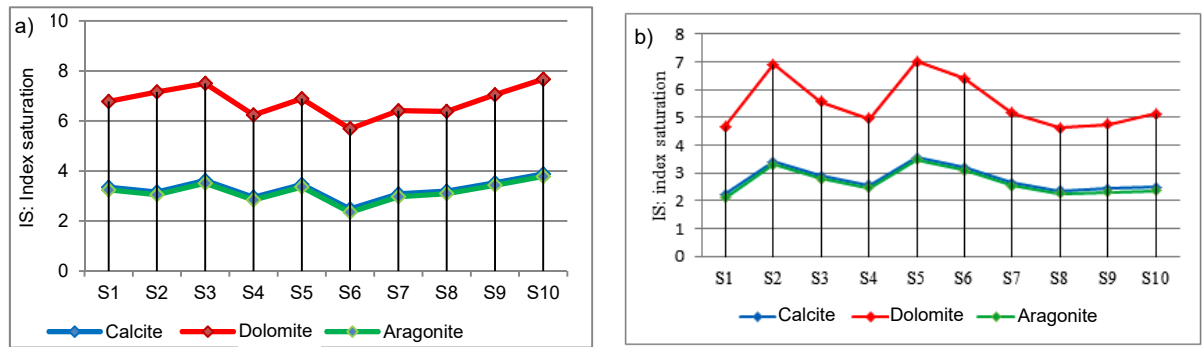source: own study

Fig. 9. State of carbonated minerals in the Hammam Meskoutine's thermo-mineral waters: a) low water, b) high water;
source: own study

The reconstituted salts are reported in Tab. 4. The main purpose of these reconstructions is to account for the possible influence of the physicochemical characteristics of the aquifer rock on the chemical composition of the waters. The reconstituted salts are based on the relative content of certain ions and the following cases: $r\ Mg^{2+} + r\ Ca^{2+} > r\ HCO_3^- + r\ SO_4^{2-}$ (Fig. 10).
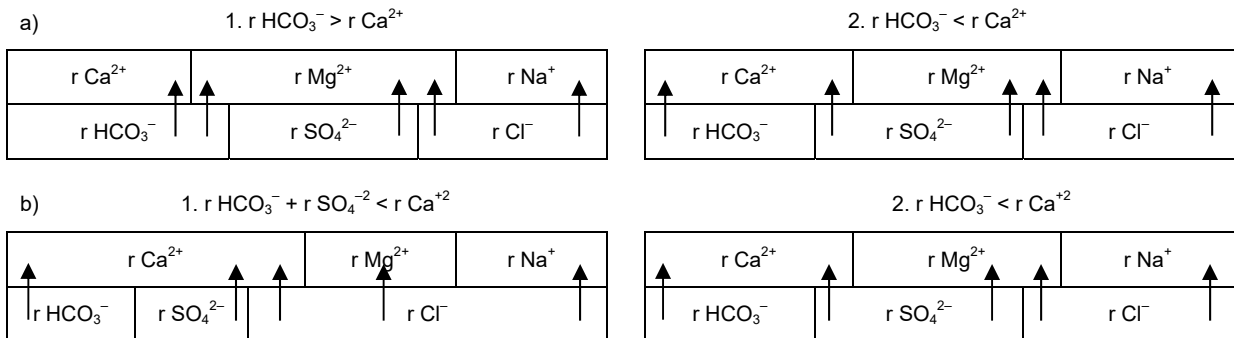

Fig. 10. Representation of the dissolved salts of the Hammam Maskoutaine's thermo-mineral waters:
a) low water, b) high water; r = atomic mass/equivalent (meq·dm^{-3}); source: own study

The surface waters deeply pass through in the cracks of the main structures; they obtain their temperature according to the depth and return to the surface strongly reheated [POVARA *et al.* 2008]. Then, the water crosses several soils types whose the composition varies from one region to another. It circulates slowly in the rock breaks, dissolves their chemical components. It's loading during its path in mineral salts and in trace elements. The products of this dissolution are on the one hand an altered rock and enriched water in minerals on the other hand. The predominant type in the carbonate-rock aquifers is generally produced by dissolution of the carbonate minerals (calcite, dolomite and aragonite), which is also due to dissolution of carbonate rocks [HAMED *et al.* 2014; MOKADEM *et al.* 2016]. If it results from a subterranean formation nourished by water which has permeated through a calcareous soil, then it will be calcareous. In contrast, if the water originally of a crystalline soils such as the sand or granite will preferably be noncalcareous. The physico-chemical characteristics of the waters are related to their subterranean passage, the depth, the temperature, the traversed rocks nature and the residence time [AIT-OUALI 2015].

Table 4. The dissolved salts of the Hammam Meskoutine's thermo-mineral ($r\ Ca^{2+} + r\ Mg^{2+} > r\ HCO_3^- + r\ SO_4^{2-}$, year 2016)

Spring	Ionic formula	The dissolved salts	Ionic formula	The dissolved salts
		Low water		**High water**
S1	$r\ HCO_3^- > r\ Ca^{2+}$	$Ca(HCO_3)_2$, $Mg(HCO_3)_2$, $MgSO_4$, $MgCl_2$, NaCl	$r\ HCO_3^- < r\ Ca^{2+}$	$Ca(HCO_3)_2$, $CaSO_4$, $MgSO_4$, $MgCl_2$, NaCl
S2	$r\ HCO_3^- < r\ Ca^{2+}$	$Ca(HCO_3)_2$, $CaSO_4$, $MgSO_4$, $MgCl_2$, NaCl	$r\ HCO_3^- + r\ SO_4^{2-} < Ca^{2+}$	$Ca(HCO_3)_2$, $CaSO_4$, $CaCl_2$, $MgCl_2$, NaCl
S3	$r\ HCO_3^- < r\ Ca^{2+}$	$Ca(HCO_3)_2$, $CaSO_4$, $MgSO_4$, $MgCl_2$, NaCl	$r\ HCO_3^- + r\ SO_4^{2-} < Ca^{2+}$	$Ca(HCO_3)_2$, $CaSO_4$, $CaCl_2$, $MgCl_2$, NaCl
S4	$r\ HCO_3^- < r\ Ca^{2+}$	$Ca(HCO_3)_2$, $CaSO_4$, $MgSO_4$, $MgCl_2$, NaCl	$r\ HCO_3^- + r\ SO_4^{2-} < Ca^{2+}$	$Ca(HCO_3)_2$, $CaSO_4$, $CaCl_2$, $MgCl_2$, NaCl
S5	$r\ HCO_3^- < r\ Ca^{2+}$	$Ca(HCO_3)_2$, $CaSO_4$, $MgSO_4$, $MgCl_2$, NaCl	$r\ HCO_3^- + r\ SO_4^{2-} < Ca^{2+}$	$Ca(HCO_3)_2$, $CaSO_4$, $CaCl_2$, $MgCl_2$, NaCl
S6	$r\ HCO_3^- < r\ Ca^{2+}$	$Ca(HCO_3)_2$, $CaSO_4$, $MgSO_4$, $MgCl_2$, NaCl	$r\ HCO_3^- + r\ SO_4^{2-} < Ca^{2+}$	$Ca(HCO_3)_2$, $CaSO_4$, $CaCl_2$, $MgCl_2$, NaCl
S7	$r\ HCO_3^- > r\ Ca^{2+}$	$Ca(HCO_3)_2$, $Mg(HCO_3)_2$, $MgSO_4$, $MgCl_2$, NaCl	$r\ HCO_3^- + r\ SO_4^{2-} < Ca^{2+}$	$Ca(HCO_3)_2$, $CaSO_4$, $CaCl_2$, $MgCl_2$, NaCl
S8	$r\ HCO_3^- < r\ Ca^{2+}$	$Ca(HCO_3)_2$, $CaSO_4$, $MgSO_4$, $MgCl_2$, NaCl	$r\ HCO_3^- + r\ SO_4^{2-} < Ca^{2+}$	$Ca(HCO_3)_2$, $CaSO_4$, $CaCl_2$, $MgCl_2$, NaCl
S9	$r\ HCO_3^- < r\ Ca^{2+}$	$Ca(HCO_3)_2$, $CaSO_4$, $MgSO_4$, $MgCl_2$, NaCl	$r\ HCO_3^- + r\ SO_4^{2-} < Ca^{2+}$	$Ca(HCO_3)_2$, $CaSO_4$, $CaCl_2$, $MgCl_2$, NaCl
S10	$r\ HCO_3^- < r\ Ca^{2+}$	$Ca(HCO_3)_2$, $CaSO_4$, $MgSO_4$, $MgCl_2$, NaCl	$r\ HCO_3^- < r\ Ca^{2+}$	$Ca(HCO_3)_2$, $CaSO_4$, $MgSO_4$, $MgCl_2$, NaCl

Explanations: r = atomic mass/equivalent ($meq \cdot dm^{-3}$).
Source: own study.

The thermo-mineral waters at elevated temperatures are enriched by the endogenous gases (CO_2 and H_2S). These gases increase the rocks dissolution and promote the upwelling of the waters towards the surface [CORNIELLO 2015]. The origin of the waters salinity is essentially due to the dissolving processes of Miocene evaporitic rocks, mainly of sulphates, and to the contribution of deep hydrothermal waters [CERON *et al*. 1999] which show signs of endogenous contamination by the CO_2. The dominance of sulphates, the chlorides, the sodium and calcium clearly shows that the mineralization of these waters is acquired mainly by the gypsum dissolution and carbonates as well as by the bases exchange with clays [BOURI *et al*. 2007]. The main minerals are gypsum $CaSO_4 \cdot 2H_2O$; the anhydrite $CaSO_4$ and the halite NaCl. Other minerals although less frequent may be important constituents of some salt deposits.

A south-north constructed section passing through the study area (Fig. 11) allows to see an anti-cline forming the limestone massifs of the mountains exposing at the Jebel Debagh level situated at Hammam Meskoutine's south. The waters have tendency to circulate in the fissured limestone formations that put into contact the constantinian neritic serie (of Guelma) with the formations of the Mio-Pliocene basin.

To confirm the circulation of Hammam Meskoutine waters in the constantinian neritic limestones, we have done extensive bibliography researches about the rock chemical analysis by diffractometry.

The limestone chemical analysis confirms clearly the carbonated constituent's nature which is specified in complement to the name of the calcareous rock (Tab. 5). Thus the nature determination of the contained elements in the limestone total-rock [NACER 2005], using the X-ray diffractometry technique, giving results with the diffractogamms form, which finally constant that most of the peaks represent the calcite with the presence of the other minerals such as Hematite and silica.
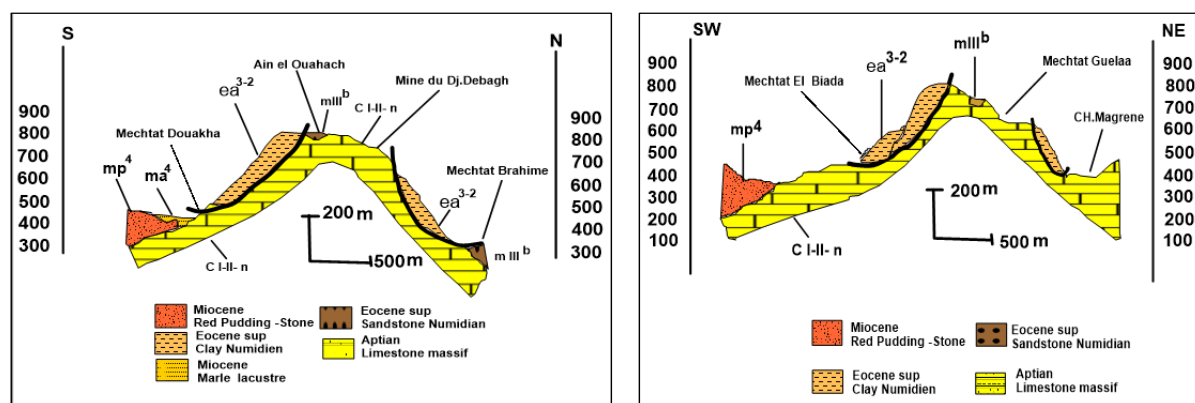

Fig. 11. Geological sections; source: FOURCADE, RAOULT [1973]

Table 5. The main carbonated constituents of limestone rock

Rock	Calcite, %	Dolomite, %
Limestone	>95	<5
Magnesian limestone	90 to 95	5 to 10
Dolomitic limestone	50 to 90	10 to 50
Limestone dolomite	10 to 50	50 to 90
Dolomite	<10	>90

Source: own study.

The limestone's geochemical composition in the nature is rarely pure. Very often, chemical elements such as the iron, aluminium, silicon are finding associated in the carbonated rock during its deposition. According to the proportion of the calcite and the dolomite, we can distinguish: pure limestone (95–100% calcite and dolomite 5% maximum), magnesian limestone (calcite with 5–10% dolomite or 5–10% Mg^{2+} not expressed as dolomite form), dolomitic limestone

(limestone with 10–50% dolomite), the aragonite and dolomite (Ca–Mg)CO$_3$). However, the geochemical composition of the neritic limestones reveals well the dissolved salts reconstitution and confirms that the chemical composition of the waters to the griffins of Hammam Meskoutine would come from this karstic reservoir.

CONCLUSIONS

The study of the mineralization origin of the Hammam Meskoutine region's thermo-mineral waters from the combination of the graphical hydro-chemical methods and saturation index calculation, has led to the identification of the waters different characteristics of the region sources. The thermal mineral waters have a temperature which varies between (41–97°C in low water) and (39–94°C in high water), with a pH that varies between (6.74–7.58 in low water; 6.01–7.51 in high water) and an varied electrical conductivity between 733–2360 µS·cm^{-1} for both periods. The most dominant facies are magnesian bicarbonated and magnesian sulphate derived from the evaporites leaching, the limestones and calcareo-dolomitics.

The major hydrogeochemic processes in the study zone are a combination of a rock dissolution phenomenas, and chemical elements precipitation. The waters are mainly supersaturated in calcium, magnesium and sulphates. The origin of this composition would be neritic limestones, confirmed by the reconstitution in dissolved salts, by the geological sections and by the diffractometry.

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Wody termalno-mineralne Hammam Meskoutine (północno-wschodnia Algieria): Skład i geneza mineralizacji

STRESZCZENIE

Północnowschodnia Algieria, w szczególności okolice miasta Guelma, obfitują w źródła termalne, których wody krążące na dużych głębokościach powodują ogrzanie wód deszczowych (o 1°C na 33 m zgodnie ze średnim gradientem geotermalnym) i poziom mineralizacji zależny od podłoża skalnego. Celem badań było ustalenie mineralizacji w wodach termalno-mineralnych Hammam Meskoutine (północnowschodnia Algieria). Badania hydrochemiczne obejmowały analizę wybranych parametrów fizycznych i chemicznych, takich jak: temperatura, pH, przewodnictwo elektrolityczne i stężenie Cl^-, SO_4^{2-}, HCO_3^-, Ca^{2+}, Mg^{2+}, K^+ i Na^+. Przetworzenie danych na diagramie ujawniło istnienie dwóch facji chemicznych – siarczanowo-magnezowej i wodorowęglanowo-magnezowej. Przewodnictwo wód przekraczało 2300 μS·cm^{-1}, a temperatura osiągała 97°C. Wyniki obliczeń wskaźnika wysycenia świadczą, że wody były przesycone minerałami węglanowymi (kalcyt, dolomit i aragonit) i mniej wysycone minerałami, takimi jak: halit, anhydryt, sylwit i gips. W składzie chemicznym dominują sole bogate w wodorowęglan i siarczan wapnia, a w mniejszym stopniu występują sole magnezu. Przekroje geologiczne analizowane w niniejszych badaniach potwierdziły, że skład chemiczny wód źródlanych jest skutkiem rozpuszczenia wapieni i gipsowo-solnego kompleksu typowego dla regionu Hammam Meskoutine.

Słowa kluczowe: *facje chemiczne, Hammam Meskoutine, mineralizacja, północnowschodnia Algieria, źródła termalno-mineralne*