I. ФІЗИЧНА ГЕОГРАФІЯ, ГЕОЕКОЛОГІЯ ТА РАЦІОНАЛЬНЕ ПРИРОДОКОРИСТУВАННЯ

UDC 504.436+553.7.031.5
DOI: https://doi.org/10.5281/zenodo.14631343

Athamena A., Belalite H., Aouissi H.A., Athamena M., Boughediri M., Laamouri M., Gaagai A., Kebaili F.K., Benselhoub A.

ORIGIN, EVOLUTION AND ASSESSMENT OF THE HYDROGEOCHEMICAL FUNCTIONING OF A THERMAL MINERAL SPRING IN BATNA (EASTERN ALGERIA)

A hydrogeological study of the thermal source of Ouled Aïcha in the Aurès Mountains showed that the source emerges in a particular natural context mainly represented by the presence of a vertical fault in the NE-SW direction affecting Cretaceous limestone. This supports the increase on the surface of moderately hot water, whose temperature is approximately 30 °C and an exploited flow of 3 L·s^{-1}. The vertical electric sounding in situ showed the in-depth presence of a saliferous conducting level within a calcareous-resistant mass, which probably settled in the fault's favor. The presence of this saliferous level strongly influences the hydrochemistry of this thermal source. Thus, the water from the source is characterized by high salinity due to its temperature, which favors the dissolution of mineral salts in sufficient quantity throughout its journey (12390 µS/cm). The high concentrations of chlorides, sodium and sulfates indicate a significant contribution of salt from evaporitic formations as for the calcium content indicates that this water is influenced by the dissolution of carbonate formations. These physicochemical characteristics provide this water therapeutic virtue, which can be attributed to its chemical composition, high rock salt content, and low nitrate content. Geothermometry has shown that these thermal waters acquire a high temperature in their original tanks coming from a depth through a fault system that affects the basement.

Key words: *source, thermal mineral spring, hydrochemistry, Aurès region, Algeria.*

© **Athamena Ali[1]✉, Belalite Halima[2], Aouissi Hani Amir[3], Athamena Malika[4], Boughediri Mabrouk[5], Laamouri Bachir[6], Gaagai Aissam[7], Kebaili Feriel Kheira[3], Benselhoub Aissa[3]✉**

[1] Department of Geology, Institute of Earth and Universe Sciences, Batna 2 University, Batna, Algeria
[2] Department of Science and Technology, Institute of Science and Technology, University Center of Mila, Mila, Algeria
[3] Environmental Research Center (CRE), Annaba, Algeria
[4] Department of Hydraulics, Faculty of Technology, Batna 2 University, Batna, Algeria
[5] Faculty of Sciences of Bizerte, University of Carthage, Carthage, Tunisia
[6] Department of Earth Sciences and Universe, Faculty of Exact Sciences, Nature and Life Sciences, University of Biskra, Biskra, Algeria
[7] Scientific and Technical Research Center on Arid Regions (CRSTRA), Biskra, Algeria

Article Info: Received: August 7, 2024;
Final revision: November 7, 2024; Accepted: January 11, 2025.

Introduction. Thermal Mineral Springs are found all over the world and have garnered a lot of interest because of their possible medicinal benefits, which differ depending on the quality of the fluids they contain [1]. Studies have been carried out worldwide to investigate the physicochemical, bacteriological, and medicinal properties of hot waters [2-6]. Hot water is widely used to treat several illnesses. All thermal spa resorts provide drinking cures, which are examples of internal treatments [7]. External treatments included massages, mud treatments, baths, showers, inhalations, gargles, and other forms of treatment. Thermal therapy is regarded as a pinnacle of natural medicine. It has demonstrated efficacious outcomes in the management of many illnesses [8, 9].

Since the first age of humanity, hot water has been sought after by humans to heal themselves. The first use of hot water for medical purposes dates back to 3000 BC. However, thermalism originated with the Romans, founders of the first "Thermes". The World Health Organization (WHO) officially recognized the International Federation of Thermalism in 1986. This recognition is based on the true scientific validity of thermal medicine and its significance [7]. At that time, these hot waters were recognized for their therapeutic benefits. After a long period of oblivion during the middle Ages, thermalism was reborn from its ashes in the 16th century. The XXI century opens the way for a new generation of exploitation of thermo-mineral waters; which combines care with relaxation and nature with conviviality [10].

Previous studies on thermalism in Algeria have outlined the main categories of thermal aquifers and concentrated on a number of thermal sources with first-rate therapeutic qualities [11-15]. These thermal sources were primarily found in the northeastern region of Algeria, central Algeria, northern Sahara, and northwestern regions.

In the “wilaya” (city) of Batna, the thermal spring “Ouled Aïcha” is located approximately 10 Km far from the southwest of Arris, in the middle of the Aurès mountain, to the right of a location known as “Tighanimine”. This spring is only in this region, and it almost does not appear because intensive plant cover dominates the massif. However, the local inhabitants have used this spring for many purposes, particularly for treatment. In recent years, this source has suffered from deterioration in its quality because of many problems, which we will focus on in this work. Consequently, the exploitation of these thermo-mineral waters constitutes a technical and scientific challenge not only for practitioners but also for scientists and researchers. Indeed, the exploitation of such mineral water deposits requires a multidisciplinary study merging different aspects of hydrogeology such as hydrodynamics and hydrochemistry.

The objective of this study was to conceptualize the hydrogeochemical functioning of the Ouled Aïcha Source, Eastern Algeria, using hydrodynamic and hydrochemical investigations. In an effort to boost the local economy, our study seeks to highlight the areas home to these thermal springs. Thus, it is essential to emphasize that the thermal sector requires more attention in Algeria, as is the case in most countries around the world.

Materials and Methods

Geographical Context of the Study Site

The Aurès are crisscrossed, from the Northeast to the South-West, by a series of extremely deep valleys (such as Wadi Labiod, Wadi Abdi and Wadi Chenaouara). The massif leans in the North to the southern limit of the neritic mole constantinois, whose altitude varies between 1000 and 1200 m and plunges in the South in the vast Saharan plain, whose altitude varies between 100 and 150 m. The differences in altitude were accompanied by climatic diversity. Indeed, the high peaks (Chèlia and Mahmel) are the domain of the cold sub-humid bioclimate, where precipitation is quite important (from 600 to 900 mm/year) and where one observes relatively persistent snow cover [16]. Outside this zone (sub-humid), a cold semi-arid bioclimatic domain with lower precipitation (300 to 600 mm/year) was observed. Of all the subdivisions of Aurès region, one of the most interesting is the famous valley of the Oued El Abiod. It is located at the southwestern end of the wilaya of Batna in a pre-Saharan area at a distance of 300 km from the Mediterranean and at the crow flies 70 km south of the chief town of the wilaya of Batna (Fig. 1).

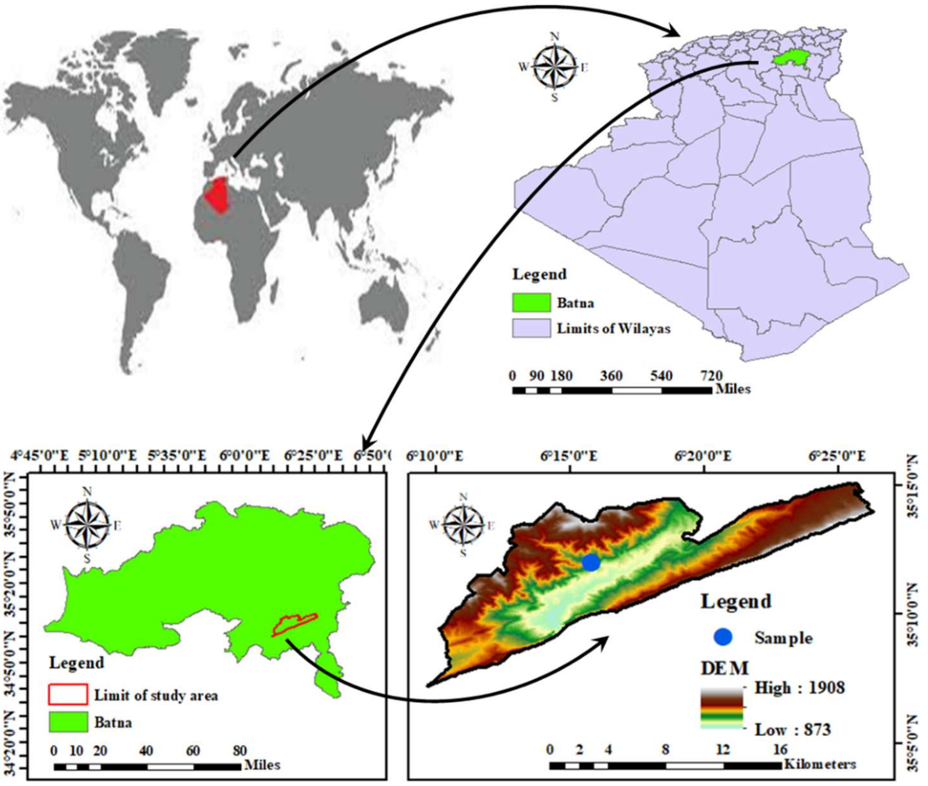

Fig. 1. Study area location (Own edition using ArcGIS Software)

It is a rugged plateau deeply ravined, sloping from North-East to South-West and squeezed like a corridor between two folds of the massif: the chain of Djebel Takroumt and Djebel Krouma to the north-west, and Djebel Ahmar Khaddou to the South-East.

The thermal Source Ouled Aïcha (Fig. 2) emerges in the center of the Aurès massif to the right of a geographical region called Tighanimine at about ten (10) km southwest of Arris in the wilaya of Batna. This locality owes its fame to its pristine landscape, mountainous climate and especially to its Sources that emerge on the eastern flank of the Aurès Mountains. The region is located at the top of the sub-catchment area of Oued Labiod 06-15 (Figure 1), which crosses it entirely and is also a part of the catchment area of Chott Melrhir. Naturally, it is limited to the southeast by the mountains of Zalato culminating in 1922 m, to the south of the mountains of Krouma culminating at 1543 and Dj. Lazrek, to the northeast by the mountains of Ichemoul and to the northwest by the mountains of El Mahmal culminating at 2321m.

Geological Context

The Aurès massif constitutes the heart of the Atlasic domain, occupying a geographical area extending from the mounts of Batna in the west to those of Nememcha-Ain Beïda in the east. The south is limited by the southern atlasic flexure. The structure of the Aurès is materialized by vast anticlines and synclines, well individualized, regular and oriented NE-SW of the axis N 50° to 60° E. This direction is generated by the atlasic phase, which has led to the emergence of this massif [17]. The Atlasic direction is affected by several fault systems that are organized in three directions: directional faults NE-SW, transverse faults NW-SE, and faults E-W. The organization is marked by a clear elevation of altitudes from north to south, from 1774 m at Djebel Bou Arif, 2321 m at Kef Mahmel and 2358 m at Ras Keltoum Djebel Chèlia. The Cretaceous was very developed in the Aurès, with a very clear opposition between two successive series, one where the sandstones dominate going up to the Albian, the other beginning with the Cenomanian and the sandstones are unknown. The sandstone series (lower Cretaceous) is approximately two thousand meters thick and contains marl and sometimes limestone but in lenses rather than in continuous layers. However, the marl and limestone series (Upper Cretaceous), which is approximately three thousand meters thick, never contains sandstone layers [17]. Indeed, the lower Cretaceous being a period of sandstone sedimentation, whereas the upper Cretaceous was a period of limestone sedimentation. All authors who have dealt with the geology of the Aurès, reported the existence of outcrops of gypsum and rock salt accompanied by variegated marlstones that were most often considered eruptive (Triassic outcrops were recognized, that of the Outaya, Maâfa, and Menâa Medina).

At the local scale of the site, many geological formations that stretch in the direction of the Atlas, with the exception of alluvium at the level of wadis and thalwegs are distinguished. These formations belong mainly to the Secondary including marl, clay and massive limestone. The site is characterized by the presence of a thick limestone bar that can exceed 400 m in thickness. These are gray limestones with characteristic elephant skin. These metric limestones are usually interspersed by layers of gray marl, with the presence of some lumachel layers of schistose gastropods [18]. Green marls, and sometimes gypsums cover this formation. Concerning the watercourses, there are very thin Quaternary formations, which result in ancient fluvial deposits, breccias and pebbles of ancient spreading, calcareous crusts, ancient scree, present and recent silts, present and recent alluvium and scree that continues to form.

The structural aspect is characterized by a general dip towards the North of about thirty degrees with a stronger straightening at the level of the summits (Fig. 2a). This configuration allows us to deduce that there is a monoclinal structure, probably on the eastern flank of a north-east-south-west anticline [18]. We have noted the presence of a vertical fault in a North-East-South-West direction, with a direction of N 20° E, (Fig. 2b).

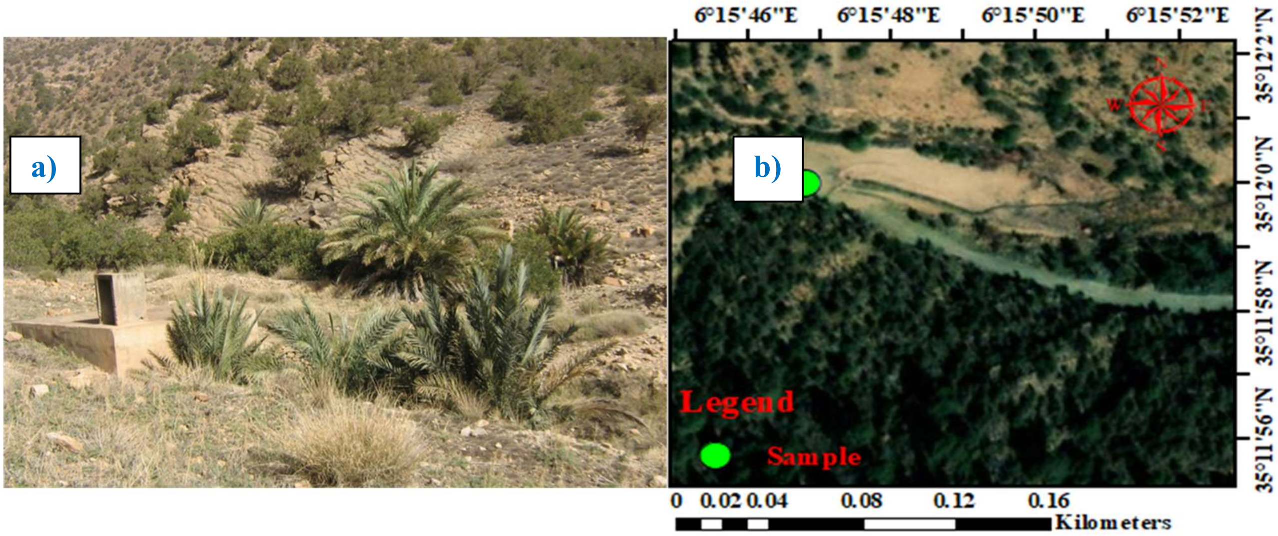

Fig. 2. Catchment chamber of the griffin: a) Photo taken by authors, b) location using Google Maps

This discontinuity has allowed the dip of the layers at the level of the hot source to change from a N 30° E direction to a N 160° E direction on both sides of the fault. Locally, the limestones are highly fissured and dislocated into metric blocks.

We can observe the geological sketch of the site (Fig .3) and the Limestone bar of the right flank of the source where one notices the straightening at the level of the Summit below (Fig. 4).

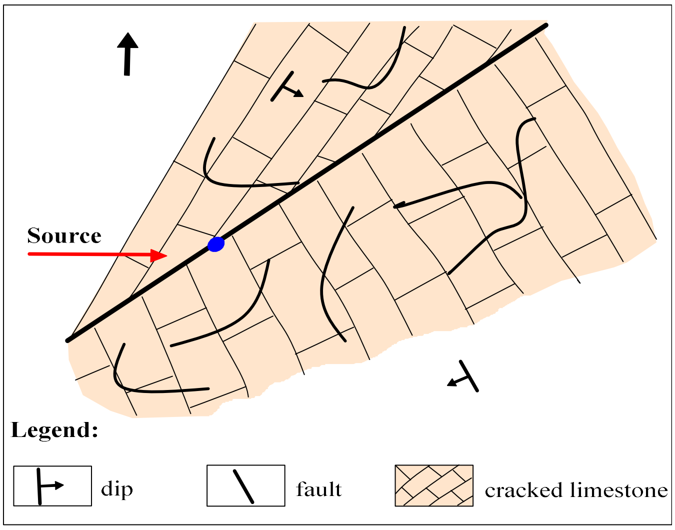

Fig. 3. Geological sketch of the site (Own edition)

Fig. 4. Limestone bar of the right flank of the source where one notices the straightening at the level of the Summit (Photo taken by authors)

Hydrogeological Context

Water Sampling and Laboratory Analysis. To achieve the results, three samples were collected. Sampling of water was carried out at the Source after 15 minutes of pumping (to remove the groundwater stored in the structure). The samples were collected in acid-rinsed polypropylene bottles of 1-liter capacity. Samples for each collection were kept in two bottles. The first is acidified to a pH < 2 using pure nitric acid, intended for the analysis of cations. The second bottle did not undergo any treatment and was intended for anion analysis. 0.45 μm cellulose acetate filters were used to filter samples immediately after collection. Physical parameters like pH, TDS and EC were determined at the site (Table 1) with the help of digital portable water analyzer kit WTW (P3 Multiline pH / LFSET). Determination of major cations and anions were realized in the laboratory using an analytical method (titrimetry), flame atomic absorption (PERKIN ELMER 1100B), potentiometric titration as recommended by [19, 20] and the technique of the center of expertise in environmental analyzes of Quebec [21] for the determination of nitrates.

Table 1

Measured in situ parameters of the Wadi and Source waters

Sample	pH	Electrical Conductivity at 25 °C (µS/cm)	Temperature (°C)
Wadi	7.15	2 820	22.8
Source	5.70	12390	30

Geophysical Survey. A geophysical investigation campaign by electrical prospecting was carried out using a vertical electrical sounding (VES) near the studied thermal in order to clarify the local subsurface, geological and hydrogeological conditions. The principle of electrical prospecting consists of injecting a current of intensity I continuously into the ground between two extreme electrodes A and B (emission line) and measuring the potential difference V generated between two median electrodes M and N (reception line). The current I is displayed on an ammeter and the potential difference V is measured on a potentiometer. The four electrodes are arranged in a single row and symmetrically with respect to the center of the device [12, 22]. The apparent resistivity is measured by progressively moving the electrodes A and B away from the center, thus increasing the depth of investigation to the vertical of the measuring station. Then, the apparent resistivities calculated as a function of the length AB/2 are plotted on a bi-logarithmic diagram, which constitutes the characteristic curve of each electrical reading made (Figure 7). The interpretation of these curves allows us to deduce the apparent resistivity of each relevant configuration, while the thickness of each formation; it is drawn from catalogs in the case of the SEV consisting of lines with low emission [22-24]. It was possible to execute a single VES due to topographic and geomorphological constraints. The current injection with a resistivity meter type GESKA 71 in a line 700 m, which provides a mean depth of investigation of about 150 m. The implementation of the survey helped to reach data reflecting the saliferous character of the area.

Hydrodynamic Characterization. The Ouled Aïcha Source is located in the carbonate formations. These hot waters emerge on the surface thanks to tectonic accident. It is a thermal karstic aquifer whose water temperature is 30 °C [18]. The Source is formed by a 25 cm wide drain that we explored to a depth of 1 m. This drain has a direction orthogonal to the fault, thus following a northwest-southeast direction. The pumping test was carried out using a motor pump whose strainer was placed in the Source's claw (Fig. 5a) with a flow rate of 5 l/s. The pumping lasted 04 hours. The static level was in the water tank that protects the Source, at 3.58 m. During the pumping test, a stabilization was noticed. A second long-term flow test. We set the pumping rate at 10 l/s (Fig. 5b). During this test, we found that the griffin dried up after a few minutes with a slight rise.

Fig. 5. The pumping test: a) Griffon of the Source; b) Second pumping test (Photos taken by authors)

Results and Discussion

Hydrodynamic Parameters. During the pumping test, we noticed a stabilization of the Source water level. Therefore, it's possible to interpret the data using Jacob's model [30-32]. The curve of pumping test formed by four parts, (Fig. 5). The first one, has a curve shape, it corresponds to the capacity effect. This part is very small because the dimensions of the griffin in which the strainer was placed are very small. The second part is formed by aligned themselves around a straight line and that corresponds to the Jacob model. This state lasted more than 90 min. The third part corresponds to the boundary effect. It is either a limit with imposed flow or a limit with imposed potential, but it seems to us that the first hypothesis is the most plausible because the flow in the wadi is almost absent except for a weak stream of water emanating from a source upstream, which would have no influence on this source. The fourth and last part corresponds to an ascent of water that occurred after stabilization but during pumping. This rise is of 6 cm which would correspond to a de-clogging of the griffon under the influence of pumping, because the source has been in lack of maintenance and abandonment for over 40 years and it is currently in charge which risks its loss [23]. The application of Jacob's model [24-27] allows estimating the transmissivity according to the following formula (1).

$$T = \frac{183 \cdot Q}{a} \qquad (1)$$

With: T – transmissivity ($m^2.s^{-1}$); Q – flow (m^3/s) or 5.10^{-3} $m^3 \cdot s^{-1}$; a – the slope of the line, i.e. 0.1.

The application of Jacob's model allows us to assign a value of 9 10^{-1} m^2/s for the transmissivity. This value seems to be very high because the water is most likely flowing in a drain. The pumping rate and the drawdown were useful to calculate a specific flow rate, which also gives a very high value of approximately 31.5 l/s/m. These parameters show that the capacities of this karstic system are important and that pumping of this griffin can be ensured with a larger flow. The second test with a pumping rate of 10 l/s dried up of the claw after a few minutes with a slight rise. We can conclude that the capacities of this karstic system are low to medium and that pumping at this claw can be done using a flow rate of 2 to 3 $l.S^{-1}$ at most (Fig 6.)

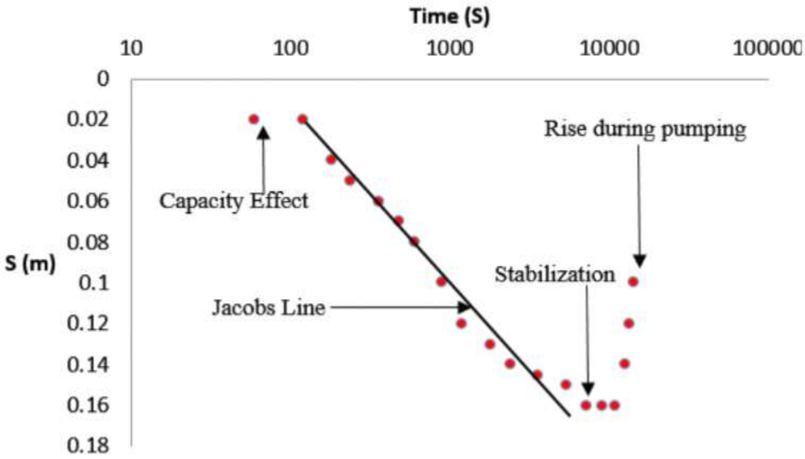

Fig. 6. Pumping test curve (Own edition)

Results of the VES. The interpretation of the VES data showed the presence of a three-field structure as shown in the experimental curve (Fig. 7). This is a downward curve with three terrains, with a highly resistant terrain at the surface corresponding to the alluvium of the wadi. These alluvial deposits are approximately 4m thick and have a resistivity of about 160 Ω.m. The second terrain, attributed to hydrothermal karstified limestones, extends to 60 meters depth. The presence of warm (30°C) salty water within these limestones caused their resistivity to drop to 100 Ω.m. The whole rests on a conductive formation characterized by a resistivity of 30 Ω.m. This latter layer, which we attributed to saline formations, would have risen along the major fault.

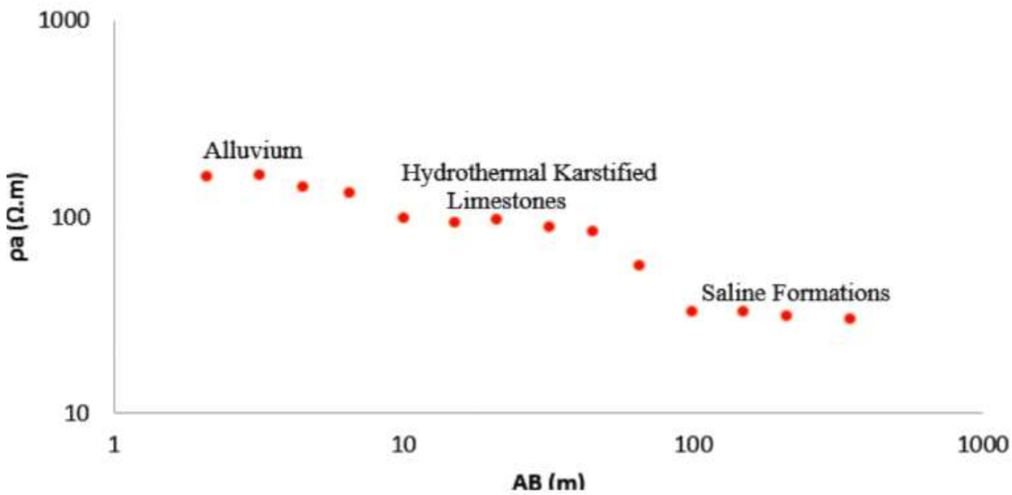

Fig. 7. Experimental curve (Own edition)

Mineralization processes. The overall mineralization of groundwater is often linked to the nature of geological formations, heavy precipitation and the dilution effect [15, 28-30]. Several studies have been carried out on this subject in the Algerian Context [14, 31-33]. These studies highlighted the role of these factors in increasing water mineralization.

Consequently, the elements, which are in the solution, are informative on the nature of the lithology [34]. Emerging with a temperature of about 30 °C, the waters of the Ouled Aïcha Source are considered, according to the classification proposed by Castany (1974) [35], as being mesothermal. The temperature measured at emergence is not necessarily representative of the real temperature of the griffon, as the thermal waters may have cooled during their ascent to the surface through degassing, heat exchange with the walls of the hydrothermal circuit, or mixing with cold water at the surface or at depth. They have an acidic pH of about 5.70 due to the karstic character of this water which, under the effect of temperature, dissolves much more CO_2, thus conferring this acidity.

The electrical conductivity reported at a standard temperature of 25 °C is about 12390 µS/cm with a total dissolved salt of about 7404 mg/l at 105 °C. This high conductivity, which gives it the character of a water very rich in mineral salts, is due to the dissolution of mineral salts from salt-rich formations along the path of the hot water [11, 13]. The redox potential of the water of this Source is negative with an order of -148.3 mv combined with the very low value of dissolved oxygen (0.18 mg/l), leads us to believe in a deep origin of this water.

The Piper diagram [36] and Schoeller Berkaloff diagram [37] displayed in Fig. 8 and Fig. 9 shows that the waters of the source present a sodium hyper chloride facies, testifying to the influence of the saliferous formations on their chemistry. The characteristic formula of the waters is: r Cl^- > r SO_4^{2-} > r HCO^{3-} and r Na^+ > r Ca^{2+} > r $Mg2^+$. The high concentrations of chlorides, sodium and sulphates indicate an important saliferous contribution from the evaporitic formations (gypsum), while the high concentrations of calcium indicates that this water is influenced by the dissolution of evaporate (gypsum or anhydrite) formations (Fig. 8) according to the formula (2). In addition, the high chloride and sulfates contents testify to the evaporitic origin, the first from the dissolution of Halite and the second from the dissolution of the gypsum. In confined aquifers, high chloride contents are expected due to the presence of evaporitic formations rich in chlorine [38]. The nitrate content does not indicate any anthropic pollution.

$$CaSO_4 + 2(H_2O) = Ca^{2+} + SO_4^{2-} + 2(H_2O) \quad (2)$$

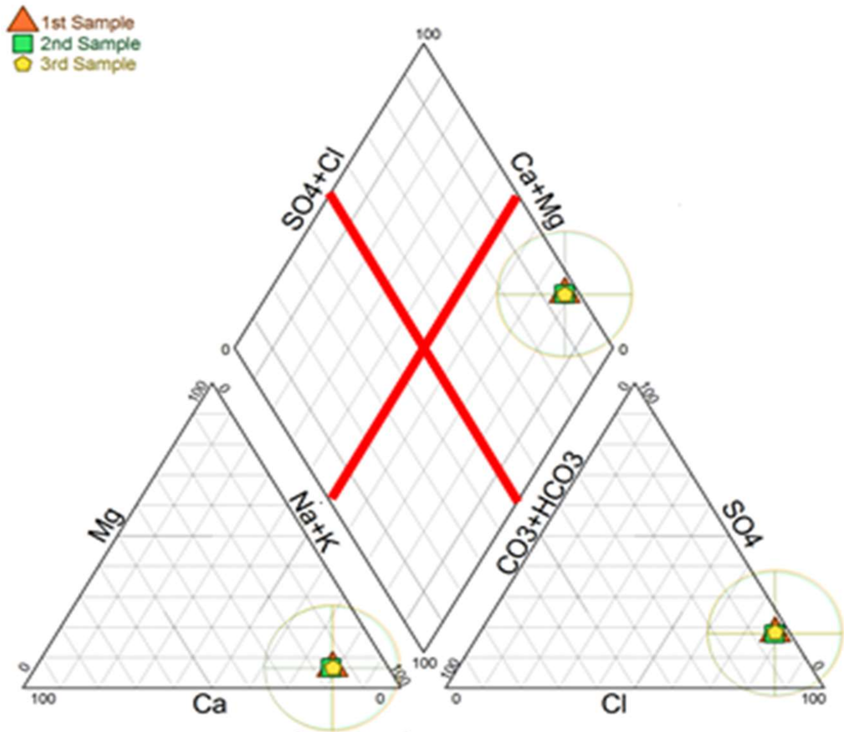

Fig. 8. Representation on Piper diagrams (Own edition)

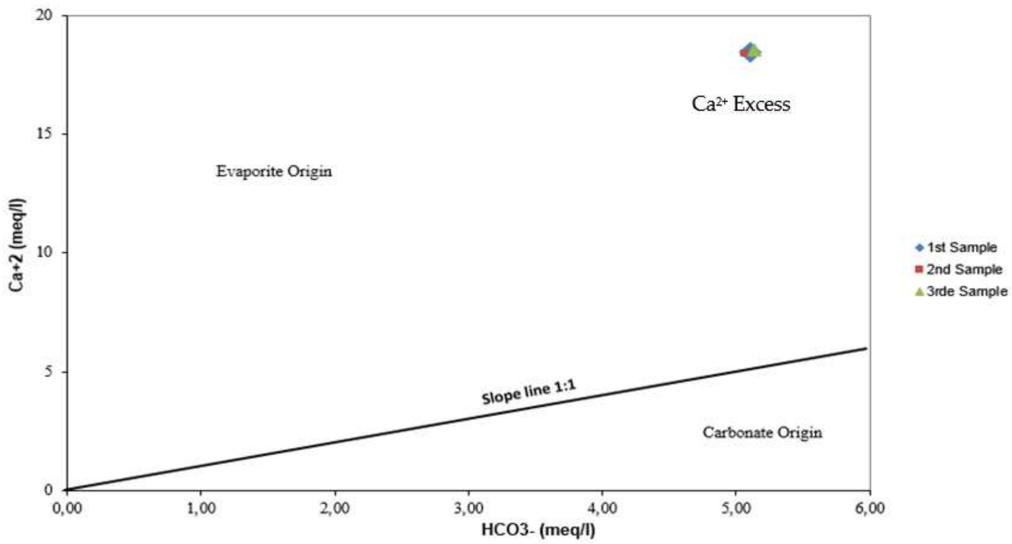

Fig. 9. Origin of the Ca (Own edition)

The chemistry of the water is acquired by the interaction of water with collecting rocks. The transfer of the analytical point of the thermal Source of Ouled Aïcha on the Na^+/Cl^- diagram showed a good distribution around a straight line of slope of halite, this translates a molar ratio Na/Cl (R = 0.99) similar to that of halite (Na/Cl halite = 1.00) as shown in Fig. 10. According to this approach, the salinity of these thermal waters would result from a dissolution of salt formations (chlorides and sodium are chemical species that can exist in water either following the dissolution of halite or from a mixture with seawater). The second hypothesis is ruled out because of the distance of the study area from the Mediterranean Sea of over 300 km.

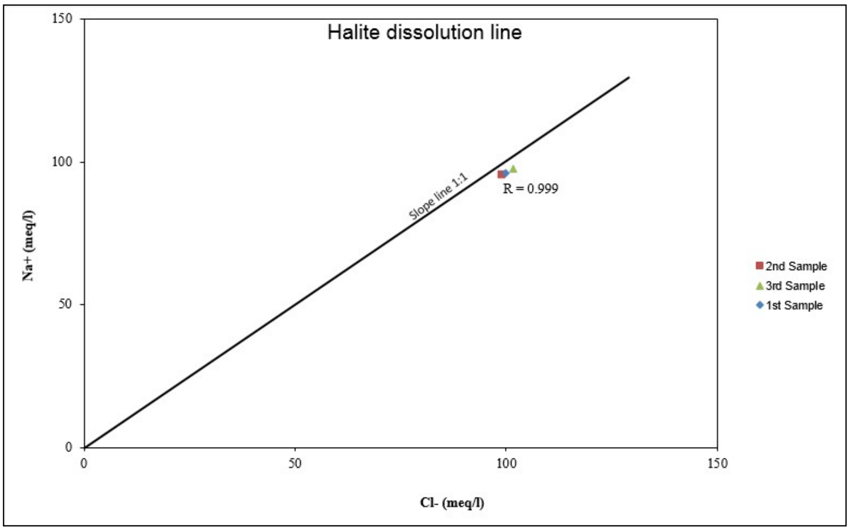

Fig. 10. Cl vs Na (Own edition)

On the other hand, it was found that there is a good agreement between sulphates and calcium (r = 0.9) and EC - $HCO_3/(Cl + SO_4)$ (r = 0.73) which reinforces this hypothesis(dissolution of salt formations). The dissolution of anhydrite or pyrite according to the formula proposed by Appelo and Postma [39], according to the formula (3).

$$FeS_2 + 3.5O_2 + H_2O \rightarrow Fe^{2+} + 2SO_4^{2-} + 2H^+ \quad (3)$$

It explains the presence of sulphates in large quantities in the waters of thermal Sources (> 20 meq/l). The strong ratio molaire Na-Cl (R = 0.99) and Ca-SO_4 (R = 0.9) and EC vs Ca/(HCO_3+SO_4) (R = 0.84), indicate a dissolution of the halite, anhydrite or gypsum and of epsomite according to the formulas (3, 6 and 7), all confirmed by the saturation indices (SI), defined by the formula (4):

$$IS = log(IAP/K) \quad (4)$$

Where: IAP is the ion activity and K is the equilibrium constant.

Equilibrium is reached when IS = 0. If SI>0, the water is supersaturated, precipitation of minerals is necessary to reach equilibrium, on the opposite side, if SI <0, water is under saturated, the dissolution of minerals is necessary to reach equilibrium. These indices (SI) with respect to carbonate (calcite, dolomite and aragonite) and evaporate (gypsum, anhydrite and halite) minerals were calculated by using the computer chemical program PHREEQC written by Plummer et al. [40] and the expression of Deby and Huckel [41] was used for the computation of coefficient activities (Table 2). Indeed, the saturation indices of the elements evaporates range between -0.76 and -3.86. While the values of IS of carbonate minerals range between -1.08 and -2.35. Let us that the state of balance is done in the interval of -0.5 to 0.5, that the saturation indices indicate an under-saturation state of groundwater with respect to halite, gypsum, anhydrite calcite, aragonite and dolomite (Equations 2, 5 and 6).

$$NaCl \rightarrow N^{+} + Cl^{-} \quad (5)$$

$$MgSO_4 + 7H_2O \rightarrow Mg^{2+} + SO_4^{2-} + 7H_2O \quad (6)$$

Table 2

Stability index of water vis-à-vis carbonated and evaporitic elements

Minerals	**Carbonate minerals**			**Evaporitic minerals**		
	Calcite	Aragonite	Dolomite	Anhydrite	Gypsum	Halite
1st Sample	-1.08	-1.22	-2.35	-0.76	-0.57	-3.86
2nd Sample	-1.09	-1.23	-2.35	-0.77	-0.57	-3.87
3rd Sample	-1.08	-1.22	-2.34	-0.75	-0.56	-3.85

Therapeutic Analysis. The water from the Ouled Aïcha Source, with a sodium chloride content of 3550 mg/l, has a therapeutic effect on the mucous membranes. Chloride and sodium waters generally have a stimulating effect on growth and are indicated in the treatment of developmental disorders, enuresis, digestive tract disorders, and liver and biliary tract disorders. This water is also rich in magnesium, more than 50 mg/l (97.39 mg/l), a regulatory element involved in all metabolisms involving calcium and phosphorus. With a sulphate content of 1100 mg/l, this water can be used for its diuretic action, in the treatment of digestive tract diseases, intestinal and liver disorders. Moreover, the presence of calcium and magnesium intervenes in the treatment of eczemas, after-effects and scars of burns. Its therapeutic indication is valid (Rh-VR) both for rheumatism of the locomotor system (muscle, joint and bone) and for the respiratory tract (ear infections, asthma, bronchitis) and ENT, especially of allergic origin (rhinitis, rhinopharyngitis, allergic asthma, ear infections …).

Conclusion. The study of the water chemistry of the Ouled Aïcha hot Source using different geological, geophysical, hydrodynamic and hydrochemical tools has allowed to identify its typological characteristics. The water from the hot source has acquired a sodium chloride facies predominantly at depth. These conditions have allowed the alteration of various minerals such as aragonite, dolomite, calcite, gypsum, anhydrite and halite as shown in the modeling. Under these conditions, water is undersaturated in evaporites and carbonates according to different values of the stability index. This movement permits, then, the dissolution of the evaporite and carbonate minerals. The physico-chemical characteristics give this water strong therapeutic virtue thanks to its chemism, its richness in mineral salts and its low nitrate content. In spite of these hydro-chemical characteristics, which are in favor of a therapeutic use, the temperature and the flow rate remain factors, which are against this hypothesis. Thus, a temperature of 30°C at emergence with an operating flow rate of 3 l/s, limits its use. These two parameters can be improved with a deep borehole. This structure could greatly improve the flow rate and, above all, would allow warmer water to be collected at depth.

Acknowledgments. Many thanks are addressed to the MESRS (Ministry of Higher Education and Scientific Research of Algeria) and the DGRSDT (Directorate General of Scientific Research in Algeria) for their support.

References

1. Ranjit, M. (2022). Hot and Mineral Spring Water for Health Benefits. In: Hot Springs in Nepal. Springer, Cham. doi: https://doi.org/10.1007/978-3-030-99500-3_5

2. Delgado, J., Juncosa, R., Meijide, R., Vázquez, A., Barrientos, V. (2007). Características termohidrogeoquímicas de las aguas subterráneas en Galicia. In: O valor acrescentado das Ciências da Terra no termalismo e no engarrafamento da água, Artigos seleccionados do II Fórum Ibérico de Águas Engarrafadas e Termalismo / H.I. Chaminé, J.M. Carvalho (eds.). Edição do Departamento de Engenharia Geotécnica/Laboratório de Cartografia e Geologia Aplicada, Instituto Superior de Engenharia do Porto, Porto, pp. 281-299.

3. Delgado-Martin, J., Juncosa-Rivera, R., Falcón-Suárez, I. et al. (2013). Four years of continuous monitoring of the Meirama end-pit lake and its impact in the definition of future uses. *Environ. Sci. Pollut. Res.* 20, 7520-7533. doi: https://doi.org/10.1007/s11356-013-1618-9

4. Juncosa R, Meijide R, Delgado J. (2011). Fontes minerais da Galicia: Características hidroxeolóxicas, físico-químicas e indicaÇoes terapéuticas. In: Termalia'11-Encontro Internacional sobre Âguas termais / Alberto Lima (ed.). Universidade do Minho, Portugal, pp. 51-73.

5. Juncosa Rivera, R., Delgado Martin, J., Menéndez Lolo, J. A., Valle Garcia, R., García Morrondo, D. (2015). Análisis hidrogeológico de la escombrera exterior de la antigua mina de As Pontes. *Ingeniería Del Agua*. 19(2), 75-87. doi: https://doi.org/10.4995/ia.2015.3530

6. Marques, J., Carreira, P., Aires-Barros, L. et al. (2000). Nature and role of CO_2 in some hot and cold HCO_3/Na/CO_2-rich Portuguese mineral waters: a review and reinterpretation. *Environmental Geology*. 40, 53-63. doi: https://doi.org/10.1007/s002540000151

7. Mouchane, M., Taybi, H., Bargach, K. et al. (2024). Comparative Study of Two Ferruginous Thermal Sources, Carbogaseous in the Eastern Rif, Morocco. *Chemistry Africa*. 7, 2807-2820. doi: https://doi.org/10.1007/s42250-024-00913-6

8. Huang, A.; Seité, S.; Adar, T. (2018): The use of balneotherapy in dermatology. *Clin. Dermatol*. 36, 363-368.

9. Cavallo, P.; Proto, M.C.; Patruno, C.; Del Sorbo, A.; Bifulco, M. (2008): The first cosmetic treatise of history. A female point of view. *Int. J. Cosmet. Sci*. 30, 79–86.

10. Nghargbu, K. (2021): Balneotherapy: An Overview of Healing with Natural Waters. In: Practical Applications of Medical Geology / M. Siegel, O. Selinus, R. Finkelman (Éds.), Springer International Publishing, pp. 697-719. doi: https://doi.org/10.1007/978-3-030-53893-4_21

11. Issaadi, A. (1996). Mécanismes de fonctionnement des systèmes hydrothermaux. Application aux eaux thermominérales algériennes et aux eaux de Hammam Bou-Hadjar. B*ulletin Service Géologique d'Algérie*. 7 (1), 71-85.

12. Athamena, M. (2007). Étude des ressources thermales de l'ensemble allochtone sud sétifien. Mémoire de Magister, Univ. Batna. Algérie, 150 p.

13. Boudoukha, A. Athamena, M. (2012). Caractérisation des eaux thermales de l'ensemble Sud sétifien. Est algérien. *Revue des sciences de l'eau / Journal of Water Science*. 25(2), 103-118. doi: https://doi.org/10.7202/1011602ar

14. Boudoukha, A., Athamena, M., Benaabidat, L. (2015). Etude du potentiel hydrothermal de Hammam Sokhna, Est Algérien. *Larhyss Journal*. 24, 161-174.

15. Athamena, A., Gaagai, A., Aouissi, H. A., Burlakovs, J., Bencedira, S., Zekker, I., Krauklis, A. E. (2022). Chemometrics of the Environment: Hydrochemical Characterization of Groundwater in Lioua Plain (North Africa) Using Time Series and Multivariate Statistical Analysis. *Sustainability*. 15(1), 20. doi: https://doi.org/10.3390/su15010020

16. Ali, A., Redha, M. M., Fouad, D., Halima, B. (2019). The Impact of the Mobilization of Water Resources in Semi-Arid Areas on Sustainable Development: The Case of Timgad Basin, Northeastern of Algeria. In: Advances in Sustainable and Environmental Hydrology, Hydrogeology, Hydrochemistry and Water Resources / H. Chaminé, M. Barbieri, O. Kisi, M. Chen, B. J. Merkel (Eds.). Springer International Publishing, pp. 355-357. doi: https://doi.org/10.1007/978-3-030-01572-5_83

17. Laffite, R. (1939). Etude géologique de l'Aurès (Algérie). Thèse 3e cycle, Faculté des Sciences d'Alger, 451 p.

18. BEGH. (2008). Étude des potentialités thermales de la source Chir Ouled Aïcha, Tighanimine. Rapport.

19. Rodier, J. (2016). L'analyse de l'eau. 10e édition Dunod. Paris, 1365 p.

20. APHA. (1995) American Public Health Association. Standard methods for the examination of water and wastewater (19^{th} ed.). New York, USA.

21. Centre d'Expertise en Analyse Environnementale du Québec. (2008). Détermination des nitrates et des nitrites : méthode colorimétrique automatisée avec le sulfate d'hydrazine et le N.E.D., MA. 300 – NO_3 1.0, Rév. 1, Ministère du Développement durable, de l'Environnement et des Parcs du Québec, 12 p.

22. Chapellier, D. (2000). Prospection électrique de surface. Cours en ligne de Géophysique. Université de Lausane. Institut Français du Pétrole. URL: https://wwwig.unil.ch/pdf/doc_pro/pro_f.pdf

23. Athamena, M., Athamena, A., Menani, M. R. (2023). Study of the thermal sources of the Bellezma mounts, Eastern Algeria. *Algerian Journal of Environmental Science and Technology*, 3309-3323.

24. Jacob, C. E. (1944). Notes on determining permeability by pumping tests under water-table conditions, U.S. Geological Survey, 25 p.

25. Cooper, H.H., Jacob, C.E. (1946). A generalized graphical method for evaluating formation constants and summarizing well-field history. *Eos Trans. AGU*. 27(4), 526-534.

26. Sato, T., Ueshita, K. (1985). Transmissivity tensor identification from pumping test data. *Soils and Foundations*. 25(3), 127-132.

27. Kruseman, G. P. De Ridder, N. A. (1994). Analysis and Evaluation of Pumping Test Data (2nd ed.), Publication 47, Intern. Inst. For Land Reclamation and Improvement, Wageningen, The Netherlands, 370 p.

28. Gouaidia, L. (2008). Influence de la lithologie et des conditions climatiques sur la variation des paramètres physico –chimiques des eaux d'une nappe en zone semi-aride, cas de la nappe de Meskiana, nord-est algérien. Doctoral Thesis. Université de Badji Mokhtar, Annaba. 130 p.

29. Athamena, A., Menani, M. R. (2018). Nitrogen flux and hydrochemical characteristics of the calcareous aquifer of the Zana plain, north east of Algeria. *Arabian Journal of Geosciences*. 11(13), 356. https://doi.org/10.1007/s12517-018-3681-5

30. Gaagai, A., Aouissi, H., Bencedira, S., Hinge, G., Athamena, A., Heddam, S., Gad, M., Elsherbiny, O., Elsayed, S., Eid, M., Ibrahim, H. (2023). Application of Water Quality Indices, Machine Learning Approaches, and GIS to Identify Groundwater Quality for Irrigation Purposes: A Case Study of Sahara Aquifer, Doucen Plain, Algeria. *Water*. 15(2), 289. doi: https://doi.org/10.3390/w15020289

31. Demdoum, A. (2010). Etude hydrogéochimique et impact de la pollution sur les eaux de la région d'el Eulma. Thèse doctorat d'état, Université Mentouri Constantine.

32. Athamena, A. (2018). Flux azoté : Origine et devenir dans les eaux souterraines, cas de la région de Zana, Est algérien. Thèse, University of Batna 2.

33. Belalite, H. (2021). Etude Hydrogéologique des plaines de Zana et de Gadaine dans un contexte de changement climatique et de contraintes anthropiques pour l'élaboration d'un schéma de gestion intégrée des ressources en eau (Nord- Est Algérien). Thèse, University of Batna 2.

34. Belalite, H., Menani, M. R., Athamena, A. (2022). Calculation of water needs of the main crops and water resources available in a semi-arid climate, case of ZanaGadaïne plain, Northeastern Algeria. *Algerian Journal of Environmental Science and Technology*, 2477-2488.

35. Castany, G. (1974). Traité pratique des eaux souterraines. Dunod (Éditeur), Paris.

36. Piper, A. M. (1944), A graphic procedure in the geochemical interpretation of water-analyses. *Eos Trans. AGU*. 25(6), 914-928, doi: https://doi.org/10.1029/TR025i006p00914

37. Schoeller, H. (1935) : Utilité de la notion des échanges de base pour la comparaison des eaux souterraines vadoses. *Bull. Soc. Geo. France 5° série*, T.V. 1935, pp. 651-657.

38. Blum, A., Chery, L., Barbier, J., Baudry, D., Pelelet-Giraud E. (2001). Contribution à la caractérisation des états de référence géochimique des eaux souterraines. Outils et méthodologie. Rapport BRGM/RP-51549-FR, 5 Volumes.

39. Appelo, C. A. J., Postma, D. (1993). Geochemistry, groundwater and pollution. *Journal of Hydrology*. 155(1-2), 295-296.

40. Plummer, L. N., Vacher, H. L., Mackenzie, F. T, Bricker, O. P, Land, L. S. (1976). Hydrogeochemistry of Bermuda: A case history of ground-water diagenesis of biocalcarenites. *Geological Society of America Bulletin*. 87(9), 1301–1316. doi: https://doi.org/10.1130/0016-7606(1976)87<1301:HOBACH>2.0.CO;2

41. Debye, P. Hückel, E. (1923). The theory of electrolytes. I. Lowering of freezing point and related phenomena, *Physikalische Zeitschrift*, 24, 185-206.

Резюме

Атгамена А., Белаліт Н., Ауісі Н.А., Атгамена М., Бугедірі М., Лаамоурі М., Ґааґай А., Кебайлі Ф.К., Бенселгуб А. **Походження, еволюція та оцінка гідрогеохімічного функціонування термального мінерального джерела в Батна (Східний Алжир).**

Гідрогеологічне дослідження термального джерела Ouled Aïcha в горах Орес показало, що джерело виникає в певному природному контексті, головним чином представленому наявністю вертикального розлому в напрямку північ-північ, що зачіпає крейдяні вапняки. Це сприяє виходу на поверхню помірно-гарячої води, температура якої становить приблизно 30 °C, а експлуатаційний дебіт – 3 л/с. Вертикальне електричне зондування in situ показало глибинну наявність соленосного провідного рівня в межах вапнякового стійкого масиву, який, ймовірно, осідав у напрямку розлому. Наявність цього соленосного рівня сильно впливає на гідрохімію даного термального джерела. Так, вода з джерела характеризується високою мінералізацією, зумовленою температурою, яка сприяє розчиненню мінеральних солей у достатній кількості на всьому шляху її проходження (12390 мкСм/см). Високі концентрації хлоридів, натрію та сульфатів вказують на значний внесок солей з випаровувальних утворень, а вміст кальцію вказує на те, що ця вода формується під впливом розчинення карбонатних утворень. Ці фізико-хімічні характеристики надають цій воді лікувальних властивостей, які можна пояснити її хімічним складом, високим вмістом кам'яної солі та низьким вмістом нітратів. Геотермометрія показала, що ці термальні води набувають високої температури у своїх початкових резервуарах, надходячи з глибини через систему розломів, яка зачіпає породи фундаменту.

Ключові слова: *джерело, термальне мінеральне джерело, гідрохімія, регіон Аурес, Алжир.*