Mining of Mineral Deposits
Volume 17 (2023), Issue 2, 20-27

MMD
JOURNAL / MINING.IN.UA

https://doi.org/10.33271/mining17.02.020

Polymetallic mineralization hosted in the Neogene sedimentary strata of the Algerian Tellian Range: A comprehensive overview

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Abstract

Purpose. In the electronics industry, stibium (Sb) is an important element used in the development of silicon-based devices. The metallogenic district of Guelma, known for its polymetallic antimony mineralization, is not currently exploited. The research purpose is to characterize the minerals and gang formations of antimony elements required as dopants during the growth of monocrystalline silicon.

Methods. The research methods include detailed geological mapping and sampling, XRD mineralogical identification, XRF geo-chemical analysis, and atomic absorption spectrophotometry.

Findings. The results obtained prove that Sb mineralization is the youngest in the North-East of Algeria, since it is hosted in the dolomitized lacustrine limestone of the Mio-Plio-Quaternary. The mineralization has been deposited by the replacement and filling open spaces. A supergene alteration of the Nadorite mineral has led to the antimony sulfides appearance.

Originality. Unique mineral species of the world have been identified: Nadorite in Jebel Nador, Flajolotite in Jebel Heimel, valentinite in Jebel Senza, senarmontite in Jebel Hammimat, and cervantite near Aïn Kerma. The Ham-man N'Baïls deposits still contain significant reserves of Zn, Sb, and Pb.

Practical implications. With the help of this study, we have answered questions related to the origin of the mineralizing fluids responsible for the formation of deposits. In addition to the epigenetic nature of the mineralization with the formation of unique and rare minerals throughout the world, the presence of gold in this region has been proven by chemical analysis.

Keywords: *Nadorite, Flajolotite, Gold, Mio-Pliocene, lacustrine limestone*

1. Introduction

Polymetallic mineral exploration and prospecting in Algeria is an area of significant interest due to the country's diverse mineral resources. A literature review on this topic reveals that Algeria has a wealth of mineral resources, including polymetallic deposits, which have been actively mined since the beginning of the last century. In recent years, there has been renewed interest in exploration and development of these deposits, particularly in the Tellian Range, which is known to contain significant mineralization. The study of polymetallic mineralization hosted in Neogene sedimentary strata in the Algerian Tellian Range is important because it can provide a better understanding of the geology and mineralization potential of this region. This can lead to the identification of new targets for exploration and development of new mining projects that can contribute to the country's economic growth and development. Additionally, the study can provide valuable insights into the geological processes that have led to the formation of these deposits, which can be applied to other regions with similar geological settings.

In recent years, several studies have been conducted on polymetallic mineralization in Algeria. One such study was conducted by Bouzidi and Boularbah in 2019 [1], where they performed a detailed mineralogical and geochemical analysis of the polymetallic mineralization in the Oued Amizour deposit located in the north-eastern Algeria. Another study by Bouchoucha et al. [2] in the same year presented a research on the mineralogy and geochemistry of polymetallic mineralization in the Ain Barbar deposit in the north-eastern Algeria. Merabet and Bouhlel in 2020 [3] provided an overview of the mineral resources in Algeria and highlighted the importance of polymetallic mineralization in the country's economy. In 2021, Bouabdellah, et al. [4] discussed the potential for mineral exploration in Neogene sedimentary basins in Algeria, including those that host polymetallic mineralization. Additionally, Hamoudi et al. [5] in the same year presented a case study of polymetallic mineralization in the Azzaba area of the north-eastern Algeria and discussed the geochemistry and origin of the deposits.

Algeria can boast a wide range of mineral resources, which has earned it a reputation as a hidden geological treasure [6]-[8]. Almost all chemical elements in Mendeleev's periodic table are present in significant volumes and concentrations, resulting in a variety of minerals [9], [10]. For ex-

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Received: 2 January 2023. Accepted: 17 April 2023. Available online: 30 June 2023

Mining of Mineral Deposits. ISSN 2415-3443 (Online) | ISSN 2415-3435 (Print)

ample, helium is contained in the hydrocarbons of the Sahara, while the tin from the Rehla deposit and wolfram from the Hoggar deposit contain 1% lithium. The Bechar bituminous coal reserves in the southwest of the country exceed one billion tons. Additionally, the Tell region is home to abundant reserves of barium sulfate ($BaSO_4$) and strontium sulfate ($SrSO_4$). Jebel Guettara in the Ugarta range contains 3 Mt of manganese with 47.2% content, and in the north – 3.3 Mt with 30% content. The Sahara can boast significant iron ore reserves with 25 billion tons of oolitic iron, a fifth of which is in Gara Djebilet with a content of 58 to 60%. In the north, several hundred polymetallic mines have been operated since the beginning of the previous century, including those with a very high content of copper, lead, and zinc.

Other deposits have been discovered in the Sahara, such as the Tan Chaffao deposit, 6.6 Mt with copper (0.56 to 1.2%), zinc (1.65%), lead (0.43%), gold (1.62 g/t). At Eglab, in addition to polymetallic mineralization, it also contains gold (11.7 g/t) and silver (9.0 g/t). In terms of rare earth elements such as carbonatites and fenites, there are four deposits in the Ordovician of the Sahara, including one with 50 Mt and a content of 6.69%, which makes it the largest deposit in the world. Coltan (niobium, tantalum) is present in Hoggar, in the Rechla and El Karoussa deposits, where it is associated with topaz and fluorite. The wolfram-tin reserves brought Algeria to the 2nd place in the world with 98000 tons. Uranium has been found in Hoggar (Timgaouine, where it is estimated at 26000 tons. Thus, gigantic reserves exist in the Silurian of the Sahara, where they reach up to 16500 t/km². Vanadium: this metal occurs in the Silurian with reserves of 200 billion tons. Chromium: very abundant and outcropping chromite resources have been found in Hoggar. Thorium: there is a deposit of 600000 tons of Th in the Sahara. Last but not least is gold. The main auriferous districts of Algeria are located in Hoggar with 300 indices and deposits. The major sites are located in Ouzzal (25 g/t), the Pharusian zone (500g /t), the central Hoggar (50 g/t), and in the east of the Hoggar at Tiririne (25 g/t). This list is not exhaustive [11]. There are other useful metals and substances (Fig. 1).

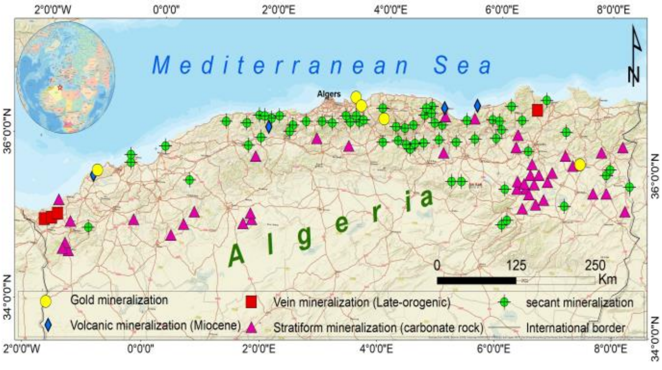


Figure 1. Main mineralization in the north of Algeria

On the eastern margin of the North African Ore Belt in the north-eastern Algeria, due to its geological complexity, many deposits containing metals such as copper, aluminium, lead, zinc, silver, gold, chromium, nickel, cobalt, manganese, molybdenum, tungsten, vanadium, mercury, magnesium, platinum, and titanium have been discovered. Despite the significant metallogenic properties of the area, it requires further investigation. Although the major deposits in the north-eastern Algeria were identified over a century ago, there has been limited research on this subject [12]-[17]. Our study has a purpose to compare data on mineralization associated with the Neogene metasomatic in the north-eastern region of Algeria and to examine the deposition conditions in relation to metallogenic characteristics.

The polymetallic mineralization of lead (Pb), zinc (Zn), antimony (Sb), and arsenic (As) of the Hammam N'bail intra-mountain basin was formed during the Mio-Pliocene in lacustrine limestone. This mineralization is characterized by individualization by simple paragenesis of nadorite ($FeSbO_4$) and flajolotite ($PbSbO_2Cl$) minerals. These deposits are related to oxide-type antimoniferous mineralization hosted in carbonate rocks. Concentrations of polymetallic minerals are associated with recent hydrothermalism due to hot springs above 50°C. The presence of gold mineralization, often associated with similar paragenesis, has been demonstrated by atomic absorption on galena samples.

2. Study area

The study area belongs to the Hammam N'bail municipality, province of Guelma. It is connected by the provincial road CW 19 to the national road RN 20. It is located 32 km east of the main city of the province, 82 km from Annaba harbour and about 88 km from the Algerian-Tunisian border. It is bounded by 371529 to 390106 E longitudes and 4009193 to 4031589 N latitudes (UTM 32N, WGS 48) (Fig. 2).

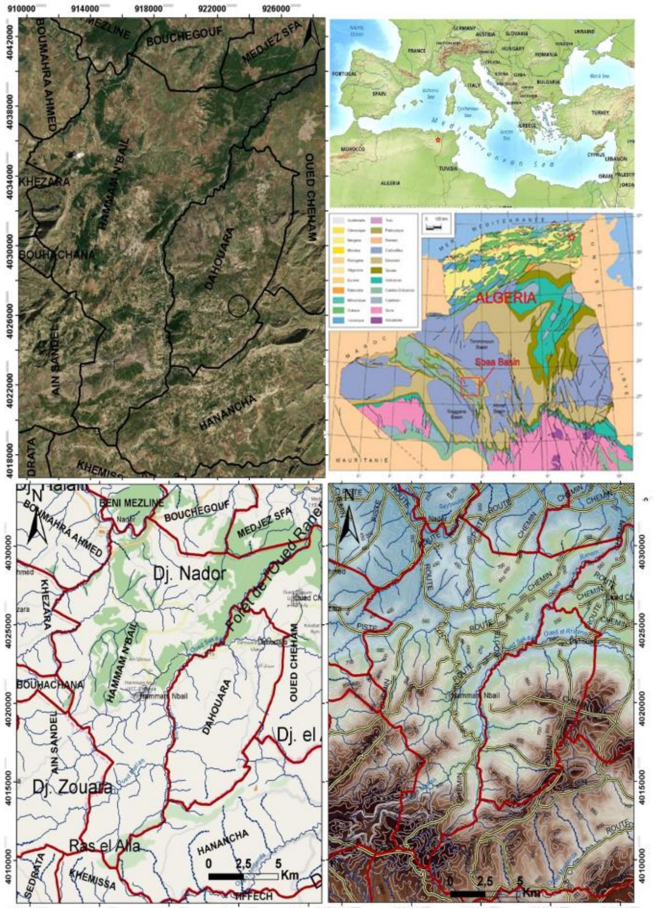


Figure 2. Geographical location of the study area

The Neogene basin of Hammam N'bail is filled with 1500 m of alternating marls-clays, lacustrine limestone, conglomerates at the base and travertines at the top. This Atlassic area, with affinities with the Tellian units, the Numidian nappes, Aïn M'Lila mole and the Aurès chain, extends over 15 km long and 5 km wide between the diapiric massif of Nador in the North and the Sellaoua area in the South.

The topography of the basin is hilly with steep mountain slopes. The region is characterized by a Mediterranean climate, with hot, dry summers and cold, wet winters. Precipitation reaches an interannual average of 800 mm/year [18]. The plant cover is composed of Aleppo pine forests and diss scrub. The R'biba wadi and the El Hammam wadi streams drain the basin. The Eocene limestone bars at the edges of the basin constitute the most interesting aquifers. The thermal spring of Hammam N'bail delivers sodium chlorinated water at 42°C with an average flow of eight (08) l/sec. The Hammam N'bail deposit was discovered in 1845, and was exploited by the company of the old mountain "Vieille Montagne". Its exploitation was resumed in 1940 with the Ain Kerma mining company. Over its entire operating period (from 1873 to 1968), 300000 tons of zinc ore, 2000 t of lead and 65000 t of antimony were extracted. The grades vary from 24 to 40% Sb and from 15 to 40% Zn and 30% Pb. The Hammam N'bail deposit contains six ore bodies.

The morphology of the Neogene basin of Hammam N'bail is marked from the North by the diapir of Nador-Souk Ahras, from the south by Jebel Zouara, to the east by the Safiet Ain Kebch range, and to the west by the Sfahli Mountains (Fig. 3).

The study area has a Mediterranean climate, characterized by a hot and dry summer and a cold and wet winter, and with interannual precipitation of 800 mm/year. The vegetal cover is composed of Aleppo pine forests and diss scrub. The R'biba wadi and the El Hammam wadi drain the basin, and the Eocene limestone bars at the edges of the basin constitute the most interesting aquifers.

The region's primary structural characteristics are distinguished by the Tellian units stacking from N to S on a comparably scaled substrate; marked by diapiric extrusions and post-sheet tectonics. The seismogenic zone of Guelma is a consequence of recent tectonics impacting the PQ formations and is linked with the faults of Bouchegouf and Hammam N'bail. The presence of thermal springs in association with these structures indicates that they are still active [19].

3. Methods

The geographical position of the sampling points was determined using GPS, but also using GIS-based geological mapping. In addition, the basemap image from Argis online, made it possible to visualize the study area. For samples obtained from underground, the depth at which the extraction was made was recorded. Sampling was carried out in accordance with the BRGM protocol. This protocol describes not only the procedure during the sampling, but also the steps preceding it for the preparation of the materials used for the sampling, as well as the transport to the laboratory [20]-[23].

The *in-situ* characterization of the samples is done by describing the following elements:

– lithology: the name and the characteristics of the facies;
– alterations: type of alteration, style, intensity, etc.;
– sulphides: type, style and importance of sulphide, etc.;
– textures: schistosity, grain size, homogeneity, etc.;
– structures: the presence of fracturing, faults, breaches, etc.;
– mineralized veins and leached corridors, etc.

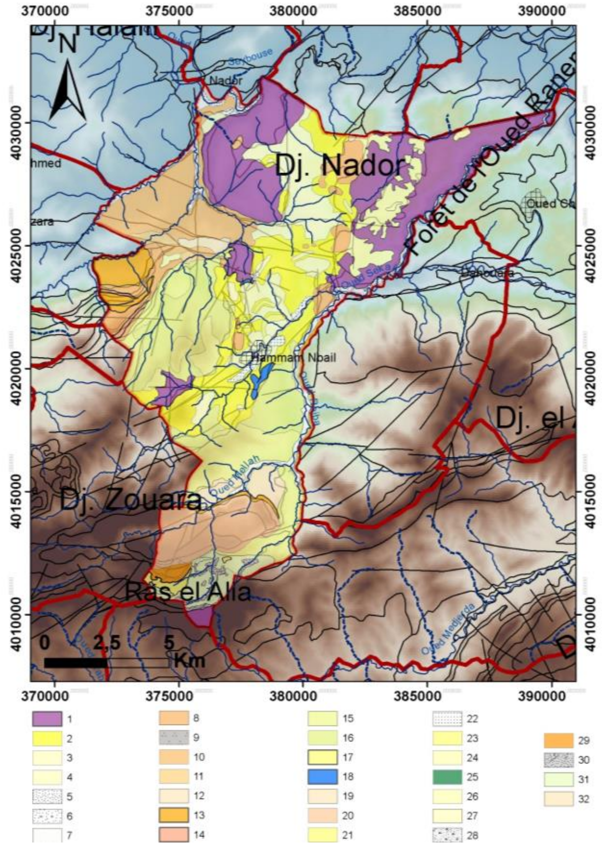


Figure 3. Lithostratigraphic map of the study area [1 – Triassic: Clayey gypsum sandstone with fragments and rocks (t). 2 – Serravalian: Sandstone red clay and puddingstones (m^{4b}). 3 – Serravalian: Gray clay with gypsum (m^{4a}). 4 – Zanclean: Late Pliocene travertines (P1t). 5 – Quaternary: Current alluvia (A). 6 – Quaternary: Screes and slope deposits (a). 7 – Quaternary: Recent alluvium (a^2). 8 – Danian: Black limestone with Nummulites (e^{aIV}). 9 – Quaternary: Ancient alluvial deposits in current valleys (q^1). 10 – Selandian: Clay and sandstone (e^{2a}). 11 – Selandian: Sandstone scree (e^2). 12 – Selandian: Quartz sandstone (e^{2b}). 13 – Danian-a: Marls with lumachelles (e^{aIII}).14 – Danian-b: Limestone and bituminous marl limestone with flint (e^{IV}). 15 – Maastrichtian: Limestone and marly limestone at Inoceram (C^6). 16 – Cam-Maest: Marl and gray marl-limestone ($C^{5\text{-}6}$). 17 – Miocene: Sandstone conglome-rates (m). 18 – Lias: Liassic limestones ($J^{3\text{-}2}$). 19 – Danian: Black clays (e^V). 20 – Montian: Limestones with Nummulites (e^{bIV}). 21 – Aquitanian: Sandstone with puddingstones (m^{1a}). 22 – Quaternary: Quaternary Travertines (T^1). 23 – Messinian: Nador Tra-vertines (m^{4t}). 24 – Franchian: Recent travertines (T). 25 – Upper Senonian: gray marls ($C^{4\text{-}5}$). 26 – Pliocene: Red clays, sandstones and puddingstones, intercalation of marl and lacustrine limestone (P^b). 27 – Franchian: Conglomerates, sandstones, and clays (P^q). 28 – Quaternary-a: Fluvial alluvium of submersible land (A^f). 29 – Ypresian: Massive limestones with Nummulites ($e^{4\text{-}5}$). 30 – Quaternary: Arable land, slope formations and alluvial deposits (Q). 31 – Campanian: Limestones with Inoceram and marls ($C^{5\text{-}6}$). 32 – Selandian: Quartzitic sandstone (e^{2b})]

Geochemical, mineralogical and spectrometric analyzes were carried out to characterize the mineralization of the deposit, as well as the fluids responsible for their formation.

X-Ray Diffraction (XRD) analyzes were applied to nine powder samples of the whole rock. This will make it possible to identify the mineralogical composition of the samples analyzed. A Bruker D8-system type device was used.

X-Ray Fluorescence (XRF) analyzes were performed to complement the XRD analyses. A mobile gun-type XRF device suitable for *in-situ* measurements of the sample was used. The portable X-ray fluorescence analyzer provides results in the form of concentrations. The program provided allows the measurement of elements with two filters: a "heavy" type filter: Ni, Cu, Zn, As, Se, Rb, Sr, Ag, Cd, Sb, Ba, Hg and Pb, and a "light" type filter: S, Cl, K, Ca, Sc, Ti, V and Cr.

To analyze the gold content in the samples, the material was first dried and crushed to obtain aggregates with a D90 of 2 mm. Next, 250 g of the material was ground in a disc grinder to produce a pulp with a D95 of 75 µm. 50 g of the resulting pulp was heated to 1500°C for an hour in the presence of a Pb flux. This process causes the gold to oxidize and form a complex with the Pb. The mixture was then transferred to a Mn crucible and returned to the oven, where Mn-Pb complexes were formed, and the gold was reduced to free grains.

The geoscientific literature on the polymetallic deposits of the NE of Algeria is quite rich in references [24]-[27].

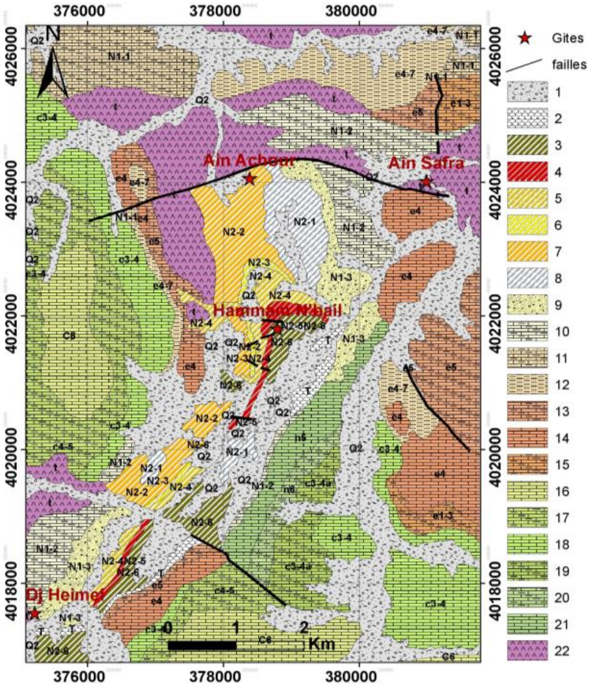
4. Results and discussion

Several studies have addressed the deposit conditions of polymetallic mineralization and its relationship with various geological factors [28]-[34].

Field studies of the study area have identified the main geological features. We have noticed that the Mio-Pliocene stratigraphic series of the Hammam N'bail basin is a fluvial-lacustrine mega sequence with an average thickness of 1500 m. Continental deposits are represented by middle to upper Miocene composed of pebbles, puddingstones and conglomerates. There is an upper Miocene with a sebkha regime of clay and gypsum black marls deposits. The lower Pliocene is represented by lacustrine limestone reflecting a lagoon regime. Quaternary of thermal activity is represented by a thick series of travertines (Fig. 4).

This series can be subdivided into six sublayers:

Sublayer (L01): it begins with fluvial conglomerates with dolomitic limestone elements, and sandstone with a thickness of 30 m. Above, microconglomerates and sands appear in small intercalations, and then sandstone and calcareous marls appear with conglomerate lenses with a thickness of 60 m. The whole is topped with sandstone marls of 50 m thick.



Legend			
1	Q	Clays, brown and yellowish pebbles	Q2
2	Q	Travertines	Tr
3	MPQ	Gray marls	L6
4	MPQ	Pink lacustrine limestone hosting mineralization	L5
5	MPQ	Gray to reddish marls	L4
6	MPQ	Lacustrine limestone	L3
7	MPQ	Gray marl and gypsum clay	L2
8	MPQ	Conglomerates, sandstones, and marls	L1
9	MPQ	Conglomerate and clays	SL3
10	MPQ	Gray marls and conglomerates	SL2
11	MPQ	Sandstone and marls	SL1
12	Numidian	Sandstone and clays	e4-7
13	Lutetian	Black marls	e5
14	Ypresian	Bituminous and siliceous limestone	e4
15	Paleocene	Black marls	e1-3
16	Maestrichtian	Gray to white limestone	C6
17	Upper Senonian	Gray marls	c4-5
18	Lower Senonian	Limestones and marls	c3-4
19	Coniacian-santonian	Marls	c3-4a
20	Albian	Gray marls and limestones	n6
21	Aptian	Limestones and marls	n5
22	Trias	Variegated clays, sandstone and gypsum	t

Figure 4. Geological sketch of the study region with distribution of metalliferous deposits

Sublayer (L02): it includes gray and red clays with gypsum in platelets; there are beds of sandstone and marl clay. Greyish red marl clays have gully occurrence. Its total thickness exceeds 800 m.

Sublayer (L03): these are micritical limestones with alternations of sub-vertical metric red clays which reach 60 m in thickness. In this level, there is disseminated galena mineralization.

Sublayer (L04): it is formed by black marls with gypsum interstratified with sandy red clays. The thickness of this level is 100 m. During the deposition of ore, these formations served as a screen for the spread of mineralization.

Sublayer (L05): represented by lacustrine limestone of pinkish to whitish colour and lumpy structure alternating with dark grey clay marls and reddish-brown clay. In this same level, there is an intercalation of detrital limestone and detrital organogenic limestone. The total thickness reaches 120 m. This level is called the "main host level" since it hosts the mineralization. The pink lacustrine limestone has a micritic to dolomicrite structure; it contains detrital quartz and calcite which fills veinlets and openings, iron oxides, clay minerals.

Sublayer (L06): it is formed by black clays with gypsum, with past lenticular limestone of ochre colour and of small thickness. This level can reach 120 m in thickness. Given that Quaternary is represented by travertines and alluvial deposits, the thickness of the travertines testifies to the thermal activity.

The structure of the graben syncline was formed by consecutive tectonic phases. It is divided into three main compartments, bounded by large transverse faults:

In the southern block, to the left of Hammam Wady, where the Triassic straddles the Mio-Pliocene formations, antimony, arsenic and copper indices were discovered.

The middle block is bounded to the south by the southern fault, to the north by a sublatitudinal fault, axing the main deposit of the polymetallic antimony deposit of Hammam N'Baïls.

The northern block includes rocks from the termination of the syncline. Most of the mineralization is of Pb-Zn located in carbonate formations of Pliocene age. Besides Pb and Zn, the district includes (Zn, Sb) mineralization at Chaabet Khalfa; (Zn-Fe) at Jebel Chirga; (Cu) at Jebel Alia, (Cu, Zn, and Pb) at Jebel Habiche, etc. The deposits have a vein-fractured morphology.

4.1. Gitology and Geochimical features of the deposit

The DRX analysis protocol was acquired at the Technopole B. Sedria, Tunisia. Nine samples yielded the following mineral assemblage: nadorite, flajolite, galena, kaolinite, smithsonite, sphalerite, siderite, geothite, cerussite, calcite, dolomite, fluorite, and quartz.

The results of chemical analyzes by atomic absorption of current travertines indicate high levels of lead and zinc (Table 1). SONAREM reports (1971) indicate abnormal levels of Sb, Hg, Pb, Zn, Ni, and B. The gold could not be analyzed due to the lack of an analysis device [35].

Table 1. Results of chemical analysis of travertines

Element	Pb	Zn	Cu	Fe	Ni	Mn	Sb	B	Hb
Sample	3.70	3.05	0.08	0.75	0.05	0.03	2.17	0.07	–

The main mineralized bodies are located in the western part of the basin in the Mio-Pliocene formations (Fig. 5). Mineralization is known to a depth of 150 m and occurs in veins and lenses. The mineralization refers to three levels:

The lower limestone level L3 is galena veins intersecting the benches. This mineralization is of little importance and has never been exploited.

The level of pink and white lacustrine limestone (L5). This is where the main mineralization is concentrated.

The levels of limestone intercalated in the gray clays with gypsum (L6). Lenses of detrital limestone at the top of the Mio-Pliocene series form the host disseminated mineralization of antimony and arsenic.

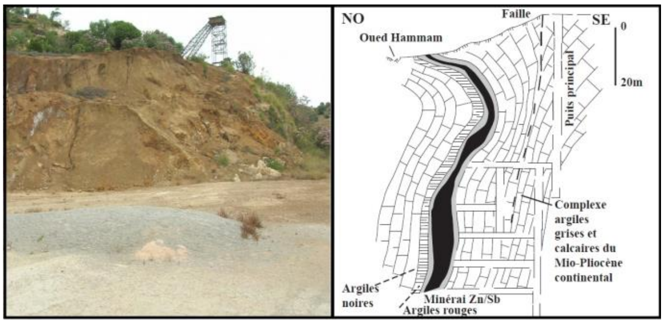

(a) (b)

Figure 5. Antimony mine of Hammam N'Baïls (a); cross section of the Hammam N'Baïls deposit (b)

Six north-south oriented ore bodies were discovered in the pink-white lacustrine limestone (L5) dislocated into compartments by east-west-trending faults. They extend for a distance of 1.8 km with a thickness of 2 to 20 m. They include the main lodging, Deb Deb, third lodging, fourth, fifth, and fifth intermediate (Fig. 6). The parameters of the main ore deposits are listed in Table 2.

Table 2. Characteristics of the ore deposits

Deposit	Mineralization	Content Sb-Pb-Zn
Main	Galena-Nadorite	2.16-3.20-3.00
Deb-Deb	Galena Antimony	1.70-3.30-1.51
Third	Galena-Arcenic	2.45-1.71-1.01
Fourth	Galena-Cerussite	4.23-1.52-6.08
Fifth	Galena Smithsonite	7.58-2.45-6.68
Fifth intermediate	Antimony Zinc	6.42-2.33-7.13

The main body was mined with an open-cast quarry and with underground galleries up to 130 m deep. The total extent of this deposit reaches 220 m, the mineralization is located in two layers of lacustrine limestone separated by clay levels. In the west of the body, fine mineralization of galena is distributed in dissemination in white and grey limestones of the third level. In the ore bodies, the metallic minerals recognizable in the mine are nadorite, galena, flajolotite and antimony yellow ochres.

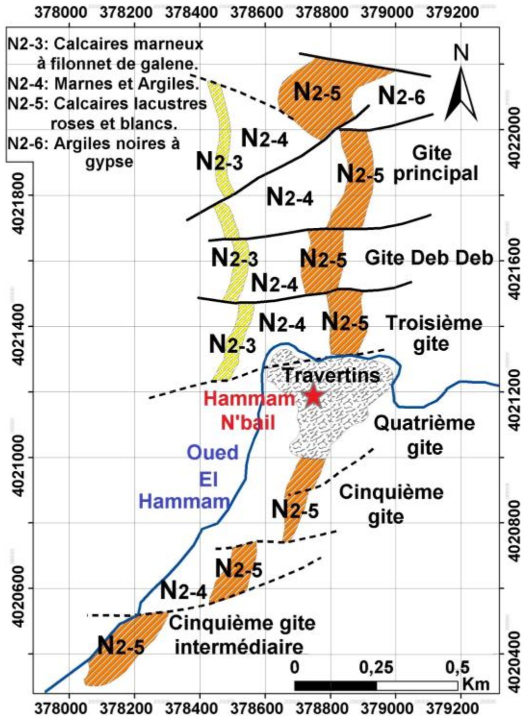


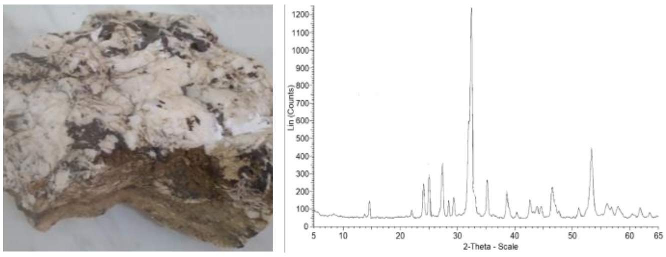
Figure 6. Sketch of the Hammam N'bail ore bodies

4.2. Mineralogy of the mineralized body

The Hammam N'bail deposit mineralization is a simple paragenesis represented by galena, nadorite, squawcreekite (flajolotite), sphalerite, and smithsonite. Dolomite, siderite and calcite are the main gangue minerals with rarely quartz, barite and fluorite. The presence of gold has been demonstrated by atomic absorption in Hammam N'bail by the ORGM (2004) [36]. Galena, smithsonite assembly gave 1.4 g/t of gold. It is not observed in the microscope, as it is expressed in ultramicroscopic form.

4.2.1. Nadorite ($PbSbO_2Cl$)

Nadorite is a lead halide, which was discovered and described for the first time by Flajolot (1870) in the region of Nador, from which it takes its name. It is common on the Hammam N'bail deposit and is expressed over the entire extent of the ore bodies (Fig. 7). It contributes significantly to providing antimony and lead during mining. From the crystal-chemical point of view and according to its properties, nadorite belongs to the class of halides, a subclass of oxyhalides.



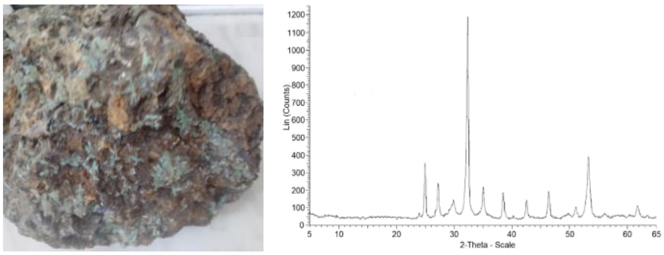
(a) (b)

Figure 7. Nadorite ganges sample: (a) general view; (b) powder diffractogram

It is a translucent mineral that crystallizes in the orthorhombic system and is yellow to black-brown in colour. It has a resinous, fragile, brittle adamantine shine, since it often occurs in strips and in platelets. It also occurs in tabular and prismatic form. Nadorite occurs in the form of fibers, needles, and in lamellae grouped in sheaves and in filling of veinlets.

4.2.2. Squawcreekite (Flajolotite) ($FeSbO_4$)

This type of mineral was also described for the first time in Hammam N'bail. It is often associated with nadorite. It filled the open space with a powdery aspect of lemon-yellow colour, easily recognizable with the naked eye. This mineral is the result of the supergene alteration of nadorite (Fig. 8).



(a) (b)

Figure 8. Squawcreekite (Flajolotite) sample: (a) general view; (b) powder diffractogram

Although various types of minerals can be found in different formations, their concentrations are typically insufficient for profitable mining. In contrast, metal deposits are relatively scarce, indicating that their concentrations are sufficient for profitable mining, provided that various economic factors are favorable. Mineral exploration aims to identify such useful deposits, but this is becoming increasingly challenging as deposits are increasingly found underground. Therefore, future explorations are likely to concentrate on developing techniques for detecting deep deposits below the surface. Sophisticated techniques have enabled the discovery of metallic minerals that are highly concentrated in rich masses due to magmatic, hydrothermal, or erosion/weathering processes.

Sulfide minerals of metals such as chromium, platinum, nickel, copper, and iron precipitate in magma-cooled bodies. These minerals settle to the bottom of an intrusion and form a thin high-grade layer, resulting in the formation of igneous deposits. On the other hand, hydrothermal deposits, which are rich in copper, lead, zinc, gold, silver, molybdenum, tin, mercury, and cobalt are formed when hot solutions circulate through fractured rocks. The solution, heated by meteorites or nearby intruders, leaches much of the dissolved metal from the surrounding rock as it moves. As the solution encounters varying pressures and temperatures, metals such as sulfides, pure metals such as gold, silver and copper settle out. This process is usually repeated several times until the heat source cools down or the fracture system is filled with mineral deposits. Our study of polymetallic mineralization hosted in sedimentary strata of northern Algeria is a significant contribution to the future of mineral exploration in North Africa. Our findings demonstrate the potential for the discovery of significant Cu, Zn, Sb, and Pb mineral deposits in the region.

Further research is necessary to explore the full extent of these mineral deposits and their economic potential. This can involve detailed geological mapping, geophysical surveys, and geochemical analyses to locate potential deposits and determine their characteristics.

In terms of mineral prospection, the development of new exploration techniques and technologies is essential for the discovery of deeper and more complex mineral deposits. This can involve the use of advanced imaging-geophysical and hyperspectral-remote sensing methods, as well as the integration of artificial intelligence and machine learning algorithms to analyze large datasets.

Our study strives to contribute to the knowledge of polymetallic mineralization in sedimentary strata in Algeria, providing a foundation for future exploration and development of mineral resources in the region. The potential of these mineral deposits can have a significant impact on the economic development of North Africa, providing employment opportunities and generating revenue for local communities. Ultimately, the aim is to promote sustainable mineral development that benefits both the environment and society.

5. Conclusions

The Hammam N'bail's Neogene basin lies within the Tellian and Numidian sheets, as well as in the Sellaouas unit. This basin, which collapsed within the mountain range, is surrounded by normal faults extending in the NE-SW and NNW-SSE direction. The basin geological composition comprises alternating layers of Mio-Plio-Quaternary sedimentary rocks with a thickness of approximately 1500 m. These layers consist of marl-clay, lacustrine limestone, conglomerates at the bottom, and travertines at the top, indicating past occurrence of thermal activity in the area.

The Sb, Pb, Zn mineral deposits found in the area are among the most recent in the north-eastern Algeria. They are located within partially dolomitized lacustrine limestone formations dating back to the Mio-Plio-Quaternary era. These mineral deposits possess distinctive characteristics, including the presence of unique mineral species that were first identified and described in this region. These species, such as nadorite and flajolotite, are rare and not commonly found in other locations around the world.

The mineralization process in the lacustrine limestone occurred in two ways: replacement and filling of open spaces, and in two distinct stages: sulfides predominate in one, and oxides in the other. During the sulfide stage, abundant hypermagnesian fluids were responsible for the deposition of zoned porphyritic dolomites, altering the host rock in certain areas, and resulting in the placement of sulfides, primarily galena, followed by chalcopyrite, sphalerite, and marcasite. At the nadorite-oxide stage, after sulfide deposition, the fluids became less rich in Mg and oxidizing conditions prevailed, resulting in the formation of oxides and hydroxides, which were associated with calcite as a matrix. Additionally, a supergene alteration phase of nadorite, lead and zinc antimony sulfides led to the emergence of flajolotite, cerussite and yellow antimony ochres.

Hydrothermal alterations have affected the dolomite, and micritic limestones have been altered by hypermagnesian fluids, leading to the deposition of zoned porphyritic dolomite. The mineralization process was initiated by brines containing Cl, Na, and Mg originated from the dissolution of halite in the Triassic gypsum saline. The mineralization was then deposited in Mio-Pliocene lacustrine limestones by hot chlorinated saline fluids, which were likely mixed fluids from both deep and basin sources. Besides the unique minerals found in this region, the presence of gold has been confirmed by chemical analysis, but further research is needed to determine how gold manifests itself mineralogically and the accompanying hydrothermal alterations.

Acknowledgements

This study was conducted under the supervision of IAWRSMB in Tunisia and the Laboratory of Applied Research in Engineering Geology, Geotechnics, Water Sciences, and Environment at Setif 1 University in Algeria. The authors would like to express their gratitude to the General Directorate of Scientific Research and Technological Development (DGRSDT-MESRS) for providing technical support. Additionally, they would like to extend their appreciation to the editor and reviewers for their valuable feedback, which helped to improve the manuscript.

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Поліметалеве орудненння, розміщене в неогенових осадових товщах Алжирського Телліанського хребта: комплексний огляд

К. Зігмі, Ф. Захрі, Р. Хаджі, К. Бенмарс, Ю. Хамед

Мета. Дослідження геологічних особливостей мінералів та групових утворень сурм'яних елементів поліметалевого орудненння в неогенових осадових товщах Алжирського Телліанського хребта на основі комплексу експериментальних та польових досліджень, необхідних як легуючі добавки при вирощуванні монокристалічного кремнію.

Методика. Використано комплексний методологічний підхід, що включає детальне геологічне картування та відбір проб, XRD мінералогічну ідентифікацію, XRF геохімічний аналіз та атомно-абсорбційну спектрофотометрію.

Результати. Отримані результати доводять, що орудненння сурми є наймолодшим явищем на північному сході Алжиру, оскільки залягає в доломітизованих озерних вапняках міо-пліо-четвертинного періоду. Визначено, що мінералізація наносилася заміщенням та заповненням відкритих ділянок. Визначено, що гіпергенне перетворення мінералу надориту призвело до появи сульфідів сурми. Встановлено присутність золота, що підтверджено хімічним аналізом, але необхідні подальші дослідження, аби визначити, як золото проявляється мінералогічно та супутні гідротермальні зміни.

Наукова новизна. Виявлено унікальні види мінералів світу: надорит у Джебель-Надорі, флайолотит у Джебель-Хеймелі, валентиніт у Джебель-Сенза, сенармонтит у Джебель-Хамімат та сервантит поблизу Айн-Керми. Родовища Хамман Н'Бейлс все ще містять значні запаси Zn, Sb і Pb.

Практична значимість. За допомогою цього дослідження надано відповідь на питання, пов'язані з походженням мінералізуючих рідин, відповідальних за формування покладів. Окрім епігенетичного характеру орудненння з утворенням унікальних та рідкісних мінералів у всьому світі, хімічним аналізом доведено присутність золота в цьому регіоні.

Ключові слова: *надорит, флайолотит, золото, міо-пліоцен, озерний вапняк*