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Sedimentary Controls of Carbonate-hosted Copper Mineralization in the Anti-Atlas, Morocco: the Role of Evaporites

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Abstract. To address the challenges of the energy transition and the increasing demand for raw materials such as copper (Cu), it is essential to discover new resources. After porphyry Cu deposits, sediment-hosted stratiform deposits represent a significant global source of Cu. The Morocco's Anti-Atlas Mountains host numerous Cu occurrences within the Ediacaran and early Cambrian carbonate sedimentary cover of the Precambrian. The Adoudou Formation, in particular, is key for understanding the formation of these deposits. This study aims to enhance the understanding of stratabound Cu deposits by focusing on the sedimentary factors and scales that governed their formation through a source-to-sink approach. The study highlights the presence of vanished evaporites, with evidence from facies associations, collapse breccias, and bipyramidal quartz with sulfate inclusions. These evaporites acted as a major source of sulfur for the formation of Cu-bearing metal complexes. Lithological variations associated with these evaporites may have controlled Cu enrichment within a specific stratigraphic interval.

1 Introduction

Copper's role in the energy and digital transitions underscores its importance to global economic growth, fuelling rising demand and the need for proactive exploration.

While porphyry-type deposits contribute 70% of to the global copper (Cu) resources, sediment-hosted stratiform Cu deposits play an important second role (11%), and are therefore worthy of investigation (Singer 2017).

In southern Morocco's Anti-Atlas Mountains (MAAM), numerous Cu occurrences occur within Ediacaran and early Cambrian carbonate sedimentary rocks lying unconformably on the basement. Although several deposits have been studied, no model on the scale of the MAAM can explain how these numerous mineralizations were deposited, and the debate remains open as to their syn- or epigenetic origin. (Bouchta et al. 1977; Leblanc 1986; Pouit 1966; Skácel 1993; Benssaou et Hamoumi 1999; Bourque 2016; Oummouch et al. 2017; Ait-Yazza et al. 2023).

This study focuses on the Bou Azzer-El Graara inlier (Fig. 1), located in the central part of the MAAM. The mineralization has been classified into two types (Bourque 2016): stratabound (Cu mineralization confined to a single stratigraphic level) and folded-band (mineralization associated

with deformation and localized in fold hinges. The stratabound level is often located at this stratigraphic position, at the beginning of the sedimentary series, at the scale of the inlier.

Several factors, such as the presence of sulfur, organic matter, oxidized sediments, porosity (vertical heterogeneities), and permeability, influence the formation, concentration, circulation, and preservation of mineralization and may control its distribution. This study seeks to assess the role and impact of these elements in the host sediment on the control of stratabound mineralization.

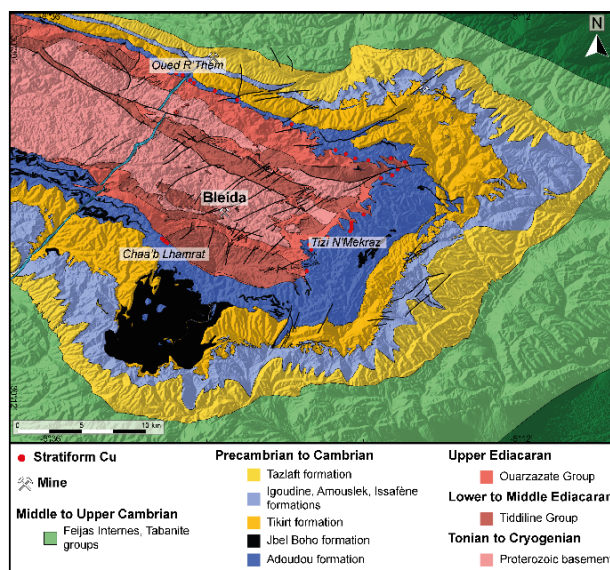


Figure 1. Geological map of the Bou Azzer-El Graara Inlier.

2 Geology of the Bou Azzer-El Graara Inlier

The NW-SE trending Bou Azzer-El Graara inlier, is located in the central part of the MAAM, on the northern margin of the West African Craton. It exposes a late Ediacaran to early Cambrian sedimentary cover unconformably overlying a Proterozoic basement (Fig. 1; Choubert 1963; Soulimani et al. 2013). The sedimentary sequence includes the Taroudant and Tata groups, composed respectively of the Adoudou (dolostone) and Tikirt (silt and sandstone) formations, and the Igoudine, Amouslek and Issafène, (dolostone and silts) and Tazlaft (sandstone) formations (Fig. 2; Soulimani et al. 2013). This study focuses on the carbonates from

the Adoudou Formation, which were deposited during a regional marine transgression from the NW of the MAAM at the end of the Ediacaran. The stratabound-type mineralization (Bourque 2016) is located in the lower half of this formation (Fig. 2).

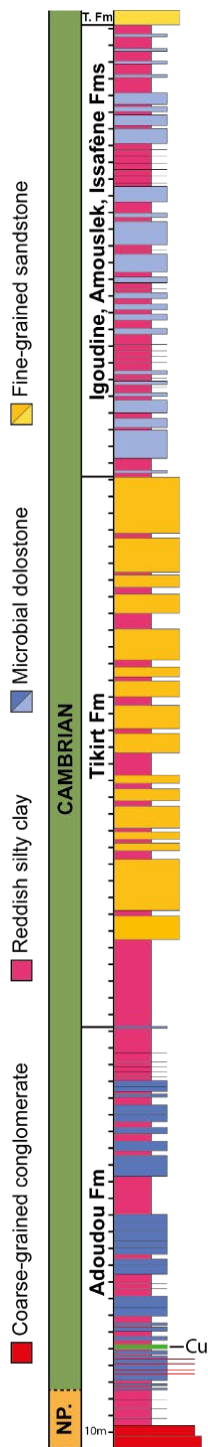


Figure 2. Sedimentary sequence of the Ediacaran- Lower Cambrian series (T Fm.: Tazlaft Fm.; NP: Neoproterozoic).

3 Methodology

A sedimentary sequence was logged in the field, recording facies, depositional sequences in order to characterize variations in the hosted sediment.

Sampling was focused on the lower part of the Adoudou Formation. Samples were collected from beds and interbeds below and within the mineralized layer (Adoudou Fm.) for sedimentary petrology, diagenetic characteristics, and petrophysical properties as well as geochronology.

The petro-diagenetic study followed a workflow including petrographic analyses, cathodoluminescence, SEM-EDS, and μ XRF analyses.

The cathodoluminescence analyses were performed at the GeoHeLiS platform (OSUR) using a Reliotron cathodoluminescence system. SEM-EDS analyses were performed on the CMEBA platform (Institute of Chemical Sciences of Rennes) using a JEOL IT-300 LA. Finally, XRF analyses were carried out at BRGM (Orléans) using a Bruker Tornado M5.

4 Results

4.1 Facies Association

The sedimentary series begins with breccias composed of coarse, sub-angular clasts embedded in a reddish silty matrix, overlying the basement. Current and wave ripple marks are visible. These breccias are followed by reddish meter-thick silts (Fig. 2).

The Adoudou Formation consists of dolostone beds, 10–70 cm thick, pale fawn to cream or dark brown, with nodular and ribbon chert. These beds show microbial laminated fabrics, with laminates

that are mostly planar to slightly wavy, crinkly, or tufted. Laminite growth can form meter-scale polygons with compressive boundaries, occasionally leading to tepee structures. Small (1 cm) domal stromatolites are common, while medium-sized (30 cm) domes, are rare, but well developed in certain layers. Locally, angular, non-oriented breccias of tabular clasts, within a fine-grained matrix, occur at the base of dolomitic beds.

Recessive meter-thick clastic interbeds, composed of reddish silts and clays, alternate with the dolostone (Fig. 3), occasionally reaching several meters in thickness. An intermediate heterolithic facies, between the interbeds and the dolostone, consist of alternating thin silty, clayey, and dolomitic beds, with brecciated textures in its uppermost part. Both facies show nodular, disrupted, or brecciated textures.

Fine- to very fine-grained well-sorted siliciclastic fractions are commonly incorporated into the dolomitic facies. Well-rounded to spherical quartz and lithic sand grains (up to 1 mm), with frosted surfaces also occur. Gypsum pseudomorphs have been observed within carbonate beds.

The stratabound mineralization is hosted within a level comprising three dolomitic beds, separated by brecciated clay-rich interbeds (Fig. 3). An intraformational breccia layer marks the base of the second dolomitic bed. Sulfides (bornite, chalcopyrite, covellite, digenite) occur as millimeter-sized disseminated grains within the microcrystalline dolomite and also in cherts. Oxidized mineralization (malachite) occurs in fractures, within cherts, and possibly in stockwork structures.

A powdery, light reddish clay-rich interbed, 2 meters thick, overlies the mineralized horizon (Fig. 2, 3).

4.2 Diagenetic Study

Several successive diagenetic phases have been identified from the laboratory analyses. They were discriminated based on petrographic and mineralogical criteria, rather than fluid temperatures. Multiple carbonate and silica phases, within a relative temporal framework, were distinguished by petrography using textural criteria such as grain size, shape and transparency. Cathodoluminescence further discriminated several generations of carbonates that were indistinguishable by optical microscopy. Micro X-ray fluorescence (μ XRF) mapped the distribution of major elements (Ca, Mg, Si, K, Al, Fe) within carbonates and silica and detected trace elements, some of which being locally abundant (Cu, S, Ti, Mn). Finally, SEM-EDS analyses provided additional confirmation and support through spot analyses.

The first phase was characterized by dolomitization and silicification of microbial mats. Then, early diagenesis was characterized by a



Figure 3. A) Weathering profile of the lower part of the Adoudou Fm. B) Insert shows detail of the stratabound interval.

widespread microcrystalline dolomite (Fig. 4A), millimeter-sized euhedral calcite crystals, and bipyramidal quartz (very early) commonly found in cavities, often euhedral but slightly corroded with Ca and S inclusions (Fig. 4B, C). A grain of euhedral quartz was observed together with frosted quartz grains in a dolomite bed, recording aeolian reworking of early diagenetic features.

Burial diagenesis, defined by euhedral, iron-rich saddle dolomite, and microcrystalline quartz (Fig. 4A), along with fibrous amorphous silica polymorphs and megaquartz. These silica phases form the nodular and banded cherts.

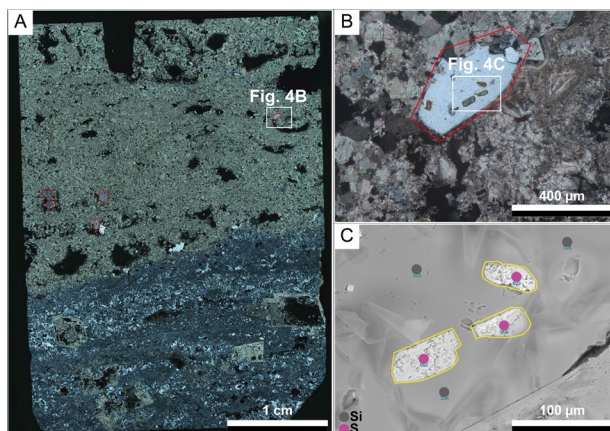


Figure 4. A) Thin section of a non-mineralized carbonate sample with siliceous chert. B) Close-up of bipyramidal quartz. C) SEM-EDS analyses of Ca and S inclusions.

Stratabound mineralization is related to the diagenetic history of the carbonates. Early, minimally altered Cu sulfides (bornite, chalcopyrite), are finely dispersed within the early diagenetic microcrystalline dolomite. Other sulfides (chalcocite, covellite) and Cu carbonate (malachite), resulting from the alteration of early sulfides, are associated with supergene alteration and later fracturing event.

5 Discussion

The basal clastic part of the sedimentary series indicates the reworking of basement elements in a continental fluvial environment. These sediments reflect oxidizing depositional conditions and may have acted as a buffer for the circulation of oxidized fluids.

The lower part of the Adoudou Formation, above the clastic member, was deposited in a mixed carbonate-evaporitic-low clastic system of low relief that evolve from shallow marine environments to continental flats.

Microbial carbonates include lacustrine or marine facies from subtidal to supratidal environments. Microbial facies exhibit growth forms and textures in both lacustrine and marine deposits, as described in ancient and modern analogues (Chraiki et al. 2023; Strohmenger et al. 2011; Mettraux et al. 2011). The different morphologies of the microbial facies (planar to tufted laminites to domal fabrics) appear to record different water depths, with domal stromatolites in slightly deeper waters.

The association of heterolithic, nodular to brecciated interbeds is interpreted as sabkha deposits in a supratidal or continental environment, under an arid climate. Although no evaporite beds are preserved, several indications point to the presence of vanished evaporites. Intraformational breccias at the base of carbonate beds are interpreted as collapse breccias resulting from evaporite dissolution. Petrographic and diagenetic analyses support field observations. Euhedral bipyramidal quartz with sulfate inclusions (gypsum or anhydrite) is commonly observed in thin sections, indicating the presence of evaporites during deposition to very early diagenesis (Grimm 1964 ; Gresse, 1968). Several occurrences of gypsum and halite pseudomorphs have been reported in the literature (Algouti et al. 2000; Chbani et al. 1999; Soullaimani et al. 2013; El Kabouri et al. 2024). Similar facies in the western Anti-Atlas have been interpreted as records of sabkha environments (Benssaou and Hamoumi 1999, 2001, 2003; Oummouch et al. 2017).

Carbonates with greater proportions of fine clastic grains, and larger rounded and frosted grains, indicate an aeolian input of silt to shallow lakes and/or the marginal sea. This aeolian regime suggests that continental flats were deflated, with the erosion of pre-lithified sabkha sediment, and reworked grains of euhedral quartz.

The thicker sabkha level located directly above the mineralized horizon suggests a greater abundance of gypsum and halite from marine water influx, which may have restricted the vertical circulation of metalliferous fluids. This may explain the

stratabound Cu enrichment at this stratigraphic position. The diagenetic study highlights distinct diagenetic phases (primary, early, burial and late). Syngenetic carbonates include an early dolomitization event that masks the mineralogy of the primary carbonate sediment as well as that of the microbial mats. Early sulfides (bornite, chalcopyrite) are disseminated within this phase. Epigenetic carbonates, such as saddle dolomite, may record different types of higher-temperature fluids. This petrographic association suggests an early origin of the sulfides (bornite, chalcopyrite), which may be confirmed by Re/Os radiometric ages on sulfides.

6 Conclusions

This sedimentological and diagenetic study confirms:

1. The presence of evaporites. The heterolithic, nodular to brecciated facies are interpreted as sabkha sediments in a supratidal environment. Carbonates record several indicators of "vanished evaporites," such as collapse breccias and bipyramidal quartz with sulfate (Ca, S) inclusions. These evaporites are an important source of sulfur and salt.
2. The Cu enrichment in the host beds may have been induced by lithological variations (silts/evaporites vs. carbonates) limiting the vertical circulation of mineralizing fluids.
3. The early sulfides (bornite, chalcopyrite) may be related to early diagenetic carbonate phases.

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