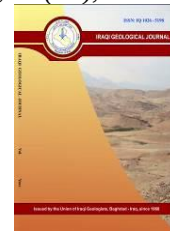




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Sedimentology, Metallographic Characteristics and Geodynamic Evolution of the Merija Copper Deposit (Marginal Folds Basin, Eastern High Atlas, Morocco)

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Abstract

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The Merija copper deposit is located in the Marginal Folds of the Moroccan Eastern High Atlas. It is a stratiform deposit hosted in sandstone-conglomerate formations of the Infra-Cenomanian, consisting of copper carbonate and sulphide mineralization (malachite, azurite, traces of chalcopryrite, chalcocite, and covellite). This mineralization exhibits different forms: dissemination in the sandstone-conglomerate host rocks and fillings of centimetric veins, sometimes with calcite. Moreover, microscopic examination shows that the mineralization is disseminated in the carbonate matrix, filling of the inter-granular spaces of the sandstone-conglomeratic material. The mineralogical association is composed of: a primary paragenesis with chalcopryrite, a secondary cementation paragenesis with chalcocite and covellite and a secondary oxidation paragenesis with malachite. This latter is the most dominant mineral presenting a micro-fibrous texture surrounding the sulphides of the primary and secondary paragenesis, composed of chalcopryrite, chalcocite and covellite. It is associated with a quartz-calcite gangue. The copper mineralization at Merija is heterogeneously distributed within the surrounding sandstone-conglomerate formation due to the diversity of paleocurrents carrying the leached copper. The rich paleocurrents trends S, SW, and SE, whereas the poor ones present an N and NW directions. These paleocurrents are derived from a fluvio-deltaic channel system that controlled sedimentary deposition in the area during the Infra-Cenomanian. This sedimentary type mineralization is probably related to a process of alteration and deposition of detrital materials loaded with copper minerals and derived from a protore copper-bearing. This alteration process gave rise to the malachite and azurite mineralization resulting from the replacement phenomenon of chalcopryrite, chalcocite and covellite.

Keywords: Copper mineralization; Sedimentary deposit; Infra-Cenomanian; Merija deposit; Marginal folds; Morocco.

1. Introduction

The Moroccan Eastern High Atlas is a metallogenic province that hosts Mississippi-Valley-Type (MVT) base metal deposits, such as Jbel Bou Dhar, Jbel Houanite, Jbel Bou Arhous and Jbel Skindis (Choulet et al., 2014), as well as pre-atlasic gold, copper and iron deposits explored in Tamlalt, Jbel Rhals (Lafforgue, 2016; Verhaert et al., 2018). Additionally, the northern front of the Eastern High Atlas hosts sedimentary Pb-Zn-Cu mineralizations such as the Merija deposit (study area) and the Bou-Sellam deposit (Caïa, 1968, 1969, 1972, 1976). Numerous stratiform Pb-Zn-Cu deposits in Lower Cretaceous detrital terrains have been discovered in the African continent (Caïa, 1976). For instance, Ain-Sefra (Cu) in Algeria (Cailleux and Thébaud, 1962), Kroussou (Pb) in Gabon (Carrie et al., 1966; Demange, 1971) and Cachoeiras (Cu) in Angola (Peres, 1970). In Morocco, this sedimentary mineralization is found in the central High Atlas, the Azilal province, in particular, consisting of the Tansrift copper deposit (Ibouh et al., 2011). Moreover, the Marginal Fold regions, at the North of the Eastern High Atlas, hosts two main deposits: the Merija (Cu) and Bou-Sellam (Pb-Zn) (Caïa, 1968, 1969, 1972). All these mineralisations are stratiform deposits, hosted in basal formations of the Lower Cretaceous in a sedimentary context (Caïa, 1976).

The Marginal Folds domain consisting mainly of Lower and Upper Cretaceous formations, overlay, unconformably, a deformed Middle Jurassic sequence. They are ENE directed upright fold, formed during the atlasic tectonics, and limited to the south by the North Atlasic Fault (Choubert, 1939). Since the publications of Caïa (1968, 1969, 1972), the mineralization of the Merija deposit has not been studied. The main aim of this study is to investigate a detailed sedimentological and metallographic analysis, in order to comprehend the emplacement mechanism of the Merija copper mineralization and its geodynamic evolution.

2. Geological Setting

The Merija deposit is located in the Marginal Folds region, at the northern margin of the Eastern High Atlas. It is bounded to the East and North-East by Jbel Mechkakour, Jbel Bou Kechba and the High Plateaus. To the North, it is limited by the Plateau of Rekkame, and by the Middle Moulouya to the West. Geologically, the study area is characterized by Cretaceous terrain covering a Jurassic sequence that crops out as “windows” (Caïa, 1968, 1969). The thickness of the Infra-Cenomanian series is more important in the South (Mazer, Bou-Sellam, Merija) compared to the North (Ksar Kaddou and Ras Rcheg) (Caïa, 1969) (Fig.1).

Locally the Merija deposit corresponds to a NE-SW anticlinal structure that extends of about 12 km in length and 3,6 km in width. It is characterized by sedimentary series, represented by a Middle to Upper Jurassic sequence that crops out at the core of the fold, and covered by Cretaceous formations represented by the red beds of the Marginal Folds (Caïa, 1972; Haddoumi et al., 2018). These Jurassic-Cretaceous terrains are overlain by recent Pliocene-Quaternary sedimentary cover (Fig.2).

Three major units can be distinguished in the study area: (i) Middle and Upper Jurassic unit, (ii) Infra-Cenomanian unit and (iii) Cenomanian-Cenomano-Turonian unit (Caïa, 1972) Fig.3A). The former unit begins with Upper Bajocian - Middle Bathonian terrains materialized by marls and Rhynchonella limestones with emersion surfaces (Caïa, 1972) (Figs. 3B and B'). The Late Jurassic is mainly made of detrital sedimentation represented by clays and red sandstones. This unit present a thickness that exceeds 100 m (Fig.4). The Infra-Cenomanian formations overlying, unconformably, the Upper Jurassic stratas, are mainly detrital rocks, materialized by 25 m of sandstones and conglomerates sequences (ic1), surmounted by 150 m of sandstones and red shales with gypsum (ic2).

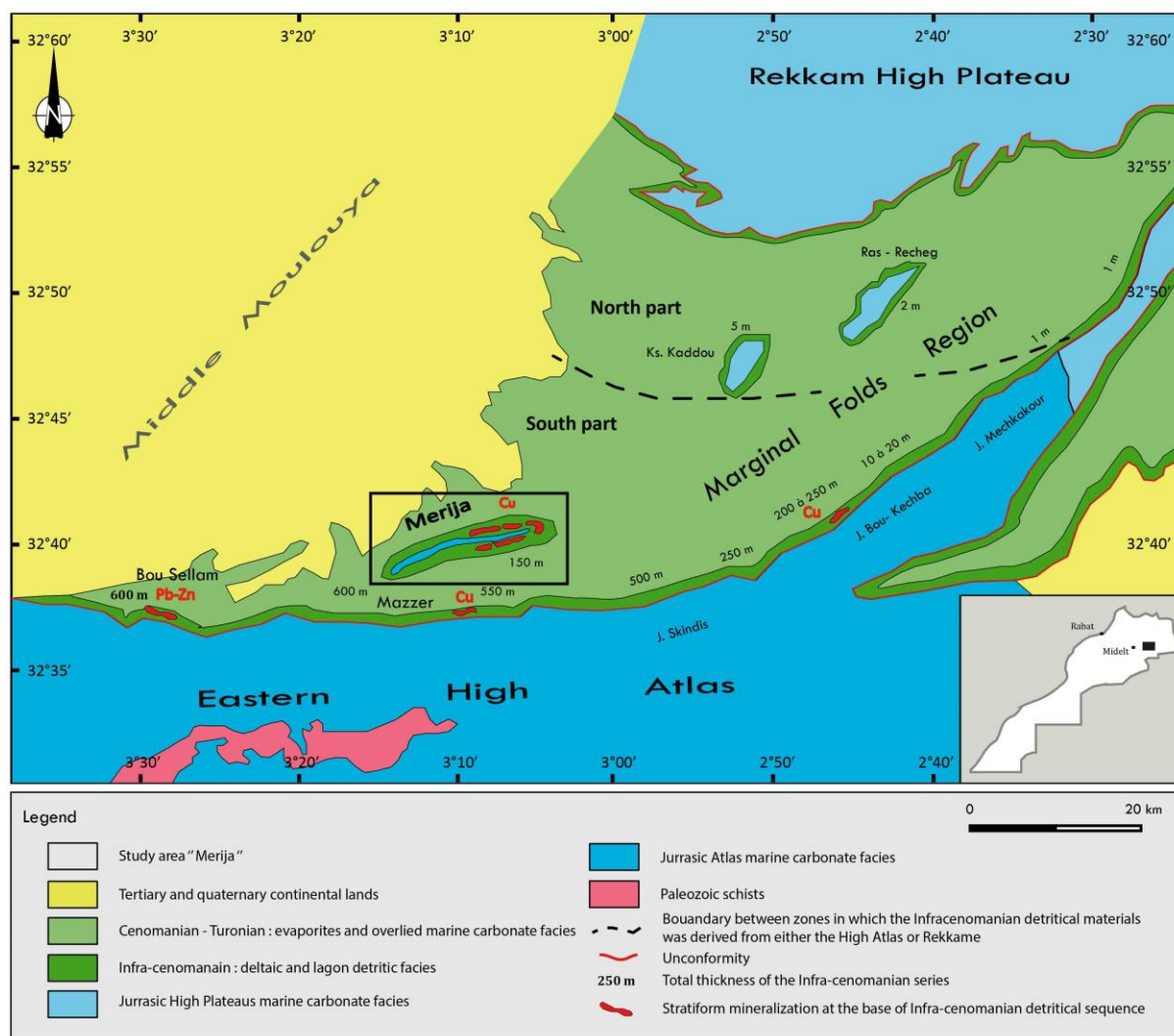


Fig. 1. Geological map of the Marginal Folds (modified after Caïa, 1969)

The sandstones and conglomerates constitute the host of the Merija copper mineralization (Caïa, 1969; Figs. 3C, C' and 4). The Upper Cenomanian and Cenomano-Turonian unit of Merija is the result of a marine transgression giving rise to gypsum versicolored marls and yellowish limestone beds (Cenomanian), capped by a carbonate bar with oysters and urchins (Caïa, 1972). This unit presents a thickness of about 200 m (Fig.4).

The Merija area is affected by the E-W to ESE-WNW compressive phase of the Alpine orogeny cycle, giving rise to an ENE-trending anticline with an eroded Jurassic core and shallowly dipping Cretaceous flanks (Aït brahim et al., 2002; Beauchamp, 2004). The NNW limb dips by 15°, while the SSE limb dips by 30° (Fig.5). The brittle deformation of the study area is manifested by several faults' systems and diaclasses, some of which are mineralized. The structural analysis of the measured fractures presents two major fault networks: ENE-WSW and the NW-SE to NNW-SSE trends (Fig.6). These two faults' networks result from two compressive tectonic regimes, during the post Infra-Cenomanian and Eocene-Oligocene periods, with a N-S to NE-SW direction in this latter (El Kochri and Chorowicz, 1996; Aït Brahim et al., 2002).

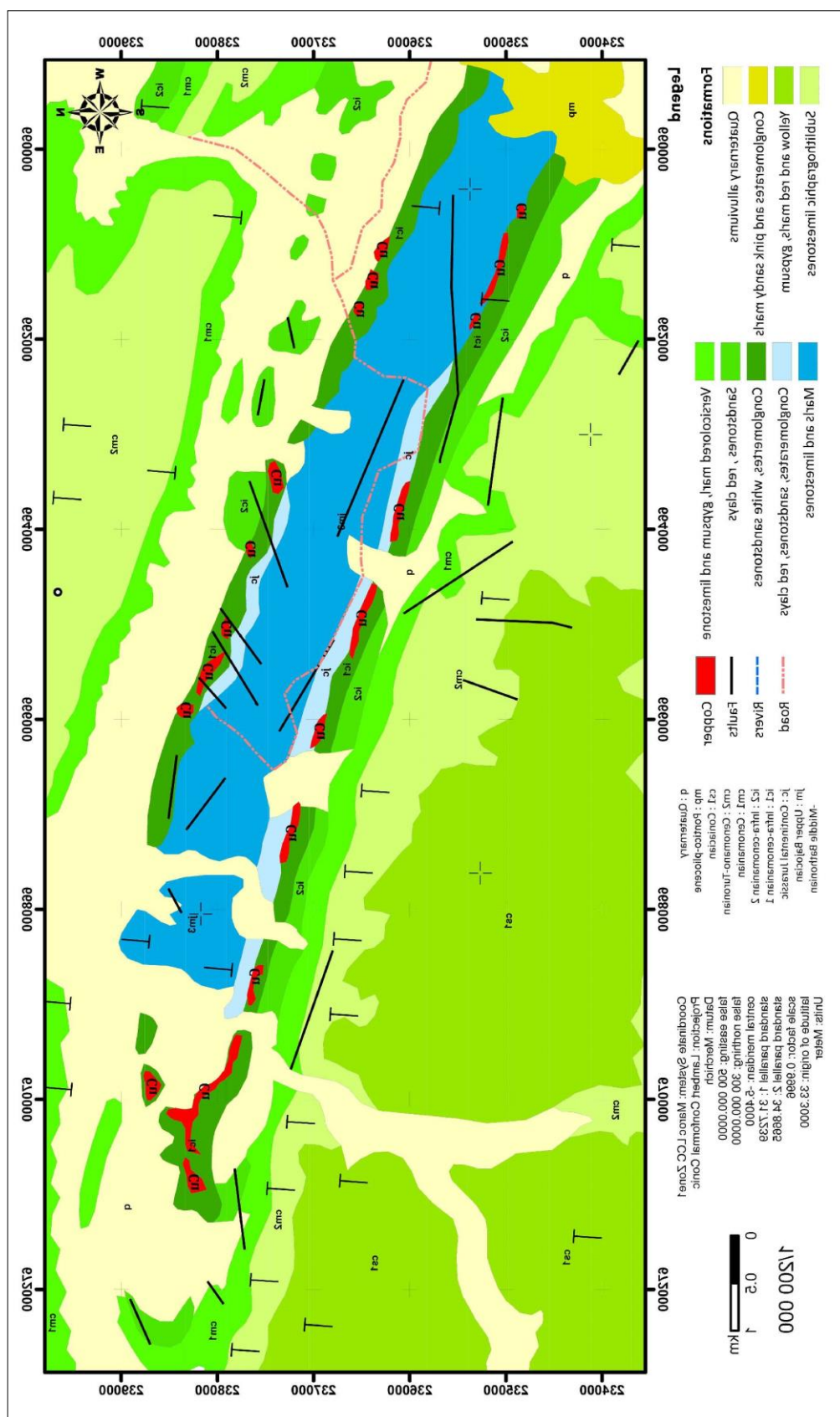


Fig. 2. Geological map of the Merija deposit (Marginal Folds of the Eastern High Atlas) extracted from the geological and mineralization map of the regions located south and east of the Middle Moulouya at 1/200 000 (modified after Caïa, 1972).

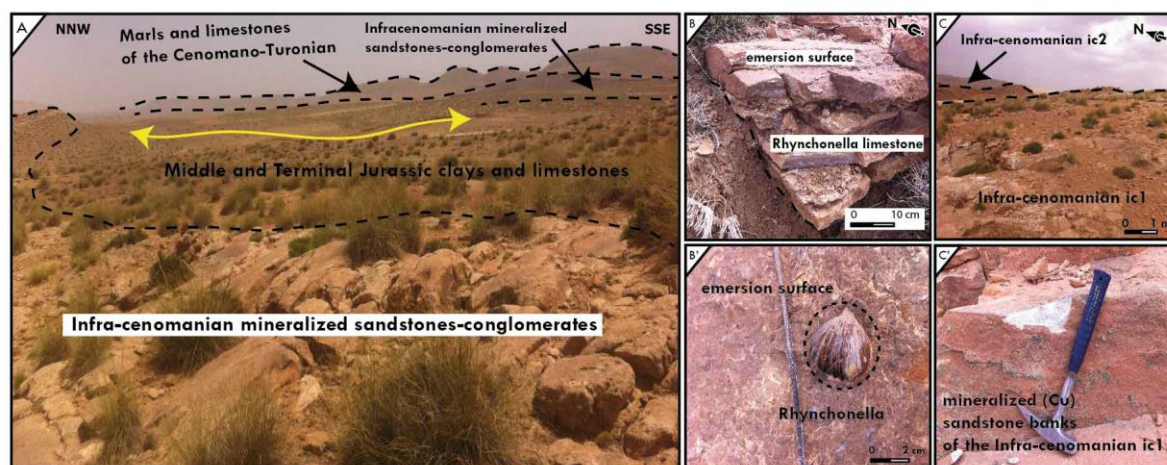


Fig. 3. Lithostratigraphy of the Merija deposit: (A) Panoramic view showing some geological outcrops of the Merija deposit; (B) and (B') Middle Jurassic Rhynchonella limestone showing an emersion surface and fossil fragments; (C) Infra-Cenomanian outcrops; (C') banks

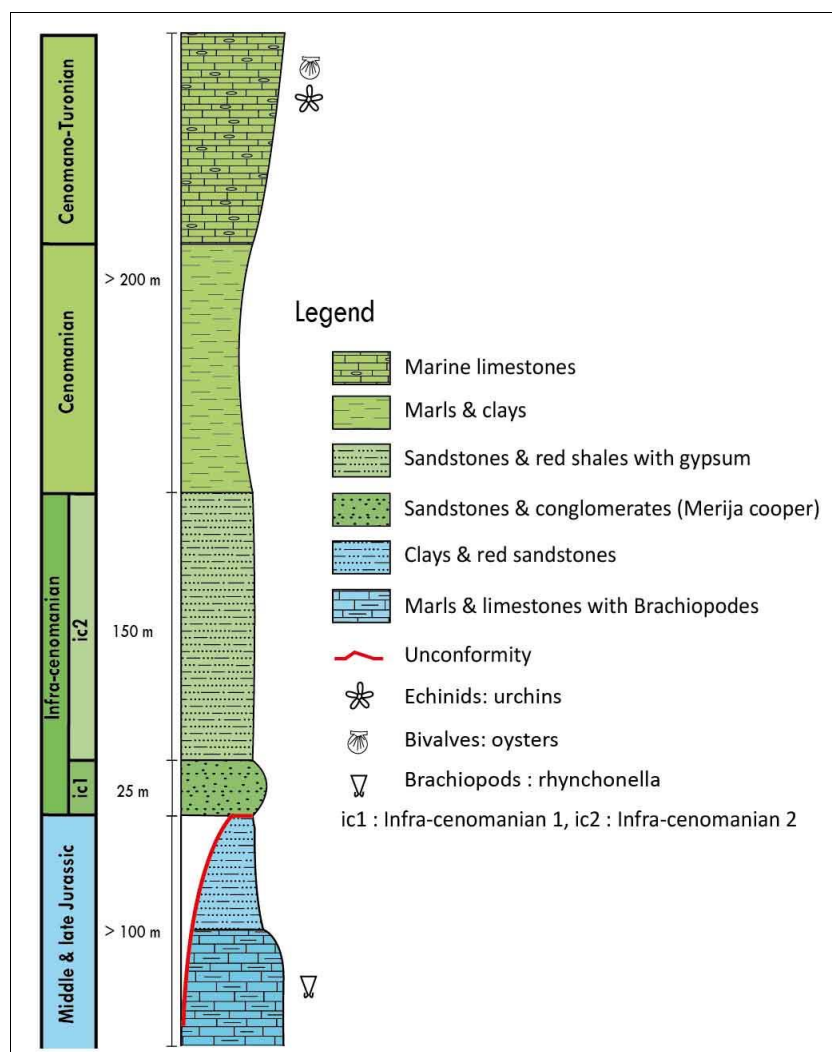


Fig. 4. Lithostratigraphic log of the Merija area, Marginal Folds, Eastern High Atlas

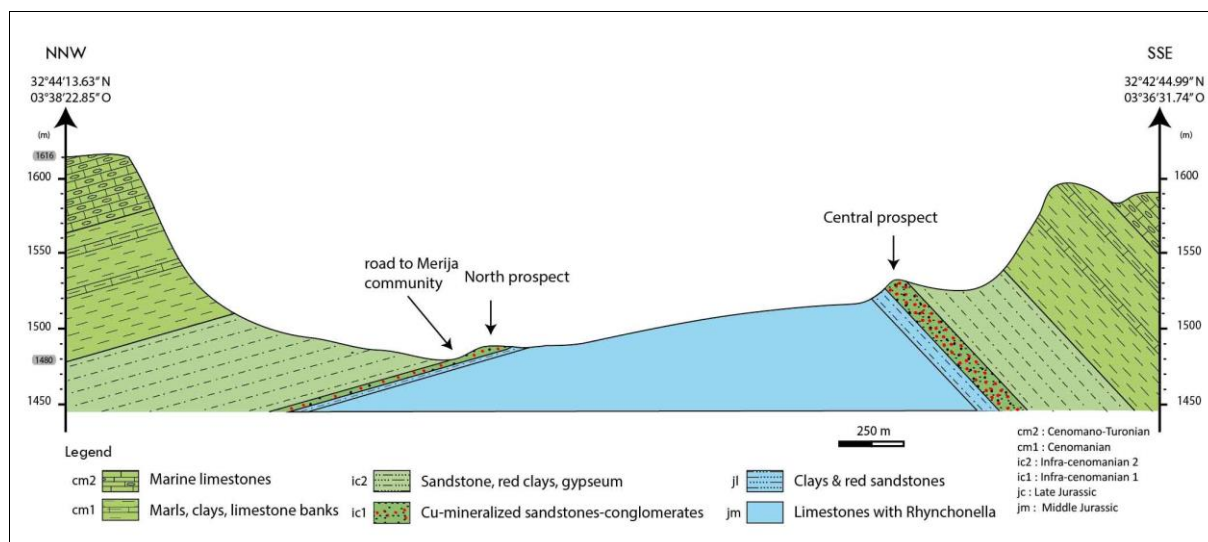


Fig. 5. Geological cross section of Merija sector, Marginal Folds, Eastern High Atlas.

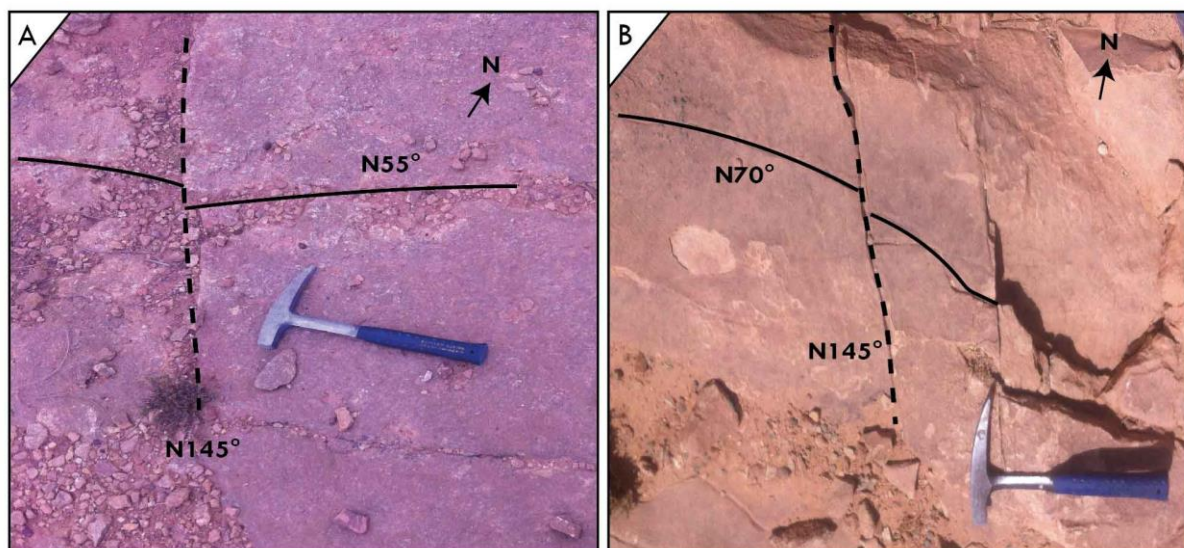


Fig. 6. (A) Diaclases network affecting the Jurassic limestones; (B) the Infra-Cenomanian sandstones of the Merija deposit.

3. Materials and Methods

The present study is mainly based on in-site analysis in the Merija deposit, coupled with laboratory work. During the first phase, a geological mapping of the sandstone-conglomerate Infra-Cenomanian formation in the Merija deposit was carried out, furthermore, a detailed sedimentological log of the latter was established. This allowed us to characterize the depositional environments and their relationship with the copper mineralization. Additionally, systematic sampling has been taken in several exploration trenches, where samples were collected from various mineralized lithostratigraphic levels, following the vertical and the lateral evolution of the sandstone-conglomeratic facies. In laboratory, thin sections were examined using polarizing microscope to identify mineral species, textures and paragenesis. Once this first petrographic examination was done, we proceed to metallographic examination of polished thin section to identify metallic minerals using the reflecting microscope.

These methods of identification of mineral species and their textural arrangement, combined with structural and sedimentological analysis of the host rocks and mineralization, allowed us to infer the geodynamic control responsible for the establishment of the Merija deposit mineralization and, thus, to propose its genesis model.

4. Results

4.1. Sedimentological Characterization

A detailed geological survey of the basal part of the Merija Infra-Cenomanian (ic1) unit, that forms the host of the copper mineralization, reveals a succession of 6 distinct facies from the base to top: (i) basal conglomerate, (ii) lower sandstone-I, (iii) interbedded clays and silts, (iv) lower sandstone-II, (v) upper conglomerate and (vi) upper sandstone.

4.1.1. Basal conglomerates

The basal conglomerates form a 20 cm to 30 cm sedimentary cover, overlaying unconformably the Jurassic Rhynchonella limestone (Caia, 1969). They are brown, yellow, and white heterometric polygenic puddings, with fragments of rounded to sub-rounded limestone and of Rhynchonella fossils remains and sometimes rounded fragments of quartz, 3cm in diameter. These materials are not granoclassified (Figs. 7A and A').

4.1.2. Lower sandstone-I

The lower sandstone-I overlies the basic conglomerates. They have a thickness range from 30 to 160 cm. They are homogeneous with carbonate binder, and characterized by: (i) medium to fine grain size of 1 to 2 mm, with rounded to sub-rounded limestone fragments, (ii) positive grain size grading and (iii) presence of iron oxides grains, and malachite dispersed in these facies (Figs. 7B and B'). These sandstone beds show horizontal stratification in the lower levels and oblique stratification in the upper ones, presenting a bevelling of the banks towards the North from 150 to 30 cm.

4.1.3. Interbedded clays and silts

The clay-silt alternation is deposited on the lower sandstone-I and shows a thickness that varies from 5 to 60 cm. The silt levels are homogeneous and friable with a carbonate binder, representing a bevelling (Figs. 7C and C').

4.1.4. Lower sandstone-II

The lower sandstone-II of the Infra-Cenomanian detrital unit shows thickness of 50 to 270 cm. They are white sandstones, homogeneous with carbonate binder, with a horizontal stratification at the base and oblique towards the top. The grain size of these sandstones is medium to fine (Fig. 7D and D').

4.1.5. Upper conglomerates

The upper conglomerates have an average thickness of 50 cm presenting a positive grano-classification. They are polygenic puddings, with carbonate binder and heterometric elements from 1 to 10 cm in size (Figs. 7E and E').

4.1.6. Upper sandstone

The upper sandstones have an average thickness of 120 cm. They are white, homogeneous and friable with a carbonate binder and fine grain size with horizontal stratification at the base and oblique

towards the top. Iron oxides minerals are represented by scattered black spots in this facies (Fig. 7F and F').

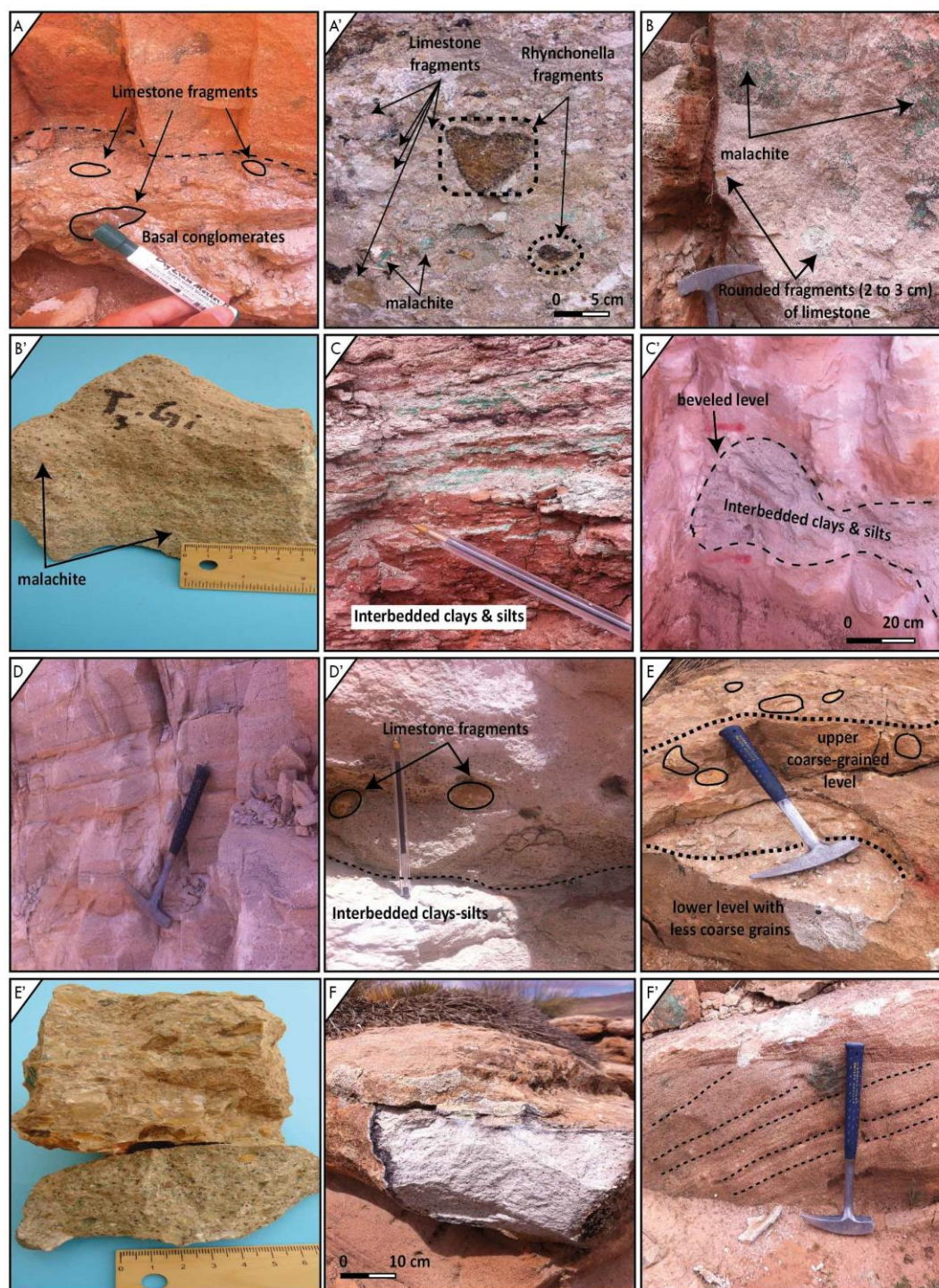


Fig. 7. Sandstone-conglomerate facies of the Merija deposit: (A) basal conglomerates with rounded limestone fragments; (A') Rhynchonella fragments; (B) lower sandstone-I contains limestone fragments; (B') shows a positive granoclassification; (C) and (C') interbedding of clays and silts which presents a bevelling; (D) and (D') bank of the lower sandstone-II which contains fragments of limestone; (E) and (E') samples taken from the upper conglomerate strata; (F) and (F') upper sandstone bank with oblique stratification.

4.2. Geodynamic Reconstitution

All the results obtained from the lithostratigraphic and sedimentological data presented above, allow us to infer that the deposition of the Infra-Cenomanian (ic1) unit of Merija was by a fluvial-deltaic system with channels (Fig.8). An analysis of the paleocurrent records at different facies of the Merija Infra-Cenomanian unit (lower sandstone and upper sandstone) reveals several paleocurrents with different origins and directions: i) S and SW paleocurrents, recorded and observed at the lower sandstones (Fig.9A); ii) SE paleocurrents, recorded and observed at the upper sandstone; iii) NW and N paleocurrents, also observed at the lower and upper sandstones (Figs. 9C, D and E); iv) Areas with interference of SW and N stream directions (Fig.9B).

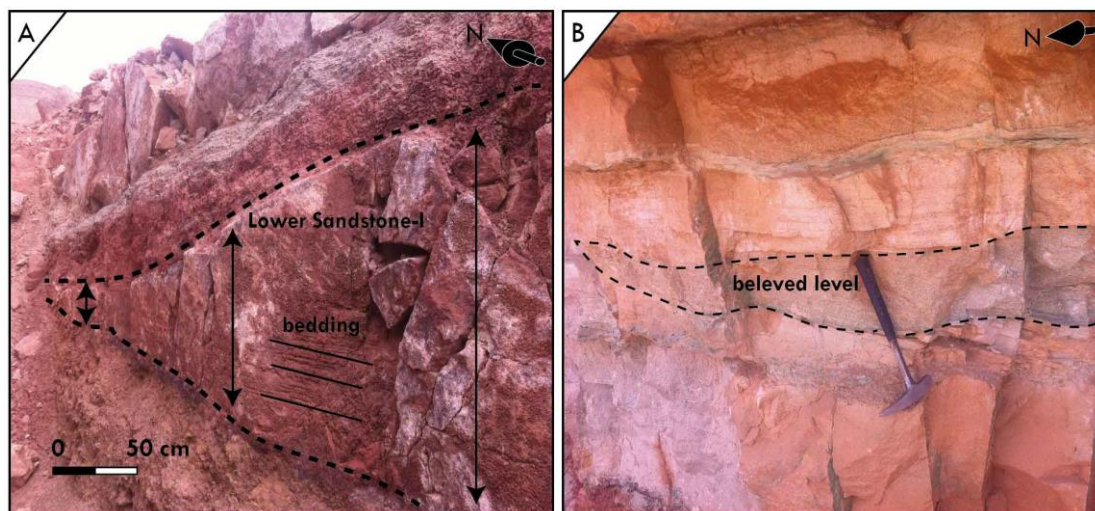


Fig. 8. (A) Beveling of the lower sandstone-I and (B) a sandstone lens

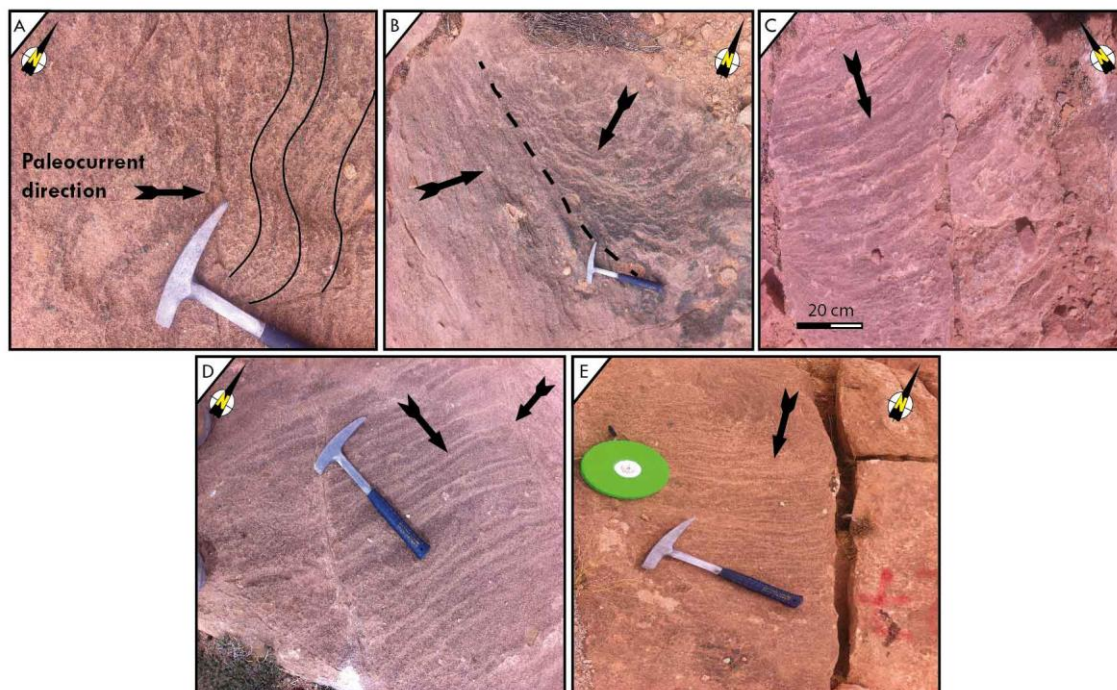


Fig. 9. Sedimentary structures of the sandstone terrains of the Merija area

Marine sedimentation during the Jurassic ends by the emersion of the Atlas basin during the final Middle Jurassic period (Haddoumi et al., 2008). This emersion was abrupt and was represented in the Merija sector by ferruginous emersion surfaces rich in Rhynchonella. This Jurassic bedrock is affected by Nevadian tectonics that developed ridges and depocenters (Du Dresnay, 1964; Laville and Piqué, 1992) that will be the receptacle of the detrital sedimentation of the Infra-Cenomanian in an ejective style (Schaer and Kiraly, 1972). The fluvio-deltaic system of the sandstone-conglomerate terrains of the Merija was triggered after the emersion of the Atlas basin (Haddoumi et al., 2008, 2018).

The flow of this sedimentation system is periodic, indicating a high energy periods and low energy periods. The high-energy flow characterizes a rapid sedimentation environment, emplacing the conglomeratic levels. During the low-energy period, the sedimentation environment become uniform depositing the sandstone levels (lower and upper sandstones). This energy decrease tends to be damped at the interbedded clay and silt in a deltaic environment located throughout the sandstone package.

The fluvio-deltaic sedimentation giving rise to the sandstone-conglomerate terrains of the study area was guided by various paleocurrents: S, SW, SE, N and NW. The grain size ranges from medium to coarse in the S, SW and SE paleocurrents, into fine-grained in the N and NW trending paleocurrents. This variation in grain size indicates a contrast in flow energy between different paleocurrents. i.e the energy of the S, SW and SE paleocurrents is stronger than those of the N and NW. Additionally, the marked color contrast between the facies of the Merija Infra-Cenomanian unit may support this difference in paleocurrent origin. This sedimentary process is generated following to an intense erosion of the relatively High Atlasic relief in the south and the Rekkam High Plateau in the north (Caïa, 1969, 1976) throughout the Nevadin tectonics (Du Dresnay, 1964; Mattauer et al., 1977; Laville and Piqué, 1992). This erosion is justified by the large fragments of limestone and quartz, incorporated in the detrital sediments.

The limestone fragments and fossils remain observed are derived from the Lias and Dogger limestones, whereas the quartz fragments are probably of Saharan domain origin (Choubert and Faure-Muret, 1962). The sedimentation of detrital materials eroded during the Infra-Cenomanian is carried out in a syn-sedimentary context during the Infra-Cenomanian, where there was a dynamic sedimentary receptacle (Nevadian tectonics) (Du Dresnay, 1964; Mattauer et al., 1977; Laville and Piqué, 1992).

4.3. Petrographic Characterization

The petrographic study of the samples from the different mineralized sandstone-conglomerate facies of the Infra-Cenomanian unit of Merija, under polarized light (LPNA) and analyzed light (LPA) shows that:

The basal and upper conglomerates present a mineralogical association with sub-angular to rounded quartz, dark gray to brown allochaemes, associated with intraclasts of remains, altered limestones and bioclasts with sparitic cement, and calcite crystals. All these constituents are bound by a carbonate microcrystalline matrix (Figs. 10A and B).

The lower and upper sandstones exhibit a mineralogical association consisting mainly of quartz, limestone intraclasts remains of very altered and small fossils, calcite crystals and sometimes microfragments of roots. Opaque minerals, probably corresponding to iron oxides and sulphides, are also present in the carbonate matrix of this sandstone facies (Figs. 10C, D, E and F).

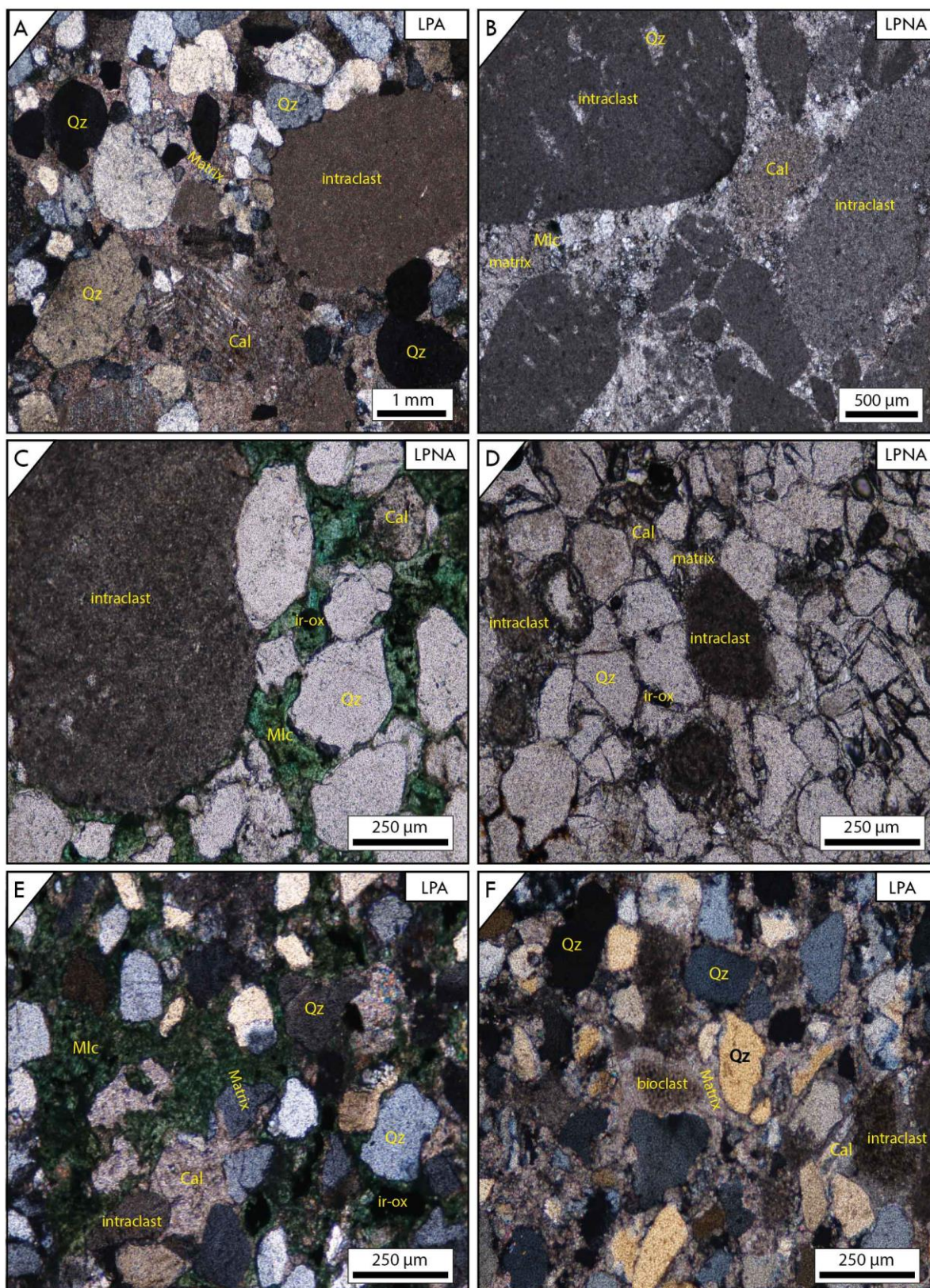


Fig. 10. Thin sections of (A) basal conglomerates; (B) upper conglomerates; (C) lower sandstones-I of the S, SW, SE paleocurrent zone; (D) lower sandstone-I of the N, NW paleocurrent zone; (E) upper sandstones of the S, SW, SE paleocurrent zone; (F) upper sandstones of the N, NW paleocurrent zone; Qz: quartz, Cal: calcite, Mlc: malachite, ir-ox: iron oxides, LPNA: polarized light, LPA: polarized and analyzed light.

4.4. Mineralization

The Merija deposit is characterized by a stratiform copper mineralization. It is hosted in the basal sandstone-conglomerate formation of the Infra-Cenomanian (ic1) (Caïa, 1969) and is essentially materialized by malachite, locally associated with calcite. The copper mineralization of Merija is presented, often as heterogeneous disseminations in the series of the sandstone-conglomerate formation. This mineralization can be present in the form of centimetric veinlets.

4.4.1. Stratiform mineralization

- Along the bedding of the strata: these are greenish millimetric lines that follow the bedding of the sandstone facies. These lines do not present a crystalline form visible to the naked eye (Fig.11A).
- Disseminations: these are small greenish millimetric spots, clearly visible to the naked eye. These scattered spots are more frequent on coarse facies, forming the filling of inter-granular spaces. This dissemination is also observed in the silts of the clay-silt alternation in the form of very fine grains incorporated in the silty sediment with very high concentration (Fig.11B).
- Aggregates: the stratiform mineralization at Merija may occur in the form of centimetric aggregates, probably due to the dissolution of the carbonate binder of the sandstone facies, favoring the precipitation of these malachite aggregates in the form of residual mineralization (Fig.11C).

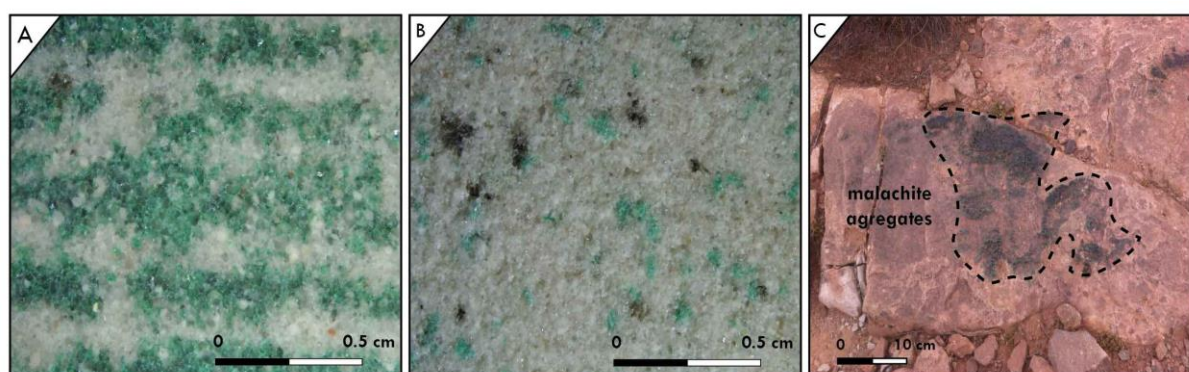


Fig. 11. Macro-samples showing the morphologies of the stratiform ore body, (A) following the bedding of the layers; (B) disseminated form; (C) as aggregates.

4.4.2. Veins

This is a filling of centimetric veinlets of a thickness of 3 to 5 cm, trending NW-SE, NNW-SSE and ENE-WSW affecting the basal sandstone-conglomerate facies of the Merija Infra-Cenomanian unit. The filling of these veins is often marked by malachite with microcrystalline and fibrous textures associated with crystallized calcite. This mineralization in veins and veinlets is probably the result of a later remobilization of the stratiform ore leading to the re-concentration and crystallization of malachite and calcite in fractures (Fig.12).

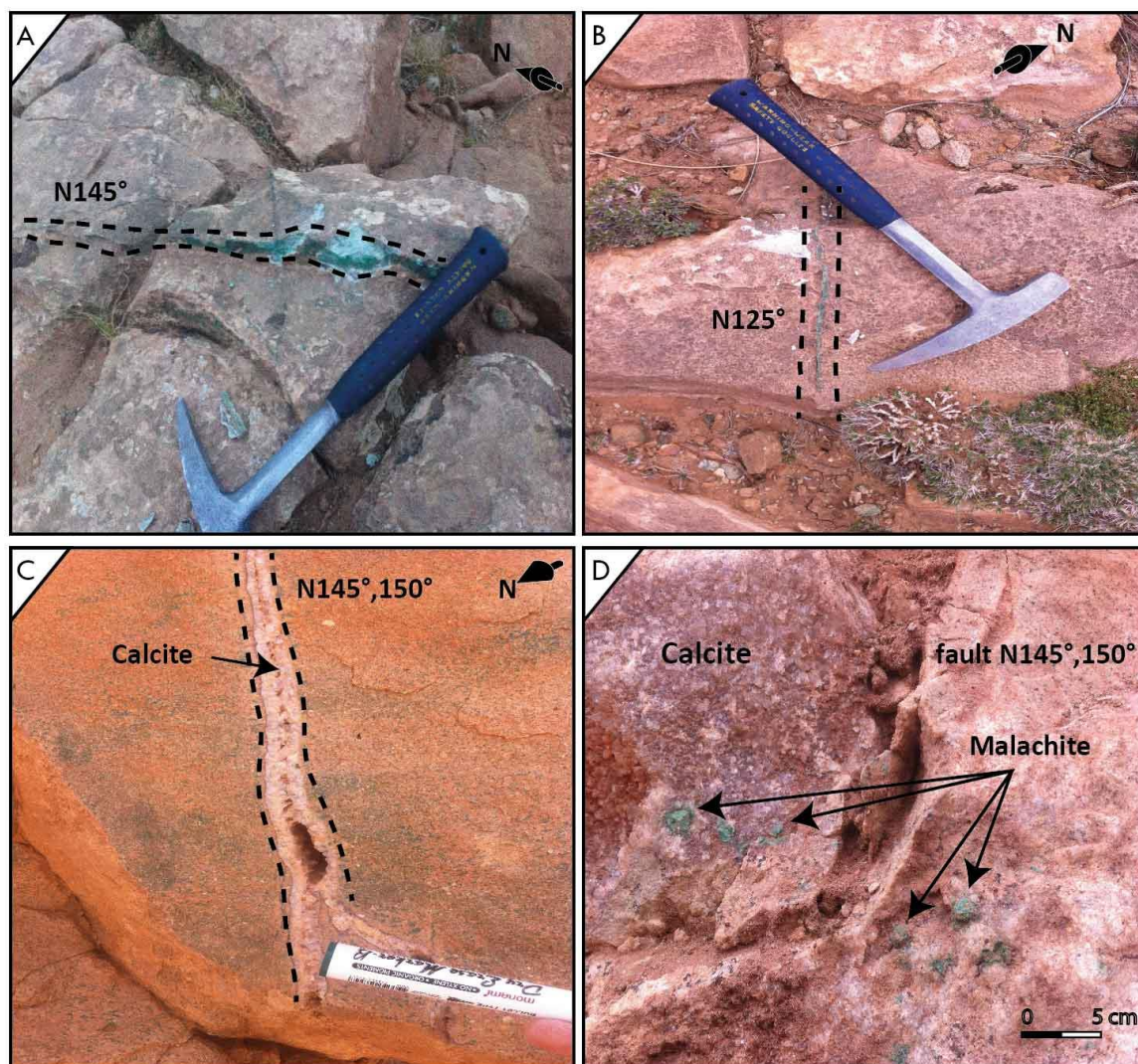


Fig. 12. (A) and (B) malachite veinlets; (C) and (D) calcite veins associated with malachite crystals

4.5. Metallographic Characterization

Metallographic examination of thin sections made from samples of the different basic facies of the Merija Infra-Cenomanian (ic1) unit shows a mineralogical association composed of primary and secondary sulphides, carbonates and oxides that appear as filling of the inter-granular spaces between quartz crystals in a carbonate matrix. The primary and secondary sulphides are represented by chalcopryrite, chalcocite and covellite. Chalcopryrite occurs as rare rounded grains, due to the reworking of the mineral during its depositional process. Chalcocite and covellite occur as rare aggregates developing at the edges of chalcopryrite (Figs. 13A and B). Secondary minerals are represented by malachite, azurite and iron oxides (Figs. 13C, D, E and F). Malachite is the most dominant mineral in the mineralogical association represented as disseminations with a fibrous microcrystalline texture and develops at the extremity of the sulphides (Fig.14). The copper mineralization of Merija is associated with a gangue materialized by quartz and calcite.

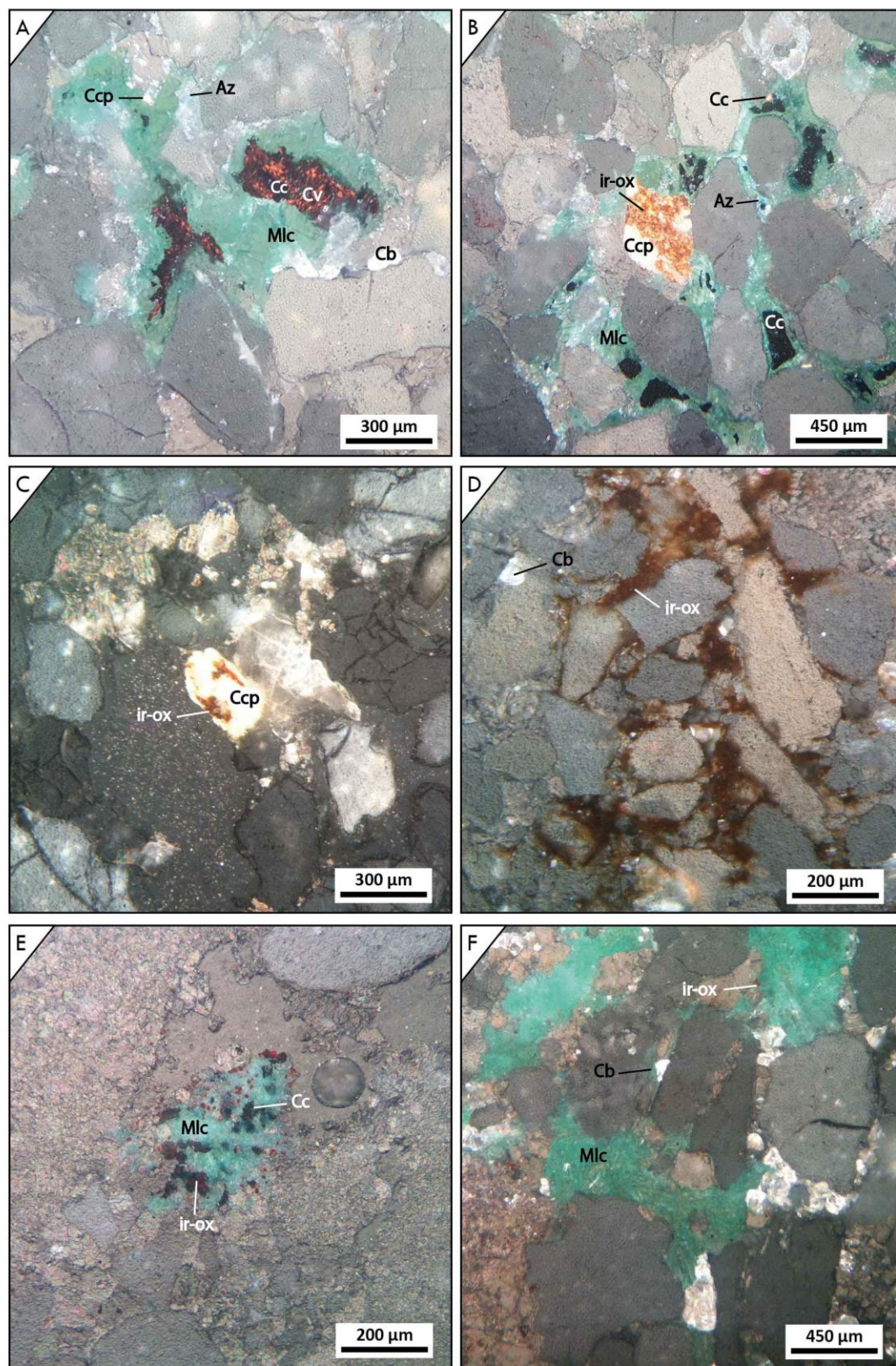


Fig. 13. Thin sections observed under a metallographic microscope in polarized reflected light of: (A) and (C) the lower sandstones-I; (B) and (D) lower sandstones-II; (E) upper conglomerates; (F) sandstone II; Ccp: chalcopyrite, Cv: covellite, Cc: chalcocite, Mlc: malachite, Az: azurite, ir-ox: iron oxides and Cb: transparent carbonate.

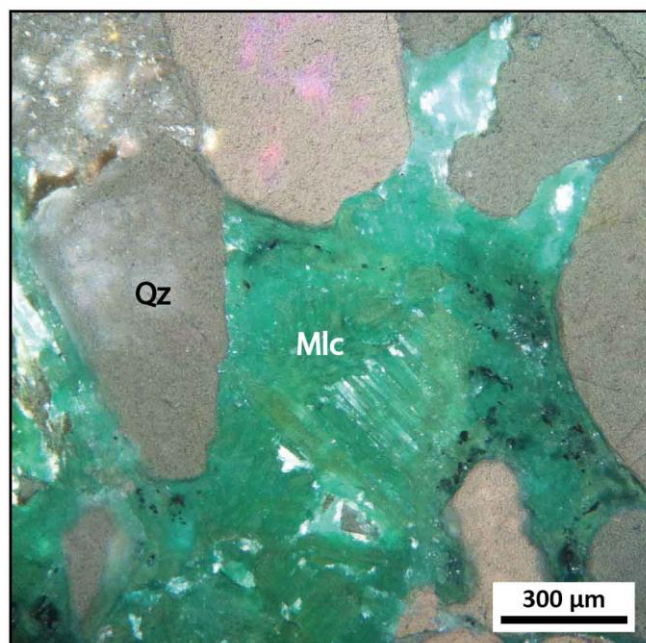


Fig. 14. Thin section observed under a metallographic microscope in polarized light, showing the fibrous microcrystalline texture of malachite (Mlc) with quartz crystals (Qz).

The results obtained from the metallographic characterization of the Merija copper mineralization show that it is made of two distinct mineral paragenesis associated with a quartz-carbonate gangue (Fig.15). The primary paragenesis of the Merija copper mineralization is represented by chalcopyrite grains of rounded shape. This morphological aspect shows that these chalcopyrite grains are reworked from a protore deposit. The secondary paragenesis of the Merija copper deposit is characterized by two phases: (i) a cementation phase represented by covellite and chalcocite that replace the primary chalcopyrite and (ii) an oxidation phase marked by malachite and azurite that develop at the edges of chalcopyrite, chalcocite and covellite. This oxidation phase is also characterized by iron oxides.

Mineral	Primary phase	Secondary phase	Supergene phase
Chalcopyrite	—————	- - - - -	
Covellite		—————	- - -
Chalcocite		—————	- - -
Malachite			—————
Azurite			—————
Iron oxides			—————
Calcite	—————		

Fig. 15. Paragenetic succession of the different mineral species of the Merija deposit

4.6. Distribution of Mineralization

The stratiform copper mineralization of Merija is characterized by a heterogeneous distribution along the host sandstone-conglomerate formation (Fig.16). This copper enrichment is the result of a sedimentary process generated by a system of paleocurrents (Caña, 1969, 1976). These paleocurrents

have a diversified provenance implying a diversity of detrital material sources. This may explain, presumably, the unequal distribution of mineralization in the same facies within the same lithostratigraphic level of the Infra-Cenomanian. Caia (1969, 1976) attributed this heterogeneity of distribution to the concentration of mineralization that tends to be in the paleochannel environments rather than in the interchannel spaces. Thus, the copper-enriched zones are derived from the S, SW and SE paleocurrents, which are very rich in mineralization. However, the copper-depleted zones were established by N and NW paleocurrents. These data, therefore, indicate that the control of the distribution of mineralization is related to the richness of the source and/or the degree of leaching of the source deposit.

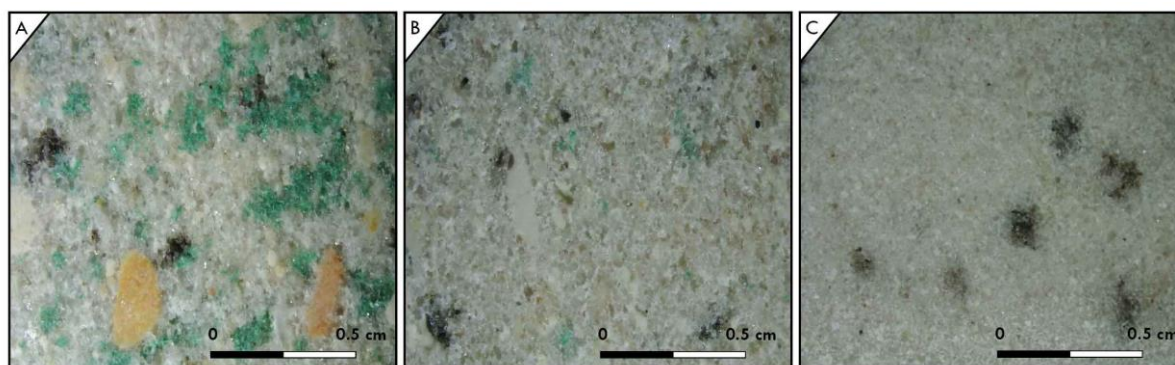


Fig. 16. Marco-samples illustrate the distribution of mineralization at the same lithostratigraphic level, (A) and (B) rich to medium concentration; (C) low to barren.

5. Discussion

Copper mineralization is disseminated in the sandstone-conglomerate terrain, developing in the carbonate matrix that fills the inter-granular spaces of the bearing facies. This morphological aspect indicates that the mineralization was deposited according to a syngenetic model via a detrital sedimentary process. This is evidenced by the reworked limestone and fossil fragments embedded in the sandstone-conglomerate facies. They are products of the erosion of the Lias and Dogger reliefs of the Eastern High Atlas in the south and the Rekkame Plateaus in the north, relatively raised during the late-jurassic pre-cretaceous period (Caia, 1969, 1976; Michard and Sougy, 1974, 1975; Mattauer et al., 1977). This genetic relationship between the emplacement of the mineralization and its detrital host, and the absence of any evidence of hydrothermal phenomena, confirm that this is, indeed, a sedimentary type deposit (Caia, 1969, 1976) generated by all the surface geodynamic processes previously discussed.

The sedimentological data shows that there are several major source directions of the detrital bearing material, and thus, probably, several copper sources. The S, SW, and SE trending paleocurrents produced zones of rich mineral concentration, whereas the N, NW directions are the origin of the highly depleted to barren zones. The S, SW and SE sources probably correspond to the MVT mineralization (Mississippi-Valley-Type) Lower Jurassic limestone related to the Atlas basin metalliferous deposits, and/or Hercynian basement deposits. The N and NW sources are probably the Jurassic limestone plateaus further north (Rekkame Plateau) that may contain MVT copper concentrations. The difference in concentration is due to the degree of leaching and/or the richness of the source deposit. Primary paragenesis is characterized by a reworking of chalcopyrite by placing it in the form of rounded grains. Sometimes these grains show supergene alteration to secondary sulphides and iron oxides. Chalcocite and covellite are probably formed during the cementation phase of the copper protore deposit, by the re-precipitation of copper in a reducing environment (Reichert and Borg 2008; Choulet et al., 2014).

This chemical process is the result of the reaction of sulfate products of copper previously formed by the oxidation of copper protore deposit (Jébrak and Marcoux, 2008).

The malachite and azurite with the iron oxides paragenesis were precipitated during the oxidation phase of the supergene alteration. This phenomenon is generated by the gravitational percolation of meteoric waters during the Alpine uplift, in an oxidizing environment by the chalcocite, covellite and sulfates produced during the cementation phase (Choulet et al., 2014). Malachite is formed from the reactions of soluble copper, which comes from copper sulfates, with carbonic acids, previously formed during the cementation phase. Azurite is expressed very rarely by replacing malachite by the phenomenon of pseudomorphosis (Kharis, 2015). Iron oxides result from the probable oxidation of pyrite or from the iron contained in the system. The copper veins that cross the sandstone-conglomerate formation are due to the later remobilization of the stratiform ore, leading to the reconcentration and crystallization of the malachite and the calcite in fractures.

6. Conclusions

From the macroscopic and microscopic results obtained, it is found that the Merija deposit characterizes the oxidation phase of a protore deposit, and displays an abundance of the malachite mineral with some traces of primary and secondary sulphides, represented by chalcopyrite, chalcocite and covellite. In summary, this deposit comes from the desegregation of protore deposits with primary sulphide ores, and their reworking by the surface paleocurrents loaded with altered detrital materials. This phenomenon is carried out at the time of deposition of the detrital host material in a fluvio-deltaic system during the Infra-Cenomanian (ic1) (Fig.17).

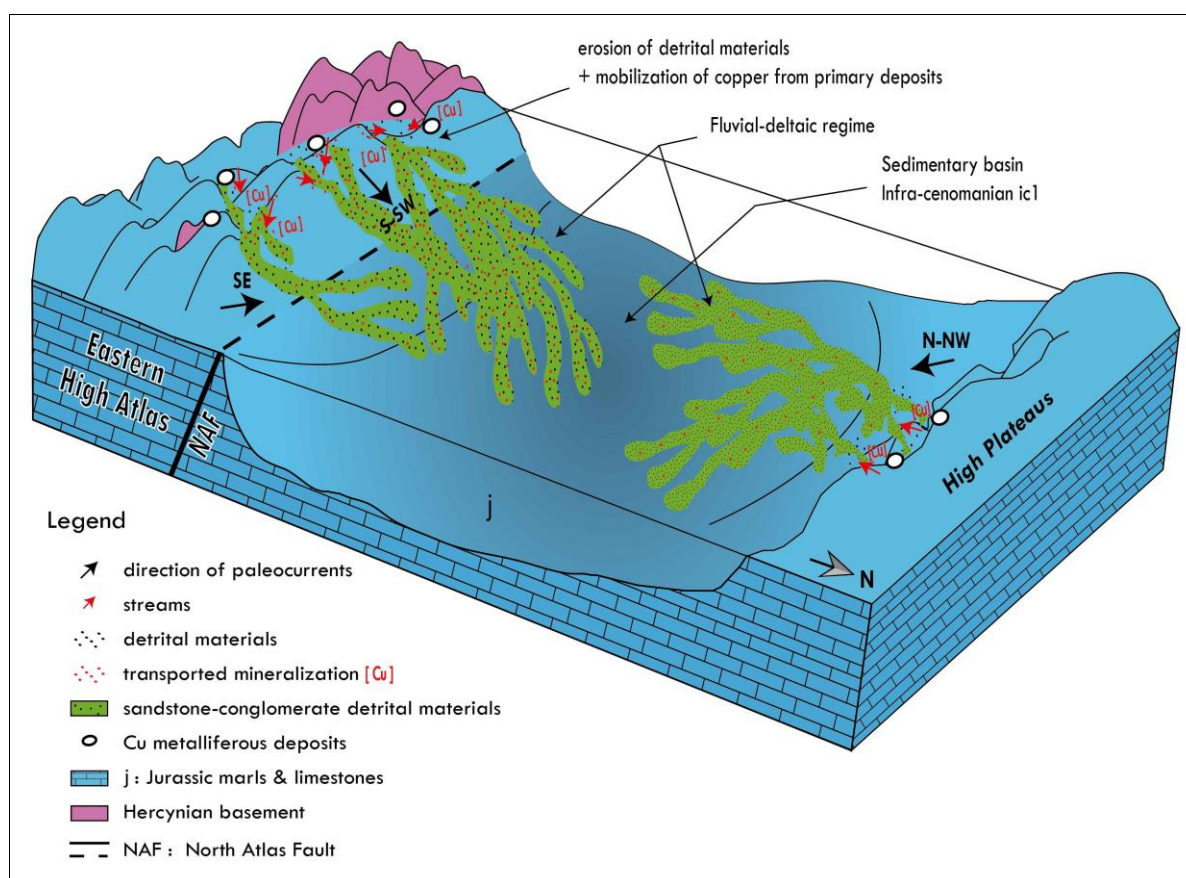


Fig. 17. Geodynamic model of the stratiform copper deposit of Merija.

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References

- Ait Brahim, L., Chotin, P., Hinaj, S., Abdelouafi, A., El Adraoui, A., Nakcha, C., Dhont, D., Charroud, M., Sossey Alaoui, F., Amrhar, M., Bouaza, A., Tabyaoui, H., Chaouni, A., 2002. Paleostress evolution in the Moroccan African margin from Triassic to Present. *Tectonophysics* 357, 187-205.
- Beauchamp, W., 2004. Superposed folding resulting from inversion of a synrift accommodation zone, Atlas Mountains, Morocco. in K. R. McClay, ed., *Thrust tectonics and hydrocarbon systems*. American Association of Petroleum Geologists, 82, 635-646.
- Caïa, J., 1968. Minéralisations plombo-cupro-zincifères dans les formations grés-conglomératiques continentales du début de l’Infracémomanien en bordure septentrionale du Haut Atlas oriental (Maroc): Acad. Sci. Paris Comptes rendus, s6r. 267, 283-286.
- Caïa, J., 1969. Les minéralisations plombo-cupro-zincifères stratiformes de la région des plis marginaux du Haut Atlas oriental: un exemple de relations entre des minéralisations et une sédimentation détritique continentale: Morocco, Service géol. Notes, 29, 107-120.
- Caïa, J., 1972. Carte géologique et minéralisations des régions situées au Sud et à l’Est de la moyenne Moulouya (Haut Atlas oriental, régions des Plis marginaux, Rekkame). Notes et Mémoires du Service géologique du Maroc, Rabat, n° 233.
- Caïa, J., 1976. Paleogeographical and Sedimentological Controls of Copper, Lead, and Zinc Mineralizations in the Lower Cretaceous Sandstones of Africa. *Economic geology*, 71, 409-422.
- Cailleux, A., Thébault, J.Y., 1962. Les concentrations de cuivre stratiformes de l’Atlas saharien (Algérie), in Lombard, J., and Nicolini, P., eds., *Gisements stratiformes de cuivre en Afrique: International Geology Congress, 21st, Copenhagen 1960, Symposium, 1*, 33-42. (Paris, Assoc. Services Géol. Africains).
- Carrie, M., Knup, M., Nicolini, P., 1966. Minéralisations plombo-zincifères du Crétacé gabonais, in *Gisements de plomb-zinc en Afrique: Tunis Annales Mines Géologie*, 23, 295-393.
- Choubert, G., Faure Muret, A., 1962. Evolution du domaine atlasique marocain depuis les temps paléozoïques, *Livre à la mémoire du Professeur Paul Fallot*. Société géologique de France, Paris, 447-527.
- Choubert, G., 1939. Sur le Crétacé du Maroc oriental. *Comptes Rendus des Séances de l’Académie des Sciences de Paris*, t. 208, n° 3, 209-211.
- Choulet, F., Charles, N., Barbanson, L., Branquet, Y., Sizaret, S., Ennaciri, A., Badra, L., Chen, Y., 2014. Non-sulfide zinc deposits of the Moroccan High Atlas: multi-scale characterization and origin. *Ore Geology*, 56, 115-140.
- Demange, M., 1971. Plomb-zinc-barytine-fluorine et métaux connexes: Plan minéral, Rgp. Gabon. Minist. Mines, Direct. Mines, 201-213.
- Du Dresney, R., 1964. Les discontinuités de sédimentation pendant le Jurassique dans la partie orientale du domaine atlasique marocain, leurs conséquences stratigraphiques et leurs relations avec l’orogénèse atlasique. In *Coll. Jurassique, Luxembourg, Comm. Strat. Congr. Géol. Intern. Luxembourg, Inst. Grand-ducal*, 899-912.
- El Kochri, A., Chorowicz, J., 1996. Oblique extension in the Jurassic trough of the central and eastern High Atlas (Morocco). *Canadian Journal of Earth Sciences*, 33, 84-92.
- Haddoumi, H., Charrière, A., Andreu, B., Mojon, P.-O., 2008. Les dépôts continentaux du Jurassique moyen au Crétacé inférieur dans le Haut Atlas oriental (Maroc) : paléoenvironnements successifs et signification paléogéographique. *Carnets de Géologie. Notebooks on Geology*.

- Haddoumi, H., Charrière, A., Feist, M., Baidder, L., Ferrière, J., Karim, M., Ettachfini, E., Mamoun, S.D., Chennouf, R., Rachdi, A., Adardor, S., 2018. A Barremian Aptian Tethyan precursor of the Cretaceous marine flooding of Morocco Evidence from the red-bed series within the Marginal Folds the eastern High Atlas.
- Ibrouh, H., Michard, A., Hibti, M., EL Amari, K., 2011. Le cuivre des couches rouges de Tansrift (Atlas d'Azilal).
- Jébrak, M., Marcoux, E., 2008. Géologie des ressources minérales, Ministère des Ressources Naturelles et Faune, Québec, Canada.
- Kharis, A., 2015. Caractérisation litho-structurales, métallogéniques, et phases fluides de la minéralisation à Cu, Pb et Ba du district minier d'Oumjrane-Boukerzia (Anti-Atlas oriental, Maroc) Thèse de doctorat, Université Moulay Ismail-Faculté des Sciences Meknès.
- Lafforgue, L., 2016. Place de la minéralisation de manganèse de Bouarfa dans l'évolution méso-cénozoïque de l'oriental marocain. Thèse de Doctorat à l'université Paris-Saclay.
- Laville E., Piqué A., 1992. Jurassic penetrative deformation and Cenozoic uplift in the central High-Atlas (Morocco): a tectonic model. Structural and Orogenic inversions. *Geologische Rundschau*, 81, 1, 157-170, Stuttgart.
- Mattauer, M., Tapponnier, P., Proust, F., 1977. Sur les mécanismes de formation des chaînes intracontinentales. L'exemple des chaînes atlasiques du Maroc. *Bulletin Society Géology*, 19, 521-526.
- Michard, A., Sougy J., 1974-1975. L'orogénèse hercynienne à la lisière nord-ouest de l'Afrique, structure des chaînes primaires du Maroc au Sénégal, in : La chaîne varisque d'Europe moyenne et occidentale. Coll. Intern. C.N.R.S., Rennes, éd. C.N.R.S., Paris.
- Peres, A.M., 1970. Novas ocorrências minerais em Angola (II): Angola, *Servicos Geologia Minas Bull.* 22, 5-90.
- Renfro, A. R., Genesis of evaporite-associated stratiform metalliferous deposits-a sabkha process: *Econ. Geol.*, 69, 33-45.
- Reichert, J., Borg, G., 2008. Numerical simulation and a geochemical model of supergene carbonate-hosted nonsulphide zinc deposits. *Ore Geology*, 33, 134-151.
- Schaer, J.-P., Kiraly, L., 1972. Fissuration dans les roches carbonatées du Haut Atlas au Sud de Midelt. *C.R. activ. Serv. Carte géol. Maroc*, 44-47 (néd.).
- Verhaert, M., Bernard, A., Saddiqi, O., Dekoninck, A., Essalhi, M., Yans, Y., 2018. Mineralogy and Genesis of the Polymetallic and Polyphased Low Grade Fe-Mn-Cu Ore of Jbel Rhals Deposit (Eastern High Atlas, Morocco), *Minerals*, 8(2), 39.