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Research Article

Geology and Metallogenesis of the Sediment-Hosted Cu-Ag Deposit of Tizert (Igherm Inlier, Anti-Atlas Copperbelt, Morocco)

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The Tizert Cu-Ag deposit is the largest of a series of sediment-hosted copper deposits of the Anti-Atlas copper province in Morocco. Mineralized rocks in the deposit contain disseminated sulphides within a Late Ediacaran, dominantly siliciclastic sedimentary formation named the Basal Series. Isopach map of the Basal Series thickness shows that during the Late Ediacaran the area was composed of large subsiding zones separated by paleohighs. The ore-grade zones are well developed along basin margins adjacent to the basement paleohighs. These mineralized zones display a lateral sulphide zoning with central bornite-chalcocite zones grading outward to intermediate chalcopyrite and external pyrite zones. There is also a vertical sulphide zoning with evolution from bornite and chalcocite dominant mineralized rocks at the bottom to chalcopyrite and pyrite dominant mineralized rocks at the top of the lithostratigraphic succession. A second style of mineralization is represented by sulphide filled fractures and veins present in the Basal Series, as well as in the basement and the overlying dolomites. The similarity of the paragenetic sequences between the disseminated and the vein-hosted mineralization suggests that they may be related to the same mineralizing event, the disseminated style of mineralization being rapidly followed by the onset of the vein-style mineralization.

1. Introduction

Sediment-hosted stratiform copper deposits are widely distributed on earth and constitute an important source of copper at the global scale [1–3]. They are typically hosted by extensional intracratonic basins, and their genesis is interpreted as the product of diagenetic to epigenetic deposition of copper (with variable amounts of other metals) from evolving basin- or subbasin-scale fluid-flow systems through the host sedimentary rocks. Thus no consensus has yet been reached concerning the timing of the precipitation of copper sulphides relative to the deposition of the sedimentary host rocks and the length of time of mineralization. The origin of some deposits, for example, the White Pine deposit in the USA, is related to diagenetic processes [4–6] while several other deposits, for example, the Paleoproterozoic Nussir deposit in Arctic Norway, have been interpreted as epigenetic [7]. The copper mineralization in stratiform deposits may also result from the superposition of multiple phases throughout the sedimentary-tectonic evolution of the host basins, for example, the Cu-Co ore deposits in the western part of the Lufilian fold-and-thrust belt [8–10]. The early diagenetic view is suggested in cases where textures link early bacterial sulfate reduction with mineralization while the late diagenetic view is supported in cases where the ore zones are broadly transgressive relative to lithologies and the sulphide mineral paragenetic sequence exhibits textures documenting replacement of early diagenetic sulphides by late copper sulphides. The epigenetic view is supported when the copper sulphide mineralization displays an intense structural control indicating that mineralization took place contemporaneously with basin inversion and orogeny.

The Anti-Atlas Belt in Morocco comprises large Proterozoic basement inliers consolidated during the Eburnean and the Pan-African orogeny [11] and a Late Ediacaran to Paleozoic sedimentary cover weakly folded during the Hercynian orogeny [12, 13]. The terminal Neoproterozoic to Lower Cambrian cover includes important copper orebodies (Figure 1), with up to 200 occurrences [14], some of which are currently mined. Active mines include the Tazalaght mine whose reserves are estimated to 260,000 t with 1.89% Cu [15], the Ouansimi mine whose reserves are estimated to 1,087,000 t with 2.63% Cu [16], and the Agjgal mine whose reserves are estimated to 5,000,000 t with 1% Cu and 20 g/t Ag [17], while others are presently closed (e.g., Talat N'ouaman, Assif Imider, and Cheikh Imi N'irifi deposits). These orebodies are hosted by Upper Neoproterozoic volcanic and volcaniclastic formations, for example, Alous [18] and Assif Imider [19] deposits, or by terminal Neoproterozoic clastic and carbonaceous sedimentary formations, for example, Tizert, Tiferki, and Talat N'ouaman deposits [14, 16, 20, 21].

The Tizert copper deposit is the largest copper deposit in the western Anti-Atlas. It is located at the northern border of the Igherm inlier. The deposit was discovered in 1969 and the first studies, carried out by the Bureau des Recherches Pétrolières et Minières (BRPM) between 1970 and 1975, allowed estimation of the reserves to 1,062,000 t with 2.3% Cu and 65 g/t Ag [15]. Exploration studies performed by the Managem group since 2011 have extended the deposit to the west; the northern extent of the deposit has yet to be defined. The resources are presently estimated to 56,820,000 t with 1.03% Cu and 23 g/t Ag [22]. Here we describe the copper-bearing minerals in Tizert, the nature of their host rocks, and the relationship between the mineralized rocks, bedding, and compressional structures, in order to discuss whether the mineralization was synsedimentary, diagenetic, or epigenetic. The collected field, mineralogical, and geochemical data allowed us to define the nature of the mineralized rocks, the vertical and the lateral extent of the mineralized zones, the morphology of their envelopes, and their relationships with the host rocks. An integration of the Tizert Cu deposit into the post-Pan-African tectonic evolution of the western Anti-Atlas is presented.

2. Geological Setting

2.1. The Anti-Atlas. The Anti-Atlas Belt is located along the northern border of the West African Craton in Morocco, from the Tindouf Basin to the south to the Hercynian South Atlas Fault to the north (Figure 1). Weakly folded Ediacaran to Paleozoic sedimentary formations rest upon a Proterozoic basement that outcrops in several inliers. The basement includes Paleoproterozoic metamorphosed clastic sediments, migmatites, orthogneiss, and granites dated at 2050 ± 6 Ma [23] and a Pan-African belt where ophiolitic complexes are preserved along the Anti-Atlas Major Fault [24]. The Pan-African cycle (900–560 Ma) began with an important dislocation of the northern and eastern margins of the WAC and formation of an oceanic domain [25, 26]. This oceanic domain was closed during a first Pan-African tectonic event (D1) at ca. 660 Ma [11, 27–29]. Then a late orogenic, volcanic, volcaniclastic, and conglomeratic formation, the Lower Ediacaran Tiddiline Formation (Figure 2), was deposited during the waning stages of the Pan-African collision and deformed by a second event (D2) around 600 Ma [11, 30]. This formation, which rests unconformably upon the D1-folded Pan-African assemblages, was tilted, faulted, and folded during the Pan-African D2 compressional event, with development of axial-planar cleavage (Figure 3(a)). The Tiddiline Formation displays in the Bou Azzer and Igherm inliers eroded surfaces and striated quartzitic pebbles related to glacial erosion [31]. Subsequent active extensional faulting associated with postorogenic collapse led to deposition of up to 2000 m of volcanic, volcaniclastic, and conglomeratic rocks of the Upper Ediacaran Ouarzazate Group (≈600–560 Ma; [32, 33]). This group is overlain by a Late Ediacaran/Early Cambrian clastic and carbonate sedimentary series (the Adoudou Formation) [27, 34]. Subsequently, up to 10 km of shallow marine sediments, beginning by the "Lie de Vin" Series and ending by the "Jbel Ouarkziz" sandstones and limestones, was deposited from the Cambrian to the Carboniferous [35], with only one noteworthy interruption in the Late Cambrian. During the Late Carboniferous the Late Ediacaran and Paleozoic sedimentary cover was involved in polyharmonic folding above the basement blocks [12, 36, 37]. The basement blocks were uplifted by Hercynian inversion of preexisting rift-related faults [13, 28, 38–40].

2.2. The Adoudou Formation. The Adoudou Formation forms a broad outcrop in the Anti-Atlas and the southwestern High Atlas and represents the oldest volcano-sedimentary complex unconformably covering the Neoproterozoic Ouarzazate Group [41]. The Adoudou Formation was deposited during a major marine transgression that advanced from the west, where the sedimentary units are thicker and carbonates are more abundant than in the east [42, 43]. It has been subdivided into two members [44], the Tabia and Tifnout members that correspond respectively to the Basal Series and the Lower Limestone.

The Basal Series was deposited in a series of linked half grabens bounded by steep normal faults [45–50]. In the western Anti-Atlas where it is relatively thick (up to 250 m), the Basal Series is composed of three units [51]: (1) a lower massive conglomeratic unit, the Basal Conglomerate, dominated by massive conglomerates and secondary breccia, sandstones, and shales, locally interbedded with volcanic ashes and flows; (2) a middle unit, the Basal Limestone, composed of dolostones, limestones, and shales; (3) an upper unit, the Slates and Sandstones, which is a shale-dominated unit.

The overlying Lower Limestone is a rather monotonous sequence of shallow marine carbonates interbedded with mudstones, shales, and sandstones that reaches about 1,000 m in the western Anti-Atlas but only 200 m in the Bou Azzer area in the Central Anti-Atlas and <50 m in the Saghro inlier in the eastern Anti-Atlas [49, 52, 53]. In the western Anti-Atlas, the base of the Lower Limestone is characterized by a partly silicified dolostone bed, 50–200 m thick, the Tamjout Dolomite [54, 55].

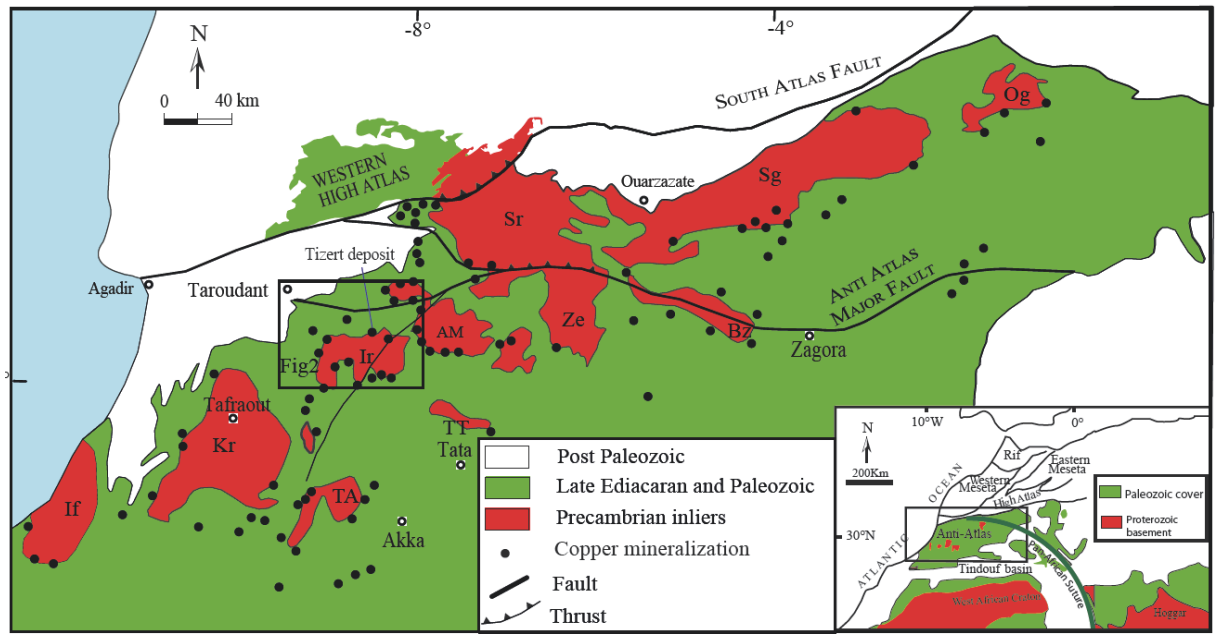

Figure 1: Copper mineral occurrences of the Anti-Atlas Copperbelt (modified from [14]). Inliers abbreviations: If, Ifni; Kr, Kerdous; Ir, Igherm; TA, Tagragra d'Akka; TT, Tagragra Tata; AM, Agadir Melloul; Ze, Zenaga; Sr, Sirwa; Bz, Bou Azzer-El Graara; Sg, Saghro; Og, Ougnate. Inset, location of the Anti-Atlas within the structural domains of NW Africa.

In the Central Anti-Atlas, andesitic, trachytic, and basaltic flows are interbedded with the Lower Limestone. The most important geochronological record is represented by the Jbel Boho syenite plug, which was dated at 534 ± 10 Ma by U/Pb dating [56]. The conspicuous presence of microbial mats and stromatolites and the occurrence of the calcified red algae *Kundatia composita* KORDE reported in the Lower Limestone [57] represent the most important paleontological record of the Adoudou Formation.

3. Sampling and Analytical Methods

This work is based on a structural study performed in the field, coupled with description and correlation of 500 drill cores. This high-density drill control allowed construction of an isopach map and well-constrained cross sections. Samples collected on both outcrops and drill cores were used for petrographical, mineralogical, and geochemical studies. Up to 70 thin and polished sections were studied by transmitted and reflected light microscopy. 60 unoriented powder samples of the siliciclastic host rocks were used for X-ray determination. Qualitative compositions of sulphide minerals from ten polished sections were determined using a Philips XL30 scanning electron microscope using SE, BSE, and EDS detectors. Operating conditions were an accelerating voltage of 30 kV, a beam current of 20 nA, and counting times of 20 s. Whole-rock geochemical data of drill core samples collected at different depths were determined at the Reminex Research center. For the major elements analysis, 0.5 g of the sample is crushed at less than 100 μm and dissolved by fusion at 500°C during 45 min with 2.5 g of sodium peroxide in a zirconium crucible [58, 59]. The melt is then dissolved with 100 ml of hydrochloric acid (28% HCl) and the solution is analyzed using an ICP-AES ULTIMA 2C using the Jobin Yvon-HORIBA device. For the other elements, 0.25 g of the sample is dissolved by microwave-assisted acid attack (50% HCl and 50% HNO3) during 45 min at 220°C. The solution is then analyzed by ICP-MS Thermo X'Serie 2.

4. Geology of the Tizert Cu Deposit

4.1. Lithostratigraphic Succession of Tizert. The Tizert deposit is hosted by Ediacaran sedimentary formations at the northern border of the Igherm inlier. Geological mapping, fieldwork, and lithological description of drill cores have allowed us to construct the lithostratigraphic column of the Tizert region (Figure 3(b)). The oldest lithostratigraphic unit encountered in the Tizert area is the Lower Ediacaran Tiddiline Formation, which is here considered as the basement. It is composed of very poorly sorted conglomerates including decimetric to metric pebbles and boulders cemented by an argillaceous matrix and locally crosscut by rhyodacitic dykes. The pebbles include quartzite, granite, diorite, and mafic rocks sourced from the Eburnian and Pan-African basement. Moderately folded [60], the conglomerates have a cleavage formed during Pan-African D2 deformation and are unconformably overlain by the Ouarzazate Group and Adoudou Formation. The Ouarzazate Group, represented locally by some volcanic and conglomeratic rocks, is much reduced or almost absent in the Tizert region. The Late Ediacaran Adoudou Formation includes the Basal Series, which corresponds to the Tabia member, and the Lower Limestone, which corresponds to the Tifnout member [44].

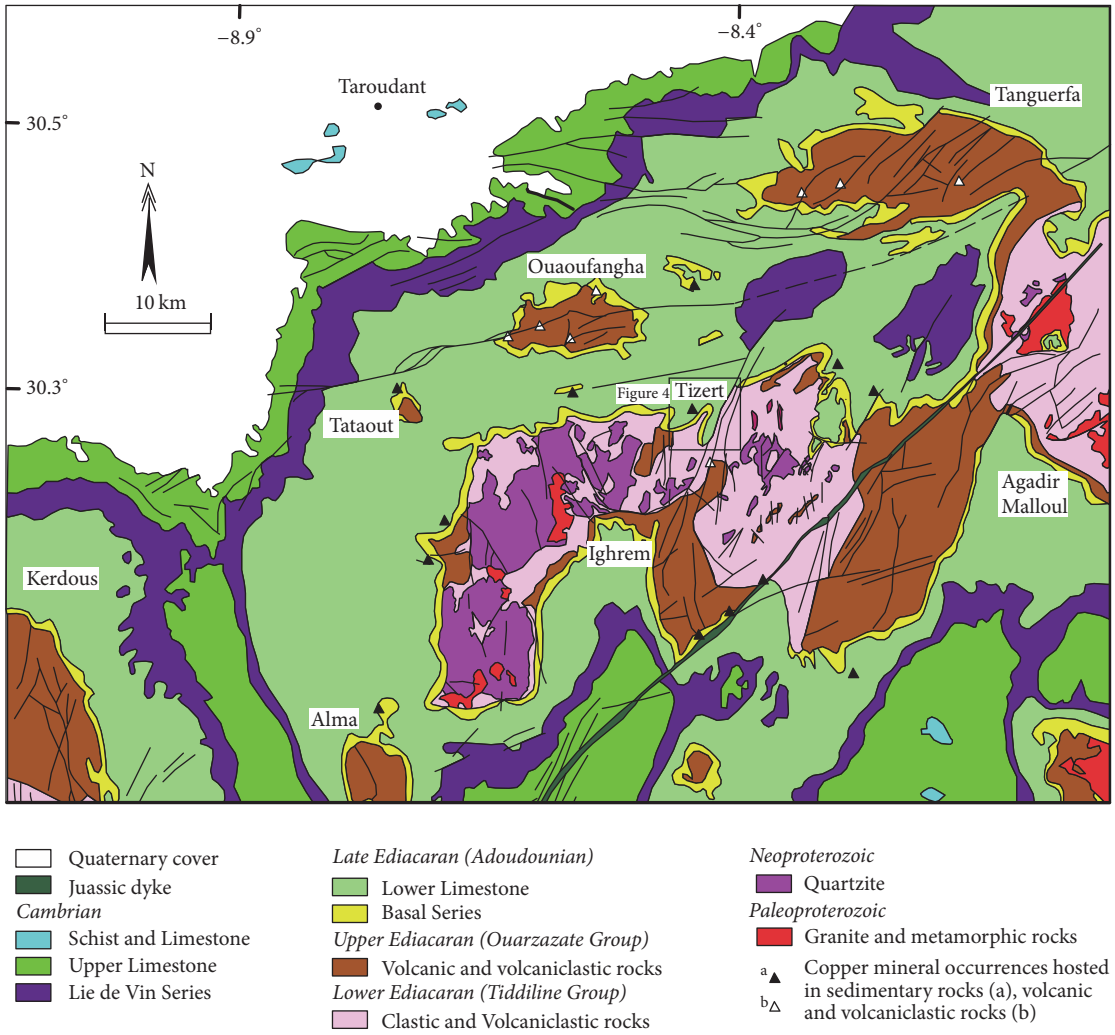

Figure 2: Geological and structural map of the Taroudant-Igherm inlier (modified from the 1/100000 geological map of Taroudant-Igherm, 1983).

The Lower Limestone is marked at its base by a massive dolomite bed, the Tamjout Dolomite (Figure 3(b)), which is characterized by the presence of abundant quartz and calcite nodules and veins, and encloses interbedded silicified horizons at its top. Locally thinly and irregular bedded dolostones with possible stromatolitic laminae are present in Tizert at the base of the Tamjout Dolomite. The Tamjout Dolomite is present almost all over the western Anti-Atlas and described as stromatolitic carbonates locally interlayered with silicified and brecciated evaporitic layers [61]. The Tamjout Dolomite is overlain by layered dolostones and limestones with intercalated siltstone layers. To the north, the Adoudou Formation is overlaid by the Lie de Vin Series (Figure 4), which is composed of purple argillite and dolomitic limestone, and represents a significant sea level regression. The base of the Lie de Vin Series corresponds to the Precambrian-Cambrian boundary in the Anti-Atlas [62]; it is overlaid by the Upper Limestone.

4.2. The Basal Series. The vertical lithologic succession of the Basal Series in Tizert is composed of two siliciclastic units, the Basal Conglomerate at the base and the Slates and Sandstones at the top, separated by a carbonate unit, the Basal Limestone (Figure 3(b)).

(i) The Basal Conglomerate is a very poorly sorted, 8 to 15 m thick purplish conglomerate composed of 0.4 to 9 cm long angular to subrounded clasts. The coarser clasts are generally of a quartzitic composition while the finer ones are essentially of an epiclastic origin that is tufs, ignimbrites, trachytes, and andesites. The clasts are cemented by sandstone with a quartz-sericite-chlorite-bearing matrix. The elements of the matrix are 0.05 to 0.5 mm long and include epiclastic debris, quartz grains, plagioclase, and potassic feldspar accompanied by some detrital muscovite. The matrix is rich in hematite, goethite, and leucoxene. To the top of the unit, lenticular dolomitic

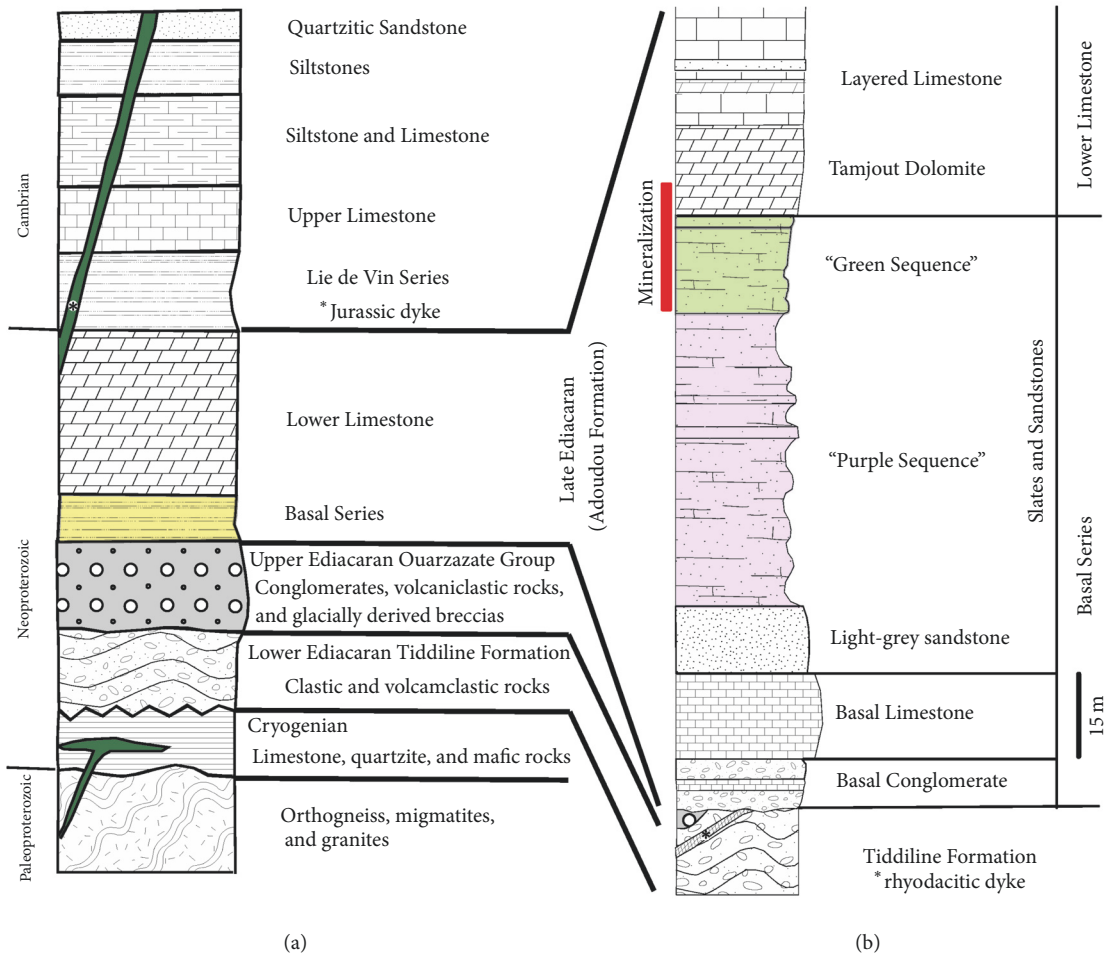

Figure 3: Synthetic lithostratigraphic columns of the Igherm inlier (a) and Tizert area (b). Note that in Tizert region the Ouarzazate Group is much reduced or almost absent.

sandstones with desiccation cracks and dissolution cavities of evaporitic minerals are intercalated within the conglomerate [45]. The Basal Conglomerate is interpreted as a fluvial system or a terrestrial slope of a fan delta developed along a lacustrine border [61].

(ii) The Basal Limestone is a carbonate-bearing unit forming a laterally impersistent dolomitic limestone. It attains 10 m in thickness and forms a cliff with a gradational boundary with the underlying Basal Conglomerate. The cliff is composed of meter-thick beds of dolostones to weakly sandy dolostones with planar and wavy stromatolite laminae. The dolomitic beds are composed of 0.04 to 0.7 mm long dolosparitic grains associated with quartz grains in a subsaccharoidal texture. This unit represents a well-developed cyanobacterial stromatolite formation on a shallow carbonate platform [45, 61].

(iii) The Slates and Sandstones include (i) a light-grey sandstone horizon, 8 to 11 m thick, composed of metric lenticular sandstone beds showing cross lamination and paleocurrent ripples. The sandstones are composed of contiguous grains, 0.05 to 0.5 mm long, of quartz, feldspar, and muscovite generally welded by carbonate cement. These sandstones were interpreted as having been deposited in a braided fluviatile system [45]; (ii) a thick (20–40 m) purplish hematite-bearing siltstone sequence, with intercalated beds of sandstone, microconglomerate, and dolomite. The siltstone forms centimeter-scale laminated beds alternating with shales. The matrix is essentially composed of quartz, sericite, and chlorite. The intercalated microconglomerates are very poorly sorted and composed of angular to subrounded epiclasts with a fine sandstone matrix. The interbedded sandstones form 0.5- to 3 m thick beds composed of quartz and feldspar grains cemented by a carbonate matrix. The dolomitic beds are present at the top of the siltstone sequence and are composed of microdolosparite with subordinate quartz and feldspar grains. This purplish sequence exhibits desiccation cracks; it has been interpreted as evoking a deltaic environment [45]; (iii) a green siltstone sequence, 10–12 m thick,

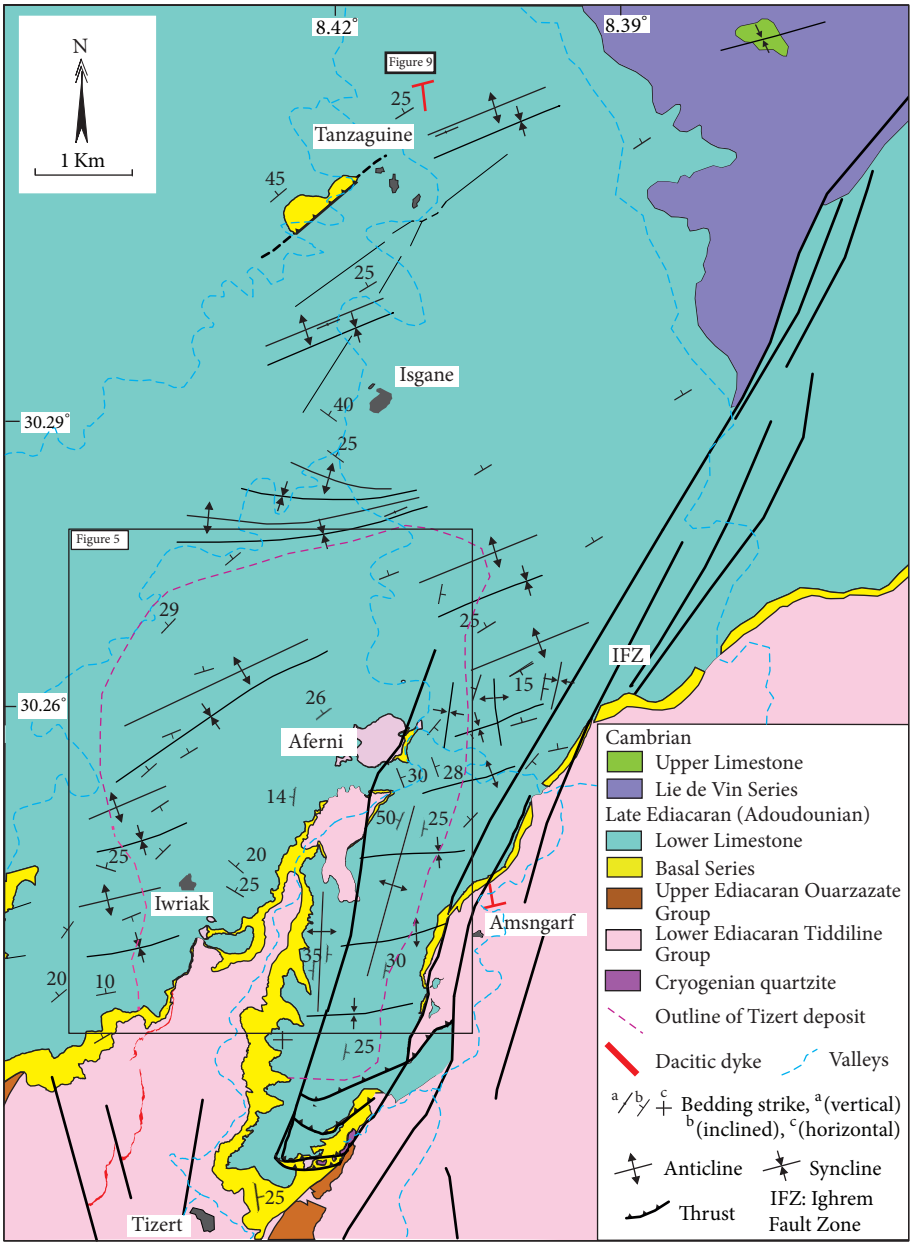

Figure 4: Geological and structural map of the Tizert area. Location of Figure 5 and the cross section of Figure 9 are indicated.

composed of alternating horizons of fine- to middle-grained sandstones with shaly sandstone. The matrix is heterogeneous and shows an increasing content of the carbonate fraction upward. The top of the Slates and Sandstones succession is marked by micro-conglomerates containing, in addition to quartz and feldspar grains, polygenic clasts including tuf debris, quartzite, and sericitoschists. This green siltstone sequence exhibits paleocurrent ripples; it has been interpreted as characterizing a shallow marine tide and emersion-dominated deposits [45].

The thickness of the Basal Series varies significantly across the Tizert area, from 0 m to > 100 m. The measures of the thickness performed on the drill cores allowed construction of the isopach map presented in Figure 5. The map shows that the Basal Series decreases in thickness towards basement paleohighs where Lower Limestone dolomites and carbonates directly overly the conglomerates of the Tiddiline Formation (Figures 6 and 7). Two main paleohighs are identified (Figures 5 and 6) and named the Aferni and Iwriak paleohighs. The Aferni paleohigh is characterized by the presence of second-order depressions, zones of thicker Basal Series that surround the paleohigh (Figure 6(b)). The "Basal Limestone" carbonate horizon within the Basal Series is thickest where the Basal Series is thick and thins towards the paleohighs where it pinches out. The boundaries of the basement paleohighs are marked by development of coarse

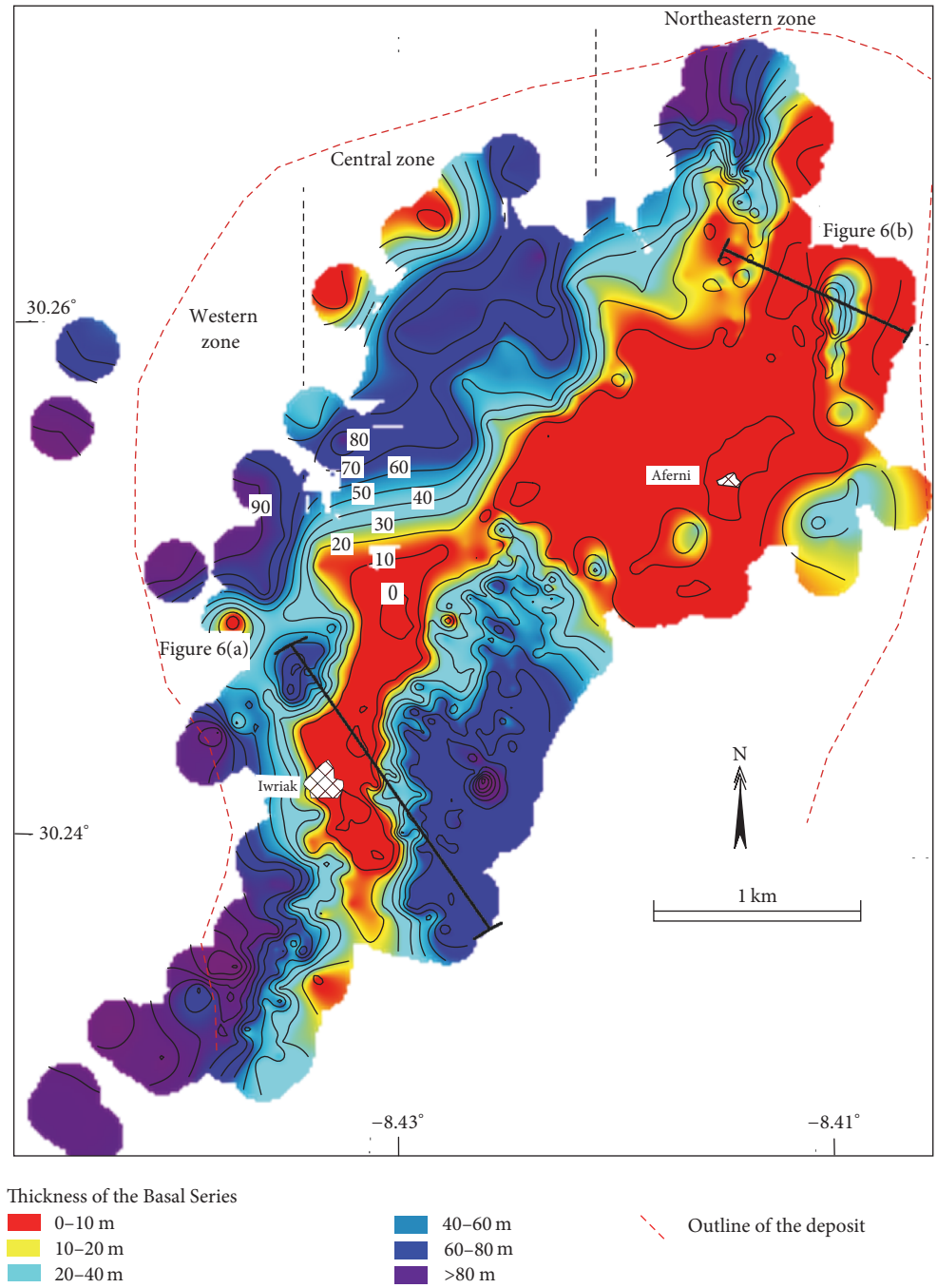

Figure 5: Isopach map of the Basal Series thickness. Location the cross sections of Figure 6 is indicated.

and poorly sorted breccia, with a sandstone matrix enclosing angular to subrounded fragments of carbonates. Some boundaries of the basement paleohighs (e.g., Aferni) are SE-NW trending normal faults, which are accompanied by a gentle convex bending of the hanging wall beds indicating synsedimentary extensional activity (Figure 7(b)). Such a synsedimentary extensional activity is also indicated by the presence of normal faults that offset the dolomite and sandstone horizons within the Basal Series. We interpret these field relationships to show that, during the Late Ediacaran, the area was composed of extensional basins or depressions that were separated by narrow (100–500 m across) ridge-like basement paleohighs, such as the Aferni and the Iwriak paleohighs.

The basin architecture during deposition of the Basal Series is very similar to that of the basal portion of the sequence hosting the stratifrom copper deposits of the Zambian Copperbelt which contains continental sandstones and conglomerates deposited in a series of restricted sub-basins controlled by extensional normal faults bounded by

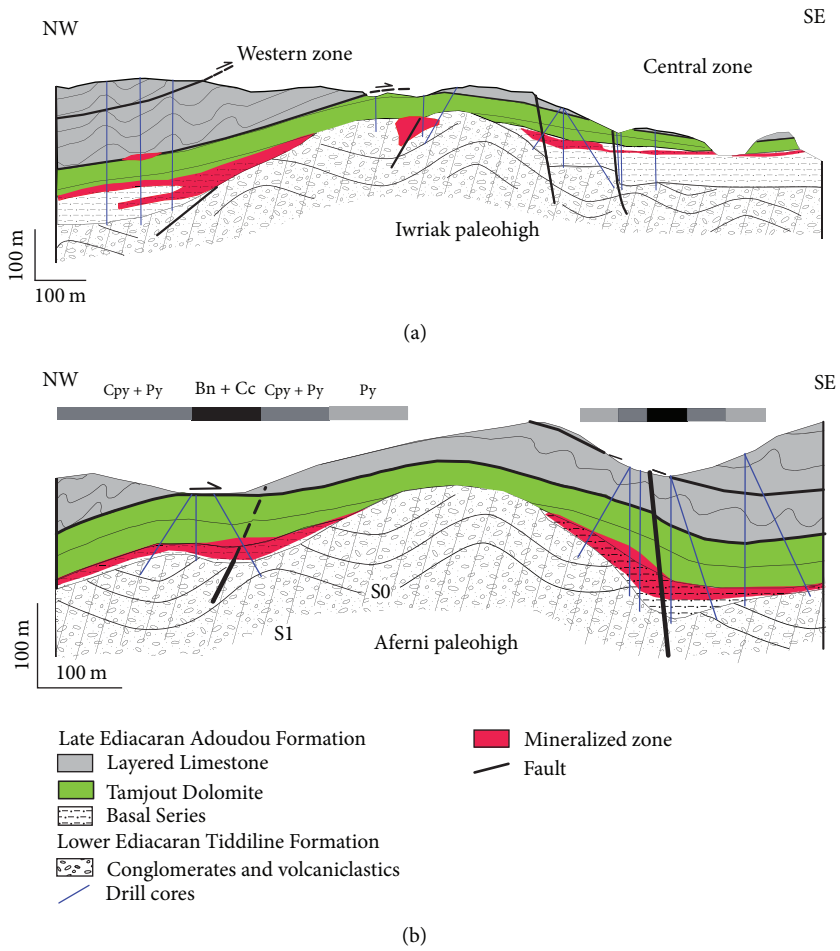

Figure 6: Cross sections throughout the Tizert deposit showing the envelopes of the mineralized zones (see location in Figure 5). (a) NW-SE cross section through the western and central mineralized zones around the Iwriak paleohigh; (b) NW-SE cross section around the Aferni paleorelief showing the extension of the mineralized zones and the lateral sulphide zoning. Pyrite (Py), chalcopyrite (Cpy), bornite (Bn), and chalcocite (Cc).

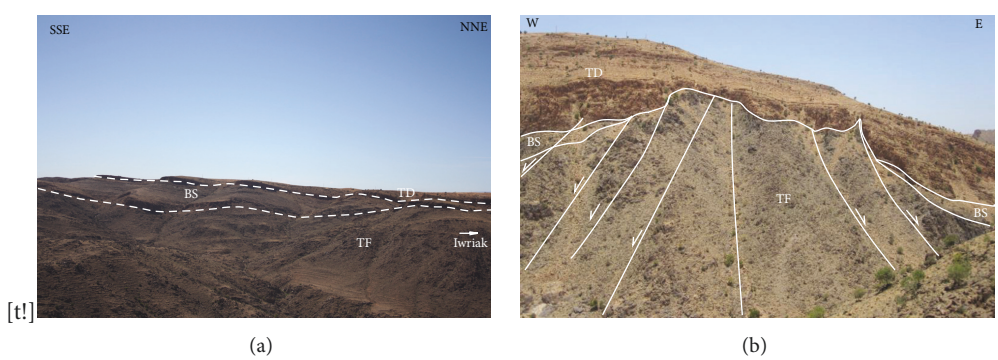

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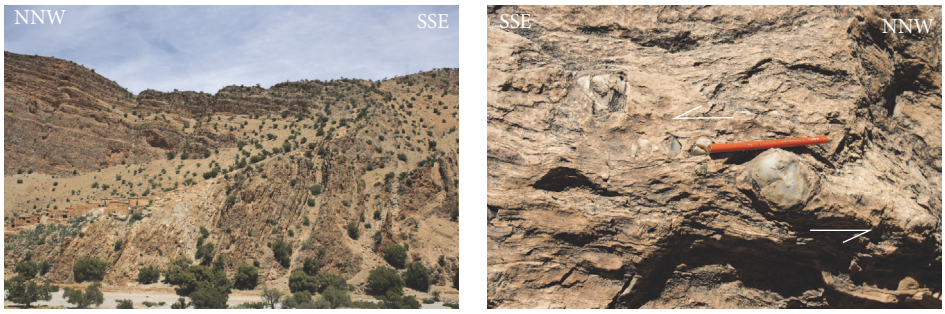
Figure 7: Field view photographs of the Tizert area. (a) Southern flank of the Iwriak paleohigh showing the Basal Series (BS) overlying the Tiddiline Formation (TD) and overlaid by Tamjout Dolomite (TD). (b) Northward view of the Aferni paleorelief showing normal faults affecting the Upper Ediacaran Tiddiline Formation and the overlying Adoudou Formation.

basement cored topographic highs [10]. The normal faults, which affect the Basal Series, do not offset the Tamjout Dolomite and the overlying layered limestone, confirming that such extensional activity was contemporaneous with deposition of the Adoudou Formation. The transition from the clastic- dominated formations of the Basal Series to the dolostone-dominated formations of the Lower Limestone reflects the end of an environment with abundant regional



(a) (b)

Figure 8: Field view photographs showing a south verging propagation fold (a) and a subhorizontal decollement horizon in the Lower Limestone (b). This decollement is a 2–4 m thick subhorizontal horizon localized along a silicified and brecciated evaporitic layer at the top of the Tamjout Dolomite. Note the cataclastic to mylonitic texture with asymmetric pressure shadows around rigid objects.

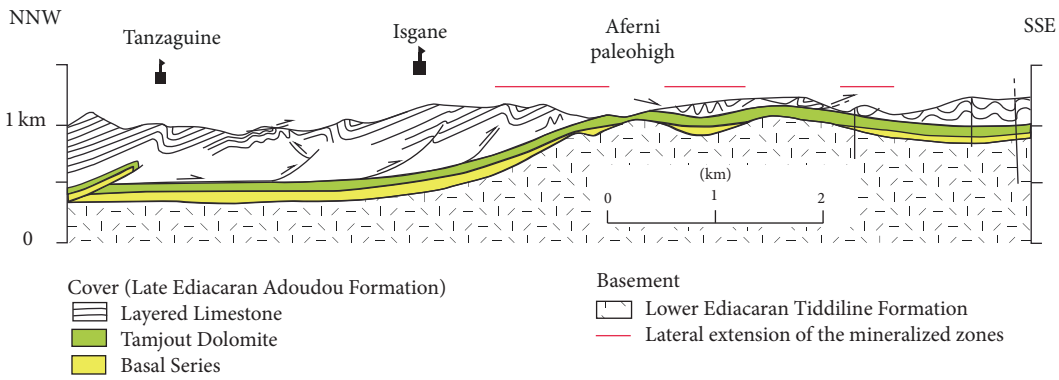


Figure 9: General synthetic NNW-SSE vertical geological section through the Tizert region (see location in Figure 4).

block faulting and the beginning of an environment with a thermal subsidence-dominated regime [44, 63].

4.3. Hercynian Structures. Although the northern border of the Igherm inlier is mainly covered by the Taroudant Group, in the Tizert area this succession is dissected by a number of steep-sided river valleys, providing excellent cross sections through the Adoudou Formation.

The preexisting normal faults that bound the Tizert basement highs were not inverted during the Late Carboniferous shortening (Figure 7). The Tamjout Dolomite that lays upon the Basal Series and the paleohighs is still subhorizontal to weakly dipping. On the contrary the overlying carbonates show multiscale folds and decollement horizons (Figure 8). The decollements are localized at different levels of the Adoudou Formation. A decollement is localized along a silicified and brecciated evaporitic layer at the top of the Tamjout Dolomite. This decollement is a 2–4 m wide subhorizontal horizon characterized by meter-scale folding, cataclastic to foliated texture with asymmetric pressure shadows around rigid objects (Figure 8(b)).

The largest and the dominant folds of Tizert present a kink-band geometry with narrow sharp hinge zones and long, gently dipping back limbs, while the fore limbs are short and steeply dipping (Figure 8(a)). These folds are south verging with subhorizontal fold hinges trending E-W although north verging folds are locally present (Figures 4 and 9). Bedding thickness is fundamentally preserved within the folds, which locally display thrust faults on their short limbs. These folds are therefore interpreted as fault propagation folds that grew at the tip of blind thrusts and back thrusts that terminate upward from a flat decollement localized along the upper boundary of the Tamjout Dolomite (Figure 9). One thrust fault outcrops in the northwestern part of the Tizert region where the Basal Series lays over the Lower Limestone along a ENE-WSW trending thrust dipping 45° to the northwest (Figure 4), namely, the Tanzaguine thrust. In the Basal Series deformation is marked by development of a schistose fabric that is more pronounced in the siltstone layers than in the interbedded sandstone and the carbonate layers.

The eastern part of the Tizert area is marked by the presence of a NNE trending subvertical fault corridor, the Igherm fault zone (Figures 4 and 9). To the south the fault zone constitutes the boundary between the Neoproterozoic basement and the Late Ediacaran cover. In the basement the fault zone consists of a 40 meter-wide near-vertical sinistral shear zone where the conglomerates, the volcanic and volcaniclastic rocks, are foliated. In the cover, the width of the fault corridor reaches 900 m and is composed of four brittle faults that cut across the Adoudou Formation. In this area, the south verging E-W trending folds coexist with N-S trending folds. Such fold interference patterns with dome and

(a) (b)

Figure 10: Drill core photos showing (a) bedding parallel disseminated mineralization and fracture-hosted copper mineralization and (b) copper sulphides (chalcocite and bornite) along carbonaceous stylolites. S_0, bedding.

basin structures have also been described further south of the Igherm inlier [36, 37].

To sum up, the initial horizontal Late Ediacaran-Lower Cambrian sedimentary sequence in the Tizert area has been detached along decollement horizons and deformed in subparallel sets of folds and faults independently from the underlying basement. Such decollement horizons occur also at different levels of the Paleozoic cover of the Anti-Atlas, along incompetent units of the Middle Cambrian, Silurian, and Upper Devonian [13]. This thin-skinned tectonics style indicates that the Anti-Atlas corresponds to a fold-and-thrust belt during the Hercynian orogeny. Nevertheless, the folding in the Adoudou Formation could have occurred much earlier by gravity sliding along evaporites above the Tamjout Dolomite.

5. Copper Mineralization

The "economic" mineralized zone extends laterally for more than 5 km along the Basal Series. The sulphides are mostly hosted by the Basal Series and the thickness of the mineralized zone reaches 45 m. Within this unit, most of the sulphide minerals are disseminated within siltstone, sandstone, and microconglomerates of the green sequence (Figure 3(b)). Locally later copper sulphide minerals are present at the bottom of the Basal Series, in the upper conglomerates of the Tiddiline Formation, and at the top of the Basal Series, in the Tamjout Dolomite. In these formations, sulphides occur essentially in fractures and in quartz veins and/or quartz and calcite geodes.

The eastern boundary of the deposit is the Igherm fault zone; the northern and the western boundaries of the deposit are not exposed and are not yet fully defined, but the ongoing drilling makes progress towards defining the boundaries of the economic mineralized zones. However, the Basal Series lithologies that overly the Lower Adoudou dolomites along the Tanzaguine thrust do not contain any copper sulphides. To the south of the Iwriak village, the vertical and horizontal extension of the mineralized zone decreases progressively until total disappearance.

5.1. Disseminated Mineralization. Disseminated sulphide minerals are concentrated with siltstone, sandstone, and microconglomerate beds (Figure 10(a)). Framboidal pyrite grains have been observed within siltstone layers (Figure 11(a)). The primary assemblage consists essentially of pyrite, chalcopyrite, bornite, and chalcocite. The mineralization is developed in the matrix by sulphide replacement of feldspar and the micrite and sparite carbonate cement (Figures 11(b) and 11(c)). Chalcocite develops at the expense of pyrite and chalcopyrite (Figures 11(d), 11(e), 11(f), and 11(g)) while chalcocite and bornite show myrmekitic associations (Figure 11(h)). Concentration of the disseminated sulphides depends on the porosity of the host rocks; it shows centimeter to meter-scale variations depending on the grain size of the detrital components of the sedimentary layers. The sulphide minerals are larger and the concentration of copper is higher (up to 14 wt. % Cu) in the coarser sedimentary beds. However, the ore zone envelopes are transgressive across the different lithologies of the Basal Series and show an increasing thickness towards the basement paleohighs (Figures 6(a) and 6(b)). The location and the geometric relationships between the mineralized zones and their host rocks in Tizert are vey similar to those described in the sediment copper deposits of the Zambian Copperbelt [10].

The basement paleohighs allow subdivision of the deposit into three zones: a western zone, a central zone, and a northeastern zone (Figure 5). In the western zone, the sandstones and microconglomerates of the Basal Series host a mineralized horizon whose total thickness locally exceeds 50 m near the basement paleohigh (Figure 6(a)). The mineral paragenesis consists essentially of chalcocite and bornite while pyrite and chalcopyrite are minor.

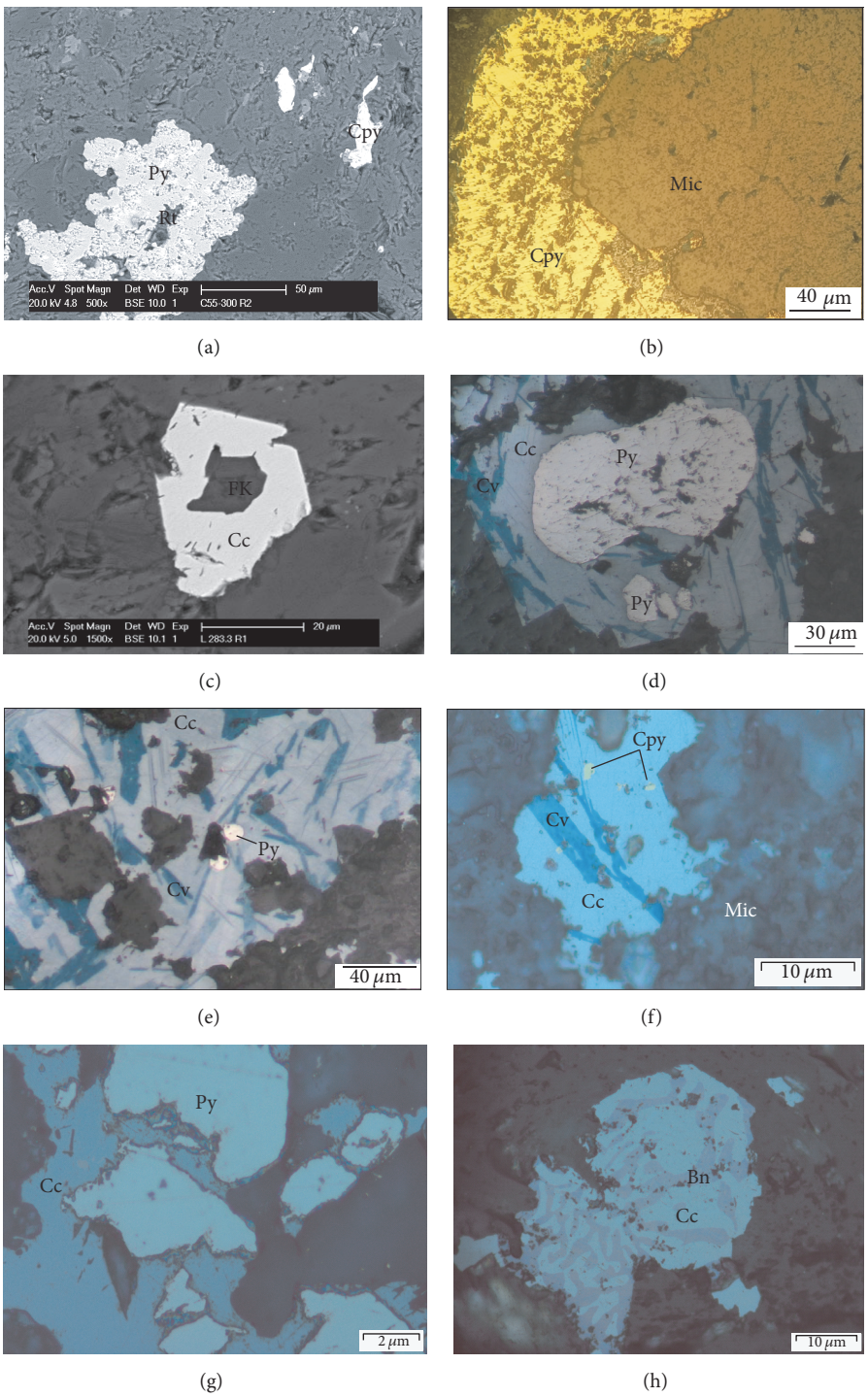


Figure 11: Paragenetic associations and replacement textures. (a) Framboidal pyrite (Py), chalcopyrite (Cpy), and rutile (Rt). (b) Micrite (Mic) replaced by chalcopyrite (Cpy). (c) Potassium feldspar (FK) inclusion within chalcocite (Cc). (d) Pyrite (Py) replaced by chalcocite, which is in turn transformed into lamellar covellite (Cv). (e) Relicts of pyrite within chalcocite. (f) Chalcocite (Cc) replacing chalcopyrite and covellite replacing lamellar Cc. (g) Replacement of pyrite (py) by chalcocite (Cc). (h) Myrmekitic association of chalcocite (Cc) and bornite (Bn).

The central zone is characterized by the presence of siltstone layers within the Basal Series. The thickness of the mineralized horizon reaches 20 m in the center of the depression, with a paragenesis dominated by chalcopyrite and pyrite (60–90 wt.% of total sulphides) and 30 m near the paleohigh, with a paragenesis dominated by bornite and chalcocite. The metallic paragenesis is generally an association of pyrite and chalcopyrite, or bornite and chalcocite, and shows a clear lateral variation at each side of the basement paleohigh. In the northeastern zone, the total thickness of

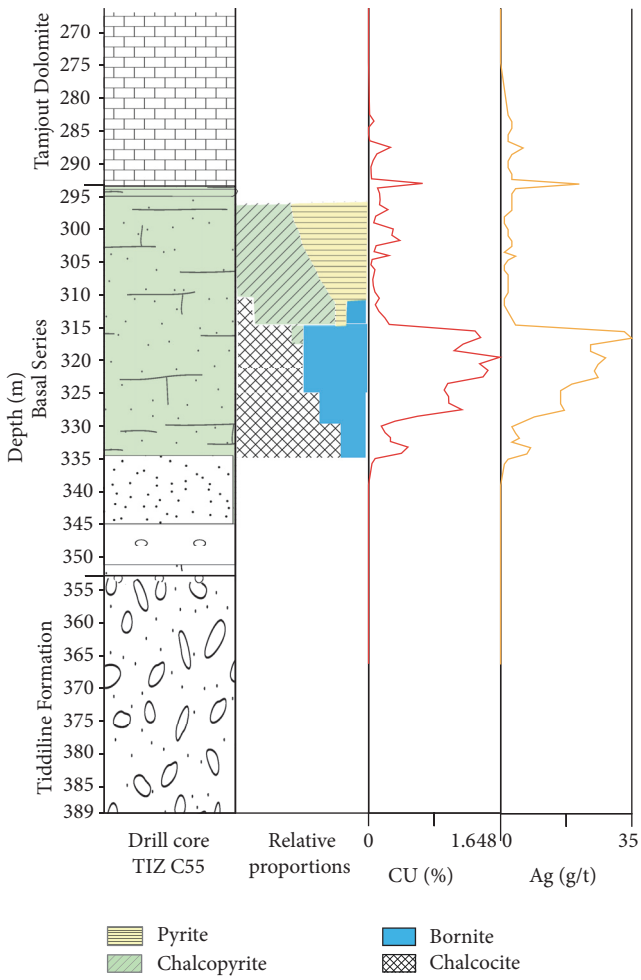


Figure 12: Vertical variation showing the evolution of the mineral paragenesis and the Cu and Ag contents along the Basal Series. There is an evolution in the disseminated mineralization from chalcocite and bornite-rich horizons at the bottom of the siltstones to chalcopyrite and pyrite-rich horizons at the top of the Basal Series. Note also the Cu- and Ag-rich zone at the base of the Tamjout Dolomite due to fracture-hosted sulphide minerals (in decreasing abundance: pyrite, chalcopyrite, chalcocite, and bornite).

the mineralized rocks reaches more than 45 m, including an abundant mineralization that fills veins and fractures at the base of the Tamjout Dolomite.

Two second-order depressions surround the Aferni paleohigh (Figures 5 and 6(b)). The maximal thickness of the ore zone is localized in the center of the second-order depressions where the assemblage is dominated by bornite and chalcocite and shows a lateral progressive evolution to chalcopyrite and pyrite (Figure 6(b)).

Mineralization within the Basal Series shows also a vertical zonation [60], which is present in the western ore zone, the central ore zone, and the northeastern ore zone as well. The sandstone, the microconglomerates and the siltstones include a disseminated mineralization that shows a progressive variation from bottom to top. Bornite and chalcocite are dominant in the bottom while chalcopyrite and pyrite are dominant in the top of the lithostratigraphic succession (Figure 12). Relicts of pyrite are locally found within chalcocite (Figures 11(d) and 11(e)).

5.2. Vein- and Fracture-Hosted Mineralization. A vein style of mineralization fills fractures, veins, and veinlets that crosscut the sedimentary layers and the stratified mineralization in the siliciclastic rocks of the Basal Series (Figure 10(a)). This type of mineralization also occurs in the Tiddiline Formation conglomerates underlying the Basal Series and in the Tamjout Dolomite overlying the Basal Series. Here the mineralized veins and fractures are abundant at the contact with the Basal Series and decrease upwards. The vein- and fracture-hosted sulphides are abundant near NNE striking fractures and faults and form stockwork-like mineralization or crystallize along stylolites in the carbonate rocks (Figure 10(b)). The mineral assemblage (Figure 13) is similar to that of the disseminated mineralization and is formed by pyrite, chalcopyrite, bornite, and chalcocite. Galena and/or sphalerite are locally present in both the mineralized veins and the disseminated sulphides. This paragenesis is associated with hydrothermal minerals such as calcite, dolomite, chlorite, sericite, and rarely barite. This late mineralization represents a small fraction of the total ore in Tizert, but a similar type of mineralization forms a large economic ore body in the Adoudou Formation of the Bou Azzer inlier [58, 59].

Silver is present in the vein-hosted mineralization as well as in the disseminated mineralization and shows a positive correlation with copper (Figure 12). It is present as native silver, amalgam of mercury and silver (arquerite, a rare silver-rich Ag-Hg amalgam), and eugenite ($Ag_{11}Hg_2$), or amalgam of chlorine and silver (chlorargyrite, AgCl), or as a composite copper-silver sulphide phase (stromeyerite, CuAgS) (Figure 13). These minerals are present in both styles of mineralized rocks.

A mineralization composed of pyrite, sphalerite, galena and traces of chalcocite, chalcopyrite, and malachite exists in the Tamjout Dolomite, 20 to 35 m above the Basal Series, where it is hosted within anastomosed veins of quartz, calcite, and rarely barite. This mineralization is discontinuous and noneconomically important except to the north of the deposit, at the approach of the of Aferni paleohigh, where it becomes rich in copper-bearing sulphides: bornite, chalcopyrite, and chalcocite.

5.3. Leaching and Supergene Alterations. Mineralization is leached around some near-vertical, east to southeast striking fractures that cut across the stratiform mineralization, but also locally along the contact between the Basal Series and the overlying Tamjout Dolomite. These leached zones are characterized by a red color due to a hematite alteration. A supergene-alteration phase affected both the stratiform and the vein mineralization and resulted in a paragenesis composed of chalcocite, covellite, native copper, malachite, and azurite (Figure 13). The supergene alteration is especially abundant along the contact between the Basal Series and the Tamjout Dolomite.

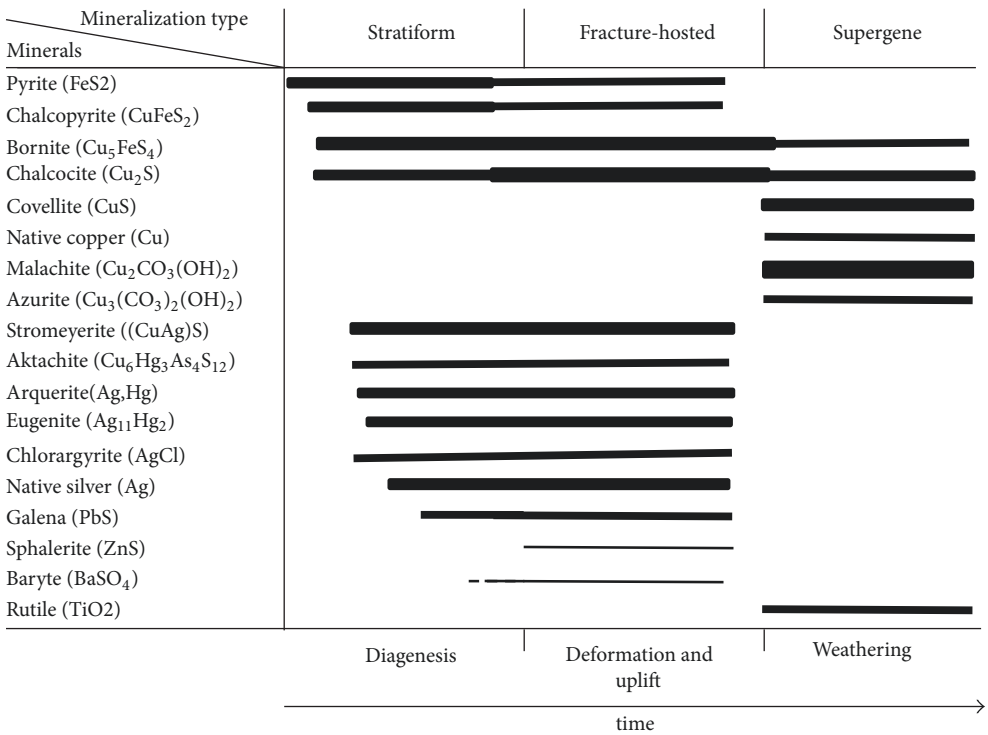


Figure 13: Paragenetic succession of the Tizert deposit.

6. Discussion

The genesis of the copper mineralization hosted by the terminal Neoproterozoic to basal Paleozoic sedimentary formations of the western Anti-Atlas is a subject of an ongoing debate [59, 64]. Their formation is related to either diagenetic and synsedimentary processes [65, 66], hydrothermal and epigenetic processes [67, 68], or superposition of both syngenetic and epigenetic processes [20, 69].

6.1. Timing of Mineralization and Genetic Processes. The textural features of the Tizert mineralization showing predominantly disseminated sulphides closely associated with structures such as sedimentary lamination (Figure 10(a)) allow affiliation of this mineralization with the sediment-hosted stratiform copper systems such as the main stratiform mineralization described as diagenetic in the Central African Copperbelt [4, 8]. In addition, sulphide zoning in the Tizert deposit conforms to that of most sediment-hosted copper deposits with central bornite-chalcocite zones grading outward to intermediate chalcopyrite and external pyrite zones (Figures 6(a) and 6(b)). Moreover, the ore-grade mineralization is well developed along basin margins adjacent to basement highs as illustrated in many sediment-hosted stratiform copper systems such as the Katangan and the Kupferschiefer basins [10, 70]. Hence the distribution, geometry, and size of mineralized zones are controlled by subbasin fault architecture, but also by the availability of both in situ and mobile reductants, the distributions of which are equally linked to basin structures [64]. The presence of framboidal pyrite within the stratabound mineralization allows relating this Cu-mineralization to sedimentary or diagenetic processes. Formation of framboidal pyrite is characteristic of synsedimentary or early diagenetic processes where sulfur results from bacterial sulfate reduction [71]. However the broadly transgressive nature of ore zones relative to lithologies allows the synsedimentary deposition of copper to be disregarded. In contrast, circulation of hydrothermal fluids during diagenesis would allow replacement of framboidal pyrite by Cu-sulphides and result in ore zone envelopes transgressive on lithologies. This is supported by the evolution from an environment dominated by regional block faulting during deposition of the Basal Series to an environment characterized by a thermal subsidence-dominated regime during deposition of the overlying Lower Limestone [44, 63]. Accordingly the Lower Limestone of the Adoudou Formation was deposited on both the paleohighs and the depressions already filled by the Basal Series. As a result the Tizert basin was sealed allowing for the possibility of establishing a long-lasting intrabasinal fluid reservoir within which convective cells can develop [72].

Formation of sediment-hosted stratiform copper deposits requires oxidized metal source beds (red beds), saline brines capable of leaching and carrying metals, and reduced facies to precipitate metals [2]. The basement of Tizert, mainly composed of continental conglomerates, together with volcanic, volcaniclastic, and intrusive rocks, contains adequate metal sources to fulfill the first condition. Although they were not observed during the course of this study, evaporites are described as lithologic components of the Basal Series [44, 45, 61]. The overlying dolomites of the Tamjout bed are locally interlayered with silicified and brecciated evaporitic

layers. They contain common calcite filled vugs that possibly represent pseudomorphs after anhydrite while disrupted laminae can be attributed to gypsum dissolution. The possible presence of a thicker evaporite sequence is suggested by the decollement at the top of the Tamjout Dolomite separating it from the folded rocks above (Figures 6 and 9). This decollement probably represents a much thicker evaporitic sequence that served as a glide plan during the Hercynian deformation. These characteristics indicate that fluids capable of leaching and carrying metals were also present in the Tizert basin.

The disseminated copper sulphides are hosted by the green sequence of the Basal Series while the purple sequence is not mineralized. It is not yet known why the green sequence represented a chemical trap that allowed precipitation of copper sulphides. Was it rich in mobile (natural gas, petroleum) reductants, or was it rich in organic matter that provides the reductants necessary to precipitate copper sulphides? Obviously the green sequence is more reduced than the purple sequence but the exact reductant is unclear. However, the absence of evidence of organic matter in the green sequence at the deposit suggests that a mobile reductant was probably involved, which favored metal deposition when oxidized Cu-charged fluids interacted with reduced sediments [73]. Such interaction would progressively decrease the Cu content of the fluid phase and produce the observed vertical and horizontal paragenetic zonations.

The presence of organic-rich and/or black pyritic sediments in the Adoudou Formation and older Precambrian formations of the Anti-Atlas supports the possible involvement of mobile hydrocarbons in the genesis of Tizert deposit. Regionally, there are strong facies changes in the Basal Series between basins and ridges [45, 61]. Microbial carbonate production, phosphogenesis, and karst development were described a few kilometers to the west of Tizert in the Basal Series onlapping the Ouaoufenga and Igherm inliers [63] and in the Basal Series of the southwestern High Atlas [74]. C and O isotopic analysis of calcite speleothems of the karst cavities are characterized by lighter $\delta^{18}O_{PDB}$ and $\delta^{13}C_{PDB}$ composition ($-6.9 < \delta^{18}O_{PDB} < -8.1$ and $-8.2 < \delta^{13}C_{PDB} < -8.5$) than the host-rock dolomite ($-4.2 < \delta^{18}O_{PDB} < -8.1$ and $-3.7 < \delta^{13}C_{PDB} < -0.2$) indicating involvement of terrestrial fluids rich in decomposing organic matter and/or microbial activity [63].

Organic-rich strata occur elsewhere in the Adoudou Formation where dark stromatolitic limestones have been described in the western and central Anti-Atlas [53, 75]. Even if the maximum measured present-day TOC in outcrop samples of the Adoudou Formation was 0.2%, the original organic-richness might have been significantly higher, because much of the organic matter may have already been converted into hydrocarbons and expelled [76]. Gas shows have been reported from the Adoudou Formation in the well AZ-1 (28°59.54′N, 8°36.23′W) on the northern margin of the Tindouf Basin [76].

Significantly older organic-rich strata are present in the central Anti-Atlas in the Bou Azzer inlier where the ophiolitic complex contains a black phyllitic sequence, 300 to 1000 m thick, composed of organic-rich shales and siltstones containing numerous small pyritic framboids [26]. The phyllitic sequence terminates with a 20 m thick volcano-sedimentary horizon that hosts the stratifrom copper-rich lenses of the Bleida mining district. These pyritic black shales were interpreted as deep-water turbidites deposited during rifting of the border of the West African Craton around 800 Ma and later deformed during the Pan-African orogeny [26, 27].

The vein mineralization, characterized by the presence of fracture and vein-hosted sulphides along with gangue minerals, shows great similarity with epigenetic mineralization such as that described in the Nchanga and Nkana deposits in the Central African Copperbelt [77–79] and in the Nussir deposit in Norway [7]. The presence of such mineralization in the basement and its abundance at the contact between the Basal Series and the overlying Tamjout Dolomite and in areas adjacent to fractures and faults indicate that this mineralization formed in the course of compression and disharmonic tectonics. The paragenetic sequence of the vein mineralization is similar to that of the disseminated mineralization, suggesting that either the two-mineralization styles could be contemporaneous or they may be distinct events with metals in the veins derived by remobilization, during Hercynian orogeny, of the earlier diagenetic sulphides [8, 80]. The presence of mineralized stylolites connected to mineralized sedimentary beds (Figure 10(b)) indicates that the vein mineralization in Tizert could be related to local remobilization, during compressional tectonics, of earlier sulphides rather than a separate mineralization generated by hydrothermal fluid circulation. Copper (re)mobilization has been documented in numerous sediment-hosted copper deposits [79–83]. At least two Cu-Co sulphide phases, diagenetic and synorogenic, are present in the Katanga Copperbelt [81]. In the Zambian Copperbelt, the primary diagenetic sulphide stock of the Lumwana Cu (-U) deposit has been remobilized for more than 40 Ma during the successive stages of Pan-African orogeny from burial, compressional tectonic deformation, and gravitational collapse [82]. In the Nkana Cu-Co deposit the rich ore bodies are localized in the hinge zones of folds where three successive generations of veins were distinguished [79, 80].

In any case, the possible presence of mobile hydrocarbons in the Basal Series would require burial of source rocks to a depth of several kilometers. Such a thickness of sediments would not appear to have been present until well into the Paleozoic, suggesting that the disseminated style of mineralization is late diagenetic. The absence of evidence for successive generations of mineralized veins and the similarity of the paragenetic sequences between the disseminated and the vein-hosted mineralization suggest that they may be related to the same mineralizing event [84]. Hence the disseminated style of mineralization was rapidly followed by the Late Carboniferous compression and the onset of the vein-style mineralization. On this basis, it appears that copper mineralization of Tizert is largely a Paleozoic event, most likely of Carboniferous age, contemporaneous with the polymetallic sulphide mineralization event in the Moroccan Meseta [85–90].

6.2. Basin Development and Inversion. The Upper Neoproterozoic-Paleozoic tectonic evolution of the Anti-Atlas is relatively well constrained. The post-Pan-African collision in the northwestern border of the West African Craton was accompanied by reactivation of basement faults, strike-slip faulting, and creation of continental basins filled by the conglomerates and coarse siliciclastic rocks of the Tiddiline Formation [11, 27, 30, 32, 91].

The postcollisional context evolved to rifting during the Upper Ediacaran-Lower Cambrian as testified by previous structural and sedimentological studies in the western Anti-Atlas and by the interleaved continental volcanism [42, 44, 45, 92, 93]. Rift volcanism was marked by the volcanics, volcaniclastics, and intrusives of the Upper Ediacaran Ouarzazate Group. Then a progressive marine transgression coming from the west deposited the Basal Series of the Adoudou Formation over the Upper Ediacaran continental deposits. The Basal Series filled the grabens and the border depressions around the emerged paleohighs. Within the Basal Series deposition of the "Basal Limestone" carbonate unit was restricted to the deepest parts within the wide depressions while the borders of the depressions received only clastic sediments. Then the Lower Limestone of the Adoudou Formation was deposited on both the paleohighs and the depressions already filled by clastic and carbonate sediments. Upon the Adoudou Formation, up to 10 km of Paleozoic sedimentary series was subsequently deposited in an overall shallow marine environment [35] before the Late Carboniferous compression let to basin inversion and the observed thin-skinned tectonics in the Tizert region. At that time, the Anti-Atlas was the foreland fold belt of the Hercynian orogeny that extended northwards in the Meseta. During this tectonic evolution, the western Anti-Atlas remained an intracratonic basin [12, 13, 94]. More interestingly, the Paleozoic sediments were deposited during a long period (>100 Ma) of tectonic quiescence and thermal subsidence [12]. This indicates that the lengthy time span of mineralization, a condition necessary for formation of giant stratiform sediment-hosted copper deposits [2], was fulfilled in the Anti- Atlas, which thus can be qualified as a Copperbelt.

7. Conclusion

This work is a contribution to the syngenetic versus epigenetic origin of the copper mineralization hosted by the terminal Neoproterozoic-Lower Cambrian sedimentary formations of the western Anti-Atlas, north of the West African Craton. The studied example, the Tizert Cu-Ag deposit, which is the largest sediment-hosted copper deposit of this metallogenic province, shows that during the Late Ediacaran the region was characterized by wide depressions separated by narrow basement highs. The Basal Series, lower member of the Adoudou Formation, was deposited in the depressions while the upper member (Lower Limestone) was deposited across both the depressions and the paleohighs. Most of the copper mineralization is present as disseminated and stratabound Cu-sulphides hosted by the uppermost siliciclastic horizons of the Basal Series. The ore-grade mineralization is well developed along basin margins adjacent to basement paleohighs. Within these zones, mineralization shows a lateral sulphide zoning with central bornite-chalcocite zones grading outward to intermediate chalcopyrite and external pyrite zones. There is also a vertical sulphide zoning with evolution from bornite and chalcocite dominant mineralization in the bottom to chalcopyrite and pyrite dominant mineralization in the top of the lithostratigraphic succession. However the ore zone envelopes are transgressive across lithologies. These characteristics, together with the presence of framboidal pyrite and replacement textures among the sulphide mineral paragenetic sequence, indicate that this mineralization occurred during an advanced stage of compaction of the sediments, most likely during a late diagenetic stage.

A second style of mineralization is represented by sulphide filled fractures and veins present in the Basal Series, as well as in the basement and the overlying dolomites in the basement and the dolomites that overlay the Basal Series. The vein- and fracture-hosted sulphide minerals display the same mineralogy and zoning as the disseminated sulphide minerals. The location of better-mineralized zones of this style of mineralization near fractures and faults indicates that it was epigenetic; it may have occurred during Late Hercynian shortening.

It is believed that the high heat flow associated with a thermal subsidence-dominated regime initiated intrabasinal convective circulation. Saline brines originated from evaporite dissolution, moved downward, and leached metals from the underlying continental conglomerates and associated magmatic rocks. The oxidized metal-rich fluids moved upward to the Basal Series where their interaction with mobile hydrocarbon-bearing sediments allowed deposition of metals. The late diagenetic disseminated mineralization was rapidly followed by the Late Carboniferous compression and the onset of the vein-style mineralization.

Conflicts of Interest

Abdellah Oummouch, Othmane Maddi, Mohamed Zouhair, and Lhou Maacha are affiliated to Managem Group, which is a Moroccan mining company (http://www.managemgroup.com/Le-groupe/Profil).

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