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The Cu-Ag-Pb Polymetallic Mineralization of Agdim-Ait Elfersi Sector, North-Eastern Part of the Saghro Massif, Morocco: Geological Setting, Ore Petrography and Geochemistry

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Abstract

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The Cu-Ag-Pb polymetallic mineralization of the Agdim-Ait Elfersi sector is situated in the eastern Anti Atlas Moroccan belt, the northeastern part of the Saghro inlier. The mineralization is hosted in the volcanic rocks of late Neoproterozoic and the detrital sedimentary rocks of the Lower Cambrian. A network of faults has affected this area; it is a brutalizing deformation with NW-SE, NE-SW, E-W, and NNE-SSW directions. NW-SE and NE-SW structures have a metallogenic significance. This tectonic canvas was used as a target of a mineralization vein with Cu, Ag, and Pb in this area. By combining geological, structural, and metallogenic characteristics, it can be assumed that the Cu-Ag-Pb mineralization of the Agdim-Ait Elfersi sector is linked to two major events. A late Pan-African event linked to the extensional tectonics of the late Neoproterozoic, responsible for the establishment of mineralization at the level of the basement, and then a late Hercynian-Atlasic event, which manifests by the remobilization of metals in NE-SW oriented structures. Geochemical analysis shows the polymetallic character of this mineralization. The high contents of silver and mercury observed indicate the presence of similarities of an Ag-Hg epithermal type of mineralization in this area. Geological context, as well as mineralogical and textural characters of the Agdim-Ait Elfersi sector are reminiscent of epithermal-type mineralization as in the Imiter and Zgounder deposit.

Keywords: Polymetallic mineralization; Agdim-Ait Elfersi; Saghro massif; Ag-Hg epithermal; Late Neoproterozoic; Lower Cambrian

1. Introduction

The Moroccan Anti-Atlas is a vast metallogenic province (Fig. 1-b) that contains numerous deposits and showings of base and precious metals known for more than long years ago. Some deposits are still in operation, and many deposits were abandoned. The Anti-Atlas underwent an extensional tectonic phase at the end of the late Neoproterozoic; it is responsible for the establishment of significant volcanic activity, materialized by the acidic and basic volcanic flows, which form the Ouarzazate group. This magmatic activity has a very interesting effect on the transfer of elements from the mantle to the surface. It could be the source and the convective motor necessary for the formation of a base and a precious metal deposits on the anti-Atlas belt (Cheilletz et al., 2002; Levresse et al., 2004; Gasquet et al.,

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2005; Marcoux and Wadjinny 2005; Tuduri et al., 2006, 2018; Pelletier et al., 2007; Bouabdellah and Slack, 2016). The previous work and geological studies that had been carried out on this transition zone between the Late Neoproterozoic and the Lower Cambrian in the Saghro inlier, particularly in its northeastern part, are very limited. These studies have emphasized the importance of felsic volcanism generated by this extensional late Neoproterozoic tectonic, in relation to the deposition of the silver mineralization, but they overlook the effect of the Hercynian and Alpine orogeny on the Pan-African structures, knowing that the fault axes that affected the Precambrian basement are continuous in the Paleozoic cover. Indeed, the debate on the saghro ore deposits (Levresse et al., 2004; Tuduri et al., 2006, 2018; Diallo et al., 2021) are for the most part Ediacaran in age and magmatic-hydrothermal related, this discussion meet in a point of the connection and association of magmatic-hydrothermal fluids in the formation of mineralizing events.

The current study aims to characterize the Cu-Ag-Pb polymetallic mineralization of the Agdim - Ait Elfersi sector, on one hand, by combining geological setting, ore petrography, and geochemistry data; on the other hand by trying to emphasize the role of the Hercynian and Alpine orogenesis on the establishing of mineralization in the transition zone between late Neoproterozoic and Lower Cambrian, northeast of the Saghro massif. In fact, the Agdim - Ait Elfersi sector is a good example for emphasizing the mineralization of this transition zone. The Agdim-Ait Elfersi sector is located in the Tinghir province, at 25 km as the crow flies southeast of the city of Tinghir, near the Agdim N Ikhrttan village. This area is located at an average altitude of 1300 m where there is a semi-desert climate. The access to the area is via a track from the road that leads to Alnif through the rural commune of Ait El-Ferssi and the Agdim N Ikhrttan village.

2. Geological Settings

2.1. Anti-Atlas Belt

The mountain range of the Moroccan Anti-Atlas, located on the northern edge of the West African Craton (Fig.1-a), belongs to the Pan-African orogenic belt (Choubert, 1963; Leblanc and Lancelot, 1980; Thomas et al., 2002; Ennih and Liégeois, 2008; Hefferan et al., 2014). It stretches 750 km in a WSW-ENE direction, from the Atlantic, where it extends the Zemmour range to Tafilalet. It is the major structural domain of southern Morocco, limited to the south by the Carboniferous basin of Tindouf and by a major tectonic lineament called the major South Atlas Accident in the North (fig.1-b) (Choubert, 1963; Thomas et al., 2004; Gasquet et al., 2005, 2008). The Anti-Atlas is constituted by a Precambrian basement, exposed in the form of inlier (Bas Draâ, Ifni, Kerdous, Tagragra of Akka, Tagragra of Tata, Igherm, Sirwa, Zenaga, Bou Azzer, Saghro, and Ougnat) under a Paleozoic and post-Paleozoic cover (Fig.1-b). The oldest formations have been recognized in the south of the Major Anti-Atlas Fault (Choubert, 1963; Bouougri, 2003; D'Lemos, Inglis, and Samson 2006; Gasquet et al., 2005, 2008), include meta-sedimentary and meta-volcanic complexes intersected by Paleoproterozoic plutonic intrusions (Gasquet et al., 2008). Recently, Mesoproterozoic rocks are recognized by basic dykes dated by U-Pb on baddeleyite at 1385-1415 Ma (El Bahat et al., 2017) and sediments from the Taghdout-Lkest Group, whose zircon dates have revealed ages of 1416-1380, 1650, 1750, and 2040 Ma (Youbi et al., 2013) and 1700 Ma (Ikenne et al., 2017).

The Neoproterozoic of the Anti-Atlas was subdivided into several groups, the oldest of which form Cryogenian units. These are the Lkst-Taghdout and Tachdamt-Bleida groups (1000-690 Ma), Iri group (760-740 Ma), Bou Azzer group (762-697 Ma), and Saghro group (760-610 Ma). The Anzi, Bou Salda, Dades and Tiddiline groups form the Ediacaran units; Ouarzazate group (580-540 Ma) covers these units (Álvaro et al., 2014; Gasquet et al., 2008; Hefferan et al., 2014; Karaoui et al., 2015; Soulaïmani et al., 2018). The margin of the West African Craton (WAC) is experiencing a major transgression towards the southeast at the Paleozoic. The first deposits are detrital, followed by Cambrian platform

sedimentation. It was during this period that Tata and Taroudant groups were deposited (Choubert, 1963; Destombes et al., 1985; Álvaro et al., 2014; Landing et al., 2006). They are constituted of limestone and dolomite, separated by Taliwine formation marking a brief episode of regression. The Precambrian-Cambrian boundary in the Anti-Atlas is placed under the contact between the lower dolomite and the Taliwine formation dated Tommotian (Sdzuy, 1978; Tucker 1986; Latham and Riding, 1990). Geochronological dating by U-Pb on zircon places this boundary beside the lowest carbonate unit of Addoudou formation, under the Tata group (Maloof et al., 2005; Landing et al., 2006; Letsch et al., 2019).

Fig. 1. (a) Location of the Anti-Atlas belt at the northern limit of the West African Craton (Fabre 2005; Liégeois et al., 2005; Ennih and Liégeois, 2008); (b) Main geological units and major mining districts of the Moroccan Anti-Atlas (Hollard et al., 1985; Thomas et al., 2004; Mouttaqi et al., 2011; Tuduri et al., 2018)

2.2. Sagharo Massif

The Sagharo massif is located in the west of the eastern Anti-Atlas. It is formed by the oldest formations outcrop in four sectors that will also be defined as smaller inlier, surrounded by thick late Precambrian and Adoudounian formations. These sectors are Sidi Flah - Bou Skour and Kelaa M'gouna inlier in the western part; Boumalne and Imiter inlier in the eastern part (Hindermeyer et al., 1974). Siliciclastic and metasedimentary rocks compose the sagharo group in the eastern anti atlas Moroccan belt, a Cryogenic age has been attributed to these rocks (Ouguir et al., 1996; Fekkak et al., 2003; Thomas et al., 2004). Even so, it was considered as an Ediacaran in age (Liégeois et al., 2006; Abati et al., 2010) based on the geochronological dating by the U-Pb method and their stratigraphic position in the central anti atlas. The vocano-sedimentary cover of the Ouarzazate group, whose type features have been defined in the Ouarzazate region (Hindermeyer 1953; Boyer and Leblanc, 1977; Boyer et al., 1978) is

covered the saghro group. This volcano-sedimentary cover is characterized by a calco-alkaline strongly potassium to shoshonitic magmatism of volcanic arc type (Gasquet et al., 2005; Walsh et al., 2012; Baidada et al., 2018; Yajoui et al., 2020), associated with plutonic intrusions attributed to 590-540 Ma (De Wall et al., 2001; Gasquet et al., 2005; Walsh et al., 2012; Baidada et al., 2018; Errami et al., 2020).

2.3. Agdim Ait Elfersi Sector

The Agdim-Ait Elfersi sector is located at the eastern of the Jbel saghro massif, in the Neoproterozoic - Paleozoic transition zone. The Paleozoic sedimentary series outcrops in the north of the study area rest in the major type of angular unconformity on the volcanic and volcano-clastic rocks of the Ouarzazate group (Dal Piaz et al., 2007; Malusà et al., 2007). The Neoproterozoic rocks is formed by volcanic and pyroclastic rocks (Dal Piaz et al., 2007; Malusà et al., 2007). They are represented by two complexes, an andesitic-rhyolitic complex of Ijgui-Jbel Merrou, and a pyroclastic complex of Thiboula-Bou Afzad (Dal Piaz et al., 2007). The Paleozoic rocks are represented by the Lower and Middle Cambrian and the Ordovician features with a stratigraphic gap during the Upper Cambrian (Hindermeyer et al., 1974; Du Dresnay et al., 1988; Malusà et al., 2007).

Fig. 2. Geological map of the Jbel Saghro inlier (Hindermeyer 1953; Hindermeyer et al., 1974; Tuduri et al., 2018)

3. Materials and Methods

The volcanic rocks of the Precambrian basement and the detrital rocks of the Lower Cambrian host the Agdim-Ait Elfersi mineralization. With the aims of characterizing, the Cu-Ag-Pb veins mineralization's of this sector, geological and mineralized-structures maps have been produced. Field mapping are carried out in three phases, which have a progressive relationship, detailed planning, description/collecting, and reporting/interpretation. Geological study summarizes the different features and structures defined in the field. Geological sections had been chosen to intersect perpendicularly the contact of the transition zone between the late Neoproterozoic and Lower Cambrian and the various mineralized structures. About 60 samples were collected from the surface for petrographic, mineralogical, and geochemical characterization. Thin and polished sections were prepared at the Faculty of Science of Marrakesh. They are microscopically investigated using crossed polarized light

(XPL), plane polarized light (PPL), reflected light photomicrographs and scanning electron microscopy (SEM). The geochemical analyses were carried out by the Baraka Mining Company at the ALS laboratory in Spain. Geochemical samples are analyzed for 17 elements (Au, Ag, Hg, As, Bi, Cd, Co, Cr, Cu, Fe, Mg, Mn, Mo, Ni, Pb, S and Zn) using inductively coupled plasma atomic emission spectroscopy (ICP-AES) and atomic absorption spectroscopy (AAS) method.

4. Results

4.1. Geological and Structural Study

The Agdim-Ait Elfersi sector, formed by two large composite of rocks (Fig.3), a volcanic and pyroclastic rocks of the terminal Neoproterozoic, surmounted by detrital sedimentary rocks of the Paleozoic cover (Dal Piaz et al., 2007; Malusà et al., 2007). The terminal Neoproterozoic is represented by volcano-sedimentary rocks, called the Ouarzazate group. Indeed, these rocks are neither folded nor metamorphosed on a regional scale. This complex comprises a panoply of volcanic and pyroclastic rocks outcropping to the south of the study area (Fig.3). It constituted by a stack of terms and features, from basic to intermediate features, corresponding to porphyritic andesite, to more acidic terms, corresponding to pink rhyolites generated by the transtensional tectonic event of the Anti-Atlas Moroccan belt during the transition phase between the terminal Neoproterozoic and the Lower Cambrian. Without forgetting the ignimbrites and volcanic tufts which come from the pyroclastic projections and the chaotic breccias which corresponds to the detrital sedimentary features. These sets of rocks were cut by a set of doleritic, andesitic and rhyolitic dykes.

Fig. 3. Geological map of Agdim-Ait Elfersi sector. These formations were affected by very important brittle tectonics (Fig.3 and Fig.4 h).

The Paleozoic cover is characterized by a series of lateral detrital and carbonate features attributed to Lower and Middle Cambrian (Fig.3), with rare calcareous intercalations attached to the Tata Group. The basic conglomerates rest in angular unconformity on the Neoproterozoic formations. These

conglomerates contain pebbles and subangular elements with variable sorting. Their composition is polygenic and dominated by volcanic and pyroclastic rocks elements. An association of clay and carbonate mixed platform of the Amousslek-Issafene formation marks the passage to the sandstones of Asrir formations (Fig.3). This formation caps the summit of the Lower Cambrian corresponds to a rose sandstone bar composed of a monotouns stack of multidicemeter lenticular layers of fine-grained sandstones. The middle Cambrian begins with Micmaca barcia invaded by green pelites of Jbel Wawrmast formations and the sandstone of Tabanite group (Fig.3). The remainder of the Paleozoic series are the Ordovician deposits of the external Feijas group with a stratigraphic gap during the Upper Cambrian.

The relationships between the different structures raised in the field allow us to identify and distinguished three main fault systems. This is a brittle deformation defined as follows:

- NE-SW System

This system brings together faults from various directions between $N45^{\circ}$ and $N65^{\circ}$ (Fig.4 a-b-c-e and h); it is well exposed in the field and constitutes the most abundant and important family in our study area. This network of faults affects both the Precambrian basement and Paleozoic cover. These structures have a strong dip, predominantly south-easterly, and present a dominant dextral movement rather than a sinister one; less described. The NE-SW system intersects the entire structures oriented $N110^{\circ}$ to $N140^{\circ}$ and that of $N80^{\circ}$ to $N100^{\circ}$.

Fig. 4 . Photograph showing a brittle deformation defined in the study area: a-b-c-e and h) NE-SW fault system with striation in (b); S-C shears fabrics in (c); dextral and sinistral kinematics in (e) and (h); d) E-W fault system; f-g and i) NW-SE fault system with a dextral kinematics in (f-i); and j) Rosette diagram for faults of the Agdim Ait-Elfersi sector

- E-W system

It is represented by the structures essentially oriented N80 to N100 with a subvertical dip (Fig.4 d). It is an abundant family and develops mainly at the transition zone between the Neoproterozoic and the Lower Cambrian. These structures show in their kinematics sinistral strike-slip movement and sometimes a dextral strike-slip movement. The sinistral clearance appears to be more abundant.

- NW-SE system

It has dextral kinematics and brings together all the structures which have a varied direction between N110 to N140 (Fig.4 g) with an essentially subvertical dip, sometimes reaching 65° towards the northeast. This family mainly affects the Precambrian basement with a decametric to kilometer extension. These structures are less expressed and intersected by other fault systems detected in the field. On the surface, these structures have a pull-apart opening confirming dextral kinematics (Fig.4 f and i). The structural synthesis of the Agdim - Ait Elfersi sector indicates the presence of breaking and strike-slip tectonics associated with a shear zone with the development of the C / S fabrics (Fig.4 c). This shear zone is linked to an intersection between two complex systems of faults (Fig.7); E-W fault in the north with a dextral movement and NE-SW fault with a sinister movement in the south (Fig.7).

4.2. Petrography and Hydrothermal Alterations

4.2.1. Basic to intermediate rocks

The basic to intermediate corteges are andesitic rocks. These basic to intermediate rocks of the late Neoproterozoic series of the studied sector present two types of deposits, either andesitic lava flows or intrusive dykes in the volcanic series. All of these rocks are dark, grey in color, sometimes brown to greenish.

- Brown to greenish porphyritic andesites (Fig. 5 a and a'): Macroscopically, they are brown to greenish porphyritic rocks with small tablets of feldspar. In the thin section, they have a porphyritic microlithic texture with the development of a primary paragenesis formed by plagioclase, pyroxene, and opaque minerals. The plagioclase phenocrysts, very abundant, vary in size from 1 to 5mm. They are polysynthetic twins and altered to sericite and calcite. Pyroxene appears in phenocrysts can reach 1mm and is transformed slightly into amphibole and chlorite.
- Dark gray porphyritic andesite (Fig. 5 b and b'): Macroscopically, they are porphyritic rocks of a dark grey color with small tablets of feldspar. In thin section, they have a more or less brecciated porphyritic microlithic texture, formed of very abundant plagioclase, calcite, chlorite and opaque minerals more abundant than in brown to greenish porphyry andesite. The plagioclase phenocrysts vary in size from 0.5 to 2 mm; they are polysynthetic twinning and deteriorate into sericite and calcite. Their breccia appearance can be explained by a brittle deformation linked to a late hydraulic pressure.

4.2.2. Acid rocks

The felsic rocks of the series studied consist of rhyolitic, rhyodacite, dacitic, and pyroclastic rocks. They present two types of deposits, either in the form of acidic volcanic flows or in the form of intrusive dykes in the volcanoclastic series.

- Dacites (Fig. 5 c, c', d and d'): They are reddish to purplish colored rocks. In thin section, they have a brecciated aspect (Catalasite) and showing a primary paragenesis formed by quartz, plagioclase, biotite, and opaque minerals. Secondary paragenesis is expressed by sericite, chlorite and iron oxides. Quartz scarce compared to plagioclase. It is xenomorphic up to 0.5 mm in size. We also note the appearance of a secondary quartz linked to the phenomenon of recrystallization, either in late fractures or at the edges of primary quartz. Plagioclases are twinned polysynthetic and have

a millimeter size; they are automorphic to subautomorphic and partially altered to sericite. Biotite is very rare and altered to chlorite. It appears in elongated crystals sometimes in rods of brown tint. Opaque minerals are also observed in this rock; they have an inframillimetric size.

- Rhyodacites (Fig. 5 e and e'): In the thin section, they present a primary paragenesis formed by quartz, plagioclase, biotite, and opaque minerals. Secondary paragenesis is expressed by chlorite, sericite, and iron oxides. Compared to dacites, they differ only in the proportions of the primary mineral phases expressed as phenocrysts. They were marked by an increase in quartz percentage. Rhyodacites distinguished from rhyolites by the absence of potassium feldspar in their phenocrystalline phase.
- Pink rhyolites (Fig. 5 f and f'): They are pink to whitish colored rocks. In thin section, they have a fibrous appearance and show a primary paragenesis formed by quartz, plagioclase, potassium feldspar (microcline), and opaque minerals, while secondary paragenesis is expressed by sericite. According to microscopic observation, chlorite and iron oxides are associated with a late event as they crystallize in cracks and pull-apart structures observed in this rock.

Fig. 5. Photomicrograph of thins sections of the volcanic rocks of the study area: Brown to greenish porphyritic andesites (a-PPL and a'-XPL); Dark gray porphyritic andesites (b-PPL and b'-XPL); Dacites rocks (c and d-PPL, c' and d'-XPL); Rhyodacites rocks (e-PPL and e'-XPL) and pink rhyolites (f-PPL and f'-XPL)

4.3. Hydrothermal Alterations

Hydrothermal alterations are expressed in the form of hydrothermal circulations around and in the various features, of the Neoproterozoic basement and of the Paleozoic cover. Hydraulic breccia (Fig.6 e and f), altered corridors and oxidation zones have an orientation coinciding with the main directions of the mineralized veins. The most discreet manifestations of this circulation of the fluid are marked by the presence of carbonate veins (Fig.6 c) sometimes associated with quartz and iron oxides, filling fractures mainly in andesites, rhyodacites and pink rhyolites. The most dominant hydrothermal alterations in Agdim-Ait Elfersi sector correspond in particular to:

- *Silicification*

It is highlighted by the abundance of lenticular of silica (Fig.6 b), veinlets and veins of quartz in the different features of the studied sector. Almost all the thin sections studied show the presence of two generations of quartz. The first generation is in the form of a filling of the fractures and late

microfractures that affected the volcanic features. The second is occurring in cracks and mineralized veins in the form of saccharoid quartz and hilly quartz.

- *Hematitization*

It affects the majority of features in the study area (Fig.6 a). This phenomenon is well developed around veins, cracks and iron caps carrying mineralization. At the level of thin sections, the development of iron oxides in all the features studied is the main cause of this alteration (Fig.5 d and f).

- *Chloritization*

Macroscopically, chloritization affects the majority of features in the area studied. It is clearly visible in the form of millimeter veinlets, especially in rhyolites (Fig.6 d), grey to greenish rhyodacites and also in the form of cement in hydraulic breccias. On the microscopic scale, chloritization marked by the presence of replacement texture chlorite around the ferromagnesian minerals, it is an outcome of a chlorite hydrothermal circulation (Fig.5 e).

- *Carbonatation*

It is very abundant in the study area, on a macroscopic scale, it consists in the replacement of fractures and veins by calcite and ankerite (Fig.6 c). In thin sections, it is marked either by the presence of calcite minerals resulting from the alteration of plagioclase feldspar (especially in andesitic features), or by the replacement of microfractures by carbonates.

- *Sericitization*

In thin sections (Fig.5), it is marked by the presence of sericite in the secondary mineralogical parageneses of the rocks studied, especially in the andesitic and rhyolitic features. This type of alteration results from the transformation of plagioclases into sericite.

Fig. 6. Hydrothermal alteration from the Agdim -Ait Elfersi sector: a) iron oxides vein in the rhyolite rocks; b) lenticular silica in altered rhyolite; c) carbonate veins; d) Chlorite vein in the pink rhyolite; d and f) mineralized hydraulic breccia in the pink rhyolite

The terminal Neoproterozoic magmatic rocks of the studied area show the presence of two components, on the one hand, a basic to intermediate cortege made up of flows and dykes of porphyritic andesites, on the other hand, an important acidic cortege of rhyolitic and pyroclastic rocks. These rocks exhibit a significant degree of hydrothermal alteration, during which the primary minerals have been partially or completely transformed into secondary products. We thus distinguish silicification, sericitization, haematization, chloritization, and carbonation as types of hydrothermal alterations.

The expression of hydrothermal circulations is in the form of altered corridors, zones of oxidation and hydraulic breaches. Their orientation coincides with the main directions of potential structures in mineralization. The greatest concentrations of these hydrothermal expressions were observed in the rhyolitic features. Their cement (Fig.6 f and Fig.8 f) consists of chlorite, quartz, iron oxides, malachite and sometimes chalcopryite. Consequently, the rhyolite could constitute the source and the convective motor of hydrothermal circulations responsible for deposits and the genesis of polymetallic mineralization of the Agdim - Ait Elfersi sector.

4.4. Mineralization

The studied sector presents disseminated and vein type mineralization. It is disseminated in the rhyolitic features of the felsic volcanism of the Ouarzazate group (Fig.8 d and Fig.9 a), and in the following vein form of the mineralized structures hosted in the formations of Neoproterozoic basement and their Paleozoic cover, specifically in the detrital features of the Lower Cambrian (Fig.7). These structures are veins, faults, and recesses filled by hydrothermal circulations with intense breccia and oxidation (Fig.7 e) that varies from one zone to another depending on the nature of the filling and the lithology hosted. The potential mineralized structures of Agdim Ait Elfersi have NW-SE, E-W, and NE-SW principal directions, with a length of 200-300 m and 20-50 cm in thickness.

Fig. 7. Mineralization-structures map of the study area

The ore mineralogy of Agdim – Ait Elfersi sector are represented by sulfides were introduced during different hydrothermal episodes as indicated by the development of hydrothermal breccias and the presence of sulphide minerals (Fig.8 f) in the hydrothermal weathering minerals. Field observations of the mineralized structures (Fig.8 a, b and c) and the reflected light microscopy (Fig.9) combined with scanning electron microscopy Fig.10 have revealed the presence of a very diverse range of minerals. All ores minerals are fine grained and accompanied by gangue minerals, such quartz, barite and chlorite. Minerals identified in the Agdim - Ait Elfersi sector by optical microscopy include chalcopyrite, chalcocite, galena, sphalerite, pyrite, cerussite, covellite, digenite, malachite and azurite. Gold and silver are not observed microscopically in the studied samples, they were detected by geochemical analyzes. SEM analyzes revealed the presence of silver in the chemical composition of chalcocite, chalcopyrite and pyrite (Fig.10 a and b).

- **Pyrite (FeS_2)**

Pyrite is the most abundant mineral in the studied area; it crystallizes in the form of a classical cubic habitus (Fig.9 a), large in size, generally of the order of a centimeter, scattered in pink rhyolites and andesite dykes of the volcanic series. In mineralized structures, it is xenomorphic and associated with chalcocite and chalcopyrite. Pyrite crystals are fully or partially pseudomorphs to iron oxides.

- **Chalcopyrite (CuFeS_2)**

Chalcopyrite is associated with pyrite and chalcocite. It exists in small xenomorphic crystals disseminated (Fig.9 c and d) in the quartz and barite matrix of the various mineralized structures observed at the scale of the area studied. Chalcopyrite is partially or totally replaced by malachite and / or azurite.

- **Chalcocite (Cu_2S)**

The chalcocite is a mineral species composed of copper sulphide (Fig.9 g) with the chemical formula Cu_2S . Semi-quantitative Scanning Electron Microscope analyzes indicate that chalcocite contained traces of Ag, Fe, Mn, Co, Ni (Fig.10 b).

- **Galena (PbS)**

Galena is very abundant, especially in the structures-oriented NE-SW, and occurs in the form of crystals disseminated in the quartz matrix (Fig.9 b). Crystals are fully or partially pseudomorphs to cerussite.

- **Sphalerite (ZnS)**

Sphalerite is very small and occurs as inclusions in chalcopyrite (Fig.9 e). It is in traces associated with chalcopyrite and these minerals alteration.

- **Cerussite (PbCO_3)**

Cerussite is a secondary alteration mineral of galena with the chemical formula PbCO_3 . It comes in the form of a replacement texture in the borders of the galena. The microfractures that have affected galena are clogged by cerussite (Fig.9 b).

- **Covellite (CuS) and digenite (Cu_9S_5)**

Covellite and digenite are alteration minerals that appearing in the secondary phase. They are linked to the destabilization and alteration of chalcopyrite (Fig.9 f).

- **Malachite $\text{Cu}_2(\text{CO}_3)(\text{OH})_2$ and Azurite $\text{Cu}_3(\text{CO}_3)_2(\text{OH})_2$**

Copper carbonates are secondary oxidation minerals that indicate the presence of a cementation zone linked to a supergene alteration episode.

- **Iron oxides**

Iron oxides (Goethite, etc.) are very abundant throughout the area studied. They borrow the same forms from ancient pseudomorphs pyrite. These oxides are evidence of strong oxidation linked to a late hydrothermal event.

Fig. 8. Photograph showing minerals from the mineralized structures of the Agdim - Ait Elfersi sector: a) Malachite, barite and iron oxides; b) Malachite, azurite and galena in a quartz matrix; c) Gossanous Polymetallic vein; d) Quartz, barite, chalcocite, malachite, chalcopyrite and oxides; e) malachite and azurite disseminated in rhyolitic rocks and f) Chalcopyrite, malachite and oxides in a hydraulic breccia

Fig. 9. Reflect light photomicrographs of polished sections from the studied area: a) pyrite and chalcopyrite disseminated in rhyolites; b) Galena showing triangle pits and replaced by cerussite; c) Inclusions of pyrite and chalcopyrite in a hexagonal section of quartz; d and f) Replacement of chalcopyrite in covellite, deginite and goethite; e) Inclusion of sphalerite in chalcopyrite and g) Chalcocite and chalcopyrite crystals in quartz matrix

Fig. 10. SEM images and energy dispersive spectroscopy (EDS) of the mineralization of study area: a) chalcopyrite; b) chalcocite; c) galena and d) pyrite

5. Discussion

5.1. Paragenetic Sequence

The distinction between the different paragenetic stages of polymetallic mineralization in the Agdim - Ait Elfersi sector is based on the nature and textures of the mineralogical assemblages of the different veins and on the mode of establishment observed. Three stages have been observed explaining the majority of textures and mineralogical assemblages of the polymetallic mineralization of the Agdim-Ait Elfersi sector (Fig. 11):

- **Stage 1**

It corresponds to the establishment of base metal paragenesis in veins and disseminations in the Precambrian basement, especially in the rhyolitic features. It is associated with white barite, gray barite and iron oxides paragenesis. The metallic phases are essentially characterized by pyrite and chalcopyrite.

- **Stage 2**

It is characterized by the deposition of most of the polymetallic Cu-Ag-Pb mineralization in the broadly oriented NE-SW and E-W structures, which affected the Precambrian basement and its Paleozoic cover. This episode is associated with the deposition of an essential quartz matrix, sometimes

with pink barite and quartz saccharoide. The metallic phases are represented by chalcopyrite, chalcocite, galena, sphalerite, and pyrite.

• Stage 3

It is characterized by the supergene alteration phenomena that are responsible for the dissolution of primary minerals and the neoformation of alteration minerals, such as cerussite, covellite, digenite, malachite, azurite, and iron oxides.

Fig. 11. Paragenetic sequence of the polymetallic mineralization of the study area

5.2. Geochemistry Data

A sampling campaign was carried out in the area studied. These samples, 34 in number, were taken at surface in mineralized structures across the study area. The elements targeted in this campaign are copper, lead, silver, gold, mercury, zinc and iron. The correlation between these elements, especially between Ag-Hg, Cu-Hg, Cu-Ag, Ag-Pb, Au-As and Au-Pb, shows a strong positive correlation with a correlation coefficient (R^2) which varies between 0.1704 and 0.8038. These correlations reflect the mineralogical associations between these elements, particularly between Ag-Hg, Cu-Hg and Cu-Ag.

Geochemical analyzes of samples taken from mineralized structures in the Agdim - Ait Elfersi sector showed firstly the polymetallic character of this mineralization and then the existence of clear geochemical bonds and associations between the targeted elements. The high contents of Ag, Cu and Hg are comparable with those which characterize epithermal-type deposits in the world (White and Hedenquist, 1990; Taylor 1995; Hedenquist et al., 2000; Sillitoe et al., 2003; Einaudi et al., 2003; Wang et al., 2019; Dilles and John 2020). Therefore, the high levels of silver and mercury in some samples analyzed probably indicate the existence of an Ag-Hg epithermal system at the depth of this study area.

5.3. Structural, Lithological and Hydrothermal Control

The structural synthesis of the cinquefoil zones in polymetallic mineralization of the Agdim Ait Elfersi sector indicates the presence of a breaking break-out tectonics associated with a shear zone with the development of the C / S fabrics. This mineralization is relatively controlled by a conjugate fault system, probably operated during the Hercynian and/or Alpine orogeny. It corresponds to a complex system formed by an intersection between faults and strike-slip faults with E-W and NE-SW directions. Indeed, this shear zone is linked to two faults, one in the north with a dextral movement and the other with a sinister movement in the south.

The E-W and NE-SW strike-slip faults played during the late Pan-African phase in the Neoproterozoic basement and during the Hercynian to tardi Hercynian phase in the Paleozoic cover (Dal Piaz et al., 2007; Malusà et al., 2007). Our study highlights their importance in the genesis and the establishment of polymetallic Cu-Ag-Pb mineralization at the level of the late Neoproterozoic-Lower Cambrian transition zone in the Agdim-Ait Elfersi sector. The Agdim-Ait Elfersi sector mineralization hosts in late Neoproterozoic rhyolitic features and in Lower Cambrian detrital features, Middle Cambrian paradoxical shales play a tempering role. Rhyolites have undergone hydraulic pressure and intense hydrothermal alteration with the development of cataclasite structures. Detrital features underwent intense deformation and melonytization with the development of C / S structures.

Structural control will facilitate the circulation of hydrothermal fluids carrying mineralization (Awadh et al., 2008; Awadh and Nejbert, 2016). In addition to this structural control, there is lithological control (Awadh, 2019), which translates into rheological control. In isotropic rocks, their permeability favors hydrothermal circulation (Awadh and Nejbert, 2016), on the other hand with impermeable anisotropic rocks, which do not facilitate the circulation of hydrothermal fluids. As a result, polymetallic Cu-Ag-Pb mineralization from the Agdim-Ait Elfersi sector occurs in rhyolitic and detrital features of the Late Neoproterozoic and Lower Cambrian, respectively.

5.4. Mode of Genesis

Based on field observations, the Cu-Ag-Pb polymetallic mineralization from the Agdim-Ait Elfersi sector marks out the transition zone between the terminal Neoproterozoic basement and its Lower Cambrian detrital cover. This transition zone is associated with the establishment of rhyolitic felsic volcanism generated by the late Neoproterozoic extensional tectonics, responsible for deposits of base and precious metal mineralization in the Anti-Atlas belt (Cheilletz et al., 2002; Levresse et al., 2004; Gasquet et al., 2005; Marcoux and Wadjinny 2005; Tuduri et al., 2006; Pelleter et al., 2007; Bouabdellah and Slack 2016; Levresse et al., 2016, 2017; Pelleter et al., 2016; Tuduri et al., 2018). Areas of interest that contain mineralization are generally concentrated where there is a pink rhyolite. It should be taken into account that the greatest concentrations of hydraulic breccias and hydrothermal alterations were observed in these rhyolitic features, where these powerful structures of 10 to 30 cm on average are constituted by quartz, barite, iron oxides, malachite, pyrite and chalcopryrite.

Consequently, the rhyolitic features could then constitute the source and the convective motor of the hydrothermal circulations responsible for deposits and the genesis of polymetallic Cu-Ag-Pb mineralization of the Agdim-Ait Elfersi sector. This mineralization was remobilized and redeposited in NE-SW trending fault structures that affected the Paleozoic cover during the Hercynian orogeny, not to mention the effect of Alpine orogeny. The polymetallic Cu-Ag-Pb mineralization in this sector concerned by this present study is linked to two major events. A late Pan-African event (Levresse et al., 2004 ; Gasquet et al., 2005 ; Tuduri et al., 2006 ; Pelleter et al., 2007 ; Bouabdellah and Slack, 2016 ; Tuduri et al., 2018) linked to felsic volcanism, responsible for the establishment of mineralization at the level of the basement, and then a Hercynian and Alpine event (Wafik et al., 2017a) which manifests by the remobilization of metals in the deformation corridors corresponding to faults, veins and mainly NE-SW strike-slip fault, along the shear zones.

5.5. Regional Comparison

The Cu-Ag-Pb mineralization of the Agdim - Ait Elfersi sector, which is exceptionally rich in copper and lead, as well as the high silver and mercury contents, demonstrate that it is, as in Imiter and Zgounder deposit (Table. 1), an epithermal mineralization associated with a mega-event during the Ediacaran - Cambrian boundary. This sector has strong analogies with the silver deposits of Imiter (Orguir et al., 1994; Levresse et al., 2004; Tuduri et al., 2006; Levresse et al., 2016, 2017; Tuduri et al.,

2018) and Zgounder (Marcoux and Wadjinny 2005; Pelleter et al., 2016; EL Aouad et al., 2021), geologically (felsic volcanism), stratigraphic (Transition zone between Precambrian basement and Paleozoic cover), structural (EW, NE-SW, NW-SE fractures) and geochemical (High content of Ag and Hg). The sectors of Agdim - Ait Elfersi, Imiter and Zgounder could be expressions of the same late Neoproterozoic epithermal event (Gasquet et al., 2005; Bouabdellah and Slack, 2016; Wafik et al., 2017b; Tuduri et al., 2018), which would extend into the Anti-Atlas domain, starting more and more in define what could be a silver-bearing metallogenic province.

Table. 1. Regional comparison of Agdim – Ail Elfersi sector, Imiter and Zgounder ore deposit

	Imiter Ore deposit (Levresse et al., 2004 ; Tuduri et al., 2006, 2018).	Zgounder ore deposit (Marcoux and Wadjinny 2005; Pelleter et al., 2016).	Agdim –Ait Elfersi sector (This study)
Location	Saghro inlier, Anti Atlas	Siroua massif, Anti Atlas	Northeastern of Saghro.
Geodynamic context	Pluto-volcanic arc context	Pluto-volcanic arc context	Pluto-volcanic arc context
Metallogenic period	Late Neoproterozoic	Late Neoproterozoic	Late Neoproterozoic and lower Cambrien
Hosted rocks	Neoproterozoic black shales	Volcano-sedimentary series of Neoproterozoic	Ouarzazate group and Lower Cambrian features.
Associated volcanism	Felsic volcanic rocks (rhyolite)	Felsic volcanic rocks (rhyolite)	Felsic volcanic rocks (rhyolite)
Tectonic structure	Fracturing systems: N-S; NE-SW; E-W; NW-SE	Fracturing systems: E-W; N-S; NE-SW; NW-SE	Fracturing systems: N-S; NE-SW; E-W; NW-SE
Morphology of the deposit	Pockets, veins, stockwork	Lenticular, disseminations, lenses, veins.	Disseminations, veins, pockets, stockwork
Texture	Breccias, mosaic, disseminated.	Breccias, disseminated.	Breccias, mosaic, disseminated., banded
Hydrothermal alterations	Propylitization, silicification, kaolinization, carbonation.	Chloritization, carbonation, silicification.	Sericitization, carbonation, silicification, hematitization, chloritization.
Gangue minerals	Quartz, dolomite	Quartz, calcite, chlorite.	Quartz, barite, chlorite
Metallic minerals	Native Ag, Argentite, Galena, Pyrite, Arsenopyrite, Silver Sulfosalt.	Native mercury silver, galena, pyrite, Arsenopyrite, chalcocopyrite, sphalerite	Chalcocopyrite, chalcocite, pyrite, galena, Sphalerite.
Metals	Ag, Hg, Cu, As, Au, Pb	Ag, Hg, Pb, Cu, Au	Cu, Ag, Hg, Pb, As, Au, Zn

6. Conclusions

The Cu-Ag-Pb mineralization deposit in the Agdim Ait Elfersi sector, hosted in the rhyolitic features of the terminal Neoproterozoic and the detrital formations of the Lower Cambrian, present similar characteristics to the mineralization of the transition zone between the late Neoproterozoic and the Lower Cambrian in the Anti-atlas belt. According to the geochemical study, we figured out that the mineralized system shows a close association between precious metals and base metals, confirming its polymetallic name. The metallic procession of economic interest is Cu-Ag-Pb, metals to which Zn, Hg and Ba are largely added. The high levels of silver and mercury in some of the samples analyzed probably indicate the existence of an Ag-Hg epithermal system at depth. The Agdim - Ait Elfersi sector has strong analogies with the Imiter and Zgounder silver deposits in terms of (i) geological context: felsic volcanism, (ii) stratigraphic context: boundary of the Precambrian basement and the Paleozoic cover, (iii) structural deformation: EW, NE-SW and NW-SE fractures, and (iv) geochemical characteristics: high content of Ag and Hg.

This analogy could be expressions of the same late Neoproterozoic terminal epithermal event (Gasquet et al., 2005; Bouabdellah and Slack, 2016; Tuduri et al., 2018), which would extend into the Anti-Atlas domain, increasingly beginning to define what could be a silver-bearing metallogenic province.

Based on the different results presented in this manuscript, the following conclusions can be extracted:

- The Agdim - Ait Elfersi sector presented a polymetallic mineralization with copper, silver and lead;
- The mineralization is hosted by rhyolitic features of late Neoproterozoic and by detrital features of lower Cambrian;
- The Agdim - Ait Elfersi mineralization is associated with the Neoproterozoic and Cambrian boundary;
- The mineralization is controlled by a breaking bear up tectonics associated with a conjugate fault system, probably operated during hercynian and alpine orogeny;
- The mineralization is linked to two majors' event, a late Neoproterozoic event associated to felsic volcanism, and then a hercynian and alpine even, which manifest by the remobilization of metals in the deformation corridors;
- The sector of Agdim - Ait Elfersi has strong analogies with the Imiter and Zgounder silver deposits.

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