Textural and mineralogical constraints on the mode of formation of the bou Azzer Co-Ni arsenide mineralization (Anti-Atlas, Morocco): Tectonic implications

Tourneur Enora, Alain Chauvet, Kalin Kouzmanov, Johann Tuduri, Stanislas Sizaret

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Enora Tourneur, Alain Chauvet
University of Montpellier, France

Kalin Kouzmanov
University of Geneva, Switzerland

Johann Tuduri
BRGM, France

Stanislas Sizaret
ISTO, Geosciences Campus, France

Abstract. The Bou Azzer inlier, supposed to be the suture zone of the Neoproterozoic orogeny, is composed of an assumed ancient oceanic crust of serpentinized ultramafic rocks, gabbro and basaltic pillow rocks. This inlier hosts the Co-Ni ore deposit of Bou Azzer with two types of mineralization: i) a massive, elongated ore bodies, known as "*contact"* type mineralization, along the contact between serpentinite, quartz diorite and Precambrian volcanic rocks; and ii) a "*cross-cutting*" type represented by faults that cut all units, only mineralized at the vicinity with the "*contact*" type. A detailed mineralogical and textural study brings new arguments on the ore-formation processes at Bou Azzer. First, it appears that both types are developed within a progressive and continuous tectono-hydrothermal stage as shown by the mineralogical evolution. Second, the "contact" type exhibits two various aspects: i.e., Laminated Contact Mineralization (LCM) and Breccia-Related Contact Mineralization (BRCM) that are related to different initial textures of the pre-mineralization host rocks. Third, Ni-Co mineralization seems developing by replacement of spinel/magnetite grains of the serpentinite. All these observations are consistent with ore formation along a tectonic contact thus explaining the existence of serpentinite fragments slope breccia.

1 Introduction

Various cobalt mineralization styles on Earth can not be attributed to a single ore-forming model. At least, six major mineralization styles are known: 1) sediment-hosted stratiform Cu-Co deposits (Fay and Barton 2012); 2) ortho-magmatic sulfide deposits (Naldrett et al. 1998); 3) Co from lateritic profiles mainly exploited for Ni (Orloff 1968); 4) Co-rich crusts associated with Mn-nodules within seawater hydrothermal oxidizing venting environment (Hein et al. 2000); 5) hydrothermal/volcanogenic deposits (the Bou Azzer district) (Leblanc 1975; En-naciri 1995); 6) Five elements (Ni-Co-As-Ag-Bi) vein-type deposits (Kissin 1988; Markl et al. 2016; Burish et al. 2017). At Bou Azzer, two types of ore bodies occur – "contact" and "cross-cutting" ones, both with unclear mode of formation, especially regarding the relationships with larger scale geodynamic processes. In this contribution, we present and discuss: i) mineralogical and paragenetic features that favor coeval processes of formation for both mineralization types at Bou Azzer; ii) new textural observations helping to discuss the pre-mineralization tectonic context and its implication on the presently admitted classical model of Precambrian ophiolite for the Bou Azzer inlier (Leblanc 1976, Gasquet et al. 2005).

2 The Bou Azzer – El Graara inlier and deposits

The Bou Azzer – El Graara inlier, oriented NW-SE, is located in the central part of the Moroccan Anti-Atlas, south of Ouarzazate. The inlier is composed of a dismembered but complete sequence of an assumed ancient oceanic crust composed by serpentinized ultramafic rocks overlaid by gabbro and basaltic pillow rocks (Leblanc 1975, 1976, 1981; Bodinier et al. 1984). For this reason, this area is interpreted as being a suture zone related to the Neoproterozoic orogeny (e.g. Choubert 1963; Leblanc and Lancelot 1980; Saquaque 1992). The tectono-magmatic evolution of this area (Tuduri et al. 2018) involves a first tectono-magmatic-event, associated with massive high-K calc-alkaline magmatism emplaced in deformed meta-sediments under transpressive tectonic control (the Lower Complex); and a second transtensive deformational event, associated with intense magmatism, volcanism and volcano-clastic sediments deposition (the Upper Complex). The Precambrian group of Ouarzazate, characterizing the Upper Complex, is composed of dacitic to rhyolitic ignimbrites and andesitic tuffs (Mifdal and Peucat 1985); all intruded by a calc-alkaline to highly potassic plutonic rocks. All these Precambrian units are covered by the Cambrian sedimentary cover

(Pouit 1966; Bouchta et al. 1977; Gasquet et al. 2001).

3 Textural and paragenetic constraints on the mineralization

3.1 The Co-Ni ore deposits of Bou Azzer

Two types of ore bodies occur in the Bou Azzer district, as defined by Leblanc (1975) and En-naciri (1995) (Fig. 1):

i) The massive "*contact"* type is composed by Co-Ni-Fe arsenides hosted within a siliceous or carbonaceous gangue. This mineralization is developed systematically at the contact between serpentinites and quartz-diorite and/or Upper complex volcanic rocks south and north of the serpentinite occurrences, respectively.

ii) The "*cross-cutting"* type is composed of Co-Fe arsenide mineralization, associated with K-feldspar, quartz and carbonate gangue in veins. These veins intersect all units, and are only mineralized at the vicinity of the "contact" type ore bodies.

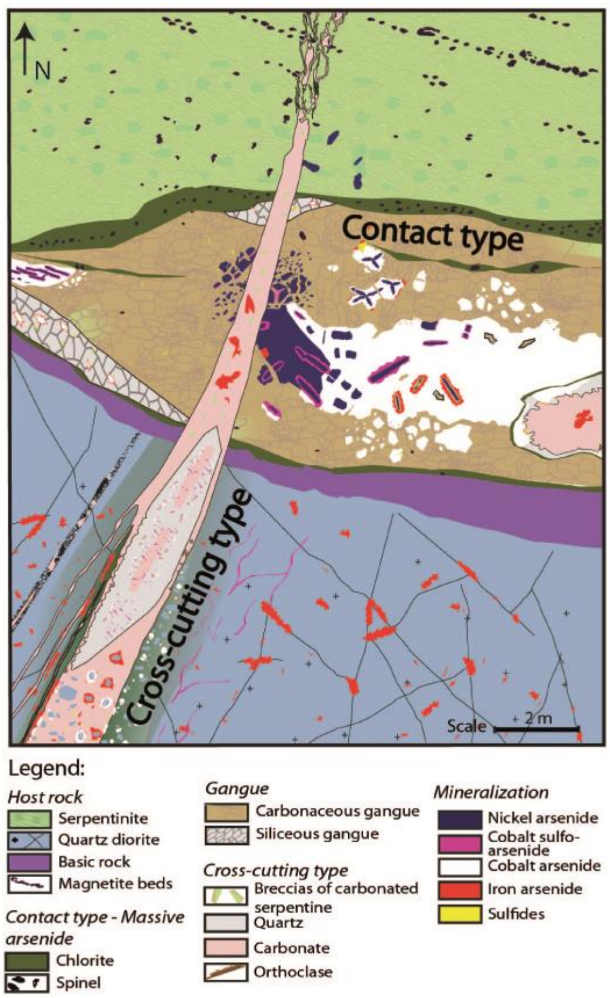

Figure 1. Model of formation of the Bou Azzer Co-Ni-rich arsenide ore deposit showing the distribution of the mineralization stages within the "*contact"* and the "*cross-cutting"* type mineralization.

Six paragenetic stages are recognized at Bou Azzer: 1) a Ni-arsenide stage with nickeline (NiAs) and rammelsbergite ($NiAs_2$); 2) a Co-arsenide stage with skutterudite ($CoAs_3$) and safflorite ($CoAs_2$); 3) a Co-sulfo arsenide stage with cobaltite (CoAsS); 4) a Fe-arsenide stage with loellingite ($FeAs_2$); 5) a Fe sulfo-arsenide stage with arsenopyrite (FeAsS); and 6) a sulfide stage with chalcopyrite, sphalerite, galena, and fahlores. The six stages are observed within the contact type mineralization, all included in a carbonaceous and a siliceous gangue whereas only the last fourth stages occur in the cross-cutting type.

A petro-structural model is proposed in order to integrate the six mineralization stages within three main events which lead to the formation of the Bou Azzer deposits (Fig. 1): 1) a Ni-Co-rich arsenide stage composed of nickeline, rammelsbergite and subsequent cobaltite and skutterudite; 2) the formation of the siliceous or carbonaceous gangue associated with the late Co-rich arsenide and the earlier Fe-rich sulfo-arsenide minerals; 3) the final formation of the cross-cutting structures that mainly host the final stage of the Co-rich arsenide mineralization event and the Fe-Cu-bearing sulfide minerals, both occurring in veins mainly composed of K-feldspar (minor), quartz and carbonate.

3.2 Textural observations on the massive type

Detailed textural analysis of the "contact" type mineralization led to the following observations:

1. Massive arsenide-rich parts of the mineralization show two distinct textural features:

- Massive lenses of lamellar nickeline surrounded by skutterudite sometimes alternating with carbonate forming a banded texture (Fig. 2a).

- Massive lenses of arsenides with isolated nuclei of elongated rammelsbergite surrounded by cobaltite, carbonate, skutterudite and chalcopyrite, all included within large euhedral skutterudite and with late carbonate (Fig. 2b);

2. The gangue of the contact mineralization is mainly carbonaceous and may exhibit several inherited fragments of serpentinite (Fig. 3a), indicating the nature of the host rock (serpentinite) prior to the formation of the mineralized structure;

3. Skutterudite is commonly fractured, with neo-serpentine infilling (Fig. 3b), thus demonstrating that serpentinization was still active at least during the earliest mineralization stages.

4. Spinels and rammelsbergite which entirely replace spinel are observed within the serpentinite close to the contact (Fig. 3b). Spinels are systematically bordered by magnetite (Fig. 3c) or rammelsbergite (Fig. 3b). In addition, cathodoluminescence imaging shows relics of spinel also frequently occurring in the core of the carbonate gangue (Fig. 3c), thus demonstrating again that serpentinite was the precursor of the mineralized gangue.

5. Cathodoluminescence imaging of the gangue carbonate shows that two textures co-exist; one dominated by large euhedral crystals evolving toward fragmented grains with a lot of space between them,

similar to textures related to dilatation breccia formed within a stress-free open space (Fig. 3d) (Jébrak 1997; Chauvet 2019).

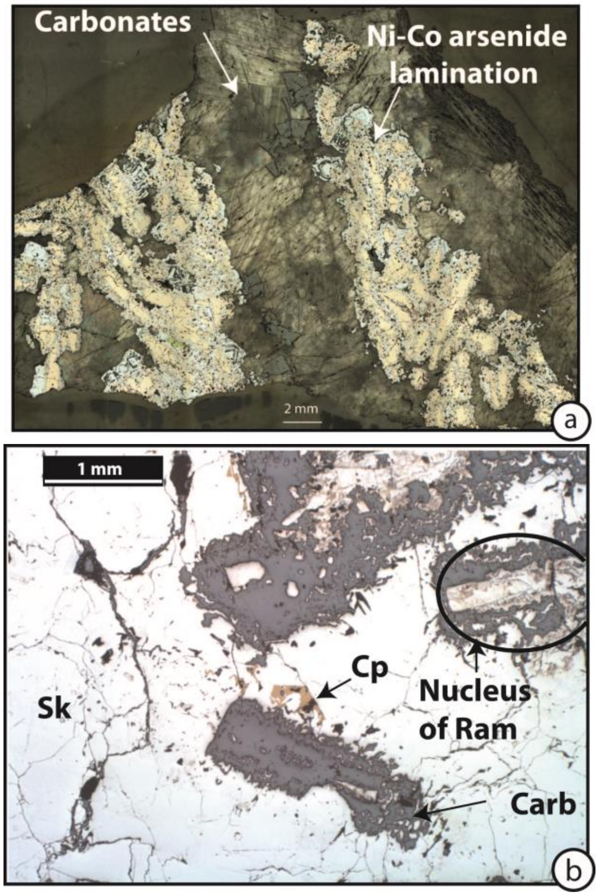

Figure 2. a. The "*contact*" type composed of laminated contact mineralization (LCM) of Ni-Co rich arsenide then surrounding by carbonate (image in reflected light). **b.** Nucleus of Rammelsbergite surrounding by skutterudite, carbonate, chalcopyrite, in a massive gangue of skutterudite and carbonates, indicates a brecciated-related environment of the contact mineralization (BRCM) (image in reflected light). Carb: carbonate, Co: Cobalt, Cp: Chalcopyrite, Ni: Nickel, Ram: Rammelsbergite, Sk: skutterudite

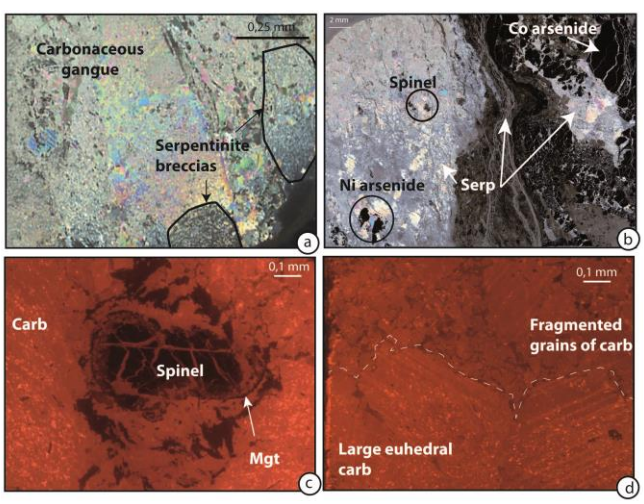

Figure 3. a. Fragments of a previously serpentinite in the carbonaceous gangue (image in polarized light) **b.** Few information of texture are visible: fractured skutterudite by serpentinite, spinel entirely replaced by rammelsbergite, spinel is observed in the serpentinite host rock (image in polarized light). **c.** Spinel is included also in the carbonaceous gangue of the "contact" type, is bordered by magnetite (image of cathodoluminescence – CL). **d.** The carbonaceous gangue shows two types of texture: brecciated texture of thin carbonates and euhedral texture of large carbonates (image of CL). Carb: carbonate, Co: Cobalt, Mgt: Magnetite, Ni: Nickel, Ram: Rammelsbergite, Serp: serpentinite

4 Formation of the Bou Azzer ore deposit and tectonic implications

Two main conclusions could be drown from the textural and mineralogical analysis of the Bou Azzer mineralization:

- The mineralogical evolution of both contact and cross-cutting mineralization types results from a progressive and continuous process that begins with Ni-Co ore formation followed by Co-Fe-Cu-rich stages. Ni-Co stages are encountered exclusively within the contact type while the Co/Fe/Cu stages are developed within both structures. This suggests that both mineralizations, i.e. the contact and the cross-cutting ones, are formed during the same tectono-mineralogical event even if the contact type ore bodies were the ones that formed first.

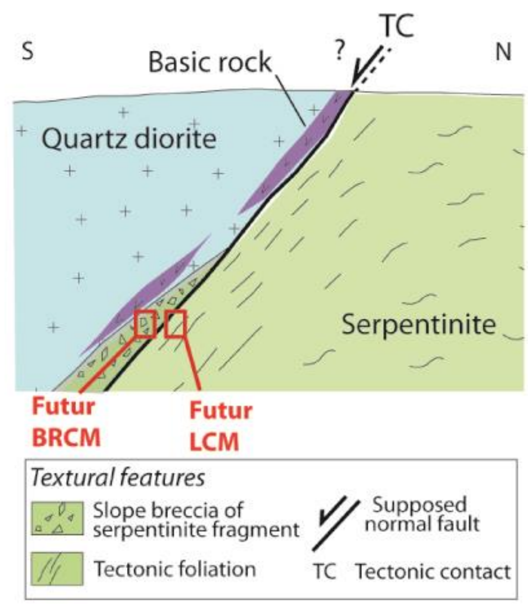

Figure 4. Example of hypothetic tectonic context consistent with the formation of serpentinite breccia that serves as receptacle for mineralization. In that case, fault motion need to be normal. (BRCM: Brecciated-related contact mineralization; LCM: Laminated contact mineralization)

- Textural features within the "*contact*" type demonstrate that these domains result from replacement and hydrothermal processes that affect a serpentinite rock. Textural constraints indicate that most of the ore bodies derived from serpentinite breccia could form Breccia-related Contact Mineralization (BRCM); although some can form, by the transformation of banded serpentinite levels, Laminated Contact Mineralization (LCM) (Fig. 4). It is suggested that such brecciated areas, characterized by high permeability, are favorable domains for fluid circulation and subsequent ore formation.

- The occurrence of relictic spinel bordered by magnetite and rammelsbergite confirms the hypothesis of replacement of serpentinite levels. It is suggested that spinel and magnetite fragments are at the origin of the Ni/Co-rich arsenides whereas serpentinite ones formed the gangues.

A first hypothesis regarding the tectonic context of ore formation at Bou Azzer is illustrated in figure 3: the brecciated levels as precursors for the formation of the contact orebodies can result from the activity of normal faults, as expected by the geometrical constraints. Such normal faults are not consistent with the classical obduction scenario and can help to the exhumation of the serpentinized mantle in this area.

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