Int J Earth Sci (Geol Rundsch) (2017) 106:2653–2665
DOI 10.1007/s00531-017-1451-3

ORIGINAL PAPER

Ore deposits and epithermal evidences associated with intra-magmatic faults at Aïn El Araâr-Oued Belif ring structure (NW of Tunisia)

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Received: 22 March 2016 / Accepted: 27 January 2017 / Published online: 21 March 2017

Abstract Hydrothermal ore deposits at Aïn El Araâr-Oued Belif location are classified as epithermal deposits type. The ore bodies are hosted by upper Turonian (8–9 M.y) volcanic rhyodacitic complex. Polymetallic sulfide orebodies are mainly concentrated within intra-magmatic faults. Petrographic, XRD, and TEM–STEM investigations revealed that ore minerals are essentially, arsenopyrite, pyrite, chalcopyrite, pyrrhotite, hematite, goethite and magnetite with Au, Ag and Pt trace metals. Gangue minerals are mainly adularia, quartz, sericite, alunite, tridymite, chlorite, phlogopite and smectite. Epithermal alteration is well zoned with four successive characteristic zones: (1) zone of quartz–adularia–sericite and rare alunite; (2) zone of kaolinite and plagioclase albitization; (3) intermediate zone of illite–sericite; (4) sapropelic alteration type zone of chlorite–smectite and rare illite. This can be interpreted as a telescoping of two different acidity epithermal phases; low sulfidation (adularia–sericite) and high sulfidation (quartz–alunite), separated in time or due to a gradual increase of fluids acidity and oxicity within the same mineralization phase. Brecciated macroscopic facies with fragments hosting quartz–adularia–sericite minerals (low-sulfidation phase) without alunite, support the last hypothesis. Geodynamic context and mineral alteration patterns are closely similar to those of Maria Josefa gold mine at SE of Spain which exhibit a volcanic-hosted epithermal ore deposit in a similar vein system, within rhyolitic ignimbrites, altered to an argillic assemblage (illite–sericite abundant and subordinate kaolinite) that grades outwards into propylitic alteration (Sanger-von Oepen et al. (1990)). Mineralogical and lithologic study undertaken in the volcanic host rock at Aïn El Araâr-Oued Belif reveals a typical epithermal low-sulfidation and high-sulfidation ore deposits with dominance of low-sulfidation. Host rocks in these systems range from silicic to intermediate for adularia–sericite type (low sulfidation) to rhyodacite for quartz–alunite type (high sulfidation).

Keywords Epithermal · Alteration · Sulfidation · Adularia · Sericite · Alunite · Tunisia

Introduction

Polymetallic sulfide and iron oxide-bearing mineralizations in the Oued Belif area are associated with calc-alkaline granitoïds and sub-alkaline basalts that were emplaced during the Serravallian to early Tortonian period (e.g., Badgasarian et al. 1972; Jaafari 1997; Talbi 1998). These magmatic events appear as a tectonic window through the allochthonous Flyschs mainly related to the Alpine and Atlasic phases (Chihi 1995; Talbi et al. 2005). Geodynamic events are related to the collision between Alkapeca (Meso-Mediterranean microplate derived from the European craton in the early Jurassic period) and African passive plate leading to the Alpine Maghrebine chain. These tectonic phases are synchronous with intense fracturations and important paleogeothermal activity (Talbi et al. 2005) in Nefza area.

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The magmatism includes basalt dikes and sills, granodiorite intrusions, dacites and rhyolites in the form of laccolith-dome, breccias and ash falls associated with major tectonic, deep-rooted trends that have pierced the overburden of upper Cretaceous and Eocene limestones and marls, and Rupelian to Serravalian siliciclastics.

Previous studies of ore deposits in the area, described the major geodynamic and magmatic constraints on the formation and later the collapse of the broad (3 × 6 km) Oued Belif caldera (Talbi 1998; Talbi et al. 1999). The genetic processes of ferruginous deposits hosted by this caldera and surrounding areas were also studied by Gottis and Sainfeld (1952), Dermech (1990), Talbi (1998) and Decrée et al. 2008a, b. The authors have attempted to elucidate the origin and composition of the iron mineralization in some dispersed samples including ring breccia of the structure.

The conclusion of these studies reported the presence of a mineral association composed of Fe (Mn) oxi-hydroxides and Pb–Zn, Fe–Cu–S sulfides, and accessory uranium in a gangue with dominant Mg-smectites, talc, chlorite and micas (Negra 1987).

Most of previous studies of Nefza-Oued Belif region mostly focused on regional geology and magmatic vents. Despite its favorable geologic context to be a metallogenic district, only few studies have been done in this matter and the areas still remain underexplored.

Nevertheless, works of Dermech (1990), Ben Aissa (1996), Talbi et al. (1999), Kassaà et al. (2003), Decrée et al. (2013) have undertaken the metallogenic aspect of Nefza region but they only focused on the polymetallic concentrations in the peripheral breccias and the external deposits of Oued Belif elliptical structure. Ore mineral expression in intra-magmatic faults of the structure stays until now rarely studied despite the several polymetallic geochemical anomalies (As, Sb, Bi, Sn, Cu, Fe, U, Ba) detected by stream sediment prospection (Ben Aissa 1991).

Moreover, the nature of metallic enrichment emphasizes the problem of the source of the mineralizing fluids and their role in magmatic rock alteration. Indeed, some studies based mainly on clays analysis disagree between the effect of a superficial fluid origin and a deep one.

The aims of our study, through a well-selected cross section in the inner magmatic outcrops of Oued Belif structure (Aïn El Arâar locality), are: (1) to identify the mineral association and paragenesis by petrographic observation in transmitted, reflected-light microscope and TEM techniques; (2) to study, by metallic as well as no metallic mineral phases, the nature and chronology of minerals formation, mineralizing fluids and the associated alteration pattern; (3) to compare our results with other deposits in a same magmatic and geodynamic context.

Regional tectonic setting

Northern Tunisia, located in North Africa, belongs to the west Mediterranean Alpin mountains range also called Maghrébide (Fig. 1). This belt stretches over a distance of 2000 km and includes the marocain rif, the Atlas coast of Algeria (Kabylie and Till), the northern Tunisia (Kroumirie-Nefza), Sicily (except its southeastern part) and Calabria (Durand-Delga 1980). The current tectonic configuration and magmatic outcrops, of northern Tunisia, results in the compilation of several tectonic events related to the diverging and converging motions of African and European plates.

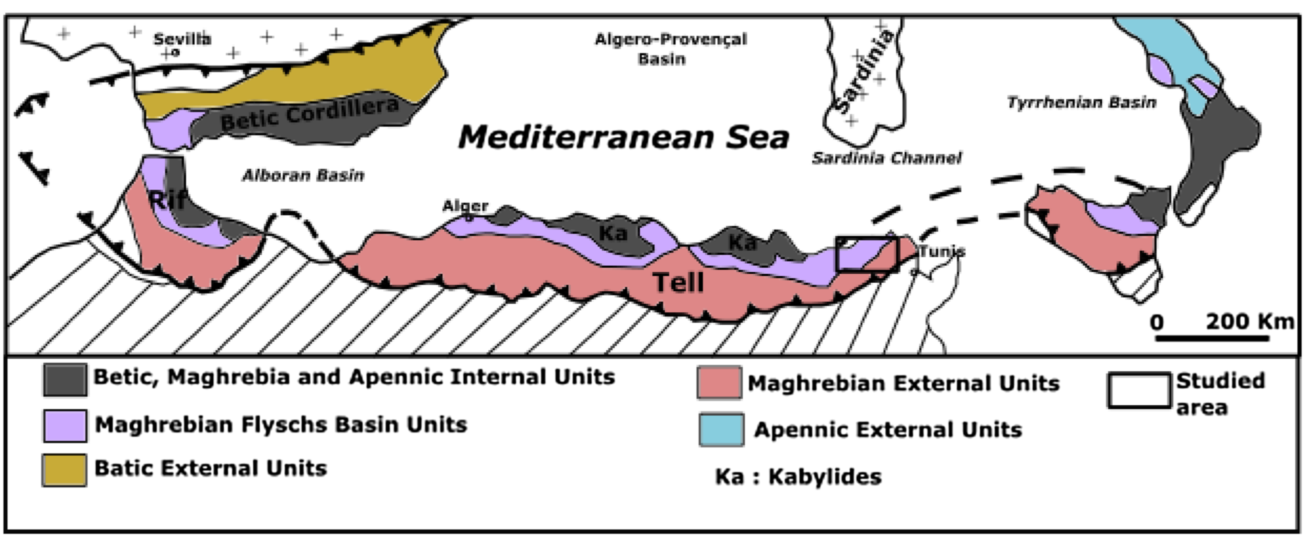


Fig. 1 The studied area within its regional geodynamic Mediterranean context (redrawn after Rouvier 1987)

From late Cretaceous to actual time, three main tectonic phases have shaped the current configuration of the North African margin: (1) the converging Pyrenean phase dated from the middle to late Eocene (Boccaletti and Guazzone 1974; Rehault et al. 1984) accompanied by an alkaline magmatism (Laridhi-Ouazaa 1994; Beji Sassi et al. 1996) in NW of Tunisia which includes magmatic breccias and carbonated micro-breccia with pyroclastic elements within "Adissa/Ain Draham tellian units" without evidences of metamorphic facies. (2) The Langhian-lower Serravalian compressive Alpine phase (Tlig et al. 1991) characterized by the development of thrustings, folding and shearing deformation structures (Chihi 1995). At the Mediterranean scale, this phase could be the consequence of the collision between the front North African plate with the Southern margin of Eurasian plate (Cohen et al. 1980; Dewey et al. 1989; Argniani 1990). (3) The Atlasic phase (Cohen et al. 1980; Tlig et al. 1991; Talbi et al. 2005) that extend from upper Miocene to Pliocene, expressed by the overthrust and the folding of the numidian and tellian thrusts (Philip et al. 1986).

The Alpine phase (Tlig et al. 1991) was expressed by an intrusive calc-alkaline affinity granitoïds at the Galite locality (Rekhiss 1996; Talbi 1998) and at the Nefza region (Laridhi-Ouazaa 1994; Talbi 1998). The end of this phase was characterized by the generation of a rhyolitic magma following a basic injections (Talbi 1998). This fact caused a physico-chemical disequilibrium between the two magmas leading to an ignimbritic eruption and explosions at Oued Zouara, hybrid rhyodacitic degassed domes at Oued Belif and the dacites of Jebel Haddada.

The acid magmatism in the Nefza region has continued during the beginning of the Atlasic phase by the emplacement of the granodiorite of Ragoubet El Alia (12.9 M.y) during the Serravallian–Tortonian and the Rhyodacite of Ragoubet Es Seid (8–9 M.y). At the end of the Atlasic phase, the calc-alkaline (acid) magmatism exchange to alkaline (basic) due to a relaxation phase during the upper Miocene–basal Pliocene [upper Tortonian-Messinian (Talbi et al. 2005)].

The polymetallic ore deposits associated with the magmatism within the Oued Belif structure still raise the problem of the contribution of the magmatic source of the mineralizing fluids. Occurrence of geochemical indicators, such as Cu, Hg, As, Sb, and Sn suggests that the source of fluids should be essentially deep and the contribution of magmatic fluid not negligible.

Local geological setting

Polymetallic mineralization of Oued Belif (Fig. 2b) belongs to the magmatic province and the mining district of base metals and mercury of N–W of Tunisia (Gottis and Sainfeld 1952). A variety of exploitable mineralization and signs were inventoried: (1) ferruginous mineralization (Fe, Cu, REE, U, Au) within the ring breccia of Oued Belif-Nefza (Gun 1995; Ben Aissa 1996; Limited 2004; Decrée et al. 2013), (2) disseminated mineralization of Zn–Pb (Ba–Sr ± Hg) in neighboring areas and at Sidi Driss mine, (3) mercury mineralization at Aïn Allega, (4) Missisipi Vally type mineralization Pb–Zn (MVT) (Gharbi 1997; Abidi et al. 2010), (5) mineralization of dacitic breccia at Ras Rajel containing up to 48 g/t Ag, 0.3% Zn, 0.5% Pb and 52 ppb Au (Ben Aissa 1996; Limited 2004), (6) Cu–Ag–Au mineralization showing up to 4.9% Cu and 119 g/t Ag in the veins of Oued El Maâden (Limited 2007). These mineral expressions are in relationship with the Cap Serrat-Ghardimaou shear zone (Fig. 2a) where the complex elliptically shaped structure of Oued Belif is closely associated (Gottis and Sainfeld 1952; Crampon 1971; Ben Aissa 1991; Talbi et al. 2005; Decrée et al. 2014). Magmatic outcrops in the inner part of Oued Belif structure are cross cut by a fault system allowing the circulation of hydrothermal fluids with some copper signs and trace of Au, U and REE (Ben Aissa 1991, 1996; Gun 1995; Talbi et al. 2005).

Opinions were divided regarding the nature and the origin of this structure; (1) a volcanic body which took along the Triassic salt-bearing formations during its ascension (Crampon 1971), (2) an old Triassic diapir that would subsequently serve as a path for magmatic fluid ascension in the Miocene (Mauduit 1978), (3) a structure resulting of the rise of a Triassic diapiric materials, coupled with a Miocene magmatism (Crampon 1971; Clochiatti and El Ghozzi 1977), (4) a calderic subsidence (Gottis and Sainfeld 1952) associated with a magmatism and followed by an hydrothermal activity with the intervention of magmatic fluids (Talbi et al. 2005). The hypothesis of a calderic subsidence seems to be the most plausible at geodynamic and magmatic levels since such structures were also described in SE of Spain (Rytuba et al. 1990).

Several magmatic outcrops occupy the Oued Belif structure center (Fig. 2b). A rhyodacitic dome-lava flow of Ragoubet Es Seid dated between 8.3 ± 0.8 M.y and 9 M.y according to, respectively, Bajanik, 1971 and Bellon, 1976 and coinciding with the upper Tortonian. A granodioritic intrusion (Mauduit 1978) of Ragoubet El Alia dated at 12.9 ± 0.5 M.y (Bellon 1976) and coincides with basal Serravallian–Tortonian. This granodioritic intrusion is related to the Serravallian compressive phase (Alpine collision). Rhyolitic magmatism and breccia elements have also been reported (Slim 1981; Halloul 1989).

The rhyodacitic dome of Ragoubet Es Seid (Fig. 2) seems to be accompanied with an hydrothermal mineralization characterized by geochemical association of Cu, As, Sb, U, W, S (Ben Aissa 1991; Loukil 1993) of deep

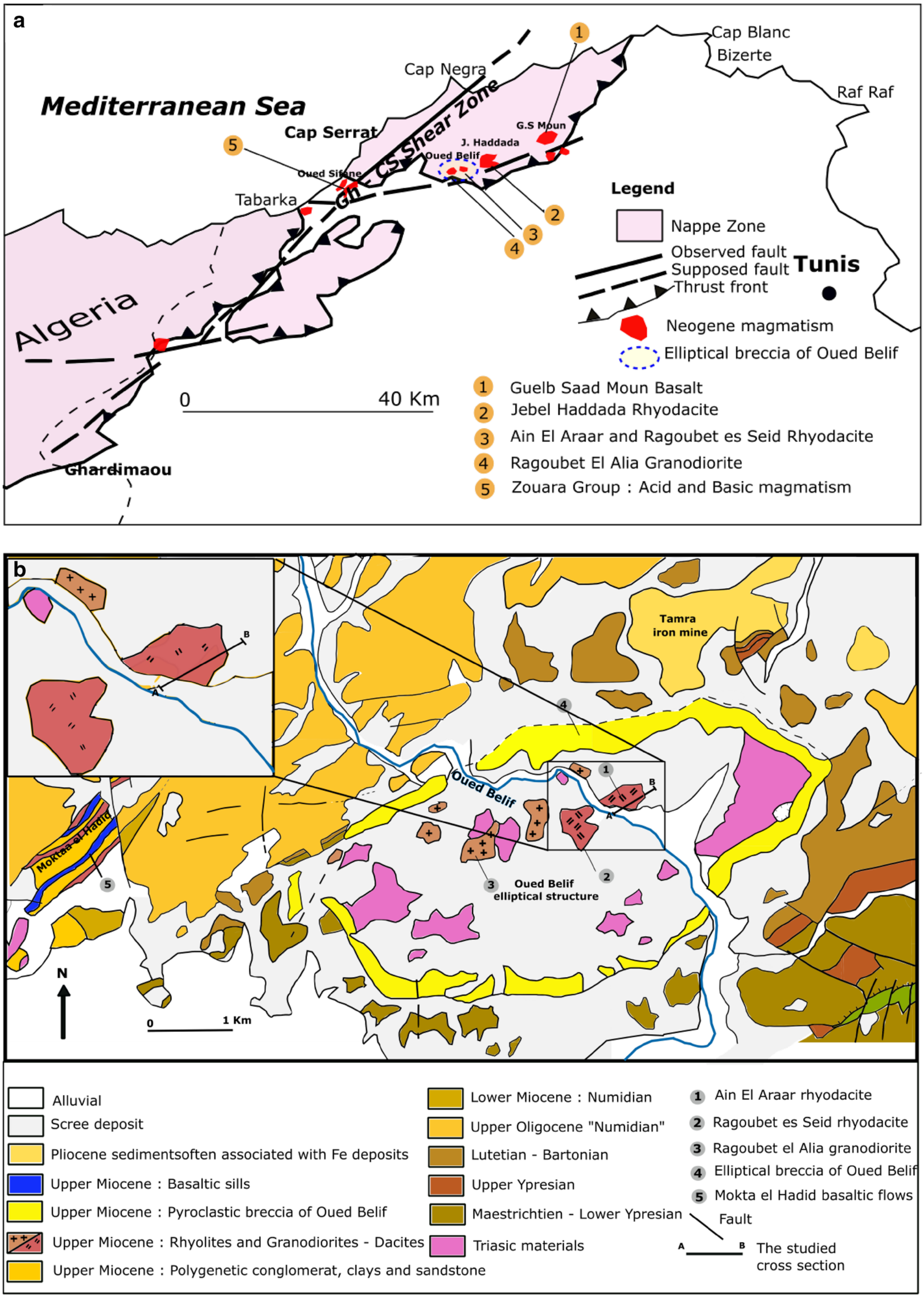


Fig. 2 **a** Structural setting of the numidian nappe with the Cap Serrat–Ghardimaou shear zone and Neogene magmatism. **b** Simplified geologic map of the studied area modified and redrawn after Gottis and Sainfeld 1952 and Rouvier (1987). The line (**a, b**) corresponds to the section showed in Fig. 3

origin. The rhyodacitic dome seems then to be the seat of an hydrothermal circulation with subsequent rock alteration and ore deposits.

Sampling and methods

Fieldworks on intra-magmatic veins system and its associated hydrothermal alteration patterns were done by a cross section within the rhyodacitic dome of Si Belgassem (Figs. 2, 3). Original rhyodacitic rock texture is sometimes obscured by fluid circulation effects. Twenty-four samples were collected from the inner fault system mineralization crossing the magmatic rock (veins, breccias, mineralized faults) and its associated alteration pattern. Four intra-magmatic host mineralisation body types were recognized:

- Breccia with altered rhyodacitic clasts and blocks;
- breccia–veins with silicic and vacuoled loose blocks and debris generally cemented by a Fe-rich silica;
- Fe-rich jasper veins;
- Fe-oxides rich veins with disseminated sulfides.

The mineralogical analyses were operated by X-ray diffractions (XRD) type “BRUKER D8 ADDVANCE” equipped with Cu–Kα filter, using whole rock powders, oriented aggregates in crude, ethylene–glycol-treated and heated (500 °C) samples.

The observations of mineral assemblages, paragenetic and chronological successions were carried out by microscopy in transmitted and reflected light, as well as by imagery in transmission electron microscopy (TEM) with 200 kv acceleration potential. Punctual geochemical analyses were performed by scanning transmission electron microscopy (STEM).

Results

Mineral association and parageneses

Polymetallic mineralization is essentially contained in breccia, breccia–veins, Fe-oxides veins and jasper veins affecting the rhyodacitic volcanic rock (Fig. 3). It can also be observed under a disseminated form in the advanced argillic alteration patterns at the volcanic wall rock.

Volcanic rock type

The NE–SW “Ain El Araâr” cross section represents a volcanic outcrop that had undergone an alteration due to hydrothermal fluid circulating. The precursor of the altered rock is a rhyodacite with a millimetric biotite and porphyric feldspar crystals.

Microscopic observations in unaltered rock show porphyritic crystals within a glassy matrix. Phenocrysts are represented by plagioclase (40%), biotite (20%), quartz (20%) and sanidine (20%). Zircon, accessory mineral cubicle shaped, has been also observed as inclusions in biotite crystals (Fig. 5a).

Wallrock alteration

Alteration of the volcanic host rock was accompanied by major compositional changes. Primary minerals have been transformed due to fluid–wallrock interaction. Data indicate that hydrothermal alteration process was sufficiently evolved to lead the substitution of almost the totality of primary minerals (biotite, sanidine and plagioclase) and the formation of secondary hydrothermal alteration minerals mainly constituted by chlorite, smectite, sericite, phlogopite, illite, kaolinite and accessory

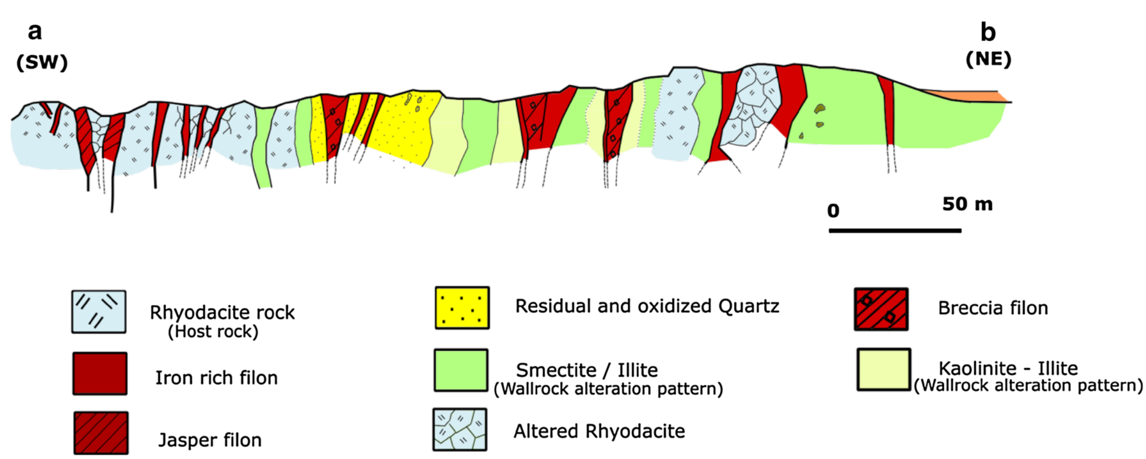
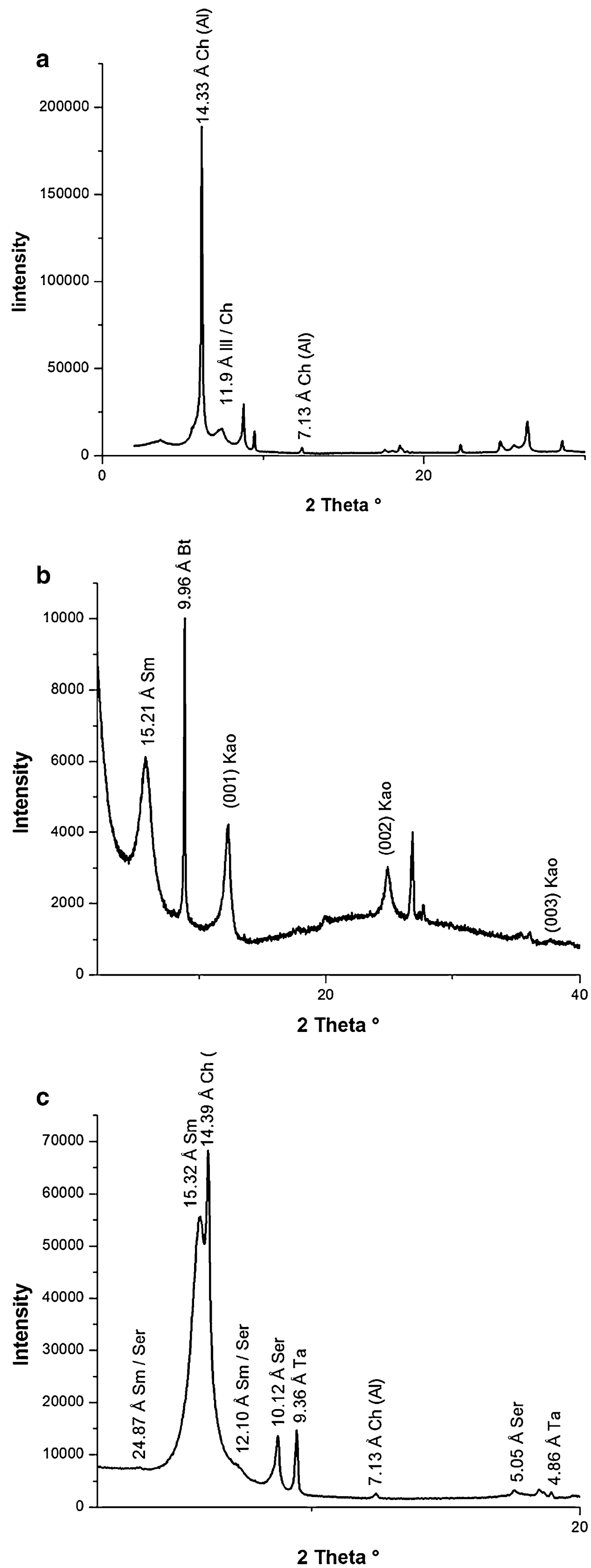


Fig. 3 Detailed cross section (**a, b**) through the rhyodacite of Aïn El Araâr. The unaltered volcanic rock that confines the mineralization is the volcanic “host rock”; “Wallrock alteration” corresponds to the host rock which has undergone some alteration

Fig. 4 Detailed RX diffractograms of neoformed argillic minerals. **a** ▸ RX diffractogram of aluminous chlorite. **b** RX diffractogram showing smectite and kaolinite. **c** RX diffractogram of smectite/sericite, sericite and talc. *Ch (Al)* aluminous chlorite, *Sm* Smectite, *Bt* Biotite, *Kao* Kaolinite, *Sm/Ser* Smectite/Sericite, *Ser* Sericite, *Ta* talc



by talc (Fig. 4a–c, 5b) and, to a lesser extent, by adularia (Fig. 5c), albite, alunite, tridymite, chalcedony and opal (Fig. 5c, d).

In the breccia–veins, supposed to be the core or close to the hydrothermal fluids conduces (Fig. 3), two hydrothermal paragenetic associations were recognized: quartz–adularia and scarce alunite, quartz–adularia–sericite. These associations reflect an intense alteration and leaching processes by hydrothermal fluids, causing a total vanishing of the host rock's primary minerals paragenesis, leaving behind only primary quartz grains as residual silica. The observed pores and vugs (Fig. 5e) are mainly the result of feldspar phenocrysts disbandment. Prismatic crystals of adularia (Fig. 5c), sericite and new-formed quartz, subsequently germinate in these vugs and secondary in micro-fractures (Fig. 5f). Field observations indicate that these alteration minerals are contained in fragments and angular blocks constituting the breccia–veins and cemented by iron-rich silica cement (Fig. 8a).

Zoning is a principal characteristic feature in the hydrothermal deposits system types. Indeed, from the innermost to the outermost of the breccias–veins, four typical hydrothermal alteration zones laterally succeed: (1) zone of quartz–adularia–sericite–alunite (Fig. 5c, d), (2) zone of quartz–kaolinite and plagioclase albitization, (3) intermediate zone of illite–sericite, (4) sapropelic alteration type zone of chlorite–smectite and rare illite.

The breccia–veins hosting quartz–adularia–sericite and scarce alunite mineral association in silica debris and blocks cemented by Fe-rich silica, traduce the reactivation of pre-existing faults leading to a new hydrothermal fluids circulating.

The kaolinite zone (Fig. 4b) indicates an advanced argillisation by hydrothermal fluids under acidic conditions. Moreover, scarce alunite occurrence may suggest the contribution of a high-sulfidation acidic fluid.

The illite–smectite intermediate zone expands after the quartz–kaolinite one away from the hydrothermal conduct. It reflects a lesser effect of hydrothermal mineralizing fluids. In fact, far from fluid conduct, the wall rock tends to neutralize the acidic character of these fluids.

The chlorite–smectite zone (Fig. 4c), the outermost part from the hydrothermal conduct, reflects a lower alteration of the host rock (sapropelic argillisation) with a transformation of biotite into chlorite and smectite.

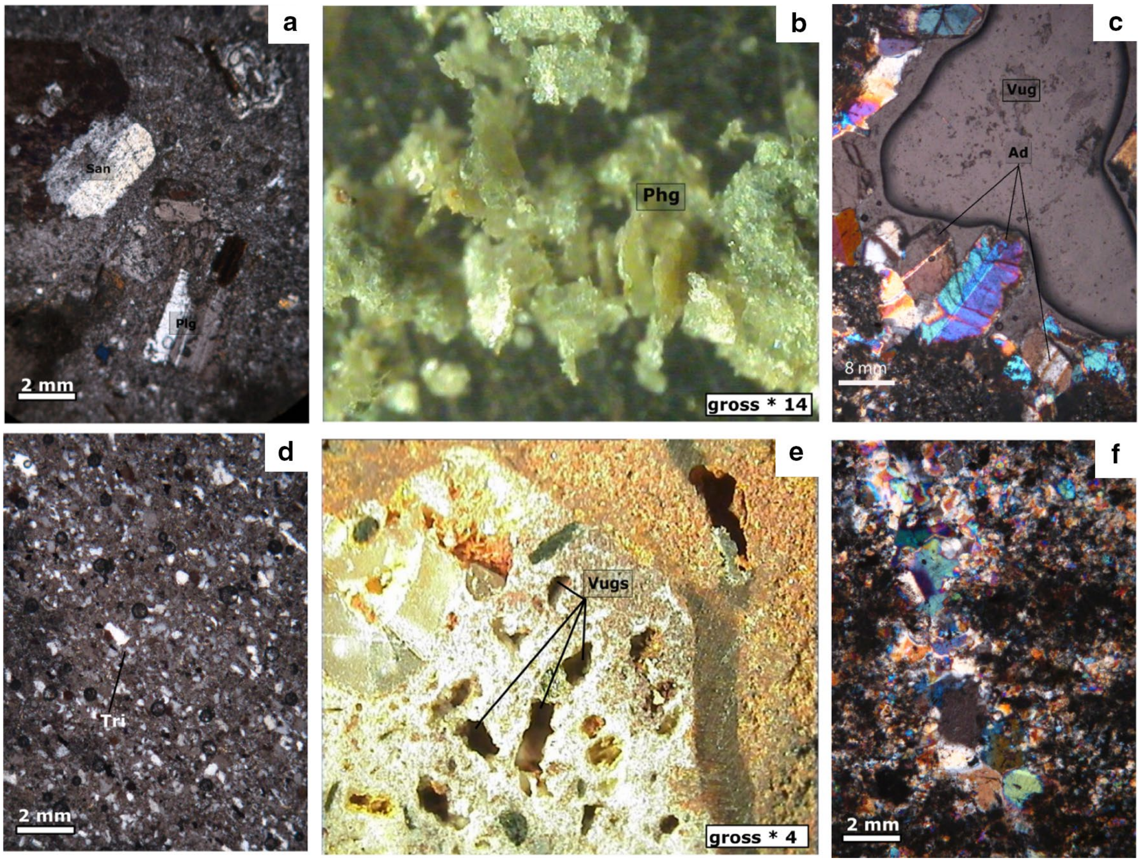


Fig. 5 **a** Photomicrograph of unaltered rhyodacitic rock showing orthoclase (sanidine) and plagioclase minerals (*San* Sanidine, *Plg* Plagioclase). **b** Photomicrograph of phlogopite crystals (*Phg* Phlogopite). **c** Photomicrograph of euhedral (prismatic) adularia growing in vug (quartz–adularia and rare sericite facies) (*Ad* Adularia). **d** Photomicrograph of neoformed silice, tridymite and quartz (*Tri* Tridymite, *Qz* Quartz). **e** Photomicrograph of neoformed quartz in micro-fissures

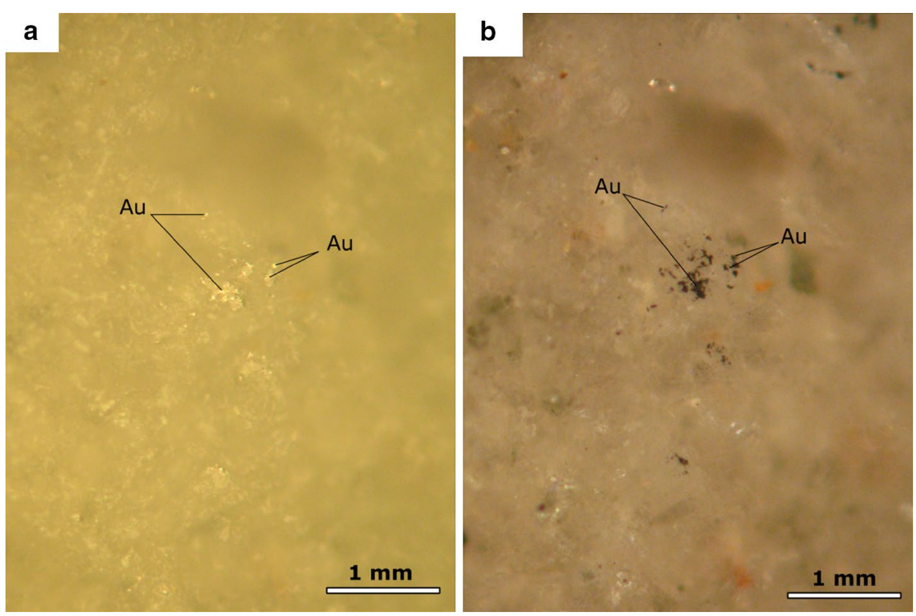


Fig. 6 **a** Photomicrograph of hydrothermal breccias showing at least three hydrothermal stages. **b** Photomicrograph of typical losangic arsenopyrite (Asp: Arsenopyrite). **c** Photomicrograph of different habitus of arsenopyrite with Saint André macle. **d** Photomicrograph of globulous or fromboidal chalcopyrite and pyrite (*Chp* chalcopyrite, *Py* pyrite)

Metalliferous mineralization

The Aïn El Arâar-Oued Belif ore deposits occur in faults within rhyodacite outcrops. Polymetalliferous sulfide-bearing mineralization is essentially contained in N 80° and N 155° faults exemplified by breccias and veins. These ore deposits were also detected in the advanced argillic alteration zones in contact with these faults. In breccia and veins, the host rock facies are: (1) sulfide breccia–veins, (2) jasper veins with chalcedony and (3) nearly coherent iron-bearing veins with sulfides and oxi-hydroxides. Ore is composed of arsenopyrite, pyrite, pyrrhotite, chalcopyrite, hematite, goethite and magnetite. Gangue minerals are mainly quartz, adularia, tridymite, chalcedony, sericite and scarce alunite.

Arsenopyrite is mainly in rhomboidal crystals form locally altered in the Fe-oxides–sulfides-rich veins (Fig. 6b). Other arsenopyrite habitus were also recognized such as triangular forms, in stairs and in Saint Andre twin macle (Fig. 6c). Punctual STEM analyses of this mineral in iron-rich phase (Fig. 7a, b), fairly confirm the content of As (0.3 to 2.9%), S (0.1 to 0.6%), Si (1.1 to 4.4%), Ca (0.9%), Cr (10.8%), Mn (1.0%), Zn (12.9 to 30.6%), Fe (21.9 to 96.8%), Co (15 to 27.3%), Au (0.7 to 4.3%), Ag (0.4 to 8.4%), Pt(0.3 to 4.2%), Bi (0.8 to 1.7%) and Cl (1.3%) Table 1. Pyrite was observed especially in the breccia–vein within fragments and blocs, in vacuolated siliceous blocks within the iron-bearing veins and in the advanced argillic facies. Pyrite appears in cubic sections, triangular, granular and fromboidal forms with a pale yellow coloration (Fig. 6d). Some pyrite sections contain fine inclusions with a higher reflecting power. Such inclusions were also observed as disseminated fine grains or concentrated

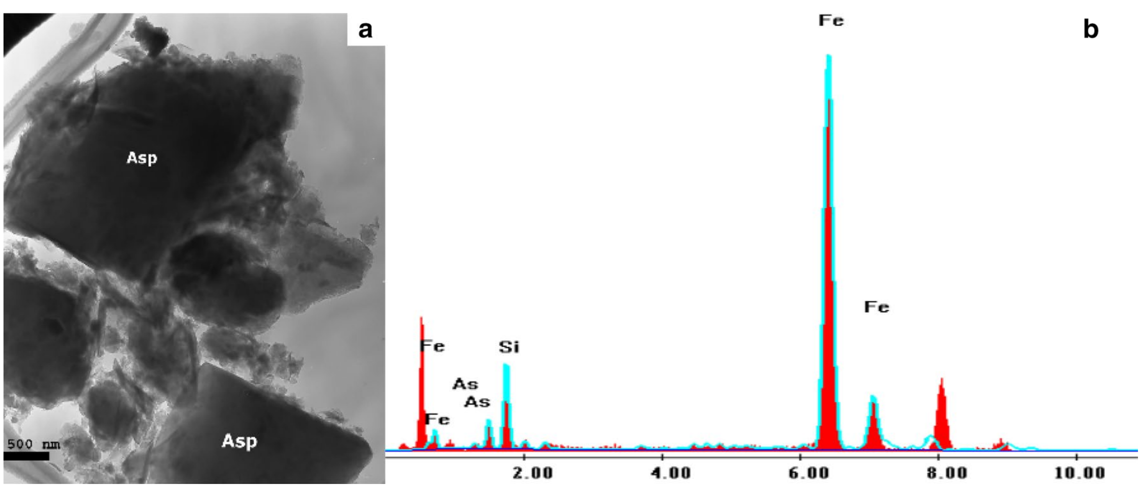


Fig. 7 TEM punctual imagery showing the presence of arsenopyrite

Table 1 STEM electron microprobe analysis in weight % for iron-rich phase

Elements weight %	A	B	C	D	E	F
S	0.2	0.6	0.4	0.1	0.1	0.3
As	0.3	0.5	2.9	1.7	0.3	0.5
Si	1.3	1.7	–	4.4	–	1.1
Ca	0.9	–	–	–	–	–
Cr	10.8	–	–	–	–	–
Mn	1.0	2.6	–	–	–	–
Zn	–	12.9	30.6	–	–	–
Fe	83.7	77.0	21.9	90.3	96.8	77.7
Co	–	–	27.3	–	–	15.0
Au	0.7	1.3	4.3	0.8	0.8	1.7
Ag	0.7	1.8	8.4	0.4	0.7	1.5
Pt	0.3	1.5	4.2	0.6	0.5	1.1
Bi	–	–	–	1.7	0.8	–
Cl	–	–	–	–	–	1.3

– Not detected, A, *B, C, D, E, F* iron-rich veins in micro-veins (Fig. 6). These fine grains are assigned, according to their microscopic characteristics as gold nuggets. Gold also occur as disseminated grains and micro-fracture fillings in sulfide veins (Fig. 6). Chalcopyrite has been found in the veins and in breccia–veins. This mineral can also occur in disseminated fine grains or in spherules aggregates forms with intense yellow color (Fig. 8d). Pyrrhotite substitute, sometimes fully or partially, the arsenopyrite (Fig. 9a). Chronologic mineral replacement sequence of sulfides by oxidation is generally successively ordered: goethite, hematite and then magnetite (Fig. 9a–c). The occurrence of these minerals, also confirmed by XRD, can testify a gradual increasing of oxidation conditions near the top of the acidic epithermal system.

Discussion

Mining is especially developed in the regions bordering the elliptical structure of Oued Belif where mineral deposits are exploited for iron at Tamera-Douahria mines and for iron–lead–zinc at Sidi Driss mine. The peripheral breccias were only locally exploited for iron at Boukhchiba old mine. Inside the structure, several exploration and prospection works were done but no deposits with economic interest were discovered despite the qualitatively rich polymetallic geochemical association mentioned by strategic stream sediment prospections (Ben Aissa 1991), copper-rich deposits (14% Cu) at subsurface investigations and signs of rare metals according to analysis results of prospecting campaigns in the area (Ben Aissa 1996). Metallogenic

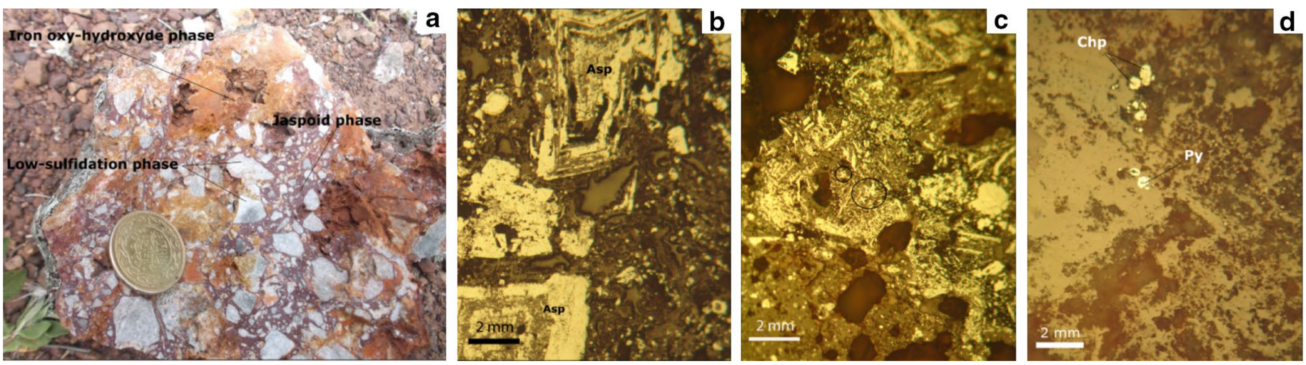


Fig. 8 Photomicrographs of gold as dissemination in sulfide-veins. **a** Gold in silica matrix observed under a natural light (Au: *Gold*). **b** Gold in silica matrix observed under a polarized light (Au: *Gold*)

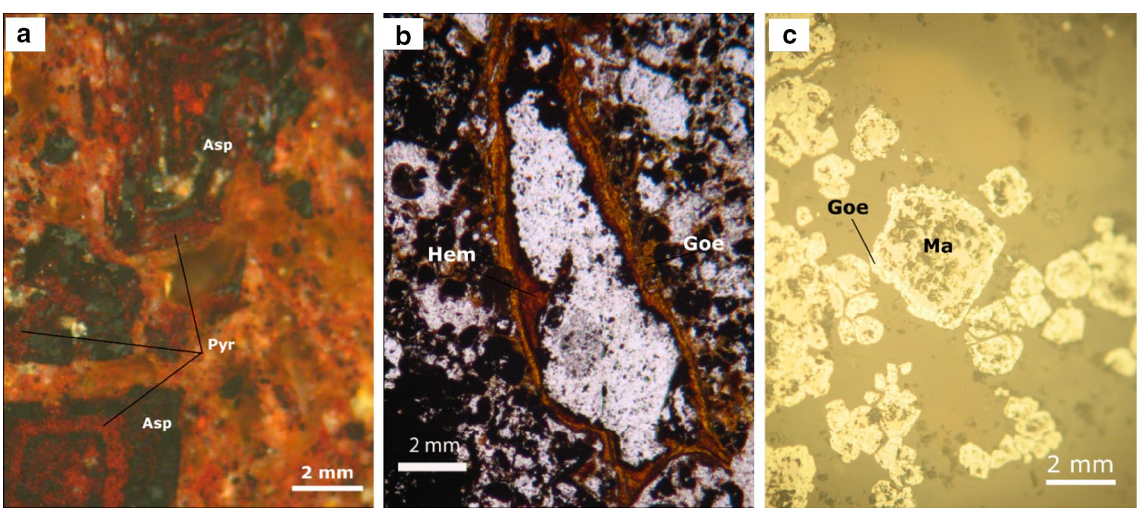


Fig. 9 **a** Photomicrograph of altered arsenopyrite into pyrrhotite (*Asp* arsenopyrite, *Pyr* pyrrhotite). **b** Photomicrograph showing the chronology between hematite and goethite (*Hem* hematite, *Goe* goethite). **c** Photomicrograph showing the chronology between magnetite and goethite (*Ma* magnetite, *Goe* goethite)

model of mineral deposits and the nature of mineralizing fluids associated with ore mineralizations in the inner part of Oued Belif structure are until now understudied.

We mention here that polymetallic sulfide and iron oxide-bearing mineralization is concentrated in faults, veins and breccias affecting the rhyodacitic dome as well as in its wall rock alteration facies at Aïn El Arâar locality (Oued Belif-Nefza areas, NW of Tunisia). These deposits rank well in the context of epithermal ore deposits. Indeed, hydrothermal alteration of the rhyodacitic rock, in the most altered facies, is pushed to quartz–adularia–sericite mineral association. This type of alteration is characteristic of low-sulfidation epithermal-type deposits (Queralt et al. 1996).

Cavity and vugs filled by adularia–sericite and then by alunite, in lithoclastic fragments and blocks in breccia–veins as well in nearly coherent iron-bearing veins, indicate that hydrothermal conditions may be evolved and changed from a low-sulfidation epithermal type to a high-sulfidation epithermal one and then, a possible telescoping between the two types of alteration; high-sulfidation type seems to be posterior to the low-sulfidation one since alunite occurrence as vugs (high sulfidation) is posterior to the adularia–sericite minerals (low sulfidation). The different tectonic directions faults affecting the rhyodacitic massif with two major directions (N80° and N155°) support the telescoping and the polyphasing of mineralizing process.

Successively, an iron-rich silicic phase was responsible of iron-rich jasper deposits cementing fragments and blocks in breccia–veins or constituting a pure iron-rich jasper veins. Epithermal phases were also accompanied by the deposit of metal-sulfide mineralization such as pyrite, chalcopyrite, arsenopyrite and by traces of Au–Ag in sulfide minerals or disseminated as micro-grains. The following circulating fluid was very oxidizing leading to the partial oxidization of primary metal-sulfide minerals successively into goethite, hematite and magnetite. The last fluids were highly silicic rich with consequently silica deposits (chalcedony) in the remaining available spaces. The high-silicic-rich hydrothermal deposits were also mentioned elsewhere in Oued Belif areas (Talbi 1998). This author described jasper veins where micro-fissures and vugs are totally colmated by quartz and chalcedony.

Polymetallic deposits at Oued Belif-Ain El Araâr, in Nefza area of northwestern Tunisia, are low-sulfidation epithermal deposits with some feature of high-sulfidation ones. This system displays similar features with well-known epithermal systems around the world, such as Red Mountain, Colorado (Lipman et al. 1976; Mehnert et al. 1973; Gilzean et al. 1984), Julcani, Peru (Petersen et al. 1977; Noble and Silberman 1984), Summitville, Colorado (Mehnert et al. 1973), Goldfield, Nevada (Silberman and Ashley 1970), Creede, Colorado (i.e., Steven and Ratté 1973; Plumlee and Hayba 1985), Rodalquilar, Spain (Sanger-von Oepen et al. 1989; Arribas et al. 1995a) Lepanto, Philippine [i.e., Garcia (1991); Arribas et al. (1995b)], Spahieva, Bulgaria (Velinov et al. 1990).

Mineralogical characteristics, wallrock alteration type as well as the nature of polymetallic sulfides at Aïn El Arâar localty (Oued Belif, Nefza NW Tunisia), show particularly striking similarities with epithermal system features in SE of Spain like at Lomilla Caldera (Queralt et al. 1996; Arribas 1992). The similarities consist of the nature and the age of the magmatic host rock, polymetallic mineralizations, alteration products as well as geodynamic context which fits into the same alpine late Miocene orogeny (Maghrebides in northern Tunisia and Betic belt in Spain).

Epithermal mineralizations of SE of Spain are related to radial fractures associated with the Lomilla Caldera (Cunningham et al. 1990). The mineralizations associated with this Caldera are reported in several localities: Maria Josefa, Triunfo gold mines and Mazarron (Rytuba et al. 1990; Sanger-Von Open 1990; Queralt et al. 1996). The Maria Josefa mine is an example of a system of low-sulfidation type of veins showing three paragenetic associations: quartz–adularia, quartz–adularia–sericite and quartz–sericite (Queralt et al. 1996), affecting the ignimbritic rhyolites and passing gradually to argillisation facies of illite–sericite and propylitic alteration type (Sanger-Von Oepen et al. 1990). Close to the veins systems, the volcanic rocks are altered to abundant illite/sericite and subordinate kaolinite. Hydrothermal alunite, pyrophyllite and diaspore do not occur and alteration grades outwards to propylitic alteration (Sanger-Von Oepen et al. 1990). Similar to Oued Belif-Aïn El Araâr deposits, the sulfide-minerals in the vein structures at Maria Josefa have been oxidized to various extents in the near-surface environments (Kisters 1988). In our studied region, we suggest that beside near-surface oxidization of pre-existing sulfides minerals, a late supply of an iron-rich fluids, leads to the deposits of secondary iron oxides mineral near the surface (hematite, goethite and magnetite). In addition, metalliferous mineralization within veins and hydrothermal breccia is, as at Maria Josefa gold mine, accompanied by a hydrothermal wallrock alteration with a well-zoned pattern. It ranges from quartz–adularia–sericite and quartz–adularia–scarce alunite near or in the hydrothermal conduct, to propylitics alteration of smectite–chlorite assemblages forward the conduct.

Alunite is a typical mineral in advanced argillic alteration zones of high-sulfidation epithermal systems. Despite its small amount, the occurrence of this sulfate, in Oued Belif-Ain El Araâr location, was confirmed by XRD and petrographic observations. Alunite and adularia are two antagonistic minerals and cannot be synchronous (Kanazirski 1992). Adularia is accepted to be formed in rather neutral conditions while alunite traduces acid sulfate and oxidizing conditions. This supports the assumption, in our case, of a telescoping between two different acidic epithermal phases (an early low-sulfidation and a late high-sulfidation epithermal phases). Apart from its hypogene magmatic hydrothermal alteration origin, the presence of alunite might be associated with a supergene origin in the low-sulfidation alteration type (Hayba et al. 1985; Heald et al. 1987; Rye et al. 1992) subsequently to the oxidation of H_2S in the top of boiling part of low-sulfidation systems (Rye et al. 1992).

The similarities between the mineral deposits type of Oued Belif with that of calderic structure of Lomilla caldera (Sanger von-Oepen 1989, 1990) support the hypothesis of a same structural context of deposits. This hypothesis is also suggested by the geophysical works (Jallouli et al. 2003) that mention a shallow-concealed magmatic sill which could be the roof of Oued Belif intrusions. In addition, drilling holes done by "Office National des Mines" (O.N.M), related to the mining prospection project in the area, have crossed a plutonic facies under 200–250 meters deep. This plutonism is the precursor of the caldera emplacement since many calderas in the world derive from batholites (Lipman 1984).

Conclusion

The epithermal system and associated mineral deposits at Oued Belif-Aïn El Araâr location are originally ranged under low-sulfidation epithermal type with a later telescoping by a high-sulfidation epithermal one. Ore bodies are essentially veins and hydrothermal breccias affecting rhyodacitic rocks of 8–9 M.y in age (upper Tortonian). Ore mineralization is formed by pyrite, arsenopyrite, chalcopyrite pyrrhotite, Fe-oxi-hydroxides and Fe-oxides. Traces of native Au, Ag and Pt are confirmed by punctual geochemical analysis (S.T.E.M.) as well as by petrographic observations of Au and Ag. Field and microscopic observations indicate that mineralizing fluid nature, evolve and change leading to a succession of mineral paragenesis deposits. At least, five mineralizing fluid of different nature contributing to mineral deposits can be successively distinguished: (1) low-sulfidation fluid, (2) high-sulfidation fluid, (3) silica–iron-rich fluid, (4) iron-rich fluid and (5) high-silicic-enriched one. These hydrothermal mineralizations are deposited after nearly the same Miocene geodynamic and magmatic events as those of Lomilla Caldera areas (Maria Josefa and Triunfo gold mines, Mazarron) in SE of Spain at the northern margin of Mediterranean Sea.

This type of deposits is widely known to have an economic interest especially for their trace Au–Ag-bearing mineralization. However, further surface and subsurface investigations in a tectono-magmatic context should be carried out to allow a greater impetus for a profitable exploitation.

Acknowledgements We would like to thank Laboratoire de Physique des Matériaux Lamellaires et Nanomatériaux Hybrides (PMLNMH) for permitting unlimited access to perform the XRD analyses and to TEM laboratory. We are also grateful to Dr. Jalila Karoui for the remarkable help with the petrographic observations and to Pr. Hassen Abdallah "Institut Nationale de Recherche Scientifique et Technique" of Borj Cedria, Tunisia for allowing photoshoots under petrographic microscope. The authors are indebted to Prof. V. Gardien and other anonymous reviewer for the comment and enhancing the quality of the manuscript.

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