Re/Os Age Determination, Lead and Sulphur Isotope Constraints on the Origin of the Bouskour Cu–Pb–Zn Vein-Type Deposit (Eastern Anti-Atlas, Morocco) and Its Relationship to Neoproterozoic Granitic Magmatism

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Abstract

The newly re-evaluated Bouskour deposit is a large, polymetallic vein-type system in the Precambrian Sidi Flah-Bouskour inlier of the eastern Anti-Atlas orogen. Resources are >53 Mt at 0.8 % Cu, of which 21 Mt has a higher grade of 1.3 % Cu and 9 g/t Ag. Host rocks are assigned to the Ediacaran Ouarzazate Group, and consist of a succession of mafic-ultramafic to felsic igneous rocks, both intrusive and extrusive, with ages ranging from 570 ± 5 to 557 ± 5 Ma, partly intruding Cryogenian basalt and andesite. Among these igneous bodies, intrusive felsic rocks are by far the most abundant lithologies, consisting of three elongate, NW-SE-trending, calc-alkaline intrusions referred to as: (1) Bouskour Granodiorite, (2) Bouskour Granite dated at 570 ± 5 Ma, and (3) amphibole-bearing Bouskour Granodiorite. An extensive dike

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system of red to white aphanitic rhyolite locally known as the “Bouskour rhyolitic dike swarm” intruded all older units at 564 ± 7 to 562 ± 5 Ma. Cu–Pb–Zn sulphide mineralization produced an array of five transtensional, N-S and ENE- to NNW-trending vein systems referred to as “Filon Principal,” “Filon Ouest,” “Filon I,” “Filon II,” and “Filon Camra.” The veins are up to 20 m wide and extend laterally from a few hundred meters to more than 10 km, spaced 50 to >1000 m apart, striking predominantly N160° E with steep dips (70° to ∼90°). Characteristic are comb, cockade, laminated, breccia, and crack and seal textures, suggesting that episodic mechanisms were important in vein formation. Sulphide minerals consist predominantly of various proportions of chalcopyrite, bornite, galena, sphalerite, pyrite, and arsenopyrite, with subordinate tetrahedrite-tennantite, magnetite, cassiterite, and rutile. The hydrothermal alteration assemblage comprises sericite, epidote, chlorite, quartz, and carbonates (calcite, dolomite). Three successive stages of ore deposition are recognized. The earliest stage (I) is referred to as “Cu–Zn–(Fe–As–Co–Bi–Sn) stage” is followed by the main Cu–Pb–Zn sulphide stage (II), which accounts for most of the exploited sulphide ore at Bouskour. The latest stage (III) forms late fillings in calcite or quartz veins or within older stage I and II assemblages, and includes Au–Ag–Cu–(Zn–Pb) mineralization. New ^{187}Re/^{188}Os age dating of a single molybdenite crystal from stage II yields an age of 574.9 ± 2.4 Ma. This age coincides, within analytical uncertainty, with a SHRIMP U–Pb age on zircon from the Bouskour Granite. The age correspondence suggests a foremost role of granite-derived hydrothermal fluids in the genesis of this polymetallic vein system, consistent with sulphur and lead isotopic data. This timing of mineralization relates to the final, post-collision extensional stage of the Pan-African orogeny.

1 Introduction

The Bouskour deposit (lat 30°55′46.59″ N; long 6°18′4.86″ W) in southeastern Morocco (Fig. 1) is one of the most productive Cu–Pb–Zn ± Ag ± Au vein-type deposits of North Africa wherein mineralized structures are intimately associated with granitic intrusions of Neoproterozoic age. To date, no detailed geochronologic and isotopic geochemical studies have been performed on this deposit, except for a few reconnaissance surveys carried out during exploration and mine planning (Marcoux and Jébrak 2012; El Azmi et al. 2014). Accordingly, the origin of the deposit remains poorly understood and critical ore genetic constraints are lacking. The absence of precise age determination required previous workers to constrain the timing of mineralization by crosscutting relationships (Marcoux and Jébrak 2012; El Azmi et al. 2014).

In this contribution, we document and interpret the geologic history, mineralization, alteration, and paragenesis of the Bouskour deposit. More importantly we contribute, for the first time, a Re/Os molybdenite age together with sulphur and lead isotope data relevant to the age of mineralization and source(s) of sulphur and metals. Collectively, these results place new constraints on the origin and evolution of the Cu–Pb–Zn ± Ag ± Au mineralization and related implications

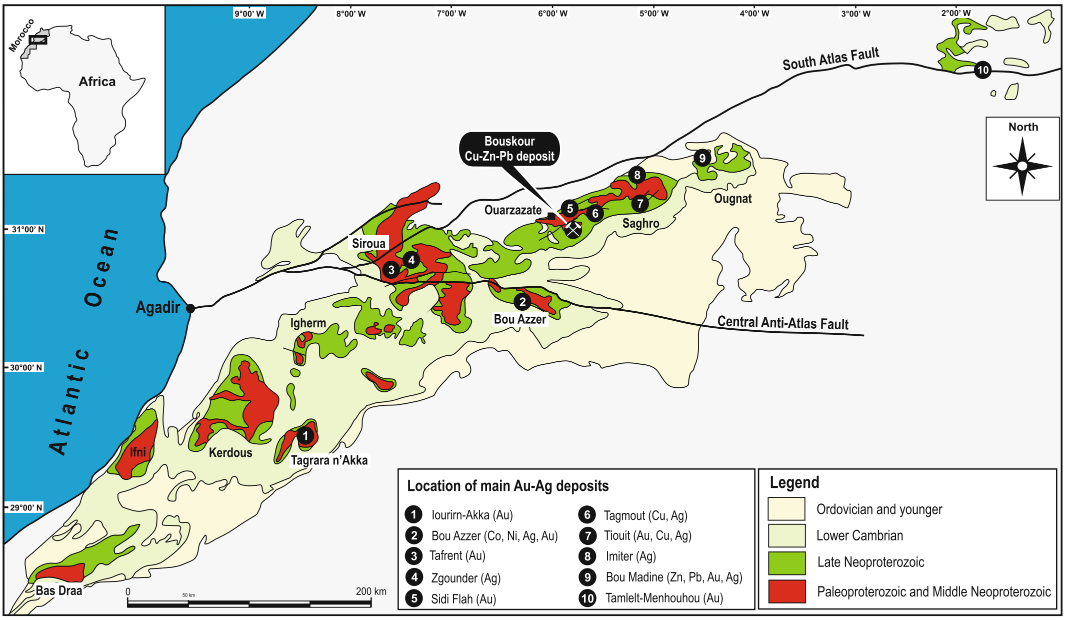


Fig. 1 Regional geologic setting of Anti-Atlas system in southern Morocco showing location of Bouskour Cu–Pb–Zn district, and regional-scale faults and their relationship to similar polymetallic mining camps

for understanding ore-forming processes with respect to Neoproterozoic magmatism.

2 Exploration History

Mining activity in the Bouskour district goes back to the medieval period. In recent times, mineralization in the district was re-discovered in the late 1940s by “la Société Minière de Jbel Sarhro” (Sosarhro), and since then has been mined intermittently for Cu–Ag, Pb, and Zn. During the French colonial period, between 1948 and 1950, upper parts of the main vein were exploited, yielding an estimated 10,000 t of ore extracted at an average grade of ~2 % Cu. After many years of closure and following regional aeromagnetic surveys, the “Bureau de Recherches et de Participation Minière” (BRPM, actual ONHYM), and “la Société des Mines de Bouskour” in conjunction with the former Soviet Union consulting group Technoexport conducted, between 1958 and 1977, a multidisciplinary regional exploration program. This program integrated geologic mapping and multi-element geochemical surveys that resulted in delineation of promising Cu–(Pb, Zn) targets.

In 1977, the Bouskour mine closed due to decreasing prices and ore grade with depth. At the time of the closure, remaining ore reserves were estimated at 0.43 Mt. Managemgroup, a subsidiary of ONA Holding, later purchased the assets and started an ambitious exploration program using surface mapping, geophysical surveys, mineralogical studies, and diamond drilling campaigns to reassess the mineral potential of the district. About 10,000 m of drilling (mostly diamond drill holes) were completed, providing an extensive database for geologic modeling and resource estimation. Subsequent resource estimates released by the mining company have delineated a global resource of >53 Mt at an average grade of 0.8 % Cu and 8 g/t Ag, of which 21 Mt has a higher grade of 1.3 % Cu (Maacha et al. 2011).

3 District Scale Geology

The Precambrian Sidi Flah-Bouskour inlier of the eastern Anti-Atlas orogen, which in its southern termination hosts the Bouskour Cu–Pb–Zn deposit (Fig. 1), is a Neoproterozoic basement massif located in the central part of the larger Saghro massif. The inlier consists of a succession of Cryogenian (middle Neoproterozoic; 850–630 Ma) to Ediacaran (late Neoproterozoic; 630–542 Ma) deformed and metamorphosed volcanic-sedimentary, volcanic, and intrusive rocks interpreted to have been emplaced either in a back-arc environment (Saquaque et al. 1992; Leblanc and Moussine-Pouchkine 1994; Bouougri and Saquaque 2004) or in an intra-continental basin synchronous with Pre-African rifting (Fekkak et al. 2003).

The resulting Neoproterozoic country rocks were heterogeneously deformed and metamorphosed during two Pan African events, B_1 and B_2, from about 760–550 Ma (Leblanc and Lancelot 1980; Saquaque et al. 1989; Walsh et al. 2002; Thomas et al. 2004; El Hadi et al. 2010). The B_1 event was collisional and gave rise to strong folding and ophiolite emplacement; B_2 caused moderate shortening and tliting. The metamorphic grade of the country rocks is middle to upper greenschist facies, reaching amphibolite facies in the vicinity of the intrusive rocks.

The geology of the Bouskour district has been summarized by Tixeront (1971), Clavel and Tixeront (1971), Ezzouhairi (1989, 1997, 2001), Ezzouhairi et al. (2008), and Walsh et al. (2008). The following description summarizes work by these authors supplemented by our own observations.

Exposed rock types are stratigraphically assigned to the middle to late Neoproterozoic Ouarzazate Supergroup, and are geodynamically related to the post-collision extensional stage of the Pan-African orogeny (Thomas et al. 2002; Walsh et al. 2012). The oldest rocks (Fig. 2), which constitute part of the Saghro Group (Gasquet et al. 2005; Benziane 2007) or the Sidi Flah Group (Fekkak et al. 2001, 2003), comprise a Cryogenian succession of turbiditic to flysch-like (Walsh et al. 2008) sequence of black shale, sandstone, siltstone, greywacke, tuff, limestone, jasper, and rare conglomerate; these strata are interbedded with, and overlain by, basaltic to andesitic flows and sills of the Sidi Flah-Bouskour metamorphic series (Walsh et al. 2008). The unconformably overlying Ediacaran Ouarzazate Group (Thomas et al. 2002) that hosts the Bouskour vein system comprises a wide spectrum of mafic-ultramafic to felsic igneous rocks, both intrusive and extrusive, having ages ranging from 570 ± 5 to 557 ± 5 Ma (Walsh et al. 2008, and references therein), partly intruding the Cryogenian basalts and andesites (Fig. 2). The mafic-ultramafic intrusions dated at 561 ± 2 Ma (TIMS U–Pb zircon geochronology; Chebbaa 1996) and 563 ± 5 Ma (SHRIMP U–Pb zircon; Walsh et al. 2008) consist of fine-grained olivine-gabbro and serpentinized peridotite (dunite, wherlite) (Ezzouhairi et al. 1998; Saquaque et al. 1992; Fekkak 2000; Thomas et al. 2002; and present study). The mafic volcanic rocks that host the southernmost part of the Bou Skour vein system (i.e., Amas central and Cobra orebodies; Fig. 3) are basaltic to andesitic in composition; felsic intrusions, flows and dikes which in turn host the northern orebodies (i.e., Anne-Marie, Chaigne, and Panthere; Fig. 3) are aphanitic to porphyritic dacite and rhyolite. Red rhyolitic rocks from the Bouskour area have a SHRIMP U–Pb zircon age of 564 ± 7 Ma (Walsh et al. 2008). Intrusive felsic rocks, which constitute the most abundant lithology in the district (Fig. 2), comprise three elongate, NW-SE-trending, calc-alkaline intrusions referred to as (1) Bouskour Granodiorite, (2) Bouskour Granite, and (3) Bouskour amphibole-bearing Granodiorite; the two first intrusions host approximately two thirds of the ore zones within the Bouskour vein system (Fig. 3). The Bouskour Granite, dated at 570 ± 5 Ma (SHRIMP U–Pb zircon; Walsh et al. 2012), forms an elongate, NW-SE-trending, multi-phase pluton that covers an area of 40 km^2 at surface (Fig. 2). Most Bouskour granitic rocks are granodiorite, but a few are monzogranite. The granodiorite is equigranular in the central part of the pluton, grading to a porphyritic amphibole-bearing granodiorite along the margins. Based on whole-rock

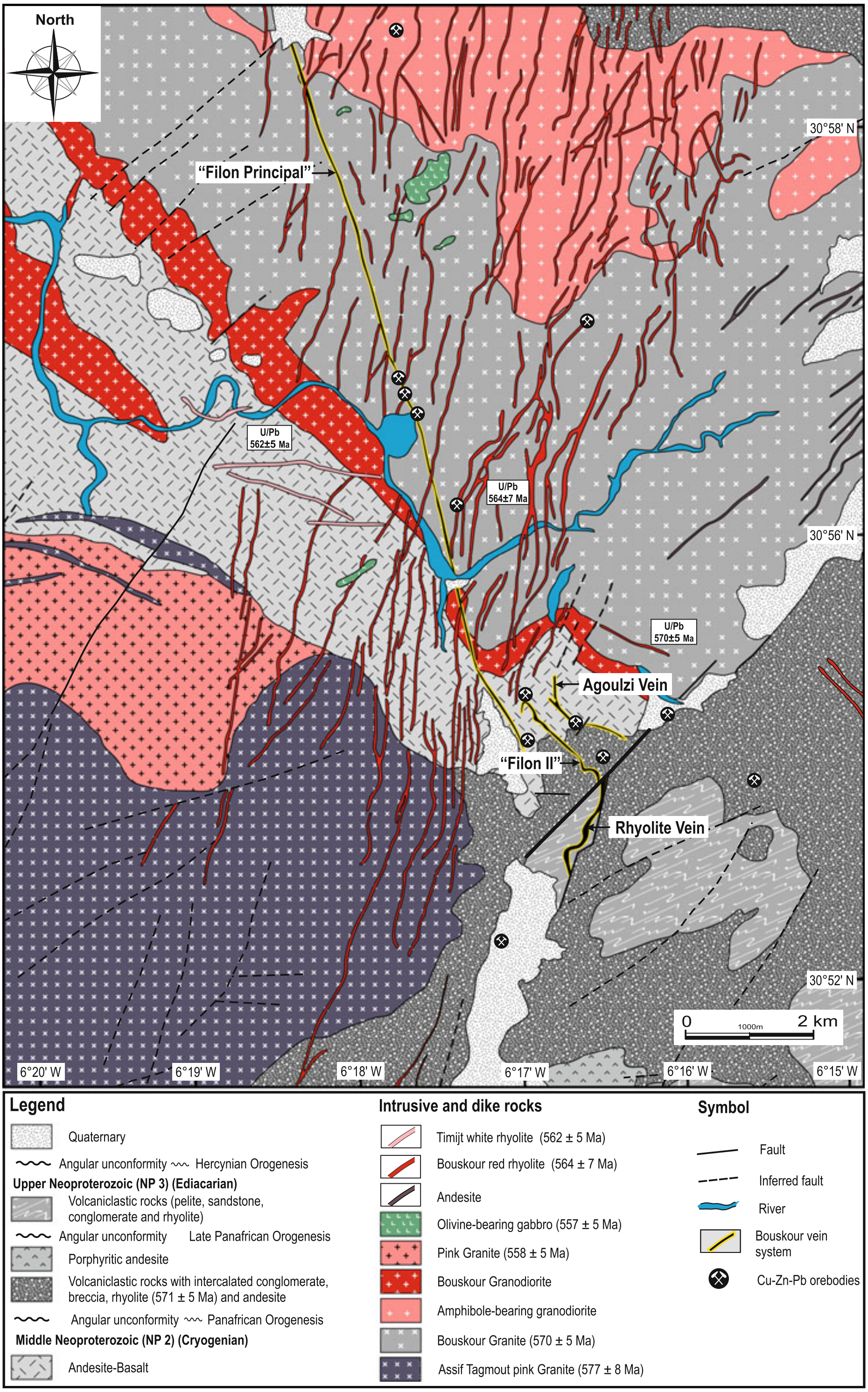
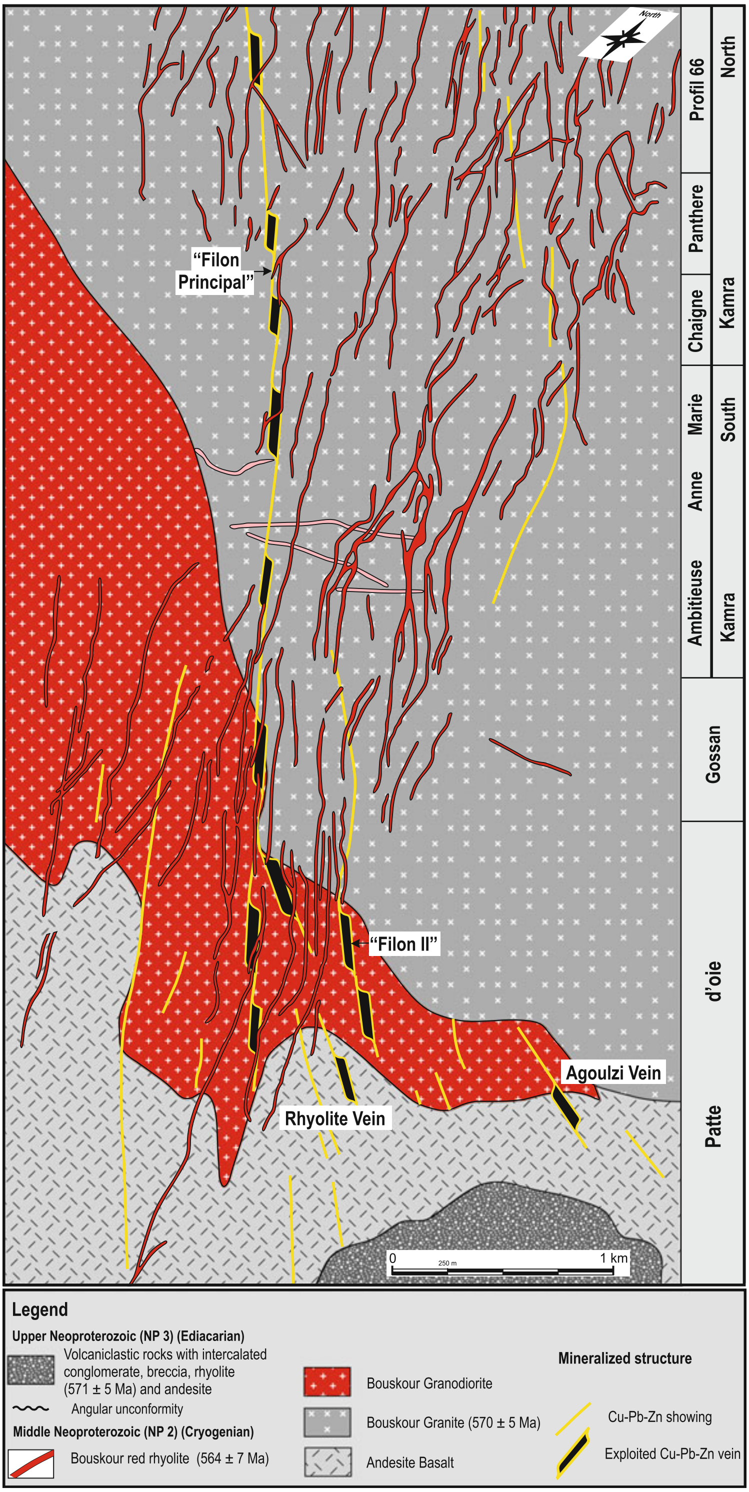


Fig. 2 Geological map of Bouskour Cu–Pb–Zn district (modified after Walsh et al. 2008) showing main lithostratigraphic units, extent of structures, and relative position of known vein-type orebodies and their relationships to late Neoproterozoic igneous rocks

Fig. 3 Detailed geologic map of Bouskour district showing distribution of major economic veins and their spatial relationships to late Neoproterozoic igneous rocks, particularly rhyolitic dikes



and radiogenic isotope geochemistry, the Bouskour intrusion is a high-K, calc-alkaline granodiorite of island-arc affinity, having a mantle derivation with negligible crustal contamination (Ezzouhairi et al. 2008). Intrusion of the granodiorite produced a 300-m-wide contact metamorphic aureole of massive hornfels comprising biotite, cordierite, and andalusite.

During late Neoproterozoic time and prior to the Cambrian, a system of extensive (up to 25 km long), N-S-trending, 5-km-wide, red to white aphanitic rhyolitic dikes (564 ± 7 to 562 ± 5 Ma; Walsh et al. 2012) locally known as the "Bouskour rhyolitic dike swarm" intruded and cut all older units (Figs. 2 and 3).

4 Mineralogy, Alteration, and Paragenesis

Cu–Pb–Zn ± Ag ± Au sulphide mineralization consists of an array of transtensional N-S and ENE- to NNW-trending vein systems (Fig. 3). Five principal mineralized veins, referred to as "Filon Principal," "Filon Ouest," "Filon I," "Filon II," and "Filon Camra," together with two less-economic structures "Agoulzi Vein" and "Rhyolite Vein," have been exploited both from open pits and underground workings. The veins are up to 20 m wide and extend laterally from a few hundred meters up to more than 10 km, are spaced 50 to >1,000 m apart, and strike predominantly N160° E with steep dips (70° to ~90°). The veins display comb, cockade, laminated, breccia, and crack and seal textures, suggesting that episodic, multiple mechanisms were important in vein formation. Early precipitated minerals are cut, or are brecciated and cemented by the succeeding minerals. Overall, the textural features indicate that mineralization took place in open spaces.

The main vein "Filon Principal" is historically and economically the most important and accounts for more than 80 % of the total mineral resources of the district. This vein truncates all major igneous units including the Cryogenian andesite and the Ediacaran Bouskour Granite and Bouskour Granodiorite. The vein is >10 km long and varies from 0.5–20 m wide, dips steeply to the south, has a vertical extension of more than 150 m, and comprises a succession of strongly mineralized "dilational jogs" and barren segments. The economic ore zones, grading 1.5–3 % Cu (Clavel and Tixeront 1971), consist of seven mined orebodies, and include from north to south: "Profil 66," "Panthère," "Chaigne," "Anne-Marie," "Ambitieuse," "Gossan," and "Patte-d'Oie" (Fig. 3). The "Patte-d'Oie," ore zone is the most promising, where an intensive exploration program has been conducted by Managemgroup over the last past 5 years (2007–2012). A reconnaissance diamond drilling program has been carried out, resulting in the delineation of a new stockwork zone of Cu-rich mineralization at depths of 150–160 m.

Pervasive hydrothermal alteration has affected, to varying degrees, all country rocks particularly those adjacent to the mineralized structures. Alteration halos range from centimeter-wide selvages to 2-m-wide (up to 6 m) zones that envelope the veins. The alteration halos consist mainly of sericite, epidote, chlorite, quartz, and carbonates (calcite, dolomite), with variable amounts of sulphides (chalcopyrite, galena, sphalerite, pyrite); no vertical or lateral mineral and/or geochemical zoning is evident, although Tixeront (1971) reported vertical mineral zonation within the "Chaigne," "Panthère," and "Patte-d'Oie" veins. Electron microprobe analysis indicates that chlorite in the veins has an average composition of clinochlore with a structural formula $(Fe_{1.97}Mg_{2.69}Al_{1.26})\ Si_{2.86}Al_{1.14}O_{10}\ (OH,\ O)_8$ (Marocux and Jébrak 2012).

All of the mineralized veins display similar mineral assemblages but the relative proportions of base-metal sulphides relative to other minerals vary among the veins. Sulphide minerals are dominated by chalcopyrite, bornite, galena, sphalerite, pyrite, and arsenopyrite, accompanied by minor molybdenite with secondary covellite and chalcocite. Sulphosalts (tetrahedrite-tennantite) and oxides (magnetite, cassiterite, rutile) are also present. Non-sulphide gangue minerals, whose development relates to the composition of the host rocks, consist predominantly of quartz where the mineralized veins cut the Bouskour Granite, and conversely calcite and dolomite where the veins traverse the andesite. An idealized sequence of mineral deposition, drawn from mineral assemblages and textural and crosscutting relationships, shows the existence of three successive stages of ore deposition, each of which is separated by episodes of intense shearing and brecciation.

The early stage referred to as “Cu–Zn–(Fe–As–Co–Bi–Sn) stage” comprises quartz, calcite, pyrite, arsenopyrite, sphalerite, chalcopyrite, bornite, covellite, digenite, chalcocite, tetrahedrite-tennantite ± rutile ± magnetite ± cassiterite. The subsequent stage (main Cu–Pb–Zn sulphide stage II) accounts for most of the exploited ore, and consists of sequentially deposited chalcopyrite, sphalerite, galena, bornite, covellite, digenite, chalcocite, and tetrahedrite-tennantite ± molybdenite; this paragenesis is spatially associated with a distinctive, strong chloritic and locally silicic alteration zone. The latest stage (III), referred to as Zn–Pb–(Cu) sulphide ± Au ± Ag stage, occurs in calcite or quartz veins or as late fillings within the older stage I and II assemblages.

In addition to the three hypogene stages, a post-ore supergene stage (IV) is well developed in the uppermost sulphide-rich part of the mineralized structures, where oxidized zones extend more than 110 m deep. The mineral assemblage of this supergene stage consist of varying amounts of goethite, hematite, lepidocrocite, malachite, azurite, chrysocolla, wulfenite, and autunite.

5 Sulphur and Lead Isotope Geochemistry and Re/Os Geochronology

A suite of representative sulphide (i.e., galena, pyrite, chalcopyrite) separates from the recently reworked Filon II, Agoulzi Vein, and Rhyolite Vein orebodies (Fig. 2) were analyzed for sulphur and lead isotope compositions (Table 1). Sulphur isotope analyses were carried out at the Environmental Isotope facilities of the University of Waterloo (Canada) using an Isochrom Continuous Flow Stable Isotope Ratio Mass Spectrometer GVI Micromass coupled to a Carlo Erba Elemental Analyzer CHNS-O EA1108. The data are reported as per mil (‰) deviations relative to the Canyon Diabolo troilite (CDT) standard. Analytical uncertainty (2σ) is ± 0.12 ‰. Lead isotopic compositions were determined on galena using a multi-collector–inductively coupled plasma–mass spectrometer (MC–ICP–MS) instrument (Micromass Isoprobe) operated in “solution mode” with an Aridus nebulizer system.

Re/Os analyses were performed on a single molybdenite separate from stage II of the “Patte-d’Oie” vein system. The sample was collected from drill core F2SC312 (X = 415422, Y = 434021, Z = 1550) at a depth of 623 m. Analyses were performed by J. Perello, Vice President of Antofagasta copper mining group.

The δ^{34}S values are all negative, ranging from −9.3 to −2.7 ‰ (avg −6.1 ± 2.6 ‰, $n = 9$), and show relatively little variation with respect to location in the deposit. These rather uniform δ^{34}S values are similar to but more negative than those that characterize igneous sulphur (−3 to +1 ‰; Hoefs 2009). The observed range in sulphur isotope compositions could be explained by the interaction of a magmatically derived ore fluid with an isotopically low end member (e.g., −9.3 ‰), such as that inferred for biogenic pyrite within the Cryogenian black shale country rocks. Alternatively, such low δ^{34}S values in the sulphides could record somewhat low temperatures of deposition, in the range of ~150–200 °C (see Ohmoto and Goldhaber 1997). The more negative δ^{34}S values may also reflect boiling processes during mineralization (see Drummond and Ohmoto 1985). Indeed, it is well established that boiling will lead to a loss of H_2 and oxidation of the ore fluid, which ultimately results in lower δ^{34}S values in sulphides (e.g., Duuring et al. 2009; Kamvong and Zaw 2009). Based on these

Table 1 Sulphur and lead isotope compositions of sulphide separates from the Bouskour Cu–Pb–Zn deposit

Vein system	Sulphide	δ^{34}S	^{206}Pb/^{204}Pb	^{207}Pb/^{204}Pb	^{208}Pb/^{204}Pb
Filon II	Pyrite	−3.1	–	–	–
Filon II	Pyrite	−2.7	–	–	–
Filon II_Level-140	Chalcopyrite	−6.6	–	–	–
Filon II_Level-140	Chalcopyrite	−6.3	–	–	–
Agoulzi	Galena	−9.2	–	–	–
Agoulzi	Galena	−3.3	–	–	–
Rhyolite	Chalcopyrite	−6.1	–	–	–
Rhyolite	Galena	−9.3	17.738	15.523	37.616
Rhyolite	Galena	−8.1	17.768	15.524	37.710
Rhyolite	Galena	–	17.883	15.526	37.619
Rhyolite	Galena	–	17.913	15.541	37.675
Rhyolite	Galena	–	17.946	15.537	37.614
Rhyolite	Galena	–	17.947	15.537	37.607
Rhyolite	Galena	–	17.950	15.538	37.619
Rhyolite	Galena	–	18.080	15.552	37.687

constraints, and notwithstanding the possible involvement of externally derived bacteriogenic sulphur, we attribute the limited spread in δ^{34}S values at Bouskour to a large-scale hydrothermal system with a homogeneous source of sulphur that was likely entirely of magmatic origin.

Lead isotope ratios for galena separates range from 17.785 to 18.113 for ^{206}Pb/^{204}Pb, 15.521–15.552 for ^{207}Pb/^{204}Pb, and 37.620–37.823 for ^{208}Pb/^{204}Pb (Table 1). These values plot between the orogene and mantle growth curves of Zartman and Doe (1981) (Fig. 4). Accordingly, we interpret the tight linear clustering of Pb isotope data as reflecting the mixing of lead from isotopically homogeneous mantle and various crustal reservoirs during leaching and fluid transport, as also suggested by the sulphur isotope data reported above.

A Re/Os molybdenite age determination yields a weighted average age of 574.9 ± 2.4 Ma (2-sigma). This age is broadly consistent, within analytical uncertainty, with the 570 ± 5 Ma SHRIMP U–Pb zircon age for the Bouskour Granite reported by Walsh et al. (2012).

6 Discussion

The conclusions drawn herein are based on geological and mineralogical information on the vein systems, on limited sulphur and lead isotope data, and more importantly on one Re/Os molybdenite age determination. In the absence of reliable fluid inclusion and additional geochronological constraints on mineralization, our interpretations thus could change when new data become available.

Earlier studies (Clavel and Tixeront 1971; Tixeront 1971) classified the Bouskour deposits as a typical zoned vein system whose genesis is directly related to emplacement of the Bouskour granitic complex. More recently, Marcoux and Jébrak (2012) and El Azmi et al. (2014) have argued that the veins should be considered part of a porphyry copper system. However, several lines of evidence obtained from the current study are inconsistent with such a model: (1) there is no zoned distribution of alteration assemblages or sulphide minerals (i.e., bornite, chalcopyrite, pyrite) as is commonly described for typical

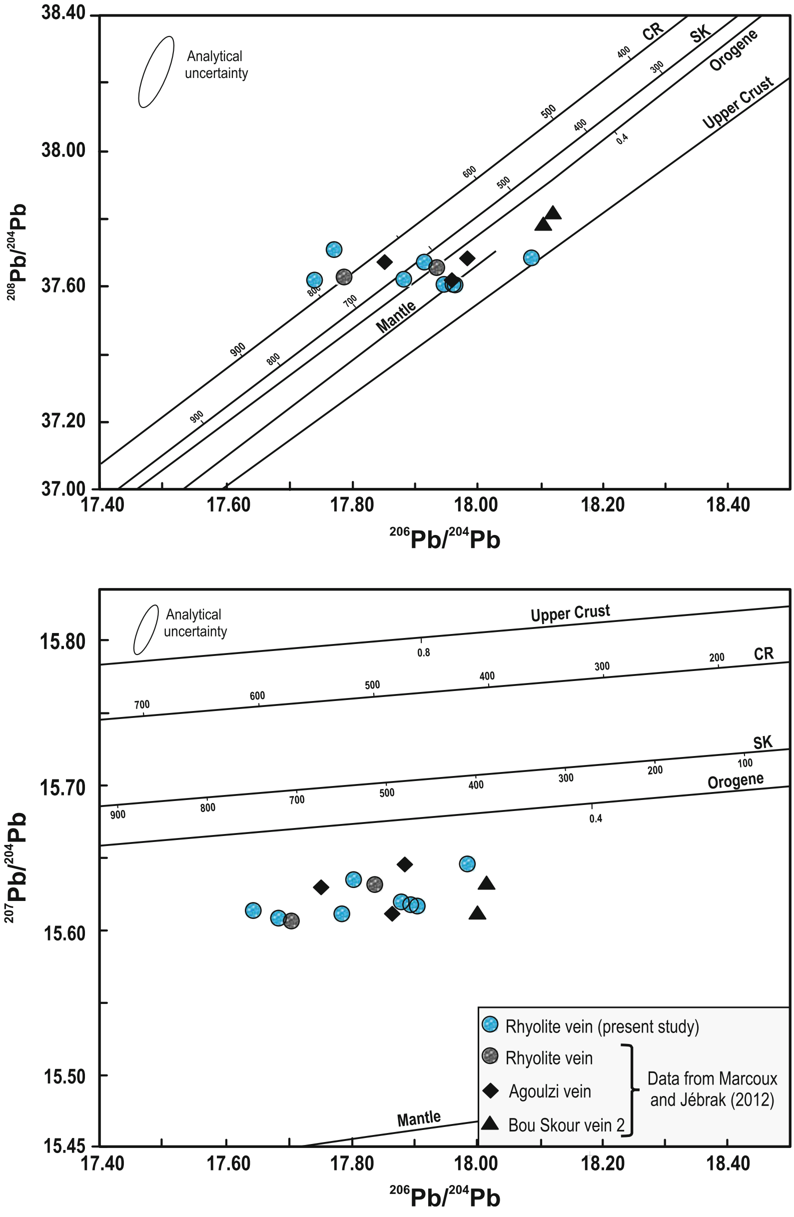


Fig. 4 Lead isotopic compositions of galena ores from the Rhyolite vein system of the Bouskour Cu–Pb–Zn deposit, plotted on **a** ^{208}Pb/^{204}Pb versus ^{206}Pb/^{204}Pb and **b** ^{207}Pb/^{204}Pb versus ^{206}Pb/^{204}Pb diagrams. Evolution curves of Stacey and Kramers (1975) and Cumming and Richards (1975), labelled SK and CR, respectively; along with the evolution curves for Upper Crust, Mantle and Orogene from Zartman and Doe (1981), are shown for reference

porphyry Cu deposits; (2) alteration mineral assemblages that are diagnostic of porphyry Cu deposits (i.e., potassic, phyllic, propylitic) predate the bulk of the vein sulphide minerals; (3) areas having high Cu contents are correlated with zones of weak potassic alteration (<2 % K_2O; Marcoux and Jébrak 2012), which is the inverse of that displayed in typical porphyry Cu systems; (4) the bulk of Bouskour ores do not occur within vein stockwork structures, instead being hosted by a transcrustal, kilometer-long megastructure; (5) anhydrite that characterizes porphyry Cu systems is absent in the veins; and (6) the presence of a Sn–Fe–As–Co mineral paragenesis in the veins, although uncommon, is absent in porphyry Cu systems. Collectively, these lines of evidence argue against a purely porphyry Cu model for the Bouskour vein mineralization, pointing instead to a classical granite-related polymetallic vein system. Paragenetic studies indicate that the paleohydrothermal history of the ore-forming vein system comprised three main contrasting hydrothermal events. However, it is unclear whether these events are genetically related to the protracted evolution of a single mineralizing fluid, or alternatively to three separate hydrothermal episodes.

The earliest of the three stages referred to as the "Cu–As–(Sn) stage" exhibits a stockwork of Cu-rich mineralization having an assemblage of ore minerals (pyrite, arsenopyrite, chalcopyrite, sphalerite, galena, tetrahedrite-tennantite), cassiterite, stannite, native bismuth and Bi-sulphosalt, and alteration assemblages similar to those commonly reported for volcanic-hosted massive sulphide (VHMS) deposits. Accordingly, we interpret this early type of mineralization, which is confined exclusively to the Cryogenian andesites, as representing the stockwork zone of a possibly hidden VHMS system that existed on or beneath the Cryogenian seafloor.

The second Cu–Pb–Zn stage of mineralization, which is by far predominant and economically the most important, is epigenetic, structurally controlled, and consists of open-space fillings of brittle structures that were likely open to the surface. Structural constraints based on geometry of the mineralized vein systems led Clavel and Tixeront (1971) to favor an Hercynian age for the Cu–Pb–Zn sulphide mineralization. This inferred age is in accord with the time span of mineralizing hydrothermal events dated at 250 to 210 ± 10 Ma (Ghorbal et al. 2008; Sebti et al. 2009; Barbero et al. 2011) that affected most Hercynide domains of North Africa (Valenza et al. 2000; Cheilletz et al. 2010) and Western Europe (Sánchez et al. 2006). However, crosscutting relationships indicate that the mineralized structures cut the 570 ± 5 Bouskour Granite but in turn do not transgress overlying 558 ± 4 Ma upper Neoproterozoic strata, thereby bracketing the mineralization between 570 ± 5 and 558 ± 4 Ma. More interestingly, the Re/Os molybdenite age of 574.9 ± 2.4 Ma (2-sigma) reported here is similar, within analytical uncertainty, to the 570 ± 5 Ma SHRIMP U–Pb zircon age reported for the Bouskour Granite (Walsh et al. 2012). This new Re–Os molybdenite age provides strong evidence for contemporaneity between emplacement of the Bouskour Granite and the spatially associated Cu–Pb–Zn sulphide mineralization. Accordingly, a genetic relationship between mineralization and the Bouskour Granite is therefore indicated. These relationships thus suggest that the bulk of Bouskour Cu–Pb–Zn mineralization, veining, and alteration occurred late in the tectonic history of the Bouskour area, towards the end of the latest phase of Pan-African deformation, contemporaneously or immediately after emplacement of the 570 ± 5 Ma Bouskour Granite, as also suggested by the sulphur and lead isotope data discussed above. Moreover, the trend of Pb isotope data (Fig. 4) together with the presence of abundant mafic and ultramafic igneous rocks in the footwall succession, suggests derivation of the galena-hosted lead from sources in both the deep crust and mantle, although a contribution of lead from the middle crust (orogene) cannot be ruled out.

Owing to the absence of reliable fluid inclusion data, the main stage of copper deposition is estimated to have occurred at temperatures of 200–400 °C based on the common occurrence of "chalcopyrite disease" in sphalerite grains (Barton and Bethke 1987). This interval of temperatures matches those bracketed between 260 and 305°C based on equilibrium temperatures inferred from chlorite geothermometry (Marcoux and Jébrak 2012).

Sulphur together with lead isotope compositions indicate that the hydrothermal fluids were predominantly magmatic although the involvement of meteoric water remains possible. However, the data are insufficient to confidently define relative proportions of magmatic fluid and meteoric water in the mineralizing process. Exsolution of magmatic SO_2 could have produced a shallow crustal fluid reservoir enriched in SO_2 or SO, either through condensation into meteoric water or through the disproportionation of the magmatic gas phase (see Rye 1993).

Indeed, it is well documented that in shallow crustal environments like the one inferred here for Bouskour ore deposition, exsolution of hydrothermal fluids from a crystallizing magma can release large volumes of gases, including oxidizing components such as $SO_{2(g)}$, acidic components such as $HCl_{(g)}$, and smaller volumes of dense, saline brines (Bodnar et al. 1985). The occurrence of acidic fluid conditions during emplacement of the copper mineralization at Bouskour is supported by the coexistence of illite-chlorite alteration assemblages (see Hedenquist and Browne 1989; Bove et al. 2002).

The paragenetically late third stage (III) characterized by base-metal ± Ag ± Au ± copper sulphide mineralization remains enigmatic and its emplacement is poorly constrained due to the lack of reliable geochemical data. Further studies are thus required to adequately characterize this stage. However, when considered regionally, stage III could be correlative with the Hercynian auriferous base-metal stage that typifies the metal deposits of the Anti-Atlas system (e.g., Bou Azzer and Bou Madine deposits described in this volume).

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