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Géoscience

Sciences de la Planète


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Volume 353, issue 1 (2021), p. 81-99

<https://doi.org/10.5802/crgeos.54>

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Original Article — Tectonics, Tectonophysics

The Cu–Pb–Zn-bearing veins of the Bou Skour deposit (Eastern Anti-Atlas, Morocco): structural control and tectonic evolution

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Abstract. In the central Saghro massif of the Moroccan Anti-Atlas belt, the Bou Skour polymetallic deposit is hosted within mafic to felsic rocks of the Ediacaran Saghro Group and the lower Ouarzazate Group together with Pan-African plutons and dykes. The mineralizations occur in a brittle-ductile shear zone as a vein-type system recently dated at 574.9 ± 2.4 Ma. In this contribution, a new multi-scale structural mapping and vein system analysis have been integrated to understand structural control and tectonic evolution of the Bou Skour deposit. The most important mineralized structures are known as “*Filon Principal*”, “*Filon 1*”, and “*Filon 2*” and are mainly hosted within NNW to NW transcrustal faults. They are represented as en-echelon tension gashes occasionally associated with horsetail satellite structures pointing to left-lateral strike-slip movement. The age and tectonic patterns are coherent with the NW–SE shortening of the last stage of the Pan-African orogeny rather than with post Pan-African events. Subsequent collapses and tilted blocks were accommodated by NE- to ENE normal and strike-slip faults in response to the Late Ediacaran–Cambrian extension events. Much later, probably during the Variscan or even Atlasic shortening, conjugated strike-slip reverse faults and related folds occurred, disrupting most of the rhyolitic dykes as well as the major mineralized structures.

Keywords. Structural mapping, Mineralized structures, Bou Skour, Central Saghro massif, Anti-Atlas.

Manuscript received 27th February 2021, revised 15th March 2021 and 31st March 2021, accepted 31st March 2021.

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1. Introduction

Along the northern margin of the West African Craton (WAC) (Figure 1A), the Precambrian Saghro massif constitutes an important metallogenic province of the Moroccan Anti-Atlas belt (Figures 1B and C). Numerous potential deposits are located in this region, including the Imiter world-class silver and the Bou Skour polymetallic deposits, which are, economically, the most productive. Located in the central Precambrian Saghro massif, the Bou Skour deposit remains one of the leading Cu–Pb–Zn ± Ag ± Au vein-type deposits of North Africa (Figure 1C). The first discoveries of this mining district date back to medieval times and subsequently was mined by “la Société Minière de Jbel Sarhro” in the 1940’s. Mining activity was continued in 1948 by “la Société Minière d’Issougrri” and then by “la Société Minière de Bou Skour”, which in 1950 revealed interesting anomalies through geophysical prospecting. Between 1955 and 1971, after several years of closure, the latter company merged with the former “Bureau de Recherches et de Participation Minière” (BRPM, currently ONHYM) and Managem Group (filiale of SNI Holding) in order to undertake advanced exploration survey, to start the exploitation in 1958 with more than 10,000 t/year of metal, and to discover two additional anomalies in 1971 [Maacha *et al.*, 2011]. However, the exploitation was abandoned in 1977 due to both poor ore quality and the decline of metal prices on the international market. Starting in 2008, Reminex, a subsidiary of Managem Group, began extensive exploration programs, including geophysical survey and more than 70,000 m of core drilling, leading to the discovery of more than 53 million tons of resources at 0.8% Cu and 9 g/t Ag, of which 21 Mt contain a high-grade of 1.3% Cu [Maacha *et al.*, 2011].

Throughout this period, numerous metallogenic and geological studies supported and guided the exploration activities of the Bou Skour deposit until a good geological knowledge of this area was achieved [Bouabdellah *et al.*, 2016, Clavel and Tixeront, 1971, El Azmi *et al.*, 2014, El Ouardi *et al.*, 2016, Maacha *et al.*, 2011, Marcoux and Jébrak, 2012, Startsyne *et al.*, 1975, Tixeront, 1971, Walsh *et al.*, 2008a]. The geological mapping covering the study area corresponds to 1:50,000 map sheets of Bou Skour [Walsh *et al.*, 2008a], whereas the recent metallogenic, geochronological, and structural studies

were conducted by El Azmi *et al.* [2014], Bouabdellah *et al.* [2016] and El Ouardi *et al.* [2016], respectively. Nevertheless, the fracturation-mineralization reports and their tectonic implications for the Bou Skour deposit are still insufficiently known. Obviously, deciphering the tectonic control of the mineral deposits already known and operated is an important task as a guide for further discovery of ore bodies. Hence, the present work investigates tectonic control on the mineralized veins of the Bou Skour deposit with an emphasis on their relationship with regional tectonic events. We provide a new structural map of the deposit, accompanied by a discussion of the geometry and spatial distribution of the vein system in relation to fault network patterns.

2. Regional geological setting

The Moroccan Anti-Atlas represents the most important segment of the Neoproterozoic Pan-African belt, also defined as the Cadomian orogen in the northern edge of the WAC (Figure 1A). All the Anti-Atlas Pan-African/Cadomian belt was subsequently topped by the Ouarzazate Group between 570–545 Ma, then by a thick Paleozoic cover [Blein *et al.*, 2014b, Gasquet *et al.*, 2008, Soulaïmani *et al.*, 2014, 2018]. Even though the area has been affected by the Variscan events [Burkhard *et al.*, 2006], the Anti-Atlas belt is currently exposed to altitudes up to 1000 m due to the Atlasic vertical movements [Frizon de Lamotte *et al.*, 2009, Gouiza *et al.*, 2016, Malusa *et al.*, 2007, Oukassou *et al.*, 2013]. The oldest rocks of the Anti-Atlas belt belong to the Paleoproterozoic basement (~2 Ga) [Thomas *et al.*, 2002], which outcrops uniquely in the Anti-Atlas inliers south of Anti-Atlas Major Fault (AAMF), i.e., the Bas Draa, Ifni, Kerdous, Tagragra, Tata and Zenaga inliers (Figure 1A). The ~2 Ga-old basement is overlain by the late Paleoproterozoic Taghdout Group [Ikene *et al.*, 2017, Soulaïmani *et al.*, 2019] whose deformed platform beds are intruded by numerous Mesoproterozoic mafic dykes [El Bahat *et al.*, 2013].

Along the AAMF, Neoproterozoic meta-ophiolites and oceanic arc units whose evolution is recognized between ca. 760–740 Ma and 660–640 Ma occur in the Bou Azzer-Siroua Pan-African suture zone [Blein *et al.*, 2014a, El Hadi *et al.*, 2010, Inglis *et al.*, 2005, Triantafyllou *et al.*, 2016, 2018]. To the northeast of the AAMF, the Pan-African units correspond to the Early

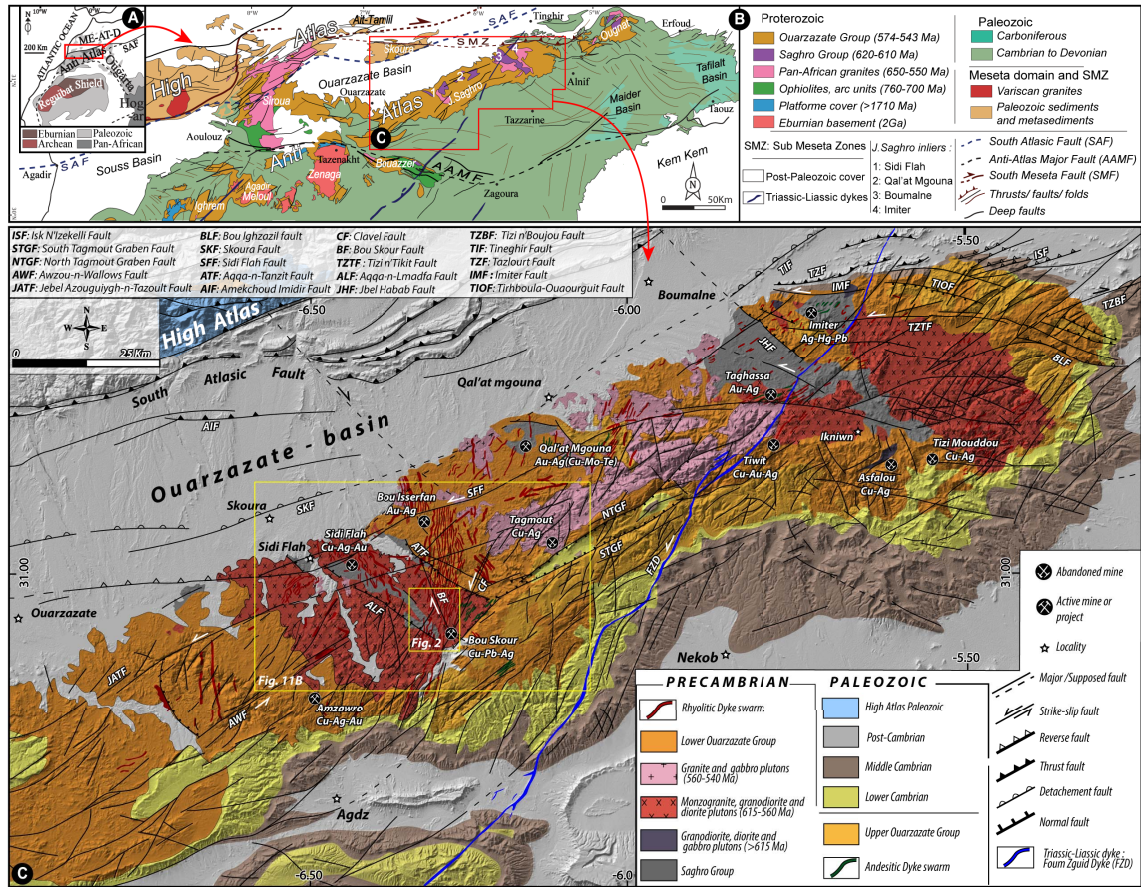


Figure 1. (A) Location of the Anti-Atlas belt on the northern edge of the WAC. Dashed black line: Variscan deformation front. ME-AT-D: Meseta-Atlas-Domain. WAC: West African Craton [Michard et al., 2008]. (B) Geological map of the central, eastern Anti-Atlas belt and adjacent Meseta-Atlas domain. Folds and faults are numerated after Michard et al. [2010]. (C) Structural map of the Saghro massif, interpreted from Hindermeyer et al. [1977], Tuduri et al. [2018], Hejja et al. [2020], Aabi et al. [2020], and this work.

Ediacaran folded clastics and turbidites of the Saghro Group outcropping in the Siroua, Saghro and Ougnat massifs [Abati et al., 2010, Michard et al., 2017] (Figure 1B). In the Saghro massif, the oldest exposed rocks correspond to the 620–580 Ma old Saghro Group, essentially composed of low-grade turbidites and shales locally interbedded with mafic to intermediate volcanic rocks [Fekkak et al., 2003, Gasquet et al., 2008, Michard et al., 2017] (Figure 1C). Such units occur from west to east in the Sidi Flah, Qal’at Mgouna, Boumalne, and Imiter inliers (Figure 1C). These Early Ediacaran sequences were folded and affected by many NW–SE and ENE–WSW conjugated strike-slip shear zones [Saguaque et al., 1992] during

the last stages of the Pan-African orogeny [Michard et al., 2017, Soulaïmani et al., 2018].

The Late Ediacaran volcanic and volcani-clastic rocks of the Ouarzazate Group which has been divided into upper and lower parts (Figure 1C), unconformably lie upon the folded Saghro Group and extend over more than half of the Saghro Massif [Walsh et al., 2012]. Both the Saghro and Ouarzazate Groups were intruded by numerous Pan-African plutons and dykes [Errami et al., 2009]. In the Saghro Massif and adjoining areas, this period is known for active transtensional and extensional faulting that controls the thickness of the Ouarzazate Group deposits and associated magmatic intrusions [Errami and Olivier,

2012, Hejja *et al.*, 2020, Karaoui *et al.*, 2021, Walsh *et al.*, 2012]. Paleozoic deposits surrounding the massif are made up of terrigenous clastic deposits and minor carbonates, the age of which range from Cambrian to Carboniferous [Cerrina Feroni *et al.*, 2009]. NW–SE Cambrian rifting resulted in numerous tilted blocks around the Saghro massif [Hejja *et al.*, 2020]. During the important Late Devonian extensional event, normal faulting likely affected the massif similar to the nearby Ougnat massif [Baïdier *et al.*, 2008]. Subsequently, the pre-existing normal faults were locally inverted during the Variscan orogeny.

In the northeastern part of the Saghro Massif, two Variscan shortening phases have been described (Hejja *et al.*, 2020 and references therein), while in the southwestern Saghro, most of the extensional structures have been reversed in response to the N–S Variscan deformation [Walsh *et al.*, 2012]. Post-Variscan tectonic events were primarily expressed, in the Saghro massif, by numerous north to NNE-trending faults and related dykes (e.g. Triassic–Jurassic Foug Zguid dyke) (Figure 1C). These transtensional structures have cut across the Precambrian–Paleozoic deformed terrains during the Central Atlantic rifting [Hejja *et al.*, 2020]. Throughout the Cenozoic, due to the Atlasic compression, the Meso–Cenozoic sedimentary cover of the Ouarzazate basin was affected by east to ENE-trending reverse faults and related folds, whereas the structures of the Saghro basement were variably inverted [Hejja *et al.*, 2020, Pastor *et al.*, 2012, Soulaïmani *et al.*, 2014].

3. Local geological setting

The Bou Skour Cu–Pb–Zn vein-type deposit, the subject of the present study, is located in the central Saghro massif, about 60 km as the crow flies east of the Ouarzazate city (Figure 1C). It occupies the southern part of the Sidi Flah inlier and is hosted within Precambrian extrusive and intrusive igneous rocks. The extrusive rocks, which are considered the oldest units in the prospect area, consist of Early Ediacaran andesitic–basaltic rocks (Figure 2). Brittle–ductile deformation affected these rocks during the last Pan-African event (Cadomian phase), expressed by schistosity metamorphism and less developed orthogonal cleavages [Walsh *et al.*, 2008b]. The metamorphosed andesitic–basaltic rocks of the Saghro

Group are subsequently intruded by various Pan-African plutons and dykes [Fekkak, 2000, Gasquet *et al.*, 2005, Michard *et al.*, 2017]. These include the Bou Skour granite and granodiorite massifs (570 ± 5 Ma), which occupy the northern and eastern sides of the mining area, while the pink Assif Tagmoute granite (577 ± 8 Ma) occurs to the west (Figure 2). Amphibole-bearing granodiorite can be seen in the northeastern part of the ore deposit.

A system of felsic and mafic dykes with different directions and petrographic nature crosscuts these Ediacaran formations. The most important set belongs to the rhyolitic dyke swarms of Sidi Flah, which shows a dominant NNE–SSW direction and a metric thickness of each dyke; it was locally dated at 564 ± 7 Ma [Walsh *et al.*, 2008b, 2012]. All these Early Ediacaran rocks are topped to the south by the volcano-sedimentary series of the Late Ediacaran Ouarzazate Group (Figure 2).

4. Methodology

Structural mapping was carried out in the prospect area in order to establish a detailed survey of the Bou Skour mineralized veins and to understand their distribution and tectonic control. The 1:50,000 Bou Skour geological map and its explanatory notice [Walsh *et al.*, 2008a,b]), accompanied by many unpublished documents (Managem data), were used as supports to guide the fieldwork survey. This was complemented by satellite imagery analysis combined with field structural observations and measurements (fault plane directions and striation, fold axes, etc.). The structural data were analyzed using stereoplots. Finally, microstructural thin-section examination was completed on oriented samples from selected zones to constrain the geometry and kinematics of the mineralized structures.

5. Results

5.1. Vein system description

The Bou Skour deposit comprises several ore bodies of different sizes and mineral parageneses, referred to, from north to south, as Panthère, Chaigne, Anne-Marie, Chapeau de Fer and Patte-d’Oie (Figure 2). The latter is considered economically the most important and hosts the major part of the metal stock of

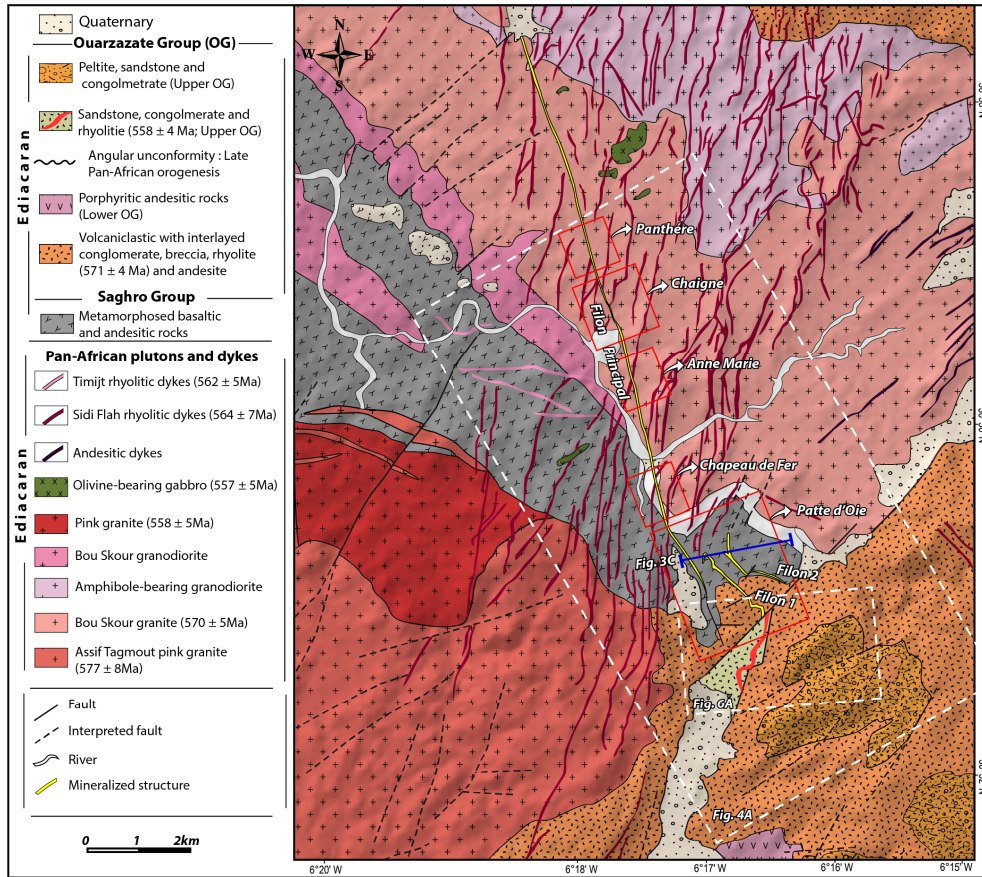


Figure 2. Geological map of the Bou Skour polymetallic deposit (simplified after Walsh et al., 2008a). See Figure 1C for location.

the district [El Azmi et al., 2014]. Generally, the mineralization of this deposit is cupriferous, but sometimes it exhibits a polymetallic character.

From a morphological point of view, the mineralization is predominantly vein-type, developed either along NNW–SSW and NW–SE major faults or in ramifications between these faults with a dominant NNW–SSE direction. The most important structures are the “Filon Principal (FP)”, “Filon 1 (F1)”, and “Filon 2 (F2)” (Figures 2 and 3C).

The FP is an up to 10 m-wide structure, which is considered as the longest of the deposit; it extends over 10 km long (Figures 2 and 3A). It is oriented N165° to N170° with a sharp body that most often protrudes into the topography (Figures 2, 3A and C). The FP hosts more than 80% of the total mineral resources of the Bou Skour mineralized

structures [Bouabdellah et al., 2016]. In its northern part, the FP is intra-granitic (granite of Bou Skour) with a well-preserved ore body that frequently shows tracks of oxidized copper minerals (Figures 2 and 3A–B). At this place, particularly in the Panthère district, this mega-structure is accompanied on both sides by several parallel satellite structures extending over several meters. Moving southward, the FP emerges from the Bou Skour granites and becomes hosted within metamorphosed andesitic and rhyolitic rocks of Saghro and lower Ouarzazate Groups as more or less quartz-injected carbonate tension gashes before disappearing beneath the volcano-sedimentary strata of the upper Ouarzazate Group.

The F1 corresponds to NW-trending subvertical structure that spread laterally over 1 km and

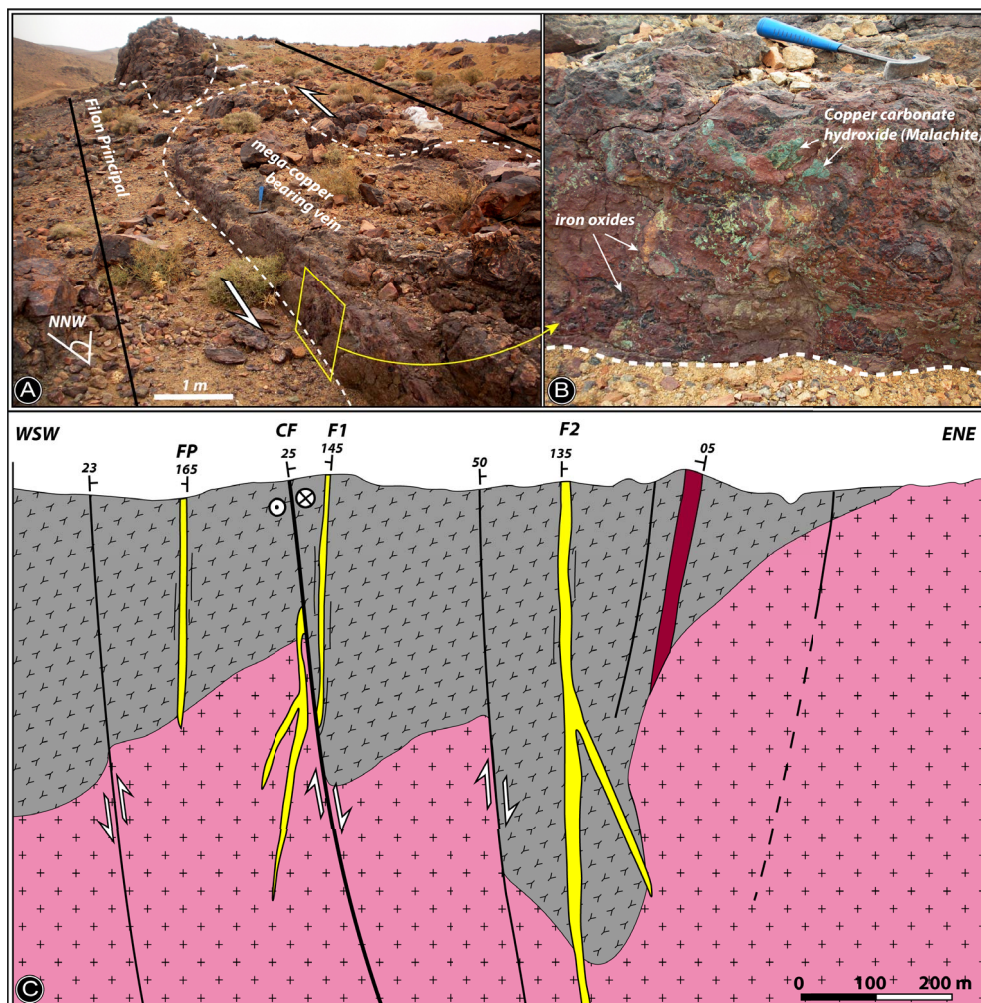


Figure 3. Field pictures of a mega-copper bearing veins associated with the FP structure (A) and showing tracks of malachite and many iron oxide minerals (B). (C) Transversal cross-section through the major mineralized structures of the Patte d’Oie district interpreted from two cored drilling (Managem data). See Figure 2 for location and stratigraphic symbols. FP: Filon Principal; F1: Filon 1; F2: Filon 2; CF: Clavel Fault.

can be only seen in the sector of Patte d’Oie (Figures 2 and 3C). It is located a few tens of meters to the east of the FP and hosted in the north by the Saghro Group andesitic formations, then in the south by the lower Ouarzazate Group volcanic rocks (Figure 2). The gangue minerals of the F1 are carbonated and the body is relatively regular within the andesitic rocks, where it is several meters thick, but in the rhyolite rocks, the F1 is reduced to small quartz veins.

About 300 m west of F1, the sub-vertical F2 con-

stitutes the third mineralized structure of the Patte d’Oie, embedded in the metamorphic rocks of the Saghro Group (Figure 3C). It first shows a NW–SE direction, then as it heads to the north, the structure curves to the northeast and plunges in the N40° direction (Figure 2). The gangue of the ore-body consists either of dolomite and quartz-injected calcite or of mineralized andesitic breccia cemented by dolomite and quartz. Other structures called “Rhyolite Vein” and “Agoulzi Vein” are eco-

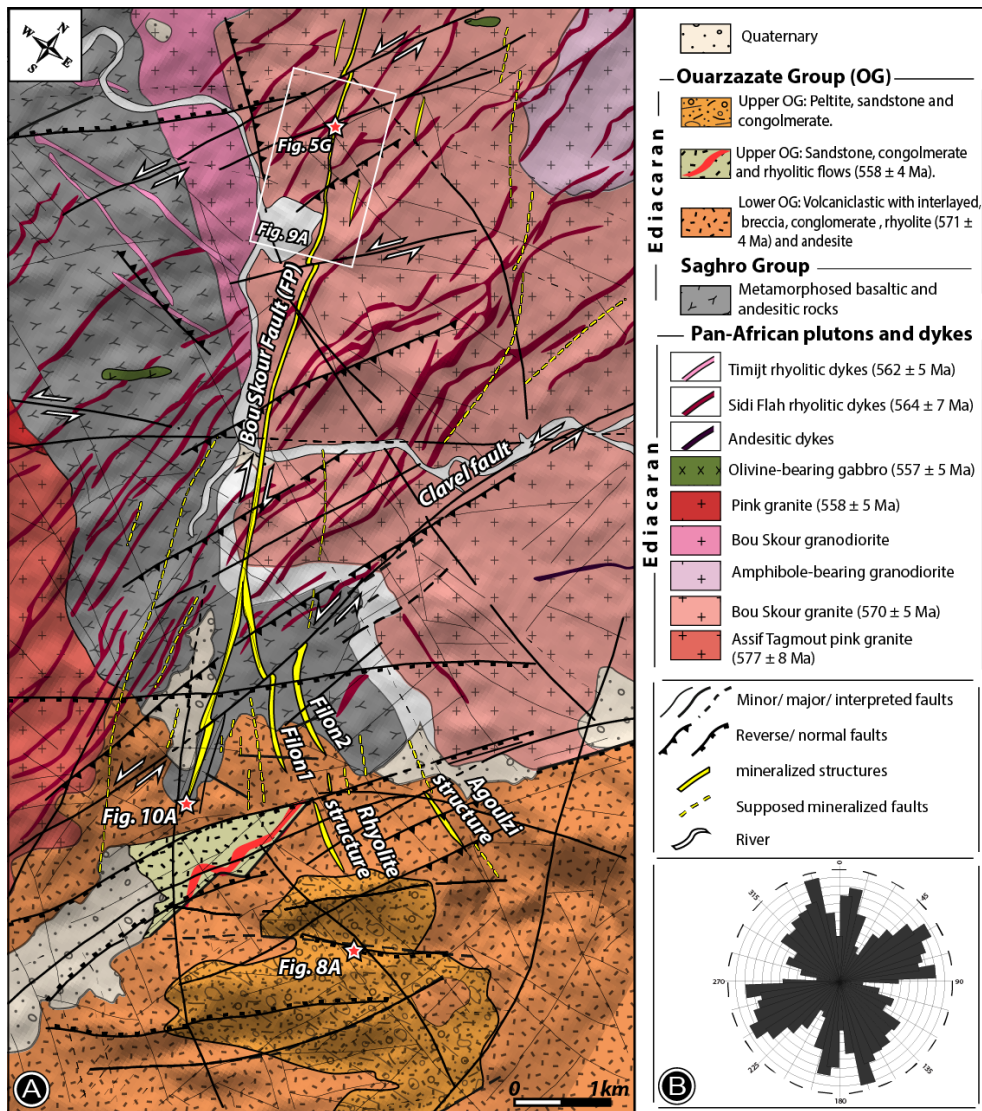


Figure 4. (A) Structural map of the Bou Skour polymetallic deposit. See Figure 2 for location. FP: Filon Principal. (B) Rose diagram of faults crosscutting the Bou Skour district.

nominally less important and can be seen south of the deposit hosted within the rhyolitic complex of the lower Ouarzate Group. They exhibit the same directional patterns as the F1. The FP, F1 and F2 form a succession of mineralized tension gashes oblique to their envelope and decrease their dip as they get deeper, where they branch out into secondary satellite veins whose mineralogical composition remains almost unchanged (Figure 3C).

5.2. Fault kinematics and directional analysis

Based on our investigations, there is strong evidence that the Bou Skour deposit is predominantly affected by brittle tectonics. The new established structural map of the study area (Figure 4A) allows us to better understand the relationships between fracturing and mineralization, and to highlight three systems of faults with metric to kilometeric extension (Figure 4B).

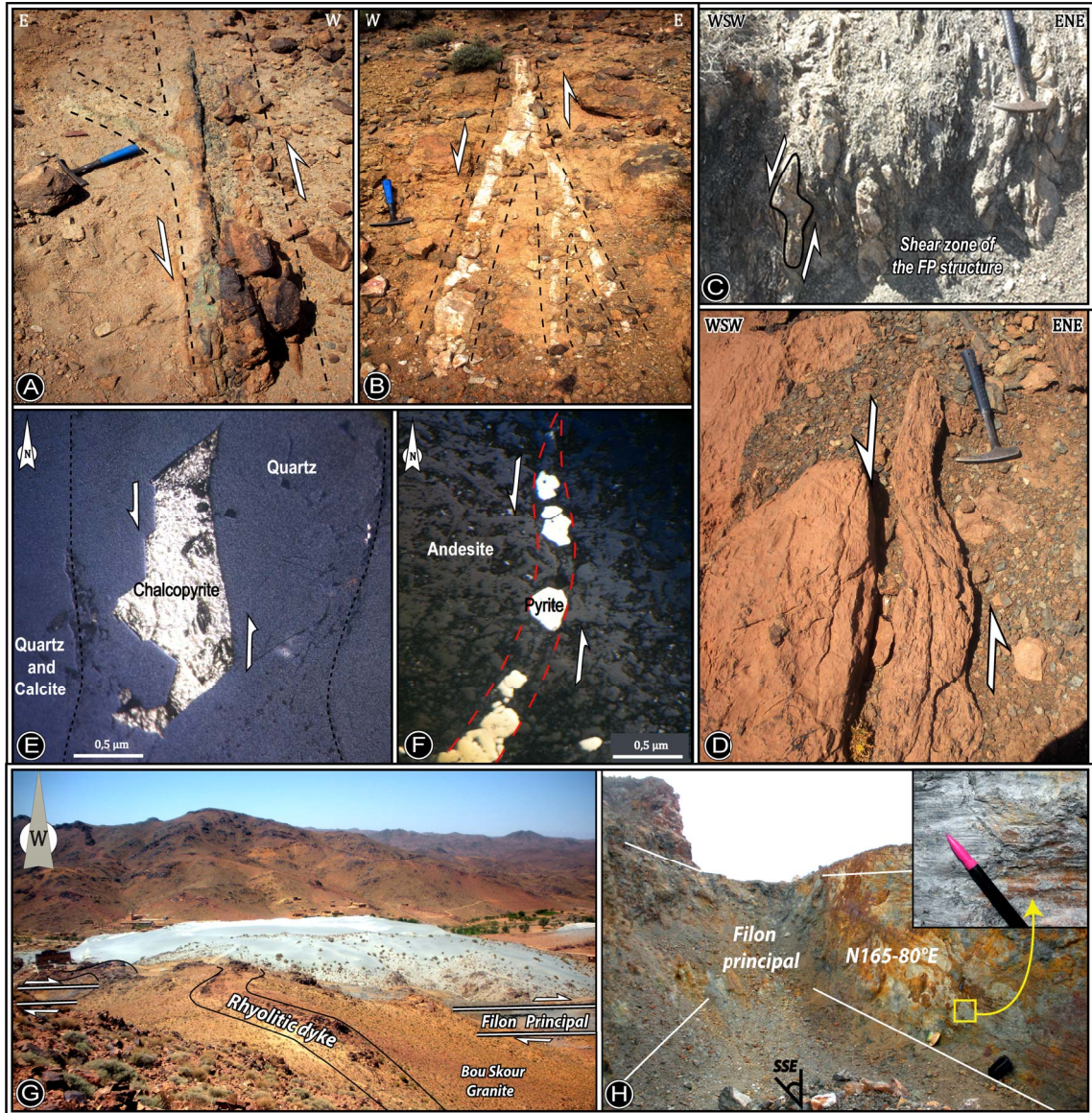


Figure 5. Copper-(A) and quartz-(B) bearing structures exhibit geometry of sinistral horsetail splay. Hydrothermal tension-gashes associated with sinistral shearing observed within FP (C) and F1 (D) structures. Photomicrographs of micro-veins filled by chalcopyrite (E) and pyrite (F) recording sinistral kinematics. Right lateral strike-slip reactivation of the NNW-SSW FP displaces one of the rhyolitic dykes (G) and is recorded by sub-horizontal slickensides in the FP wall (H). See Figure 4A for the point of view of (G).

5.2.1. NNW-SSE to WNW-ESE system

The NNW-SSE to WNW-ESE system represents the direction of the major mineralized structures of the deposit. Over about 10 km, the Bou Skour fault

where the FP is lodged has a N165 direction with a fault plan steeply dipping either to the east or to the west (Figures 1C, 3C, 4A and 5H). It crosses Precambrian outcrops including the Bou Skour granite, metamorphic Saghro Group, lower Ouarzazate

Group rhyolitic flows and even the network of rhyolitic dykes. The Bou Skour fault and the related FP exhibit evidence of left lateral strike-slip movement, and this kinematics is accommodated by a horsetail splay at its southern tip. Some satellite structures of the FP record the same geometrical style (Figures 5A and B).

Besides, numerous microscopical and macroscopical sigmoidal tension gashes associated with the FP body can be observed, which confirms the left lateral kinematics (Figures 5C and D).

In the Patte d'Oie sector, this fault system hosts the two F1 and F2 sub-vertical structures, directed N135 and N145, respectively (Figure 4A). The mineralized body of these structures shelters lenticular structures associated with left lateral kinematic similar to those of the FP. Accordingly, the directional and morphological relationships of these structures with the FP confirm the horsetail splay of the Bou Skour mineralized structures associated with a sinistral movement (Figure 4A).

To the north of the deposit, in the Panthère sector, the Bou Skour Fault shows a right lateral strike-slip reactivation associated with sub-horizontal slickensides (Figures 4A and 5G–H).

5.2.2. *N–S to NNE–SSW system*

This is the less frequent fault system, mainly represented by the Sidi Flah rhyolitic dyke swarm. It has a pluri-kilometric extension with an individual dyke thickness up to 20 m. The dykes crosscut the lower Ouarzazate Group as well as other older formations and are buried under the upper Ouarzazate Group (Figure 2).

To the southern part of the Bou Skour deposit, in the Patte d'Oie district, many NNE-trending strike-slip faults can be observed, which cut across the volcano-sedimentary formations of the upper Ouarzazate Group (Figures 6A and 7). The kilometeric Clavel Fault constitutes a good example of this fault system (Figure 2). It corresponds to a N25° major structure, crosscutting all Precambrian outcrops as well as the mineralized structures. It exhibits a character of left lateral strike-slip fault dipping 15° to the south and offsets F1 and FP by about 10 m. Hence, the junction points between this fault and the mineralized structures form tectonic nodes favoring the concentration of the mineralization.

5.2.3. *NE–SW to ENE–WSW system*

This system of NE- to ENE-trending faults represents the dominant system in terms of frequency. The faults have pluri-metric to kilometeric extension and cut across all Precambrian formations. The ENE–WSW faults are occasionally slightly mineralized, as particularly observed in the Patte d'Oie district. According to our field observations and measurements, the kinematics of this system correspond to a transtensional and extensional regime. This was attested in the southernmost part of the deposit, where the volcanoclastic formations of the upper Ouarzazate Group are jagged by NE-trending normal faults into a system of tilted basement blocks (Figures 7 and 8A–B).

Further to the north, between Chapeau-de-Fer and Panthère districts, this system appears as en-echelon pluri-metric faults crosscut the Bou Skour granite and dislocate both dyke swarms and mineralized structures (Figures 9A–C). These steeply dipping structures exhibit normal throw associated with a sinistral component where the fault plan bears steeply dipping slickenside (Figures 8C and D).

In summary, the geometry and extensional patterns of this fault system may have evolved during the Late Ediacaran–Cambrian extensional events that have been repeatedly described in the Saghro massif [Aabi *et al.*, 2020, Hejja *et al.*, 2020, Soulaïmani *et al.*, 2014].

However, this system of NE- to ENE trending faults locally reveals an oblique, moderate reverse motion. These reverse structures affect all the previous structures and seem to be conjugated with other reverse dextral faults-oriented NW–SE and occasionally associated with folds deforming the mineralized body of the FP (Figures 10A–C). These compressional structures could be the consequence of N–S shortening of the Variscan or Atlasic compressions [Walsh *et al.*, 2012].

6. Discussion

6.1. *Tectonic control on mineralized veins*

Based on the structural map (Figure 4A) and the outcrop survey (Section 5) we may propose a new model explaining the control of the mineralized veins by the regional tectonic events (Figure 11A). The most important polymetallic structures of the Bou

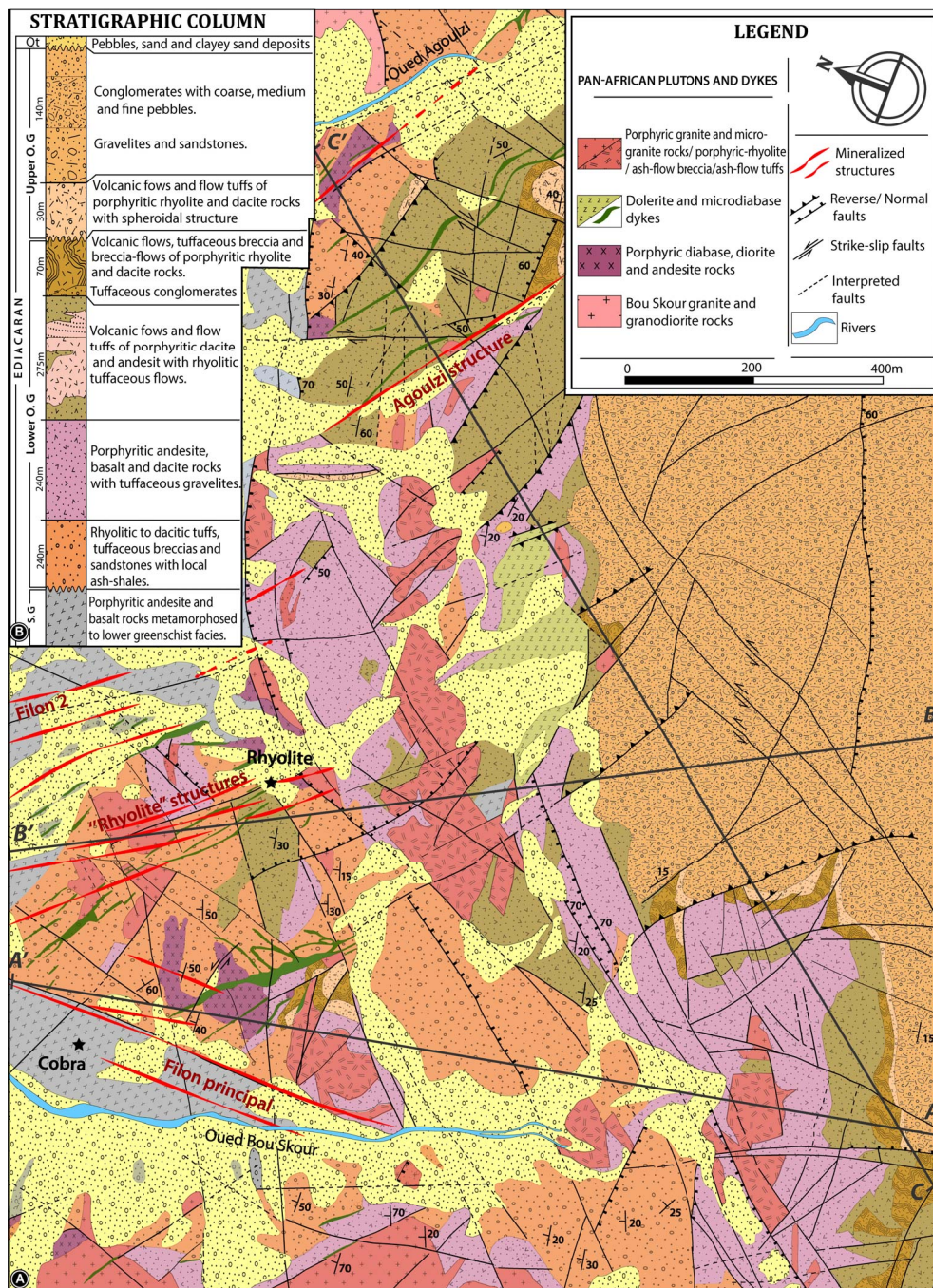


Figure 6. Detailed Geological map (A) and stratigraphic column (B) of the Patte d'Oie mining district of the Bou Skour polymetallic deposit (Startsyne et al., 1975, modified). SG: Saghro Group; OG: Ouarzazate Group; QT: Quaternary terrains; see Figure 2 for the location of (A).

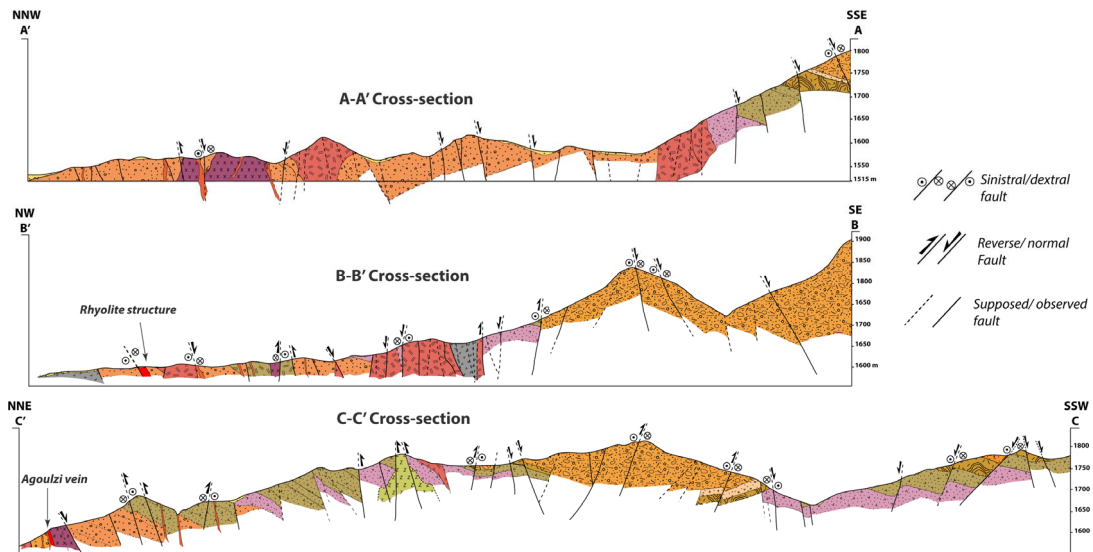


Figure 7. Detailed geological cross-sections illustrating the fault kinematics across the Precambrian outcrops of the Bou Skour area (Startsyne et al., 1975, modified). See Figures 6A and B for location and stratigraphic signatures.

Skour deposit, particularly the FP, F1, and F2 and their satellite structures, are sheltered along NNW to NW transcrustal faults, which cut across the Precambrian basement. All these polymetallic structures occur as en-echelon quartz and carbonate-bearing veins hosted within deformed Ediacaran intrusive and effusive rocks of the Saghro and lower Ouarzazate Groups. The shape and geometry of these tension gashes reveal a left lateral kinematic emplacement in a brittle-ductile regime along the shear zones of the NNW–SSE Bou Skour fault that coincides with the FP, F1 and F2 structures. The observed kinematics is confirmed by the horsetail splay at the FP southern tip and in the satellite mineralized structures (Figures 5A–F and 11A). At a larger scale, the directional and morphological relationships of F1 and F2 with FP can be regarded as a kilometeric sinistral horsetail of a shear zone oriented NNW–SSE to NW–SE (Figure 11A). All these structural elements point to a NW–SE shortening control of the Bou Skour veins system (Figure 11A).

Recent dating of the molybdenite from these veins yielded an age of 574.9 ± 2.4 Ma [Bouabdellah et al., 2016]. A similar age of 570 ± 5 Ma is attributed to the NW-elongated Bou Skour granitic pluton, where

the FP is hosted [Walsh et al., 2012]. Therefore, this confirms the syn-plutonic emplacement of the mineralized structures [Bouabdellah et al., 2016, Clavel and Tixeront, 1971]. According to these data and our structural findings, the Bou Skour mineralized structures may have resulted from the NW–SE late Pan-African deformation (before ~ 570 Ma; Soulaïmani et al., 2018) as well-defined in the Saghro-Ougnat massifs [Michard et al., 2017].

However, the Bou Skour shear zone, where the FP, F1 and F2 are sheltered, has been subsequently remobilized, demonstrating a right lateral strike-slip displacement (Figures 5G–H and 9A). At a large scale, this mega-structure seems to be, kinematically, conjugated with the major, sinistral NE-trending Sidi Flah fault located at the northern limit of the central Saghro massif (Figure 11B). This tectonic setting would have developed before the emplacement of the upper Ouarzazate Group, since the southern branch of the Bou Skour fault does not affect the latter formations.

Our proposal for the Bou Skour veins emplacement agrees with the findings of Bouabdellah et al. [2016], who suggests that the veins were formed towards the latest phase of the Pan-African

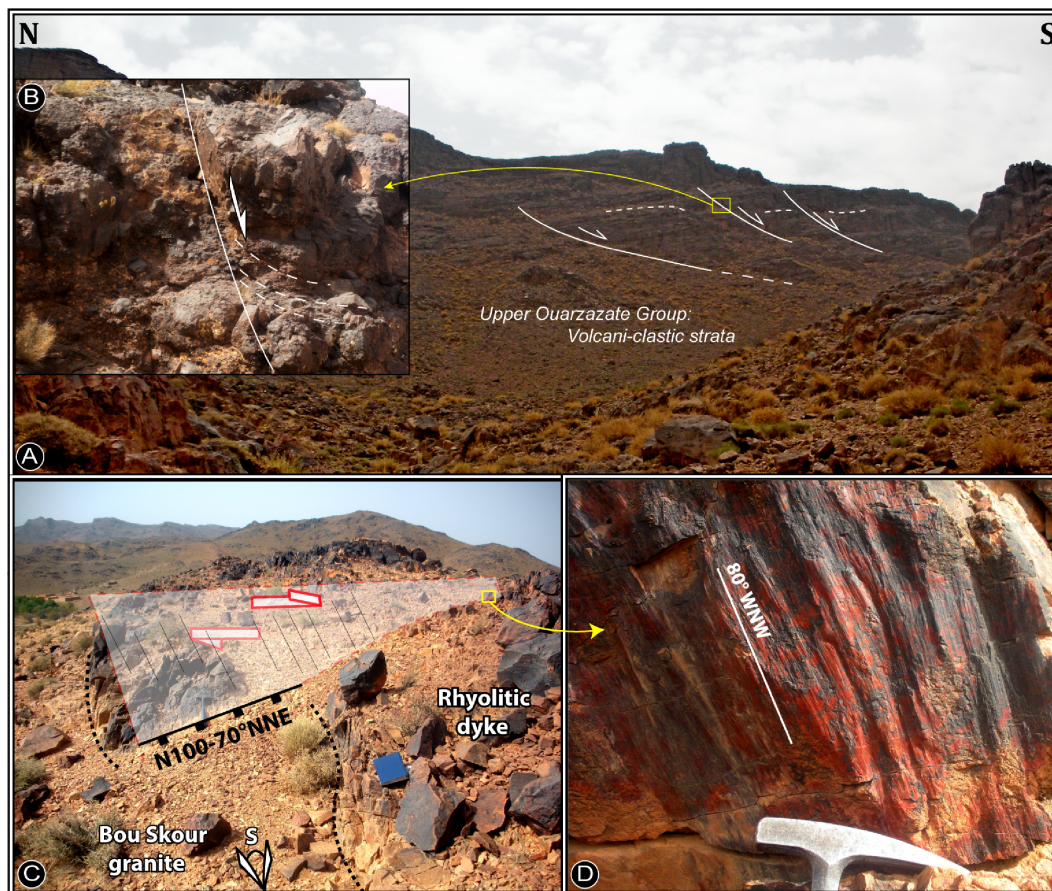


Figure 8. (A, B) Tilted blocks in the volcano-sedimentary strata of the Late Ediacaran upper Ouarzazate Group controlled by numerous NE- to ENE strike-slip normal faults (see Figure 4A for location). Rhyolitic dyke dissected by N100-70°NNW normal sinistral faults (C) associated with steeply dipping slickensides (D).

deformation, contemporaneously or immediately after the emplacement of the 570 ± 5 Ma Bou Skour granite.

Nevertheless, numerous lines of evidence provided in the present research are inconsistent with several pre-existing studies: (i) there is no evidence indicating the sinistral displacement of rhyolitic dykes along the FP, described by El Ouardi *et al.* [2016]; contrarily, the shift is clearly controlled by a dextral reactivation (Figures 5G–H and 9A); (ii) Start-syne *et al.* [1975], Harfin [1984], Maacha *et al.* [2011], El Azmi *et al.* [2014] and El Ouardi *et al.* [2016] place the Bou Skour ore emplacement after the latest Pan-African events, likely during the Variscan or Alpine cycles. Our conclusions are not in agreement with

such proposals, given that the southernmost segment of the veins system (574.9 ± 2.4 Ma; Bouabdelah *et al.*, 2016), is obviously buried under the upper Ouarzazate Group volcano-sedimentary rocks and related rhyolitic flows dated at 558 ± 4 [Walsh *et al.*, 2012] (Figures 4A and 6A).

Elsewhere in the Saghro massif, some polymetallic vein-type deposits may have been controlled by the same tectonic event as the Bou Skour deposit. In the Au–Ag Bou Isserfan deposit located in the northern part of the central Saghro massif (Figure 11B), NNW-polymetallic shear structures hosted within the lower Ouarzazate Group are interpreted as contemporaneous with those of the Bou Skour deposit [Tuduri *et al.*, 2018].

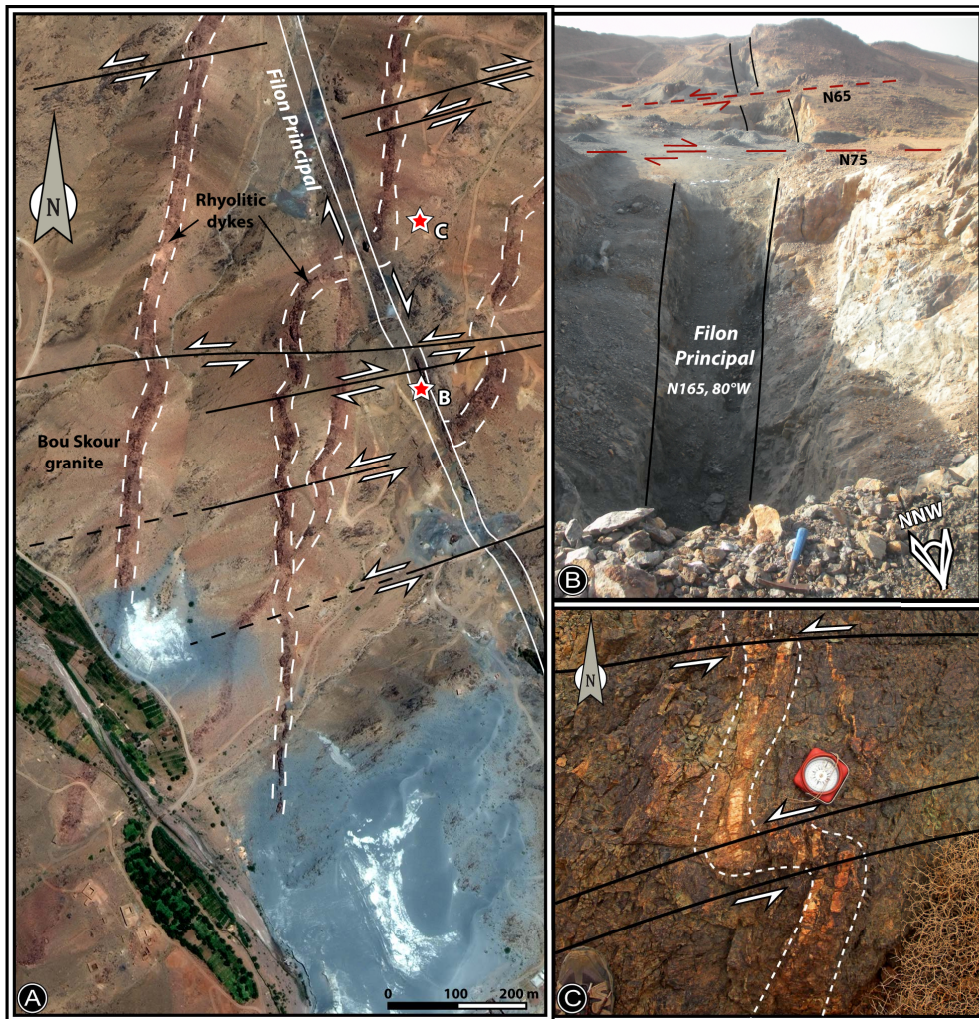


Figure 9. Outcrop and satellite views illustrate a set of en-echelon ENE- to NE faults that disrupt the rhyolitic dykes (A) and FP (B) as well as the associated minor structures (C), showing a dominant normal sinistral movement. The location of (A), which includes that of (B) and (C) is shown in Figure 4A.

6.2. Post Pan-African tectonic evolution of the Bou Skour deposit

From Late Ediacaran to Cambrian times, the Bou Skour area underwent a succession of transtensional and extensional tectonic events. During this period, numerous NE-trending normal faults and ENE-trending sinistral faults were responsible for the collapse and offset of the ore bodies with development of tilted blocks within the volcano-

sedimentary strata of the upper Ouarzazate Group. The reconstruction of paleo-stress computed from our field measurements of these structures gives a NE–SW to ENE–WSW and NW–SE opening regimes that respectively coincide with the Late Ediacaran transtensional tectonic event and the Cambrian rifting (Figures 12A and B), well-described in the eastern Anti-Atlas [Baidder et al., 2008, 2016, Errami and Olivier, 2012, Pouclet et al., 2018, Raddi et al., 2007, Soulaïmani et al., 2014].

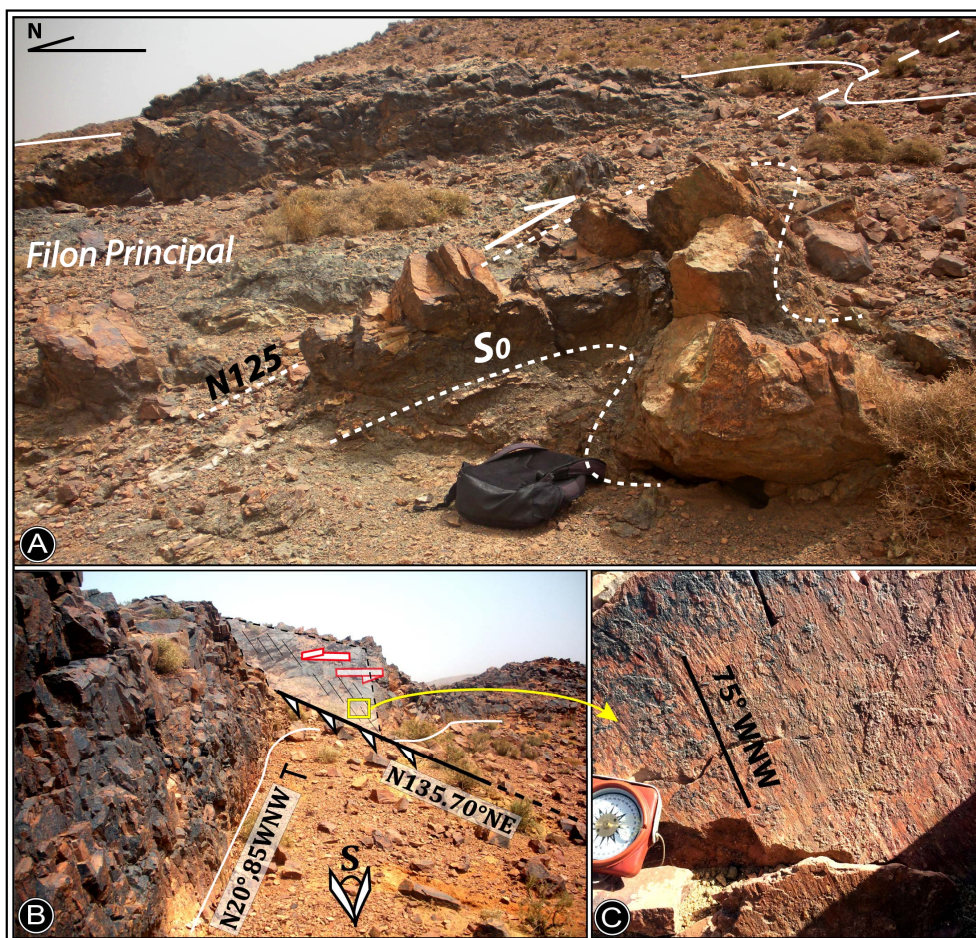


Figure 10. (A) N125-trending fault and associated fold deforming both the FP-mineralized body and the hosting andesitic rocks (see the location of A in Figure 4A). (B) Reverse dextral displacement of a rhyolitic dyke along N135-70°NE fault bearing dip striations in the fault plane (C).

Similar tectonic patterns were recently observed in the Ediacaran–Cambrian contact zone located in northeastern [Hejja *et al.*, 2020] and southwestern Saghro massif [Aabi *et al.*, 2020].

Much later, during the Variscan orogeny or the Atlasic compression, numerous pre-existing basement extensional faults experienced moderate tectonic inversion. This corresponds to NW–SE reverse dextral faults and associated folds deforming and crosscutting the mineralized veins, the hosted Precambrian rocks, and the extensional structures. This set appears to be conjugated with other NE–SW inverted sinistral faults, pointing to a N–S direction of compression (Figures 12C and D). The same stress field

was previously described in the southern Saghro massif and linked to the Variscan shortening [Walsh *et al.*, 2012].

7. Conclusions

The present work clarifies the complex structural configuration of the Precambrian hosted Bou Skour deposit and the understanding of the tectonic control of its polymetallic Cu–Pb–Zn vein system. Based on extensive structural field data coupled with the existing geological data, the following conclusions are reached:

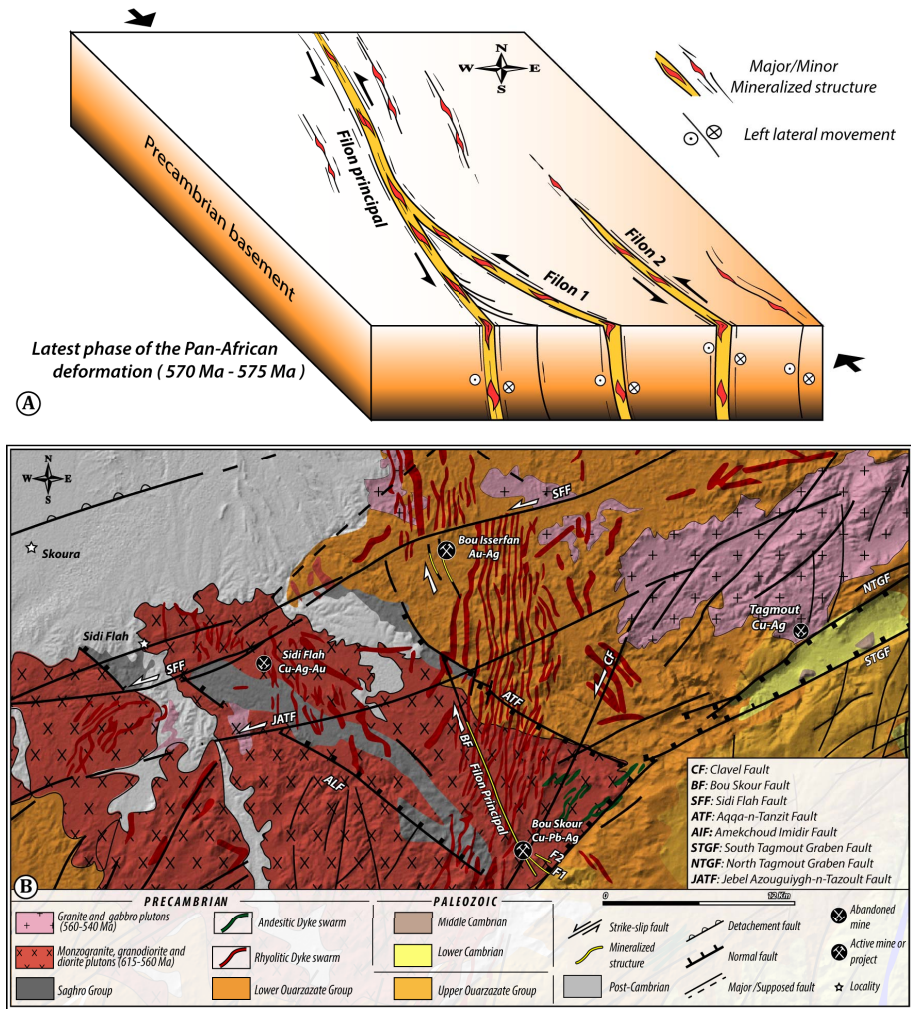


Figure 11. (A) Block diagram showing the NW-SE tectonic control of the main polymetallic vein system of the Bou Skour deposit during the last phase of the Pan-African orogeny. (B) Geological map of the northern central Saghro massif, illustrating the correlation between the reactivated Bou Skour and Bou Isserfan NNW-mineralized structures (interpreted from Tuduri et al. [2018], and Aabi et al. [2020]). See Figure 1C for (B) location.

- (1) An updated structural map has been established, which allows us to define at least three main systems of faults trending NNW-SSE to WNW-ESE, N-S to NNE-SSE, and NE-SW to ENE-WSW.
- (2) The mineralization of the Bou Skour deposit is predominantly of the vein type, and the most important structures (e.g., FP, F1, F2) are hosted within the NNW-to NW fault system.
- (3) The corresponding vein system, which was recently dated at 574.9 ± 2.4 Ma [Bouabdellah et al., 2016], is mainly hosted within mafic to felsic rocks of the Ediacaran Saghro and lower Ouarzazate Groups together with Pan-African plutons.
- (4) The major mineralized structures correspond to en-echelon tension gashes occasionally associated with horsetail satellite structures implying sinistral movement.

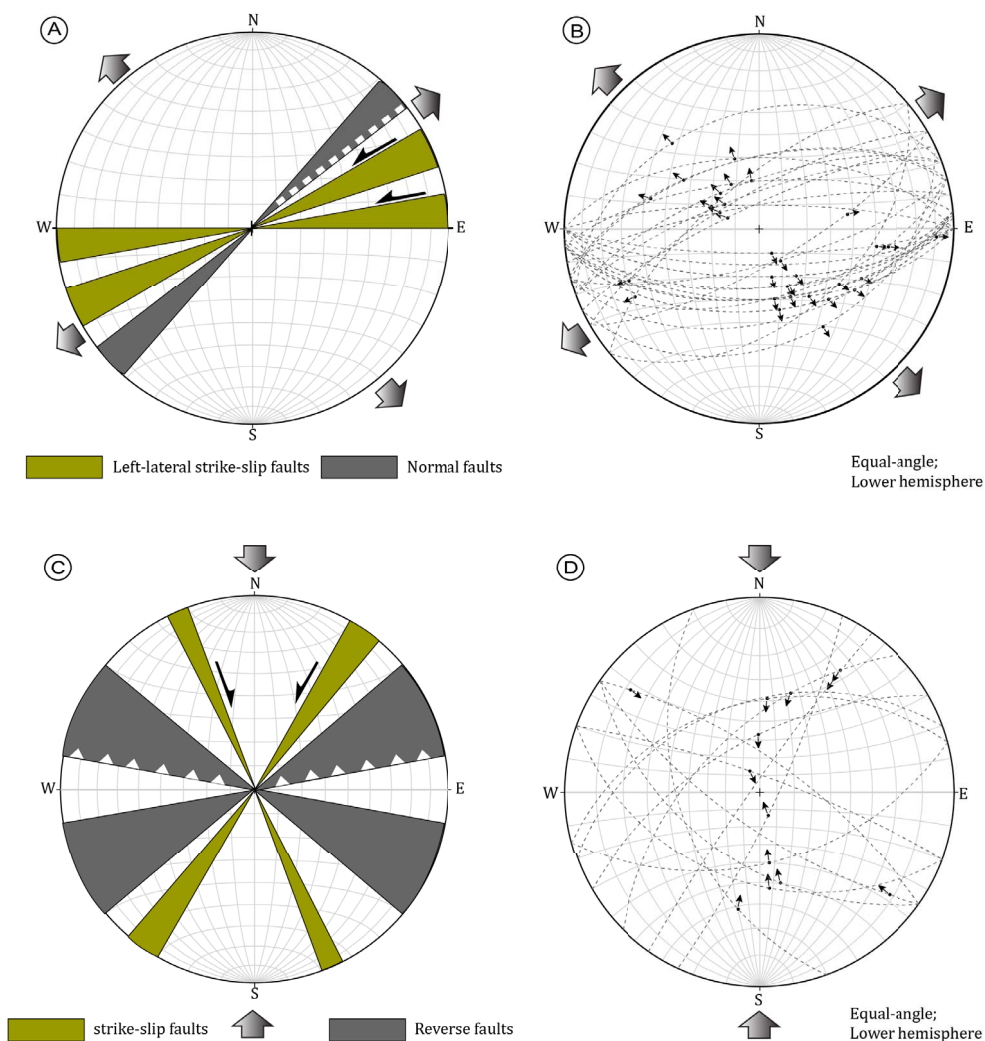


Figure 12. Bidirectional stress field (A) and stereograph (B) of extensional/strike-slip faults with its associated slickensides during the NE- to ENE- Late Ediacaran transtensional event and the NW-SE Cambrian rifting. Stress field (C) and stereograph (D) of compressional faults and its associated slickensides during the N-S Variscan or Atlasic shortening.

- (5) The age and tectonic patterns are consistent with the NW-SE shortening that occurred during the last stage of the Pan-African orogeny (Cadomian phase) rather than during post Pan-African events as suggested previously.
- (6) Subsequent extensional block tilting and reverse strike-slip faults oriented NE to ENE and NW-SE disrupt the FP, F1, and F2, most likely in response to the Ediacaran-

Cambrian extension and the Variscan or Atlasic shortening, respectively.

Acknowledgments

The authors would like to thank the MANAGING group for logistical support during the field survey. They would also gratefully thank Editors in chief for their pertinent comments and Professor André Michard (Paris-Sud University) for his fruitful and

constructive reviews which helped to improve this study.

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