INSTITUT DE FRANCE
Académie des sciences

Comptes Rendus

Géoscience

Sciences de la Planète

Ayoub Aabi, Lahssen Baidder, Younes Hejja, Mohammed El Azmi, Abdellah Nait Bba and Khadija Otmane

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

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

Published online: 4 May 2021

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

Les Comptes Rendus. Géoscience — Sciences de la Planète *sont membres du Centre Mersenne pour l'édition scientifique ouverte*
www.centre-mersenne.org
e-ISSN : 1778-7025

Comptes Rendus
Géoscience — Sciences de la Planète
2021, 353, nº 1, p. 81-99
https://doi.org/10.5802/crgeos.54

Original Article — Tectonics, Tectonophysics

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

Ayoub Aabi[*, a], **Lahssen Baidder**[a], **Younes Hejja**[a], **Mohammed El Azmi**[b], **Abdellah Nait Bba**[a] and **Khadija Otmane**[a]

[a] Department of Geology, Faculty of Sciences Ain Chock, Hassan II University, Casablanca, Morocco

[b] Managem, Twin Center, Tour A, angle Bd Zerktouni-Abdelkarim Khattabi, Casablanca, Morocco

E-mails: aabi.ayoub@gmail.com (A. Aabi), lbaidder@gmail.com (L. Baidder), youneshejja@gmail.com (Y. Hejja), m.elazmi@managemgroup.com (M. El Azmi), abdellahnaitbba@gmail.com (A. Nait Bba), otmanekhadija@gmail.com (K. Otmane)

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.

* Corresponding author.

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'Issougri" 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 metallogenical 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 metallogenical, 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, Soulaimani 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 [Ikenne et al., 2017, Soulaimani 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

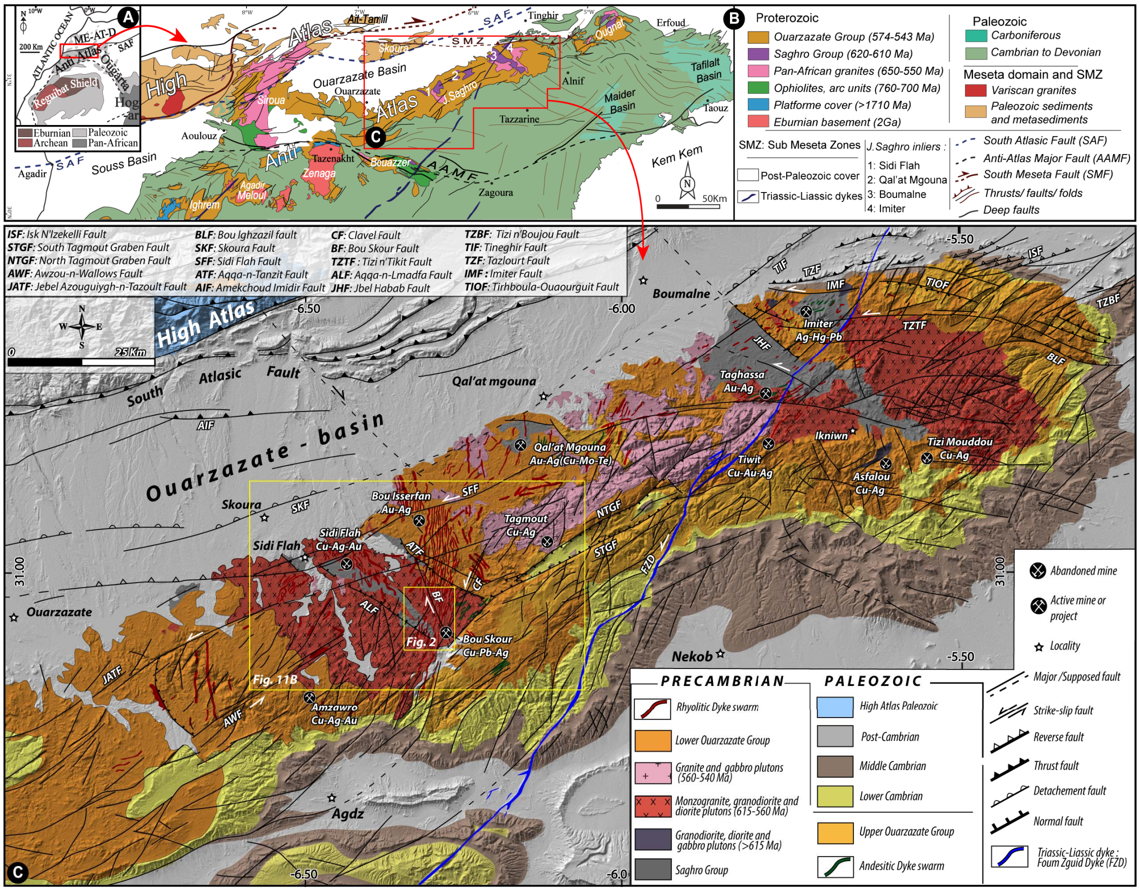

Figure 1. (A) Location of the Anti-Atlas belt on the northern edge of the WAC. Dashed black line: Variscan deformation front. ME-AT-D: Meseta-Atlas-Domain. WAC: West African Craton [Michard et al., 2008]. (B) Geological map of the central, eastern Anti-Atlas belt and adjacent Meseta-Atlas domain. Folds 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 [Saquaque et al., 1992] during the last stages of the Pan-African orogeny [Michard et al., 2017, Soulaimani 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 [Baidder 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 Foum 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, Soulaimani 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

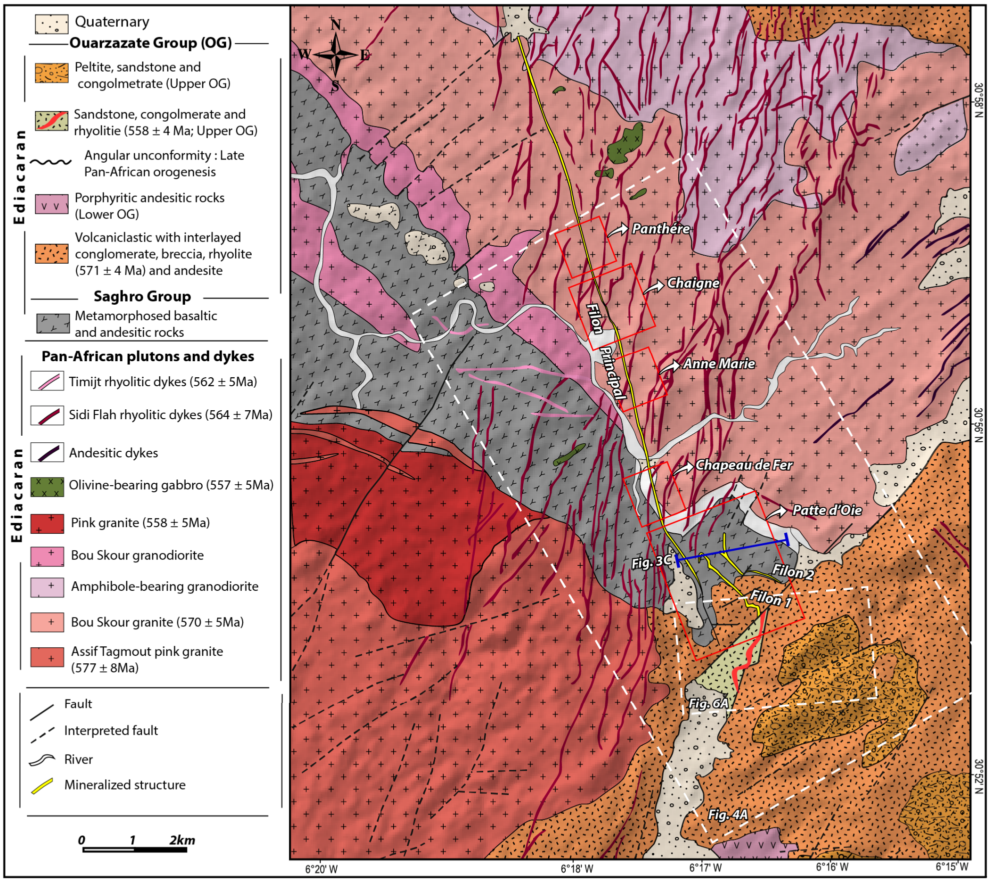

Figure 2. Geological map of the Bou Skour polymetallic deposit (simplified after Walsh et al., 2008a). See Figure 1C for location.

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

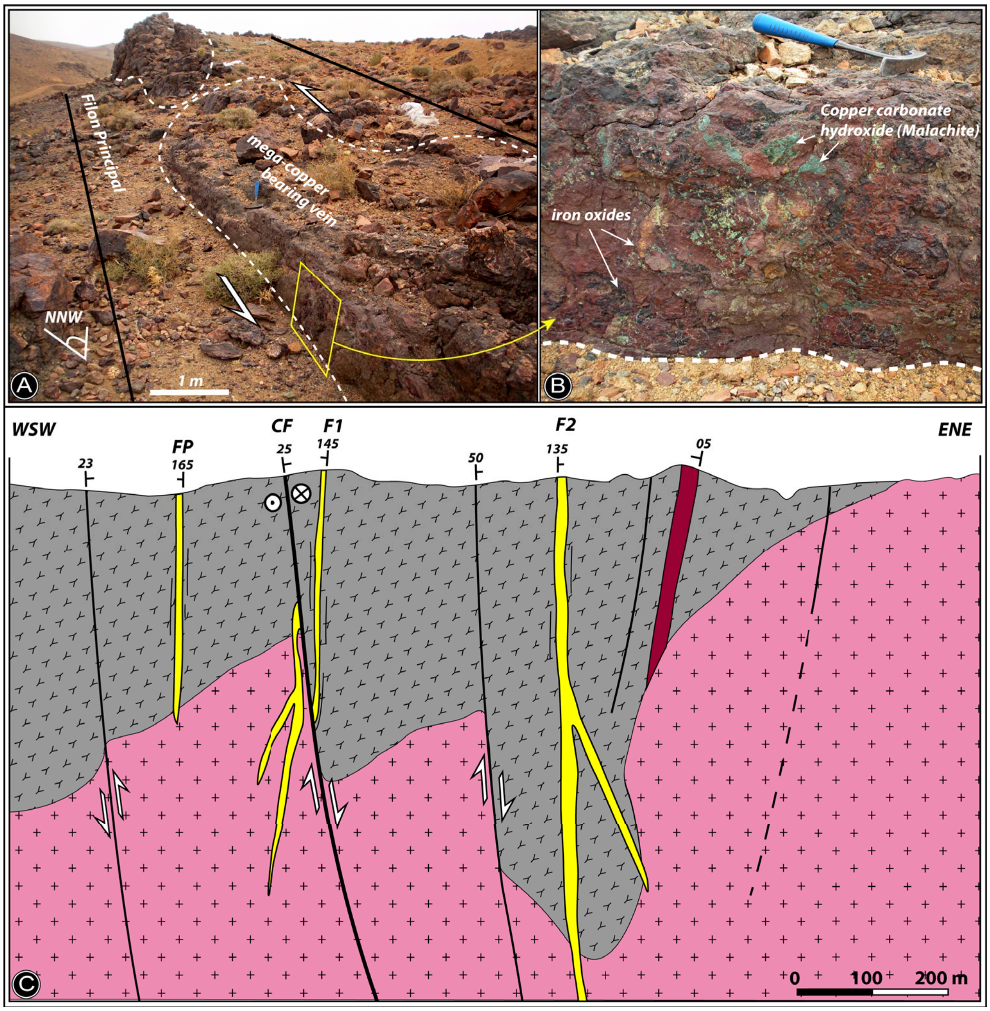

Figure 3. Field pictures of a mega-copper bearing veins associated with the FP structure (A) and showing tracks of malachite and many iron oxide minerals (B). (C) Transversal cross-section through the major mineralized structures of the Patte d'Oie district interpreted from two cored drilling (Managem 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 constitutes 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-

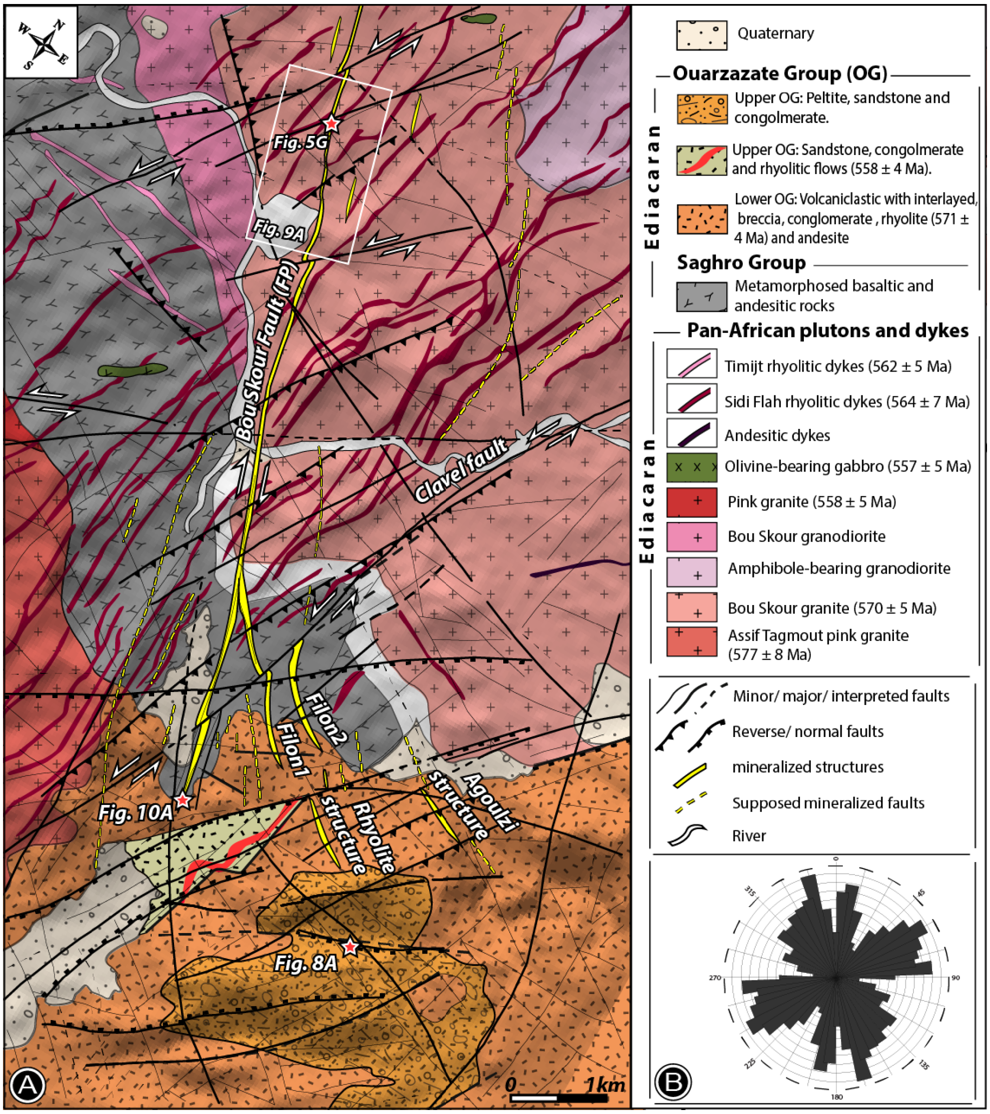

Figure 4. (A) Structural map of the Bou Skour polymetallic deposit. See Figure 2 for location. FP: Filon Principal. (B) Rose diagram of faults crosscutting the Bou Skour district.

nomically less important and can be seen south of the deposit hosted within the rhyolitic complex of the lower Ouarzazate 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 kilometric extension (Figure 4B).

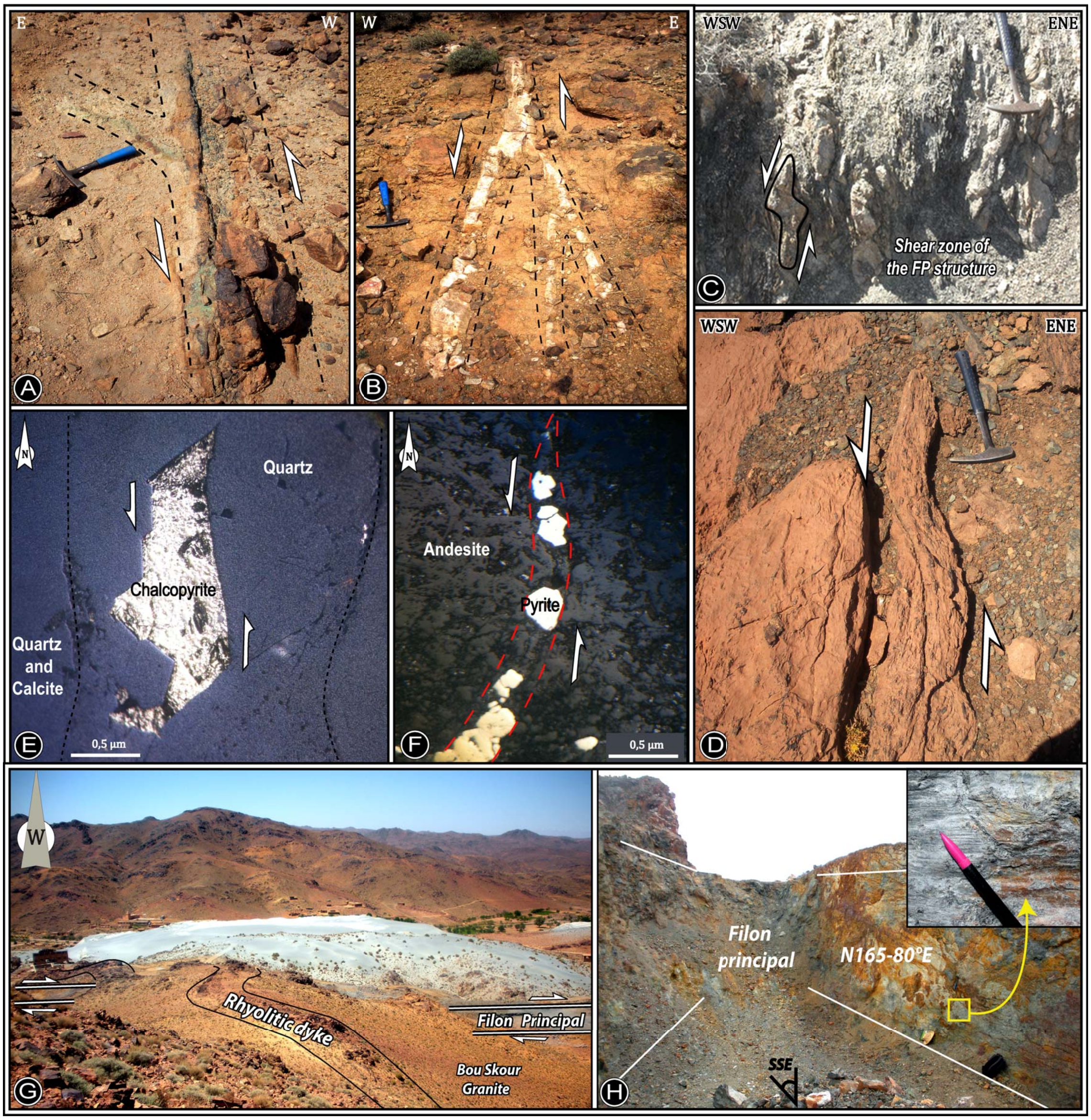

Figure 5. Copper-(A) and quartz-(B) bearing structures exhibit geometry of sinistral horsetail splay. Hydrothermal tension-gashes associated with sinistral shearing observed within FP (C) and F1 (D) structures. Photomicrographs of micro-veins filled by chalcopyrite (E) and pyrite (F) recording sinistral 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 Panthére 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 kilometric 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 kilometric 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 volcaniclastic 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, Soulaimani 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

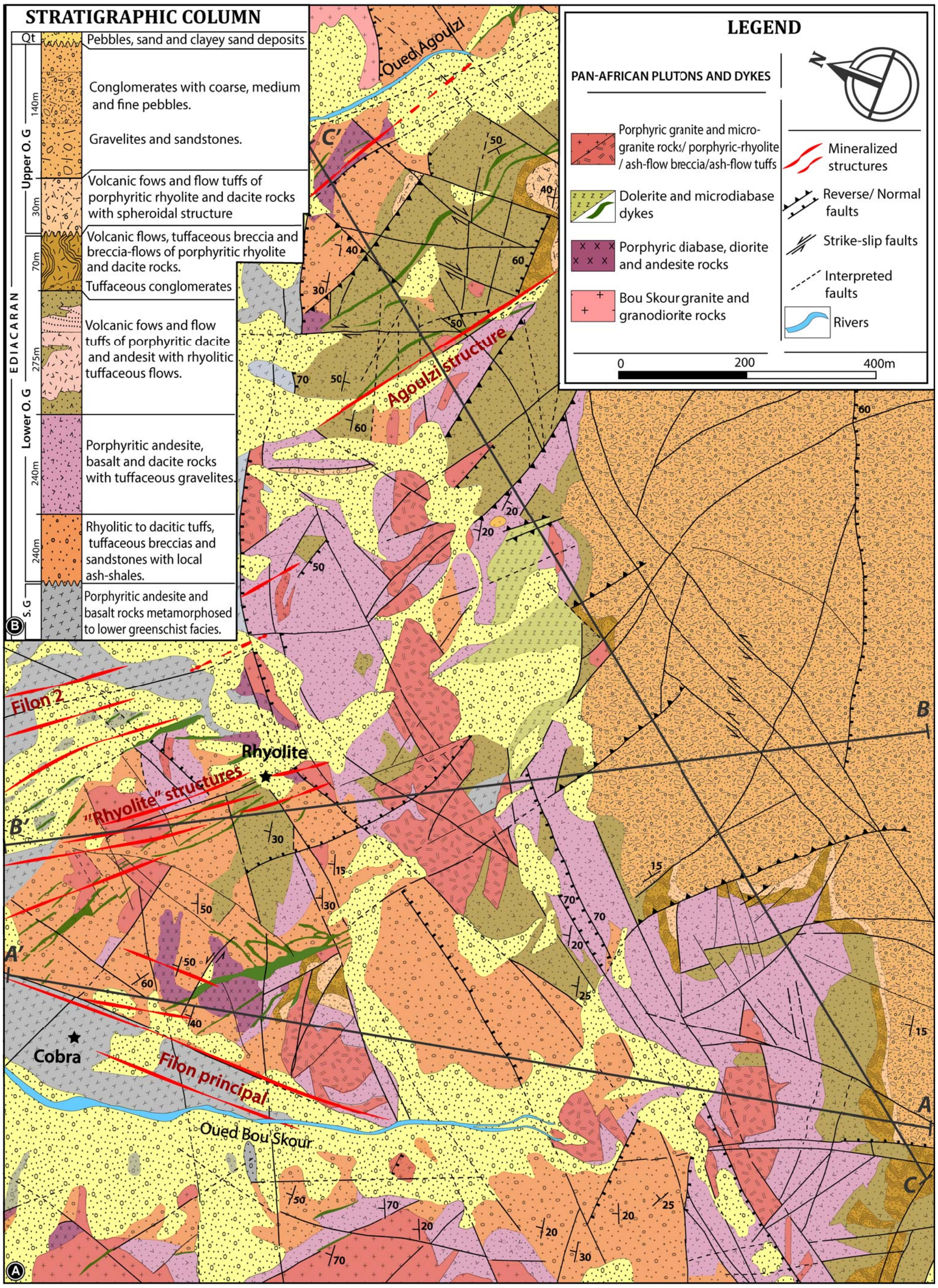

Figure 6. Detailed Geological map (A) and stratigraphic column (B) of the Patte d'Oie mining district of the Bou Skour polymetallic deposit (Startsyne et al., 1975, modified). SG: Saghro Group; OG: Ouarzazate Group; Qt: Quaternary terrains; see Figure 2 for the location of (A).

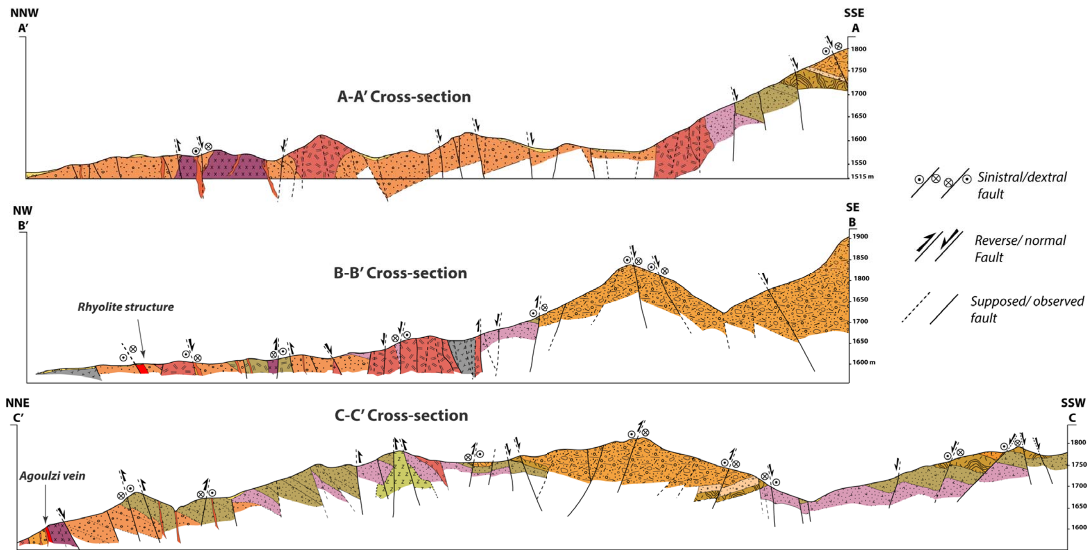

Figure 7. Detailed geological cross-sections illustrating the fault kinematics across the Precambrian outcrops of the Bou Skour area (Startsyne et al., 1975, modified). See Figures 6A and B for location and stratigraphic signatures.

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 kilometric 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; Soulaimani 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

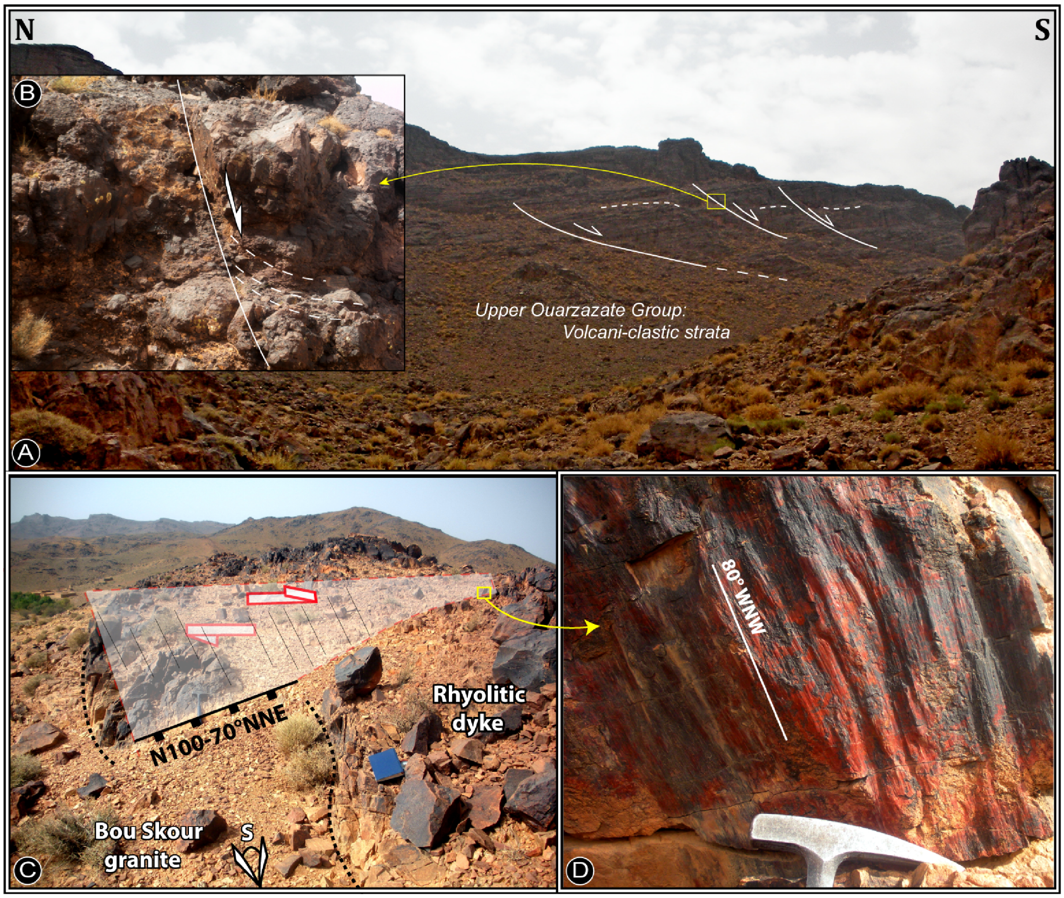

Figure 8. (A, B) Tilted blocks in the volcano-sedimentary strata of the Late Ediacaran upper Ouarzazate Group controlled by numerous NE- to ENE strike-slip normal faults (see Figure 4A for location). Rhyolitic dyke dissected by N100-70°NNW normal sinistral faults (C) associated with steeply dipping slickensides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

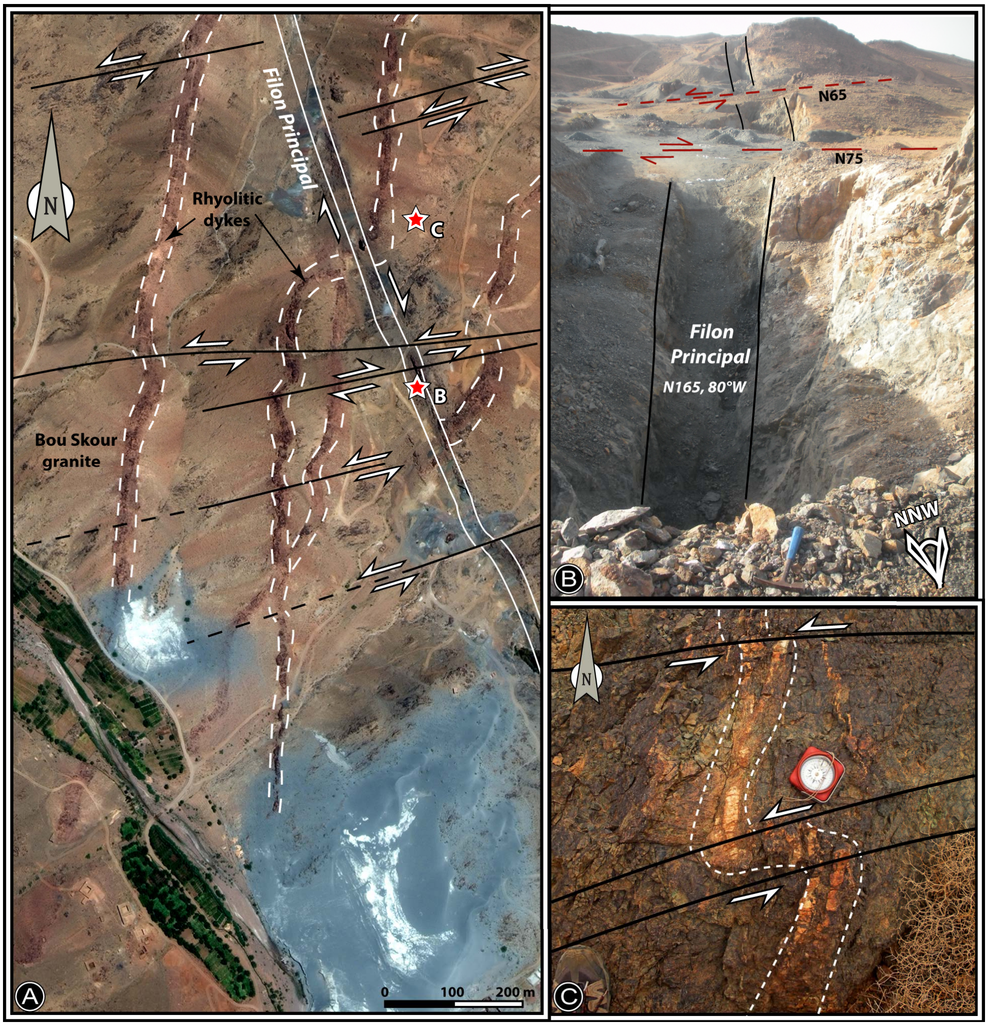

Figure 9. Outcrop and satellite views illustrate a set of en-echelon ENE- to NE faults that disrupt the rhyolitic dykes (A) and FP (B) as well as the associated minor structures (C), showing a dominant normal sinistral movement. The location of (A), which includes that of (B) and (C) is shown in Figure 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, Soulaimani et al., 2014].

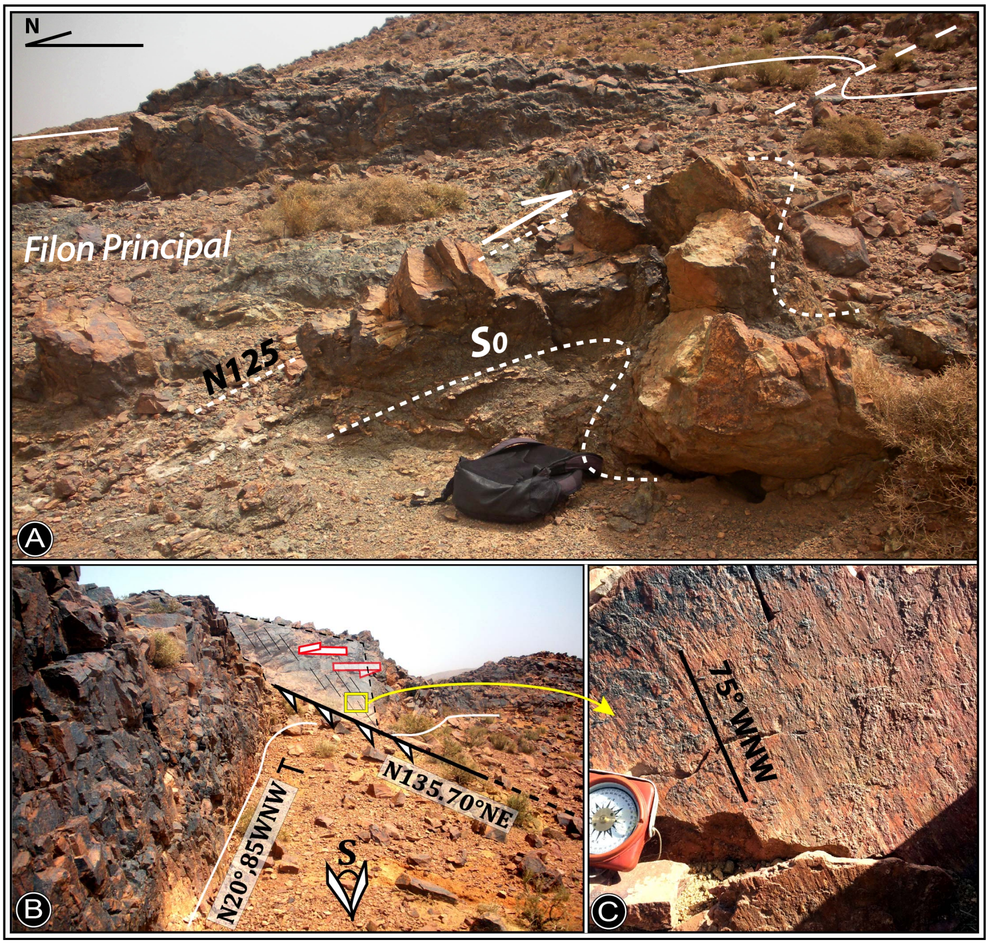

Figure 10. (A) N125-trending fault and associated fold deforming both the FP-mineralized body and the hosting andesitic rocks (see the location of A in Figure 4A). (B) Reverse dextral displacement of a rhyolitic dyke along N135-70°NE fault bearing dip striations in the fault plane (C).

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:

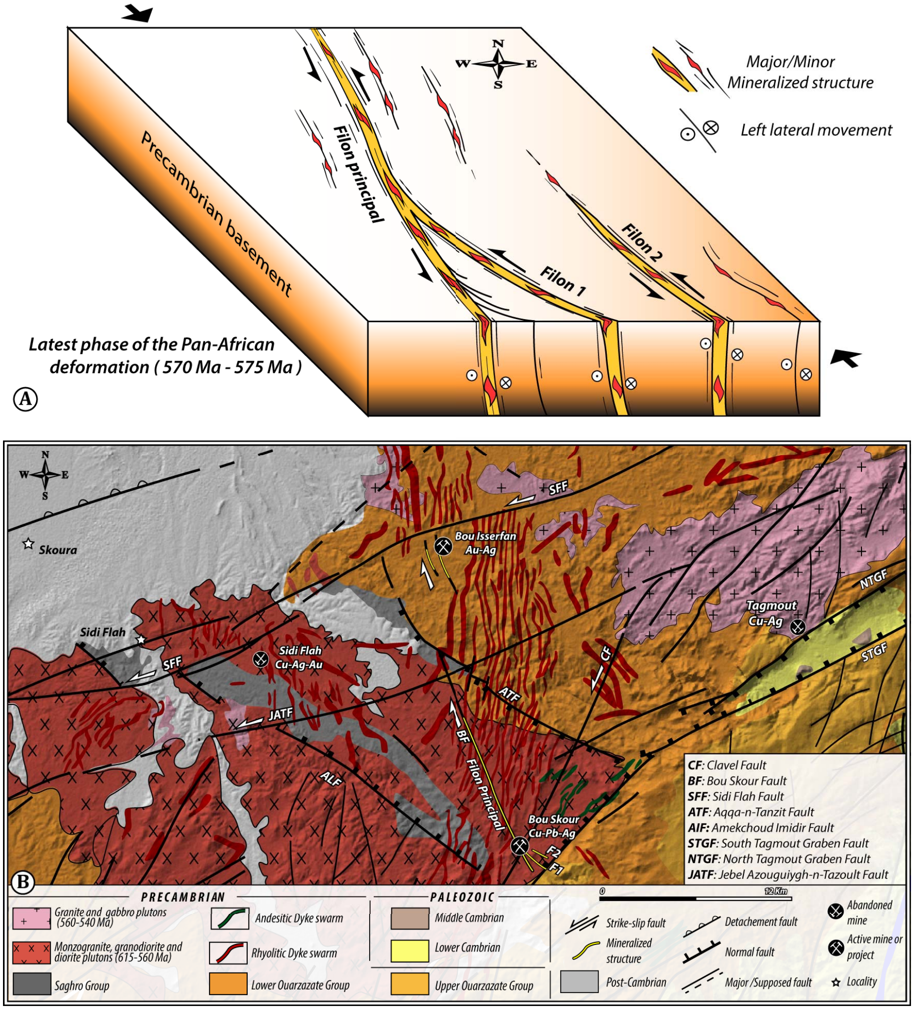

Figure 11. (A) Block diagram showing the NW–SE tectonic control of the main polymetallic vein system of the Bou Skour deposit during the last phase of the Pan-African orogeny. (B) Geological map of the northern central Saghro massif, illustrating the correlation between the reactivated Bou Skour and 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.

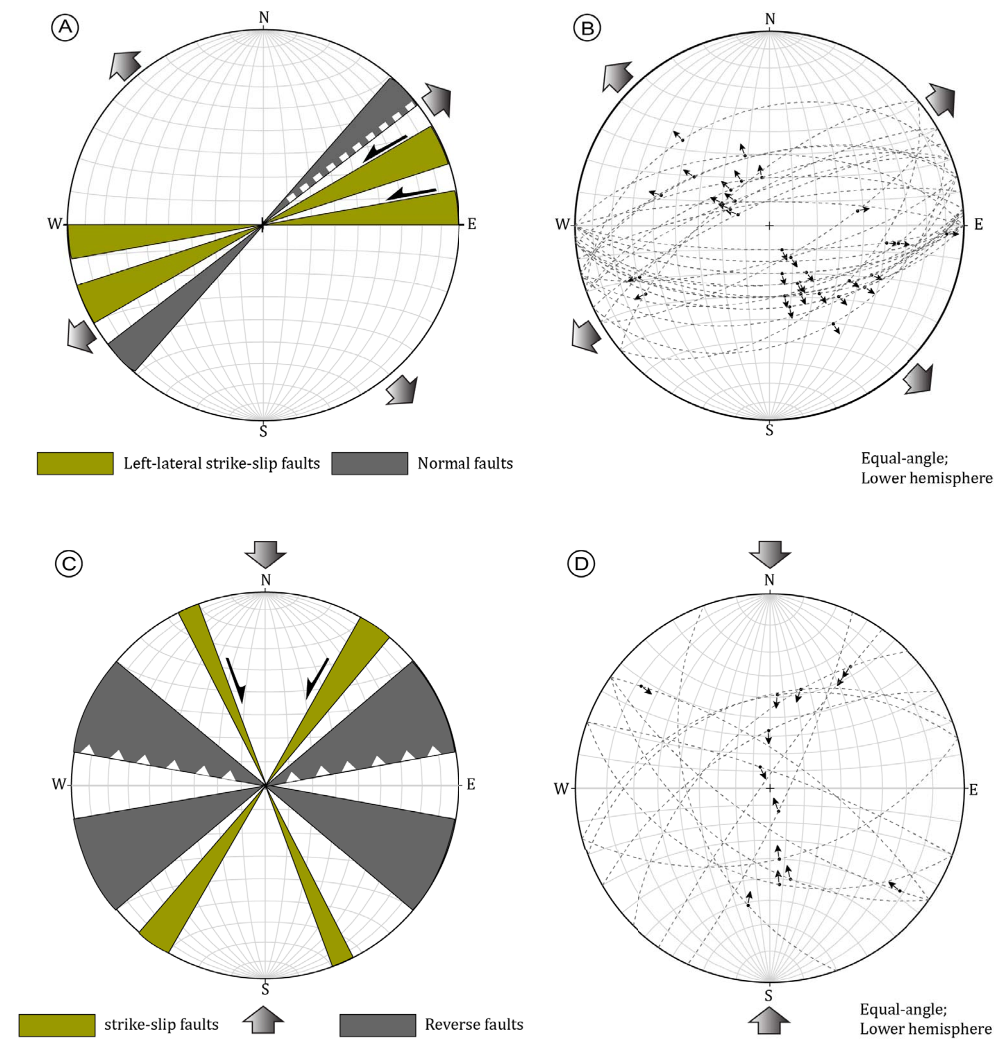

Figure 12. Bidirectional stress field (A) and stereograph (B) of extensional/strike-slip faults with its associated slickensides during the NE- to ENE- Late Ediacaran transtensional event and the NW–SE Cambrian rifting. Stress field (C) and stereograph (D) of compressional faults and its associated slickensides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

References

Aabi, A., Hejja, Y., Nait Bba, A., Baidder, L., Bannari, A., Boujamaoui, M., Hamzaoui, A., El Azmi, M., Zouhair, M., and Maacha, L. (2020). Surface and subsurface structural modeling in a superposed tectonic context: An integrated approach using remote sensing, aeromagnetic and structural field data from the south-western Saghro massif (Eastern Anti-Atlas, Morocco). *J. Afr. Earth Sci.* (submitted).

Abati, J., Aghzer, A. M., Gerdes, A., and Ennih, N. (2010). Detrital zircon ages of Neoproterozoic sequences of the Anti-Atlas belt. *Precambr. Res.*, 181, 115–128.

Baidder, L., Michard, A., Soulaimani, A., Fekkak, A., Eddebbi, A., Rjimati, E. C., and Raddi, Y. (2016). Fold interference pattern in thick-skinned tectonics; a case study from the external Variscan belt of eastern Anti-Atlas, Morocco. *J. Afr. Earth Sci.*, 119, 204–225.

Baidder, L., Raddi, Y., Tahiri, M., and Michard, A. (2008). Devonian extension of the Pan-African crust north of the West African Craton and its bearing on the Variscan foreland deformation: evidence from eastern Anti-Atlas (Morocco). In Ennih, N. and Liégeois, J. P., editors, *The Boundaries of the West African Craton*, volume 927, pages 453–465. Geol. Soc. London, Spec. Publ.

Blein, O., Baudin, T., Chèvremont, Ph., Soulaimani, A., Admou, H., Gasquet, D., Cocherie, A., Egal, E., Youbi, N., Razin, Ph., Bouabdelli, M., and Gombert, Ph. (2014a). Geochronological constraints on the polycyclic magmatism in the Bou Azzer-El Graara inlier (Anti-Atlas, Morocco). *J. Afr. Earth Sci.*, 99, 287–306.

Blein, O., Baudin, T., Soulaimani, A., Cocherie, A., Chèvremont, P., Admou, H., Ouanaimi, H., Hafid, A., Razin, P., Bouabdelli, M., and Roger, J. (2014b). New geochemical, geochronological and structural constraints on the Ediacaran evolution of the south Sirwa, Agadir Melloul and Iguerda inliers, Anti-Atlas, Morocco. *J. Afr. Earth Sci.*, 98, 47–71.

Bouabdellah, M., Maacha, L., Jébrak, M., and Zouhair, M. (2016). 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. In Bouabdellah, M. and Slack, J. F., editors, *Mineral Deposits of North Africa*, pages 277–290. Springer International Publishing, Cham, Switzerland.

Burkhard, M., Caritg, S., Helg, U., Robert-Charrue, C., and Soulaimani, A. (2006). Tectonics of the Anti-Atlas of Morocco. *C. R. Geosci.*, 338, 11–24.

Cerrina Feroni, A., Ellero, A., Malusa, M. G., Musumecci, G., Ottria, G., Polino, R., and Leoni, L. (2009). Transpressional tectonics and nappe stacking along the southern Variscan front of Morocco. *Int. J. Earth Sci.*, 99, 1111–1122.

Clavel, M. and Tixeront, M. (1971). Une gîte de cuivre filonien, hydrothermal intraplutonique: Bou Skour (Anti-Atlas, Maroc). *Notes et Mem. Serv. Geol. Maroc*, 237, 203–228.

El Azmi, D., Aissa, M., Ouguir, H., Mahdoudi, M. L., El Azmi, M., Ouadjo, A., and Zouhair, M. (2014). Magmatic context of Bou Skour copper deposit (eastern Anti-Atlas, Morocco): petrogrography, geochemistry and alterations. *J. Afr. Earth Sci.*, 97, 40–55.

El Bahat, A., Ikenne, M., Soderlund, U., Cousens, B., Youbi, N., Ernst, R., Soulaimani, A., ElJanati, M., and Hafid, A. (2013). U-Pb baddeleyite ages and geochemistry of dolerite dykes in the Bas Draa inlier of the anti-atlas of Morocco: newly identified 1380 Ma event in the west African craton. *Lithos*, 174, 85–95.

El Hadi, H., Simancas, J. F., Martìnez-Poyatos, D., Azor, A., Tahiri, A., Montero, P., Fanning, C. M., Bea, F., and Gonzàlez-Lodeiro, F. (2010). Structural and geochronological constraints on the evolution of the Bou Azzer Neoproterozoic ophiolite (Anti-Atlas, Morocco). *Precambr. Res.*, 182, 1–14.

El Ouardi, H., Karaoui, B., Mahmoudi, A., El Azmi, M., and Zouhair, M. (2016). Microtectonic analysis of the copper-bearing deposits of Bouskour mining district at Saghro inlier (Anti Atlas, Morocco). *GeoTemas*, 16(1), 113–116.

Errami, E., Bonin, B., Laduron, D., and Lasri, L. (2009). Petrology and geodynamic significance of the post-collisional Pan-African magmatism in the eastern Saghro area (Anti-Atlas, Morocco). *J. Afr. Earth Sci.*, 55, 105–124.

Errami, E. and Olivier, P. (2012). The Iknioun granodiorite, tectonic marker of Ediacaran SE directed tangential movements in the eastern Anti-Atlas, Morocco. *J. Afr. Earth Sci.*, 69, 1–12.

Fekkak, A. (2000). *Les Groupes du Néoprotérozoïque inférieur de Sidi Flah, Kelaat Mgouna et Tiboulkhirine (Saghro, Anti-Atlas, Maroc): témoins d'un rift intracontinental pré-panafricain.* PhD thesis, Moulay Ismail University, Meknès, Morocco. 265 p (unpublished).

Fekkak, A., Pouclet, A., and Benharref, M. (2003). The middle Neoproterozoic Sidi Flah Group (Anti-Atlas, Morocco): Synrift deposition in a Pan-African continent/ocean transition zone. *J. Afr. Earth Sci.*, 37, 73–87.

Frizon de Lamotte, D., Leturmy, P., Missenard, Y., Khomsi, S., Ruiz, G., Saddiqi, O., Guillocheau, F., and Michard, A. (2009). Mesozoic and Cenozoic vertical movements in the Atlas system (Algeria, Morocco, Tunisia): an overview. *Tectonophysics*, 475, 9–28.

Gasquet, D., Ennih, N., Liégeois, J. P., Soulaimani, A., and Michard, A. (2008). The Pan African belt. In *Continental Evolution: The Geology of Morocco*, volume 116 of *Lecture Notes in Earth Sciences*, pages 33–64. Springer-Verlag Publishing, Berlin.

Gasquet, D., Levresse, G., Cheilletz, A., Azizi-Samir, M. R., and Mouttaqi, A. (2005). Contribution to a geodynamic reconstruction of the Anti-Atlas (Morocco) during PanAfrican times with the emphasis on inversion tectonics and metallogenic activity at the Precambrian-Cambrian transition. *Precambr. Res.*, 140, 157–182.

Gouiza, M., Charton, R., Bertotti, G., Andriessen, P., and Storms, J. E. A. (2016). Post-Variscan evolution of the Anti-Atlas belt of Morocco constrained from low-temperature geochronology. *J. Earth Sci.*, 106, 593–616.

Harfin, M. (1984). Synthèse géologique préliminaire de Bou Skour, ONA, SMBS. 32 p.

Hejja, Y., Baidder, L., Ibouh, H., Nait Bba, A., Soulaimani, A., Gaouzi, A., and Maacha, L. (2020). Fractures distribution and basement-cover interaction in a polytectonic domain: A case study from the Saghro Massif (Eastern Anti-Atlas, Morocco). *J. Afr. Earth Sci.*, 162, article no. 103694.

Hindermeyer, J., Gauthier, H., Destombes, J., Choubert, G., Faure-Muret, A., Laville, E., Lesage, J. L., and Du Dresnay, R. (1977). Carte géologique au 1/200 000, Jebel Saghro Dadès (Haut Atlas central, sillon Sud-Atlasique et Anti-Atlas oriental). *Notes et Mem. Serv. Geol. Maroc*, 161.

Ikenne, M., Soderlund, U., Ernst, R., Pin, C., Youbi, N., and El Aouli, E. H. (2017). A c. 1710 Ma mafic sill emplaced into a quartzite and calcareous series from Igherm, Anti-Atlas, Morocco: evidence that the Taghdout passive margin sedimentary Group is nearly 1 Ga older than previously thought. *J. Afr. Earth Sci.*, 127, 113–135.

Inglis, J. D., D'Lemos, R. S., Samson, S. D., and Admou, H. (2005). Geochronological constraints on Late Precambrian intrusion, metamorphism, and tectonism in the Anti-Atlas Mountains. *J. Geol.*, 113, 439–450.

Karaoui, A., Breitkreuz, C., Karaoui, B., Yajioui, Z., Mahmoudi, A., Zanetti, A., and Langone, A. (2021). The Ediacaran volcano-sedimentary succession in the western Skoura inlier (Central High Atlas, Morocco): facies analysis, geochemistry, geochronology and geodynamic implications. *Int. J. Earth Sci. (Geol. Rundsch)*, 110. https://doi.org/10.1007/s00531-021-01997-y.

Maacha, L., Ouadjou, A., El Azmi, M., Zouhair, M., Saquaque, A., Alansari, A., and Soulaimani, A. (2011). Bouskour copper and silver mine (J Saghro inlier, eastern Anti-Atlas). *Notes et Mem. Serv. Geol. Maroc*, 564, 59–64.

Malusa, M. G., Polino, R., Feroni, A. C., Ellero, A., Ottria, G., Baidder, L., and Musumeci, G. (2007). Post-Variscan tectonics in eastern anti-atlas (Morocco). *Terra Nova*, 19, 481–489.

Marcoux, E. and Jébrak, M. (2012). Le projet à cuivre de Bou Skour. Unpublished Confidential Report, ManagemGroup, 105 p.

Michard, A., Hoepffner, C., Soulaimani, A., and Baidder, L. (2008). The Variscan belt. In Michard, A., Saddiqi, O., Chalouan, A., and Frizon de Lamotte, D., editors, *Continental Evolution: the Geology of Morocco*, volume 116 of *Lecture Notes in Earth Sciences*, pages 65–131.

Michard, A., Soulaimani, A., Hoepffner, H., Ouanaimi, H., Baidder, L., Rjimati, E. C., and Saddiqi, O. (2010). The South-western branch of the Variscan belt: evidence from Morocco. *Tectonophysics*, 492, 1–24.

Michard, A., Soulaimani, A., Ouanaimi, H., Raddi, Y., Aït Brahim, L., Rjimati, E.-C., Baidder, L., and Saddiqi, O. (2017). Saghro Group in the Ougnat Massif (Morocco), an evidencefor a continuous Cadomian basin along the northern West African Craton. *C. R. Geosci.*, 349, 81–90.

Oukassou, M., Saddiqi, O., Barbarand, J., Sebti, S., Baidder, L., and Michard, A. (2013). Post-Variscan exhumation of the Central Anti-Atlas (Morocco) constrained by zircon and apatite fission-track thermochronology. *Terra Nova*, 25, 151–159.

Pastor, A., Teixell, A., and Arboleya, M. L. (2012). Rates of Quaternary deformation in the Ouarzazate Basin (southern Atlas front, Morocco). *Ann. Geophys.*, 55, 1003–1016.

Pouclet, A., El Hadi, H., Alvaro, J.-J., Barintzeff, J.-M., Benharref, M., and Fekkak, A. (2018). Review in the Cambrian volcanic activity in Morocco: geochemical fingerprints and geotectonic implications of the rifting of West Gondwana. *Int. J. Earth Sci.*, 107, 2101–2123.

Raddi, Y., Baidder, L., Michard, A., and Tahiri, M. (2007). Variscan deformation at the northern border of the West African Craton, eastern Anti-Atlas, Morocco: compression of a mosaic of tilted blocks. *Bull. Soc. Geol. France*, 178, 343–352.

Saquaque, A., Benharref, M., Abia, H., Mrini, Z., Reuber, I., and Karson, J. A. (1992). Evidence for a Panafrican volcanic arc and wrench fault tectonics in the Jbel Saghro, Anti-Atlas, Morocco. *Geol. Rundsch.*, 81, 1–13.

Soulaimani, A., Michard, A., Ouanaimi, H., Baidder, L., Raddi, Y., Saddiqi, O., and Rjimati, E. C. (2014). Late Ediacaran–Cambrian structures and their reactivation during the Variscan and Alpine cycles in the Anti-Atlas (Morocco). *J. Afr. Earth Sci.*, 98, 94–112.

Soulaimani, A., Ouanaimi, H., Michard, A., Montero, P., Bea, F., Corsini, M., Molina, J. F., Rjimatif, E. C., Saddiqi, O., and Hefferan, K. (2019). Quartzite crests in Paleoproterozoic granites (Anti-Atlas, Morocco); a hint to Pan-African deformation of the West African Craton margin. *J. Afr. Earth Sci.*, 157, article no. 103501.

Soulaimani, A., Ouanaimi, H., Saddiqi, O., Baidder, L., and Michard, A. (2018). The Anti-Atlas Pan-African belt (Morocco): overview and pending questions. *C. R. Geosci.*, 350, 279–288.

Startsyne, F. V., Prokhorov, V. W., and Skolov, R. J. (1974–1975). Les caractéristiques géologiques et géochimiques de la bordure sud du gisement cuprifère de Bou Skour (Anti Atlas, Maroc). Technoexport, Mission géologique. 28 p.

Thomas, R. J., Chevallier, L. P., Gresse, P. G., Harmer, R. E., Eglington, B. M., Armstrong, R. A., de Beer, C. H., Martini, J. E. J., de Kock, G. S., Macey, P. H., and Ingram, B. A. (2002). Precambrian evolution of the Sirwa window, anti-atlas orogen, Morocco. *Precambr. Res.*, 118, 1–57.

Tixeront, M. (1971). Les formations précambriennes de la région minéralisée en cuivre de Bou Skour (Anti-Atlas marocain). *Notes et Mem. Serv. Geol. Maroc*, 237, 181–202.

Triantafyllou, A., Berger, J., Baele, J. M., Bruguier, O., Diot, H., Ennih, N., Monnier, C., Plissart, G., Vandycke, S., and Watlet, A. (2018). Intra-oceanic arc growth driven by magmatic and tectonic processes recorded in the Neoproterozoic Bougmane Arc complex (Anti-Atlas, Morocco). *Precambr. Res.*, 304, 39–63.

Triantafyllou, A., Berger, J., Baele, J. M., Diot, H., Ennih, N., Plissart, G., Monnier, C., Watlet, A., Bruguier, O., Spagna, P., and Vandycke, S. (2016). The Tachakoucht–Iriri–Tourtit arc complex (Moroccan Anti-Atlas): Neoproterozoic records of polyphased subduction-accretion dynamics during the Pan-African orogeny. *J. Geodyn.*, 96, 81–103.

Tuduri, J., Chauvet, A., Barbanson, L., Bourdier, J.-L., Labriki, M., Ennaciri, A., Badra, L., Dubois, M., Ennaciri-Leloix, C., Sizaret, S., and Maacha, L. (2018). The Jbel Saghro Au(–Ag, Cu) and Ag–Hg metallogenetic province: product of a long-lived Ediacaran tectono-magmatic evolution in the Moroccan Anti-Atlas. *Minerals*, 8, 592.

Walsh, G. J., Benziane, F., Aleinikoff, J. N., Harrison, R. W., Yazidi, A., Burton, W. C., Quick, J. E., and Saadane, A. (2012). Neoproterozoic tectonic evolution of the Jebel Saghro and Bou Azzer-El Graara inliers, eastern and central Anti-Atlas, Morocco. *Precambr. Res.*, 216, 23–62.

Walsh, G. J., Benziane, F., Burton, W. C., El Fahssi, A., Yazidi, A., Yazidi, M., Saadane, A., Aleinikoff, J. N., Ejjaouani, H., Harrison, R. W., Stone, B. D., and Kalai, M. (2008a). Carte géologique au 1/50 000, Feuille Bou Skour. *Notes et Mem. Serv. Geol. Maroc*, 469, 131.

Walsh, G. J., Benziane, O., Burton, W. C., Yazidi, A., EL Fahssi, A., Yazidi, M., Saadanie, A., Aleinikoff, J. N., Ejjaouani, H., Harrison, R. W., and Stone, B. (2008b). Carte Géologique du Maroc au 1/50 000, feuille Bou Skour-Notice explicative. *Notes et Mem. Serv. Geol. Maroc.* 469 (bis), 132 p.