Analysis of tectonic fracturing in the Mibladen ore deposit (Upper Moulouya, Morocco) and its impact on the Pb-Ba mineralization emplacement

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Abstract

The MVT-type Pb-Ba mineralizations of the Mibladen ore deposit are hosted by Jurassic carbonates as well as Infracenomanian conglomerates and sandstones. The mineral paragenesis is mainly composed of galena and barite with lesser chalcopyrite and pyrite, accompanied by supergene oxidation minerals. This ore deposit is the result of a major epigenetic mineral stage with economic orebodies occurring as replacement of pre-existent carbonate rocks, fillings of karst cavities, interstratal joints, collapse-breccias, fractures and faults. Structural and microtectonic analyses we carried out in this ore deposit, allowed us to highlight two main fracture networks controlling ore deposition within karst cavities and interstratal joints: i) NNW-SSE to NNE-SSW trending tension gashes and normal faults; ii) ENE-WSW to E-W trending reverse faults with strike-slip components and transtensive relay zones. All of these structures are developed under a regional compressional tectonic regime divided into extensional and transtensional episodes (σ1-σ2 and σ2-σ3 permutations) with sub-meridian σ1 axis and sub-equatorial σ3 axis. This compressive tectonic event caused the uplift of Mibladen area and favored the circulation of mineralizing fluids along the NW-SE and ENE-WSW major faults such as Amourou and Aouli Faults, during the Infracenomanian period (Upper Jurassic-Early Cretaceous).

Keywords: Microtectonic analyses, MVT-type mineralizations, Mibladen ore deposit, Upper Moulouya, Morocco.

1. Introduction
The Moroccan Atlas system includes several Mississippi Valley-type (MVT) ore deposits with economic Pb-Zn-Ba orebodies. These MVT-type occurrences are hosted in large metallogenic provinces in north-western Africa from Tunisia to Morocco (Bouabdellah and Sangster 2016).

The Upper Moulouya lead district is about 100 km from the junction of the Middle Atlas and the High Atlas belts, north of Midelt city (Fig. 1), in the Meseta-Atlas domain of Morocco (Michard 1976; Michard et al. 2008). It is the second largest producer of Pb in Morocco with a tonnage (production + reserves) exceeding 31 Mt of ore at an average grade of ≈4.5 wt% Pb (Annich and Rahhali 2002; Rahhali 2002). This mining district displays three main types of ore deposits (Fig. 1): Aouli vein-type deposits hosted in Paleozoic schists and granites, Zeida red bed-type deposits hosted in Triassic arkoses and conglomerates, Mibladen MVT-type deposits hosted in Jurassic carbonates and Infracenomanian continental strata (e.g., Bouladon 1959; Amade 1965; Emberger 1965a, b; Felenc and Lenoble 1965; Dagallier 1973, 1976, 1977; Schmitt 1976; Jébrak et al. 1998; El Jaouani 2001; Naji 2004; Margoum 2015; Margoum et al. 2015; Bouabdellah and Margoum 2016; Bouabdellah and Sangster 2016).

The MVT-type Pb-Ba ore deposit of Mibladen, subject of this study, is located south of the Aouli inlier, 15 km north-east of Midelt (Fig. 1). It has become world famous for its beautiful vanadinite crystals (Jahn et al. 2003; Praszkier 2013). Currently, the Mibladen mine is closed, its total production (from 1938 to 1983) is estimated about 6.253.000 t of ore at an average grade of ≈5 wt% Pb (Annich and Rahhali 2002; Rahhali 2002), accounting for approximately 30 % of Moroccan Pb production (Bouabdellah and Sangster 2016). The Pb-Ba mineralized zone covers an ENE-WSW trending band. It extends over a strike length of 15 km and is 1 to 4 km wide. This mineralized band is framed by two major faults: the ENE WSW Amourou Fault in the south and the NE-SW Aouli Fault in the north (Fig. 2).
Fig. 1. Location of the Upper Moulouya lead district, modified from the geological map of Morocco at 1/1,000,000 (Hollard et al. 1985).

Pb-Ba Mineralizations of Mibladen ore deposit are structurally controlled (Dagallier and Macaudière 1987; El Jaouani 2001; Naji 2004). Prior to the present work, no detailed study concerning fracturing analyses, paleostress reconstructions and the determination of the regional tectonic regime associated to the emplacement of Mibladen mineralizations has been established, except for a few very limited and not in-depth studies. For this reason, we focused our work on the analysis of tectonic fracturing at different scales and paleostress reconstruction in this ore deposit. This paper aims to: i) determine the relationships between tectonic episodes and ore depositional stage in the Mibladen deposit; ii) determine the relative age of the Pb-Ba mineralization emplacement; iii) propose a model for the Pb-Ba mineralization emplacement in the Mibladen ore deposit based on the results of this work and available data from previous studies. The distribution of Pb-Ba mineralization in the Mibladen sedimentary series is represented in a set of lithostratigraphic columns. The results
of structural analyses and paleostress reconstruction are presented on a set of rose diagrams and stereoplots.

2. Methods

For each mining site, we carried out multi-scale structural and microtectonic analyses for the Pb-Ba mineralization and its host rocks. We also carried out lithostratigraphic sections showing the arrangement of Pb-Ba mineralization in its host sedimentary units.

In order to determine the set of the structural systems controlling ore deposition and to reconstruct the associated paleostress fields, we used the Win-Tensor program (Delvaux 1993; Delvaux et al. 1997; Delvaux and Sperner 2003; Delvaux 2012) to process field data measurements collected from faults and tension gashes. The calculated stress tensors are based on four parameters: the main stress axes $\sigma_1$, $\sigma_2$, $\sigma_3$ with $\sigma_1 \geq \sigma_2 \geq \sigma_3 \geq 0$ and the stress ratio $R = (\sigma_2 - \sigma_3) / (\sigma_1 - \sigma_3)$ with $0 \leq R \leq 1$ (e.g., Angelier 1989, 1991, 1994; Gephart et Forsyth 1984; Vandycke and Bergerat 1992; Lund and Townend 2007; McFarland et al. 2012). The automatic processing of microtectonic measurements is first carried out using the "Right Dihedron method" developed by Angelier and Mechler (1977) and improved by Delvaux and Sperner (2003). The obtained stress tensor using this method is then used in the "Rotational Optimization method" (Delvaux and Sperner 2003). This method is based on a composite function $F_5$ which must be minimized. For slickensided fault planes, this function minimizes the slip deviation between the observed and resolved slip vectors, and it maximizes the resolved shear stress magnitude in order to favor slip on the fault plane (Angelier 1991; Delvaux and Sperner 2003). For tension gashes, it minimizes both the resolved normal and shear stress magnitudes to favour fracture opening and prevent slip on the plane (Angelier 1991, 1992; Delvaux and Sperner 2003). Results showing a value of $F_5 > 20$ for tension gashes and $F_5 > 22$ for striated fault planes are excluded from the calculations (Delvaux and Sperner 2003).

3. Regional geological framework

3.2. Paleozoic basement

The MVT-type Pb-Ba mineralizations of the Mibladen ore deposit are hosted in the Mesozoic cover unconformably overlying the deformed Paleozoic basement of the Aouli inlier (Fig. 2). This Paleozoic basement consists of a metasedimentary series mainly represented by Cambro-
Ordovician schists and quartzites (Hoepffner 1987; Rhinane 1990; Hoepffner et al. 2006). These metasediments correspond to old flysch sequences of active continental margin (Vauchez 1976; Filali 1996; Filali et al. 1999). They are intercalated by metavolcanic rocks (Rhinane 1990) and amphibolite sills (Emberger 1965a) assimilated to old intraplate alkali basalts (Ganzeev and Mtiaev 1978). These amphibolites testify the Cambro-Ordovician intraplate rifting stage in the northwestern edge of Paleo-Gondwana (Ouali et al. 2001). All of these terrains underwent Eo-variscan syn-metamorphic phase dated at 366 ± 7 Ma (Rb/Sr whole rock: Tisserant 1977; Clauer et al. 1980), which generated an epizonal regional metamorphism characterized by biotite ± garnet parageneses (Vauchez 1976; Hoepffner 1987; Rhinane 1990; Filali 1996; Filali et al. 1999; Dahire 2004). The regional metamorphism is superimposed by a thermal metamorphism with a large contact aureole (Fig. 2) related to the emplacement of Aouli granitoids dated at 347 ± 17 and 319 ± 12 (Rb/Sr whole rock: Tisserant 1977; Clauer et al. 1980), hen at 333 ± 2 et 319 ± 1,5 Ma (U/Pb on zircon: Oukemeni 1993; Oukemeni et al. 1995). These granitoids include several magmatic suites ranging from basic to peraluminous anatectic suites (Emberger 1965a; El Mourouah et al 1993; Oukemeni and Bourne 1994; Filali et al. 1999; Dahire et al. 2002; Dahire 2004; Elabouyi et al. 2019). These magmatic suites are characterized by the outcrop of different granitic facies: gabbro-diorites and granodiorites in Sidi Ayad area, granites with biotite in the central part of the main pluton and two-micas granites in the two small isolated plutons of Perdreaux and Poulet (Fig. 2).
3.2. Meso-Cenozoic cover

**Fig. 2.** Geological map of Mibladen (Raddi et al. 2013, modified).
The Paleozoic basement of the Aouli inlier is unconformably overlain by Meso-Cenozoic cover represented by volcanic and sedimentary series (Figs. 2 and 3). This cover starts with Upper Triassic detrital deposits (Ouarhache 2002) and tholeiitic basaltic flows dated from 210 ± 2.1 to 196 ± 1.2 Ma ($^{40}$Ar/$^{39}$Ar on plagioclase; Fiechtner et al. 1992), testifying of the Atlas rifting stage during the Upper Triassic period (Emberger 1965a; Fiechtner et al. 1992; Piqué and Laville 1993a, b, 1995; Ouarhache et al. 2000, 2012). On these basalts, rests a coarse detrital formation consisting of monogenic conglomerate with basaltic elements (Fig. 3), assigned to the Infraliassic? (Ouarhache 2002). Triassic deposits are followed by Liassic carbonate platform (Dagallier 1973, 1977; Saadi 1996; Igmoullan et al. 2001; Saadi et al. 2003; Saadi 2012), Bajocian marls, Infracenomanian conglomerates and marls with gypsum (Ensslin 1992, 1993; Ciszak et al. 1999), and Cenomanian-Turonian marine limestones (Charrière et al. 1998). The Cenozoic series is unconformably deposited on the Mesozoic successions (Fig. 3). It is mainly represented by continental fluvial and lacustrine deposits ranging from Oligocene to Quaternary (Dubar 1943; Raddi et al. 2013) and resulting from the erosion of Atlasic reliefs in process of uplift (Morel et al. 1993, 2000; Zouine 1993).
Fig. 3. Synthetic lithostratigraphic column of Mibladen with associated Pb-Ba mineralizations (Aouli and Zeida mineralizations are not represented here).

4. Results

4.1. Gitology and distribution of Pb-Ba mineralizations in the Mesozoic sedimentary series of Mibladen

In the Mibladen ore deposit, economic orebodies are arranged in an ENE-WSW elongated band (Fig. 4). Spatial distribution of mineralized occurrences shows the existence of two Horizons or "Faisceaux" corresponding to two different stratigraphic levels (Fig. 4). These mineralized Horizons are organized into several mining sites ("Faisceau Inférieur" or "Lower Horizon": Bou el Maden, Anne Marie, the S and the R mining sites; "Faisceau Supérieur" or "Upper Horizon": Adeghoual, the Dalles, the T Ouest, the O, the AB2, AB3, AB4 and AB5
mining sites; Emberger 1965b; Felenc and Lenoble 1965) (Fig. 4). The 2ème Horizon and Marguerite mining sites (Fig. 4) occupy probably an intermediate position between the two Horizons (Emberger, 1965b).

**Fig. 4.** Spatial distribution of mineralized occurrences in the Mibladen ore deposit (Felenc and Lenoble, 1965, modified).

Lithostratigraphic sections we carried out in each of the Mibladen mining sites (Fig. 5), allowed us to highlight the distribution of Pb-Ba mineralizations in the different terms of the Mesozoic series in this ore deposit. The majority of the mineralized bodies are hosted by argillaceous limestones, dolomitic limestones, dolostones and limestones of Middle Liassic. Early Liassic dolostones are also mineralized, they contain stratiform barite orebodies with thickness which can reach 100 cm (Fig. 6a). Pb-Ba mineralizations are also hosted by Bajocian bioclastic limestones in the AB3 mining site (Fig. 5). The last mineralized term of the Mesozoic series of Mibladen corresponds to Infracenomanian conglomerates and sandstones in the AB2 and AB5 mining sites. Pb-Ba mineralizations hosted in Early Liassic and Bajocian formations are highlighted for the first time in this work. In the S, Bou el Maden, Anne Marie and AB2 mining sites, barite ± galena are finely interbedded or disseminated within Middle Liassic marls and claystones (Fig. 5).
Fig. 5. Arrangement of Pb-Ba mineralizations within different terms of the Mesozoic series of Mibladen. (Gn: Galena, Brt: Barite, Cer: Cerussite. This is valid for all the following figures).
The morphology of economic orebodies in the Mibladen deposit is very diversified; it is represented by stratiform bodies corresponding to interstratal joint and karst fillings (Fig. 6c, e and f), dissolution cavities characterized by the substitution and replacement of the carbonate host rock by metalliferous fluids (metasomatic processes) (Fig. 9b and g). Pb-Ba mineralizations hosted in InfraCenomanian conglomerates and sandstones are characterized by the impregnation of intergranular spaces and the substitution of conglomerate carbonate cement (Fig. 6d). In addition to the strata-bound orebodies, Pb-Ba mineralizations occur as fracture and vein fillings. These fractures are sub-vertical to vertical (Fig. 7) and affect all series of the mineralized zone.

The mineralogy of the Mibladen ore deposit is not complicated, it is one of the simplest mineral assemblages ever found in a MVT district (Bouabdellah and Sangster 2016). The primary mineral paragenesis is mainly made up of barite and galena (Fig. 6) with lesser chalcopyrite and pyrite, sphalerite is virtually absent (Margoum 2015; Bouabdellah and Sangster 2016). Barite has two aspects: i) poorly-crystalized masses occupying interstratal joints, fractures and karst cavities; ii) well-crystallized masses with crested barite developed within geodes and open-spaces. Its color is white, pink or honey-pink, it is sometimes upholstered with brown shades corresponding to iron oxides. Galena is generally well crystallized with cubic or octahedral shapes; the crystal size can sometimes exceed one centimeter. Its silver content can reach 500 ppm in some mining sites (Emberger 1965b). The supergene mineralization stage results from sulphide oxidation (Bouabdellah and Sangster 2016). It is represented by mineral assemblages with cerussite, anglesite, wulfenite, vanadinite, quartz, calcite, aragonite, gypsum, manganese oxides (cryptomelane, hollandite and coronadite; Jahn et al. 2003), phosgenite (Pb₂CO₃Cl₂), mottramite (PbCu(VO₄)(OH)) and paralaurionite (PbCl(OH)) (Praszkier 2013). This is the reason for the worldwide reputation of the Mibladen ore deposit as one of the best destinations for mineral collectors.
**Fig. 6.** Gitological characteristics of Pb-Ba mineralizations in the Mibladen ore deposit. a) Barite strata interbedded in Early Liassic dolostones. b) Dissolution structures within Middle Liassic dolomitic limestones in the O mining site. c) Karst-filling of Middle Liassic limestones in the Dalles mining site. d) Impregnation of Infracenomanian conglomerates in the AB5 mining site. e) Karst-filling of Middle Liassic limestones in the AB2 mining site. f) Interstratal joint-filling in the Dalles mining site. g) Dissolution structures within Middle Liassic dolomitic limestones in Marguerite mining site. h) Mineral paragenesis of T Ouest mining site.
4.2. Structural control of Pb-Ba mineralizations in the Mibladen ore deposit

The Jurassic and Infracenomanian series hosting Pb-Ba mineralizations in the Mibladen ore deposit are intensely fractured. This tectonic fracturing is favorable to metalliferous fluid circulations (Fig. 7). In all of the mining sites, we observed vein orebodies related to sub-vertical and vertical fractures. These affect all strata bearing Pb-Ba mineralizations. They act as pathways for the circulation of Pb-Ba mineralizations, and they are responsible for their deposition into open-spaces such as ravinement surfaces (Fig. 7a), karst cavities (Fig. 7b) and interstratal joints (Fig. 7c, d and e). The mineralized structures thickness ranges from centimeters to decimeters, their intersection with the strata-bound orebodies shows significant mineral enrichment zones.

Fig. 7. Structural control of Pb-Ba mineralizations in the Mibladen ore deposit. a) Fracture responsible for ore deposition in the Middle Liassic-Infracenomanian contact. b) Circulation of metalliferous fluid into a sub-vertical fracture and its deposition in karstic cavities. c, d and
e) Fractures responsible for circulation and deposition of Pb-Ba mineralizations into Liassic interstratal joints.

Structural analyses of economic orebodies we carried out in the Mibladen mining sites show a similitude between all these sites. Pb-Ba mineralizations are controlled by two main fracture networks. The distribution of these fractures is characterized by two preferred direction systems (Fig. 8):

-ENE-WSW to E-W (N60 to N100) system characterized by vein structures developed along reverse faults with strike-slip component. These faults show slickensided planes filled by Pb-Ba mineralizations (Fig. 9a and b). These fault planes are generally non rectilinear, the strike-slip components allow the appearance of transtensive relays and pull-apart openings (Fig. 9c to g) favorable to the Pb-Ba mineralization concentrations;

![Fig. 8. Rose diagrams for mineralized structures in the Mibladen mining sites (green: reverse faults with strike-slip component, blue: tension gashes and normal faults, n = number of]
measurements. Equal-area stereographic projection, lower hemisphere. See measurement sites in Fig. 4).

-NNW-SSE to NNE-SSW (N160 to N15) system represented by vein structures developed along very frequent tension gashes and less frequent normal faults. Tension gashes (Fig. 9h and i) have centimetric thickness, they are characterized by the development of mineral-rich geodes of the supergene mineral stage.

Field observations in Mibladen mining sites, allowed us to conclude that these different mineralized structures have the same relative age and are developed simultaneously. Their intersection zones don't show any offset where these fractures are interconnected.
Fig. 9. a and b) ENE-WSW striated reverse fault filled by Pb-Ba mineralizations in the S mining site. c to g) Transtensive relays and pull-apart openings along N70 to N100 trending faults. NNW-SSE tension gashes filled by Pb-Ba mineralizations and hosted by: Bajocian limestones (h) and Middle Liassic dolomitic limestones (i).
4.3. Tectonic setting of the emplacement of Pb-Ba mineralizations in the Mibladen ore deposit

The determination of the tectonic setting responsible for Pb-Ba mineralizations emplacement in the Mibladen ore deposit is based on stress tensor calculations, paleostress reconstruction and the definition of the regional tectonic regime of the emplacement of these mineralizations. This procedure is based on field data collected from microtectonic measurements along slickensided faults (Fig. 10a) and tension gashes (Fig. 10b to 1) in the different mining sites of Mibladen.

Fig. 10. Results of the reconstruction of stress fields responsible for Pb-Ba mineralizations emplacement in the Mibladen ore deposit. a) Corresponding stereoplot of mineralized reverse
faults. b to l) Corresponding stereoplots of mineralized tension gashes. Stereograms (equal-area stereographic projection) with traces of fault planes and tension gashes, observed slip lines and slip senses, ratio R value, distribution histogram of the misfit function F5, F5-misfit function, the principal stress axes ($\sigma_1$, $\sigma_2$, $\sigma_3$) are reported. See measurement sites in Fig. 4.

Automatic stereographic projection of more than 250 microtectonic measurements, allowed us to determine a tectonic regime characterized by a NNW-SSE to N-S trending $\sigma_1$ axis and an ENE-WSW to E-W trending $\sigma_3$ axis. The calculated stereoplot from reverse faults with dextral strike-slip component in the S mining site (Fig. 10a) demonstrates a pure compressive tectonic regime with a horizontal NNW-SSE trending $\sigma_1$ axis (N162°, 06°SSW) and a sub-vertical ENE-WSW trending $\sigma_3$ axis (N55°, 71°WSW). The stress ratio $R = 0.5$; indicating that $\sigma_2 = (\sigma_1 + \sigma_3) / 2$.

In the different mining sites of Mibladen, kinematic context of the development of mineralized tension gashes is consistent with a paleostress tensor showing transtensive (Fig. 10b to k) or transpressive (Fig. 10l) tectonic regime. This tectonic regime is characterized by NNW-SSE to N-S trending $\sigma_1$ axis (N168° to N001°) and ENE-WSW to E-W trending $\sigma_3$ axis (N76° to N88°). The value of the stress ratio $R$ ranges from 0 to 1, indicates that the tectonic phase is divided into several episodes with $\sigma_1$-$\sigma_2$ and $\sigma_2$-$\sigma_3$ axis permutations. These permutations due to relative variations in principal stress magnitudes, allow the appearance of extensive and transtensive episodes during the single compressive tectonic phase (e.g., Angelier 1984; Angelier et al. 1985; Hu and Angelier 2004). These are responsible for tension gashes opening and the appearance of normal faults synchronous with reverse faults developed under the NNW-SSE compressive regime. Statistical analyses of the principal stress axes $\sigma_1$, $\sigma_2$ et $\sigma_3$ (Fig. 11) demonstrate also that this single compressive tectonic phase is divided into several episodes with $\sigma_1$-$\sigma_2$ and $\sigma_2$-$\sigma_3$ permutations.
**Fig. 11.** Statistical analyses of $\sigma_1$, $\sigma_2$ and $\sigma_3$ stress axes reported in Fig. 10 (equal-area stereographic projection, lower hemisphere).

5. Discussion

5.1. Age of Pb-Ba mineralization emplacement in the Mibladen ore deposit

Pb-Ba-mineralizations of Mibladen ore deposit are clearly epigenetic. They occur as replacement of pre-existent carbonate rocks post-dating the lithification of the host rocks (Bouabdellah and Sangster 2016). The lack of radiometric dating for these Pb-Ba mineralizations is the cause of permanent debates between researchers. In a metallogenic synthesis for the Upper Moulouya lead district, Emberger (1965b) proposed a post-Cretaceous or Atlasic age for the epigenetic stage of Mibladen mineralizations, because the Infracenomanian conglomerate is impregnated with these Pb-Ba mineralizations. Naji (2004) assigned this epigenetic mineralization stage to two distinct events: i) a NW-SE to N-S extensive tectonic event responsible for ore deposition within faults and karsts affecting the Mibladen Jurassic series; ii) a post-Cretaceous event responsible for the remobilization of the strata-bound mineralizations and their impregnation in Infracenomanian conglomerates. Combining petrographic and geochemical data, field relationships and previous tectonic studies together with the comparison to the Touissit-Bou Beker district, Bouabdellah and Sangster (2016) proposed an Atlasic (Late Miocene) age of the Mibladen mineralizations.

The results of the present study show that Pb-Ba mineralizations in the Mibladen ore deposit, were deposited under NNW-SSE compressive tectonic regime responsible for the appearance of ENE-WSW to E-W reverse faults with strike-slip component. These faults are mineralized with galena and barite which crystallize within transtensive relays and pull-apart openings developed along fault planes. The tectonic compressive regime is divided into several
transpressive and extensive tectonic episodes responsible for tension gashes and normal fault openings which are also mineralized with galena and barite. These episodes are due to stress axes permutations. During the Infracenomanian period (Upper Jurassic-Early Cretaceous), Mibladen region and its peripheries underwent a major compressive and paroxysmal NNW-SSE tectonic phase (Hinaje 2004). It led to the folding, tilting and uplift of the Jurassic series. These series underwent intense erosion with the deposition of Infracenomanian conglomerates unconformably overlying the underlying formations (Amade 1965; Emberger 1965a, b; Felenc and Lenoble 1965; Dagallier and Macaudière 1987; Hinaje 2004). In the Middle Atlas and the Central High Atlas, this compressive NNW-SSE phase is post-Bathonian and ante-Barremian (Hinaje 2004). Combining these available results with the results of the present work, we assign the emplacement of the epigenetic Pb-Ba mineralizations of the Mibladen deposit to this Infracenomanian NNW-SSE compressive phase. The impregnation of Infracenomanian conglomerates and sandstones by Pb-Ba mineralizations is not necessarily a condition for these mineralizations to be assigned to a post-Cretaceous period. We propose a model where these permeable detrital formations are traversed and impregnated by metalliferous fluids which replace conglomerate and sandstone cement and fill out open spaces (Fig. 12). The hypothesis of an epigenetic mineralization stage divided into two different events separated in time and space (Naji 2004) is unlikely in our opinion, because structures controlling ore deposition in Jurassic and Infracenomanian formations have the same age and are developed under the same compressive tectonic regime with transtensive episodes but not under a pure extensive one. The Upper Miocene age of Pb-Ba mineralizations under a N-S compressive tectonic regime proposed by Bouabdellah and Sangster (2016) is also questionable; during this period (Upper Miocene), the tectonic regime is extensive and oriented NE-SW in the northwestern part of the Middle Atlas belt (Hinaje et al. 2001), it is related to the Sefrou-Tahla-Skoura-Tazarine corridor opening (Hinaje 2004). In the Atlas belt, this regime is consistent with a NE-SW trending compression during the Middle Upper-Tortonian period and with a NW-SE trending compression during the Tortonian-Messinian time (Ait Brahim et al. 2002). In the Upper Moulouya, it is consistent with a NW-SE trending compression (Morel et al. 1993; Zouine 1993). The post-Cretaceous sub-meridian compressive regime in the Atlas and the Upper Moulouya domains is rather assigned to: the Plio-Quaternary (Ait Brahim et al., 2002), the Early Quaternary (Morel et al. 1993; Zouine 1993) or the Middle-Late Quaternary (Hinaje et al. 2001; Hinaje 2004). Moreover, the hypothesis of a post-Cretaceous age of the ore deposition is contradicted by the presence of non-mineralized Cenomano-Turonian limestones directly resting on the
mineralized Liassic carbonates of Jbel Argoud (Fig. 2), or on the Hercynian granitoids hosting Pb-Ba veins in the Assaka Ijdi syncline west of Mibladen (Emberger 1965a). In these regions, Cenomano-Turonian limestones are karstified and recorded post-Cretaceous tectonic events. Cenozoic faults and fractures affecting these limestones are barren. Dagallier and Macaudière (1987) assumed a post-Dogger, but ante-Cretaceous, age for the sub-meridian compression responsible for karstic recovery and Pb-Ba mineralization redistributions in the Mibladen deposit. Jébrak et al. (1998) have not excluded the possibility that Mibladen mineralizations are related to the tectonic phase associated with the closure of the Tethyan basin starting from the Middle Jurassic time.

The MVT-type Pb-Ba mineralizations of the Mibladen ore deposit are thus involved a major epigenetic stage assigned to the Infracenomanian period (Upper Jurassic-Early Cretaceous) and synchronous with the long period of uplift and erosion of the Upper Moulouya region during the NNW-SSE trending compression.

5.2. Proposed model for the Pb-Ba mineralizations emplacement in the Mibladen ore deposit

The Mibladen Pb-Ba mineralizations are independent in time and space from Zeida and Aouli mineralizations. They are related to a distinct metallogenic event post Triassic rifting stage, and represent a remobilization of the Zeida-Aouli concentrations, or a more recent leaching of the same sources (Jébrak et al. 1998). The study of available data from fluid inclusions together with S and Pb isotopes of the Upper Moulouya district (Duthou et al. 1976; Jébrak et al. 1998; Bouabdellah and Sangster 2016) allowed Bouabdellah and Sangster (2016) to highlight the following conclusions about the genetic model of the epigenetic mineralization stage in the Mibladen ore deposit: i) ore fluids were moderately hot (>100 °C) and derived from basins, that scavenged lead and associated metals from the underlying Hercynian granitoids and clastic rocks; ii) Domerian carbonates were the main regional aquifer for the ore brines; iii) the mechanism of ore deposition is inconsistent with a single model: there is a mixing of two incompatible fluid reservoirs; a deep-seated, basement-equilibrated hydrothermal fluid, and a surficial formation and/or meteoric water; iv) an uplift episode is necessary to create topographic slopes and favor metalliferous fluid circulations along deep ENE-WSW and NE-SW faults.
In the light of these conclusions and the results of the present work, we propose a model for the Pb-Ba mineralizations emplacement (Fig. 12), based on the following points: i) during the Upper Jurassic-Early Cretaceous period, the NNW-SSE compressive regime divided into several episodes led to the Mibladen region uplift. This is due to reverse and strike-slip faults directed ENE-WSW and NE-SW respectively, such as Amourou and Aouli Faults which bound the Pb-Ba mineralized zone of Mibladen; ii) this uplift allowed the erosion of the underlying series and the deposition of Infracenomanian continental succession represented by conglomerates and sandstones; iii) the creation of topographic slopes by this tectonic uplift favored a gravity-driven flow of surface fluids towards deep zones along major tectonic faults; iv) in their paths, these fluids cross the Liassic aquifer, leach lead accumulated in Triassic clastic rocks and Aouli veins, then they mix together with deep fluids leaching Hercynian granitoids; v) after their mixing, these two fluids produce a metalliferous fluid loaded with Pb and Ba which migrates along major faults; vi) finally, this fluid is deposited within karst cavities, interstratal joints, pull-apart openings developed along ENE-WSW faults, tension gashes and Infracenomanian syntectonic conglomerates in process of deposition. These hydrothermal and mineralizing events are probably related to large-scale crustal processes triggered during the Upper Jurassic-Early Cretaceous period in the Moroccan Atlas system such as the emplacement of magmatic intrusions in the Central High Atlas and the Middle Atlas belts (e.g., Fedan 1988; Charroud 1990; Samir 1991; Beraâouz and Bonin 1993; Lhachmi et al. 2001; Zayane et al. 2002; Ibouh 2004; Frizon de Lamotte et al. 2008; Bensalah et al. 2013; Michard et al. 2013; Guezal et al. 2014). In addition to syn-metamorphic deformations, and their associated hydrothermal manifestations in the High Atlas belt during this period (Laville et al. 1991, 1994; Laville and Piqué 1992; Hinaje 2004).
Fig. 12. Simplified schematic model for the Pb-Ba mineralization emplacement in the Mibladen ore deposit during the Infracenomanian period (Upper Jurassic-Early Cretaceous) (without scale).

6. Conclusion

Gitological, structural and microtectonic analyses associated to paleostress reconstruction in the MVT ore deposit of Mibladen allowed us to highlight the following results:

- This ore deposit involved a major mineral epigenetic stage economically more important with orebodies hosted by Jurassic carbonates and Infracenomanian continental series and occupying karst cavities, interstratal joints, fracture and faults;

- Structural control of ore deposition is favored by two main fracture networks: i) NNW-SSE to NNE-SSW tension gashes and normal faults; ii) ENE-WSW to E-W trending reverse faults with strike-slip components and transtensive relay zones;
- The tectonic setting of the mineralization emplacement is consistent with a NNW-SSE trending compression with extensional and transtensional episodes related to \( \sigma_1 - \sigma_2 \) and \( \sigma_2 - \sigma_3 \) axis permutations during the Infracenomanian period (Upper Jurassic-Early Cretaceous);

- This compressive regime favored metalliferous fluid circulations along major ENE- WSW and NE-SW trending faults such as Amourou and Aouli Faults.

References

Aït Brahim L, Chotin P, Hinaj S, Abdelouafi A, El Adraoui A, Nakcha C, Dhont D, Charroud M, Sossey Alaoui F, Amrhar M, Bouaza A, Tabayaoui H, Chaouni A (2002) Paleostress evolution in the Moroccan African margin from Triassic to Present. Tectonophysics. 357: 187-205

Amade E (1965) Les gisements de plomb de Zeïda et de Boumia. Notes et Mém. Serv. Géol. Maroc. 181: 175-184

Angelier J, Mechler P (1977) Sur une méthode graphique de recherche des contraintes principales également utilisable en tectonique et en séismologie : la méthode des dièdres droits. Bull. Soc. Géol. Fr. 7: 1309-1318

Angelier J (1984) Tectonic analysis of faults lip data sets. J. Geophys. Res. 89: 5835-5848

Angelier J, Colletta B, Anderson RE (1985) Neogene paleostress changes in the Basin and Range: a case study at Hoover Dam, Nevada-Arizona. Geol. Soc. Am. Bull. 96: 347-361

Angelier J (1989) From orientation to magnitudes in paleostress determinations using fault slip data. J. Struct. Geol. 11: 37-50

Angelier J (1991) Inversion directe et recherche 4-D : comparaison physique et mathématique de deux modes de détermination des tenseurs des paléocontraintes en tectonique de failles. Acad. Sci. Paris. 312: 1213-1218

Angelier J (1992) Sur incorporation des structures de pression et de tension dans la détermination des états de contraintes en tectonique cassante : un élargissement des méthodes d’inversion. C. R. Acad. Sci, Paris. 314: 1233-1238
Angelier J (1994) Fault slip analysis and paleostress reconstruction. In: Hancock, P.L. (Ed.) Continental Deformation. Pergamon, Oxford. 101-120

Annich M, Rahhali M (2002) Gisement de plomb de Zeida. In : Barodi E-B, Watanabe Y, Mouttaqi A, Annich M (eds) Méthodes et techniques d’exploration minière et principaux gisements au Maroc. Projet JICA/BRPM, Bureau Recherche Participations Minières BRPM, Rabat. 179-183

Bensalah MK, Youbi N, Mata J, Madeira J, Martins L, El Hachimi H, Bertrand H, Marzoli A, Bellieni G, Doblas M, Font E, Medina F, Mahmoudi A, Beraâouz EB, Miranda R, Veratim C, De Min A, Ben Abbou M, Zayane R (2013) The Jurassic-Cretaceous basaltic magmatism of the Oued El-Abid syncline (High Atlas, Morocco): physical volcanology, geochemistry and geodynamic implications. J. Afr. Earth Sci. 81: 60-81

Beraâouz EH, Bonin B (1993) Magmatisme alcalin intracontinental en contexte de décrochement : le massif plutonique mésozoïque de Tirrhist, haut Atlas central, Maroc. C. R. Acad. Sci, Paris. 317 : 643-657

Bouabdellah M, Margoum D (2016) Geology, Fluid Inclusions, and Geochemistry of the Aouli Sulphide ± Fluorite ± Barite Vein Deposit (Upper Moulouya District, Morocco) and Its Relationships to Pangean Rifting and Opening of the Tethys and Central Atlantic Oceans. In: Bouabdellah M., Slack J. (eds) Mineral Deposits of North Africa. Mineral Resource Reviews. Springer, Cham. http://doi-org-443.webvpn.fjmu.edu.cn/10.1007/978-3-319-31733-5_11

Bouabdellah M, Sangster DF (2016) Geology, Geochemistry, and Current Genetic Models for Major Mississippi Valley-Type Pb–Zn Deposits of Morocco. In: Bouabdellah M., Slack J. (eds) Mineral Deposits of North Africa. Mineral Resource Reviews. Springer, Cham. https://doi.org/10.1007/978-3-319-31733-5_19

Bouladon J (1959) Les filons de Mibladen. Deux formes d’une même minéralisation plombifère dans la région de Midelt. Congr. Géol. Inter, Mexico, (1956), 13 : 43-63

Charrière A, Andreu B, Ciszak R, Kennedy WJ, Rossi A, Vila JM (1998) La transgression du Cénomanien supérieur dans la Haute Moulouya et le Moyen Atlas méridional, Maroc. Geobios. 31 : 551-569
Charroud M (1990) Evolution géodynamique de la partie Sud-Ouest du Moyen Atlas durant le passage Jurassique-Crétacé, le Crétacé et le Paléogène : un exemple d’évolution intraplaque. Unpublished Thesis (Thèse 3ème cycle). Mohamed V Université, Rabat, Morocco, 234 pp

Ciszak R, Andrieu B, Charrière A, Ettafchini M, Rossi A (1999) Le Crétacé antéturonien du Moyen Atlas méridional et de la Haute Moulouya, Maroc : stratigraphie séquentielle et paléoenvironnements. Bull. Soc. Géol. Fr. 170 : 451-464

Clauer N, Jeanette D, Tisserand D (1980) Datation isotopique des cristallisations successives du socle cristallin et cristallophyllien de la Haute Moulouya (Maroc hercynien). Geol. Rundsh. 5 : 383-399

Dagallier G (1973) Concentration plombo-barytiques en milieu supratidal et dissolutions précoces. L’exemple de Mibladen (Maroc). C. R Acad. Sci. Paris. 276 : 3249-3252

Dagallier G (1977) Une série carbonatée littorale : le Lias moyen à Pb-Ba de Mibladen (Maroc). Sciences de la terre, t.XXI, 1 : 53-101

Dagallier G (1983) Contribution à l’étude de l’environnement de concentrations plombo-zincifères (et métaux connexes) liées aux strates. Unpublished Thesis (Doctorat d’Etat). Lorraine University, France, 273 pp

Dagallier G Macaudiere JM (1987) Contrôles tectoniques des concentrations Pb-Ba en milieu carbonaté de Mibladen (Maroc). Bull. Soc. Géol. Fr. 8 : 387-394

Dahire M (2004) Le complexe plutonique de la Haute Moulouya (Meseta oriental, Maroc) : Evolution pétrologique et structurale. Unpublished Thesis (Doctorat d’Etat). Sidi Mohamed Ben Abdellah University, Fès, Morocco, 322 pp

Dahire M, Ribeiro ML, Ntarmouchant A, El Boukhari A, Pons J, Driouch Y, Ben Abbou M, Moreira E (2002) Les granitoïdes hercyniens : cas du complexe de la Haute Moulouya (Meseta orientale, Maroc) et ses associations shoshonitiques à peralumineuse. Commun. Inst. Geol. e Mineiro. 89 : 249-264

Delvaux D (1993) The TENSOR program for paleostress reconstruction: examples from the east African and the Baikal rift zones. In: Terra Abstracts. Abstract supplement No.1 to
Terra Nova. 5, 216

Delvaux D, Moeys R, Stapel G, Petit C, Levi K, Miroshnichenko A, Ruzhich V, San’kov V (1997) Paleostress reconstructions and geodynamics of the Baikal region, central Asia, Part 2. Cenozoic rifting, Tectonophysics. 282: 1-38

Delvaux D, Sperner B (2003) New aspects of tectonic stress inversion with reference to the Tensor program, Geol. Soc. London Spec. Publ. 212: 75-100

Delvaux D (2012) Release of program Win-Tensor 4.0 for tectonic stress inversion: statistical expression of stress parameters. Geophys. Res. Abstr. 14, EGU2012-5899 EGU General Assembly, Vienna, 2012

Dubar G (1943) Notice explicative de la carte géologique provisoire du Haut-Atlas de Midelt au 1/200.000 (feuille de Midelt et de Rhéris). Notes et Mém. Serv. Géol. Maroc. 59, 1-74

Duthou JL, Emberger A, Lasserre M (1976) Résultats graphiques et interprétation de mesures isotopiques du plomb de galènes et des minéraux oxydés du Maroc. Bull. Soc. Géol. Fr. 7: 221-226

El Jaouani L (2001) Etude géologique et gîtologique des gisements plombifères de la boutonnière d’Aouli (Aouli, Zeïda, Mibladen) Haute Moulouya (Maroc). Unpublished Thesis (Doctorat National). Mohamed V Univresity, Rabat, Morocco, 221 pp

El Mourouah AEA Diot H, El Amrani I, (1993) Les massifs granitiques de la Haute Moulouya : laccolites granitiques en Meseta marocaine orientale. C. R. Acad. Sci, Paris. 317: 1469-1476

Elabouyi M, Dahire M, Driouch Y, Duchêne S, Kriegsman LM, Ntarmouchant A, Kahou ZS, Severac JL, Belkasmi M, Debat P (2019) Crustal anatexis in the Aouli Mibladen granitic complex: A window into the middle crust below the Moroccan Eastern Variscan Meseta. J. Afr. Earth Sci. 154: 136-163

Emberger A (1965a) Introduction à l’étude des minéralisations plombifères de la Haute Moulouya. Notes et Mém. Serv. Géol. Maroc. 181: 197-174

Emberger A (1965b) Eléments pour une synthèse métallogénique du district plombifère de la Haute Moulouya. Notes et Mém. Serv. Géol. Maroc. 181: 235-238

27
Ensslin R (1992) Cretaceous sedimentary tectonics in the Atlas system of Central Morocco. Geol. Rundsch. 81: 91-104

Ensslin R (1993) Die Kreide des Wentrqlen Mittelren Atlas und der Haute Moulouya, Marokko Stratigraphie, Mikrofazies, Palaogéographie und Palaotektonik. Berliner geowiss. Abh. 153 : 1-85

Fedan B (1988) Evolution géodynamique d’un bassin intraplaque sur décrochements : (Moyen-Atlas, Maroc) durant le Méso-Cénozoïque. Unpublished Thesis (Doctorat d’Etat). Mohamed V Univresity, Rabat, Morocco, 338 pp

Felenc R, Lenoble JP (1965) Le gîte de plomb de Mibladen. Notes et Mém. Serv. Géol. Maroc. 181 : 185-204

Fiechtner L, Frieddrichsen H, Hammerschmidt K (1992) Geochemistry and geochronology of early Mesozoic tholeiites from Central Morocco. Geol. Rundsch. 81 : 45 62

Filali F (1996) Etude pétro-structurale de l’encaissant métamorphique de la boutonnière d’Aouli-Mibladen (Haute Moulouya, Maroc) : conséquences sur la géodynamique hercynienne au Maroc. Unpublished Thesis (Thèse 3ème cycle). Muséum national d’histoire naturelle, Paris, France, 173 pp

Filali F, Guiraud M, Burg JP (1999) Nouvelles données pétro-structurales sur la boutonnière d’Aouli (Haute Moulouya) : leurs conséquences sur la géodynamique hercynienne au Maroc. Bull. Soc. Géol. Fr. 4 : 435-450

Frizon de Lamotte D, Zizi M, Missenard Y, Hafid M, El Azzouzi M, Charrière A, Maury RC, Taki Z, Benammi M, Michard A (2008) The Atlas system. In: Michard, A., Saddiqi, O., Chalouan, A., Frizon de Lamotte, D. (Eds.), Continental Evolution: The Geology of Morocco. Springer-Verlag, Heidelberg. 133-202

Ganzeev A, Mitiaev A (1978) Caractéristiques métallogéniques des roches éruptives de la Haute Molouya. Mines, Géologie et Energie, Rabat. 44 : 127-130

Gephart JW, Forsyth DW (1984) An improved method for determining the regional stress tensor using earthquake focal mechanism data: Application to the San Fernando earthquake sequence, J. Geophys. Res. 89 : 9305-9320
Guezal J, El Baghdadi M, Barakat A (2014) The Jurassic–Cretaceous volcanism of the Atlas of Beni-Mellal (Central High Atlas, Morocco): evidence from clinopyroxene composition. Arab J Geosci. DOI 10.1007/s12517-013-1256-z

Hinaje S, Aït Brahim L, Gourari L, et Charroud M, (2001) Evénements tectoniques et paléocontraintes enregistrées par les dépôts néogènes et quaternaires du Moyen Atlas (Maroc). Comm. Inst. Geol. e Mineiro. 88: 255-264

Hinaje S (2004) Tectonique cassante et paléochamps de contraintes dans le Moyen Atlas et le Haut Atlas central (Midelt-Errachidia) depuis le Trias jusqu'à l’actuel. Unpublished Thesis (Doctorat d’Etat). Mohamed V Univresity, Rabat, Morocco, 393 pp

Hoepffner C (1987) La tectonique hercynienne dans l’Est du Maroc. Unpublished Thesis (Doctorat d’Etat). Louis-Pasteur University, Strasbour, France, 280 pp

Hoepffner C, Houari MR, Bouabdelli M (2006) Tectonics of the North African Variscides (Morocco, Western Algeria), an outline. In: Frizon de Lamotte, D., Saddiqi, O., Michard, A. (Eds.), Recent Developments on the Maghreb Geodynamics: C. R. Geosci. 338: 25-40

Hollard H, Bronner G, Marchand J, Sougy J, (1985) Carte géologique du Maroc au 1/1.000.000. Notes et Mém. Serv. Géol. Maroc. 260

Hu JC, Angelier J (2004) Stress permutations: three-dimensional distinct element analysis accounts for a common phenomenon in brittle tectonics. J. Geophys. Res. 109, B09403. http://dx.doi.org/10.1029/2003JB002616

Ibouh H, (2004) Du rift avorté au bassin sur décrochement, contrôles tectonique et sédimentaire pendant le Jurassique (Haut-Atlas centro-oriental, Maroc). Unpublished Thesis (Doctorat d’Etat). Cadi Ayyad University, Marrakech, Morocco, 224 pp

Igmoullan B, Sadki D, Fedan B, Chellai H (2001) Evolution géodynamique du Haut Atlas de Midelt (Maroc) pendant le Jurassique : un exemple d’interaction entre la tectonique et l’eustatisme. Bull. Inst. Sci., Rabat, sect. Sci. Terre. 23: 47-54

Jahn S, Bode R, Lyckberg P, Medenbach O, Lierl HJ (2003) Marokko-Land der Schönen Mineralien und fossilien. Bode Verlag GmbH, Salzhemmendorf, Germany, 535 pp
Jébrak M, Marcoux E, Nasloubi M, Zahraoui M (1998) From sandstone- to carbonate hosted-stratabound deposits: an isotope study of galena in the Upper-Moulouya district (Morocco). Mineralium Deposita. 33 : 406-415

Laville E, Fedan B, Pique A (1991) Déformation synschisteuse jurassique, orogenèse cénozoïque : deux étapes de la structuration du Haut Atlas (Maroc). C. R Acad. Sci. Paris. 312 : 1205-1211

Laville E, Piqué A (1992) Jurassic penetrative deformation and Cenozoic uplift in the Central High Atlas (Morocco): a tectonic model. Structural and Orogenic inversions. Geol. Rundsch. 81 : 157-170

Laville E, Zayane R, Honnorez J, Piqué A (1994) Le métamorphisme jurassique du Haut Atlas central (Maroc) ; épisode synschisteux et hydrothermaux. C. R Acad. Sci. Paris. 318 : 1349-1356

Lhachmi A, Lorand JP, Fabries J (2001) Pétrologie de l'intrusion alkaline mésozoïque de la région d’Amenzi, Haut Atlas Central, Maroc. J. Afr. Earth Sci. 32 : 741-764

Lund B, Townend J (2007) Calculating horizontal stress orientations with full or partial knowledge of the tectonic stress tensor. Geophys. J. Int. 170 : 1328-1335

Margoum D (2015) Genèse des minéralisations fluoro-barytiques ± sulfures du district d’Aouli (Haute Moulouya, Maroc) : apports de la géochimie des REE, des inclusions fluides et des isotopes de Sr et de S. Unpublished Thesis (Doctorat National). Mohammed Premier University, Oujda, Morocco, 157 pp

Margoum D, Bouabdellah M, Klügel A, Banks DA, Castorina F, Cuney M, Jébrak M, Bozkaya G (2015) Pangea rifting and onward pre-Central Atlantic opening as the main ore-forming processes for the genesis of the Aouli REE-rich fluorite–barite vein system, Upper Moulouya District, Morocco. J. Afr. Earth Sci. 108 : 22–39

McFarland JM, Morris AP, Ferrill DA (2012) Stress inversion using slip tendency. C. R. Geosci. 41 : 40-46

Michard A (1976) Elément de géologie marocaine. Notes et Mém. Serv. Géol. Maroc. 252, 408 pp
Michard A, Hoepffne C, Soulaïmani A, Baidder L (2008) The Variscan Belt. In: Michard, A., Saddiqi, O., Chalouan, A., Frizon de Lamotte, D. (Eds.), Continental Evolution: The Geology of Morocco. Springer Verl. 65-131

Michard A, Frizon de Lamotte D, Hafid M, Charrière A, Haddoumi H, Ibouh H (2013) Comment on “The Jurassic–Cretaceous basaltic magmatism of the Oued El-Abid syncline (High Atlas, Morocco): Physical volcanology, geochemistry and geodynamic implications” by Bensalah et al., J. Afr. Earth Sci. 81 (2013) 60–81. J. Afr. Earth Sci. 88, 101-105

Morel JL Zouine EM, Poisson A (1993) Relation entre la subsidence des bassins moulouyens et la création des reliefs atlasiques (Maroc) : un exemple d’inversion tectonique depuis le néogène. Bull. Soc. Géol. Fr.1 : 79-91

Morel JL, Zouine EM, Andrieux J, Faure-Muret A (2000) Déformations néogènes et quaternaires de la bordure nord haut-atlasique (Maroc): rôle du socle et conséquences structurales. J. Afr. Earth Sci. 30 :119-131

Naji M (2004) Les minéralisations plombo-barytiques du district de la Haute Moulouya. Contexte géologique, contrôle tectonique et modèle de mise en place : gisements d’Aouli-Mibladen-Zeida. Unpublished Thesis (Doctorat National). Mohamed V Univresity, Rabat, Morocco, 255 pp

Ouali H, Briand B, EL Maataoui M, Bouchardon JL (2001) Les amphibolites de la boutonnière paléozoïque de Midelt (Haute Moulouya, Maroc) : témoins d’une extension intraplaque au Cambro-ordovicien. Notes et Mém. Serv. Géol. Maroc. 408 : 177-182

Ouarhache D (2002) Sédimentation et volcanismes (effusif et explosif) associés au rifting triasique et infraliasique dans le Moyen Atlas Sud-occidental et la Haut Moulouya (Maroc). Unpublished Thesis (Doctorat d’Etat). Mohamed V Univresity, Rabat, Morocco, 284 pp

Ouarhache D, Charrière A, Chalot-Prat F, El Wartiti M (2000) Sédimentation détritique continentale synchrone d’un volcanisme explosif dans le Trias terminal à Infra-Lias du domaine atlasique (Haute Moulouya, Maroc). J. Afr. Earth Sci. 31 : 555-570

Ouarhache D, Charrière A, Charlot-Prat, F, El Wartiti M (2012) Chronologie et modalités du rifting triassico-liasique à la marge sud-ouest de la Téthys alpine (Moyen
Atlas et Haute Moulouya, Maroc) ; corrélation avec le rifting atlantique : simultanéité et diachronisme. Bull. Soc. Géol. Fr. 183 : 233-249

Oukemeni D (1993) Géochimie, géochronologie (U-Pb) du pluton d’Aouli et comparaisons géochimiques avec d’autres granitoïdes hercyniens du Maroc par analyse discriminante. Unpublished Thesis (Thèse 3ème cycle). Québec University, Montréal, Canada, 141 pp

Oukemeni D, Bourne JH (1994) Etude géochimique des granitoïdes du pluton d’Aouli, Haute Moulouya, Maroc. J. Afr. Earth Sci. 17 : 429-443

Oukemeni D, Bourne JH, Krogh TE (1995) Géochronologie U-Pb sur zircon du pluton d’Aoul, Haute Moulouya, Maroc. Bull. Soc. Géol. Fr. 166 : 15-21

Piqué A, Laville E (1993a) Les séries triasiques du Maroc, marqueurs du rifting atlantique. C. R. Acad. Sci. Paris. 317 : 1215-1220

Piqué A, Laville E, (1993b) L’ouverture de l’Atlantique central : un rejou en extension des structures paléozoïques?. C. R Acad. Sci. Paris. 317 : 325-1332

Praszkier T (2013) Mibladen, Morocco. Mineral Record. 44 : 247-285

Raddi Y, Aarar M, Michard A (2013) Notice explicative de la carte géologique du Maroc au 1/50.000 (feuille de Mibladen). Notes et Mém. Serv. Géol. Maroc. 576

Rahhali M (2002) Gisements stratiformes de Mibladen. In : Barodi E-B, Watanabe Y, Mouttaqi A, Annich M (eds) Méthodes et techniques d’exploration minière et principaux gisements au Maroc. Projet JICA/BRPM, Bureau Recherche Participations Minières BRPM, Rabat. 166-170

Rhinane H (1990) Evolution tectonique et métamorphique de la Boutonnière de Midelt. Unpublished Thesis (Thèse 3ème cycle). Mohamed V Univresity, Rabat, Morocco, 169 pp

Saadi Z (1996) Evolution géodynamique triasico-jurassique de la Haute Moulouya et du Moyen Atlas méridional. Place dans l’évolution méso-cénozoïque du domaine des chaînes atlasiques (MAROC). Unpublished Thesis (Thèse 3ème cycle). Mohamed V University, Rabat, Morocco, 485 pp
Saadi Z (2012) Les bassins triasico-jurassiques de la Haute Moulouya et de la bordure méridionale du Moyen Atlas (Maroc). Contexte sédimentaire et marqueurs géodynamiques. Unpublished Thesis (Doctorat d’Etat). Mohamed V Univresity, Rabat, Morocco, 347 pp

Saadi Z, Fedan B, Laadila M, Kaoukaya A (2003) Les tidalites liasiques de la Haute Moulouya et du Moyen Atlas méridional (Maroc) : dynamique sédimentaire et contexte paléogéographique. Bull. Inst. Sci., Rabat, sect. Sci. Terre. 25 : 55-71

Samir M (1991) Les complexes plutoniques alcalins de la ride de Tazoult (Haut Atlas central, Maroc), pétrographie, minéralogie, géochimie et mécanisme de mise ne place. Unpublished Thesis (Thèse 3ème cycle). Cadi Ayyad Univresity, Marrakech, Morocco, 152 pp

Schmitt JM (1976) Sédimentation, paléogéographie, géochimie et minéralisation en plomb de la série triasique de Zeïda (Haute Moulouya, Maroc). Unpublished Thesis (Doctorat Ingénieur). ENSMP, Paris, France, 97 pp

Tisserant D (1977) Les isotopes du strontium et l’histoire hercynienne du Maroc. Etude de quelques massifs atlasiques et mésétiens. Unpublished Thesis (Thèse 3ème cycle). Louis Pasteur University, Strasbourg, France, 103 pp

Vandycke S, Bergerat F (1992) Tectonique de failles et paléo-contraintes dans les formations crétacées du Boulonnais (Nord France). Bull. Soc. Géol. Fr. 163 : 553-560

Vauchez A (1976) Les déformations anté-triasiques dans la boutonnière d’Aouli-Mibladen (Midelt, Maroc). C. R. Acad. Sci, Paris. 282 : 425-428

Zayane R, Essaifi A, Maury CR, Piqué A, Laville E, Bouabdelli M (2002) Cristallisation fractionnée et contamination crustale dans la série magmatique jurassique transitionnelle du Haut Atlas central (Maroc). C. R. Acad. Sci, Paris. 334 : 97-104

Zouine EM (1993) Géodynamique récente du Haut Atlas. Evolution de sa bordure septentrionale et du Moyen Atlas sud-occidental au cours du Cénozoïque. Unpublished Thesis (Doctorat d’Etat). Mohamed V Univresity, Rabat, Morocco, 303 pp