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The Oumjrane-Boukerzia Mining District (Eastern Anti-Atlas, Morocco): Constraints of its geological and tectono-magmatic setting

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Abstract

Purpose. The purpose of the present research is to provide a new lithological, structural and magmatic features of the Oumjrane-Boukerzia Mining District. The results obtained are used to guide exploration works for identifying the new Cu, Ni, Pb, Zn depositions and Ba-bearing mineralization within the whole Oumjrane-Boukerzia domain.

Methods. This research is based on detailed mapping, structural surveys and geochemical studies performed on the magmatic rocks in the studied area.

Findings. Structural and microstructural analyses of the studied area have revealed three complex polyphase tectonic events related to the Variscan orogeny: (i) an extensive phase during the Devonian period; (ii) a NW-SE compressional phase of Namuro-Westphalian age; (iii) a NE-SW compressional phase of Stephanian-Autunian age, and (iv) an extensive late phase probably related to the opening of the Central Atlantic ocean during the Late Trias-Jurassic periods. The sedimentary rocks of the district are locally intruded by small undated gabbroic intrusions. Geochemically, these gabbroic bodies are described as olivine-rich gabbros with a continental tholeiitic affinity and suggested to be related to the Central Atlantic magmatic province (CAMP) during the Pangea break-up.

Originality. The present study describes the host-rocks and structural events responsible for Cu, Ni, Zn, Pb deposition and Ba-bearing mineralization in the Oumjrane-Boukerzia Mining District (Eastern Anti-Atlas, Morocco).

Practical implications. The geological studies, especially lithostratigraphic, tectonic and magmatism are essential in the mineral exploration. They help exploration geologists identify and define metallotects to discover new minerals.

Keywords: *Anti-Atlas, Oumjrane-Boukerzia, Mining District, Devonian extension, Variscan compression, Central Atlantic magmatic province*

1. Introduction

During the Late Trias-Jurassic (T-J) period, the Pangea break-up led to the opening of the Central Atlantic ocean and its adjacent Tethyan margins [1]. This Atlantic expansion has been resposnible for the establishment of large volumes of tholeiitic basalts called the Central Atlantic Magmatic Province (CAMP) [1], [2] in several widespread basins around the world. However, this large igneous province has conquered a greater regional extent than previously thought [3], [4].

In Morocco, Late Triassic-Early Jurassic magmatism related to the CAMP includes the NE-SW trending of the Foum Zguid and Ighrem dolerite dykes. It is associated with sills swarms of the Draa valley sills, as well as the widespread lava flows scattered over the High Atlas, Middle Atlas, and Meseta . Furthermore, in the neighbouring south-western Algeria terranes, [5]-[7], for a long time, mafic rocks occurring as dykes and sills in the Tindouf, Reggane, Hank basins, and Bechar area, have been considered as part of the large Central Atlantic Magmatic Province (CAMP).

In the eastern Anti-Atlas, small mafic intrusions have been identified in the the Tafilalt and Maider basins. In the Tafilat area, [8] have been attributed these mafic rocks to alkaline series of Devonian age. In contrast, the olivine gabbro from the Oumjrane-Boukerzia area (part of the Maider basin) shows a continental tholeiitic composition. This new geochemical composition is more consistent with the CAMP evolution in the northern edge of the Western African Craton.

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The Oumjrane Boukerzia Mining District is located in the eastern part of the Anti-Atlas at about 50 km as south of of Alnif city and about 90 km NE of the Zagora city. It contains several Cu, Ni, Pb, Zn and Ba mineralized veins. These veins cutting the Upper Ordovician detrital sedimentary rocks have an E-W and NE-SW trending directions.. Based on observations and detailed metallogenic studies, several metallogenic models have been proposed to explain the genesis of mineral concentrations throughout the eastern and central Anti-Atlas [9]-[14]. Thus, many studies suggest that the mineralization associated with the Paleozoic cover of the eastern Anti-Atlas is due to remobilization events of the ores from the Late Neoproterozoic basement by hydrothermal fluids of Variscan and even Alpine age [14].

The present study of the Oumjrane-Boukerzia Mining District involves a multidisciplinary approach, which includes geological mapping, structural and microstructural analysis, field description of the host-rocks and a detailed petrogeochemical study of the olivine gabbro deposited during the CAMP evolution. The main goal of this contribution was to introduce and discuss the occurrence of the olivine gabbro and its possible relationship with the CAMP and so far its role in the genesis of the Cu-Ni mineralization of the Oumjrane-Boukerzia Mining District. Then, in this paper the secondary aim was to define and explore new tools and guides for mineral exploration in the whole eastern Anti-Atlas.

2. Geological setting

The Anti-Atlas corresponds to an ENE-WSW folded Paleozoic belt, revealing several Precambrian inliers. This ENE-WSW chain belt is divided into three main domains which are from south-west to north-easth: the western Anti-Atlas, the central Anti-Atlas and the eastern Anti-Atlas (Fig. 1). The first domain is considered as an eburenean terranes formed by several inliers (e.g: Bas Draa, Ifni, Kerdous, Akka, Ighrem, etc.), the central domain composed of Bou Azzer-El Graara, Zenaga and Siroua inliers which are belonging the Major Anti-Atlas fault. Whereas, the eastern domain is considered as Panafrican terranes which are represented by the Saghro and Ougnat inliers. Regarding the Major Anti-Atlas fault, the Bou Azzer-El Graara and the Siroua inliers are the only well-preserved Neoproterozoic ophiolitic crusts in the northern edge of the West African Craton.

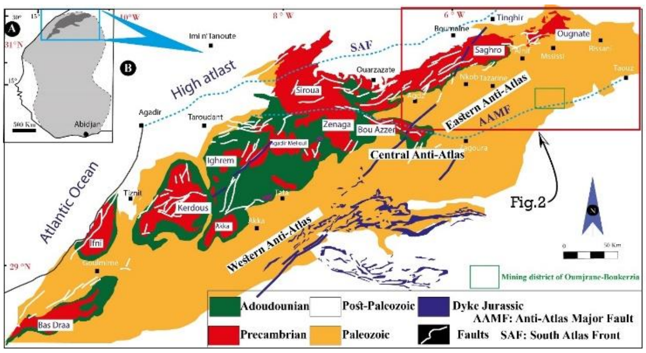

***Figure 1.** Location of the Anti-Atlas in the West African craton with Simplified geological map of the Anti-Atlas [15]*

In the last decades, several geochronological investigations [11], [16]-[21] have been divided the Anti-Atlas into three main domains:

(i) The south-western domain consists of the Lower Paleoproterozoic basement (ca. 2 Ga) unconformably overlain by volcano-sedimentary cover of the Upper Paleoproterozoic to Mesoproterozoic ages. The Lower Paleoproterozoic basement consist of low metamorphic grade silicictastic sediments intruded by several granitic plutons ([21] and references therein). The late-Paleoproterozoic to Mesoproterozoic cover is composed of limestones and quartzites outcrop in almost all the inliers of this domain. This Eburnean domain is cutted by multiple generations of dykes with ages ranging from ca. 1750 Ma to ca. 880 Ma [17], [22]-[25].

(ii) The central Pan-African Domain is represented by the Bou Azzer and Sirwa inliers in the central Anti-Atlas. These inliers are located along the Anti-Atlas Major Fault (AAMF) and host the oldest oceanic crust found in the northern edge of the West African Craton. This oceanic crust is represented by the ophiolitic complexes and their associated arc-magma. In the central domain, two tectonic Pan-African events have been recognized [26]-[28]. The first one termed “the major Pan-African phase” or “B1 phase”, dated at 685 ± 15 Ma; is characterized by recumbent isoclinal folds towards the WSW associated to a metamorphic schistosity in greenschist facies. The second event is the “late Pan-African stage” or “B2 phase”, it deforms the ophiolite as well as the lower Ediacaran series (Tiddiline series), and is dated at 615 ± 12 Ma. It produced upright folds with N115°E subhorizontal axes, accompanied by slaty cleavage.

(iii) The Post Pan-African domain (northeastern Anti-Atlas) is formed by the Upper Neoproterozoic series and consists mainly of the Saghro Group. This later is attributed to Late Cryogenian and Early Ediacaran time and is covered by the younger Bou Salda, Dadès and Mgouna groups [29]-[32].

In the three domains, these old series are unconformably covered by the late Ediacaran series represented by the voluminous volcanic sequence of the Ouarzazate Group and the associated igneous plutons related to the post-collisional stage of the Pan-African orogeny [33]-[37].

During the Paleozoic, the geological history of the Eastern Anti-Atlas (Fig. 2) is that of a stable platform interrupted by epi-orogenic movements of uplift, the main one occurring at the end of the Middle Cambrian which corresponds to a period of erosion [38], [39]. The Ordovician period started by a new transgressive event with a sedimentation resulting in a shallow epicontinental platform environment [40], [41]. The sediments are detrital-types and derived from the erosion of the uplifts of the West African Craton [42]. This period is also characterised by a major glacial event covering the whole of West Africa [43]-[47]. The Silurian is marked by thick series of black shales with graptolithes fossils.

During the Middle Devonian, the Eastern Anti-Atlas is characterized by an extensive phase, controlled by deeply Pan-African faults [39], [48], [49]. This occurred through synsedimentary normal faults [49] arguably due to back-arc extension in the foreland of the Rheic subduction [50] or to the effect of the Rheic subduction slab-pull assuming it occurred along the northwestern flank of the ocean [51], [52]. From the Upper Devonian onwards, the Anti-Atlas is characterized by a detrital sedimentation enriched by inherited fragments from the Precambrian basement. This sedimentation will continue during the Carboniferous age [53].

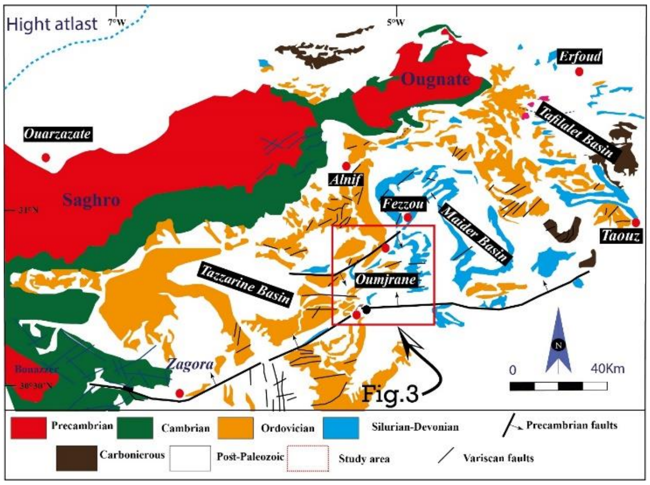

Figure 2. Geological map of the Eastern Anti-Atlas showing the location of the studied area (simplified after [50])

The Variscan orogeny results in the reactivation of inherited faults from the Cambrian-Ordovician and/or Late Devonian rifting events are occurred during the Late Carboniferous to Permian periods [39], [40], [48], [49], [54], [55] and resulted in the uplift of the present-day Precambrian inliers.

The post-Paleozoic to Alpine geological history of the Anti-Atlas is linked to two major events: the first one corresponds to the opening of the Atlantic Ocean in the Mesozoic and the second one is corresponding to the construction of the Atlas Mountains during the Cenozoic era.

3. Material and methods

Within the framework of the exploration and exploitation activities carried out by the mining company of Oumjrane (subsidiary of Managem group) on the mining property of Oumjrane-Boukerzia, this study started with the realization of the geological map and the establishment of a detailed lithostratigraphic column in order to highlight the host rocks of the mineralized bodies of the district. Structural and microstructural analyses of all the brittle and ductile structures were also carried out in order to propose a tectonic model explaining the current configuration of the district. The petrographic study was performed on macroscopic and microscopic observations of a dozen representative samples from different types of magmatic rocks identified in the studied area. These thin sections were prepared and their optical observations are carried out at the department of Geology at the Faculty of Sciences in Meknes (Morocco). These mafic rocks are sampled both in drill cores and and from the field outcrops. These samples were also the subject Whole-rock geochemistry for major elements using X-ray fluorescence, and some representatives traces elements using ICP-MS. These analyses were carried out in the laboratory of the Reminex Research Laboratory of the Managem Group in Marrakech.

4. Results

4.1. Lithostratigraphy context

The Oumjrane-Boukerzia Mining District, covered by a NE-SW trending area of 400 km^2 , is located SE of the Jbel Saghro in the central part of the eastern Anti-Atlas (Fig .2). This area is formed by Lower and Upper Paleozoic terranes and formed part of the Maïder and Tafilalt basins (Fig. 2). This subtabular Paleozoic cover is strongly deformed and exhibits folds with large curvature radius controlled by regional faults.

The lithostratigraphy of the study area ranges from Ordovician to Carboniferous formations (Fig. 3 and 4).

Ordovician formation. The Ordovician formations are the most widespread ones in this area and constitute the main mineralization host-rocks. These terranes, which are mainly detrital, have been subdivided into four groups: the External Faijas Group, the First Bani Group, the Ktaoua Group and the Second Bani Group [42] (Fig. 4). In the Oumjrane-Boukerzia sector, the first Bani outcrops widely in the core of the Boukerzia Anticline and on the Oumjrane-El Fecht track (Fig. 3). It consists alternating sandstone-quartzite and greenish pelites. Towards the top of the series, a red ferruginous level allows to locate the base of the Ktaoua series.

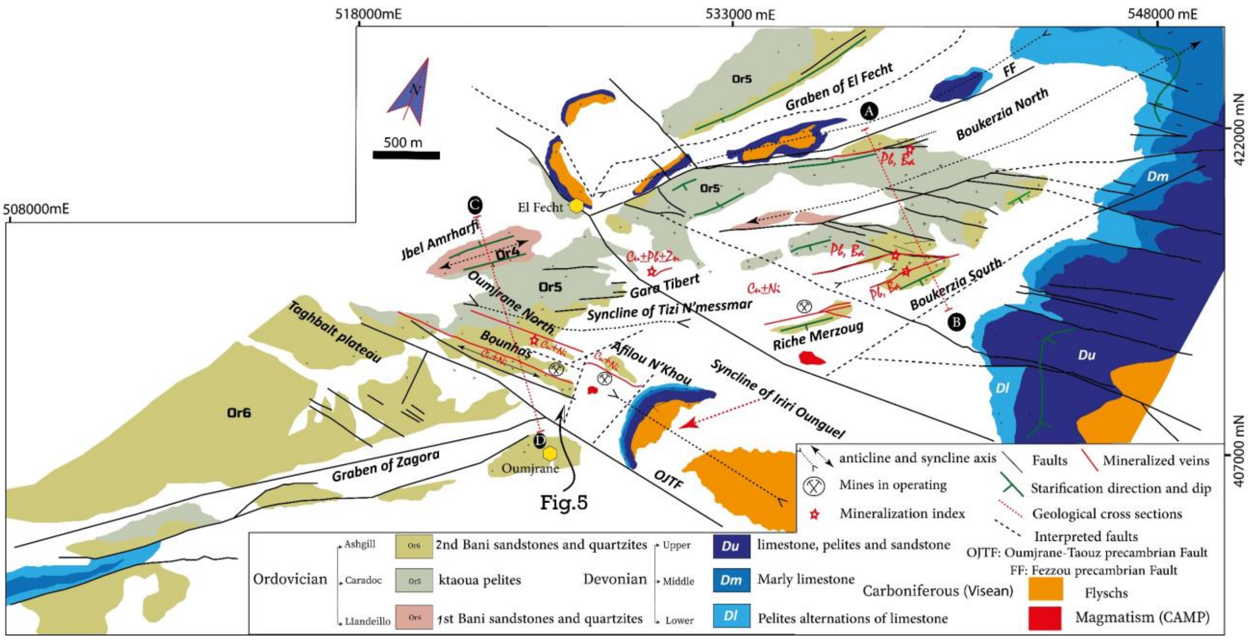

Figure 3. Detailed geological map of the Oumjrane-Boukerzia Mining District (modified after CMO internal document)

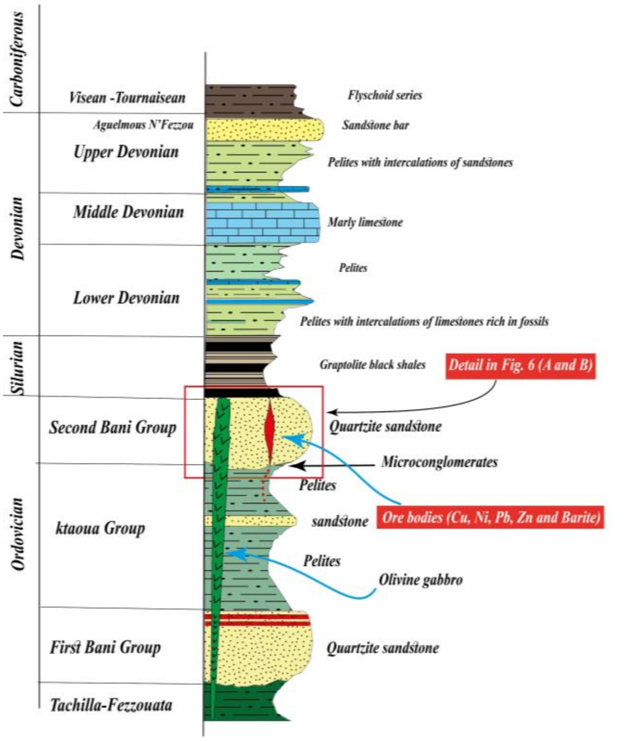

Figure 4. Synthetic lithostratigraphic column of the Oumjrane-Boukerzia

To the west of Boukerzia, the subdivision established by [42] is almost complete (Fig. 5a) and includes the Taddrist, Guezzart, Ouine Inirn and Izegguighne formations. The Bou Zeroual formation is absent. The Ktaoua group is essentially composed of pelitic facies with sandstone levels of different thicknesses and is subdivided into three formations: Lower Ktaoua, Upper Tiouririne and Upper Ktaoua (Fig. 5b, c).

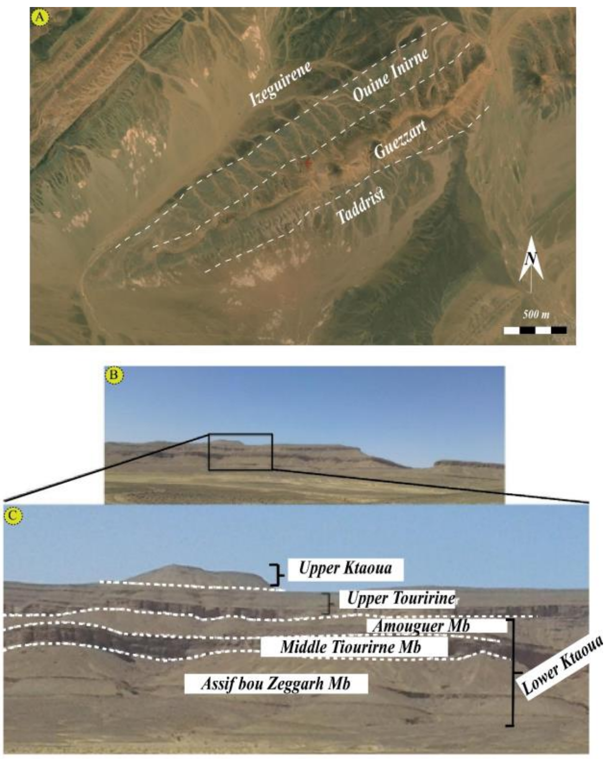

Figure 5. Panoramic views of all the formations of the 1st Bani and Ktaoua group: (a) Google Earth image showing the different members of the first Bani group; (b) panoramic view of the Ktaoua group; (c) details of Ktaoua group

In addition to the formations of the Ktaoua Group, the formations of the Second Bani Group are the most present Ordovician facies in the Oumjrane-Boukerzia Mining District. The studies carried out by [47] in the Bou Ingarf region (Anti-Atlas, Morocco); have allowed us to subdivide the Second Bani group into two main formations (Fig. 6a, b). Lower Second Bani Formation: which overlies the Upper Ktaoua Formation, through the Ouzergui Member of sandstone nature (Fig. 6c) and is formed by deposits with pelitic dominance.

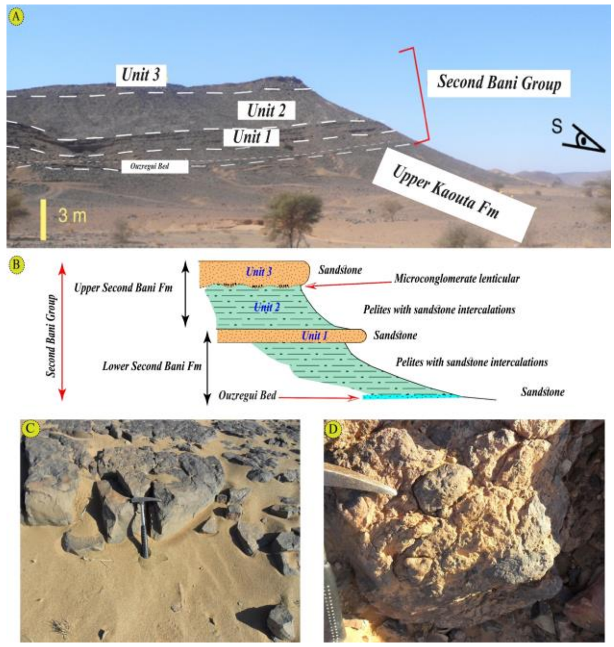

Figure 6. The different lithological units of the Second Bani Group: (a) panoramic view of the Second Bani group in the Tizi N'Messmar Syncline; (b) geological cross-section showing the different formations of the second Bani group in the tizi N'Messmar syncline; (c) reported view of the Ouzregui Bed; (d) detailed view of the microconglomerate lenses at the base of Unit 3 (Upper second Bani formation)

Upper Second Bani formation: is composed itself of four units (Fig. 6b). From bottom to the top, we can distinguish: Unit 1 with sandstone dominance; (ii) unit 2 with pelitic dominance; (iii) Unit 3, predominantly sandstone, is underlain by microconglomeratic lenses recording the glacial paroxysm (Fig. 6d) [42], [56]; and (iv) unit 4 with pelitic dominance at the base and sandstone at the top.

Silurian formation. The Silurian deposits are discontinuous and rarely outcropping in the Oumjrane-Boukerzia sector. They are mapped using their fossil richness (e.g: graptolites; Figure 7) in the depressions dug between the Ordovician sandstone roks and the widespread Devonian o carbonates in the Bounhas and Afilou N'khou areas (Fig. 7a, b).

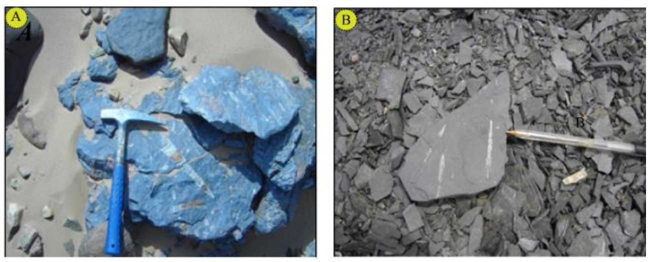

Figure 7. The different lithological units of the Silurian: (a) Ludlow Orthoceras blue limestone (Silurian); (b) Graptolite black shales (Iraoune site)

Devonian formation. The Lower Devonian is marked by its pelitic facies with intercalation of minor fossiliferous limestone beds (Figs. 4, 8 and 9). It comprises three stages: Lochkovian, Praguian and Emsian. The Lochkovian is essentially composed of pelites with a centimetric past of blue limestone with orthoceras (Fig. 9a, b).

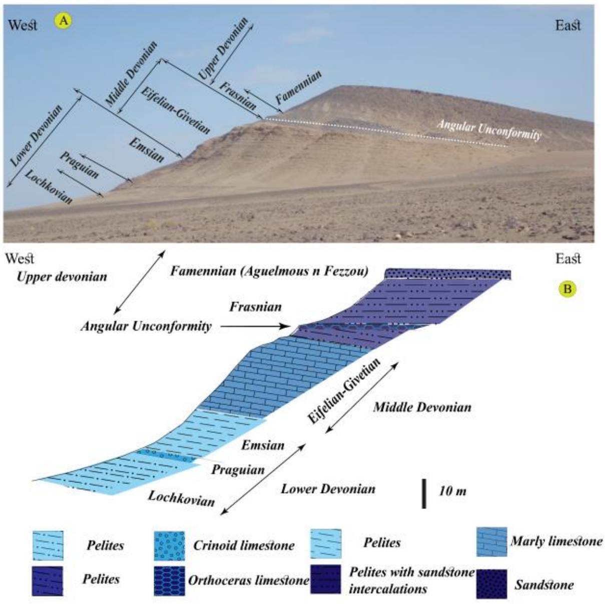

***Figure 8.** Devonian outcrops in the study area: (a) panoramic view showing the subdivision of the Devonian formations in the Iriri Ounguel syncline; (b) geological cross-section showing the different facies identified within the Iriri-Ounguel syncline*

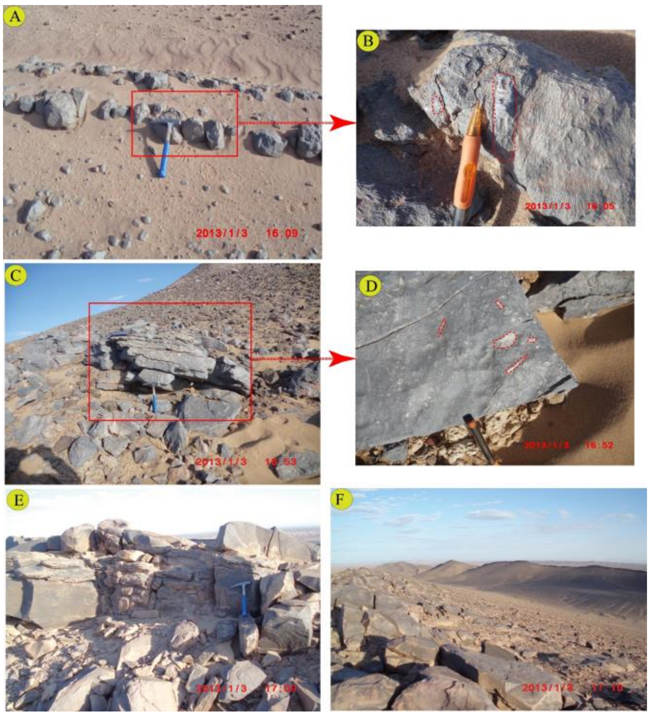

***Figure 9.** The different lithological units of the Devonian: (a), (b) and (c) Lochkovian crinoid limestones (Lower Devonian); (d) limestone band rich in Frasnian fossils; (e) detailed view of all the fossils observed in the Frasnian limestone (Upper Devonian); (f) sandstone band representing the top of the Upper Devonian (Fammenian in the Aguelmous N'Fezzou Fm); (g) carboniferous flyschoid formation*

The Praguian (3 m), formed by pelites at the base and limestones with Crinoids at the top and the Emsian (15 m), composed of greenish pelites. Contrary to the Lower Devonian, the Middle Devonian corresponds to calcareous series with 22 m in thickness. It is rich in marine fossils (e.g: Goniatites), characterizing the Eifelian-Givetian.The Upper Devonian is deposited, in an angular unconformity, on carbonate-dominated formations of Eifelian-Givetian age. It includes the Frasnian and Faminian ; The Frasnian-Famennian formations (20 m) consist of by pelitic series at the base, followed by a centimetric level of gypsum, and then by pelites with sandstone beds (Fig. 9c, d). At the top, it is marked by a sandstone horizon of great lateral extension which underlines the generalized transgression at the end of the Famennian (sandstone of Aguelmous n'Fezzou (Fig. 9e).

Carboniferous formation. The only Carboniferous outcrops are found in Tadaout N'Oumjrane area. This carboniferous facies are marked by detrital sediments (flyshoid serie) with thick series of pelitic and sandstone rocks at the top of the formation (Fig. 9f).

4.2. Structural context

Field works carried out in the studied area have been allowed us to distinguish two types of deformation affecting the geological formations of the district. The first type is a ductile and the second one is a brittle deformation (Fig. 10).

Ductile deformation. The ductile deformation in the Oumjrane-Boukerzia Mining District is essentially manifested by E-W and NE-SW trending folds (Fig. 10 and 11). These folds are characterized by large curvature radius and they are controlled by several fault corridors, considered as typical of the foreland of the Hercynian chain [50], [57].

Brittle deformation. In addition to the ductile deformation affecting the area, the mapping surveys have revealed a fairly significant brittle tectonic style. Statistical analysis of these fault planes has allowed us to distinguish two major fault families: E-W to WNW-ESE and NE-SW to ENE-WSW (Fig. 10).

E-W (and WNW-ESE) trending faults. The E-W fault family is the most dominant in the Bounhas domain. It is inhereted from the Precambrian Oumjrane-Touaz fault. This fault is responsible for the sub-E-W trending direction of Zagora graben [39]. Several branches of these E-W striking faults are mineralized in Cu ± Ni (e.g: Bounhas, Oumjrane North and Afilou N'Khou faults). The structural analysis of this family of faults has identified a polyphasic event (Fig. 12): (i) an early extensive stage during the Eovariscan orogeny (Middle Devonian), identified by the presence of patch reef limestones of Eifelian-Givetian age, affected by a network of synsedimentary faults (Fig. 12a); (ii) a dexteral motion materialized by subhorizontal striations (Fig. 12c); (iii) reverse sinister movement (Fig. 12d); (iv) the extensive avent is marked by a banded texture where mineralization appears to be developed essentially in the center of the veins (Fig. 12e).

NE-SW trending faults. This is the most expressed fault family in the Boukerzia domain. It is mainly represented by the Precambrian Fezzou Fault (FF) [49], which delimits the Boukerzia domain to the north-west (Fig. 13a). Some of these faults are mineralized in Pb + Ba. Structural surveys have revealed a polyphase event affecting this family of faults (Fig. 13). (i) extensive event during the Eovaric phase; (ii) a reverse dextral movement (Fig. 13b); (iii) a sinistral motion (Fig. 13c); (iv) a late, purely extensive style responsible for the formation of the ore bodies in the mining district (Fig. 13d).

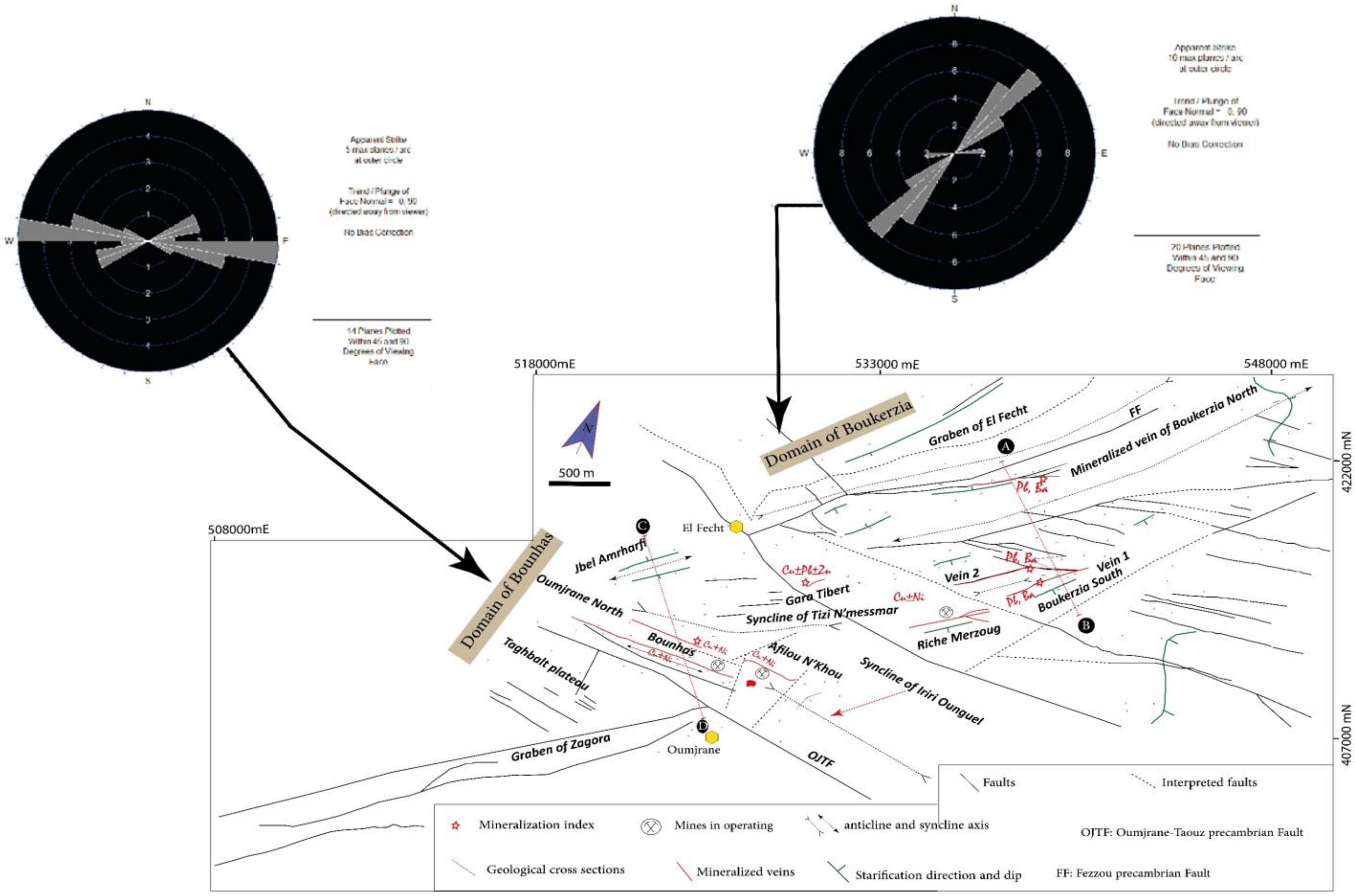

Figure 10. Detailed structural map of the Oumjrane-Boukerzia Mining District

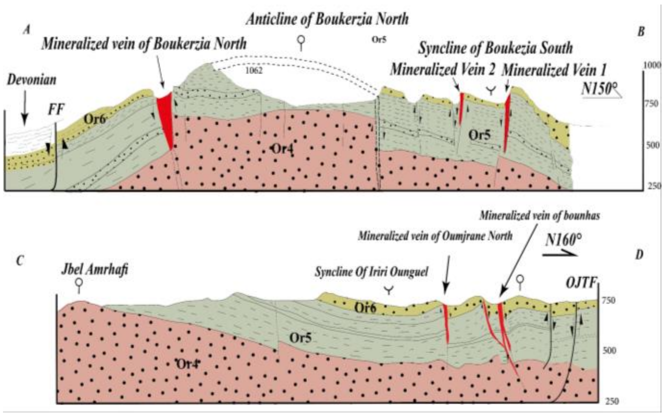

Figure 11. Geological sections (AB and CD) of the Oumjrane-Boukerzia Mining District (modified after CMO internal document). See cross-section line-transect in Figure 10. (FF: Fezzou Precambrian Fault; OJTF: Oumjrane-Taouz Precambrian Fault; Or4: 1st Bani; Or5: Ktaoua Group; Or6: 2nd Bani Group)

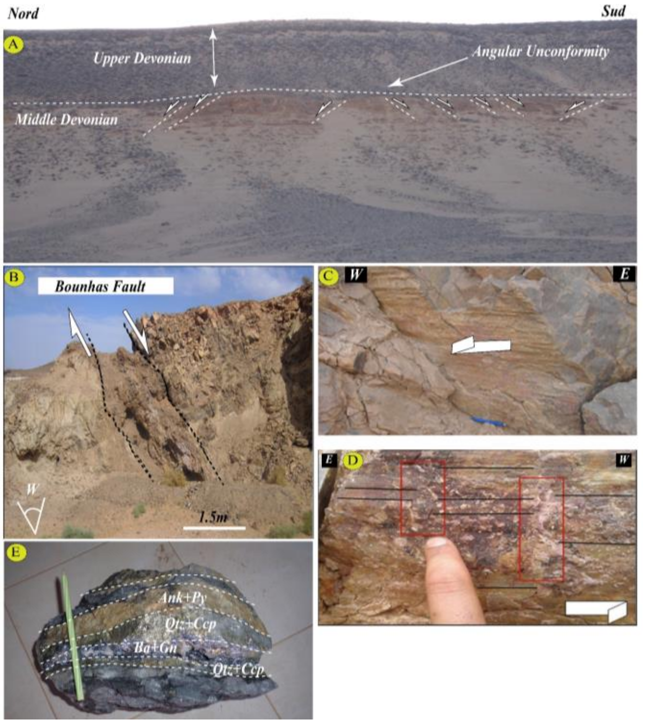

Figure 12. The different indicators of tectonic movements affecting the Bounhas domain: (a) extensional tilted blocks in Middle Devonian limestones, sealed by Upper Frasnian-Famennian layers (Late Devonian); (b) close-up view of the Bounhas mineralized fault with late reverse movement; (c) subhorizontal slickensides indicate the dextral movement; (d) subhorizontal slickensides indicate the sinistral movement; (e) banded texture indicating an extensive system of mineralization emplacement

4.3. Magmatic context

Petrography. Detailed mapping carried out has evidenced the presence of magmatic rocks in the Oumjrane-Boukerzia Mmining District. These rocks outcrop in the form of small plutons in the south of the mine of Afilou N'khou and at the east of the Riche Merzoug mine (Fig. 3).

Macroscopically, the rock is fresh, dark to greenish-gray color, massive and comprises mainly automorphic to sub-automorphic phenocrysts of millimeter to centimeter size of plagioclase and pyroxenes. The microscopic investigations revealed an olivine gabbro with coarse- grained texture.

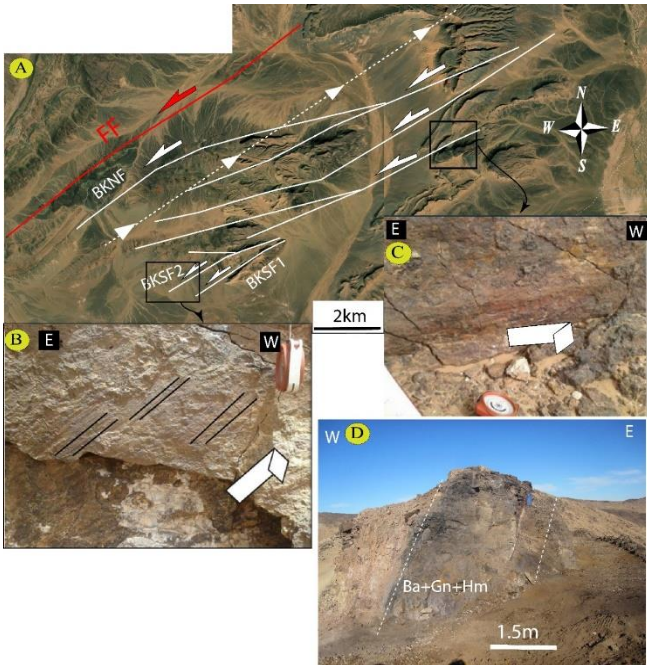

Figure 13. The different indicators of tectonic features affecting the Boukerzia domain: (a) interpreted Google Earth satellite image, showing the main tectonic structures affecting the Boukerzia domain; (b) striations within slickensides showing a dextral reverse movement observed on the NE-SW faults; (c) subhorizontal slickensides indicate sinistral movement; (d) powerful ore body indicating an extensive mode of emplacement

The mineral composition consists of clinopyroxene, plagioclase, olivine; amphibole, apatite and opaque minerals (Fig. 14a, b). The rock is strongly enriched in magnetic minerals. Due to the intense hydrothermal alteration, the primary minerals are partially or totally transfomed into secondary mineral paragenisis. This mineral paragenisis is composed of sericite, amphibole and serpentine (Fig. 14c, d).

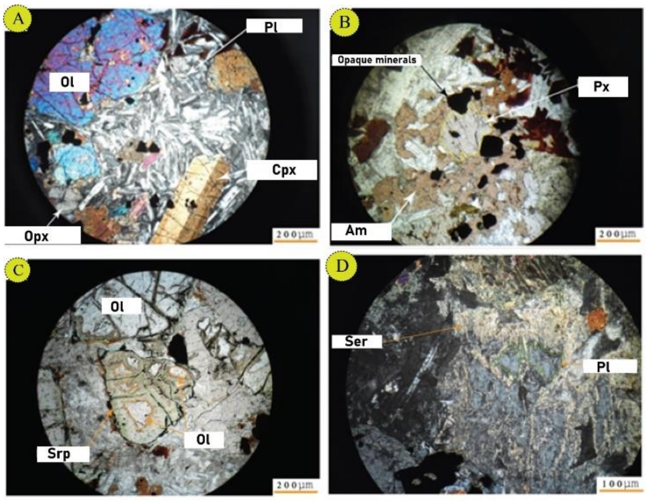

Figure 14. Photomicrographs showing the mineral paragenesis of the studied rocks: (a)-(d) phtomicrographs of olivine-bearing gabbro; Sericitized (Ser) plagioclases (Pl), Uralitization (Am) of pyroxenes (Px), serpentinized (Srp) olivine (Ol). (transmitted light-crossed nicols

Geochemistry. The geochemical analyses of the samples are reported in Table 1. The gabbro of the Oumjrane district have SiO_2 ranging from 47.18 to 51.67 wt. % and plot in the sub-alkaline gabbro field in the SiO_2 versus $Na_2O + K_2O$. The MgO contents of this mafic rock range from 5.16 to 7.3 wt. %. Furthermore, the TiO_2 contents are low and range from 1.61 to 1.93 wt. %. P_2O_5 are also low and ranges from 1.23 to 1.32 wt. %. These chemical compositions are very differents from the gabbroic rocks of the Tafilat basin [8], [58]. According to [8], these rocks show low SiO_2 contents ranging from 40.63 to 45.02 wt. % and high TiO_2 composition ranging from 2.25 to 2.63 wt. %. The P_2O_5 contents are also variables and range from 1.24 to 2.67 wt. %. The Tafilalt gabbros are characterized by their high CaO, Na_2O and K_2O contents against the Oumjrane gabbroic ones. These gechemical data have been allowed to [8] to classify the gabbroic rocks of the Tafilalt basin as a sodic-alkaline magma composition related to the Eovariscan extensional phase.

Using the ($Na_2O + K_2O$) versus SiO_2 binary diagram of [59] (Fig. 15a), the analyzed samples are plotted within the sub-alkaline gabbro field. This gabbro exhebit a definite thoeiite composition using the AFM diagram [60] (Fig. 15b). these analyzed samples reveal again a continental tholeiitic tendency using the TiO_2-K_2O-P_2O5 discrimination diagram of [61] (Fig. 15c). The same conclusion was revealed using TiO_2 versus Y/Nb binary diagram of [62] (Fig. 15d).

5. Discussion

5.1. Structural model of the Oumjrane-Boukerzia Mining District

The structural interpretation of the established geological map of the Oumjrane-Boukerzia area (Fig. 1) has allowed us to propose a tectonic model for the polyphased Variscan activities happened in the Oumjrane-Boukerzia Mining District. During the Middle Devonian, several regional faults acted as normal faults in response to the NS to NW transtensional tectonic regime. The most important are the Fezzou and Oumjrane-Taouz faults. This extensive tectonics has been widely described in the past decades at the eastern Anti-Atlas [48], [49], [54], [55], [63]-[70]. The NE-SW faults, dominant in the NE end of the district, correspond to secondary faults of the Pan-African Fezzou Fault. The E-W faults, abundant in the southern part of the district, correspond to secondary faults of the Pan-African Oumjrane-Touaz Fault (Fig. 16).

During the first phase of the Variscan orogeny (D1), the deformation of the studied area is associated with NW-SE compression giving rise to dextral motion along the E-W faults, NE-SW open folds and reverse sinisteral movements on NE-SW faults. During the second stage of the Variscan orogeny (D2), the deformation stress was changed from NW-SE to NE-SW direction and was responsible for the reverse sinistral displacement along the E-W d faults and the sinistral motion on the NE-SW faults. These results argue the previously described and discussed compressive tectonic events (D1 and D2) troughout past times in the eastern Anti-Atlas [15], [40], [48], [49], [54], [55], [57], [65], [68].

During the Upper Triassic period, the Oumjrane-Boukerzia Mining District is later affected by extensive tectonics probably related to the rifting of the central Atlantic. This event has been documented in the eastern Anti-Atlas [55], [71] and is marked by the emplacement of the large dolerite dykes of tholeiitic composition of Foum Zguid and Ighrem. In the study area and on the basis of the aforementioned geochemeical data, the Atlantic rifting is probably responsible for the emplacement of gabbroic magmatic bodies of tholeiitic affinity and several ore bodies mineralized in Cu, Ni, Pb, Zn and barite.

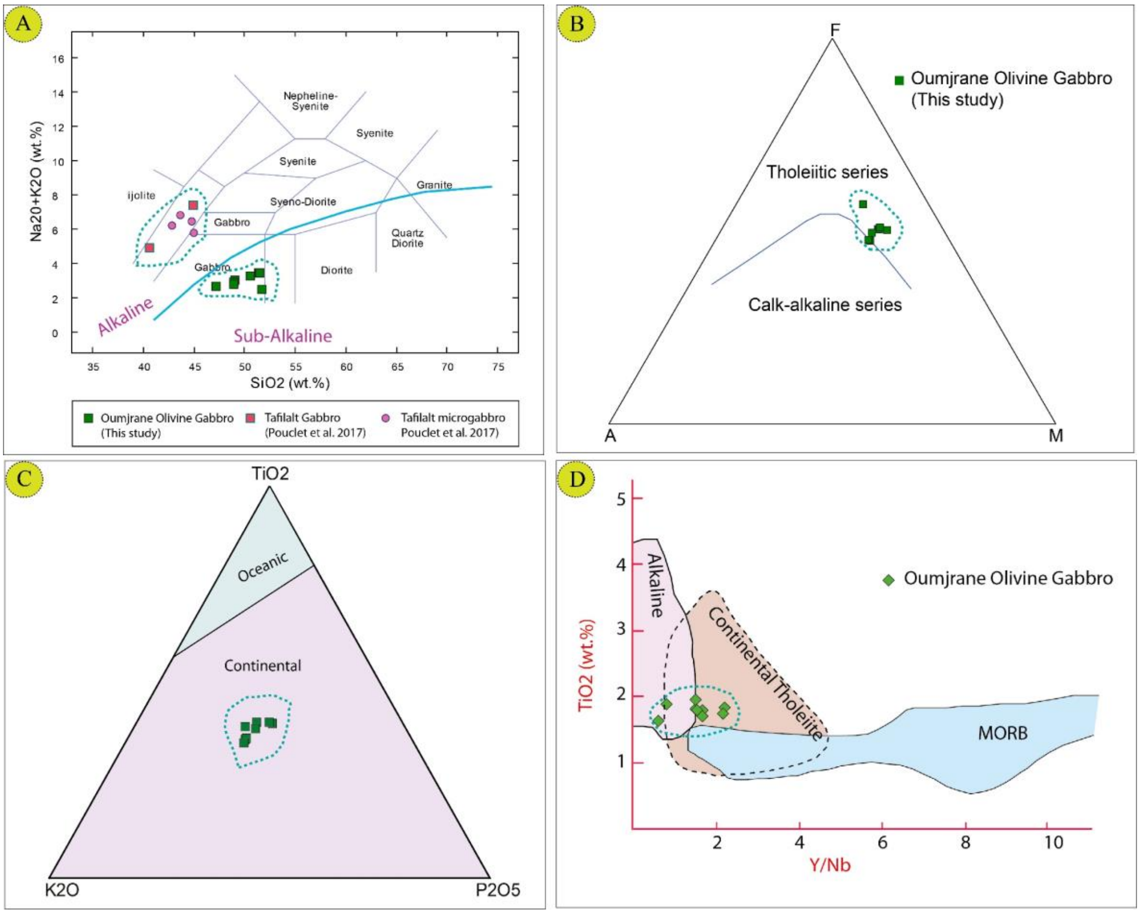

Figure 15. Classification diagrams: (a) classification of the gabbroic magmatic rocks of the Oumjrane-Boukerzia mining district in the TAS diagram (after [59]); (b) AFM diagram showing the tholeiitic affinity of the magmatic rocks of the area [60]; (c) and (d) TiO_2-K_2O-P_2O_5 diagram (after [61] and TiO_2-Y/Nb binary diagram of [62] showing a continental theleitic character of gabbroic rocks)

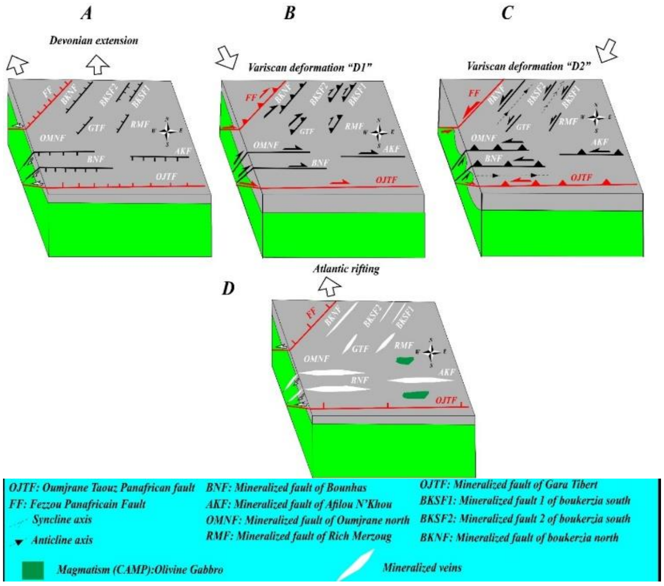

Figure 16. Block diagrams showing the kinematic evolution of the main faults affecting the Oumjrane-Boukerzia Mining District: (a) major Pan-African normal faults (OJTF and FF) developing secondary faults mineralized during Devonian extension; (b) the effect of the Variscan deformation (D1) on the Oumjrane-Boukerzia Mining District; (c) the effect of the Variscan deformation (D2) on the Oumjrane-Boukerzia Mining District; (d) the extensive post-Variscan phase (Atlantic rifting), with the setting of the mineralized veins and the magmatic bodies of the district

5.2. Possible age of gabbroic plutons

The petrographic and mineralogical studies carried out on the olivine gabbro allowed to highlight a mineralogical composition formed essentially by: pyroxene, olivine and plagioclase. The geochemical features of these magmatic facies confirm a continental tholeiitic character of these intrusive rocks. In the absence of geochronological data, the age of emplacement of these gabbroic rocks is still problematic in this area. However, similar rocks have been studied and dated in the eastern Anti-Atlas, particularly, in the Maïder [72], Tafilalt basins [8] and in the southwestern domain of Algeria [5], [6].

The Tafilalt magmatism consists mainly of doleritic basalts, gabbros, lamprophyres and olivine basalt [8]. These mafic rocks show an alkaline affinity and were emplaced during two magmatic events [8]: 1 – an early event, during the Upper Devonian (Famannian-Tournaisian) and 2 – a late event during the Visean. This magmatic activity is attributed to the Upper Devonian-Lower Carboniferous [8]. According to [58], the Tafilalt magmatic bodies were emplaced during an extensive pre-rift event in the Late Permian period.

In the Maïder basin, the gabbroic rocks have been recognized and they are composed mainly of clinopyroxene, biotite and plagioclase. geochemically, these rocks display an alkaline affinity. Based on K/Ar method on biotite, these mafic rocks have yielded an age of ca. 140 Ma [72].

South-eastward in Algeria terranes and more precisely in the Bechar, Reggane, Hank and Tindouf basins, numerous magmatic manifestations have been identified and studied by [6]. Petrographically, these rocks display a mineralogical composition of doleritic and rare basaltic lava flows. Chemically, they are homogeneous and show acontinental tholeiitic affinity. These magmatic manifestations are part of the Large Central Atlantic Magmatic Province (CAMP = 200 Ma) [6] (Fig. 17).

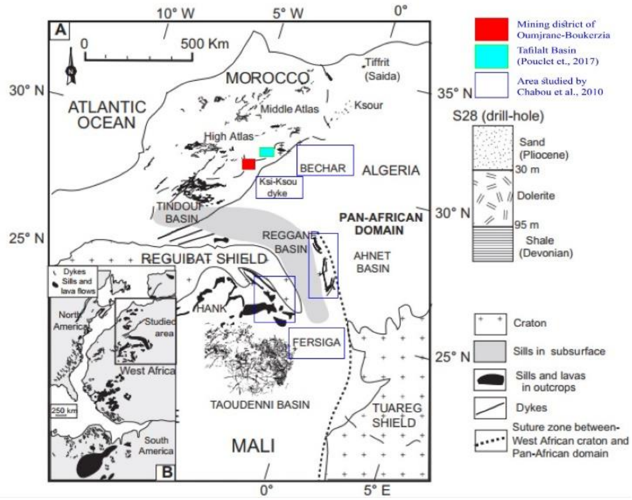

Figure 17. Magmatism of the CAMP Province in the North Afica: (a) geographic location of the Oumjrane-Boukerzia Mining District (studied area), the Tafilalt Basin and the Algerian areas studied by [6] in a schematic map showing the CAMP magmatism of Northwest Africa [6]; (b) general map of the CAMP provinces, modified from [1], [2], [73], [74]

The magmatic intrusions of the Oumjrane-Boukerzia Mining District show many similarities with their nearby magmatic bodies of the southwestern Algeria. This magmatic event isprobably connected to the large Central Atlantic Magmatic Province (CAMP) along the north-eastern edge of Western African Craton.

6. Conclusion and further perspectives

On the basis of the aforementioned studies, the main concluding remarks of this work are the following:

– the Oumjrane-Boukerzia Mining District is composed essentially of detrital sedimentary formations of Ordovician, Devonian and Carboniferous ages. The Ordovician Fm. is formed by alternating sandstone-quartzite bars and pelites. The Devonian Fm. is essentially pelitic at the base, carbonated in the center and sandstone-pelite at the bottom. The Carboniferous Fm. is characterized by an essentially flyschoid sedimentation;

– the Oumjrane-Boukerzia area is affected by a very complex and polyphased tectonic events related to the Variscan orogeny. Four phases of deformation have been identified: (i) an extensive Pre-Variscan phase during the Devonian age; (ii) a Late-Variscan compressive phase (D1) related to the NW-SE compression of Namuro-Westphalian age, (iii) a late-Variscan phase, attributed to the NE-SW compression of Stephano-autunian age and (iv) extensive phase attributed to the opening of the central Atlantic ocean;

– the sedimentary rocks of Oumjrane-Boukezia area include a plutonic magmatic rock. The petrographic investigations classified this mafic rock as an olivine gabbro. Chemically, the rock shows a continental tholeiitic composition. The age of emplacement can be probably related to Central Atlantic rifting (Upper Triassic-Lower Jurassic (CAMP);

– the ore bodies of the Oumjrane-Boukerzia Mining District are hosted in detrital sedimentary rocks of the Upper Ordovician, precisely in the sandstone-pelitic formations of Unit 3 of the Upper Bani Formation. These veins are girdled by E-W and NE-SW faults. These faults correspond to the secondary faults of the major Precambrian faults (Fezzou fault and Oumjrane-Taouz fault);

– the mineralized bodies in the district show banded textures, reflecting an extensive emplacement mode which could be linked with the Central Atlantic rifting.

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Гірничодобувний район Оумджрейн-Букерзія (Східний Анти-Атлас, Марокко): обмеження його геологічного та тектоно-магматичного середовища

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Мета. Дослідження літологічних, структурних та магматичних особливостей гірничодобувного району Оумджрейн-Букерзія для забезпечення керівництва геологорозвідувальними роботами з виявлення нових відкладень Cu, Ni, Pb, Zn та Ba-вмісної мінералізації в межах всієї площі.

Методика. Це дослідження ґрунтується на детальному картографуванні, структурних зйомках та петрографічних і геохімічних дослідженнях магматичних порід досліджуваної території. Зразки порід відбиралися як із бурових кернів, так і з польових відслонень.

Результати. Виявлено на основі структурного та мікроструктурного аналізу досліджуваної території три складні поліфазні тектонічні зміни, пов'язані з Варісканським орогенезом: (i) екстенсивна фаза протягом Девонського періоду; (ii) фаза стиснення з північного заходу на південний схід Намуро-Вестфальського віку; (iii) фаза стиснення у північно-східному/південно-західному напрямках Стефансько-Автунського віку; (iv) обширна пізня фаза, ймовірно, пов'язана з відкриттям центральної частини Атлантичного океану в пізньому Тріас-Юрському періоді. Визначено, що осадові породи району подекуди локально прорвані невеликими недатованими габровими інтрузіями, які геохімічно описуються як багаті на олівін з континентальною толеїтовою спорідненістю та припускають, що вони пов'язані з Центрально-Атлантичною Магматичною Провінцією (ЦАМП) під час розпаду Пангеї.

Наукова новизна. Досліджено особливості вміщуючих порід та структурних змін, що відповідальні за відкладення родовищ Cu, Ni, Zn, Pb та Ba-вмісну мінералізацію в гірничодобувному районі Оумджрейн-Букерзія (Східний Анти-Атлас, Марокко).

Практична значимість. Геологічні дослідження, особливо літостратиграфічні, тектонічні та магматичні, є необхідними та важливими у розвідці корисних копалин, які допомагають геологам-розвідникам ідентифікувати та визначати металотекти для відкриття нових корисних копалин.

Ключові слова: *Анти-Атлас, Оумджрейн-Букерзія, гірничодобувний район, Девонський період, Варісканське стиснення, Центрально-Атлантична Магматична Провінція (ЦАМП)*