Bull. Min. Res. Exp. (2020) 161: 13-32

Bulletin of the Mineral Research and Exploration

http://bulletin.mta.gov.tr

The role of variscan shortening in the control of mineralization deposition in Tadaout-Tizi N'rsas mining district (Eastern Anti-Atlas, Morocco)

Mustapha AIT DAOUD[a]*, Abdelhafid ESSALHI[a], Mourad ESSALHI[a] and Abdeslam TOUMMITE[a]

[a]*Géophysique, Géoresources et Patrimoine, Faculté des Sciences et Techniques, Université Moulay Ismaïl, BP. 509, Boutalamine, 52000 Errachidia, Maroc*

Research Article

Keywords:
Tadaout-Tizi n'Rsas Anticline, Tafilalet, Eastern Anti-Atlas, Variscan Shortening, Normal Faults.

ABSTRACT

The abundance of the NE-SW direction veins mineralized in barite, copper, lead and zinc in the Tadaout-Tizi n'Rsas (TTR) anticline make this area one of the principal vein fields in Tafilalet (easternmost border of the Eastern Anti-Atlas). Reactivation of faults and alternation of competent (thicks Ordovician series, Silurian limestone and Devonian limestone) and incompetent levels (Silurian shales and Devonian marls) have an important role in the deformation of the TTR anticline during the NE-SW Variscan shortening. Our work based on lineaments extraction using a Landsat 8 OLI combined with some geological cross sections, shows a N130° major fold corresponding to TTR anticline. This big fold shows internal N130°, N95° and N20° minor folds. This structure indicates that the TTR area was formed in the hinge between the Anti-Atlas and the Ougarta belts. A number of these folds are the consequence of the underlying Precambrian faults reactivation and alternation of competent and incompetent levels. Brittle tectonics is dominated by NE-SW normal faults which result from the NE-SW shortening consequence of the Gondwana and Eurasia continents collision. Consequently, the mineralization of TTR is necessarily related to late or post-Variscan orogeny.

Received Date: 19.07.2018
Accepted Date: 16.01.2019

1. Introduction

The Tafilalet region corresponds to the easternmost part of the Moroccan Anti-Atlas. This region, principally formed by Paleozoic formations, was the subject of several studies; biostratigraphic and sedimentological ones (Choubert, 1943; Termier ve Termier, 1948; Destombes, 1963, 1968, 1971, 2006; Hollard, 1967, 1974, 1981; Wendt, 1985; Raddi vd., 2007; Brachert vd., 1992), and paleogeographic, paleobathymmetric or paleoecological ones (Mounji et al., 1998; Belka, 1998; Hilali et al., 1999; 2001). The geological mapping of this area corresponds to 1/200.000 map sheet of Tafilalet-Taouz (Destombes and Hollard, 1986), whereas the most important metallogenic work was realized on the M'Fis deposit (Makkoudi, 1995). More recently, some tectonic and magmatic studies were performed (Baidder et al., 2016; Pouclet et al., 2017; Robert-Charrue, 2006). Over the last two decades, the National Geological Mapping Program [Programme Nationale de la Cartographie Nationale (PNCG)] produced several geological maps with the scale of 1/50.000, like Irara, Marzouga, M'Fis, Taouz and El Atrous which contains our study area (TTR).

This work focusses on the tectonic control of the TTR deposit and discusses the role of Variscan shortening in the formation of a geometric trap, and the rock mechanical behavior changing. A structural

Citation Info: Ait Daoud, M., Essalhi, A., Essalhi, M., Toummite, A. 2020. The role of variscan shortening in the control of mineralization deposition in Tadaout-Tizi N'rsas mining district (Eastern Anti-Atlas, Morocco). Bulletin of the Mineral Research and Exploration, 161, 13-32. https://doi.org/10.19111/bulletinofmre.524167

* *Correponding Author: Mustapha AIT DAOUD, aitdaoud.mus@gmail.com*

model of the deposit will be considered as an exploration guide in the Tafilalet region.

The Tafilalet region has a big mining vocation; it has been the site of lead-zinc production in the past, but now the exploitation concerns mainly the barite ore bodies. The main vein fields of Tafilalet are M'Fis, Shayb Arras, Njakh, Bouizrane, Ras Kammouna, Bou Mayz, Tijekht and TTR. The latter comprises more than twenty veins of Cu, Pb, Zn and barite. The present paper aims to analyze and understand the relationship between the Variscan tectonics and the large distribution of mineralized veins in TTR.

2. Geological Framework and Previous Works

Geographically, The TTR anticline is located in the south of Erfoud, and in the southwest of the touristic dunes of Merzouga, precisely in the NW part of Taouz village. It extends more than 16 km between 30°54' and 31°00'N latitudes, and between 4°00'W and 4°14'W longitudes. It is located in the easternmost part of the Anti-Atlas belt, in the south-eastern part of Ougnat-Ouzina Ridge, between the Tafilalet plain (east) and the Maider basin (west) (Figure 1).

Moroccan Anti-Atlas, located at the northern rim of the West African Craton (WAC), is laterally limited by the Atlantic Ocean to the west and by the Hamada in the east. This chain corresponds to a large Paleozoic folded belt formed by a number of Precambrian inliers affected by Eburnean and Pan-African orogeneses. As a result of the post-Variscan erosion, the Precambrian rocks are exposed in the center of all inliers. The Anti-Atlas is considered as an arch continued southwest into the Zemour belt and southeast into the Ougarta belt (Haddoum et al., 2001) (Figure 2).

The Anti-Atlas belt display an ENE-striking where Precambrian basement is exposed in an ENE–WSW series that outcrops in several inliers (Bas Draâ, Ifni, Kerdous, Tagragra of Akka, Tagragra of Tata, Igherm, Sirwa, Zenaga, Bou Azzer, Saghro and Ougnat). All these inliers are distributed along two major fault zones: the South Atlas Fault (SAF) and the Anti-Atlas Major Fault (AAMF) (Choubert, 1964; Gasquet et al., 2008, 2005; Thomas et al., 2004) (Figure 3). This Precambrian basement is an assemblage of crystalline, metamorphic and sedimentary rocks. We can, then, distinguish two assemblages: (i) an older Paleoproterozoic substratum (~2 Ga) structured during the Eburnian orogenesis and (ii) a more recent Neoproterozoic cover associated with the Pan-African cycle (800 - 560 Ma). Classically, the Precambrian formations of the Anti-Atlas are divided into two domains from west to east: (i) a cratonic domain where Proterozoic substratum outcrop and belong to the WAC, and (ii) a Pan-African mobile domain where only the Neoproterozoic formations outcrop (Choubert, 1964). Cratonic and mobile domains are separated by the AAMF (Choubert, 1947).

The Paleozoic cover of the Anti-Atlas Precambrian inliers is predominantly deposited in a shallow marine environment. During the Lower Cambrian, an important carbonate platform was deposited in the western Anti-Atlas (Boudda et al., 1979; Geyer and Landing, 1995). Deposits from Middle Cambrian to

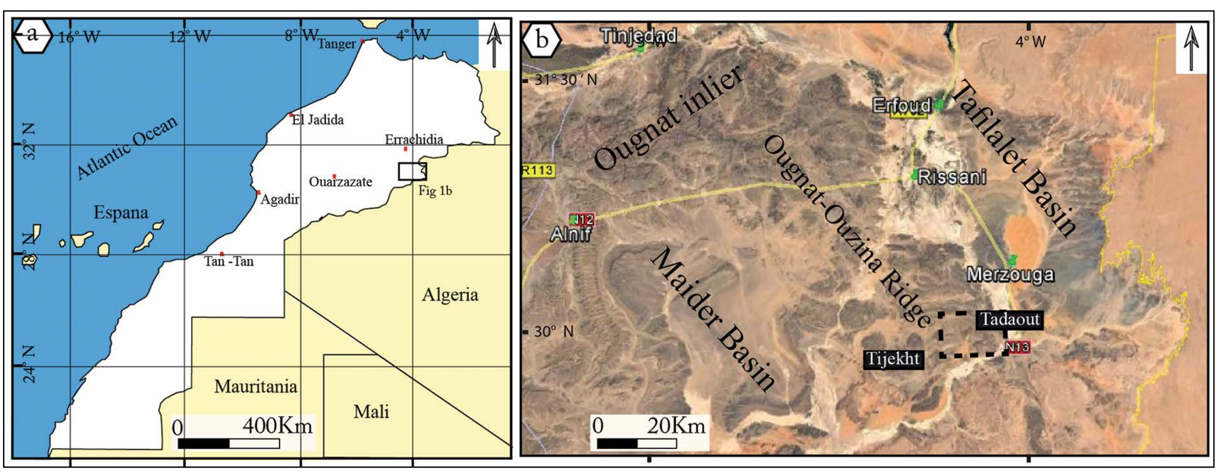

Figure 1- a) Geographic map of Morocco and b) Google maps image showing the eastern part of the Eastern Anti-Atlas. Dashed black rectangle in b indicates the study area.

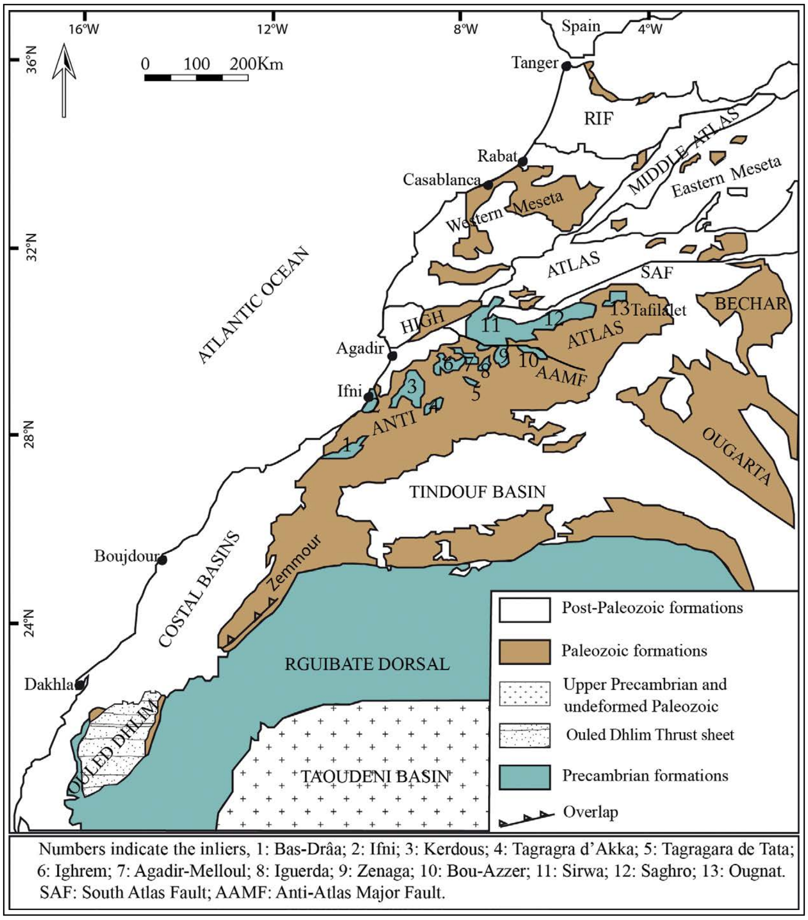

Figure 2- Moroccan structural domains. The Anti-Atlas belt is located between Zemmour and Ougarta belts (Pique, 1994).

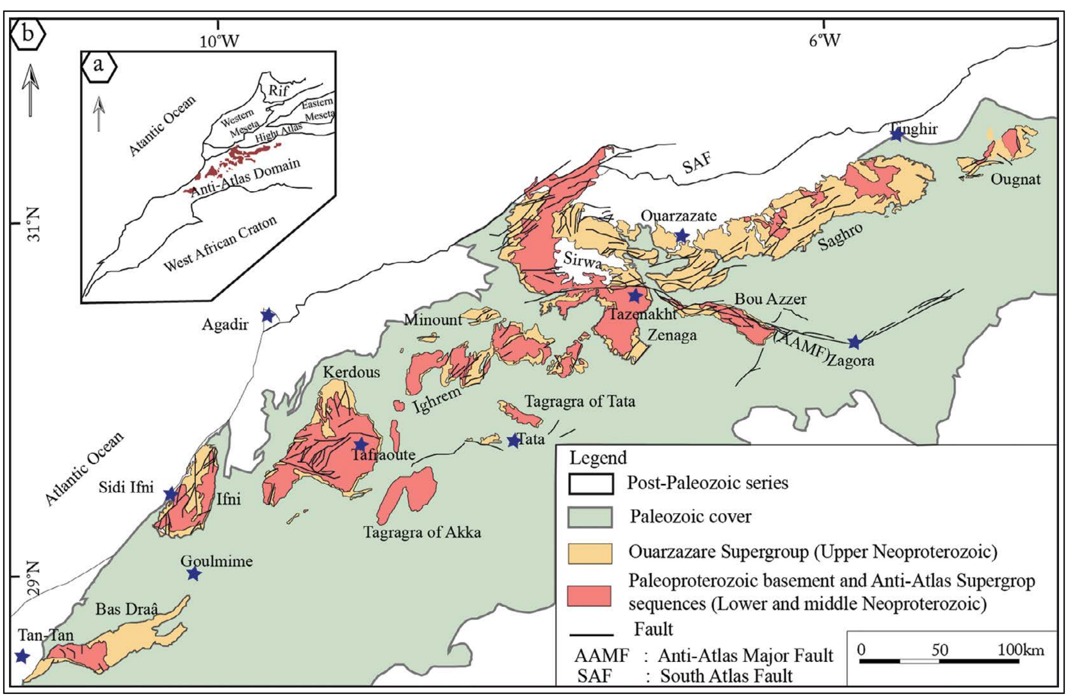

Figure 3- a) Moroccan geological domains, b) Anti-Atlas geological map showing all Precambrian inliers surrounded by Paleozoic rocks, adapted from 1/1.000.000-scale geological map of Morocco (Service Géologique du Maroc, 1985).

Late Silurian are dominated by WAC sedimentary inputs (Buggisch and Siegert, 1988; Destombes, 1976). The carbonate sedimentation restarted at the end of Silurian (Hollard, 1981) and continued during the Devonian, being combined with clastic inputs, throughout the Anti-Atlas region and beyond (Wendt, 1985). A renewed increase in detrital input is marked in the lower Carboniferous from the east, south and in places from the north (Michard et al., 1982; Pique and Michard, 1989).

In the Eastern Anti-Atlas, Paleozoic sequences overlie the Precambrian basement that crops out widely in the Saghro and the Ougnat massifs. This continental basement formed through the Pan-African orogeny was converted into an extending metacratonic domain in the latest Neoproterozoic times (Ennih and Liégeois, 2001; Gasquet et al., 2005). From Early/Middle Cambrian to early Carboniferous, the whole area was flooded by the Paleozoic seas (Raddi et al., 2007) (Figure 4). Around the Precambrian culminations, the sediments of Cambrian/Ordovician are exposed and constitute a SE-trending folded ridge (Ougnat-Ouzina Ridge) between Tafilalet basin to the east and Maider basin to the west, respectively (Hollard, 1981, 1974; Raddi et al., 2007; Wendt, 1985) (Figure 1b).

Before Variscan orogeny which affects the Paleozoic formations, the Anti-Atlas knew an extension, during the Cambrian, generated in the eastern part by a N70° normal and NW-SE left-lateral faults. In Tafilalet and Ougnat-Ouzina Ridge, the Caradoc tectonic is well-expressed where a fracturing zone differed between the Tafilalet and the Maider basins with NW-SE directions (Baidder, 2007). Throughout the Variscan orogeny, the Paleozoic series of the Anti-Atlas basin were involved in folding tectonics. This tectonics coincides with the uplift of Proterozoic basement blocks bounded by inherited basement faults (Soulaimani et al., 2014). During the Devonian, the extension and dislocation of the platform, produced the differentiation of basins (Baidder et al., 2008). Variscan tectonics in this age is called Eovarisc, they are controlled by Devonian paleofaults recognized in Tafilalet-Maider area with ENE, NW, NNE and ENE to ESE directions (Baidder, 2007; Baidder et al., 2007; 2008). During the Visean, the Eastern Anti-Atlas is marked by a tectonic instability (the Mesovarisc), as a prelude to the major Variscan phase (Baidder, 2007), controlled by three families of accidents E-W, SW-NE and NW-SE in extensive left-lateral faults (pull-apart system) (Soualhine et al., 2003).

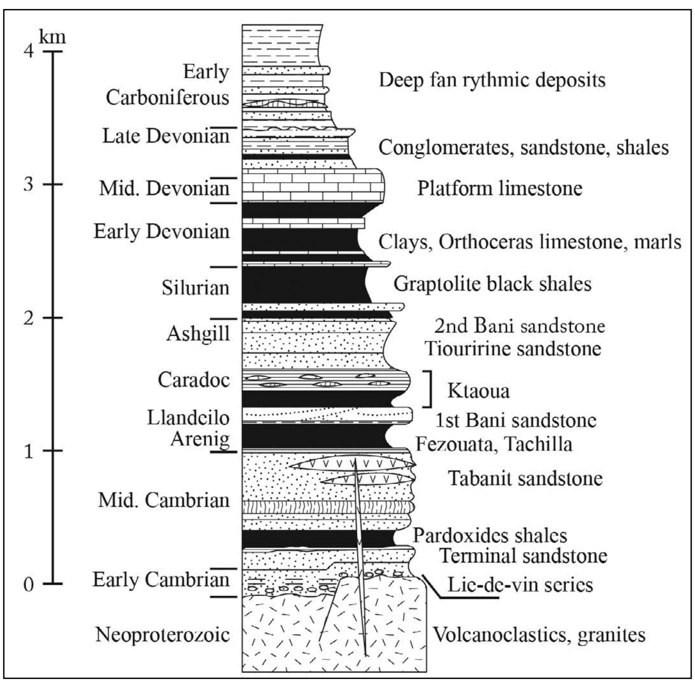

Figure 4- Synthetic stratigraphic column of the Paleozoic formations of the eastern Anti-Atlas, synthesized by (Raddi et al., 2007).

Neovarisc tectonic in the Eastern Anti-Atlas is characterized by NW-SE Namuro-Westphalian compression, responsible for E-W to NE-SW axis folds and right-lateral movements dominant associated with inverse or normal movements along major Pan-African accidents. The NE-SW Stephanian-Permian compression is responsible for the fault inversions and their dominant strike-slip throw (Raddi et al., 2007).

The folds trend analysis in the Eastern Anti-Atlas allowed to underline two preferential directions; the first with an E-W axis and the second with a NW-SE axis. The first direction dominates the west part and the last one dominates the eastern part, whereas in the south of the Precambrian inliers, both directions coexist (in the Tazzarine region; Figure 5). The E-W direction also dominates north of Ougnat and Saghro inliers with an ENE-WSW trend. However, there is an exception of isolated case to the north of the Ougnat inlier that has a N-S axis (Robert-Charrue, 2006).

According to Baidder (2007), the eastern part of Saghro and the northwestern of Ougnat show the presence of a fold system with different axis; N-S to NNE-SSW. This one characterizes the area between the northeastern of Saghro and the northwestern of Ougnat, with subhorizontal axes (Figure 5). In addition, the ENE-WSW to E-W folds are visibles between Tizi n'Boujou in the south and Jbel Tachtafacht in the north. In the south of the Ougnat inlier, the deformation of the Paleozoic sequences is strongly heterogeneous. Over tens of square kilometers, this deformation coexists with more restricted folded and faulted zones. The largest folds are observed in the Angal-Guerghis Lozenge (Raddi et al., 2007).

In the Ougnat-Ouzina Ridge, Baidder et al. (2016) distinguished between Cambrian- and Ordovician-cored folds. Three Cambrian-cored folds are identified from the north to the south of the Ougnat-Ouzina Ridge: (i) the NW-SE axis fold of Jbel Taklimt, (ii) the N120 axis fold of Jbel Renneg and (iii) the NNE axis fold of Jbel Tijekht. The Ordovician-cored folds are the (i) E-W anticline of Bou Maïz, (ii) the NW-SE axis fold of Shaïb Ras and (iii) the E-W axis fold of Tadaout (Figure 5).

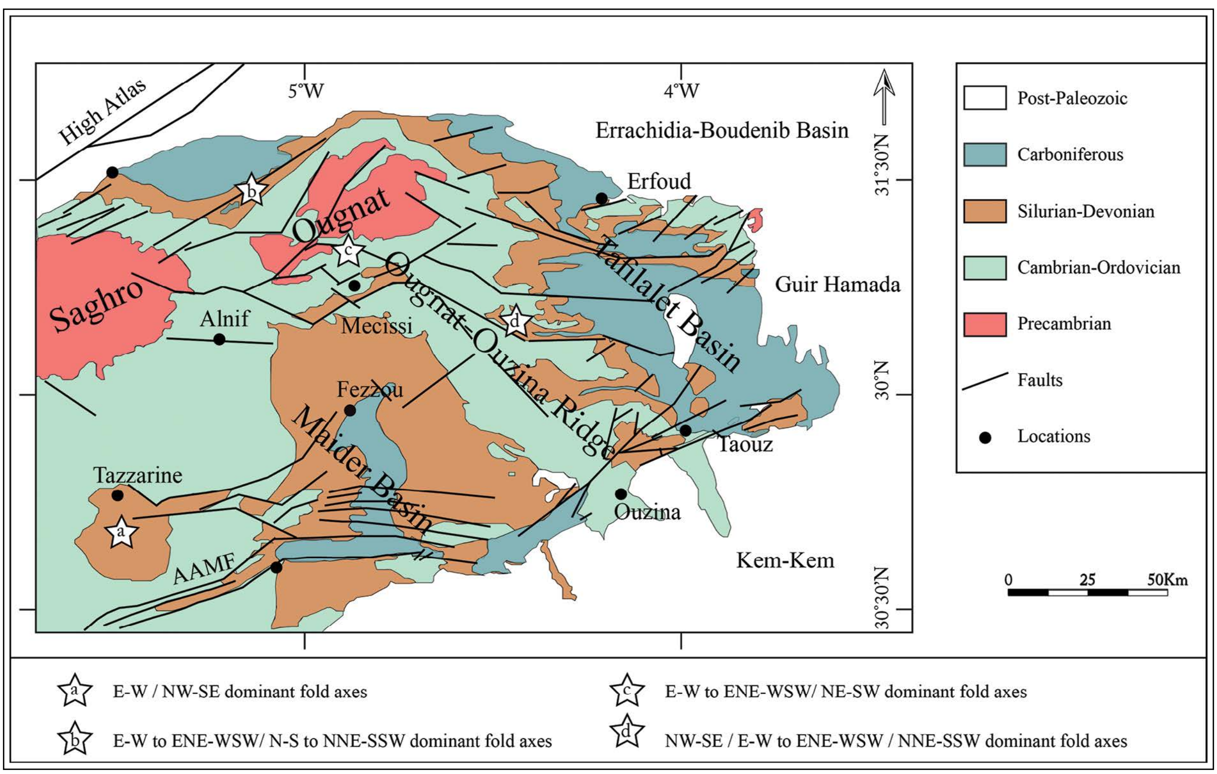

Figure 5- Geological maps of Eastern Anti-Atlas with major folds and faults located at the Eastern Anti-Atlas Paleozoic series. The starts represent the dominant fold axes by locations according to a) Robert-Charrue, 2006, b) Baidder, 2007; Robert-Charrue, 2006; Robert-Charrue and Burkhard, 2008, c) Michard et al., 2008; Raddi et al., 2007; Robert-Charrue and Burkhard, 2008 and d) Baidder et al., 2016; Benharref et al., 2014; Michard et al., 2008.

Numerous dykes and sills of the Central Atlantic Magmatic Province (CAMP), intruded the Anti-Atlas Paleozoic fold, were dated 200-195 Ma by place (Hailwood ve Mitchell, 1971; Hollard, 1973; Sebai vd., 1991; Derder vd., 2001; Youbi vd., 2003; Verati vd., 2007; Chabou vd., 2010). The Anti-Atlas belt was influenced by Variscan and Alpine orogenies. These two orogenesis affected hardly the Meseto-Atlasic domain situated at the north of the SAF and to a lesser degree, the Anti-Atlasic domain, located south of the SAF (Gasquet et al., 2005). According to the 1/200 000 Tafilalet-Taouz map (Destombes and Hollard, 1986), the massif of TTR is approximately a N120-trending anticlinal which affects the Middle Paleozoic series from Ordovician to Devonian. This massif contains doleritic intrusions localized within the Silurian, Devonian and Ordovician formations.

3. Methods

The Landsat image used in this work consists of the Landsat 8 OLI image (Operational Land Imager) acquired on 27/06/2014. The image has been downloaded from the USGS website page. It composes nine spectral bands with 30 m spatial resolution for bands 1 to 7 and 9. The resolution for band 8 (Panchromatic) is 15 m. The methodology followed for extracting lineaments from the Landsat 8 OLI image is summarized in figure 6a. After preprocessing of the Landsat 8 OLI image (radiometric calibration

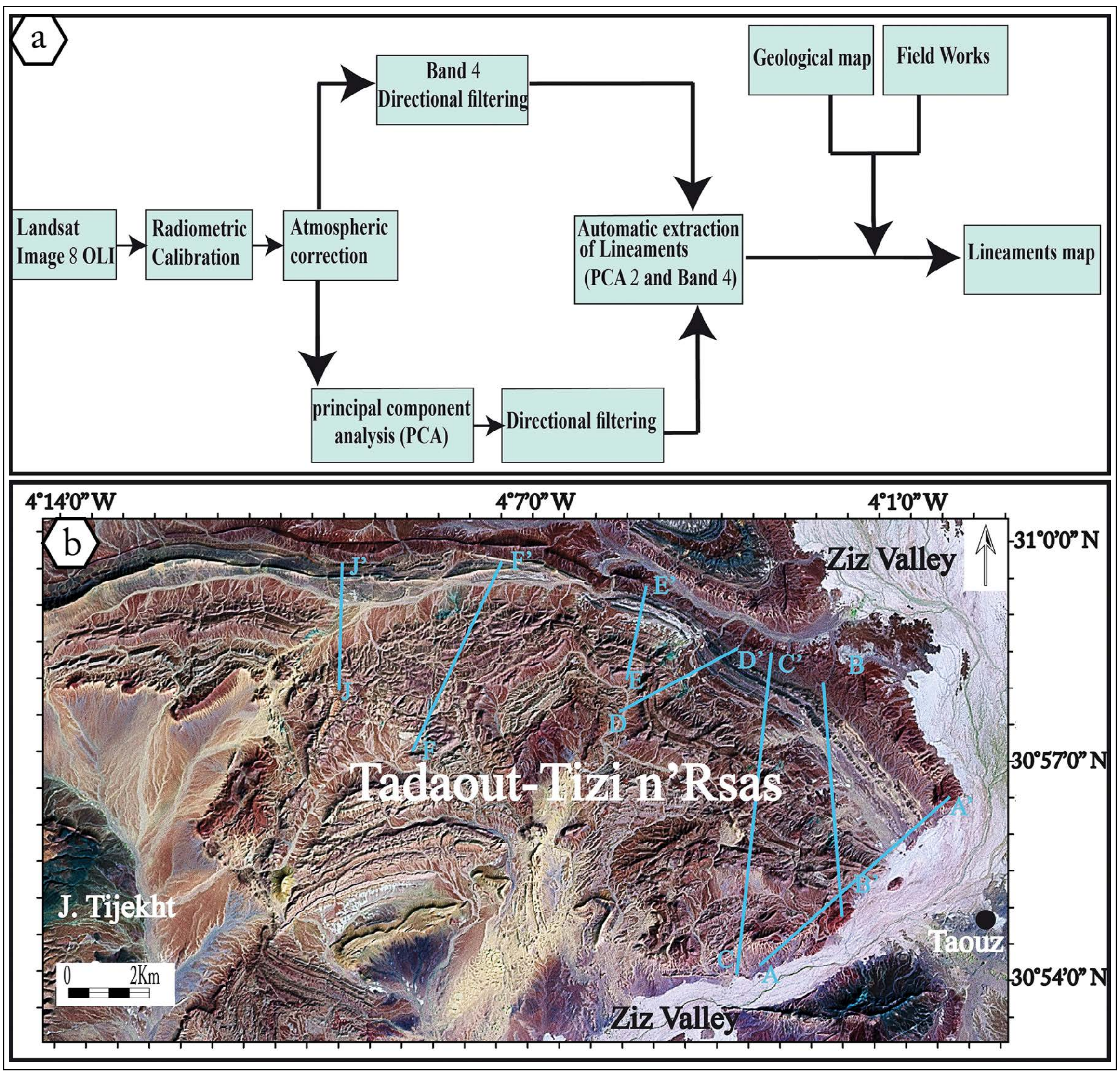

Figure 6- a) Major steps of lineaments extraction and analysis, b) landsat image of the TTR anticline showing the location of the geological cross sections.

and atmospheric correction), we calculated the principal component (PC) of the bands (from 1 to 7). Subsequently, the directional filters were applied to all bands and also on these principal component analysis (PCA) using the matrix 7-7. Many tests of automatic extraction of the lineaments are carried out on the 7 bands and on the results of the PCA. Following these tests, we selected the PCA2 and the band 4 filtered with the directional filter 45, because they give the best results. The compilation of two lineament maps extracted from PCA2 and band 4 makes it possible to establish a synthetic study area map of the lineaments. Several corrections are made to eliminate the linear structures (rivers, roads, scrapings, line of ridges, etc.

Results obtained from the automatic extraction of lineaments on the bands from 1 to 7 of the image OLI and on the results of the PCA, have been compared with the geological map of the region, and with data from our field missions. The field work is based on geological mapping following the method of cross sections whose objective is to intersect all structures of the studied area. Several cross sections were realized in order to collect as much of information as possible about the direction and the dip of tectonic structures (Figure 6b). Subsequently, the data collected are treated and presented using appropriate diagrams (Dips program).

4. Results

Stratigraphically, The TTR anticline is formed by Devonian, Silurian and Ordovician sedimentary terrains (Figure 7a). The Ordovician formations start with the "Feijas Externe" group ("Fezouata and Tachilla" shales), folowed by the "1st Bani" sandstone. This competent layer is surmounted by the "Ktaoua" shales and the "2nd Bani" sandstone (Figure 7b).The Silurian formations are composed of shales, orthoceras and crinoids limestone. These formations have a very small thickness compared to Ordovician ones (Figure 7b). The Devonian formations, which cover the north part of the region, are characterized by carbonate rocks with enormous enrichment in paleontological fossils. They are mainly composed by an alternation of marls and limestone forming the "Erfoud" and "Tafilalet" groups, and by sandstone of "Aoufilal" formations (Figure 7b).

In addition, all the Paleozoic formations of TTR are crosscut by the magmatic activity expressed by dykes and sills of the late Devonian-Early Carboniferous age (Pouclet et al., 2017) (Figures 7 and 8). Evidently, the Paleozoic sedimentary formations in the TTR are affected by a brittle tectonics at the north part of the Oumejrane-Taouz Fault (OJTF), which is the continuity of the AAMF towards Tafilalet (Baidder, 2007; Baidder et al., 2008). AAMF is considered as one of the more important major structures that impressed the Eastern Anti-Atlas (Choubert, 1947).

4.1. Extraction of Structural Lineaments from Satellite Image Landsat 8 OLI

The lineaments map, extracted automatically from the image processing, shows the dominance of a NE-SW direction. Other directions (NNE-SSW and ENE-WSW) are present but are less abundant (Figure 9a). The illustrated rose diagram of lineaments trends confirms the dominance of the NE-SW direction (Figure 9b). To validate these results we compared, in the first step, the extracted lineaments with the pre-existing 1/50.000 geological map of El Atrous (Benharref et al., 2014). The comparison with this geological map shows the presence of many analogies, although we notice the existence of a few disagreements in some segments. During the second stage of validation of our extracted lineaments, we observed linear structures on the field. This stage allowed us to confirm some linear structures, as well as to determine their movements (Figure 10).

4.2. Field Work and Structural Analysis

The TTR anticline is a WNW-ESE-trending fold with an Ordovician cored (Baidder et al., 2016; Destombes, 1963) and curved axis. It represents the hinge between the Anti-Atlas and the Ougarta belts. It is characterized by a long north limb and a short southern limb (asymetric fold). Structurally, the TTR anticline is limited to the east by the big fault of Ziz and to the northwest by a N70° fault which lodges the vein of Tizi-n'Rsas (Clariound, L, 1944; Destombes, 1963).

A set of disharmonic or entrainment folds are generated at the long limb of the TTR anticline; the majority of these folds are located in the Devonian formations. However, other folds are observable in the core of the anticline within Ordovician formations. Disharmonic folds are generated in formations as a

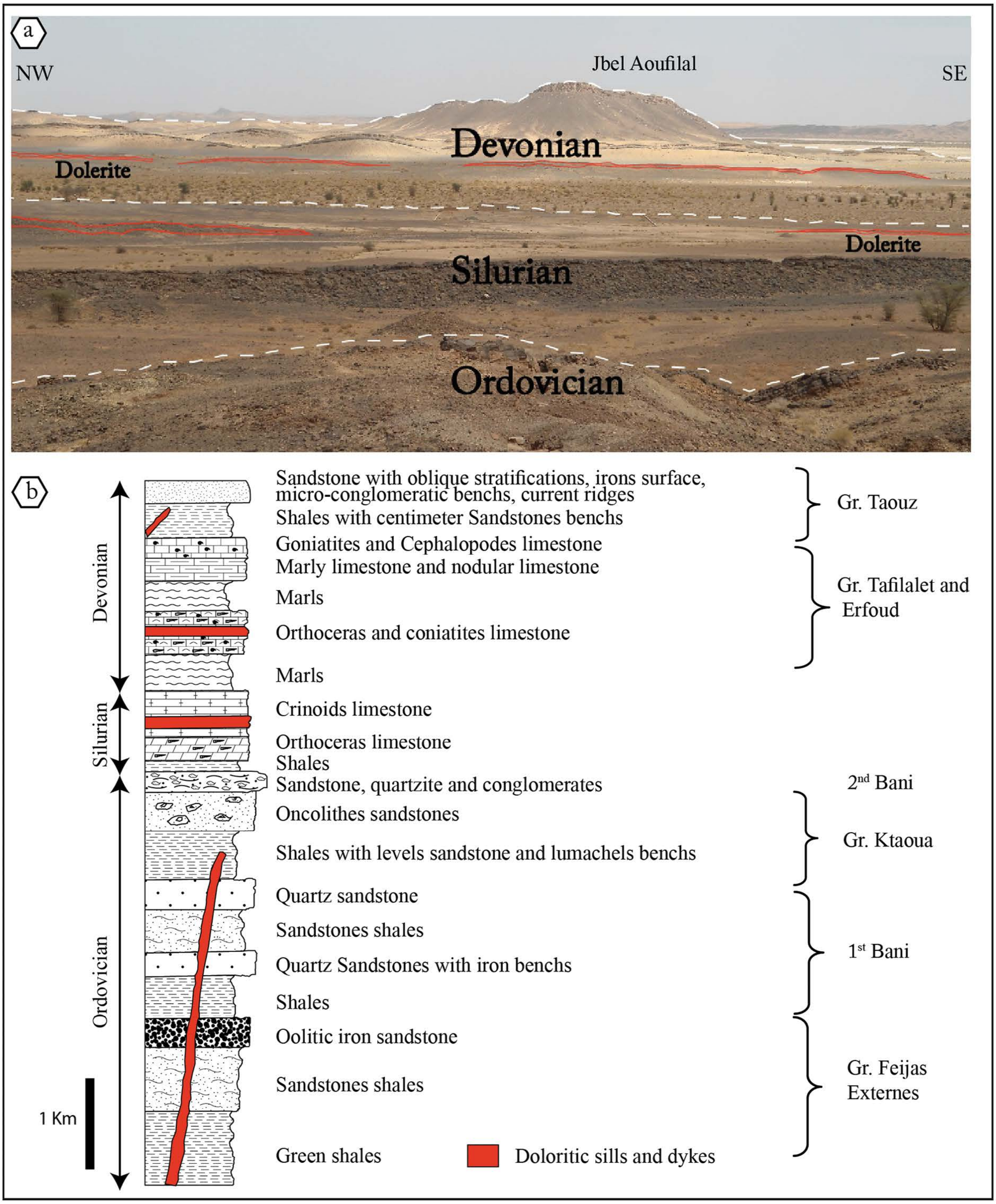

Figure 7- a) Panoramic view of the north limb of TTR anticline and b) synthetic stratigraphic column of the study area.

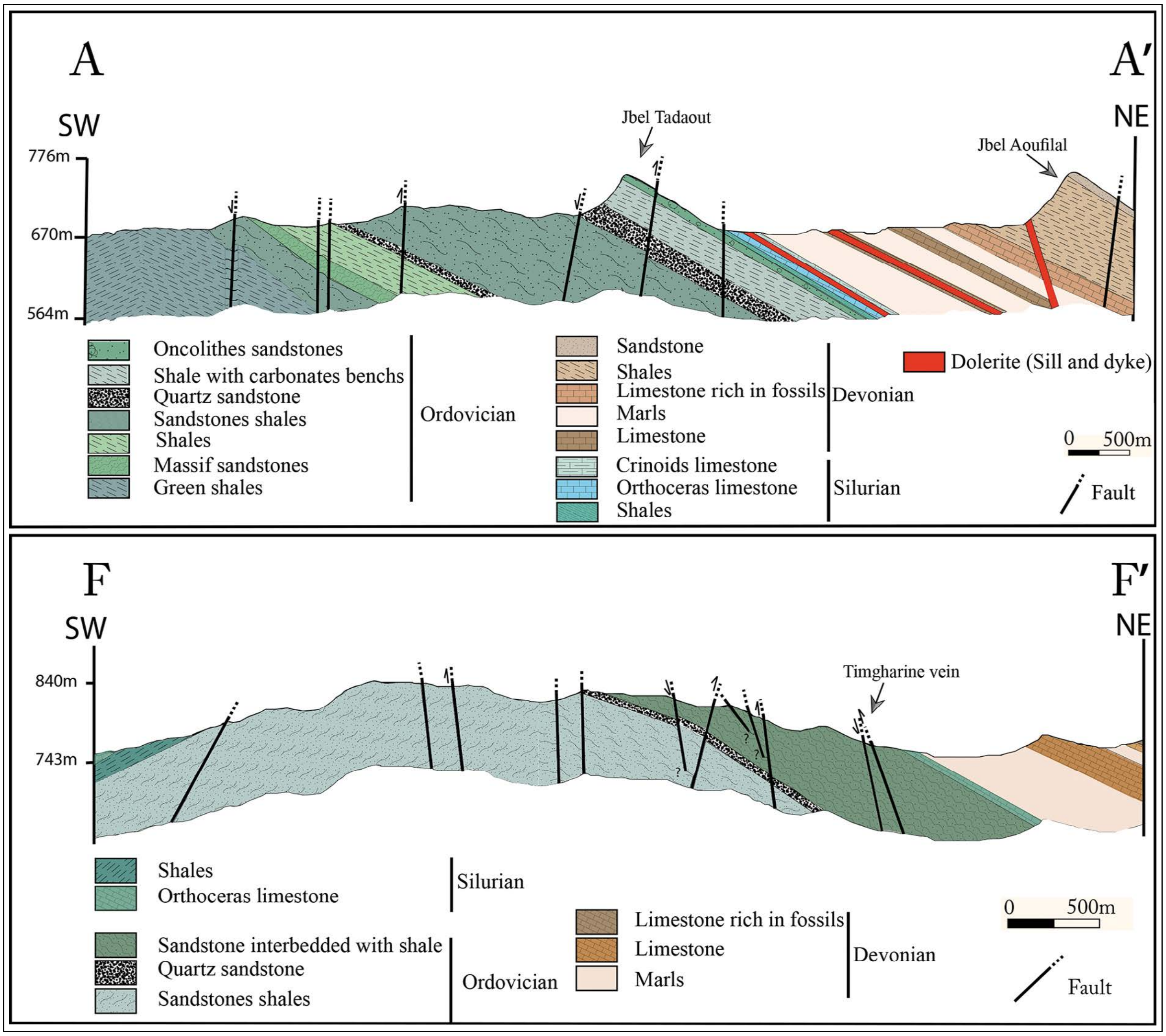

Figure 8- Geological cross sections realized in the study area. A-A' and F-F': in the Eastern and Western part of the study area, respectively. Cross sections B-B', C-C', D-D' and E-E' (in the figure 6) give similar informations.

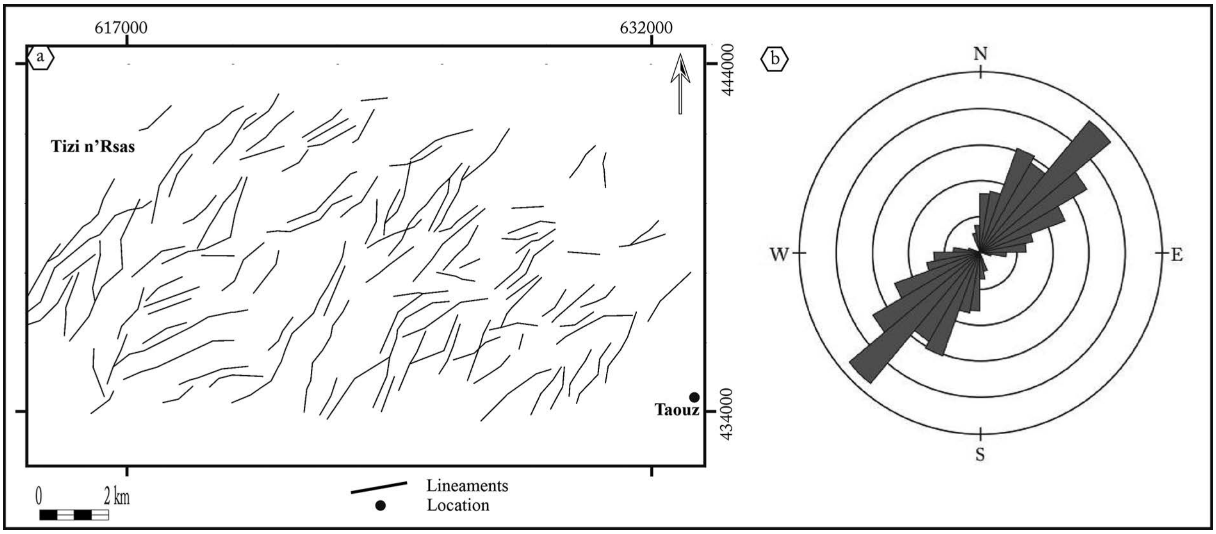

Figure 9- Results after Landsat 8 OLI image processing, a) synthetic map of lineaments and b) rose diagram of lineaments trend.

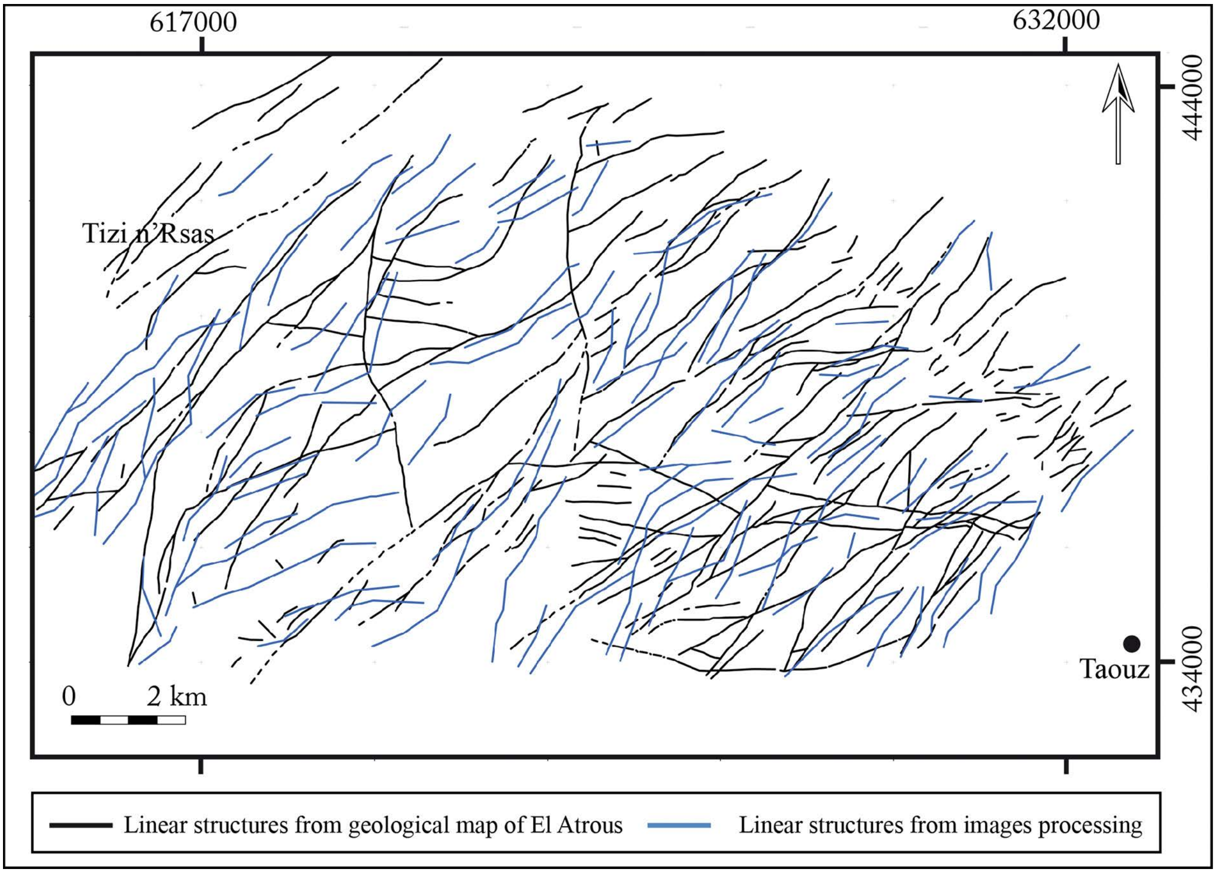

Figure 10- Superposition of the results and the geological map of El Atrous (Benharref et al., 2014).

result of the contrast of their rheologies: competent and incompetent layers. Also, there are small-wavelength folds called parasitic folds. Observed on field, this type of folding is manifested in limestone and marl formations of Devonian (Famennian, Eifelian and Emsian age formations). They are repeated more on the northern limb of the anticline of TTR. Many folds have an axis varying between N95° and N130° with a fold axis plunge of 30° to the west and northwest, respectively (Figures 11a-11e). These folds are well observed in competent layers, while incompetent ones does not show any folding structures. Other folds are generated at the Ordovician age formations; they have N20° and N130° axes exhibited in sandstone shales (Figure 11f). Silurian formations in the study area do not show any indication of folding, although these formations are located between two folded sets, Devonian and Ordovician.

The TTR anticline shows some internal structures, we can distinguish three types of fold axes; N130°, N95° and N20°. The N130° and N95° trend axes generally reflect the TTR major fold axis (WNW-ESE), which is considered as one of Variscan structures. The presence of minor disharmonic folds (N130° and N95°) within Devonian formations is probably related to (i) the folding of thick and competent Ordovician formations, which produces large folds, and (ii) the presence of incompetent formations (clays and limestone) at the bottom of the Devonian series, within the Silurian and at the bottom of Upper Devonian formations. The Devonian formations decollement involved its detachment from the Ordovician basement, this latter is characterized by the presence of rigid terrains (sandstone). The N20° directional folds within the Ordovician formations may be related to the faults crossing the TTR anticline.

North of the OJTF, TTR anticline is intensely fractured. Cartographic surveys have emphasized the important brittle tectonics whose statistical analysis has distinguished only one major fault family NE-SW. The ENE-WSW and NNE-SSW faults families are less abundant compared to the NE-SW family (Figures 8, 12a and 13). These families of faults is also reported on the rose diagram obtained by processing

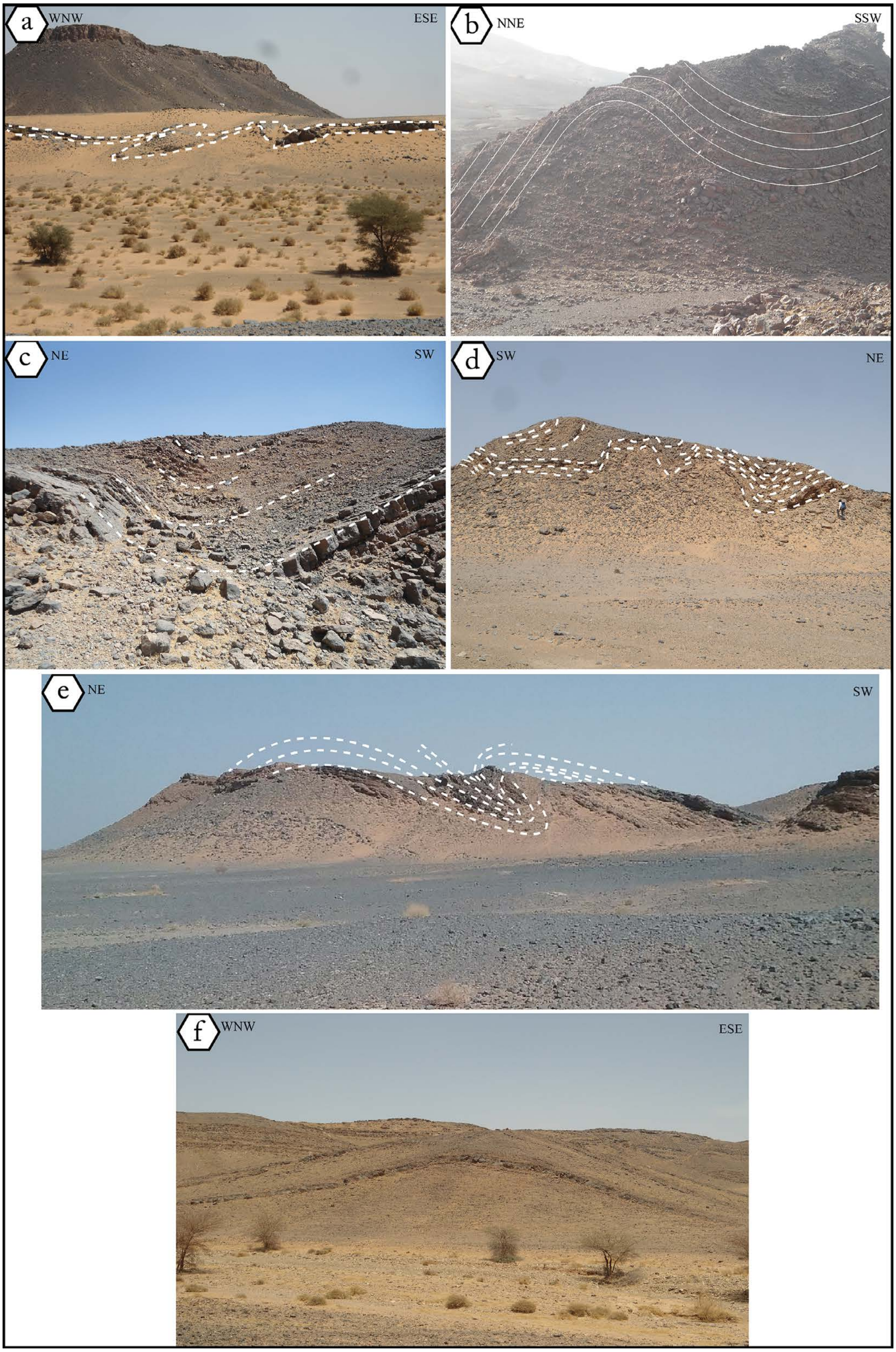

Figure 11- Photos of disharmonic folds located on the northern limb of the TTR anticline. a) N100°-trend folds within nodular limestone formations of Eifelian age, b) E-W folds at the Upper Devonian (Famenian) limestones and marls, c) NW-trend folds at the Emsian limestone formations, d) NW-trend folds in limestones and marls of Upper Devonian (Famenian), e) fold with N130° axis and f) folding of Ordovician formations with N20° axis.

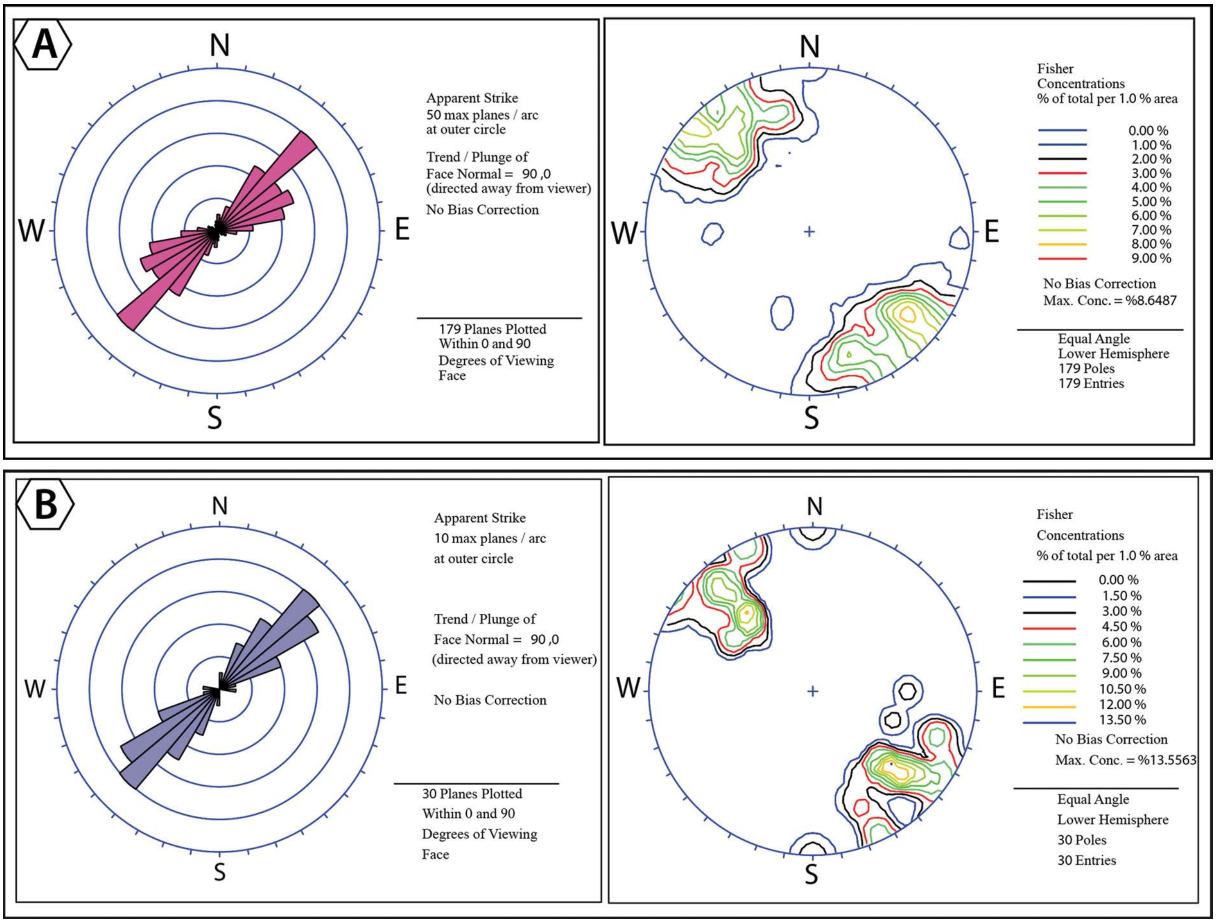

Figure 12- Statistical orientation of fracturing data of TTR anticline (equal angle, lower hemisphere), a) faults and b) veins.

of the Landsat 8 OLI image. However, the ENE-WSW family is less represented in the rose of Landsat image processing diagram. The NE-SW family (N40° to N55° trend), shows a 70° with both opposite dips to the NW and the SE. It is the most predominant family in the TTR anticline. Normal faults are predominant in this direction, but inverse and transcurrent faults exist too. Geometrically, the throw of this family of faults is low and can not reach ten metres in general (Figure 14).

Structural analysis of this fault family allows to emphasize a polyphase structuring. Here, we distinguish: (i) a reverse and strik-slip faults probably forward and can be linked to a compression perpendicular to the fault direction. It is well observed in striaes and slickensides at the mirror surface of faults. From a frequency point of view, the left-lateral faults are more dominant than the right-lateral ones in this region. These movements are probably attributed to the NW-SE major compression of Namuro-Westphalian age related to the Variscan orogeny. (ii) More dominant late normal faults are distributed along the anticline. The presence of vertical to sub-vertical striaes, slickensides in the mirror surface and also the net displacement of the layers indicate that the vertical movement is dominant in this family. Moreover, in order of frequency, the normal faults are more abundant than the inverse or transcurrent ones.

The vein field of TTR consists of more than twenty mineralized veins. From east to west, the main vein structures are: Tadaout, Bou Itberne, Bou Amane, Filon 12, Bou Faddouz, Filon 15, Bou Zeggar, El Atrous, Timgharine, Bou lmyour and Tizi n'Rsas (Figure 15). The NE-SW direction is the main carrier of barite, copper, lead and zinc mineralization in our study area, in the form of fissure veins, arranged into echelon and forming a vein field which is part of the mining domain of Tafilalet. It is important to note that these veins have been the subject of old artisanal exploitation for lead and barite mineralizations

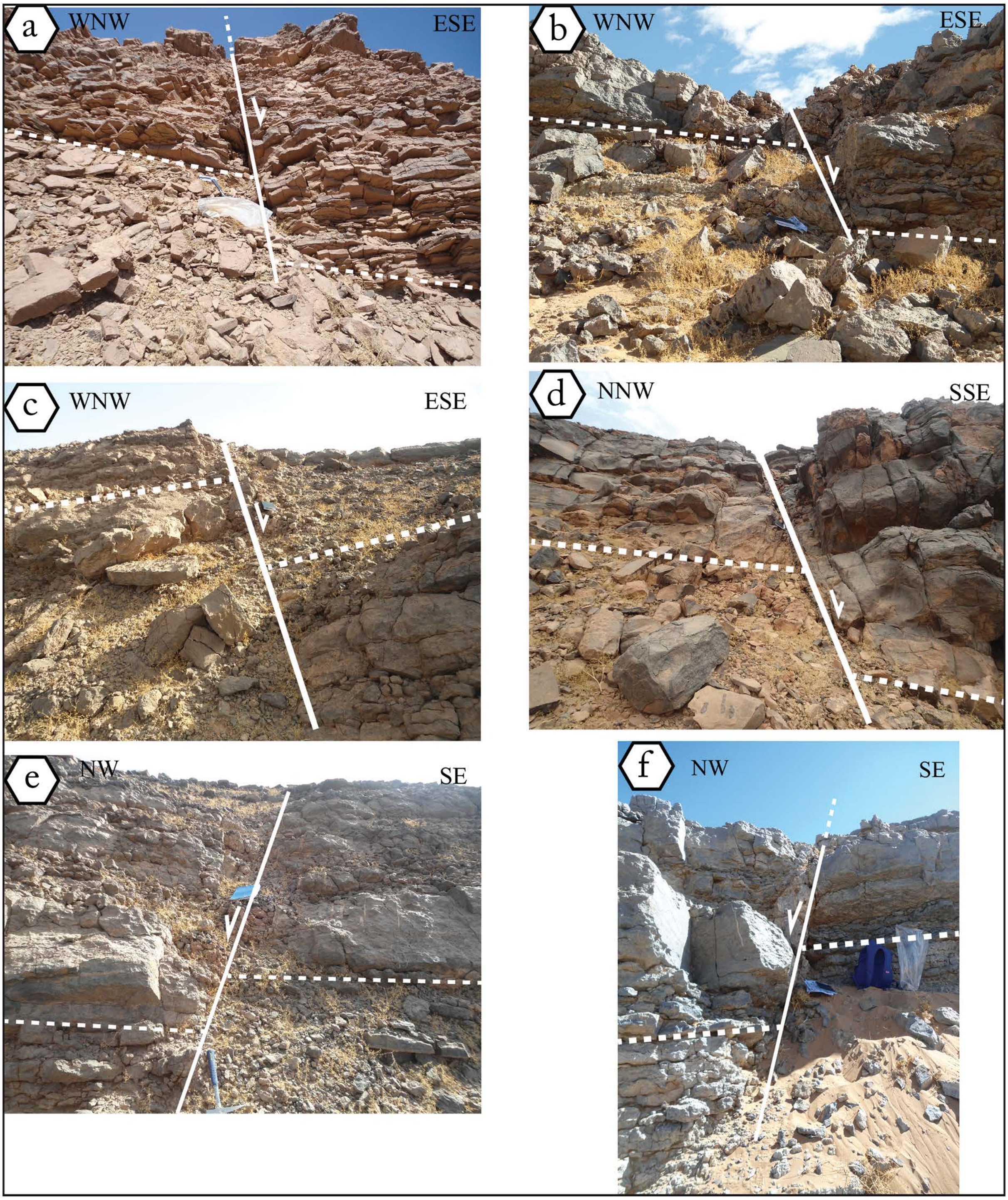

Figure 13- Faults of TTR anticline. a), b) and c) NNE direction fault families, d) ENE fault families and e) and f) NE-SW fault families.

(Figures 12b and 16). The normal movement of NE-SW direction faults is probably associated with the reactivation of this fault family during the NE-SW Late-Variscan (Stephanian-Permian) compression of the Variscan orogeny (Figure 17).

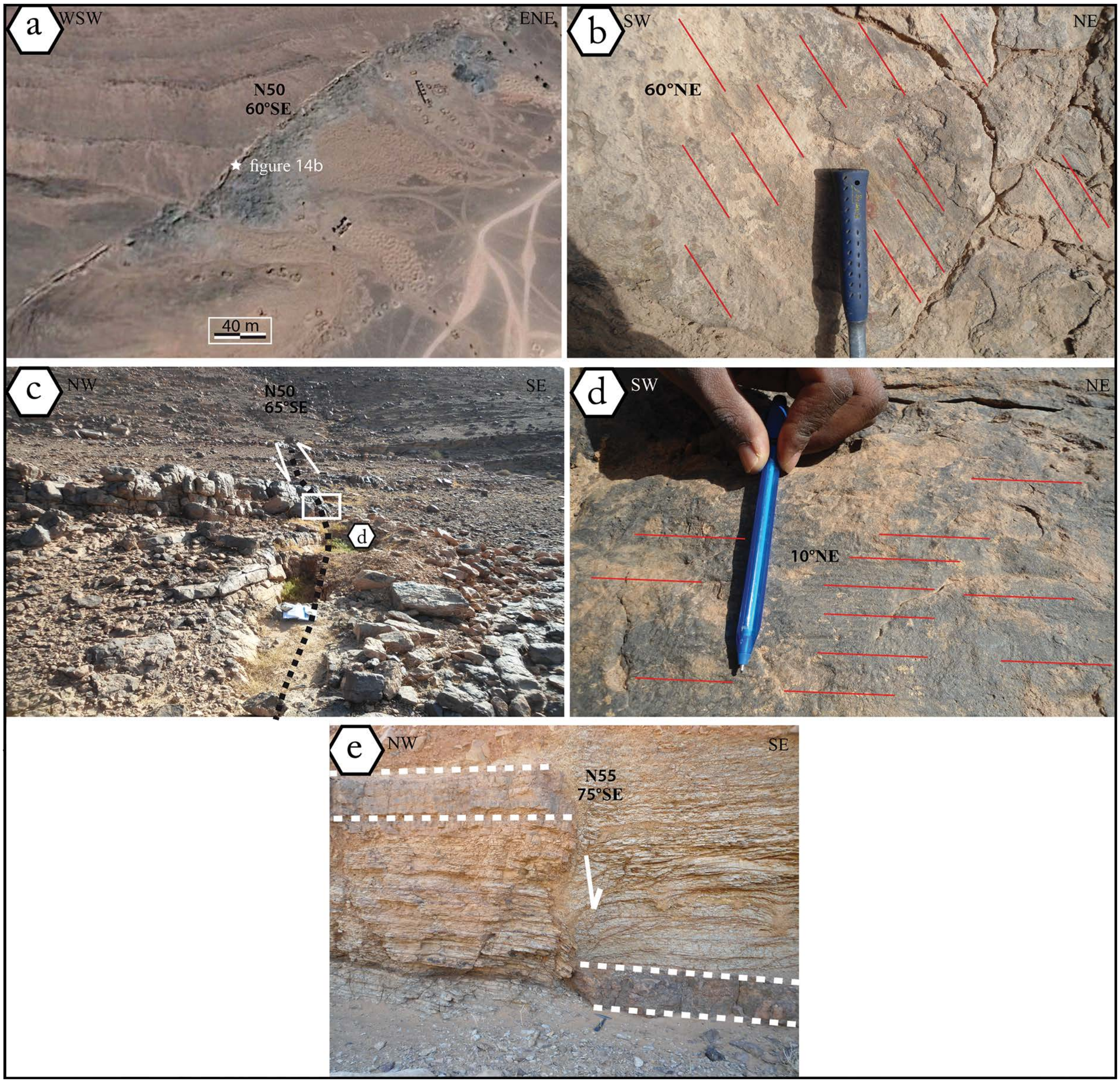

Figure 14- NE-SW directional faults: a) N50°, 60°SE mineralized vein (Tizi-n’Rsas vein), b) striaes (60°NE) on the mirror surface, c) N50°, 60°SE fault with left-lateral movement, d) striaes (10°NE) at the mirror surface, e) N55°,75°SE fault showing a vertical movement.

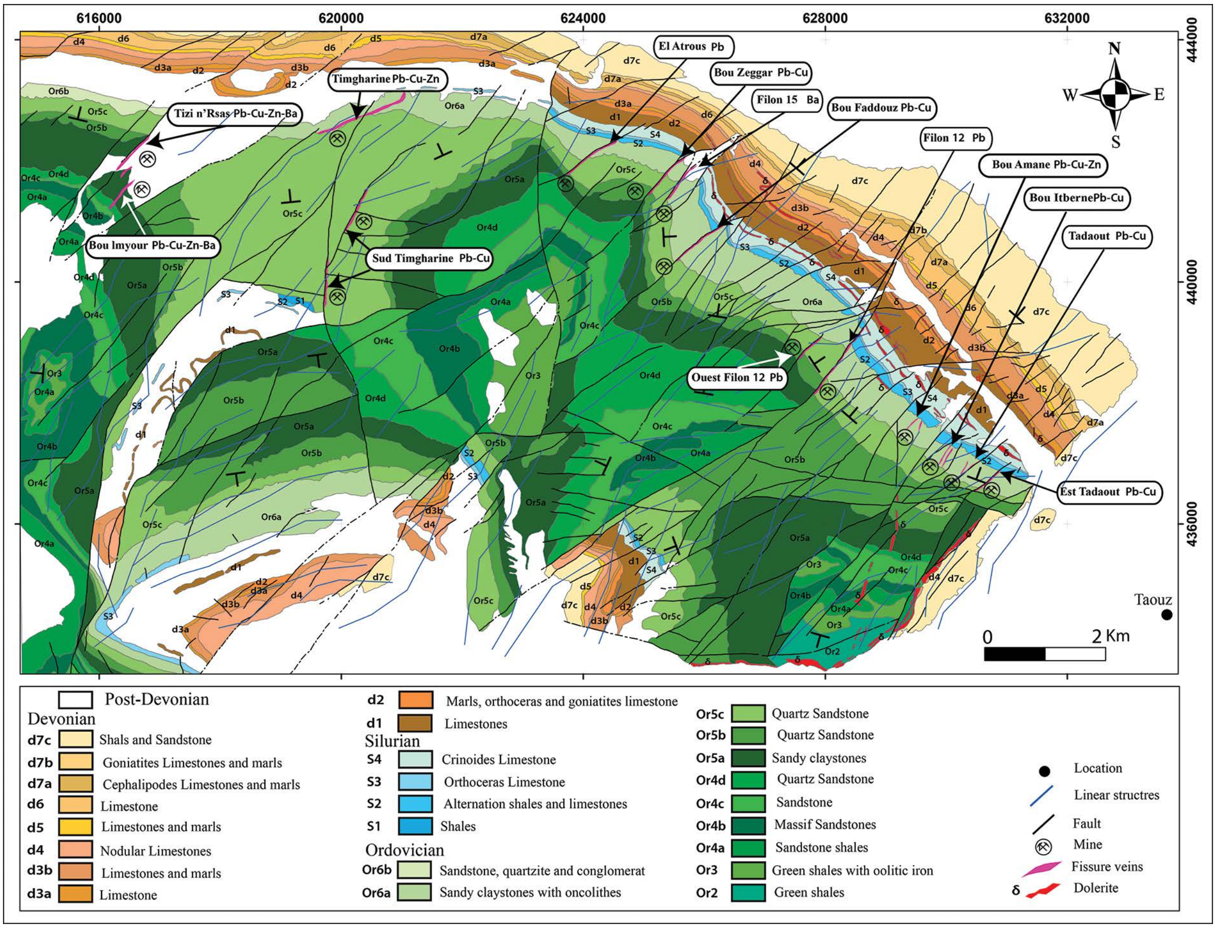

Figure 15- Geological map of study area showing the relationship between NE-trending structures and base metal mineralization (Geological map 1/50.000 of El Atrous in Benharref et al., 2014, modified).

Figure 16- NE-SW barite veins in the TTR anticline.

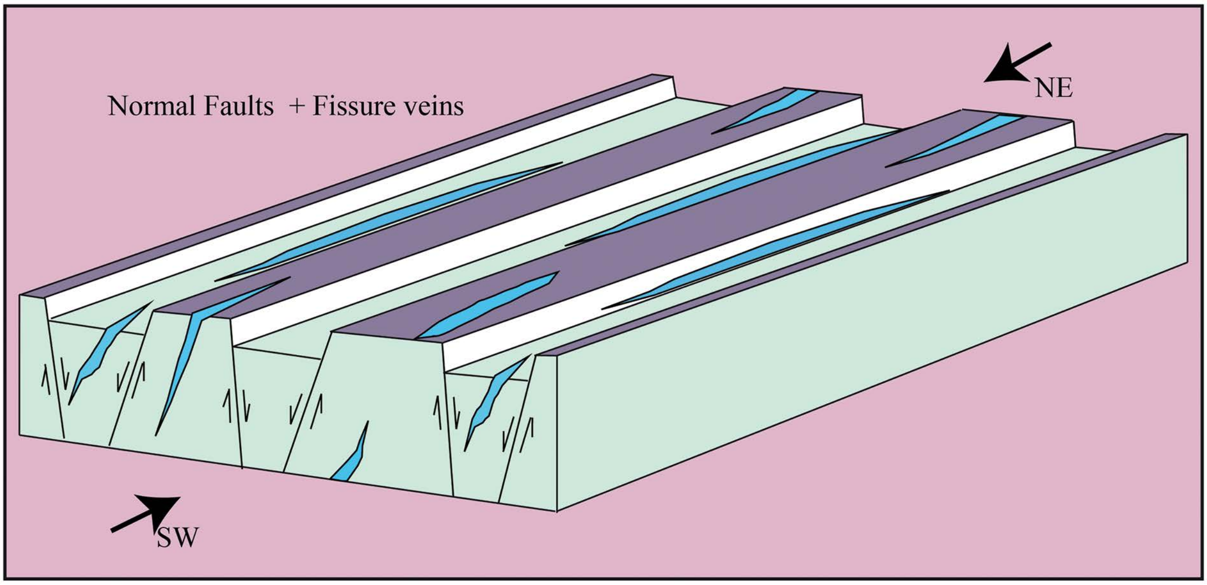

Figure 17- Bloc-diagram showing the fault movements during the Variscan orogeny (NE-SW shortening).

5. Discussion

TTR anticline is one of the major folded structures located in the Ougnate-Ouzina Ridge. It corresponds to the junction zone between Anti-Atlas and Ougarta mountains, and shows a WNW-ESE directional axis at Ordovician core. These open types of folds are well presented at the scale of the Eastern Anti-Atlas, and are consistent with a NE-trending direction of shortening (Michard et al., 2008). These pluri-kilometric regional folds are characterized by a strong thinning of limbs and an important hinge thickening and also by the presence of an intense disharmonic folding with decametric folds (Benharref et al., 2014). Baidder et al. (2016) assumes that major structures of Tafilalet and Maider, in particular the most complicated fold structures (Tijekht and Tadaout anticlines), can be explained by a combination of paleofault control of folding orientation, and superimposed compression events with different compression directions. South of the Ougnat Massif (Bouadil area), the Paleozoic cover series show a mosaic of tilted basement blocks associated with the dominance of NE- and SE-trending folds (Raddi et al., 2007).

Internal structures; minor disharmonic folds (N130° and N95°), are observed in the long north limb of TTR anticline. Likewise in the south of Eastern Anti-Atlas inliers, small scale NW-SE structures are observed. This orientation is similar to that observed in the major structures (Baidder et al., 2016; Robert-Charrue and Burkhard, 2008). The N20° axes trend is another trend of fold axes observed in the TTR anticline. These folds are late and related to the faults crossing the anticline (Baidder et al., 2016).

Like other folded structures of Tafilalet, TTR anticline shows a very intense fracturing with the dominance of NE-SW direction filled by barite, copper, lead and zinc. The Tijekht anticline located in the western part of TTR shows a N35° to N70° faults system mainly mineralized in barite. In addition, the anticline of Bou Mayz, situated in the northern part of the Ougnat-Ouzina Ridge, shows a NE-SW direction of barite mineralized faults. Likewise, the Shayb Arras anticline, located at the north of the study area, is also pierced by NE to ENE faults frequently mineralized in barite. In addition, the Znaigui and M'fis anticlines show both an ENE-trend structure (Baidder et al., 2016; Makkoudi, 1995).

The NE-SW faults are the most important and the most frequent faults in the TTR anticline, these structures are probably inherited from the Precambrian basement (Rjimati et al., 1992; Soulaimani et al., 2014; Walsh et al., 2012). During the evolution of the Lower Cambrian basin, the role of the NE-SW direction faults in extensional tectonics has been emphasized, this direction generates a NW-SE extension (Algouti et al., 2001; Baidder, 2007; Benssaou and Hamoumi, 2003;

Chbani et al., 1999; Gasquet et al., 2005; Soulaimani et al., 2003; Soulaimani and Piqué, 2004). In the Middle-Late Devonian, the Eastern Anti-Atlas was characterized by a dislocation and an extension of the Saharan platform (Baidder, 2007; Baidder et al., 2008; Wendt and Belka, 1991). According to Soulaimani et al. (2014), Devonian paleofaults are inherited from the Precambrian. The most important faults recognized in the Tafilalet-Maider area are qualitatively ordered into first order ENE-trending faults, second order NW- and NNE-trending faults and third order ENE to ESE-trending faults (Baidder et al., 2008). After Devonian, the sedimentation of the Lower Carboniferous is controlled by some old faults of the Upper Devonian (Baidder, 2007; Soulaimani et al., 2014). The Visean tectonics is controlled by three families of accidents; E-W, NE-SW and NW-SE (Soualhine et al., 2003).

In the study area, the polyphase movements of the faults are expressed by the reactivation of old faults during the Variscan orogeny, and has already been shown in the section of ductile tectonics, this zone is affected by a deformation during the Variscan collision which resulted in the reactivation of old structures. The main shortening stage responsible for the folding recognized in Eastern Anti-Atlas and Ougarta is the NE-SW Late Variscan (Stephanian-Permian) compression of the Variscan orogeny (Michard et al., 2008). This shortening corresponding to NE-SW Ouagarta compression (Donzeau, 1974; Fabre, 2005; Haddoum et al., 2001). It interferes with the NNW-SSE compression between the Meseta Block and its foreland at the regional scale, particularly well observed in the north of Saghro inlier (Malusà et al., 2007; Michard et al., 1982; Raddi et al., 2007; Robert-Charrue, 2006). The collision responsible for the Variscan deformation can be estimated to Late Carboniferous, and it results from the collision of Gondwana and Eurasia plates (Stampfli and Borel, 2002).

The majority of NE-SW faults in our study area have a normal movement, likewise Robert-Charrue, (2006); Robert-Charrue and Burkhard, (2008) announced that the Paleozoic series of the Eastern Anti-Atlas at Tafilalet and Maider are intersected by a set of normal faults that have probably result of the Central Atlantic opening related to the breakup of Pangea supercontinent. In the south-east of TTR anticline, the Cretaceous plateau is crosscut by several ENE-striking faults, parallel to the basement OJTF (Soulaimani et al., 2014), which indicates the reactivation of the paleofaults in this region at the north-south shortening alpine stage.

6. Conclusion

Our study area, TTR anticline, is one of the major folds at the Tafilalet region, it is a WNW-ESE axis fold whose represents the hinge between Anti-Atlas and Ougarta belts. At the northern limb of this anticline, three types of minor fold axes are present, (i) N20° fold can be related to the reactivation of fault crossing the anticline, (ii) N130° and N95° disharmonic folds generally reflect the TTR major fold. These folds are probably related to the folding of a serie incorporated the competent (Ordovician, Silurian and Devonian limestone) and incompetent (Silurian shales and Devonian marls) formartions. The results of ductile tectonic show that TTR anticline constitues the hinge of the arc (Zemmour, Anti-Atlas, Ougarta) that goes rounded the West African Craton. The TTR major fold shows a very intense fracturing with dominance of NE-SW normal faults. This dominance is confirmed by the lineaments extracted automatically from the Landsat 8 OLI image processing. Late Variscan NE-SW shortening is the main folding and reactivation mechanism of paleofault in this area. The NE-SW fault family is the main carrier of barite, copper, lead and zinc mineralization. We consider present results as a valuable target for advanced metallogenic researches and mineral exploration in the TTR and more generally at the Eastern Anti-Atlas.

Acknowledgements

We would like to thank Dr. A. Babni and Dr. H. Si Mhamdi for their contribution to enhancing the quality of the English language of the article. The author also wishes to thank the two reviewers for their constructive feedback, and insightful comments and recommendations.

References

Algouti, A., Algouti, A., Chbani, B., Zaim, M. 2001. Sedimentation et volcanisme synsedimentaire de la serie de base de l'adoudounien infra-cambrien a travers deux exemples de l'Anti-Atlas du Maroc. Journal of African Earth Sciences 32, 541–556.

Baidder, L. 2007. Structuration de la bordure septentrionale du Craton Ouest-Africain du Cambrien à l'Actuel : cas de l'Anti-Atlas oriental du Maroc. (Thèse d'Etat). Université Hassan II Aïn Chock, Faculté des sciences, Casablanca, Maroc.

Baidder, L., Raddi, Y., Tahiri, M., 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). Geological Society, London, Special Publications 297, 453–465. https://doi.org/10.1144/SP297.21

Baidder, L., Michard, A., Soulaimani, A., Fekkak, A., Eddebbi, A., Rjimati, E.-C., Raddi, Y. 2016. Fold interference pattern in thick-skinned tectonics; a case study from the external Variscan belt of Eastern Anti-Atlas, Morocco. Journal of African Earth Sciences 119, 204–225. https://doi.org/10.1016/j.jafrearsci.2016.04.003

Belka, Z. 1998. Early Devonian Kess-Kess Carbonate Mud Mounds of the Eastern Anti-Atlas (Morocco), and Their Relation to Submarine Hydrothermal Venting. Journal of Sedimentary Research 68.

Benharref, M., Álvaro, J.J., Hibti, M., Pouclet, A., El Hadi, H., Koukaya, A., Ettachfini, E.M. 2014. Carte géologique du Maroc au 1/50 000, feuille Al Atrous-Mémoire explicatif. Notes Mém. Serv. Géol. Maroc 555.

Benssaou, M., Hamoumi, N. 2003. Le graben de l'Anti-Atlas occidental (Maroc) : contrôle tectonique de la paléogéographie et des séquences au Cambrien inférieur. Comptes Rendus Geoscience 335, 297–305. https://doi.org/10.1016/S1631-0713(03)00033-6

Boudda, A., Choubert, G., Faure-Muret, A. 1979. Essai de stratigraphie de la couverture sédimentaire de l'Anti-Atlas: Adoudounien-Cambrien inférieur. Editions du Service géologique du Maroc.

Brachert, T.C., Buggisch, W., Flügel, E., Hüssner, H.M., Joachimski, M.M., Tourneur, F., Walliser, O.H. 1992. Controls of mud mound formation: the Early Devonian Kess-Kess carbonates of the Hamar laghdad, Antiatlas, Morocco. Geologische Rundschau 81, 15–44.

Buggisch, W., Siegert, R. 1988. Paleogeography and facies of the 'gres terminaux'(uppermost Lower Cambrian, Anti-Atlas/Morocco), in: The Atlas System of Morocco. Springer, pp. 107–121.

Chabou, M.C., Bertrand, H., Sebaï, A. 2010. Geochemistry of the Central Atlantic Magmatic Province (CAMP) in south-western Algeria. Journal of African Earth Sciences 58, 211–219. https://doi.org/10.1016/j.jafrearsci.2010.02.009

Chbani, B., Beauchamp, J., Algouti, A., Zouhair, A. 1999. Un enregistrement sédimentaire éocambrien dans un bassin intracontinental en distension: le cycle «conglomérats de base—unité calcaire—grès de Tikirtde Bou-Azzer El Graara (Anti-Atlas central, Maroc). Comptes Rendus de l'Académie des Sciences-Series IIA-Earth and Planetary Science 329, 317–323.

Choubert, G. 1943. Quelques réflexions sur la terminaison orientale de l'Anti Atlas. Bulletin de la Société d'Histoire Naturelle 61–79.

Choubert, G. 1947. L'accident majeur de l'Anti-Atlas. Comptes Rendus de l'Académie des Sciences, Paris 224, 1172–1173.

Choubert, G. 1964. Histoire géologique du Précambrien de l'Anti-Atlas. Éditions du Service géologique du Maroc.

Clarioud, L.1944. Carte géologique provisoire des plateaux et chaines du Saghro et Maider.

Derder, M.E.M., Smith, B., Henry, B., Yelles, A.K., Bayou, B., Djellit, H., Ait ouali, R., Gandriche, H. 2001. Juxtaposed and superimposed paleomagnetic primary and secondary components from the folded middle carboniferous sediments in the Reggane Basin (Saharan craton, Algeria). Tectonophysics 332, 403–422. https://doi.org/10.1016/S0040-1951(00)00298-5

Destombes, J. 1963. Le Cambrien et la base de l'Ordovicien dans la partie orientale et meridionale du Tafilalt (Maroc). Bulletin de la Société Géologique de France S7-V, 938–945. https://doi.org/10.2113/gssgfbull.S7-V.6.938

Destombes, J. 1968. Sur la presence d'une discordance generale de ravinement d'age Ashgill superieur dans l'Ordovicien terminal de l'Anti-Atlas (Maroc). Comptes Rendus de l'Academie de Sciences, Paris 267, 565–567.

Destombes, J. 1971. L'Ordovicien au Maroc. Essai de synthèse stratigraphique. Mémoires de la BRGM, Paris 73, 237–263.

Destombes, J. 1976. The Ordovician of the Moroccan Anti-Atlas. The Ordovician System 411–413.

Destombes, J. 2006. Carte géologique au 1/200 000 de l'Anti-Atlas marocain. Paléozoïque inférieur: Cambrien moyen-Ordovicien-base du Silurien.

Feuille régions de Tan-Tan–Jbel Zini (Province de Tarfaya). Mémoire explicatif, Chapitre J (Anti-Atlas sud-occidental au sud de l'oued Dra)[written in 2003]. Notes Mém. Serv. Géol. Maroc 90.

Destombes, J., Hollard, H. 1986. Carte géologique du Maroc au 1/200 000, feuille Tafilalt-Taouz. Notes et Mémoires du Service Géologique du Maroc 244.

Donzeau, M. 1974. L'Arc Anti-Atlas–Ougarta (Sahara nord-occidental, Algérie-Maroc). CR Acad. Sci. Paris 278, 417–420.

Ennih, N., Liégeois, J.-P. 2001. The Moroccan Anti-Atlas: the West African craton passive margin with limited Pan-African activity. Implications for the northern limit of the craton. Precambrian Research 112, 289–302.

Fabre, J. 2005. Géologie du Sahara occidental et central. Série/Reeks: Tervuren African Geosciences Collection. MRAC Tervuren, Belgique.

Gasquet, D., Levresse, G., Cheilletz, A., Azizi-Samir, M.R., Mouttaqi, A. 2005. Contribution to a geodynamic reconstruction of the Anti-Atlas (Morocco) during Pan-African times with the emphasis on inversion tectonics and metallogenic activity at the Precambrian–Cambrian transition. Precambrian Research 140, 157–182. https://doi.org/10.1016/j.precamres.2005.06.009

Gasquet, D., Ennih, N., Liégeois, J.-P., Soulaimani, A., Michard, A. 2008. The Pan-African Belt, in: Continental Evolution: The Geology of Morocco. Springer, pp. 33–64.

Geyer, G., Landing, E. 1995. The Cambrian of the Moroccan Atlas regions. Morocco 95, 7–46.

Haddoum, H., Guiraud, R., Moussine-Pouchkine, A. 2001. Hercynian compressional deformations of the Ahnet–Mouydir Basin, Algerian Saharan Platform: far-field stress effects of the Late Palaeozoic orogeny. Terra Nova 13, 220–226.

Hailwood, E.A., Mitchell, J.G. 1971. Palaeomagnetic and radiometric dating results from Jurassic intrusions in South Morocco. Geophysical Journal International 24, 351–364.

Hilali, A., Lachkem, H., Boulvain, F. 1999. Comparaison des Kess-Kess de Hmar Lakhdad (Emsien, Maroc) et des monticules micritiques de l'anticlinorium de Philippeville (Frasnien, Belgique). Geologica Belgica 1.

Hilali, A, Lachkhem, H, Tourneur, F. 2001. Répartition des tabulés dans les Kess-Kess emsiens de Hmar Lakhdad (SE d'Erfoud, Tafilalt, Maroc). Geologica et Palaeontologica 35,8,53-61.

Hollard, H. 1967. Le Dévonien du Maroc et du Sahara nord-occidental.

Hollard, H. 1973. La mise en place au Lias des dolérites dans le Paléozoïque moyen des plaines du Drâa et du bassin de Tindouf (Sud de l'Anti-Atlas central, Maroc). CR Acad. Sci. Paris 277, 553–556.

Hollard, H. 1974. Recherches sur la stratigraphie des formations du Dévonien moyen, de l'Emsien supérieur au Frasnien, dans le Sud du Tafilalt et dans le Ma'der (Anti-Atlas oriental). Notes et Mémoires du Service Géologique du Maroc 264, 7–68.

Hollard, H. 1981. Principaux caractères des formations dévoniennes de l'Anti-Atlas. Notes et Mémoires du Service géologique du Maroc 42, 15–22.

Makkoudi, D. 1995. Les minéralisations Pb-Ba de M'Ifiss, Etude Géologique et Contribution à la gitologie des Gisement du Tafilalet. (Thèse de 3ème cycle). Université Mohamed V, Faculté des Sciences, Rabt, Maroc.

Malusà, M.G., Polino, R., Feroni, A.C., Ellero, A., Ottria, G., Baidder, L., Musumeci, G. 2007. Post-Variscan tectonics in eastern Anti-Atlas (Morocco). Terra Nova 19, 481–489. https://doi.org/10.1111/j.1365-3121.2007.00775.x

Michard, A., Yazidi, A., Benziane, F., Hollard, H., Willefert, S. 1982. Foreland thrusts and olistromes on the pre-Sahara margin of the Variscan orogen, Morocco. Geology 10, 253–256.

Michard, A., Hoepffner, C., Soulaimani, A., Baidder, L. 2008. The Variscan Belt, in: Continental Evolution: The Geology of Morocco, Lecture Notes in Earth Sciences. Springer, Berlin, Heidelberg, pp. 65–132. https://doi.org/10.1007/978-3-540-77076-3_3

Mounji, D., Bourque, P.-A., Savard, M.M. 1998. Hydrothermal origin of Devonian conical mounds (kess-kess) of Hamar Lakhdad Ridge, Anti-Atlas, Morocco. Geology 26, 1123–1126.

Pique, A. 1994. Les domaines régionaux et leur évolution structurale. PUMAG (ed.): Géologie du Maroc.

Pique, A., Michard, A. 1989. Moroccan Hercynides; a synopsis; the Paleozoic sedimentary and tectonic evolution at the northern margin of West Africa. Am J Sci 289, 286–330. https://doi.org/10.2475/ajs.289.3.286

Pouclet, A., El Hadi, H., Bardintzeff, J.-M., Benharref, M., Fekkak, A. 2017. Devonian to Early Carboniferous magmatic alkaline activity in the Tafilalt Province, Eastearn Morocco: An Eovariscan episode in the Gondwana margin, north of the West African Craton. Journal of African Earth Sciences 129, 814–841. https://doi.org/10.1016/j.jafrearsci.2017.01.030

Raddi, Y., Baidder, L., Tahiri, M., Michard, A. 2007. Variscan deformation at the northern border of the West African Craton, eastern Anti-Atlas, Morocco: compression of a mosaic of tilted blocks. Bulletin de la Société géologique de France 178, 343–352.

Rjimati, E., Derre, C., Lecolle, M., Lillie, F., Nerci, K., Azza, A., Bennani, A. 1992. Caractéristique de la tectonique panafricaine dans le Jbel Saghro (Anti Atlas, Maroc). Notes et Mkmoires du Service Geologique du Maroc 366.

Robert-Charrue, C. 2006. Géologie structurale de l'Anti-Atlas oriental, Maroc (PhD Thesis). Université de Neuchâtel.

Robert-Charrue, C., Burkhard, M. 2008. Inversion tectonics, interference pattern and extensional fault-related folding in the Eastern Anti-Atlas, Morocco. Swiss Journal of Geosciences 101, 397–408. https://doi.org/10.1007/s00015-008-1266-0

Sebai, A., Feraud, G., Bertrand, H., Hanes, J. 1991. 40Ar/39Ar dating and geochemistry of tholeiitic magmatism related to the early opening of the Central Atlantic rift. Earth and Planetary Science Letters 104, 455–472.

Service Géologique du Maroc, 1985. Carte géologique du Maroc au 1/1 000,000.

Soulaimani, A., Piqué, A. 2004. The Tasrirt structure (Kerdous inlier, Western Anti-Atlas, Morocco): a late Pan-African transtensive dome. Journal of African Earth Sciences 39, 247–255. https://doi.org/10.1016/j.jafrearsci.2004.07.043.

Soualhine, S., de Leon, J.T., Hoepffner, C. 2003. Les faciès sédimentaires carbonifères de Tisdafine (Anti-Atlas oriental): remplissage deltaïque d'un bassin en «pull-apart» sur la bordure méridionale de l'Accident sud-atlasique. Bull. Inst. Sci. Rabat 25, 31–41.

Soulaimani, A., Bouabdelli, M., Piqué, A. 2003. L'extension continentale au Néo-Protérozoïque supérieur-Cambrien inférieur dans l'Anti-Atlas (Maroc).

Soulaimani, A., Michard, A., Ouanaimi, H., Baidder, L., Raddi, Y., Saddiqi, O., Rjimati, E.C. 2014. Late Ediacaran–Cambrian structures and their reactivation during the Variscan and Alpine cycles in the Anti-Atlas (Morocco). Journal of African Earth Sciences 98, 94–112. https://doi.org/10.1016/j.jafrearsci.2014.04.025.

Stampfli, G.M., Borel, G.D. 2002. A plate tectonic model for the Paleozoic and Mesozoic constrained by dynamic plate boundaries and restored synthetic oceanic isochrons. Earth and Planetary Science Letters 196, 17–33.

Termier, H., Termier, G. 1948. Un biotope à bryozoaires dans l'ordovicien du tafilalet (Maroc). C.R. Somm. Soc. Biogéogr. Paris 25, 26.

Thomas, R.J., Fekkak, A., Ennih, N., Errami, E., Loughlin, S.C., Gresse, P.G., Chevallier, L.P., Liégeois, J.P. 2004. A new lithostratigraphic framework for the Anti-Atlas Orogen, Morocco. Journal of African Earth Sciences 39, 217–226. https://doi.org/10.1016/j.jafrearsci.2004.07.046

Verati, C., Rapaille, C., Féraud, G., Marzoli, A., Bertrand, H., Youbi, N. 2007. 40Ar/39Ar ages and duration of the Central Atlantic Magmatic Province volcanism in Morocco and Portugal and its relation to the Triassic–Jurassic boundary. Palaeogeography, Palaeoclimatology, Palaeoecology 244, 308–325. https://doi.org/10.1016/j.palaeo.2006.06.033

Walsh, G.J., Benziane, F., Aleinikoff, J.N., Harrison, R.W., Yazidi, A., Burton, W.C., Quick, J.E., Saadane, A. 2012. Neoproterozoic tectonic evolution of the Jebel Saghro and Bou Azzer—El Graara inliers, eastern and central Anti-Atlas, Morocco. Precambrian Research 216–219, 23–62. https://doi.org/10.1016/j.precamres.2012.06.010

Wendt, J. 1985. Disintegration of the continental margin of northwestern Gondwana: Late Devonian of the eastern Anti-Atlas (Morocco). Geology 13, 815–818.

Wendt, J., Belka, Z. 1991. Age and depositional environment of Upper Devonian (early Frasnian to early Famennian) black shales and limestones (Kellwasser facies) in the eastern Anti-Atlas, Morocco. Facies 25, 51–89.

Youbi, N., Martins, L.T., Munhá, J.M., Ibouh, H., Madeira, J., Aït Chayeb, E.H., El Boukhari, A. 2003. The Late Triassic-Early Jurassic volcanism of Morocco and Portugal in the framework of the Central Atlantic Magmatic Province: An overview, in: Hames, W., McHone, J.G., Renne, P., Ruppel, C. (Eds.), Geophysical Monograph Series. American Geophysical Union, Washington, D. C., pp. 179–207. https://doi.org/10.1029/136GM010.