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Formation of septarian concretions and flattening tectonic structures in Jbel Dboa area (Tafilalt, Morocco): What relation with the setting up of a laccolithic system? Preliminary data

La formation des concrétions septariennes et les structures tectoniques d'aplatissement dans le Jbel Dboa (Tafilalt, Maroc) : Quelle est la relation avec la mise en place du système laccolithique ? Données préliminaires

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Abstract. In the Tafilalt area, located at the eastern edge of the Anti-Atlas domain (Morocco), the septarian concretions of the lower Famennian are known, for a long time, in the Jbel Dboa area. However, no explanation has ever been given about their mode of formation, or their association with flattening tectonic structures and even less their presence in the vicinity of a laccolithic system. In the present work, we consider that this triple association is not a coincidence. On the one hand, the rise and swelling of the laccolithic system creates the conditions of porosity and fluid circulation necessary for the formation of carbonate concretions. On the other hand, the opposition of the ascending force related to the rise of the laccolithic system and the descending force caused by lithostatic charge lead to the development of the septarian cracks in the concretions and cleavage planes and boudins in the host sediment marls and limestones layers respectively. If the fact that flattening tectonic structures are associated with laccoliths is a classic in geology, it is not the case of septarian concretions that would have formed at a depth greater than 3Km under the impulse of such magmatic bodies. This is exceptional or even unique in the literature.

Keywords : Morocco, Tafilalt, Septarian concretions, Tectonic flattening, Laccolithic system.

Résumé. Dans le Tafilalt, à la limite orientale de l'Anti-Atlas (Maroc), les concrétions septariennes du Famennien inférieur sont très connues dans la région du Jbel Dboa. Cependant, aucune explication n'a jamais été donnée sur leur mode de formation, ni sur leur association avec des structures tectoniques d'aplatissement et encore moins sur leur présence à proximité d'un système laccolithique. Dans le présent travail, nous considérons que cette triple association n'est pas fortuite. En effet, d'une part, la mise en place et le gonflement du système laccolithique créent les conditions de porosité et de circulation des fluides nécessaires à la formation des concrétions carbonatées. D'autre part, l'opposition de la force ascendante liée à l'élévation du système laccolitique et de la force descendante causée par la charge lithostatique conduit au développement des craquelures septariennes dans les concrétions et des plans de clivage et boudins dans les couches de marnes et de calcaires sédimentaires hôtes respectivement. Si le fait que des structures tectoniques d'aplatissement soient associées aux laccolithes est un classique en géologie, ce n'est pas le cas des concrétions septariennes qui se seraient formées à une profondeur supérieure à ٣km sous l'impulsion de tels corps magmatiques. Ceci est exceptionnel, voire unique dans la littérature.

Mots Clés : Maroc, Tafilalt, Septaria, Tectonique en aplatissement, Système laccolitique.

INTRODUCTION

At the eastern end of the Eastern Anti-Atlas (Morocco), the Tafilalt contains a Paleozoic cover that extends from Cambrian to Carboniferous (Wendt *et al*. 1984, Destombes & Hollard 1986, Baidder 2007, Benharref *et al*. 2014d, Fig. 1). In this area, the high quality of the Devonian outcrops and their fauna richness have always attracted specialized stratigraphers and paleontologists. This led to fairly extensive bibliography and good knowledge of stratigraphy, facies associations, and depositional environments of Devonian formations (Buggish & Clausen 1972, Bensaid *et al*. 1985, Wendt 1988, Becker *et al*. 1989, Walliser *et al*. 1989, Schindler 1990, Wendt & Belka 1991, Becker & House 2000, Casier *et al*. 2010, Aboussalam & Becker 2011, Becker & Aboussalam 2011, Bockwinkel *et al*. 2013).

In the Dboa area, which is a part of the Tafilalt Devonian Basin (Wendt *et al*. 1984), the lower Famennian corresponds to goniatites limestones and white and gray marls. The latter are famous because of calcareous concretions (septarian concretions) which constitute an attraction for both scientists and tourists. The presence and abundance of this kind of structures in the Dboa area have never been studied and no hypothesis for their formation has never been proposed. The Dboa area has another peculiarity, of tectonic order, which consists of an increase in the deformation intensity and the appearance of flattening tectonic structures recognized in rare areas elsewhere in the Tafilalt (Baidder *et al*. 2016) .

The purpose of this article is (i) to describe the particular sedimentary environment of the septarian concretions (ii) to decipher the tectonic structures of the Dboa area and (iii) to show that the concomitant presence of these two geological of structures in this circumscribed area is not a coincidence and (iv) if the genesis of the Septaria is related to the setting of a magmatic system so particular and characteristic of the Dboa area.

GEOLOGIC CONTEXT

The Tafilalt is located at the junction between the Ougarta belt in the Southeast and the Anti-Atlas belts in the West (Fig. 1A). It is a part of the Paleozoic domain of the Eastern Anti-Atlas. It is bordered to the North by the Cretaceous deposits of the sub-Atlas zone of Aoufous, to the South by those of Kem-Kem, to the East by the Meso-Cenozoic Hamada of Guir and to the West by the Ougnat-Ouzina axis and the Maider basin.

The Tafilalt Paleozoic sequence ranges from the Early Cambrian to the Early Carboniferous. It is made mainly by sandstones, pelites, limestones and marls (Fig. 2) (Hollard 1974, 1981, Wendt 1985, 1988, Destombes *et al*. 1985, Geyer & Landing 1995, Baidder *et al*. 2008, Ouanaimi & Lazreq 2008, Baidder *et al*. 2016, Clerc *et al*. 2013, Alvaro *et al*. 2014, Benharref *et al*. 2014a, 2014c, 2014d, Ghienne *et al*. 2014). This slightly deformed region belongs to the external domain of the Variscan belt whose metamorphic internal domain develops in the Atlasic and Mesetian domains further in north (Michard *et al*. 2010). The Paleozoic rocks are organized in a succession of anticlines and synclines with boomerang or sigmoidal trajectories. These forms have recently been interpreted as the result of the combination of polyphased Variscan deformation and controlled by fault blocks (Baidder *et al*. 2016). Anticlines, such as Znaigui or Dboa anticlines, are constituted by Cambrian, Ordovician or Devonian formations, while synclines (such as Amessoui or Marzouga synclines) contain Devonian and Carboniferous levels (Fig.1B).

Moreover, in the Tafilalt area, two magmatic events are recorded in the Paleozoic succession. The oldest belongs to middle Cambrian (Cambrian Epoch 2-3). It corresponds to volcaniclastics beds rich in pyroclasts, basaltic lava flows, submarine pillow-lavas flows and mixed volcaniclastic and volcanosedimentary deposits hosted in the Tazlaft member and the Jbel Wawrmast and Jbel Afraou fromations (Pouclet *et al*. 2018). The second magmatic event is mainly represented by a multitude of doleritic dykes and sills (Destombes & Hollard 1986, Najih *et al*. 2015, Pouclet *et al*. 2017). The age of this second event is still discussed. It was attributed to the Central Atlantic Magmatic Province by Destombes & Hollard (1986). Pouclet *et al*. (2017) are rather in favor of a Devono-Carboniferous age. These two proposals were questioned (Chabou *et al*. 2017a, 2017b, Najih *et al*. 2017). In Najih *et al*. (2018) stressed as well that the Tafilalt dolerites differ from the CAMP tholeiitic rocks, but also emphasized that they differ from the Devonian-Carboniferous intrusions of the surrounding areas (Moroccan Meseta, southern Hoggar). They are geochemically linked to the Permian-Triassic alkaline precursor of the CAMP magmatism known as Western Mediterranean Alkaline Province (Broutin *et al*. 1994, Youbi *et al*. 1995, Aït Chayeb *et al*. 1998, Lago *et al*. 2004, Scarrow *et al*. 2006, Bouloton *et al*. 2019). Recently, Najih *et al*. (2019) based on geochronological and geochemical data, attest a mid-late Permian age for these rocks , indicating a precursor magmatism that preceded the opening of the Central Atlantic Ocean.

The Dboa area, concerned by this paper, is located 12 km SE of Marzouga village and crops out 1km SE of Mfis old mining village (N31°01’25”, W3°56’05”). Geologically, it constitutes the southeastern part of the Mfis inlier, recently well studied (Wendt 1985, Destombes & Hollard 1986, Makkoudi 1995, Baidder *et al*. 2008, 2016, Kaiser *et al*. 2011, Benharref *et al*. 2014d, Berrada *et al*. 2016). The central part of the inlier displays the upper levels of the Early Devonian deposits corresponding to the Emsian marly formations and overlaid by the Eifelian and Givetian marly-limestones deposits. The Late Devonian period starts with Frasnian darky-grey limestones rich in organic materials attributed to the “Lower and Upper Kellwasser beds” (Hollard 1974, Wendt 1988). The Famennian bottom is made by white and grey marls followed by goniatitic limestones that underline the transition from the Lower to the Middle Famennian. The Late Famennian consists of an alternation of shale and pelite, headed by the much known Aoufilal sandstones (Fig. 3)

The Jbel Dboa displays a laccolithic system (DLS: Dboa Laccolith System), manifested by the emplacement of five laccolithic bodies within the marly formation from the early Famennian to the shaly pelites of the late Famennian in the southern flank of the Mfis inlier (Fig. 2). The first three (LA1, LA2, LA3) laccolithic bodies emplaced in the marly part of the Early-Famennian (d7a), then the fourth (LA4) emplaced in the Middle Famennian (d7b) and finally the fifth (LA5) in the Late-Famennian (d7c) pelites. All these bodies have a WSW-ENE orientation and a length of 3.8 km. The laccoliths are feeded by main dykes which follow the main regional faults. They are also interconnected by dykes and feed themselves the sills (Fig. 3).

PETROGRAPHY AND MINERALOGY OF THE SEPTARIAN CONCRETIONS

The formation of “septarian concretions” is very complex, already questioned but not completely elucidated. Several parameters come into play and their relative importance varies according each case (Raiswell 1971, Lindholm 1974, Curtis *et al*. 1977, Boles *et al*. 1985, Siegel *et al*. 1987, Astin & Scotchman 1988, Scotchman 1991, Desrochers & Al-Aasm 1993). The formation process of “septarian concretions” goes through different diagenetic phases and through different diagenetic zones (Surdam *et al*. 1989). The physical and chemical conditions of phases related to the depth of the zones, particularly for ancient limestone sediments, are decisive elements (Claypool & Kaplan 1974, Irwin *et al*. 1977, Berner 1981, Desrochers & Al-Aasm 1993, Coleman & Raiswell 1995). The intrinsic properties of limestone sediment such as carbon content, porosity and interstitial water chemistry also play a role in the control of the carbonate precipitation process (Astin & Scotchman 1988). Desrochers & Al-Aasm (1993) and recent work of Incerpi *et al*. (2018) have shown that hydrothermalism that accompanies plutonism contributes to the weathering of meteoric waters and influences the precipitation process.

On the other hand, the “septa” cracking system, which gives the concretion its septarian aspect, has also been the subject of several studies and explanations are numerous. One explanation assumes an initially soft concretion interior, confined within a harder cemented shell, which subsequently dehydrates with the formation of shrinkage cracks (Raiswell 1971, Pettijohn 1975). An expansion mechanism has been also evoked (Davies 1913, Astin 1986). Astin (1986) demonstrates that septarian cracks do not form by dehydratation. He suggests that they are stress-induced fractures occurred during rapid burial and compaction of the host mudrocks. Desrochers & Al-Aasm (1993) emphasized the importance of burial depth and fluid pressure in the development of cracks network and its appearance on the concretion surface.

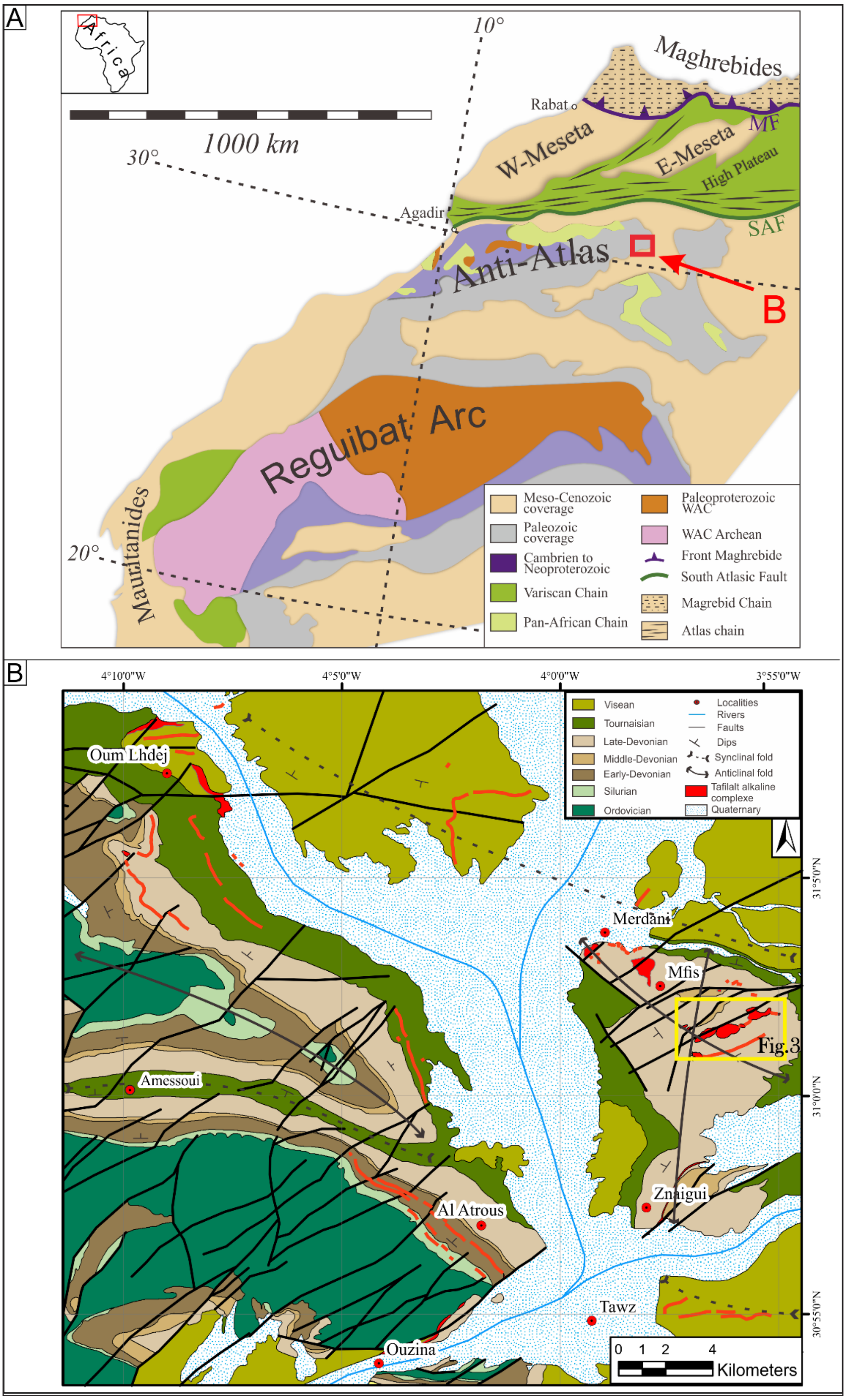


Figure 1. Geological maps: (A) Location of the Tafilalt region at the eastern part of the Anti-Atlas chain, map background after Michard *et al*. (2010). (B) Geological map of Tafilalt area redrawn from geological maps of Marzouga, Mfis, Al Atrous & Tawz (Alvaro *et al.* 2014, Benharref *et al*. 2014b, Koukaya *et al*. 2014, Tahiri *et al*. 2014).

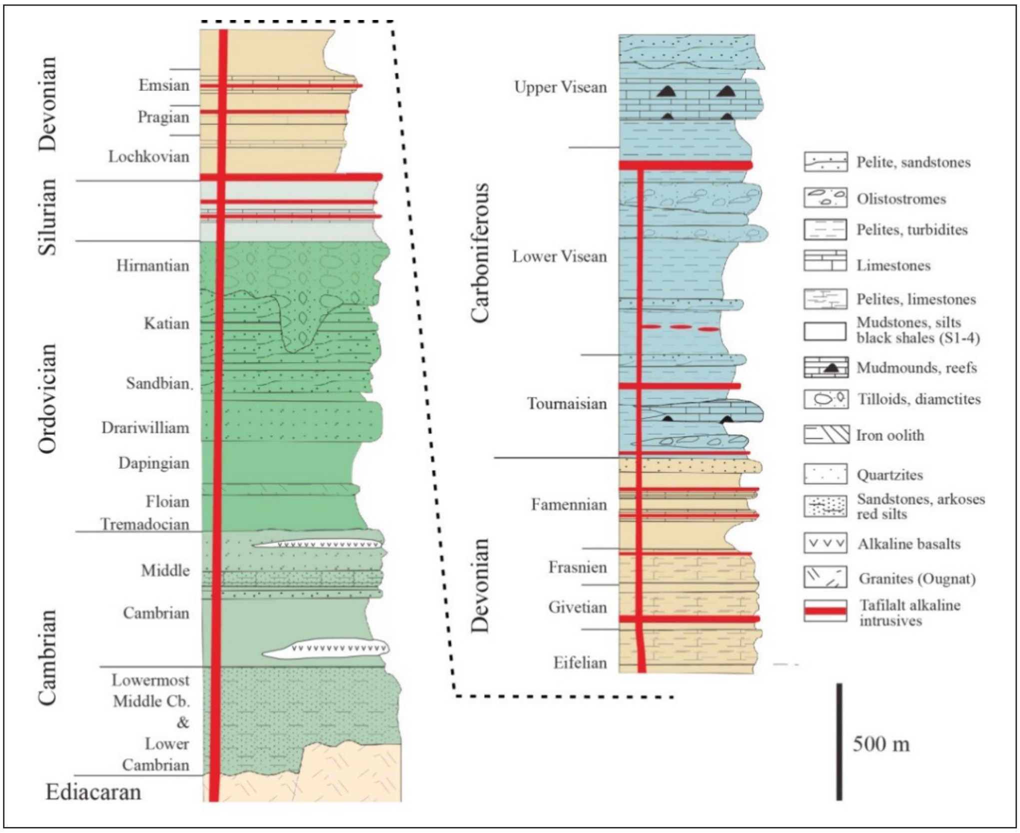


Figure 2. Paleozoic stratigraphic columns of the South Tafilalt region, after Álvaro *et al*. (2014) and Baidder *et al*. (2016), and location of the Tafilalt intrusives rocks in the lithology, after the published geological maps and this work.

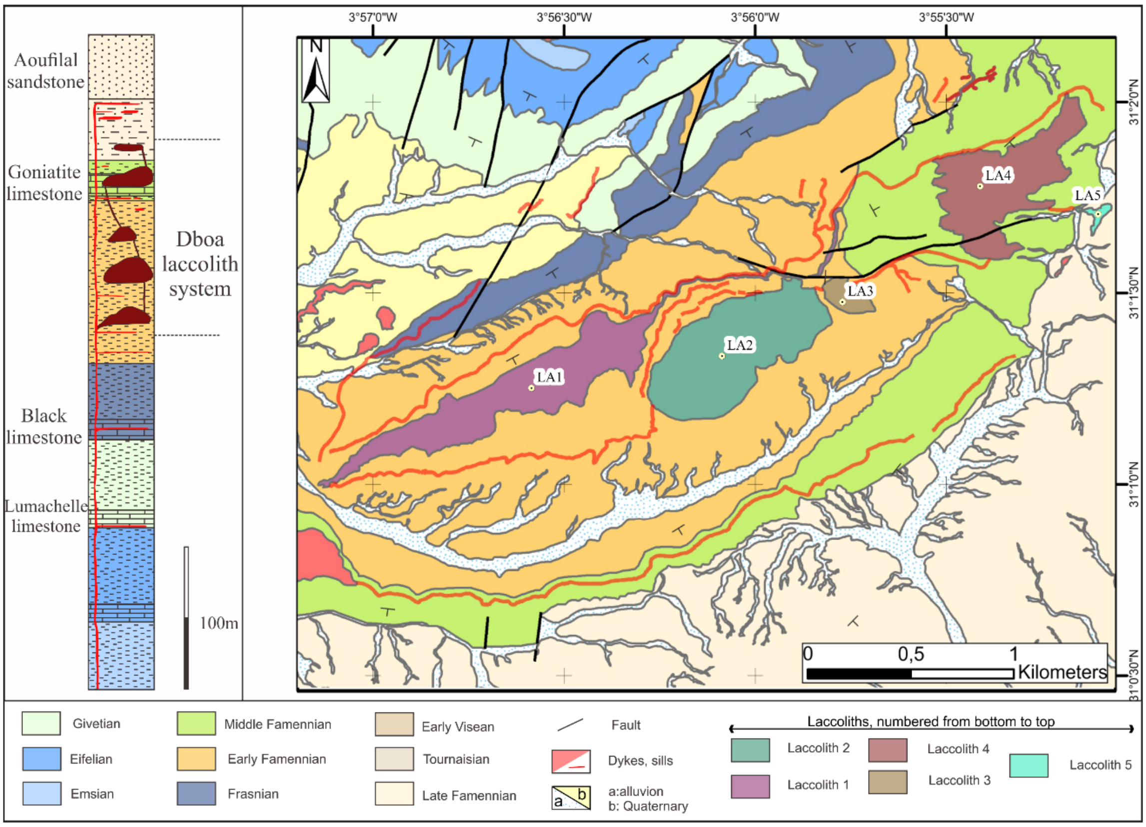


Figure 3. Geological map and stratigraphic column of laccolithic system of Dboa.

In the Dboa Study area, the Septarian concretions were described by Makkoudi (1995) as ovoid nodules of brown clayey limestone, fine or crystalline, seem burst and include ferruginous or non-ferruginous radial networks, and brownish convex calcium recrystallizations often in homogeneous cluster in the center of the nodule. The Septarian concretions are geographically localized and are always associated with laccolithic systems (Znaigui, Widane Chebbi, Jbel Dboa).

The Septarian concretions are mainly spherical and elliptical morphology, with variable dimensions, they can reach 1.5, 1.9 and 0.2m in length, width and height respectively. The concretions are molded by clastic materials and give a brief idea of the concretions growth (Fig. 4A, B). They expose several cracks at two main directions; vertical and horizontal cracks (Fig. 4C). Those cracks are filled by calcite, sulfate and/or ferruginous cements. The crack system exhibits a polygonal bursting in horizontal section and mainly vertical fractures in vertical section (Fig. 4C).

They are included in the marly level of the Early Famennian (d7a) of the DLS and located in the borders of the laccoliths. The size concretion is related to the position with respect to the laccolith axis; those of the peripheries have a small size, whereas those close to the center have a big stocky form (Fig. 5D).

TECTONIC FEATURES

In the Tafilalt, the Paleozoic cover and the basement are structured in rhombohedral blocks delimited by a network of faults, some of which are inherited from the Pan-African orogeny, and activated or reactivated during the Cambrian rifting and the Devonian dislocation of the Saharan platform (Baidder 2007, Baidder *et al*. 2016). Moreover, the structural position of the Tafilalt at the junction between the Anti-Atlas and Ougarta belts leaded to the reorientation of the regional stress during the Variscan orogeny. Hence and according to Baidder *et al*. (2016), this orogeny began the Bashkirian-Westphalian period with N-S direction of shortening (Anti-Atlas event) that converted NW-trending and NE-trending mega-faults respectively to dextral and sinistral mega shear-zones. A second NW shortening event (Ougarta event) occurred during the latest Carboniferous-Early Permian. The combination of superimposed events with distinct orientation of compression and the reactivation and inversion of an inherited faults network is in the origin of sigmoidal, croissant or boomerang shaped folds. None of the two compressive events were accompanied by regional axial plane cleavage and the physical conditions that prevailed during folding remained very low (Ruiz *et al*. 2008, Baidder *et al*. 2016). Penetrative cleavage can develop exceptionally and locally along some mega shear-zones as the Taouz shear-zone at the foot of Jbel Aroudane.

The Dboa area shows specific tectonic structures. It consists of horizontal cleavage planes and tectonic boudinage that affect mainly the clay-marly formation of the Early Famennian (d7a).

Cleavage Planes

The part of the d7a lower Famennian white gray marl between the top of laccolite 1 (axial zone) and d7b goniatitic limestones, and closed to the laccolite axis, shows regular cleavage planes parallel to the stratification (Fig. 5A). This cleavage is also observed at a narrow band below the lower limit of the laccolith (Fig. 5B and C) and between laccoliths. Cleavage planes mold concretions and boudins (Fig. 4D and 5D). These cleavage planes clearly result from flattening due to vertical compression (Fig. 6).

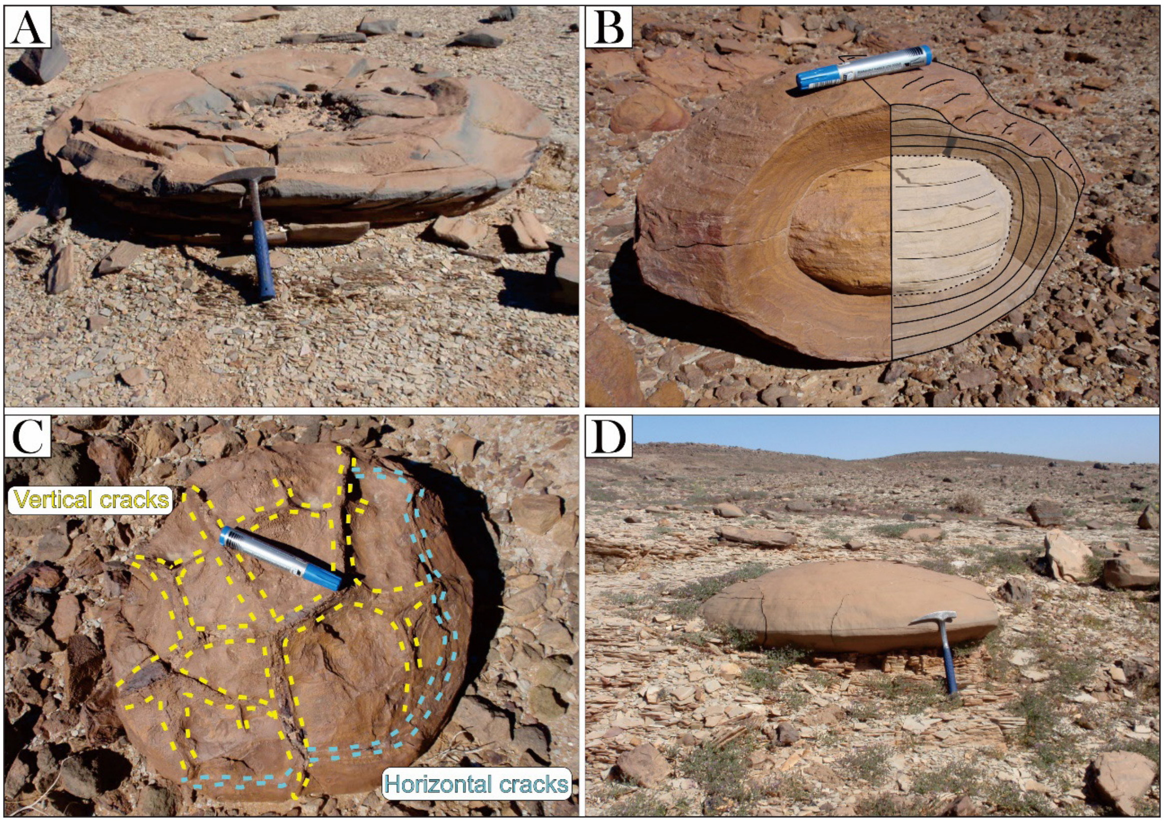


Figure 4. (A&B) Elliptical and ovoid shape of septarian concretions with the growth shape. (C) Crack system in septaria. (A&D) Stocky form of septaria next to the laccoliths.

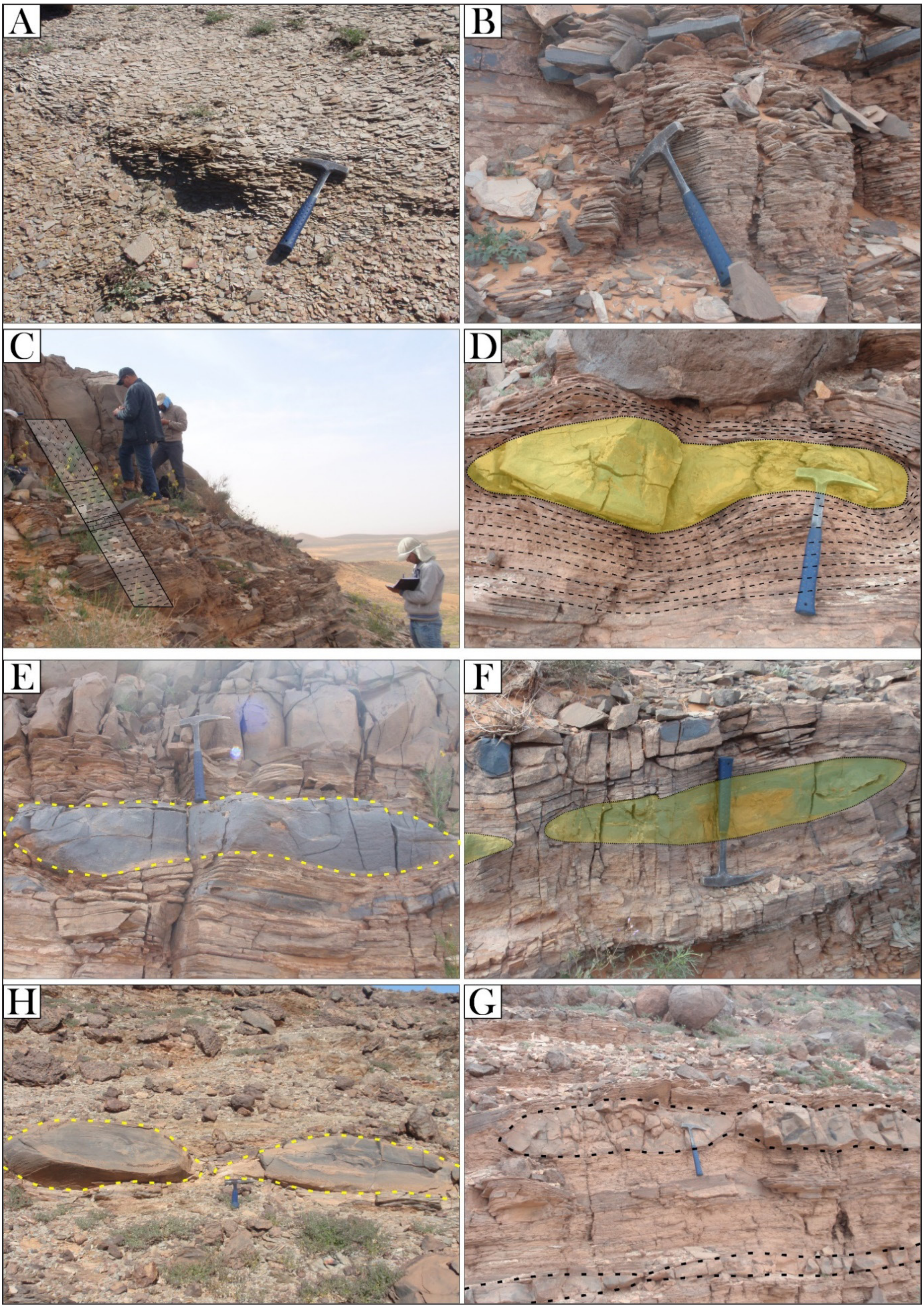


Figure 5. Tectonic features in Jbel Dboa. (A, B, C, D) flattening features below and between laccoliths. (E,F,H;G) boudin features, trapping and necked shape.

Boudins

Segmented, sausage shaped of limestone's layers are observed below the lower limit of the laccolith 1 (Fig. 5E and F) and between laccoliths 1 and 2 (Fig. 5G and H). The thin layers are completely cut into isolated boudins (Fig. 5F) while the thicker layers are only thinned with individualization of the boudins (Fig. 5G and H). The limestone layers were horizontally extended in response to the same vertical compression that gave rise to the cleavage planes (Fig. 6).

DISCUSSION

The studies carried out in the Tafilalt province and precisely in the Dboa zone show that the formation of septarian concretions and flattening tectonic structures (cleavage planes and boudinage) are spatially and intimately linked to the presence of laccolithic systems. Therefore, the mode of formation of these different structures whether diagenetic or tectonic should be designed according to the establishment of the laccolithic system.

There is almost unanimous agreement that concretions form in subsurface <30m. In general, formation by localized calcite or siderite cementation in argillaceous sediment under less than few meters of burial (Raiswell & Fisher 2000). This low depth of formation poses many problems for the different genetic models proposed, especially to consider concretion dehydration (Astin 1986) and to visualize enough compaction to develop septarian cracks. Hounslow (1997) agreed that septarian cracks are tensile fractures which may form over a wide depth range as long as the pore pressure is higher inside the concretion that in the host sediment; the formation depth is no longer a prerequisite (Hounslow 1997). Desrochers & Al-Aasm (1993) had evoked the role of plutonism and associated hydrothermalism in the formation of septarian concretions.

In the case of Dboa area, we suggest that the laccolithic system is the main driver in the septarian concretions formation. The establishment and swelling of the laccolithic system within the lower Famennian marls has caused a creation of space and an increase in the marly material porosity. If in the axial part, the shortening is rigor, laterally and in the peripheral parts, there is creation of space (Fig. 7) (Rubin 1995, Acocella & Mulugeta 2001, 2002, Kavanagh *et al*. 2006, Chanceaux 2016). The created spaces are important near the lateral edges of the laccoliths and tend to decrease, until a return to normal, laterally. The circulation of the hydrothermal fluids, but also those resulting from the sediment (still waterlogged) compacted at the apex of the laccoliteh, favor the movement and the precipitation of carbonates. The shape of the create space, important near the axis of the laccolite and weak in the peripheries, is translated by the size of the septarian concretions (see above). Since Laccolithic magmatism is mid-late Permian (Najih *et al*. 2019), it was placed under a sedimentary pile of at least 2 km or more (Baidder *et al*. 2016), this lithostatic charge alone is sufficient to explain the formation of septarian cracks. This charge was accentuated by an opposite ascending force due to the rise of the laccolithic system (Fig. 7).

This configuration with an ascending force related to the rise of the laccolithic system and a descending force caused by lithostatic weight, is at the origin of the creation of a stress vectors sufficient for the development of flattening tectonic structures, the horizontal cleavage planes and the boudinage observed in the Dboa zone. In this case, the tectonic flattening structures of Jbel Dboa cannot be related to regional Variscan deformation as suggested by Benharref *et al*. (2014) and Alvaro *et al* (2014), the regional Variscan deformation resulteing from a totally different stress field (Fig. 8).

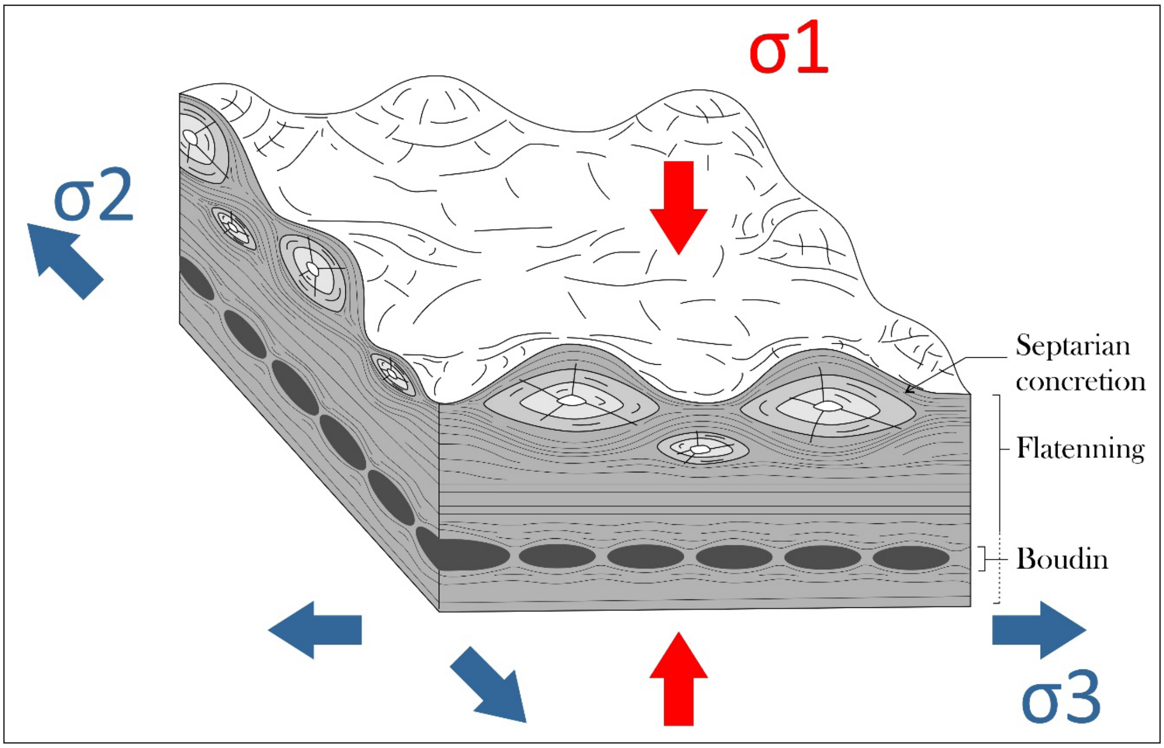


Figure 6. Cleavage planes and boudins vs tectonic stress in the Jbel Dboa area

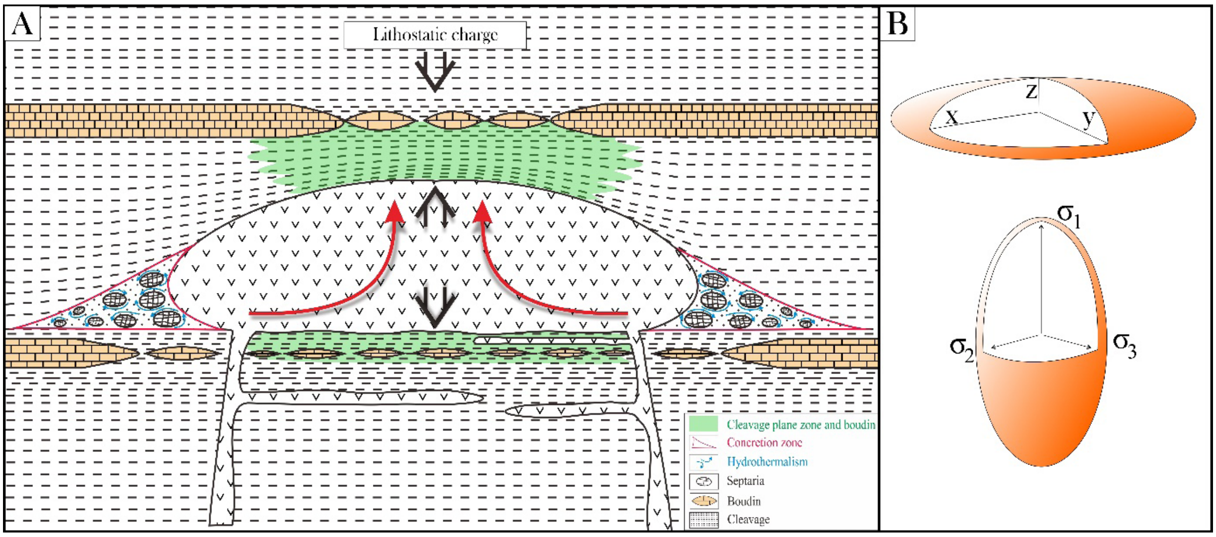
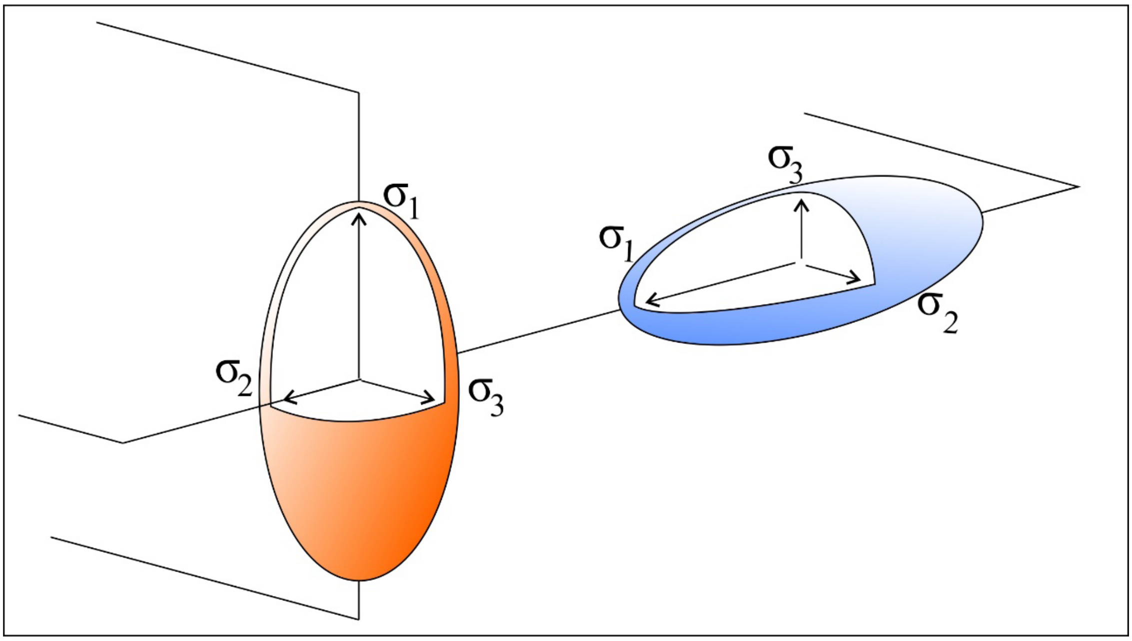


Figure.7. (A) Schematic model linking the interaction between the setting of igneous bodies and tectonic and diagenetic features. (B) Deformation and strain stress of tectonic features of Dboa system.



Figur. 8. Comparison between local strain stress of tectonic features of Dboa system and regional strain stress recorded in Tafilalt.

CONCLUSION

At the eastern edge of the Anti-Atlas, the Paleozoic deposits of Tafilalt host magmatism in the form of dykes, sills and laccoliths. The latter develop particularly in the d7a marly formation of the lower Famennian, the Jbel Dboa area is the best example. In this area a system of five laccoliths superimposed in slate took place, three in d7a marls, one in middle Famennian d7b and last one in upper Famennian d7c shales. The rise and ballooning of the laccolithic system in the marl d7a has created the conditions of space and porosity but also the circulation of hydrothermal and meteoric fluids necessary for the carbonate concretions formation. The compaction caused by the opposition of the lithostatic charge on the one hand and the ascending force in relation to the rise of the laccolithic system in the other hand would explain the development of septarian cracks. This means that the septarian concretions of Dboa area were formed at a depth greater than 3 km which is exceptional or even unique in the literature. The stress field resulting from the opposition of the ascending force related to the rise of the laccolithic system and the descending force caused by lithostatic weight leads to the development of flattening tectonic structures consisting of cleavage planes and boudinage. These structures are closed to the laccolithic system and were caused by stress vectors totally different from those of the regional Variscan deformation.

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