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The Role of Tectonic Fracturing in the Development of a Karstic System and Groundwater Exchanges in Semiarid Area: Case of Ouarsenis Mountains (Western Algeria)

Zaagane Mansour, Hamimed Abderahmane, Refas Soraya and Khaldi Abdelkader

LRSBG (Research Laboratory of Biological Systems and Geomatics),
University of Mascara, Road of Mamounia -Mascara. PO Box 305 (29000), Algeria

Abstract: The Ouarsenis area is one of the most developed karstic systems of Algeria. It is a karst reservoir drinking water with a population of more than fifty thousand people taking fully benefit from it. Numerous joint sets oriented NNE/SSW have been identified almost over the entire culminating area. These joints are the direct consequence of the following stress history: (i) a NW/SE shortening responsible for a major overlap and the first fold (P1) phase, (ii) a second NNE/SSW shortening stage responsible for the second folding (P2) phase associated with N70° sinistral strike slip trend, (iii) a WNW/ESE extension phase resulting from the change of σ_3 stress vertical axis and (iv) a shearing stress creating a N120° sinistral strike-slip fault. Only the late phases are responsible of the development of joints, which have been karstified later on. Indeed, significant families of karstified joints, i.e. N20° and N70° have been found. These joints are related to the extensional and shearing modes respectively and linked to a particular *in situ* karstogenesis. Moreover, this study suggests an ancient establishment of the karstic systems in the Ouarsenis region in at least two stages: prefigured and activated behaviors during the Cenozoic.

Key words: Structural evolution · Ouarsenis · Cenozoic tectonic events · Karstic systems · Jurassic limestone

INTRODUCTION

The Ouarsenis massif (the external Tell) belongs to the Western Tellian Atlas locating 50 km to the Southeast of the seismic area of Chlef (Fig. 1). The Ouarsenis is mainly composed of Jurassic rocks emerging like small islands and piercing the Cretaceous succession characterized by a turbidities formation (flysch of Albo-Aptian in age). This region is well known as karstic system. Indeed, the circulation of water in the Jurassic limestone forms one of the longer karstic networks in the external domain of Algeria.

The objective of the present work is to show the evolution of the karstic systems of Ouarsenis in accordance with the tectonic history of the area (from a tectonic microstructures point of view). This study is an attempt to complete and to achieve the previous structural studies on this topic [1]. The key milestones of its tectonic history will be redefined here specifically by specifying the temporality of events and their interactions with the development of the karstic system in this region.

Geological Setting

Lithostratigraphic Features: The Ouarsenis region belongs to the carbonate Mesozoic cover of the tellian chain of Algeria. The rock units involved in this cover include the Liassic limestone and the turbidities represented by the Albo-Aptian flysch (Fig. 2a). The overlying Meso-Cenozoic formations are represented by a pile of tectonic nappes coming from the detachment of only autochthonous formations. The Cenozoic deposits contain mainly gray marl with the exception of the period extending from the Paleocene to the Eocene, which is marked by calcareous marl alternating with a few passages of glauconitic-sandstone. The Post-Miocene period, which is represented by a

Corresponding Author: Zaagane Mansour, LRSBG (Research Laboratory of Biological Systems and Geomatics), University of Mascara, Road of Mamounia -Mascara. PO Box 305 (29000), Algeria. Tel: +213707005, Fax: +213707003.

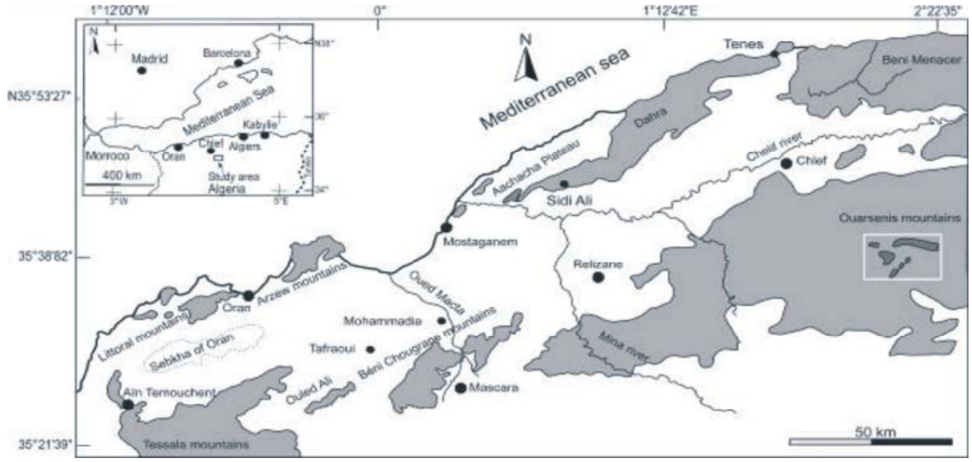

Fig. 1: Location of the Ouarsenis area in relationship with the Tellian Atlas in the north of Algeria (greyish areas). The square in the small and biggest map show the position of the study area.

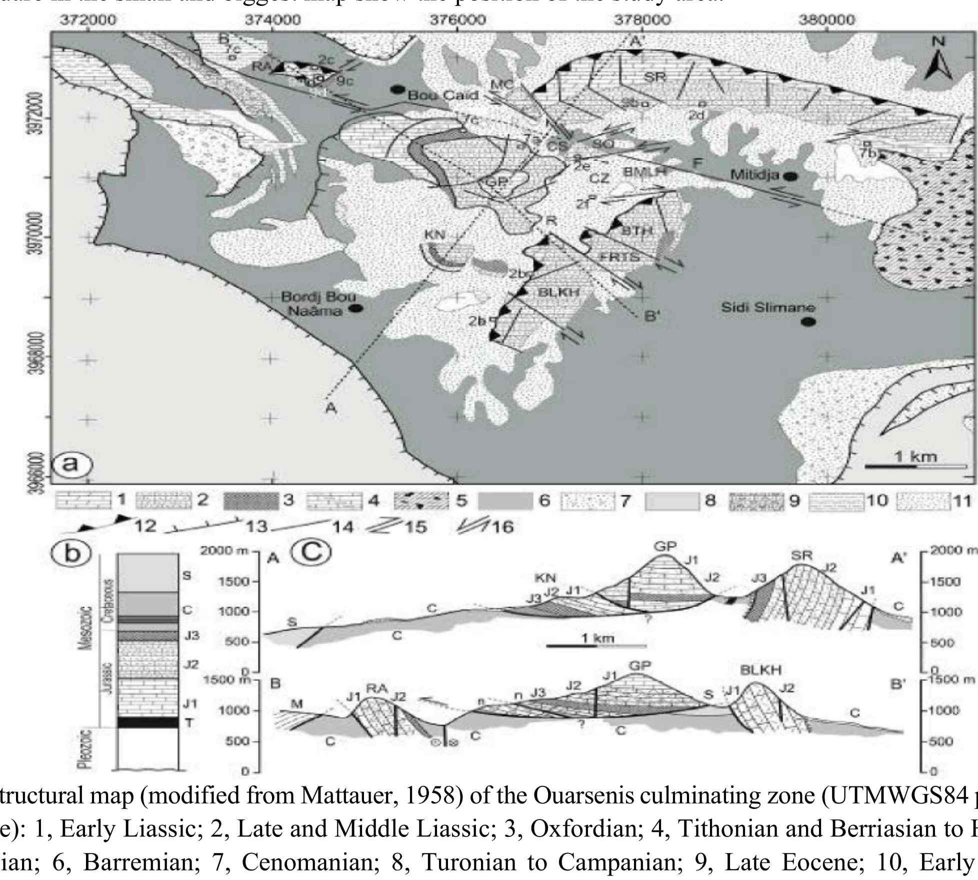

Fig. 3: A Structural map (modified from Mattauer, 1958) of the Ouarsenis culminating zone (UTMWGS84 projection 31N zone): 1, Early Liassic; 2, Late and Middle Liassic; 3, Oxfordian; 4, Tithonian and Berriasian to Hauterivian; 5, Albian; 6, Barremian; 7, Cenomanian; 8, Turonian to Campanian; 9, Late Eocene; 10, Early Miocene; 11, Quaternary; 12, thrust; 13, tectonic contact; 14, fault; 15, dextral strike-slip; and 16, sinistral strike-slip. The various structural units are represented by SR Sra Abdelkader, RA Rokba Atba, BTH Batha, FRTS Fartas, GP Grand Pic, BLKH Belkheiret, BMLH Bou Malah, SO Sidi Ouadhah, CS Senan pass, MC Chicots massif, KN Kef N'Sour, R Roubia, g and g' sinistral shears separating the BMLH and SO massifs from the central zone CZ, respectively. b: a synthetic lithostratigraphic section of various lithology especially Mesozoic, T Triassic, J1 Early Liassic, J2 Late Liassic, J3 Malm, n Berriasian to Hauterivian, C Clansayesian-Albian, S Turonian to Campanian, M Miocene. c: Illustration of schematic cross-sections AA' and BB' passing through the central massif of the GP. Open squares named 2a–9d correspond to the location of figure numbers.

lithologic marl deposited after the great overlap of internal areas, covers the different previous units. The flyschs and Tellian nappes have formed the substratum of large post-nappes basins, the spectacular example is the Lower Cheliff basin oriented WSW-ENE. The mountains bedrock consists of identical geological formations, i.e. rocks ranging from Jurassic to the Cretaceous (Fig.2b) [2, 3].

MATERIALS AND METHODS

Microtectonic Analysis: Tectonic and stratigraphic microstructures (faults, tension gashes and joints) of decimetric or decametric scales are measured and discussed hereunder.

Fault Analyses: The tectonic analysis of faults revealed the existence of four regimes of paleo-stresses. A relative chronology could be established from qualitative arguments such as stratigraphic dating of faults, crosscheck of several generations of tectonic striaes on the same fault plane and mineralization differences or grinding within the fault zones [5].

The stress chronology can be listed as follows:

- The clearest recorded stress is a pure compression mode oriented NNW-SSE. The established chronology, also confirmed by a crosscheck of striae on the same fault mirror, indicating that this stress state is the oldest one recorded within the four mountain massifs. The tensor ratio was calculated from a major class of neoformed reverse faults (Class 4) at Belkheiret site with a confirmation from two other neoformed faults (Class 1 and 2). The P1 folding with an NW-SE oriented axial plane was developed at this stress regime, which also generated the extrusion of the structural units set as crescent shape.
- The second identifies stress is a pure compression mode, oriented NNE-SSW. It has been calculated from the sinistral strike-slip neoformed fault class oriented (NW-SE Class 3). This stress loading is the cause of the development of the second folding stage (P2) with a NNE-SSW oriented axial plane.
- The third state of stress is also a pure compression phase oriented WNW-ESE. The large set of the inherited sinistral strike-slip faults can probably be associated with the neoformed faults formed during the second folding step (P2),.
- The fourth identified stress is a pure shear mode loading oriented NNW-SSE. The resulting strike slip faults can be identified only in the Grand Pic Mountains. It is characterized mainly by inherited and heterogeneous faults.
- The fifth and most recent stress state is specifically characterizes in the central part. The calculated stress tensor shows a transpressive style with an ENE-WSW direction.

Joints: The joints are the only brittle structures exhibiting differences between the four massifs. There are represented by four directions classes:

- The N20° oriented joints are the most common class characterizing the Grand Pic, Sra Abdelkader and Rokba Atba mountains. In the Grand Pic, bedding joints are horizontal, interspersed with tectonics joints and are characterized by vertical component with a dip exceeding 60°. In Rokba Atba and Sra Abdelkader, these joints are interspersed with N45° oriented joints in the Bajocian formations. This intersection forms locally a lozenge shape.
- N70° oriented joints characterize the central and southern mountain zones as well as Belkheiret, Fartas and Batha. At the Hariga sector, located in the Western part of Rokba Atba, these joints are interspersed with the N10° and N120° joints.

Table 1: Paleostress tensors from fault-slip data.) E1,E2,E3 : eigenvalues related to the principal stress σ_1, σ_2 and σ_3 respectively, n: number of fault data used for stress tensor determination; nt: total number of fault data measured; σ_1, σ_2 and σ_3: stress tensor elements; D/P: azimuth (°) and plunge (°) of principal stress axes; $R = (\sigma_2 - \sigma_3)/(\sigma_1 - \sigma_3)$: stress ratio; á: mean slip deviation [4] *the obtained stress regimes (S/R) are CP pure compression, SSP pure strike slip, TRP and TS transpression. For the abbreviations), FRTS-BTH, RA, BLKH, GP, SRA_East, SRA_West see the Figure 3.*

Zone	n	nt	E1	σ1(D/P)	E2	σ2(D/P)	E3	σ3(D/P)	á	R	S/R
FRTS/BTH	9	11	0,65	120,5/23,9	0,01	232/39,7	-0,66	7,9/40,9	16.7	0,51	CP
BKH	13	16	1,26	163,9/24,2	-0,26	256,1/38,5	-1	73,6/41,1	18.8	0,33	CP
GP	5	6	0,64	138,7/33,3	0,1	0,1/48,4	-0,75	244,1/22	19.1	0,61	SSP
RA	11	14	0,08	206,3/28,6	0,04	111,2/33,1	-0,12	324,3/43,5	19.9	0,8	CP
SRA_East	12	15	2,21	164,8/27,3	0,04	267,3/23,5	-2,21	31,7/52,6	17.6	0,51	CP
SRA_West	10	10	1,65	202,5/24,5	0,16	309,5/32,7	-1,82	83,2/47,1	11.4	0,57	CP
CZ	12	14	0,14	56,5/35,3	0,6	312,8/48,8	0.2	200,4/18,4	12,3	0,16	TRP

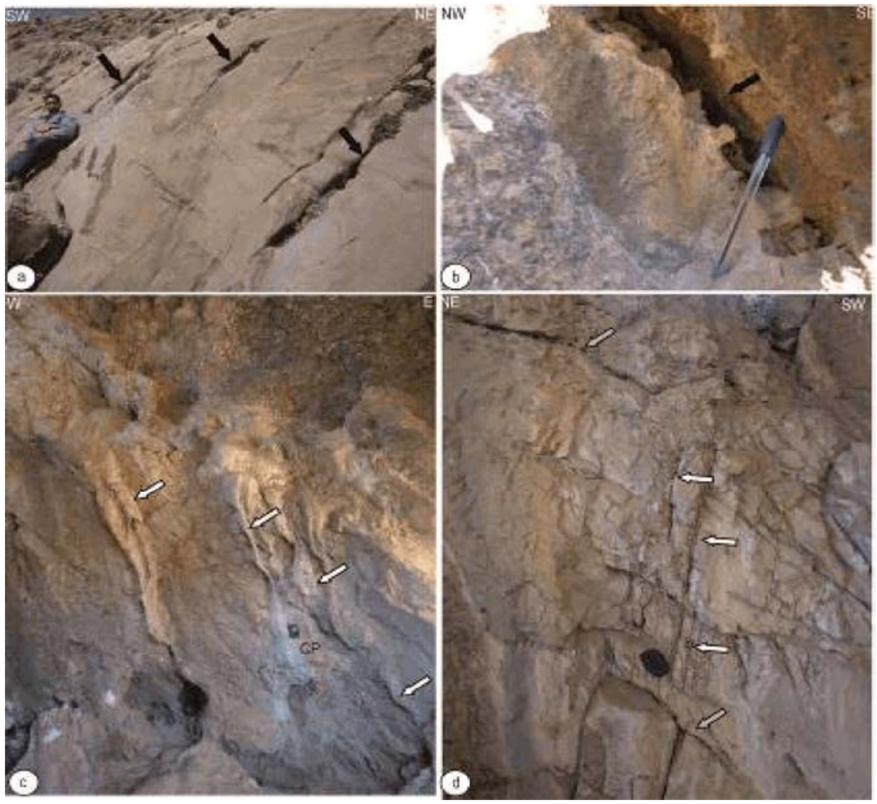

Fig. 3: Field photos showing different stage of karstogenesis, a: Dissolution of the opening joints in the Bajocian limestone rock located in the Southern part of Rokba Atba, b: Deep and vertical cave developed in detriment of a tectonic fracture, located in the southern part of the massif of Sra Abdelkader and c, d: ataractic shapes developed in the grottoes located in Rokba Atba (refers to the Fig.2c).

- The oriented N120 joints° characterize the BouMalah, Grand Pic and Batha massifs: this class of joints can be related to two different tectonic events, including: (i) the initial compressive phase responsible for the extrusion of structural unit set and (ii) the anthetic strike slip fault system related to the late shearing deformation phase.
- The N160° joint class, identified in restraint area only, especially in the northern part of the Grand Pic Neocomian Marl-limestone zone. Since all formations are oriented N120° and almost vertical in massif Sra Abdelkader, the measured joints are only bedding joints, characterized by vertical component with a dip exceeding 60°, mainly in its Eastern part.

RESULTS AND DISCUSSION

Tectonic Controls of the Karstfication Processes: Regarding the specific geomorphology of the region, particular attention has been given to the tectonic controls of the karstification processes.

The karstified structures can be defined as structures in which karstic galleries are developing due to the combined effect of preexisting tectonic joints and meteoritic water. Naturally, the shapes of the karst features are related mainly to the progressive widening of joints through chemical dissolution. According to [6], the neoformed faults and tension gashes are not involved in the karstification process. The brittle structures, which are massively affected by this particular type of erosion, are the joints. For this purpose, the joints were systematically studied. The microtectonic study revealed that two families of joints are intensively karstified: joints oriented N20° and N70° (Fig. 4).

For a specific direction, the karstification affects the joints whatever their origin either bedding joints or tectonic fractures [6]. In the Massif Belkheiret, the karstified joints are mainly vertical. In Massifs Rokba Atba and Sra Abdelkader, the N20° oriented joints are vertical and correspond to bedding planes as the lithologic formations are highly tilted.

Karst-Tectonic Relationships: The tectonic history highlights the dynamics of the karst system in the Ouarsenis region. The karstified carbonates belong to the Lower and Middle Jurassic units. There are characterized by the same altitudes, uplift rate, climate, vegetation cover and stream networks with minor differences in the local scale.

First, the Mesozoic tectonics is recorded in the surrounding areas, it is marked by: (i) a large angular unconformity related to the Albian stage and (ii) the uprisings of the funds of Tellian basin with gypsiferous intrusion. Our analysis shows that the Mesozoic tectonic is not related to the initiation of the karstic process within the mountains of Ouarsenis. Although the karst geometry sometimes overlaps with the geometry of the Mesozoic structures, this overlay is not sufficient to be linked with the genesis of the karst system in this region [6]. Moreover, no extrusions of structural units representing the culminating zone have appeared yet.

Then, a purely Cenozoic post-Langhian evolution of the region was established (Fig.4). This assertion is based on the following criteria: (i) the structural units pierce the overlying formations autochthonous and allochtonous, (ii) the nappes dynamic was attributed to the period in Burdigalian to Langhian and (iii) the overall extrusion processes took place at the same time.

Karstic mountains of massifs have been formed massively in detriment of the N20° and N70° joints, which are associated to previous tectonic phases (Fig.4). These joints have been activated in a clear way during the WNW-ESE extension step and the ENE-WSW shear step of the Cenozoic age. Their dominant presence in the karstified massifs is linked to these two later phases (Fig.4).

The study of the karstified joints provides significant information on the geometry of karst systems [6]. The origin of karstified joints is relatively various: (i) the bedding planes resulting of initial phase of lithostratigraphic deposit during the Mesozoic, becoming vertical during subsequent phases and (ii) the tectonic fractures resulted from the later stages of Cenozoic age, (Fig.3).

If their origin is various, only two families of joints are karstified (Fig. 3). It is mainly the N20° and N70° oriented joints (Fig. 4). These joints are respectively associated to a WNW-ESE extension as well as an ENE-WSW shear displacement. Therefore, there can be considered active and open, which contributed to ease underground circulation of water, the main chemical vector of the karstification. The N120° karstified joint class is related to the first tectonic stage: this class exists but only at a low frequency. It means that the first compression stage has caused the opening of the bedding joints horizontally because σ_3 axis was vertical (Fig. 4). This stage is also responsible of the overlap process pushing the under laying formation (Jurassic limestone) to overlap the upper layers (turbidities Cretaceous in age). This strain stage was at the origin of the appearing of the tension gashes. Once the Jurassic limestone exposed, the weathering of the bedding planes greatly eased the circulation of the rainfall water. These structural features and climatic conditions greatly controlled the geometry of the karst systems (Fig. 3).

However, the interpretation of the karstification of the N120° oriented joints is difficult to interpret. Tectonically, the neoformed fractures, which are mainly karstified, are related to the NNW-SSE compression phase that is considered as the second tectonic stage attributed to the Late Miocene. However, it is possible that the N120° karstified joints are probably related to bedding planes as for example in the eastern part of Sra Abdelkader.The lithostratigraphic layers are oriented N120° with a dip of 80° to the South. The microtectonic analysis shows that these joints are present at a low frequency. The latest work in karstogenesis assumes that a karstification of limestone massif is a more consequent process than the classical view did not allow glimpsing [7-9]. This karstification is not only initiated, but can develop over long periods as well as stopping occasionally: its evolution is strongly dependent of the regional tectonic and the climate histories.

In the compression of Pliocene, a hypothesis of karstogenesis in two-time embedded in tectonic history can be formulated (Fig.4). First, during the Cenozoic, under a low hydraulic gradient, the paleo-relief of the region is slightly marked; a tectonic opening process as well as presence of N20° joints would be accompanied by karstic processes, somehow incomplete, because of the presence of "ghost rock" type [8]. This type of karst is partiche case of Ouarsenis massifs, if it assumes the existence of the action of NE-SW ularly vulnerable to high water flow rate [6].

Second, during the Cenozoic terminal, under high hydraulic gradient due to the continuous exhumation, (presence of N70° joints) the joints were opened continuously and as well as karstified with transport of altered materials [10] (Fig.4). The increased activity of groundwater in the karstified limestones bedrock expels simultaneously the alteration residues of the N70° joints. This results in the formation of karst systems as observed today.

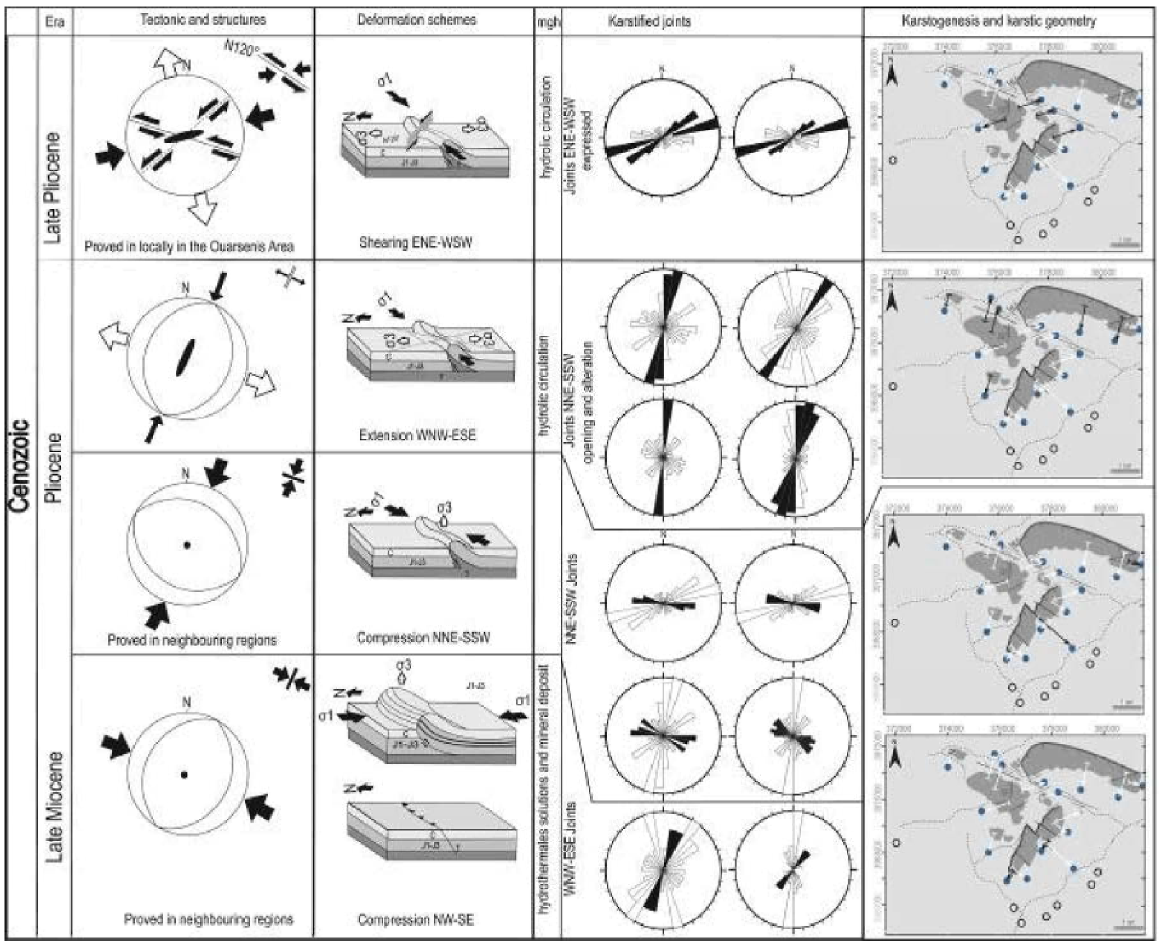

Fig. 4: Relationship between the tectonic stress and karstic structures development in detriment of pre-existent joints and fractures, tectonic and structures are showing by the black joints in the stereogram related to the stress calculated in the culminating area, the two middle columns show the deformation scheme with stress corresponding and the tectonic joints and bedding planes corresponding to each tectonic stage.
The right column show the localization of karstified joints (blacks arrow) corresponding at each tectonic events, the base of the arrow shows where the water starts to get lost in the rocky massif in the upstream and the tip of the arrow shows the outflow of water (spring) in the downstream. Blue circles correspond to sources derived from limestone mountain; the open circles are located in the Albo-Aptian turbidity formation.

Finally, both of the karstified joints sets are not present with the same intensity from a massif to another. In Bou Malah, Batha, Grand Pic and Rokba Atba massifs, the N120° joints class is no longer subject to karstification; in Grand Pic, Rokba Atba and Sra Abdelkader massifs, the N20° joints class is slightly dominant (Fig.4). This fact illustrates the action of a second important factor involved in the geometric operation of karst systems, which is of water circulation. Thus, the rose diagram of karstified joints appears to indicate the main water flow direction, which is mainly controlled by the directions of extension joints. Once the direction of the water flow controlled, the structure of the two karst systems have been greatly influenced by the intensity of these flows in a second step.

CONCLUSIONS

The link between tectonic activities was established with the development of a karstic system in a complex and tectonically overlapping domain. The structural N120° joints is observed only very seldomly. The beginning of the karstogenesis in the Ouarsenis area is undoubtedly related to a tectonic extension phase (WNW-ESE) recognized elsewhere in the Tellian chain.

The study of karstified joints indicates that the karstic systems of the Ouarsenis area are structured according to two preferred directions N20° and N70°. The Karstification of N20° joints can be explained easily by the action of the third tectonic stage. Since the Cenozoic, these joints are opened and constantly reactivated forming a preferential path for water, which is the main factor of karstification. However, the N70° karstified fractures is attributed a singular tectonic events, it is the late stage shear oriented NNE-SSW. This might be due to the Late Pliocene event acting in two stages on the karstic networks in the region of Ouarsenis.

The study confirms the existence of a direct relationship between tectonic and karst settlement. The limits of the relationship between compression and karstogenesis must be explored. Indeed firstly, it is likely that the Grand Pic, Rokba ATBA, Sra Abdelkader Belkheiret and Batha mountains have also been subjected the compressive phase Cenozoic NNE-SSW, even if there do not keep traces obvious structural. Then, it is certain that there have not undergone karstification contemporary. It is tempting to think that a threshold governs the relationship between tectonics and karstification. According to this study, it seems to trigger the whole karstification of mountains, tectonic activity should be intense enough to create new joints or perhaps even, broaden the already open joints.

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