



Iraqi Geological Journal

Journal homepage: <https://www.igi-iraq.org>



Morphogenesis of the Closed Depressions in Middle Atlas: Case of the Causse of El Menzel, Morocco

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Abstract

Received:
9 May 2023

Accepted:
11 September 2023

Published:
30 November 2023

Closed depressions are the most typical exokarstic forms of the Moroccan Middle Atlas karst. These features present a great diversity of forms and sizes related to the multiple and often obscure conditions of morphogenesis in several karstic plateaus of the tabular Middle Atlas such as that of El Menzel. This little-known carbonate panel is characterized by an important geodiversity of closed depressions with variable shapes and reliefs: poljes, uvalas, dolines, kamenitzas, and rain pits. The results confirm the tectogenetic nature of several closed depressions of which the most important are: the polje of El Menzel and the polje of Quagbat Beni Yazgha which are aligned along the major accidents of the Causse oriented NE-SW and NW-SE. The pre-established tectonic heritage Accident Median Moyen Atlasique and Accident Nord Moyen Atlasique, and the compressive tectonics and particularly extensive phases from the upper Miocene to Quaternary during the surrection of the Middle Atlas associated with the pluvial climatic phases have permitted the development of the good potential of karstification as well as the large closed depressions of the Causse.

Keywords: Karst; Closed depressions; Causse of El Menzel; Moroccan Middle Atlas

1. Introduction

Understanding the genesis and evolution of karst systems is very important given that carbonate rocks cover about 15.2% of the world's drylands and 1.18 billion people (16.5% of the world's population) live in karsts (Ford and Williams, 2007; Goldscheider et al., 2020). Today, facing the rapid growth of the world's population which reached more than 7.6 billion people in 2018 requires aggressive urbanization and land use, resulting in additional anthropogenic effects on the environment due to primary resource needs (Goudie, 2018).

In Morocco, faced with the major environmental and anthropogenic challenges confronting the country, karst research is becoming more important due to the fact that the Moroccan karst covers more than 100,000 km² or nearly 15% of the entire Moroccan territory (Nehili et al., 2021). This karst extension makes the country one of the most favorable sites for major karst research projects in North Africa. Moroccan karstic outcrops are practically present in all structural areas of Morocco, but of unequal importance: The Rif area, the Atlaso-mesetan area, and the anti-atlasic-saharian area

(Naouadir et al., 2023). These karst outcrops can be found in rock series of different ages, in particular Adoudounien and Georgian limestones (Infracambrian), Early and Middle Jurassic carbonates (Lias and Dogger), Late Cretaceous limestones (Cenomanian-Turonian) and Plio-Quaternary limestones. The Liassic limestones and dolomites represent the largest karst complex in Morocco, with an outcrop area of about 30,000 km² (Theilen-Willige and Naouadir, 2022). These carbonate formations cover almost the entire Middle Atlas with an evident impact on the landscape of its limestone Causses; this explains why the notion of karst in Morocco is closely linked to the Middle Atlas (Martin, 1981). These liassic carbonate series play a major role in the delimitation of the karstic area (Akdim, 2015). They have a great capacity to retain meteoric waters, which makes the Middle Atlas the water tower of the kingdom with its main Oueds the Sebou, Oum Er-Rbia, and Bouregreg. This implies that they contain an important water table that is retained by an impermeable floor consisting of red clays of the Late Triassic-Lower Lias (Cousminer and Manspeizer, 1976; Biron and Courtinat, 1982; Baudelot et al., 1986; Sabaoui, 1987).

Middle Atlas includes a wide range of karst forms and processes determined by the evolution of environmental conditions and geology (Mounir et al., 2019). A superficial observation does not miss the multitude of surface karst forms, from small metric cavities to large closed depressions that extend over several square kilometers (Martin, 1981). These closed depressions are characteristic of karst (Kranjc, 2013). They are invariant and appear at all scales, from millimeters to kilometers (Pardo-Igúzquiza et al., 2022).

In Middle Atlas, the closed depressions are characterized by a great heterogeneity of shape and size with varied and often obscure conditions of morphogenesis (Martin, 1981). According to some authors, these karstic forms of collapse are developed by tectonic-karst processes (Hinaje et al., 2002). Other authors show good agreement between remote sensing derived lineaments and these karst features in several Causses as in Azrou and El Hajeb (Menjour et al., 2017; Muzirafuti et al., 2019). Recently, Theilen-Willige and Naouadir (2022) cited a set of factors such as lithology, the influence of extreme meteorological events, neotectonic movements, seismic activity, volcanism associated with hydrothermal dissolution, watershed morphology, and groundwater flows that influence the development of these karst forms in the Middle Atlas.

The karst phenomena of the Middle Atlas are fascinating and complex, as it is difficult to understand all the factors that influence the development of these karst forms, due to the irregular and complex connections between the surface and the subsurface. Water flow in the karst often appears confusing (Benac et al., 2013).

Until now, there has been little information or knowledge about the closed depressions of several limestone Causses such as El Menzel Causse. This little-known Causse is marked by a remarkable karstic geodiversity in a very small area. Several factors have influenced the karstic geomorphology of the Causse, including inherited tectonic deformations, the uplift of the Atlas Mountains, fluvial dynamics, eustatic fluctuations, and bioclimatic conditions. The result is a complex geomorphology of the fragmented Causse, dissected by tectonic features, gorges of fluvial-karstic origin, and a multitude of exokarstic and endokarstic forms of structural origin such as karstic poljes (Naouadir et al., 2023). The latter is a particular type of terrain found only in karst regions (Phu et al., 2022). Studies on karst poljes have attracted many geologists worldwide due to their great scientific (Ford and Williams, 2007; Frumkin, 2013 a; Kranjc, 2013; White and White, 2013; Hiba et al., 2021; Thinh et al., 2022) and tourism importance in several countries (El-Hetty et al., 2021).

This work focuses on understanding the conditions of morphogenesis of closed depressions of the Causse such as poljes and determines the different potential karstic phases that have affected the Causse in light of the tectonic history of Middle Atlas. Thus, once we ask about the different phases of karstification, it is necessary to determine the different paleogeographic episodes of the studied area in order to examine their potential impact on the driving force and the structuring of karst paleosystems

(Delannoy, 1997). This paper has multiple objectives: -first, to highlight the richness of the Causse in terms of closed depressions, -second, to identify the factors that generate these closed depressions. Then, we focus on the role of superimposed tectonics in the evolutionary history of the large closed depressions of the Causse such as poljes and uvalas. The Field work and digital data were used in determination Morphogenesis and the tectonic history of the large closed depressions.

2. Characteristics of the Study Area

2.1. Geographic, Hydrologic, and Climatic Setting

The study area is located about 30 km northeast of the city of Sefrou and 60 km southeast of the city of Fez. It is in the central and northern parts of the Middle Atlas. Being a transition zone between the tabular Middle Atlas and the folded Middle Atlas, its topography is almost tabular, between 950 m above sea level in the northwest to 1100 m in the southeast at Ahermoumou (Martin, 1981).

On the human level, the sector of El Menzel (33° 50' 20" N, 4° 32' 45" W) gathers the whole of the Berber tribes named Ben Yazgha of the Middle Atlas. Agriculture is the main source of revenue for the population given that the Causse is rich in cultivable land and soil. This pedological richness influences human usage of the large karstic depressions such as El Menzel, Quaçbat Beni Yazgha, Tazroute, Ouled Sahnoune, Ouled Mkoudou.

Hydrologically, the karstic plateau of El Menzel is cut by large valleys draining to the largest Moroccan river. Oued Sebou strongly influences the geomorphological and hydrogeological evolution of the Causse. The latter is marked by the emergence of the main sources of Oued Sebou (Aïn Sebou, Aïn Timedrine, and Aïn Ouamender).

Ecologically, the Causse offers a wealth of forest that extends from the southeast to Taghit to the east of El Menzel to El Bouadiss. The most important example is the Royal Reserve of Ghomra which covers an area of 3000 ha and marked biodiversity (Aleppo pine, cedar, juniper thurifer, xerophyte ...) and animal (wild boar, European deer, hares, partridge, black kite, Salamandra salamandra, alytes obstetrician...).

The climate of the Causse of El Menzel is continental with average annual temperatures of 16°C and annual rainfall of about 460mm. The most dominant winds are hot and dry and blow during the summer in a north-northeast direction. In the Middle Atlas, the climate is constantly changing as evidenced by the variability of the Holocene climate (Cheddadi et al., 1998), and climate predictions indicate a warming of 4-6°C and a reduction in precipitation of 20-60% by 2071-2099 (El Jihad, 2016).

2.2. Geological Framework

The high mountain belts of High and Middle Atlas characterize the northern regions of Morocco and control their physical geography, climate, hydrology, and consequently their human geography (Frizon de Lamotte et al., 2008). The Middle Atlas is an alpine chain with an area of 23,000 km² (Baadi et al., 2021). It is a typical intracontinental chain developed at the edge of the Rif alpine chain (Charrière et al., 2011). It is elongated NE-SW and longitudinally subdivided into two major structural units separated by the Accident Nord Moyen Atlasique (A.N.M.A.) which extends from NE to SW (Termier, 1936; Colo, 1961; Martin, 1981; Charrière, 1992) (Fig.1).

The folded Middle Atlas, a more mountainous region, which peaks at 3340 m (Adrar Bou Naceur). The Meso-Cenozoic series is developed here in the large synclinal basins (Charrière et al., 2011). It is characterized by four large anticlines (Sabaoui, 1998).

The tabular Middle Atlas, classically called Middle Atlas Causse, comprising plateaus from 1000 to 2000 m high. Under the Neogene, the secondary series (discordant on the basement) is limited to

the Trias and the Lias. The tabular Middle Atlas is intersected by a N40 fault cluster: the Tizi n'Trettène fault (TNTF) (Charrière et al., 2011). The structural context that prevails in the Middle Atlas Causse is dominated by the replay of accidents inherited from the Hercynian basement (El Asmi et al., 2023).

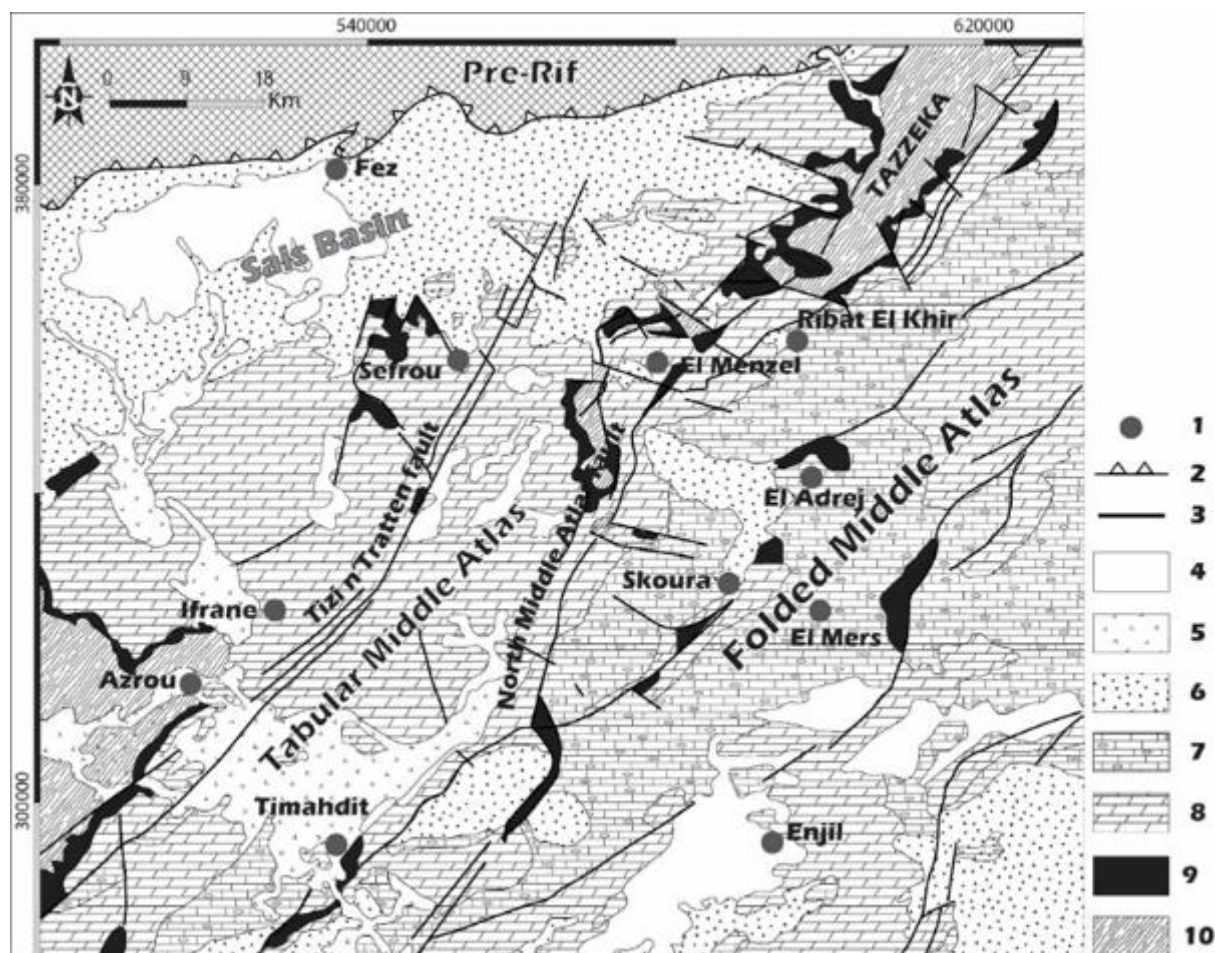


Fig. 1. Geological map showing the location of the Causse of El Menzel within the Middle Atlas (after Charrière, A. 1989). (1) Town/village; (2) Thrust fault; (3) Fault; (4) Quaternary; (5) Volcanism; (6) Eocene-Neogene; (7) Dogger-Upper Cretaceous; (8) Lias (9) Triassic and Lower Lias; (10) Paleozoic

2.3. Structural Geology

Regarding the study area, the Causse d'El Menzel is also known as the panel Oued Zra-El Menzel. It corresponds to a carbonate sedimentary envelope Jurassic massif Tazzeika (Martin, 1981). The El-Menzel unit forms a carbonate slab about 15 km wide by 25 km long (Charrière et al., 2011) (Fig. 2). It constitutes the innermost eastern zone of the tabular Middle Atlas. This panel differs from the other tabular panels only by the existence of a denser longitudinal fault system with more frequent Triassic outcrops. It is a Meso-Cenozoic unit completely detached from its substratum (Charrière, 1998).

The Causse of El Menzel corresponds to a border zone between the Causse and the folded Middle Atlas which does not correspond to a simple tectonic fault but rather to a corridor of faults whose most important constitute two beams that limit the panel of Oued Zra-El Menzel to the NW and SE. They are respectively the Accident Median Middle Atlasic (A.M.M.A), (Sabaoui and Viallard, 1987) and the accident North Middle Atlasic A.N.M.A. (Sabaoui 1998).

One of the major structural elements of the Causse d'El Menzel is the accident median atlasique (A.M.M.A.), which marks the true border between the folded Middle Atlas and the Causse Moyen-Atlasique. It is presented as a zone of post-Miocene play accidents (Charrière, 1990). The Tazrout fault and the inverse and overlapping Ben Yazraa fault constitute the main branch of this fault. These accidents were first defined by Charrière (1984) and were later included in the A.M.M.A. network by Sabaoui and Viallard in 1987. It is a network of faults trending N45. The accident nord moyen atlasique (A.N.M.A.) in the Causse, is materialized by the Taghit 1, Taghit 2, and the transverse accident of El Menzel which connects this locality to the syncline of Zloul and the accident of Oued Zra (Sabaoui, 1998).

The actual geodynamic situation is influenced by mainly two driving forces: The eastward movements due to the Middle Oceanic Rift and the movements towards the northwest related to the African Plate and European plate collision. The geotectonic movements towards NW of the African plate vary according to the specific local lithologic and structural conditions. These active tectonic processes have caused further intense faulting overprinting earlier tectonic patterns. The tectonic activity caused the uplift, faulting, folding, and fracturing of carbonate formations (Theilen-Willige and Naouadir, 2022).

2.4. Stratigraphy

The Paleozoic in the El Menzel Causse outcrops in several sectors, including Bsabis, Pont of Sebou, and El Menzel. The latter is essentially schistose; samples were taken by A. Charrière (1990) and revealed microplankton with Ordovician age associations.

Broadly speaking, the Triassic formations Middle Atlas are mostly masked by the Mesozoic carbonate series. In the El Menzel Causse, Triassic outcrops appear in the interior of the mountains along the valleys and tectonic faults such as the El Menzel fault and the Beni Yazgha thrust fault, which are marked by more or less continuous Triassic layers. The Trias is perfectly distinguishable by the red color of the argillites and the brownish color of the basalts.

The Jurassic series has marine facies. They form the major part of the Mesozoic terrain of Middle Atlas. They are concordant with the red formations of the Triassic - Late Liassic. Their lithological nature is essentially made up of dolomites, limestones, marl-limestone alternations, and silico-clastic detrital deposits (Hinaje, 2004).

3. Methodology and Analysis Tools

The structural and hydrographic analysis of the El Menzel Causse allows a good understanding of the karst processes and morphogenesis of karst features showing that tectonic constraints act as predisposing conditions and structuring of karst networks in different terrains (Shanov et al., 2015). The faults as major tectonic structures are believed to have a great influence on fluid flow (Levens et al., 1994). Thus, preferential flow paths may be well developed along fault zones due to the presence of higher roughness or the presence of breccias that have very high permeability (Jouve, 2018).

To highlight the influence of the structural network of the Causse d'El Menzel on the distribution of certain karst forms such as poljes, uvalas, and dolines Two research methods are used: A field survey providing a geomorphological description of karst features identified in the Causse in the light of its geological framework and numerical analysis of data acquired by digital mapping. The elaboration of the maps used in this work is based on the geological map of Sefrou at scale 1/100.000 and the structural map of the sector of El Menzel (Sabaoui, 1998). These two maps are digitized under GIS software in order to visualize the lithostratigraphic sets and faults in the study area. The Digital Terrain Model (DTM) with a resolution of 30 m was used for the hypsometric map and the extraction

of the water courses. The directional rosettes of the faults and streams were made using RockWork software.

4. Results

4.1. Closed Depressions in the Causse of El Menzel: Identification and Characterization in the Field

4.1.1. General morphology of the Causse of El Menzel

Landscapes are complex regimes (Favis-Mortlock, 2013), and this is particularly true for the landscapes of the Causse d'El Menzel which represents an actively tectonic area. The Causse is the witness of tangential tectonics that affects the basement and the cover (Charrière, 1998) in a compressive context characterized by a trend NW-SE shortening (Sabaoui, 1998). The general morphology of the Causse is almost tabular with a multitude of karstic features that reflects a complex morphogenetic evolution that involves several factors such as inherited tectonic deformations, the uplift of the Atlas, fluvial dynamics, eustatic fluctuations, and bioclimatic conditions. The interaction between these processes offers a good potential for karstification that produces a large system of valleys with stepped caves, deep gorges, and several closed depressions that line up along the major tectonic faults of the area such as A.N.M.A. and A.M.M.A.

Several exokarst forms are visible at small, medium, and large scales on the ground and on maps the karst plateau of El Menzel. The small ones include small cavities, rain pits, and kamenitzas, while the large ones include closed depressions such as poljes and uvalas. They are found in several sectors of great scientific interest such as Quçbat Beni Yazgha and El Menzel (Fig.2). That is why a good part of the fieldwork of this study is carried out in these two sectors which were selected for their karst richness parameter.

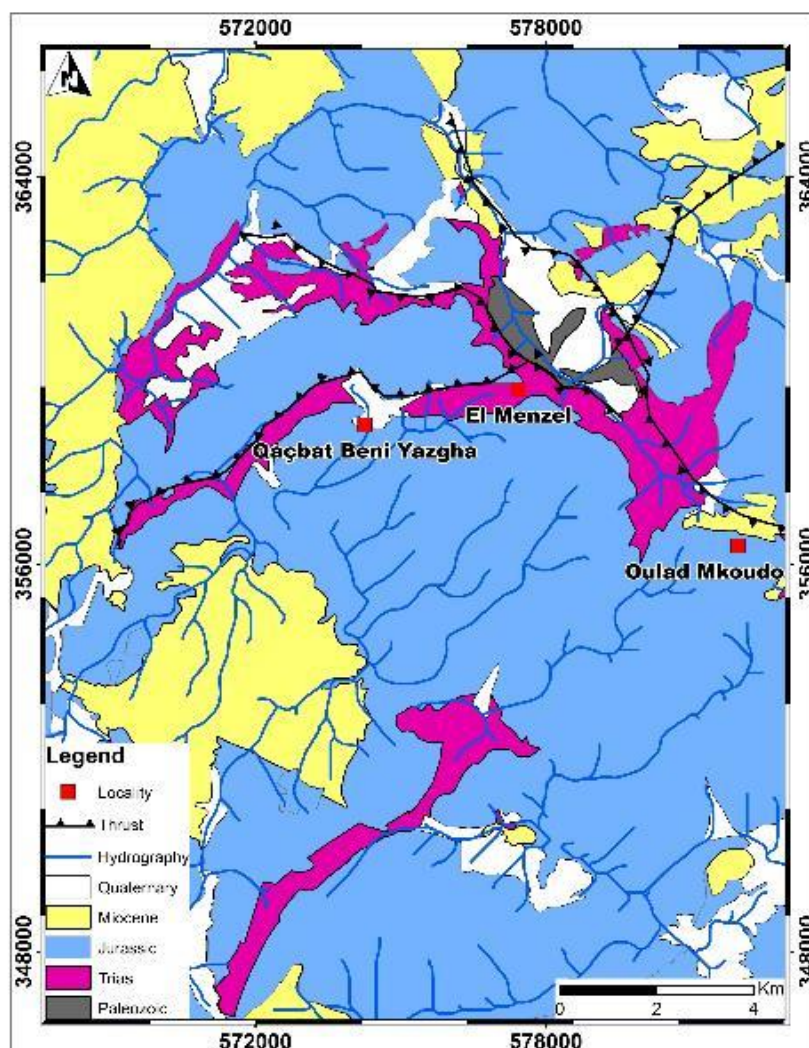


Fig. 2. Geological map of study area (Charrière, 1989 and Sabaoui, 1998)

4.1.2. The poljes

The poljes are the largest karstic forms of the Causse of El Menzel. These large endorheic karst basins can reach more than 10 km in length and 2 km in width. They take the form of low-angle, flat-bottomed, closed depressions (Ford and Williams, 2007; Frumkin, 2013 a; Kranjc, 2013; White and White, 2013). It is at the level of the poljes that the city of El Menzel and a series of Douars that surround it such as Quaçbat Ben Yazgha, Mtarnagha, and Ouled Tayeb... are established.

This setting of human habitations is not fortuitous since these poljes are marked both by the emergence of several karstic springs and rich terra rossa soil which are used in agricultural activities (cultivation of wheat, olive trees, pomegranate trees, apple trees, plum trees ...) (Fig. 3. a-b-c).

There are number poljes in the Causse: The El Menzel polje (Fig. 3. a), the Taghit polje (Fig. 3. b), the Quaçbat Beni Yazgha polje (Fig. 3. c), the Mtarnagha polje and the Mghila polje. These large karst depressions are good markers of the degree of evolution and functioning of the El Menzel karst system. They are both long and wide, indicating a late stage of evolution or a fully developed mature karst according to the denomination of Cvijic (1901).

The poljes of the El Menzel Causse are mainly developed in the massive brecciated dolomites of the Early Jurassic (Fig. 3. a-b). Their emplacement on the ground is controlled by the litho-structural arrangement of the Causse as they are aligned along a network of fault bundles oriented NE-SW and

NW-SE (Fig. 2) above. For example, the Quaçbat Beni Yazgha polje is along the Ben Yazgha thrust fault-oriented NE-SW (Fig. 4. a) and the El Menzel polje along the El Menzel fault-oriented NW-SE.

In the regions of the tabular structure, the poljes-faults dominate (Nicod, 1979), example in the tabular Causse d'El Menzel. According to Ford and Williams (2007), the poljes of the Causse are of the structural poljes type. This is the case of the depression of Quaçbat Beni Yazgha and El Menzel (Fig. 4. a) as well as other depressions of the Causse such as Tazrout along the Tazrout fault. One of the most important of these depressions is the El Menzel polje, whose width exceeds 3 km, the length exceeds 11 km, and the depth is over 200 m. This deepening results from an improvement of the karstic drainage, in particular during periods of high water (Delannoy 1997).

Often, in the field, these depressions are connected at the surface. For example, the El Menzel polje is connected with another polje called the Quaçbat Beni Yazgha polje (Fig. 4. a), 4 km long, with a width of up to 1 km and a depth of more than 100 m (Fig. 3. c). This last polje is nested within three superimposed layers of the Lias detached from its bedrock evoking a duplex system (Charrière, 1998).

The development of these large depressions is facilitated by fracturing (Figs. 2 and 6). Fracturing directly controls the contours of the large karst depressions and the density and arrangement of the residual relief (Nicod, 1979). Moreover, our field observations on the edges of the poljes of the Causse confirm still active tectonics in the Causse of El Menzel. For example, on the edges of the polje of Quaçbat Beni Yazgha, we sometimes witness steep staircase-like slopes with terraces, on which several detached carbonate rocks are found. These have rolled by gravity down to the first obstacle. Also, in the same polje, one can notice enigmatic forms called rock fans described at Dayete Hachlaf and Causse of Immouzzère in the Middle Atlas by Martin (1981) (Fig. 5. c). These edge forms, locally called Koudiat, participate in the production of terra rossa that lines the depressions and the bottom of the poljes. The development of the polje is facilitated by the presence of a great density of fractures that favor deep circulation (Fig. 5. d).

4.1.3. The uvalas and dolines

The uvalas are part of the karst depressions frequently encountered in the Causse of El Menzel. These forms of karst depressions range from 100 m to 2 km in diameter. According to Cvijic (1901), this term of Serbian origin means a valley with a gap between two mountains. This definition agrees with the spatial geomorphological organization of these karst forms in the Causse. They settle in valleys with an elongated and irregular shape, limited by karst highlands. For example, the Quaçbat Beni Yazgha area is marked by the presence of several uvalas that are connected to each other and oriented NE-SW along the Beni Yazgha fault (Fig. 4. b). The Beni Yazgha Fault is a reverse fault, weakly inclined with a towards 50 north direction between the Quaçbat of Beni Yazgha and the Oued Sebou (Charrière, 1998). Along this fault the tribe of Beni Yazgha is settled in a depression almost a kilometer long and wide. This uvalas is marked by the emergence of several permanent and temporary karstic springs: Aïn Kbir, Aïn Batout, Aïn Jal, Aïn Kef El Mejdani, Aïn Hamriya, Aïn Charij, and Aïn Ouled Lkayad.

Uvalas are commonly derived from the coalescence of several sinkholes (Fig. 5. a). These depend on the ability of meteoric waters to sink into and flow through karst rocks (Theilen-Willige and Naouadir, 2022). Faults and joints as well as bedding planes are preferential areas where water can sink and corrode the rock forming small depressions that collect rainwater. The more water, the more intensifies the dissolution, promoting the development of more depressions (Kranjc, 2013). This is particularly clear at the bottom of the Causse d'El Menzel.

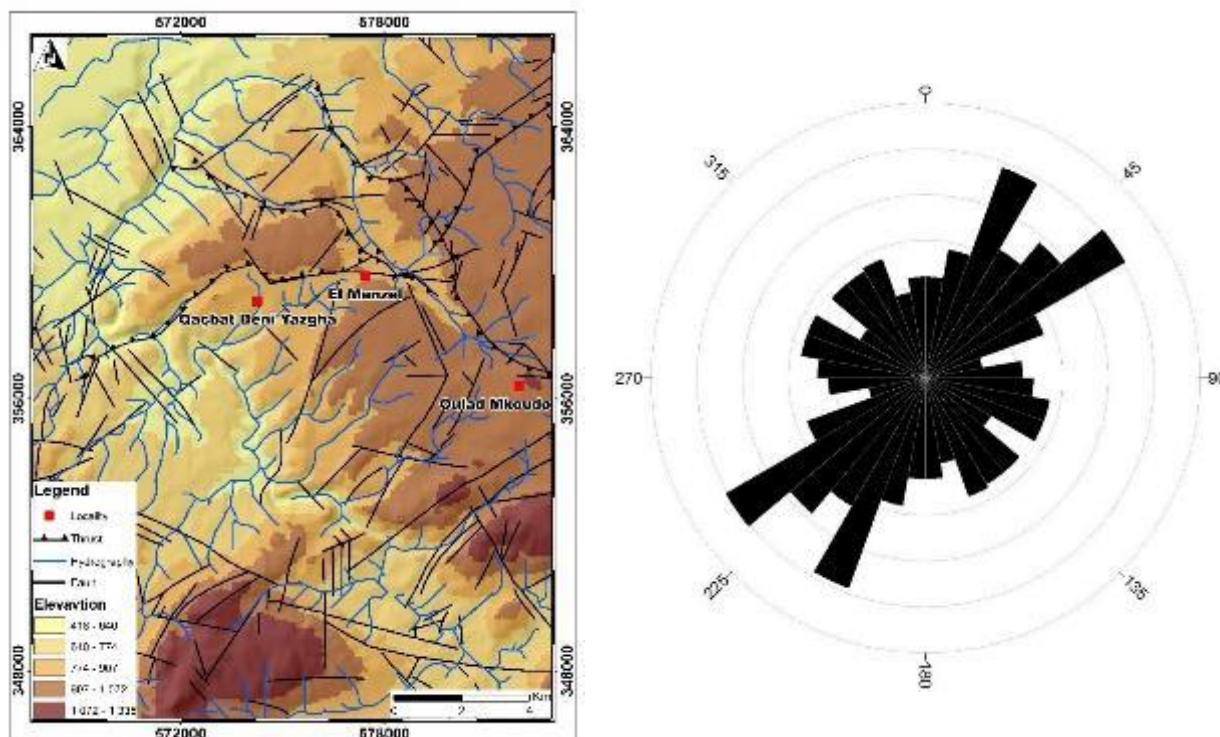


Fig. 3. Digital elevation model in color of the El Menzel Causse with the main structural alignments and the corresponding rose diagram. Heights are in meters above sea level

4.1.4. Rain pits and kamenitza

In the surface karst, closed depressions appear at all scales, from millimeters to kilometers (Pardo-Igúzquiza et al., 2022). Rain pits and kamenitzas represent the smallest karst depressions in the Causse (Fig. 5. b). They are a few centimeters in diameter and depth with an almost circular to oval shape. They trap dust, soil, and organic matter. According to Jennings (1985) these karst shapes are created by raindrops. In the study area, rain pits and kamenitzas develop at the edges of gently sloping poljes and on carbonate surfaces covered previously by soil. They are generally elongated in the direction of the slope. It is interesting to note that their establishment in the Causse d'El Menzel shows a good potential for karstification of the local rock. The main factors controlling their form are climatic conditions, weathering, low-angle slope, soil development, organic activity, contribution of CO₂, and fracturing of the rock. For this reason, micro-depressions such as rain pits and kamenitzas may provide important evidence on the karstification processes of the mountain massif (Veress, 2010).

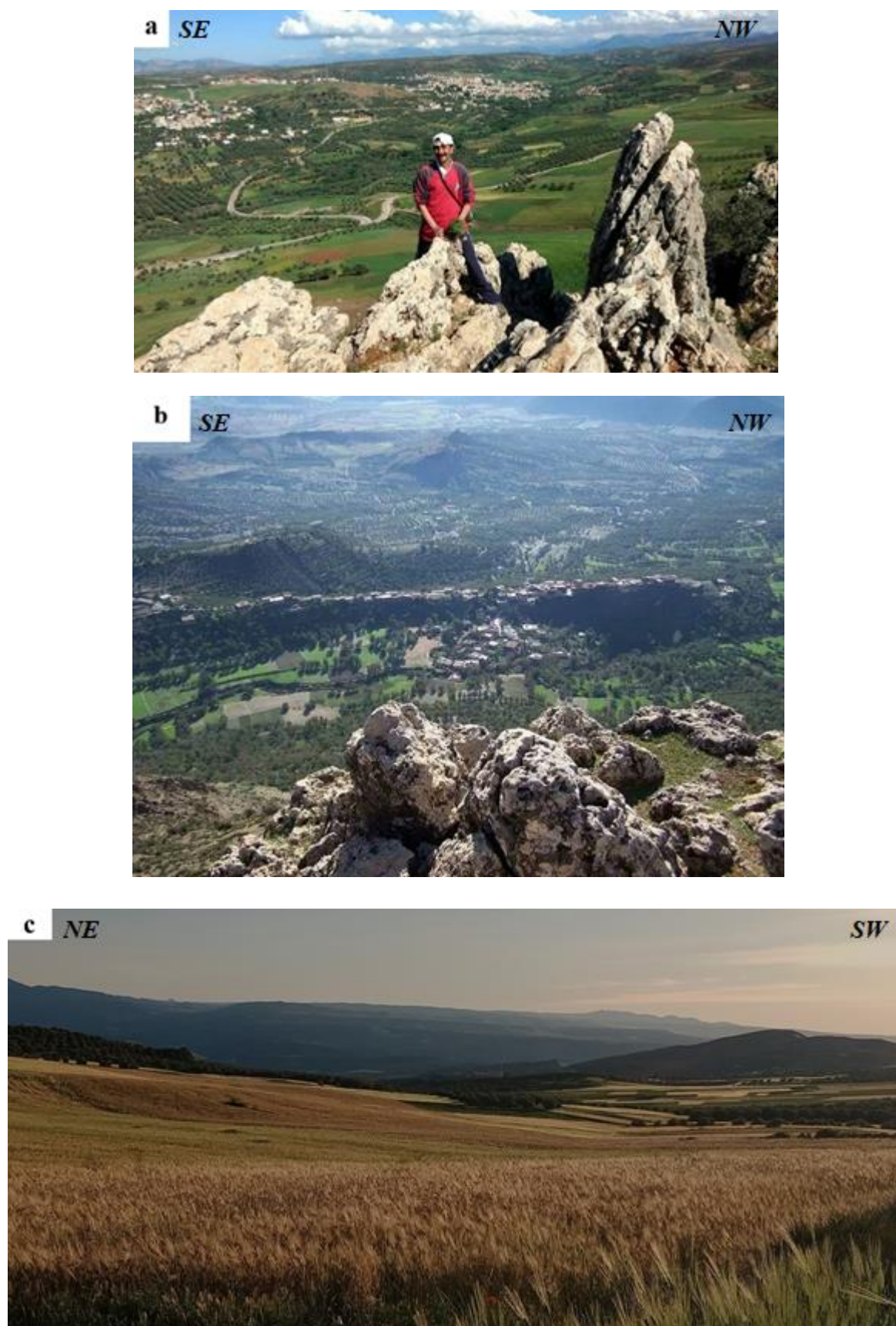


Fig. 4. Types of the polje in the study area, a- The polje of El Menzel is large enough for the city of El Menzel and the surrounding fields. b- The polje of Taghit. c- The polje of Quaçbat Beni Yazgha

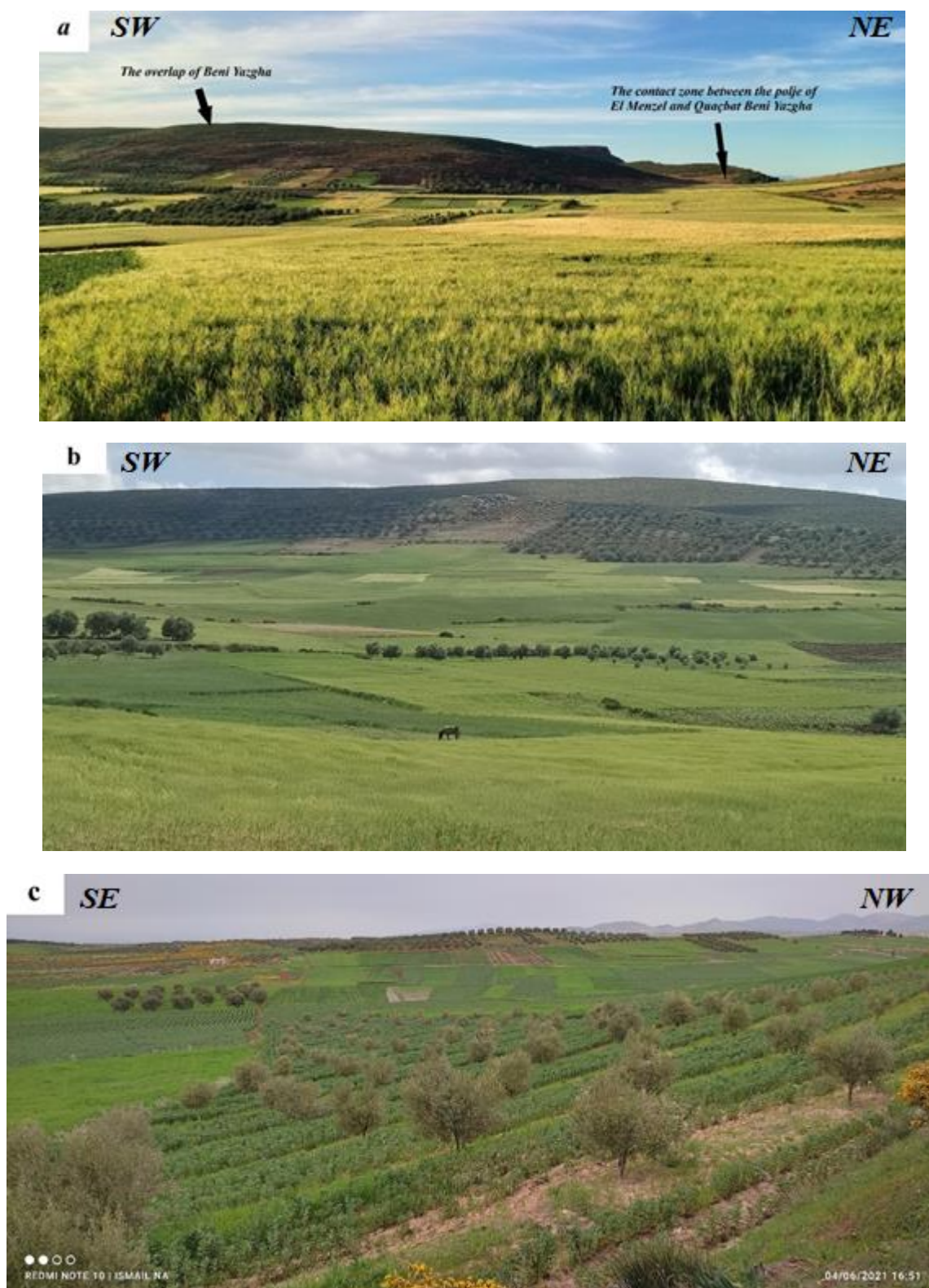


Fig. 5. A) The polje of Ben Yazgha along the thrust of Beni Yazgha builds a landscape controlled by pedological, biological, and climatic factors. B) One of the widest uvalas of the sector of Quaçbat Beni Yazgha. C) Uvalas cultivated by olive trees located in the sector of El Menzel

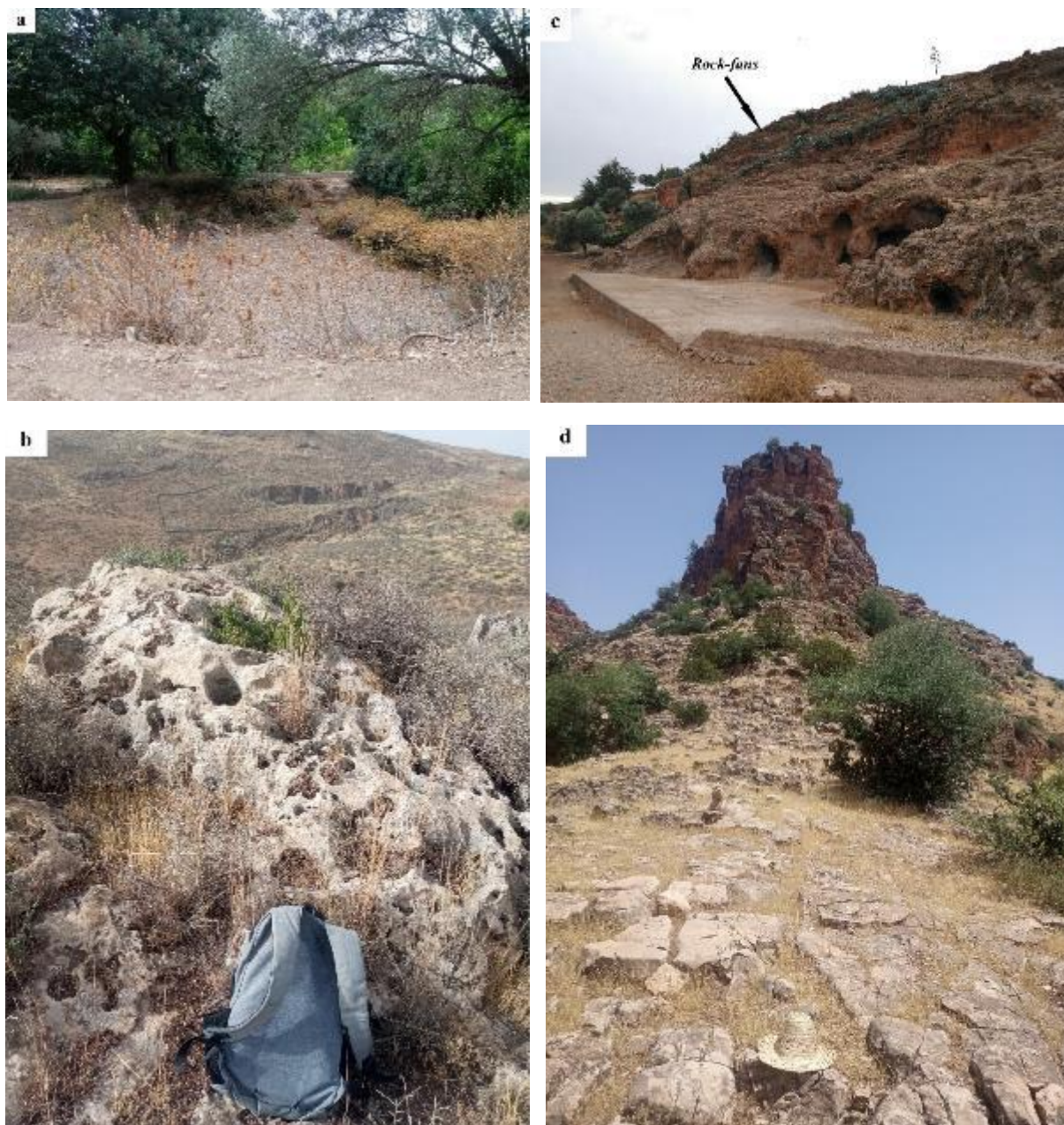


Fig. 6. a) Example of a doline in the sector of Quaçbat Beni Yazgha. b) Rain pits and kamenitza, two of the smallest closed depressions of the Causse d'El Menzel. c) Rock fans located at the edges of the polje of Quaçbat Beni Yazgha. At the foot of the rock fans, a karstic spring called Ain Kbir is located in the Douar of Quaçbat Beni Yazgha. d) Limestone pavement developed as an exokarstic form in the presence of fractures and meteoric water observed at Quaçbat Beni Yazgha

5. Discussion

5.1. The Implication of Superimposed Tectonics in the Development of Closed Depressions

Karstification is not only the result of the chemical alteration of a carbonate rock but rather other factors that contribute to it (Quinif, 1998). Tectonics controls the major directions of karst systems and determine the physical limits of karst expansion (Shanov et al., 2015). These implies that karstification and tectonics have a parallel history and that active tectonics is required for the karstification process to begin (Quinif, 1999). This approach implies that the different karstic phases of the El Menzel

Causse are correlated to tectonic phases. Since the tectonic episodes affecting a sedimentary massif influence the genesis of its karst, the latter is therefore closely related to the fracturing of the environment (Masson, 1985). Thus, when one wonders about the different phases of karstification, it is necessary to determine the different paleogeographic episodes of the studied area in order to examine their potential impact on the driving force and the structuring of karst paleosystems (Delannoy, 1997).

For closed depressions, a regime of mechanical relaxation is necessary so that the discontinuities are open enough to allow the passage of water followed by corrosion (Quinif et al., 1999). The presence of mechanically relaxed zones is very favorable to karstification (Renaut, 1967). Extensional faults and resulting open fractures influence karst development by providing a medium for fluid flow and increasing the karst hydraulic conductivity (Gustavson et al., 1982; Zhang and Sanderson, 1998; Bosak et al., 1998; Ford and Williams, 2007; Bruthans et al., 2009; Closson and Karaki, 2009; Kim and Sanderson, 2010; Zarei and Raeisi, 2010; Bruthans et al., 2017; Dimmen et al., 2017; Pisani et al., 2019). This concentration of fluid flow occurs because open fractures form zones of high connectivity and permeability in carbonate units with low porosity matrices (Rotevatn and Bastesen, 2014; Dimmen et al., 2017).

Similarly, the Causse d'El Menzel karst is part of the geological and paleogeographical history of this sector of the Middle Atlas. The latter was the seat of a polyphase of tectonic events from the Neogene to the Quaternary (Charrière, 1990; Ait Brahim, 1992; Sabaoui and Hinaje, 2000; Hinaje et al., 2002). During these periods, a significant tectonic, neotectonic, and seismic activity took place (Michard, 1976; Ramdani and Tadili, 1980; Charrière, 1990; Hinaje and Ait Brahim, 2001; Theilen-Willige and Naouadir, 2022). This explains why the Causse of El Menzel is a highly fractured and folded area (Sabaoui, 1998). These karst zones that are characterized by intensive fracturing as the panel of Oued Zra-El Menzel are called "Background deformation" according to the nomination of Rabelo et al., 2020.

The geological heritage of the Causse of El Menzel, including: Reverse faults and thrust faults of A.M.M.A. and A.N.M.A. would have influenced the evolution and the establishment of several closed depressions of the Causse such as the polje of El Menzel, the polje of Quaçbat Beni Yazgha, Taghit, Tazrout, and Mellaha ... This occurred during several extensive phases: The extensive episode of Late Miocene age (Charrière, 1990; Ait Brahim, 1992; El Hamzaoui, 1994; Sabaoui, 1998; Sabaoui and Hinaje, 2000) probably represents the stage in which the evolution of the Middle Atlas polje began (Martin, 1981; Gourari, 2001). A major phase of karstification and surface dissolution (Martin, 1981) is the extensive episode of early and middle Quaternary age (Martin, 1981; Harmand and Cantagrel, 1984; Baali, 1998; Gourari, 2001). The episode of middle-recent Quaternary age is the last important stage (Harmand and Cantagrel, 1984; Laville, 1985; Fedan, 1988; Charrière, 1990; Ait Brahim, 1992; Josnin et al., 2000; Hinaje et al., 2001). The large poljes are related to complex structures of superimposed tectonics (Nicod, 1979), and this is particularly true for several poljes of the Causse such as the El Menzel polje where the main fracture of El Menzel has been exploited at the level of its crushing zone for the evolution of the polje during each extensive tectonic phase. Each episode of brittle tectonic deformation is responsible for the creation of collapse zones where the deposits are confined, and promotes karstification and water circulation along the fault zones (Hinaje and Gourari, 2022). The surface dissolution has therefore taken advantage of areas of weakness of the Causse d'El Menzel, so it has found the best conditions near fault lines and crushing zones (Martin, 1981). These crushing zones are undoubtedly a major factor in the enlargement of poljes and uvalas. Also, the high density of fractures in the dolomitic series favors deep circulation and consequently the development and deepening of the poljes across the Causse.

Undoubtedly, the importance of the zones of relaxation is enormous (Quinif, 1983) as well as the role of the set of extensive episodes in the development of large closed depressions such as the poljes of the Causse, by accelerating the penetration and circulation of corrosive waters through localized

fissured zones. The greater the amount of water flowing into the karst, the more intense the karstification, and correlatively, more karstification is developed inducing a positive feedback and easier drainage (Mangin, 1978). From the same perspective, poljes and uvalas are also guided by tectonically deformed zones of regional extension in which corrosion is intensified. Thus, from a genetic point of view, uvalas could be considered as forms of accelerated corrosion triggered by local tectonic parameters and dynamics (Sauro, 2019). In this perspective, several authors (Guerin, 1973; Grillot and Guerin, 1975) emphasize a correlation between karstification and the nature of tectonic accidents (accident playing a major role during relaxation periods), which allows relating tectonic phases to successive karstification.

On the other hand, we must not forget the role of the atlasic compressive tectonics on the development of karst characteristics because tectonic uplift increases potential energy by creating relief and generating both the entrenchment of subaerial valleys and karst subsurface water courses (Quinif, 1999). This would also correlate with the decrease in base level of the hydrographic network. The effect of falling base level is demonstrated in the sectors of Quačbat Beni Yazgha and El Menzel by comparing the altitude of the caves. The level of relict caves passages compared to the current drainage level of the Oued Sebou shows a drop or downcutting of over 250 m. The entrenchment of valleys requires potential energy only: water and uplift (Quinif, 1999). From this point of view, three main phases of tectonic uplift have particularly marked the panel of Oued Zra-El Menzel. These play a special role during: (1) the period from the Early Cretaceous to the Middle Miocene constituting the major stage of Middle Atlasic tectogenesis; (2) the period of the Pliocene; (3) the period of the Middle Pliocene to the present time, which is accompanied by a neotectonic activity (Sabaoui, 1998). In addition, a slow sinking of the nappe seems to influence the evolution of poljes (Martin, 1981). Recently, several authors have confirmed that in low-lying mountain ranges moderate uplift generally causes deep fluvial incisions (Harmand et al., 2017).

It should not be forgotten that the time factor is fundamental to karstification, which is also prepared by the structural nature of the limestone, in terms of both lithology and tectonics (Salomon, 1999).

5.2. Hydrographic Implication in the Evolution of Closed Depressions

Recently, several studies have focused on the strong influence that fractures have on fluid flow (Rawling et al., 2001; Schultz and Fossen, 2008; Bense et al., 2013; Pardo-Igúzquiza et al., 2018). These studies indicate that faults and fractures can act as conduits or barriers for fluid flow or a combination of both (Jolley et al., 2007; Dimmen et al., 2017). This close relationship between fracturing and surface water flow explains why all closed depressions in the Causse are aligned along both faults and the drainage network such as large valleys. These implies that polje drainage are part of the karst hydrology of the Causse. This hydrology is strongly linked to the regional structural framework (Figs. 7 and 8).

The evolution of the poljes is controlled by the organization of their hydrological system: subaerial and underground hydrographic network. These are interdependent (Nicod, 1979). Moreover, some poljes have developed along typical river valleys (Sauro, 2019) like the Causse d'El Menzel. These fluvio-karst forms develop mainly in the early stages of karstification, in areas of intense rainfall when the flow in a karst system exceeds the capacity of its conduit system (Deybrodt and Gabrovšek, 2002). Evolution of the drainage towards an organized flow influences the morphological evolution of the closed depressions of the Causse. This relationship implies the inseparable character of the hydrological structure and the morphological structure (Delannoy, 1997) in the study of karst characteristics.

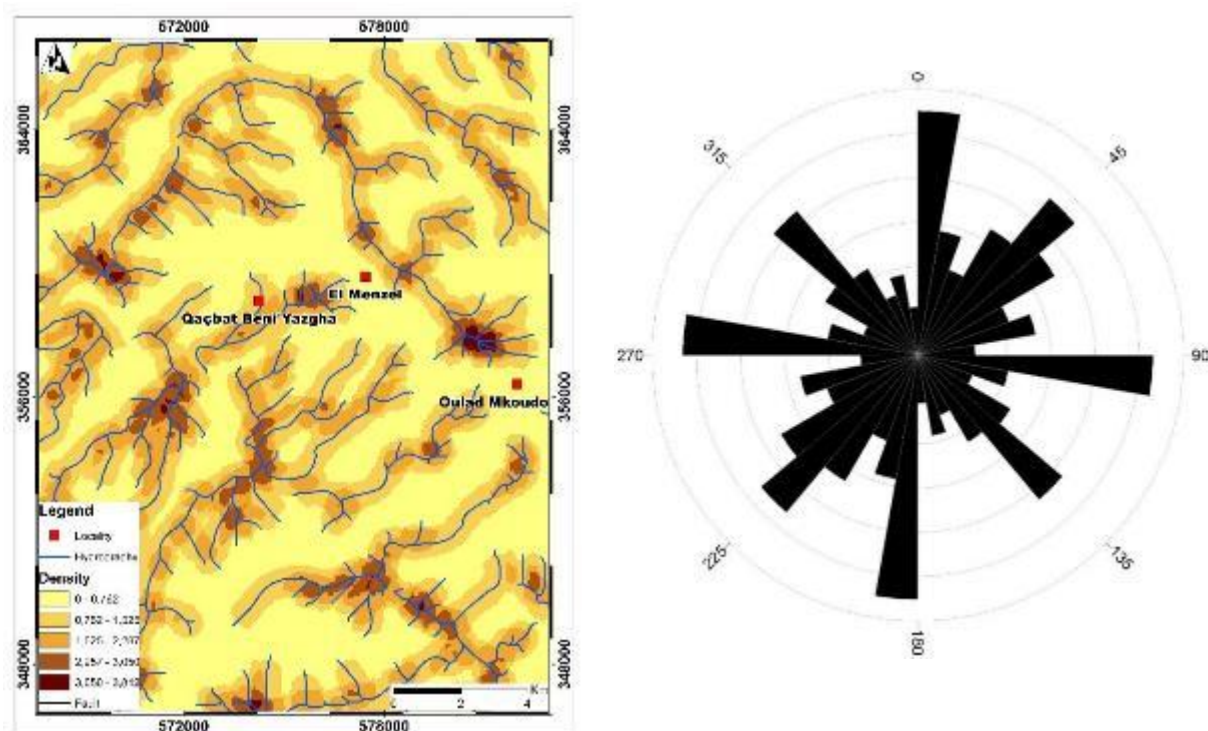


Fig. 7. Distribution map of the hydrographic network in the Causse of El Menzel with a rose diagram corresponding to the hydrographic network

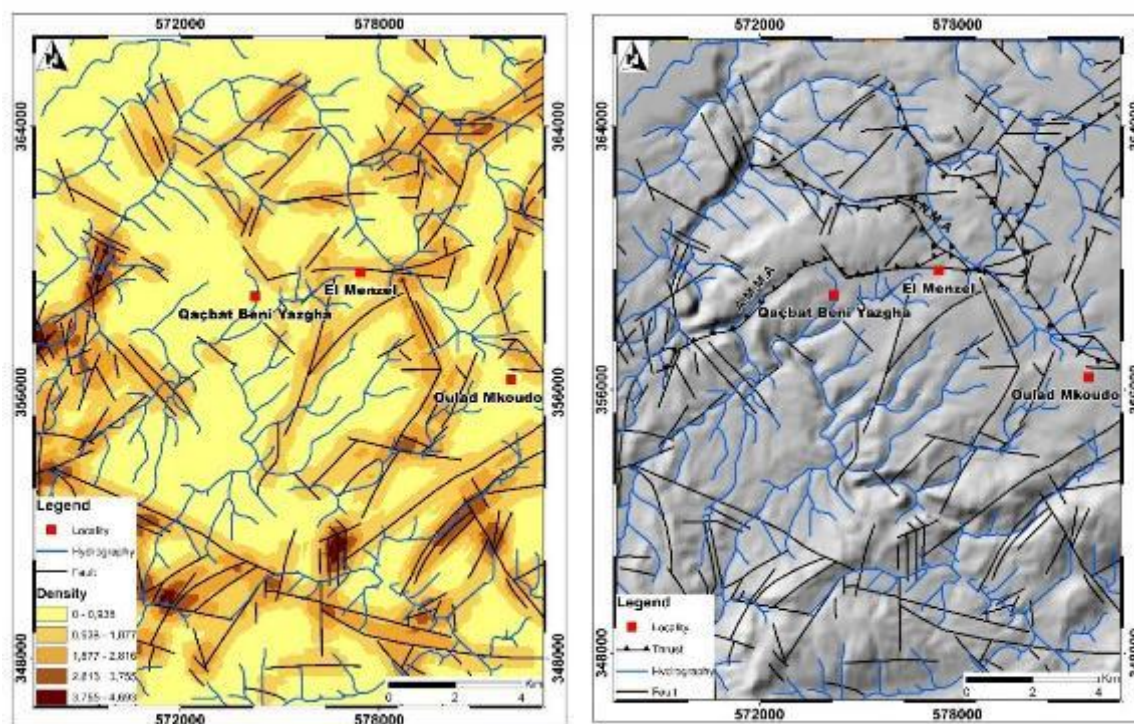


Fig. 8. A model of Spatial Density of Structural Alignments Showing that the Causse d'El Menzel is a Particularly Tectonized Area

Generally speaking, pure dolomites normally have a low dissolution rate compared with limestones; however, it is also in dolomites that the highest densities of karst phenomena are often found, which then implies long periods of time (Jouve, 2018). In a study in Pennsylvania, Rauch and White (1970) found that the greatest solubility of carbonates was achieved when the level of MgO was 1 to 3% and that striations increased the roughness (i.e. the exposed surface) of dissolved surfaces. James and Choquette (1984) suggest that calcite with a high Mg content is normally the most soluble because of the deformation of the crystal structure.

In view of the preceding, it seems to us that the essentially dolomitic lithological features of the El Menzel Causse are one of the major factors favoring a high dissolution rate for the development of the large closed depressions in the Causse. This can be confirmed by simple observation in the field, which shows us that the El Menzel and Quaçbat Beni Yazgha poljes develop mainly within the dolomitic series of the Lower Lias. The poljes and basins of the central Middle Atlas are all found in the dolomites of the Lower Lias, which at certain periods in geological history have acted as perfectly karstifiable rocks (Martin, 1981).

5.3. Climatic Effects on the Development of Closed Depressions

Dissolution takes place during whole year in karst areas of subtropical, but mainly of Mediterranean climate (Veress, 2020), To give specific karstic forms mediterranean as in the Moroccan Middle Atlas.

The role of climate is essential in the evolution of closed depressions such as the poljes of the El Menzel Causse given that the potential for karstification is closely linked to climatic conditions (Gilli, 2015). The climatic and ecological oscillations would affect the value of the H_2O+CO_2 flux which controls the intensity of dissolution and the rate of evolution of the karst system (Delannoy, 1997). Thus, the abundance of precipitation leads to favorable conditions for the evolution of poljes, especially the strong variations in hydraulic capacity, in the Mediterranean-montane climates that produce considerable variations in the level of water-circulation and karst water tables (Nicod, 1979). Therefore, in the Middle Atlas, most of the karstification takes place during the rainy phases (Martin, 1981).

6. Conclusions

To date, the closed depressions of the Causse d'El Menzel have not been the subject of any karst research work, although the Causse presents a significant geodiversity of closed depressions. This is sometimes represented by meso- and macro-forms such as uvalas and poljes which are the most distinctive exokarstic elements of the karst landscape of the Causse. The most spectacular examples are the polje of El Menzel and the polje of Quaçbat Beni Yazgha. These large poljes faithfully follow two major tectonic accidents of the Causse inherited from the Hercynian history and oriented NW-SE and NE-SW: The El Menzel fault and the Beni Yazgha thrust. These implies that the structural conditions control the extension of these karst features which are of tectogenetic origin. These present forms are due to a polyphase morphogenetic evolution that started to take place in the Late Miocene. We believe that these pre-existing faulted zones would have guided the action of dissolution on the carbonate substratum of the Causse. This occurred during several phases of extensive relaxation favorable to the establishment and evolution of poljes, from the Upper Miocene to the recent Quaternary, during the surrection of the Middle Atlas. Hence the need for interaction between several agents, both geological (rocks fractured during relaxation) and bio-climatic (climatic rainy phases with corrosive waters) in order to have a good potential for karstification and the evolution of closed depressions of the Causse of 'El Menzel.

Acknowledgements

We are very grateful to Dr. Barbara Theilen-Willige from Germany and Dr. George Veni from the United States for their always fruitful discussions in the field of karst research. We would like to thank the anonymous reviewers for their comments that improved the manuscript. The field research would not have been possible without the great support and generosity of my great family Naouadir and Lemsieh in Quaçbat Beni Yazgha and the villagers of Beni Yazgha during several years of field missions.

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