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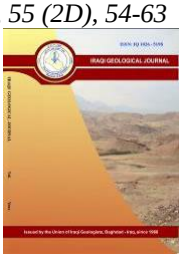

Relationship between Karstification and Tectonism in the Upper Jurassic Evaporite Formation: A Case Study of the Lalla Fatna Escarpment Safi, Morocco

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Abstract

The Upper Jurassic Evaporite Formation accumulated up to 200 m of interbedded gypsum-carbonates layers across the coastal cliffed region of Safi (Morocco) have been affected by karstification process, resulting in karst collapse and subsidence structures associated with faulting, fracturing and different types of instabilities, which are among the main causes of natural hazard risk, impacting the socio-economic and environmental issues. Surface investigation (physiognomic approach) allowed the characterization and identification of deep-seated and subjacent gypsum interstratal stages and showed that the karstic features are controlled by orientations of faults and fractures. To highlight the relationship between tectonics and karstification, in this area, fracture orientations were studied, and the result of analysis of diagrams showed that, in most cases, orientations of karst landforms are controlled by regional tectonic features.

Keywords: Evaporite; Coastal risk; Karstification; Tectonic control

1. Introduction

The evaporite deposits extended across most of the coastal cliffs of the Safi area, constituting the basal rocks of the Jurassic-Cretaceous outcrop. They are considered among the lithological controlling factors and mechanisms that cause catastrophic slope failure contributing to karstification phenomena. This activity may cause loss of human life and severe infrastructure damage. Hence, some of the buildings had to be demolished under the authority of the damage restricting the coastal development projects. Despite the importance of studies regarding the karstification process. The Jurassic-Cretaceous gypsum karst investigations in Safi areas are still in their infancy. They have undergone rather a scarce attention, despite the more or less remarkable activity. There are only a few research studies that have given attention to understanding the karstification processes of gypsum and related problems in this region. Some recent researchers using different advanced techniques to highlight this phenomenon, such as geophysical investigation, to sense buried collapse sinkholes and underground cavities, including, electrical resistivity (Ait Elfakih et al., 2018 and 2020) that have revealed the existence of voids and cavities at depth within the Jurassic formations. Similarly, sinkholes have been cataloged using remote sensing (Theilen-Willige et al., 2014; Boualla et al., 2016; Ayt Ougougdal et al., 2020; Bouzerda et al., 2020). This satellite imagery detected aligned sinkholes along structural lineaments with predominantly

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SW-NE orientations. Theilen-Willige et al. (2014) demonstrated the potential influence of these sinkholes on the stability of the coastal slopes south of the Safi city.

Karst developed in evaporite rocks has particular features owing essentially to lower mechanical strength and a higher rate of solubility. The latter depends particularly on the local geology, hydrogeological and tectonic features. Also, climatic features are a major contributing factor. Notwithstanding the semi-arid to arid conditions, sulfate (gypsum/anhydrite) rocks are dissolved more actively and at a much faster rate as compared to carbonate rocks. Furthermore, the solubility of evaporitic rocks depends on the amount of rainfall. Indeed, rainfall events in arid climates are shorter but violent and may trigger sinkhole collapse. Collapse and subsidence in evaporite formations have generally a high probability of occurrence and a wide genetic diversity (Gutiérrez et al., 2008). Beyond the lithological features, fracturing is crucial for the karstification process, the relationship between structural features and karst is well documented (Pisani et al., 2019; Menezes et al., 2020). Evaporitic karstified and fractured rocks are very complex and heterogeneous in interbedded carbonates-evaporite karst. Generally, the structure of classic karst within carbonate-evaporite successions cannot be readily distinguished (Liu et al., 2019). Likewise, some peculiarities and features distinguish between evaporite from carbonate karsts, in particular the development of interstratal karst and greater numbers of dissolution-collapse breccias (Klimchouk et al., 1996), accompanied by the high occurrence of rock failures, landslide and downfall of blocks in scarps. Those hazards may result in an important decrease in the mechanical strength of rock slopes, notably in gypsum rock (Gutiérrez, 2010). Other morpho-structures may be generated by interstratal karstification, such as, grabens, monoclinal folds and flexures, etc. (Gutiérrez, 2010; Gutiérrez and Cooper, 2013). This study focuses on a twofold approach: first, reveal and describe the evaporite dissolution structures and morphology, second, to highlight and discern the possible relationships between tectonics and gypsum karstification process and their cliff instabilities in the Safi region, to better assess and manage the natural hazard risk. To this end, field surveys and core investigations serve to recognize, identify, and describe the observed deformation, dissolution, and subsidence features as possible. Owning this knowledge will provide a better picture of the current and past karsts activities along the coastal area.

2. Geological Setting

The study area (Fig.1a) is located in the coastal region of Safi (Morocco) located at 150 km north-west of Marrakesh. Those coasts extend between the Beddouza Cape in the north and Jorf Lihoudi in the south of Safi city, approximately along about 120 km. It forms a continuously high cliffed coastline (+100m of altitude) with steeper slopes, cut in the Jurassic-Cretaceous outcrop, and oriented mainly to the west and southwest. At the foot of those cliffs, narrow beaches have developed.

2.1. Stratigraphy

The Safi coastline is part of the Coastal Block of the Moroccan western Meseta (Michard, 1976), specifically the Abda Doukkala plains, defined by flat secondary and tertiary deposits (Late Jurassic Early Cretaceous age) that hide the underlying Paleozoic basement and are covered by coastal Plio-Quaternary formations (Gigout, 1951) (Fig.1a). The late Jurassic evaporite deposits (Taj-Eddine et al., 1985) crop out in several areas throughout the Safi coastline. This evaporitic complex, up to 200 m thick and are regionally uniform, corresponding to 14–16 cyclic sequences of gypsum alternated with carbonate layer forming rhythmic strata. According to the work of Witam (1988), the elementary sequence of this complex is the Sebkha depositional environment. Consisting of microcrystalline, breccias and selenitic anhydrite/gypsum showing a variety of sedimentary structures such as laminations, tepee structure, chicken-wire and entrolithic structure, intercalated by few centimeter-thick marly interbeds, marly and limestones highly cracked and boudinated (Fig.1-b).

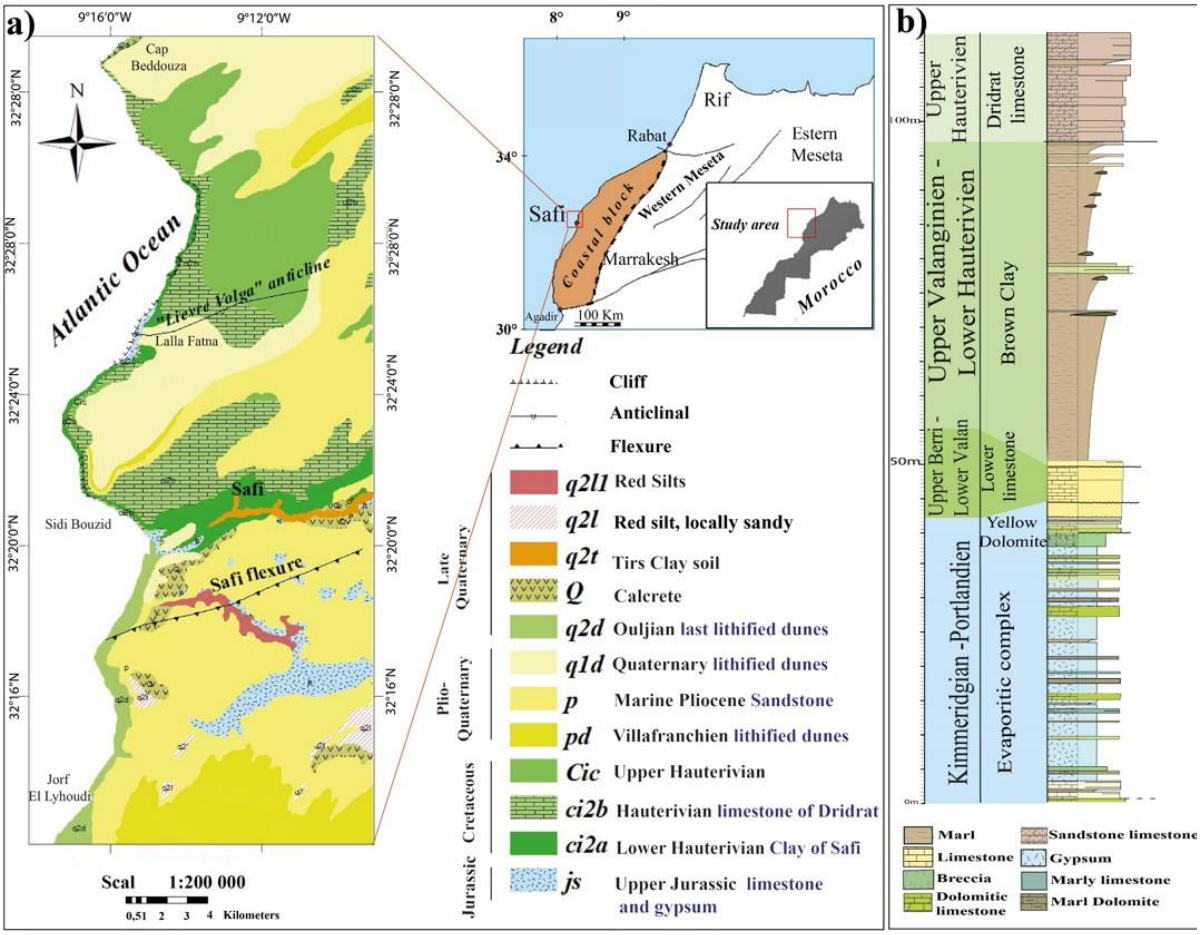

Fig. 1-a. Geological and geographic setting of the Study Area, data from Geologic map of costal Meseta (Gigout, 1951); (b) Detailed stratigraphic section of the Lalla Fatna escarpment exposed at the costal cliff (14°0037.72″S –12°3033.29″E).

2.2. Structural Setting

Distinct tectonic periods characterize the evolution of the Safi coastal basin as part of the Coastal Block of Western Meseta. This basin was structured during the Hercynian orogeny 'Eovariscan' phase (Echarfaoui et al., 2002) by a moderate deformation, which affects the Paleozoic basement yielded a kilometric open fold with the general direction of NE-SW to N-S (Michard, 1976; Hoepffner et al., 2005). The Alpine/Atlasic orogeny has been controlled by NNE-SSW extensional opening horst and graben system (Roussel and Bernardin, 1991; Michard et al., 2010). The major Atlasic orogeny expressions are EW to NE-SW prevalent trends (Ferré and Ruhard, 1975; Ruellan, 1984; El Foughali and Griboulard, 1985). Weak brittle neo-tectonic deformations of Plio-Quaternary age have been accentuated by joints and small-scale fault systems and a certain flexure (Chtaini, 1987), due to reactivation of the Hercynian and Alpine tectonics (Foughali and Griboulard, 1985; Chalouan et al., 2001; Ouadia, 1998, et Ouadia al., 2015; Chabli et al., 2014).

On a local scale, Abda-Doukalla plain south of the coastal basin, the tectonic style is gentle, the secondary cover formations are slightly undulated, flexure, and faulted, most of the tectonic structures are oriented NS with a slight inclination towards NE or NNW (Foughali and Griboulard, 1985). Between Beddouza cap and Lyhodi escarpment, the Jurassic-Cretaceous formations are affected by a series of synclinal and anticlinal undulations, among them, the 'Lièvre Volga' anticline and the Safi flexure

mainly oriented NE-SW, which uplifts the Upper Jurassic in outcrop, successively in the Lalla Fatna escarpment and the S-E Jurassic compartment which outcrops south of the Safi city.

2.3. Hydrogeology and Climate Patterns (Safi station)

The Jurassic aquifer has formed a fissure permeability (Fadili, 2014), due to the dissolution of limestone and especially gypsum. The circulation is often done by dissolution voids (karstic with very important cracking) which result from the dissolution of limestone and gypsum. This area is characterized by an arid to semi-arid climate with oceanic influence, the aridity index calculated in Safi close to -0.28 (El Ajhar et al., 2018) (Fig.2).

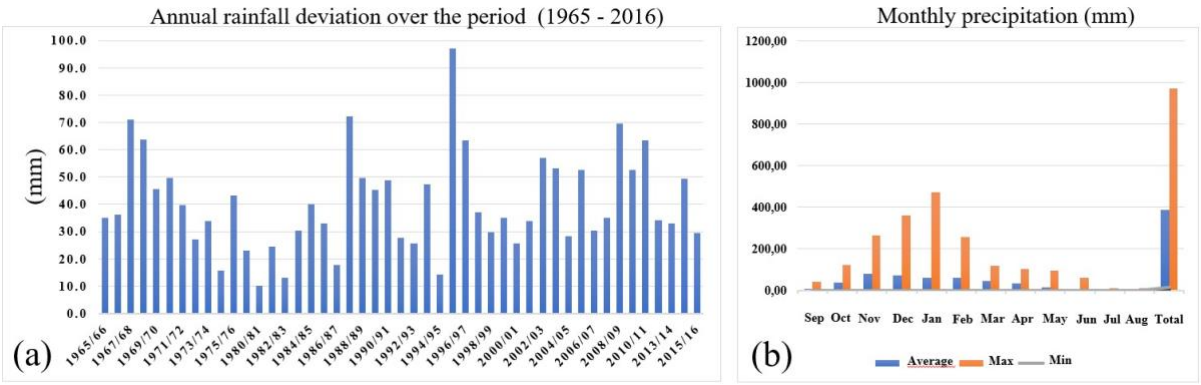

Fig. (2). Climate patterns inter-annual and intra-annual pluviometry distribution (station 6495- Safi-Morocco): (a) Annual rainfall for 51 years (since 1965 to 2016); (b) Monthly precipitation for 2014. Data provided by ABHOE (Hydraulic Basin Agency of Oum-er-Rbia).

3. Materials and Methods

To better the identification, characterization, and description of the karstification process and gypsum dissolution, surface investigation methods were used. Deformational structures and instability signs such as collapse, sag, cracks, and pipes, served as indicators for the karstification process were studied by field surveys and analyses, including recording detailed cross-sections on cliff faces where those structures are ideally exhibited.

Exhaustive data compilation on faults, joints in both late Jurassic evaporite deposits and the overlain formation were collected. In order to visualize the structural data, the Stereonet software by Richard Allmendinger © 2011- 2020 version 257 11.1.3 with an equal-area projection in the lower hemisphere was used.

4. Results and Discussion

4.1. Typology of Karst

Clear evidence of the interstratal karstification of gypsum exists. It affects the Jurassic evaporites sequence in Lalla Fatna monocline, creating the presence of most typical landforms, such as subsidence structures, collapse features, gravitational fault scarps, and landslides. The karst breakdown processes largely depend on the rheology of the caprock and/or the bedrock units and the karstification stage, Therefore, the interstratal dissolution of evaporites may drive to a ductile component of deformation, producing undulation of gypsum layers and caprock/bedrock sagging (Fig.3 a and b). This process exhibits a range of U- to V-shaped geometries (Fig.3 c). Furthermore, caprock sagging sinkholes -- subsidence structures-- that have been revealed in this area occur merely in terrains of interstratal

gypsum karst (Waltham and Fookes, 2003; Gutiérrez, 2016), more specifically in subjacent karst (Gutiérrez and Cooper, 2013). Subsequently, these mechanisms tend to develop suddenly where the overlying formations lose support and undergo collapse (Fig. 4). This brittle behavior of strata generates breccia pipes also named as vertical breakdown structures (VBSs) (Klimchouk, 2013) that crosscut the overlying lower limestone and yellow dolomites strata (transtratal-breccias), which led to unstable escarpments and numerous slope movements (Fig.4.C b and e). The latter is the first mode of collapse phenomena. Then, the second mode is related to the presence of discrete voids associated with important structural discontinuities permitting propagation of breakdown structures and favorite differential subsidence fault blocks (horst and graben shape) (Fig.4.C c and d). However, the plan view shows a cylindrical shape of these faults (Fig. 5 a). Gutiérrez and Cooper (2013) related these dropped-down fault blocks to the deep-seated interstratal karstification of gypsum.

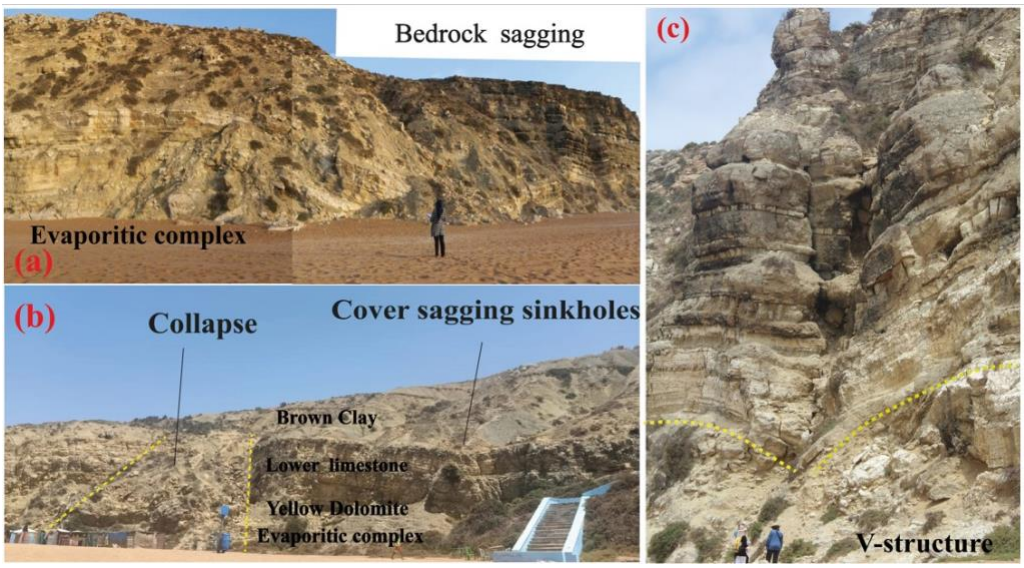

Fig. (3) Passive bending caused by progressive interstratal karstification in Lalla Fatna cliff, N Safi: (a) Bedrock; (b) and cover sagging sinkholes, producing synform and collapse strata are recorded in the yellow dolomites of the late Jurassic Kimmeridgian – upper Berriasian and the lower limestone of Late Berriasian – Valanginian basal age underlined by evaporitic complex. The collapse was due to remove of gypsum in the subsurface. Those structures are most probably related to interstratal dissolution of the evaporitic complex; (c) V-shaped geometries or V-structure at the evaporitic complex and potentially unstable block due to dissolution enlargement of joints (fractures) and dissolution-enlarged bedding planes by water percolating downward along discontinuities, and weakened by karstification processes.

In this area, the collapse dynamics were generally cataclysmic, the breccias showing angular clasts with a variety of sizes exhibit chaotic appearance. The size varies from a few millimeters to more than tens of meters cemented by a recent matrix or devoid of a matrix, giving evidence of reduced vertical breccia displacement and is possibly a result of a recent dissolution episode with roof collapse (Fig. 4.C b). These vertical breakdown structures (VBSs) are a common phenomenon of deep-seated and subjacent gypsum interstratal stages (Klimchouk, 2005). Furthermore, brecciation and disruption of the overlying carbonate strata (transtratal breccias) in the mixed carbonate/sulfate sequence of gypsum is a significant feature of the deep-seated karstification (Klimchouk, 2013). Elsewhere, speleogenesis in deep-seated gypsum karst is exclusively hypogene, and in subjacent karsts, both hypogene and epigene speleogenesis may operate with a dominance of hypogene speleogenesis (Klimchouk, 2013). Moreover, hypogenous speleogenesis has a tendency to operate in a discontinuous manner and intermittently or be repeatedly activated over a long period of time. Analyses of the morphology and characteristics of karst

throughout the coastal cliff of the Safi region provide strong evidence for a predominance hypogene speleogenetic origins, that still subsists in contemporary systems and are overprinted by surficial epigene processes and surface denudation. However, hypogenically karstified gypsum of the upper Jurassic formation is brought to the shallow subsurface by uplift, those inherited karsts from an earlier hypogenic speleogenesis operate over a long-time span phase are an active or relict system that enlarged slowly during the Quaternary.

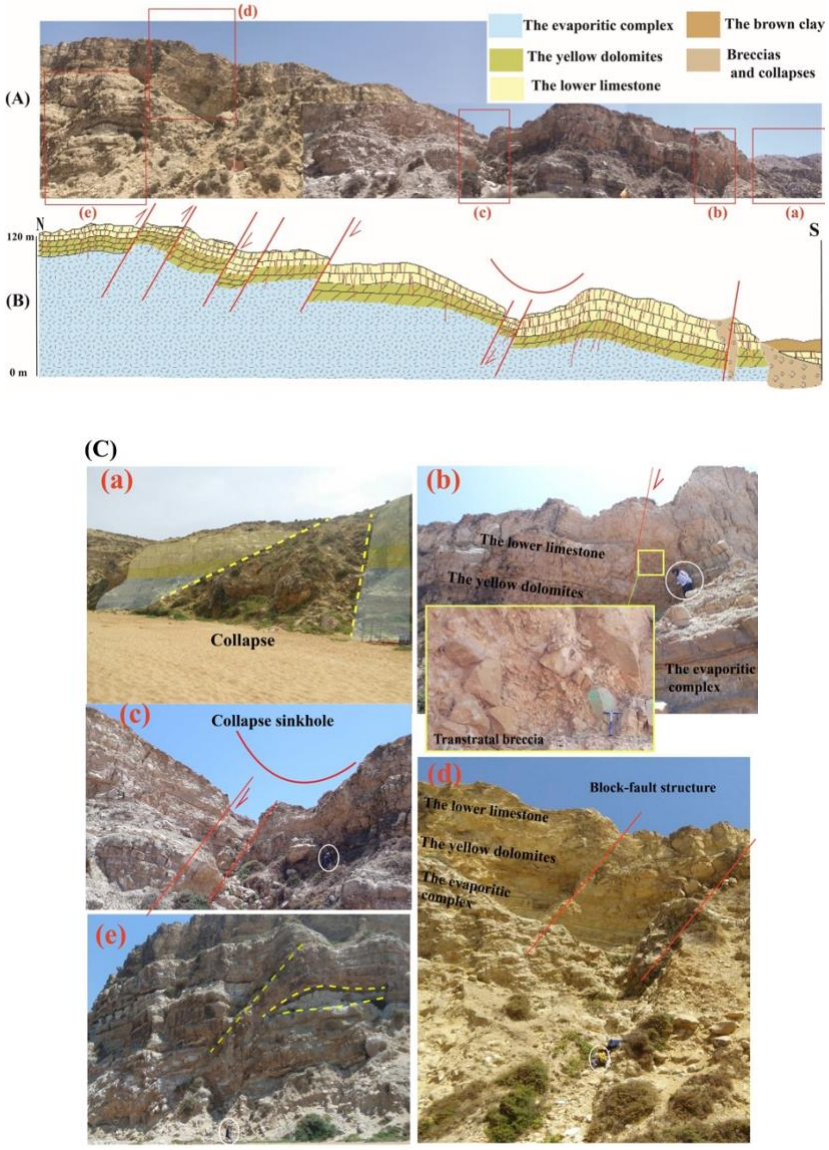

Fig. (4-A and B) Photograph and schematic cross-section of the studied area illustrating and locating the evaporitic complex karstic massif. (C), Diverse and common karst features affecting the outcropping formation exposed on a cliff slope in relation with the tectonic structures, several collapse structures can be seen: (a) Collapse sinkhole (between dashed lines) due to removal of gypsum beds, (b) a vertical breakdown structures (VBSs) that crosscut the overlying lower limestone and yellow dolomites strata (transtratal breccias) Inset shows details of the breccia showing angular clasts with a variety of sizes exhibit chaotic appearance cemented by a recent red matrix (fine silt and clay). (c) Collapse sinkhole tends to be expressed as semi-circular to elliptical form with steep walls, Note the variable amount of subsidence lead to horst and graben morphostructure, this differential karstification is related to fault-control. (d) Block-fault structure with vertical displacement between blocks. (e) High deformation in evaporites succession marked by elastic deformation of gypsum and fractured boudinated limestone interbeds, and several small breccia pipes penetrate the gypsum complex. These pipes are filled with fragments of dolomite from the overlying gypsum beds.

4.2. Identification and Characterization of Discontinuities

The Lalla Fanta escarpment ranging from 150 m in height is characterized by sub-horizontal sedimentary bedding crosscut by sets of sub-vertical faults and a system of joints orthogonal to bedding. The discontinuities identified were significant in terms of the recurrence of instabilities and the volume of material mobilized depending on orientation, density (spacing between diaclases), and persistence (depth of penetration).

Field analyses revealed a wide range of fracture orientations with millimetric to metric openings increasing the permeability of rocks and water cycle conductivity, in consequence providing necessary and favorable conditions for karstification. However, these decametric or even metric dense discontinuity networks with centimetric to metric spacing, are suitable for a destructuration of all the outcrops formations. Collapse morphologies and landslides structures including planar rock slides, rock avalanches, and rockfalls were recorded where the rock massif is extremely fractured, particularly in the yellow dolomites and the lower limestone overlying the evaporitic complex. Fault and fracture patterns inside and around collapsed areas are diverse and complicated. Indeed, cylindrical to ellipsoidal faults are developed in plain view around the collapsed zone, which are defined by subsidence rings (Menezes et al., 2020), recognized through topographic analysis (Fig. 5 a). Collapse fractures give rise to semicircular scarps controlling the plunges toward the depression and evolving to sag geometry. In front of the cliff, down-faulted topography forms a monocline structure and tilted beds, crosscut by a set of extensional parallel normal faults, along which the superimposed formations are collapsed forming a horst and graben system (Fig. 4.A; B; Fig. 4.C c and d).

Karst subsidence producing generally concentric collapse fractures reactivated as normal extensional faults (Menezes et al., 2020) even though internal contractional deformation structures, including reverse faults and kink-bands can occur. Whether the sinking material exhibits high internal cohesion and low external cohesion with regard to the surrounding rock (Soriano et al., 2019), this case manifests clearly throughout the interbedded carbonates-gypsum-clay layers (evaporitic complex formation) (Fig.5 c). The azimuth of 143 joints and faults were measured, and then rose diagrams for them were plotted. The results show that the fractures are mostly systematic and resulted from regional tectonics, since non-systematic discontinuities that cut the rocks are also detected, related to mechanical (rock condition) and physical (environmental condition) effects. In most cases the vertical displacements are generally controlled by faults mainly oriented N115, N125 that show regional trends and suggest their control by the existing structural pattern (Fig.5 d). Collapse breccias occur in several cases: (1) initial process of karstification by intense fragmentation of the lower limestone and the yellow dolomites, in place, observed along a high-density of closely spaced subvertical joints that show regional trends and suggest their control by the existing structural pattern; (2) Rotation and intense fragmentation between blocks in response to intense dissolution; the brecciation process develops to chaotic dispersion and intense breakdown of fragments and blocks of various sizes and shapes partially displaced, that occurs along a parallel NE-SW-striking to NNE-SSW-striking fracture (Fig.4). This study reveals the development of large sub-planar rock slides into the void that have been raised by tectoglyphs slide markers (Fig. 5 e).

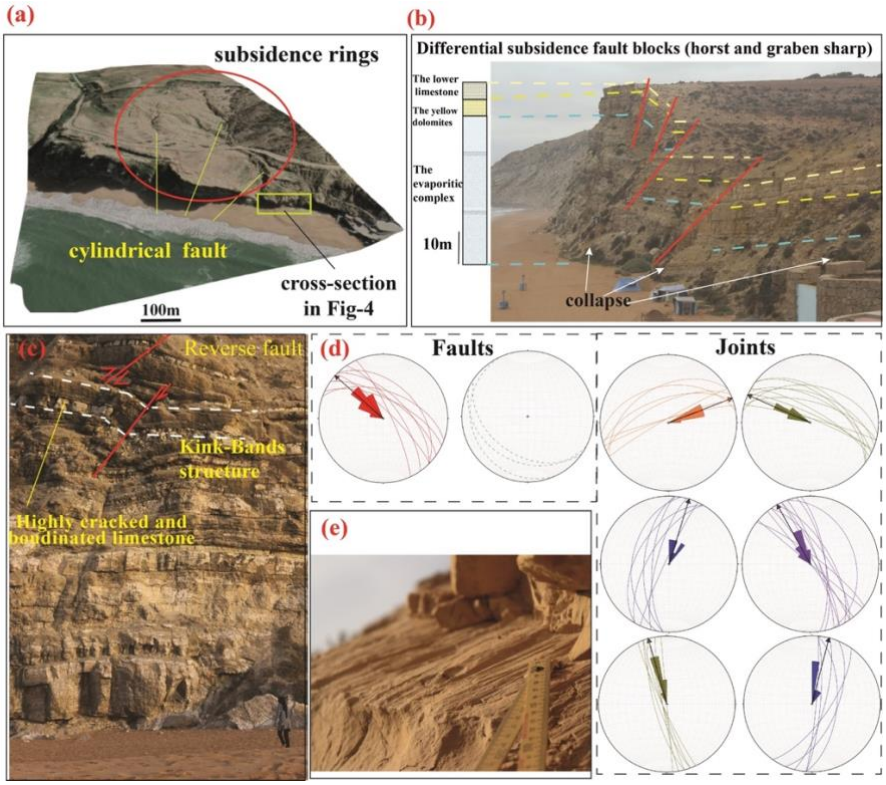

Fig. (5a). 3D block of subsidence rings at subsurface showing cylindrically sharp of fault around collapse structures. Those fractures are termed as collapse fractures and have curvilinear shapes around dolines. The outcropping formations plunge towards the depression forming a monocline structure and tilted beds; (b) The monocline structure crosscutting by a extensional parallel normal fault ,along which the superimposed formations are collapsed and rotated forming a horst and graben system, forming an area of high structural instability, these vertical displacements generally controlled by faults mainly oriented N115, N125 that show regional trends and suggest their control by the existing structural pattern; (c) contractional structures including reverse faults and kink-bands produced by capability of gypsum of flow due to plasticity; (d) Stereoplots (equal area Schmidt lower-hemisphere projection) of faults and Joints collected in outcrop area during this study (N=143) (equal-area, Schmidt lower hemisphere projection), structures were measured. The joints have three major orientations: NW- SE, E-W, NNE-SSW to N-S which likely represent a major tectonic trend within the costal block, the Stereonet plots of the joints and faults show no significant difference in terms of dip angle. All Faults show a vertical to sub-vertical geometry. Note that large dissolution features (karst) are often observed along their fracture's planes; (e) Tectoglyphs, which reveals a large sub-planar rock slides into the void.

5. Conclusions

After conducting a detailed analysis of structural and stratigraphic features on the well-exposed landforms of Lalla Fatna escarpment, the origin and the mechanism of their genesis have been demonstrated. Despite the limited data available to propose a robust hypothesis on their origin, the knowledge of the karstification process along with the data that have been collected recently concerning karstification features documented worldwide, contribute to shed some light on the hypothesis that evaporite dissolution is related to deep-seated to adjacent setting has created the observed features. To support this interpretation, the following arguments have been proposed:

- The architecture of deformation collapse and sag structures related to interstratal dissolution of evaporites.
- The spatial associations of the monocline structure with sinkholes in areas underlain by evaporitic formations are generally affected by deep-seated dissolution.

- karst development appears to have hypogene origins, epigene processes are actively overprinting features, yielding a complex speleogenetic evolution in this region.
- Faults and fractures are associated and command mainly the ground movement and increases structural instability in this area, subsidence and collapses are controlled by faults with predominantly SW-NE orientations.
- Tectonics has an important role in the genesis of karstic features in this area. In most cases, the orientations of fractures and faults are the same. The affected area may be larger than reported.

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