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Fracture systems and dissolution cavities in Wadi As Sir Formation, Thughrat Asfour area, Jordan

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Abstract

The fracture systems and their relationship with dissolution cavities and/ or karst development in the Turonian Limestone of Wadi As-Sir Formation were studied along abandoned quarries and road cuts in a folded area on the Irbid- Jerash Highway. A total of 740 fracture planes were measured in the field. Among them, sixty striated planes were analyzed for fault-strain by means of the TENSOR structural software. The other fracture data are represented as a rose diagram showing the orientation of the fractures. Four sets of fractures are distinguished in the study area these are: a) Extension fractures (having orientation NNW-SSE (N20°W to N40°W)); b) Release fractures (having orientation ENE- WSW and WNW-ESE (N70°E to S80°E)); c) Shear fractures set-1 (having orientation N- S (N10°W to N10°E)); and d) Shear fractures set-2 (having orientation ESE-WNW (S45°E to S75°E)). Results show that the dextral shear along the ENE-WSW to E-W trend reflects the majority of the analyzed fault-slip data. Plane surfaces of these dextral strike-slip faults are coated with calcite steps and/ or soil staining, suggesting water infiltration and potential dissolution processes. Thus, it can be said that fractures represented by the neoformed dextral strike-slip faults and release joints have been reactivated later and the structural control of the karst development along these structural elements is present in the hard carbonates of the study area.

Keywords: karsts/ dissolution cavities, fractures, paleostresses analysis.

1. Introduction

The growth of some caves is influenced by joints and bedding planes in carbonate rocks, but other cave systems are less obviously joint-controlled in that they exhibit a branching or linear pattern (Zumburge and Nelson, 1976).

The Wadi As-Sir Formation (Turonian limestone) is the main formation cropping out in the study area along Irbid-Jerash Highway (Fig. 1). Dissolution cavities or karst phenomena occur mainly along open fractures. The fractures and associated karstic phenomena in hard limestone and dolomites are generally not obvious on surface outcrops. Their surface expression may be inferred from the negative features in the topography (Arkin, 1980). Fractures, in this study, mean any discontinuity of a rock mass, e.g. faults, joints, cracks and veins. Since these features may be complicated by successive tectonic events and overprinting (Hancock, 1994), it is necessary to examine these weakness surfaces in relation to movement and orientation. The aim of this study is to examine the control of existing fractures along Irbid-Jerash Highway on the development of karstic dissolution cavities. Accordingly, it encompasses the following goals: 1) Measuring and classifying the fractures based on their orientation, 2) Estimating the paleostress orientations that formed these fractures.

2. Geological setting

The Dead Sea Transform (DST) extends from the Gulf of Aqaba in the south to the Taurus Mountain in Turkey in the north. It separates the Arabian plate from Palestine-Sinai Subplate (part of African plate). The DST was formed because of the northward sinistral movement of the Arabian plate associated with the opening of the Red Sea (Garfunkel *et al.*, 1981). The movement started in the Miocene and still active (Quennell, 1959; Eyal, 1996). This fault system is responsible for the formation of different structures in Jordan and in the study area (Fig. 2).

The outcropping rocks in the study area and its adjacent areas are of the Upper- Cretaceous (Cenomanian to Campanian) and belong to two groups; the oldest is the Ajlun Group and the youngest is the Balqa Group.

The age of Ajlun Group ranges from Cenomanian to Turonian. In the study area, the Ajlun Group includes Fuhais, Hummar, Shueib and Wadi As-Sir Formations, while the Balqa Group includes Wadi Umm Ghudran, and Amman Formations (Fig. 1). The Wadi As-Sir Formation covers most of the study area (Fig. 1); it is considered an index horizon in the study area and all over Jordan.

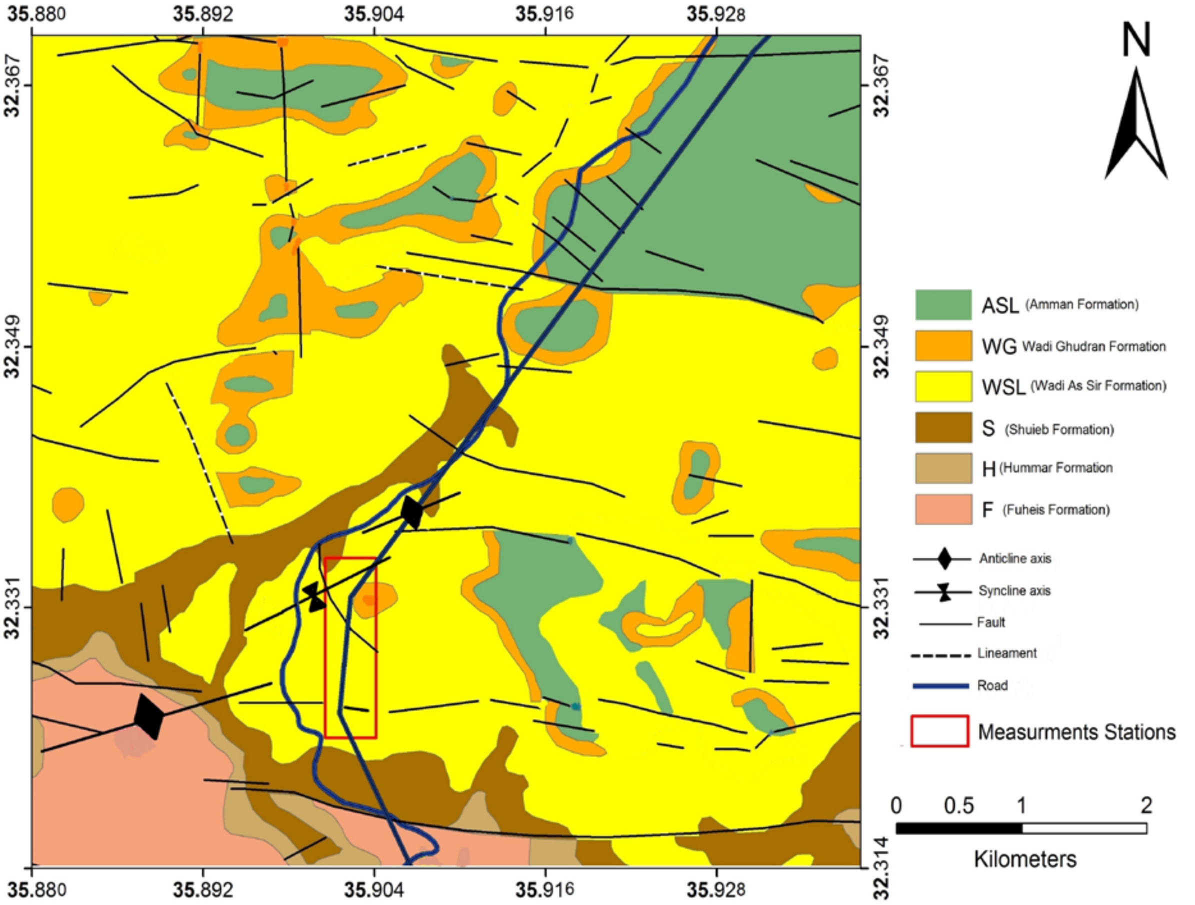

Figure 1: Location and geological map of the study area.

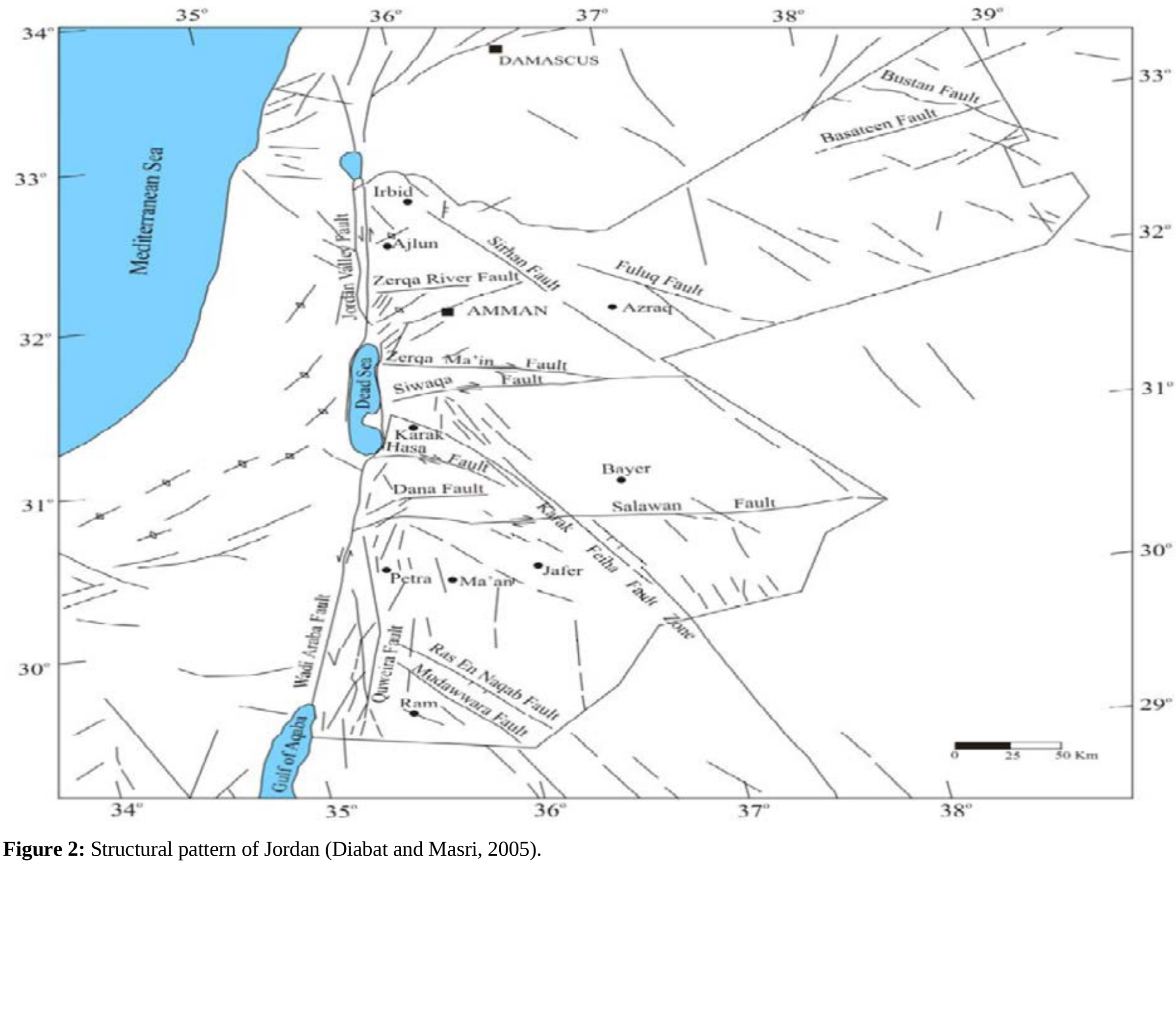

Figure 2: Structural pattern of Jordan (Diabat and Masri, 2005).

The Wadi As-Sir formation is composed mainly of limestone, marly limestone and dolomitic limestone. The upper part consists of thick-bedded crystalline fossiliferous limestone forming a prominent scarp across the study area. The prominent scarp feature of the Wadi As-Sir Formation is overlain by the pelagic deposits of the Wadi Umm Ghudran Formation, which consists of massive chalk beds (in the lower parts) and limestone, chalk and chert (in the upper parts). The youngest rock of the study area belongs to the Amman Formation. It consists of alternations of limestone, marl and chert (Abdelhameed, 1995; Powell, 1989).

3. Methodology

A total of 740 fracture planes were measured in the field using CLAR compass (Fig. 3). The data were collected from abandoned quarries and road cuts along Irbid-Jerash Highway. In particular, the readings encompassing the fractures dominating the hard carbonate rocks (Wadi As-Sir Formation) of the Thughrat Asfor region. The majority of fractures lack any surface striations, thus they were considered as joints. The measurements take into account the strike of their planes. On the other hand, sixty of these fractures showed pronounced striations (i.e. Slickenlines) across their surfaces, thus they were treated as fault-slip data. The plunge, plunge direction and the sense of movement of these fractures have been determined for each fault plane reading (Fig. 3).

Figure 3: Slickenlines show a normal- dextral movement of a fault plane.

4. Fractures

A fracture is a general term for a surface in a material across which there is loss of continuity and, therefore strength (Van der Pluijm and Marshak, 2004). Fractures range in size from grain-scale to continent-scale (Van der Pluijm and Marshak, 2004). The fractures generally are accompanied by various features, which characterize the surfaces of the break and the space between them. These include the degree of curvature, opening, continuity, roughness, surface markings and the type of infillings. These are the most important characteristics that affect the passage or percolation of waters both of meteoric and flowing along the break and the degree of aggressiveness of the water and the potential for solution to occur (Arkin, 1980; 1989).

Open and closed fractures are both observed in the study area (Figs. 4 - 8). Conjugate sets of fractures were also observed. Some fracture planes are stained by soil infillings, vertical solution rills and calcite deposits in the form of stalactites and stalagmites in some (Fig. 4).

Some fractures have preserved slickenlines whereas some fractures have preserved plumose features and tension gashes, which can be classified as shear fractures or extensional fractures, respectively.

These fractures can be divided as follows:

4.1. Release Fractures

When the stress acting on a region of crust is released, the crust elastically relaxes to attain a different shape. This change in shape may create tensile stresses within the region that are sufficient to create release joints or fractures, similar to what occurs in relation to folding; they are also called outer- arc extension joints (Van der Pluijm and Marshak, 2004). Release fracture may also form when overburden load is removed or released (Billings, 1972; Van der Pluijm and Marshak, 2004). In the study area, these fractures are oriented at ENE- WSW and WNW-ESE or have varying strikes from N70°E to S80°E (Fig. 9).

4.2. Extension fractures

This fracture set is oriented normal to the fold axes and is geometrically described as cross fracture (Billings, 1972). These fractures are mainly present at the crestal parts of the folds. Their orientations in the investigated area are NNW-SSE or varied in strikes from N20°W to N40°W (Fig. 9).

4.3. Conjugate shear fractures

A shear fracture is a surface across which a rock loses continuity when the shear stress parallel to the surface is sufficiently large (Van der Pluijm and Marshak, 2004).

Two sets of shear fractures where observed in the study area; set-1 and set-2, conjugate sets (Fig. 9)). Set-1 has orientation mainly N- S, with a range of N10°W-N10°E (Fig. 9). Set-2 has orientation mainly ESE- WNW, with a range of S45°E to S75°E (Fig. 9).

Their intersection planes are parallel to the intermediate stress direction (σ_2), whereas the acute bisector is parallel to maximum stress direction (σ_1).

Figure 4: Stalactite feature in a cavern fractured limestone.

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Figure 5: Open fractures (blue) with dissolution cavities and thin roof at the upper left.

Figure 6: Open fracture (blue) with dissolution cavities and soil staining.

Figure 7: Development of a longitudinal cave on a reactivated dextral strike- slip fault.

Figure 8: Development of a cave as a reactivation of dextral strike-slip fault at later stage as normal fault.

5. Stress Analysis

For stress analysis, the fracture orientation data are plotted on a rose diagram (Fig. 9), whereas the striated fractures were presented as fault-slip data (Fig. 11), using the TENSOR program of Delvaux (1993), and the right Dihedral method of Angelier and Mechler (1977), as well as Angelier (1979).

Rose diagram provides immediate visual estimation of stress orientation regarding any data. The principal stress direction ($\boldsymbol{\sigma_1}$) is always parallel to extensional fracture sets and normal to release fractures (Billings, 1972; Davis, 1984). Shear fractures are always oblique to the principal stress direction ($\boldsymbol{\sigma_1}$) (Billings, 1972).

Results show that the predominant trend of the fractures in the rose diagram is NNW-SSE, while the minor trends are E-W and ENE-WSW (Fig. 9).

Analysis of the fault-slip data shows a dominance of a strike-slip tensor which is characterized by the following paleostress orientations: σ_1 = 155/ 08; σ_2 = vertical, σ_3 = 245/17, thus suggesting a NNW-SSE compression ($\boldsymbol{\sigma_1}$) and ENE- WSW tension ($\boldsymbol{\sigma_3}$) paleostress state (Fig.10).

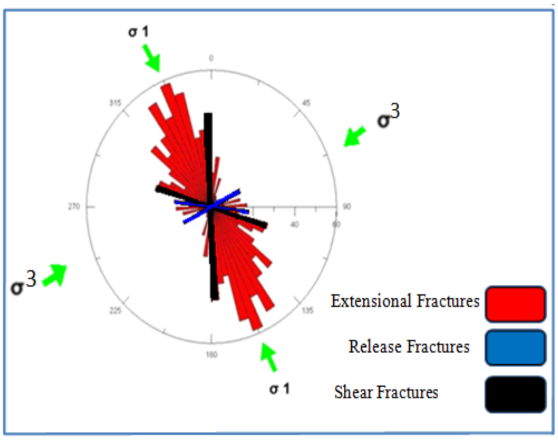

Figure 9: Strike orientation of 740 fracture planes and the generalized direction of maximum principal stress axis ($\boldsymbol{\sigma_1}$) parallel to extensional fractures and minimum principal stress axis ($\boldsymbol{\sigma_3}$) parallel to release fractures.

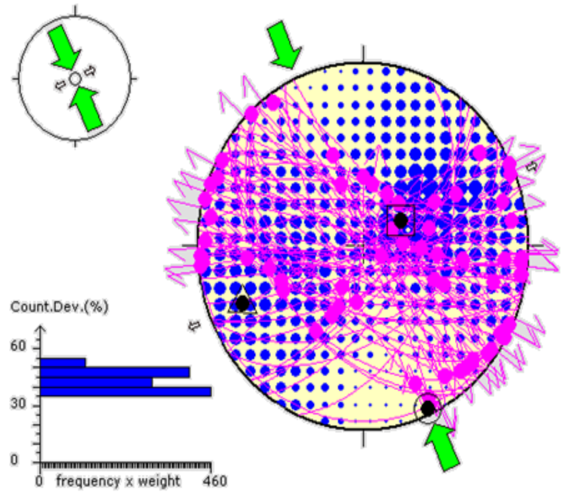

Figure 10: Principal stress axes determination by using the TENSOR program; outward ENE arrows indicate tension (**σ_3**) and inward NNW arrows indicate compression (**σ_1**), while **σ_2** is vertical.

6. Discussion

In light of their dominant parallel alignment of the investigated fractures with the maximum horizontal compressive stress axis **σ_1** (SH max) of the established regional stress fields (Eyal and Reches, 1983; Eyal, 1996; Diabat, 1999; Diabat *et al*., 2004; Eyal *et al*., 2001; Diabat 2005, 2009, 2013), the NNW-SSE fractures propagated under conditions associated with the Dead Sea stress,which is characterized by NNW- SSE maximum compression (**σ_1**). The small faults at the study area have estimated paleostress orientations: σ_1 = 155/ 08; σ_2 = vertical, σ_3 = 245/17. They have a similar orientation (but often with slightly steeper dips) to the small faults. Therefore, they are interpreted as extensional or shear fractures with the same paleostress orientations as the small faults and the associated local fold stresses. The coincidence of the NNW-SSE fractures with the maximum horizontal compression (SH max) implies the extensional nature of them. This might be triggering and it might help the karst development mainly along the open fractures of the irregular or undulating surface planes of this trend in the study area.

The ENE-WSW to E-W trend, shown in Figure (9), reflects the majority of fault-slip data that may mainly represent the neoformed dextral strike-slip faults and the release joints. Plane surfaces of the dextral strike-slip faults are coated with calcite steps or slickolites which are of importance as a sense movement indicator. Therefore, the plunge and azimuth of these structural markings were measured and analyzed. Results show that the dextral shear along these fractures (neoformed dextral strike- slip faults and the release joints) has occurred at a later stage/s as a reactivation process. These fault planes are open and calcite curtains or soil staining are observed on their surfaces, suggesting water infiltration and mobility with the subsurface (Figs. 7 and 8). Therefore, the growth of some caves and the development of karstified blocks is controlled by faults reactivated joint structures.

7. Conclusion

Based on the above facts and the relationship of fractures to the fold axes, the general behavior of fractures in the study area is as follows:

1. extension (cross) fractures have orientation NNW-SSE (N20°W to N40°W);
2. release fractures have orientation ENE- WSW and WNW-ESE (N70°E to S80°E);
3. shear fractures set-1 have orientation N- S (N10°W to N10°E); and
4. shear fractures set-2 have orientation ESE- WNW (S45°E to S75°E).

On the basis of both the orientation of release and extension fractures and the fault-slip data, the principal stress direction is swinging around NNW-SSE.

In conclusion, the minor trend (E-W to ENE-WSW) indicates that the reactivated fractures are dextral strike-slip faults, which are the dominant fracture type being affected by the karstification in the study area.

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