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Fault-related folds at the central northern part of the Cairo-Suez District, Egypt: example from Gebel Um Raqm area

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ABSTRACT

Detailed surface structural mapping of the area positioned in the central northern sector of the Cairo-Suez District (Egypt) was carried out to define the fold geometry and structural evolution of the highly deformed area in an extensional setting. This work is accomplished via field observations of the surface structures and interpretation of the high-resolution satellite images. Stratigraphically, the outcropped rock units are differentiated into four main units and are represented by the Upper Eocene, Oligocene, Lower Miocene, and Middle Miocene formations. Structurally, the Gebel Um Raqm is divided into three main sectors: northern, central, and southern. The northern sector is defined by left-stepping en echelon E-W to WNW normal faults, while the southern sector is delineated by left-stepping en echelon NW-SE normal faults. Moreover, the central sector is characterized by horst-graben faulting styles and step-faults. The structural analysis of the area revealed four main fold trends, which are identified and represented by NW-SE, E-W, WNW-ESE, and NNW-SSE. Also, the major faults are grouped into four main trends and are represented by WNW-ESE, NW-SE, E-W, and NNW-SSE. The interpreted structural geometry of folds and faults indicates that these folds are developed either by the drag of ductile beds along the fault planes as drag folds or formed between the overlapped normal faults as transfer folds.

1. Introduction

The northern part of the Cairo-Suez District (CSD) is characterized by the presence of extensional folds that are developed in the Paleogene and Neogene sediments (e.g., Gebel (G.) Hamza, G. Oweibed, and G. Nasuri (Henaish, 2018b)). Extensional folds in this study include two geometrical folds: drag folds and transfer folds (Fig. 1). In general, the intimate association of faults and folds can be referred to as fault-related folds and fold-related faults. Fault-related folds, which refer to the different types of folds formed due to the displacement along the fault planes, are the subject of this study. Jamison (1987) defines three kinds of fault-related folds: fault-bend folds, detachment folds, and fault-propagation folds. Additionally, Drag folds are geometrically-related to faulting and are resulted from the drag of ductile beds along the normal fault planes (Fig. 1A) (Schlische, 1995; Sharp et al., 2000; Abdelmaksoud et al., 2023, in press). The other term, "fold-related faults," refers to the various fault patterns attributed to the folded rocks (Moustafa, 2013). Transfer folds, on the other hand, are developed between the ends of the normal faults.

The location between these overlapped normal fault segments resulted in linked folds and normal fault arrays. The overlapped zones between the fault segments are known as transfer zones (Morley et al., 1990). These transfer zones are resulted from the fault interactions where the strain is relayed or transferred between the fault segments (Fossen and Rotevatn, 2016). Based on Morley et al. (1990) classification of transfer zones, the transfer zones are subdivided into two main types: synthetic and conjugate transfer zones. Two normal faults that dip in the same direction are defined by synthetic transfer zones (Fig. 1B). Conversely, conjugate transfer zones exist between two normal faults that dip in opposite directions (Fig. 1C, D). There are two types of conjugate transfer zones: conjugate divergent, where the faults dip away from one another, and conjugate convergent, where the faults dip toward one another. The transfer of fault displacement between these interacted fault segments is regarded as graben relay zones where the fault segments are convergent (Fig. 1C) and horst relay zones where the normal fault segments are divergent (Fig. 1D) (Gawthorpe and Hurst, 1993). The G. Um Raqm, in the northern central part of CSD, Egypt, offers an outstanding outcrop example for fault-related folds. The structural complexity of the area arises from the interaction between the inherited basement structures and the subsequent extensional rift tectonics of the Gulf of Suez. These tectonic processes have resulted

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in the development of numerous folds and normal faults that provide valuable insights into the structural evolution of the area. This paper aims to clarify the structural architecture of the G. Um Raqm and define the different fold mechanisms in such an extensional setting.

2. Materials and Methods

The current work is accomplished by mapping the surface geological structures and analyzing the measured data. The structural data is collected based on field and laboratory works. The laboratory work includes preparing all base maps using high-resolution Google Earth images and ETM + of Landsat 8 satellite images. On the other hand, the filed work was done by measuring of the observed structural features, recording the attitudes of the tilted rock units, and as discriminations of the rock units. The integrated filed and laboratory works used for analysis and interpretation of the obtained surface structural features at the G. Um Raqm. The final output structural map is created by using the Arc GIS software.

3. Regional geological setting

The CSD is a portion of an unstable shelf region that encompasses a more significant part of northern Egypt. Also, it has regional geological importance due to its structural position as a Tethyan passive continental margin segment in the eastern Mediterranean region. The structural complexity of the district due to the effects of several tectonic events that occurred during the Mesozoic and Cenozoic eras. The tectonic events comprise three deformation phases resulting from the dramatic movements of the African, Arabian, and Eurasian plates (Meshref, 1990). The first deformation phase started in Jurassic–Early Cretaceous time and is marked by the formation of the ENE and E-W oriented normal faults due to the Neo-Tethys regional rifting. The second deformation phase was developed during the Late Cretaceous–Early Tertiary time. This phase resulted from the Neo-Tethys' closure due to the convergence between the African and Eurasian plates (Guiraud and Bosworth, 1999). The structures associated with the second phase are compressional and dextral transpression on the E-W-oriented deep-seated faults. During Miocene and post-Miocene times, the CSD witnessed extensional phase due to rift between the African and Arabian plates, which is resulted in the formation of the Gulf of Suez province, which is associated with NW-SE normal faults.

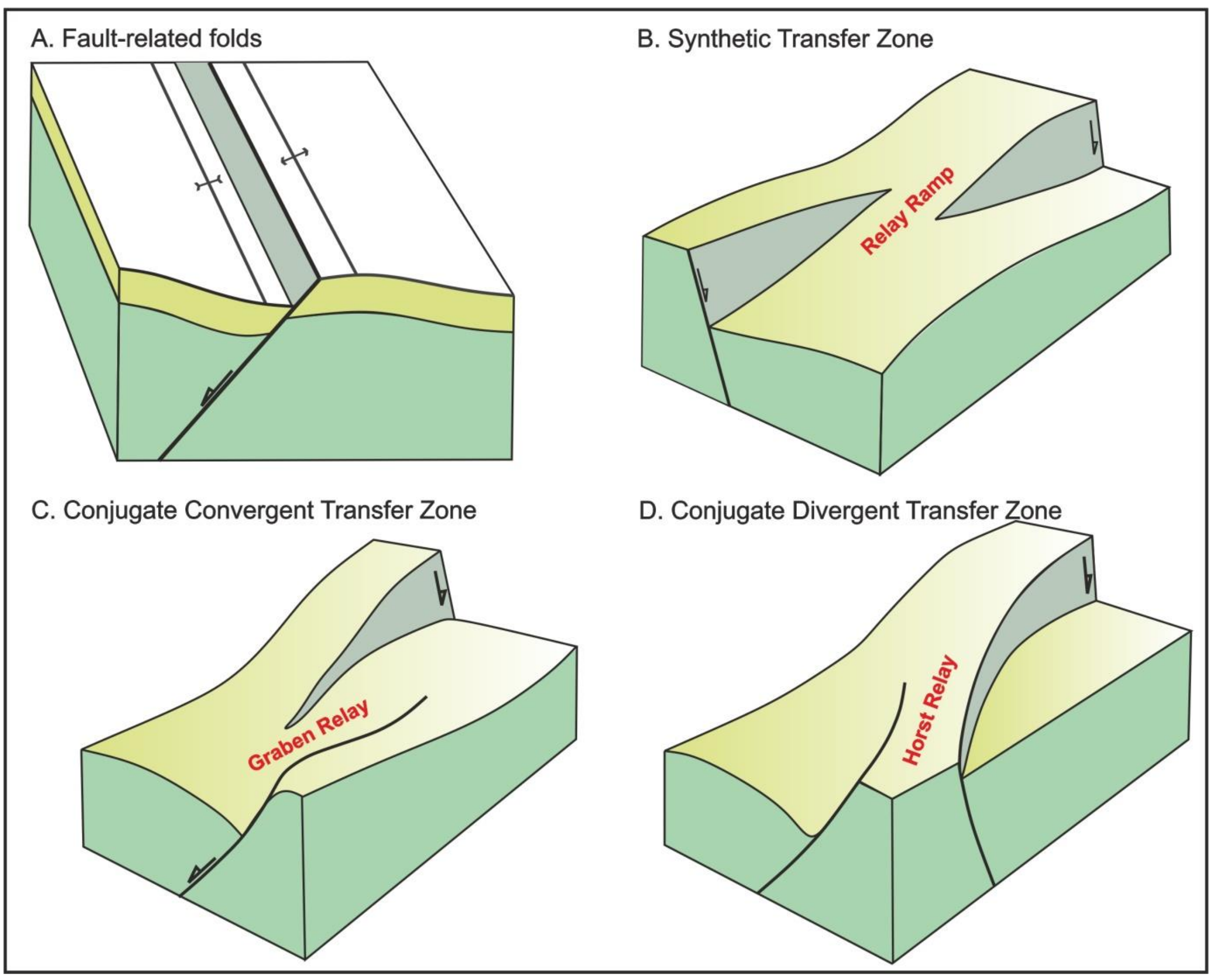

Fig. 1. Simplified sketch illustrating the common types of fault-related folds, A) drag folds along normal fault plane, B-D) soft-linkage transfer zones (after Morley et al. 1990).

During the Miocene and post-Miocene times, the CSD witnessed an extensional phase due to a rift between the African and Arabian plates, forming the Gulf of Suez province and associated with NW-SE normal faults. Additionally, this phase of continental rifting led to the reactivation of the E-W deep-seated faults by dextral transtension along the CSD. It also caused the formation of several E-W left stepping en echelon fault belts (Moustafa et al., 1998). Four main elongate en echelon fault belts belong to the CSD (Moustafa and Abd-Allah, 1991): the Shabraweet-Um Qamar, Oweibed, Ataqa-Qattamiya-Maadi, and North Galala fault belts (Fig. 2). The G. Um Raqm is related to the central part of the Shabraweet-Um Qamar fault belt (Fig. 2). The NW-SE normal faults were linked with the E-W en echelon faults in a distinguishable zigzag pattern. Moreover, the CSD represents a broad transfer zone during the Miocene and post-Miocene time, which relayed or transferred the fault displacement from the sub-basin of the northern Gulf of Suez to the underneath fault segments of the Nile Delta modern rift and the most western sector of the northern part of the Western Desert (Moustafa and Abd-Allah, 1992; Moustafa and Khalil, 2016). Accordingly, the CSD comprises transfer structures of second to third orders with different structural styles, including the present area. Furthermore, from a structural perspective, the CSD is subdivided into two main sectors. The northern sector is characterized by gentle folds that have deformed the Miocene rock units, including G. Hamza, G. Homaira, G. Oweibed, and G. Gharra. However, the southern sector is composed of tilted fault blocks, which are mainly composed of the Middle Eocene rock units, including G. Ataqa, G. Qattamiya, G. Abu Shama, and G. Mokattam. The above-mentioned structural deformation events significantly affect the distribution of the rock units along the CSD, ranging in age from the Cretaceous to the Quaternary.

4. Stratigraphy

The stratigraphic section in the study area is composed of four min rock units that are arranged from base to top: Wadi Hof Formation, Gebel Ahmar Formation, Gharra Formation, and Geniefa Formation (Fig. 3). They assigned age from the Late Eocene to Middle Miocene times. The oldest rock unit is represented by Wadi Hof Formation of the Late Eocene age (U Eo) (Farag and Ismail, 1959). It is 30 m thick and comprises interbedded limestone, claystone, and sandstone beds. It is covered unconformably by 25 m thick of the Oligocene deposits.

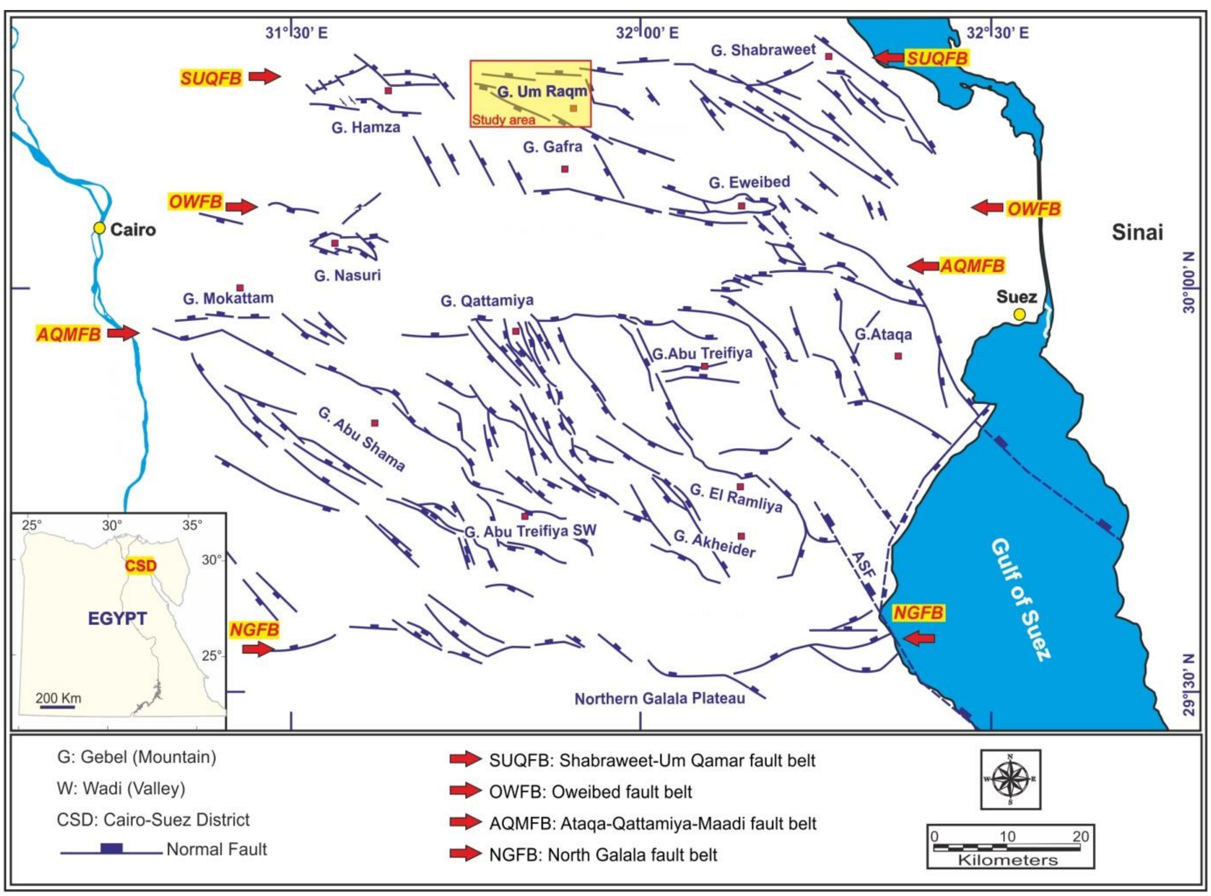

Fig. 2. Simplified structural map of the CSD and location of the study area (modified after (Henaish et al., 2023).

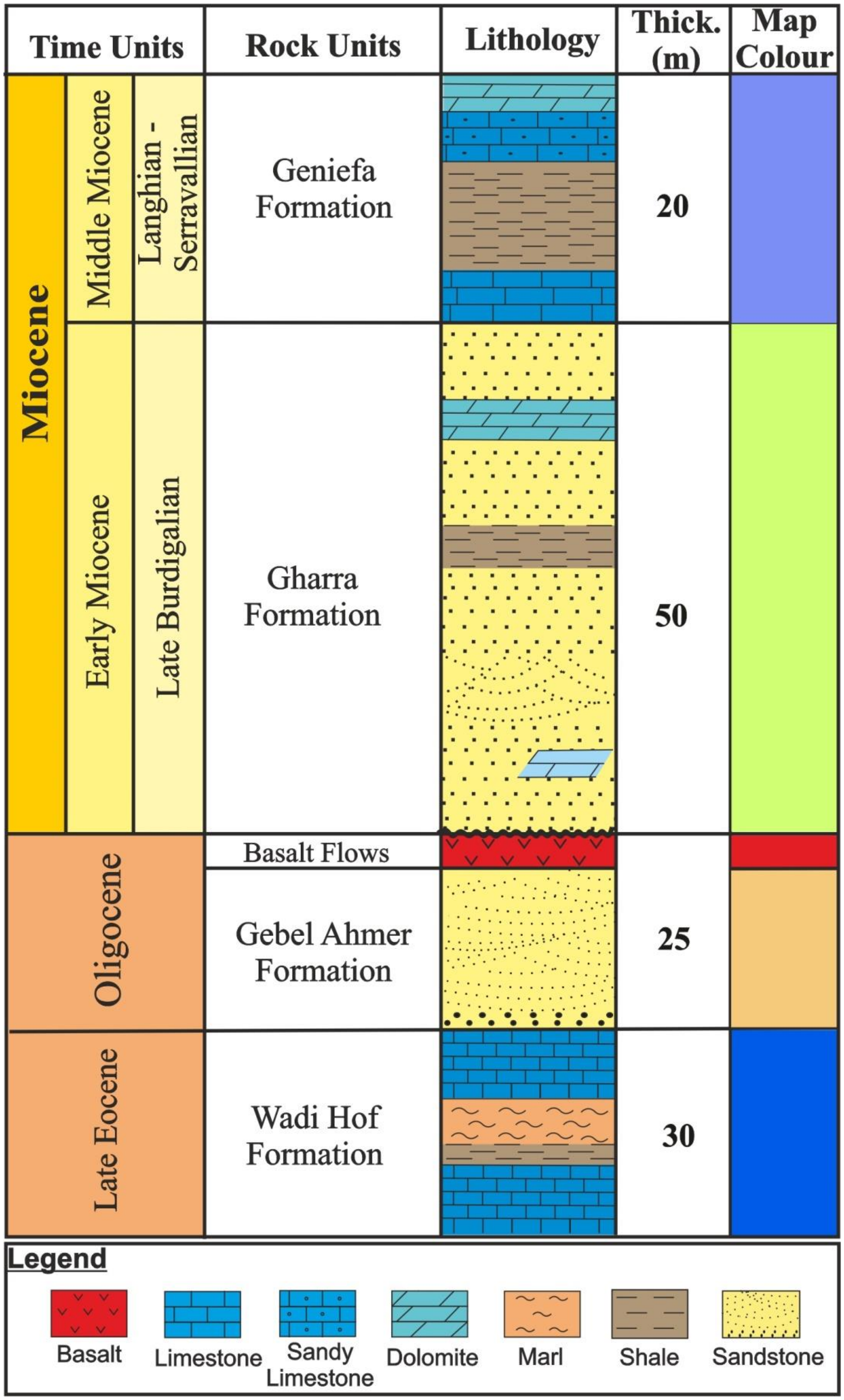

Fig. 3. Composite stratigraphic section in the G. Um Raqm. Stratigraphic section of the exposed rock units in the study area is compiled from (Farag and Ismail, 1959; Said, 1962; Ghorab and Marzouk, 1965)

The Oligocene sediments (OLG) are represented by the Gebel Ahmar Formation (Shukri, 1954), which is mainly composed of cross-bedded, varicolored, fine-to-coarse-grained sands and partially including dark brown to black gravel bands. These sediments are capped by a dark gray to brown hard sandstone bed. They were also covered by the late Oligocene to Early Miocene basalt flows (Said, 1962), which were unconformably overlain by the Miocene sediments. At the G. Um Raqm, the exposed Miocene section reaches a total thickness of approximately 70 m. They are subdivided into two main formations; the Lower Miocene Gharra Formation (LMF) and the Middle Miocene Geniefa Formation (MMF). The Gharra Formation is siliciclastic-dominated unit and reaches 50 m. It is formed of sandstone, shale, and sandy limestone. The Geniefa Formation is carbonate-dominated and reaches 20 m thickness. It is made of chalky limestone with marl and shale intercalations and is topped by highly fractured dolomite beds. The Quaternary sediments (Q) of sand and gravels covered the wadi floors, which is dissecting the area such as Wadi Gafra.

5. Results

Structural framework

The G. Um Raqm is a low topographic relief with a maximum elevation of 240 meters above sea level that is trending WNW-ESE. It has an aerial extension of roughly 200 km^2, measuring approximately 10 km long and 18–20 km wide. It is located in the central northern sector of the CSD and exhibits various structural geometries of ductile and brittle structures. The northern border of the G. Um Raqm is bounded by WNW-ESE trending normal faults with a left-stepping en echelon pattern. These faults are generally dip toward the north direction and juxtapose the lower Miocene rock units against the Oligocene sediments. On the other hand, the G. Um Raqm is also flanked by en echelon left-stepping NW-SE trending faults from the west, which are dipping towards the west direction, where they juxtapose the Lower and Middle Miocene rocks against the Upper Eocene and Oligocene sediments**.** Consequently, the G. Um Raqm seems to be a rhombic-shaped block (Fig. 4).

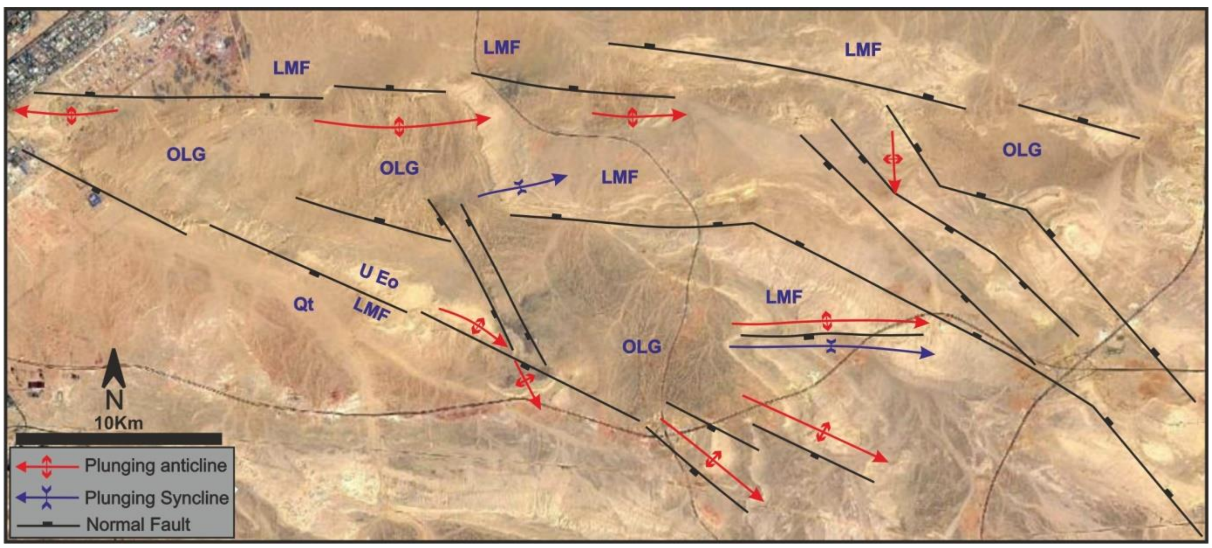

Fig. 4. Major structural features delineates the G. Um Raqm.

Structurally, the G. Um Raqm is divided into three structural sectors; northern, central, and southern sectors (Fig. 5). The beddings in the northern sector (NS) of the G. Um Raqm are primarily tilted due northwest, with gentle dip angles ranging from 7° to 12°, except areas near fault planes, where the dip amount reaches a relatively moderate 19°–22°. The measured oriented data of these mapped faults in this sector are striking N80° to N100°. There is a noticeable normal dip-slip component created on these faults. They have dip angles range between 70° and 85°. This sector is also characterized by folds. The investigated folds are plunging anticline, doubly plunging anticlines, and doubly plunging synclines (Fig.6). The plunging anticline is located to the west of the NS and has fold-axis parallel to the surrounding fault, which is trending WNW-ESE (Fig. 6A). The core of this plunging anticline is occupied by the Lower Miocene sediments (Fig. 6B). This fold is a gently dipping asymmetric anticline plunging to the WNW and dragged along WNW-ESE normal fault**.** On outcrop scale, this fold is also dissected by three NW-SE normal faults (Fig. 6B). The other folds are developed between the overlapped normal faults. The central part of Figure 6, a small doubly plunging syncline was developed in graben between two normal faults. In addition, there is also a doubly plunging anticline and doubly plunging syncline with fold axes parallel to the two overlapped normal faults. Moreover, the southern part of the Figure 6, small doubly plunging syncline and doubly plunging anticline are developed between the overlapped normal faults. The fold axes are parallel to the attitudes of the overlapped normal faults (i.e. NW-SE).

In the central part of the NS, there is also fold associated to normal fault. A plunging anticline has fold axis parallel to the strikes of the two overlapped normal faults. This fold is plunging to the W and is occupied by the Lower Miocene Formation (Fig. 7). The overlapped normal faults are striking E-W and downthrown to the north (Fig. 7).

Figure 8 shows plunging anticlines and synclines associated with normal faults. Their fold axes are parallel or make an acute angle of 45° to the attitude of the nearby faults. There are five plunging anticlines and one plunging syncline. Two plunging anticlines propagate in the footwall of the normal faults. The other three plunging anticlines are developed between the overlapped normal faults. One plunging syncline has fold-axis parallel to the normal fault and plunging to the NW. The core of these folds is occupied by the Oligocene sediments. This part of the NS is dissecting by normal faults with different geometries of horsts and step faulting. The predominant movement is dip-slip component; some of these faults show oblique-slip components with small amount of right lateral component (Fig. 8). The NW-SE and E-W normal faults are aligned in a left-stepping en echelon pattern.

Based on field investigations, some outcrops of the Oligocene sediments at the NS are dominated by extensional features of NW-SE normal faults (Fig. 9).

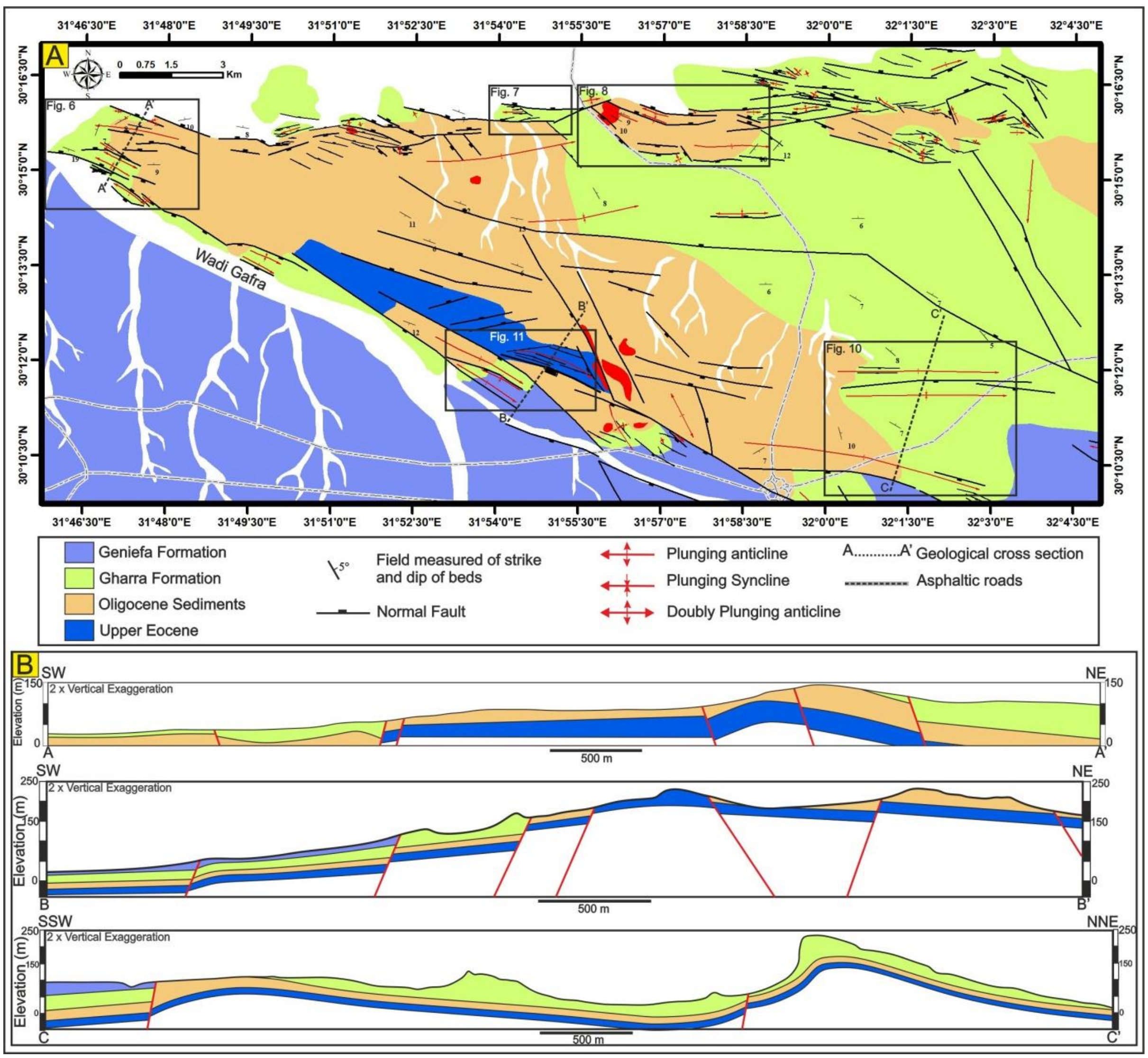

Fig. 5. A) Detailed field structural map of the G. Um Raqm in the north central part of CSD, and **B)** geological cross-sections for the study area.

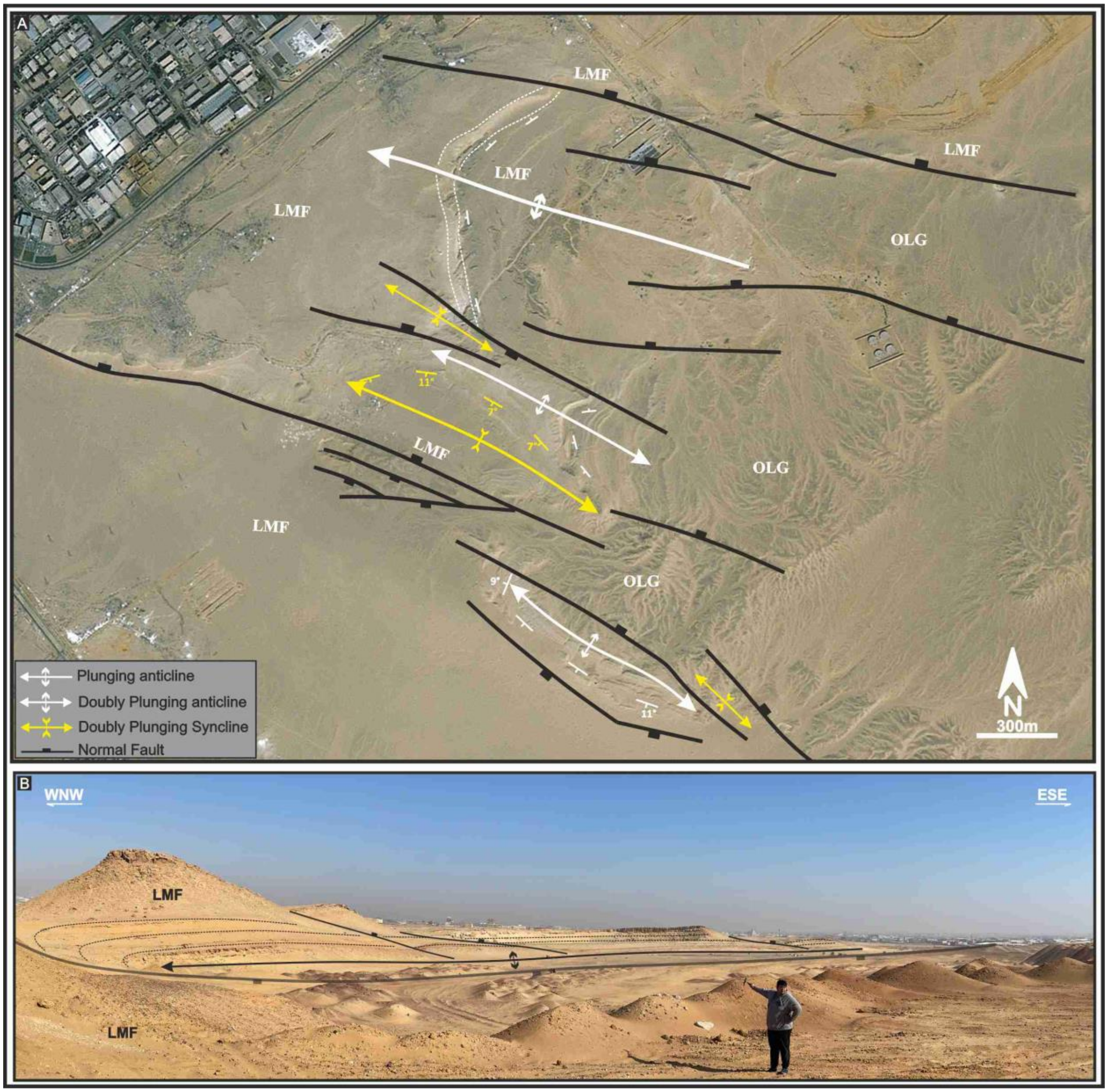

Fig. 6. (A) Google Earth satellite image shows the structural interpretation of the western part of the NS of the G. Um Raqm, which is defined by normal faults trending WNW-to NW-SE and associated with plunging anticline, doubly plunging anticlines, and doubly plunging synclines, see Fig. 5 for location. **(B)** Field photograph represents WNW-plunging anticline developed in the hanging-wall of WNN-ESE trending normal fault dissect the Lower Miocene Formation (LMF).

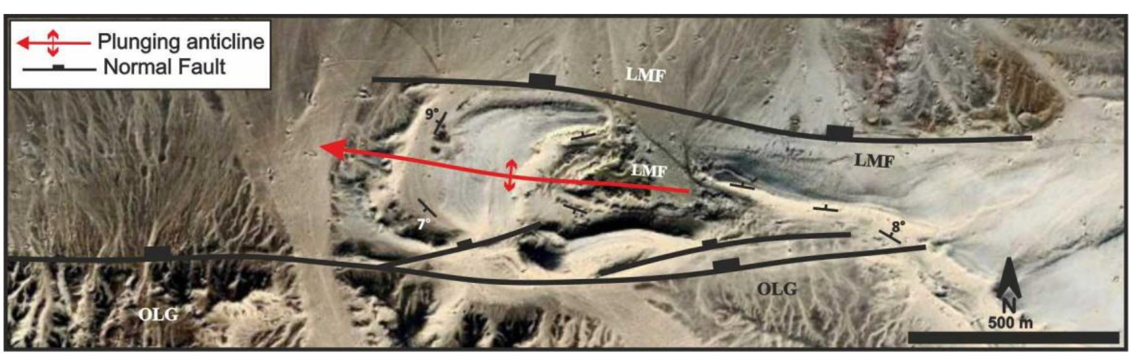

Fig. 7. (A) Google Earth satellite image shows the structural interpretation of the central part of the NS of the G. Um Raqm, which is defined by two overlapped normal faults trending E-W and associated with plunging anticline, see Fig. 5 for location.

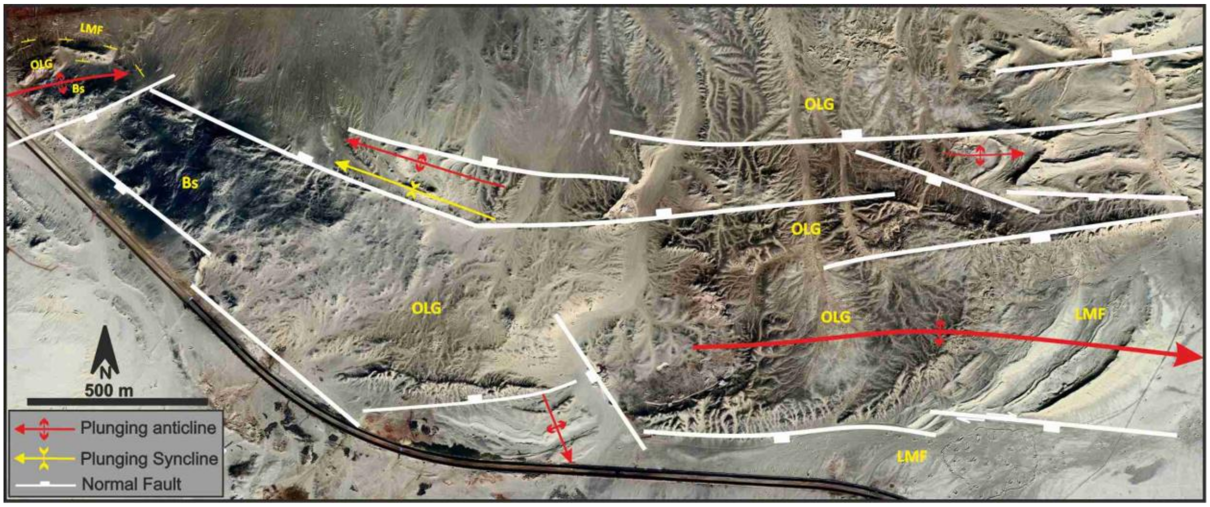

Fig. 8. Google Earth satellite image shows plunging anticlines associated with normal faults with different geometries, see Fig. 5 for location.

Fig. 9. Field photograph of the Oligocene outcrop shows some extensional normal faults trend NW-SE to create horst and step-faults.

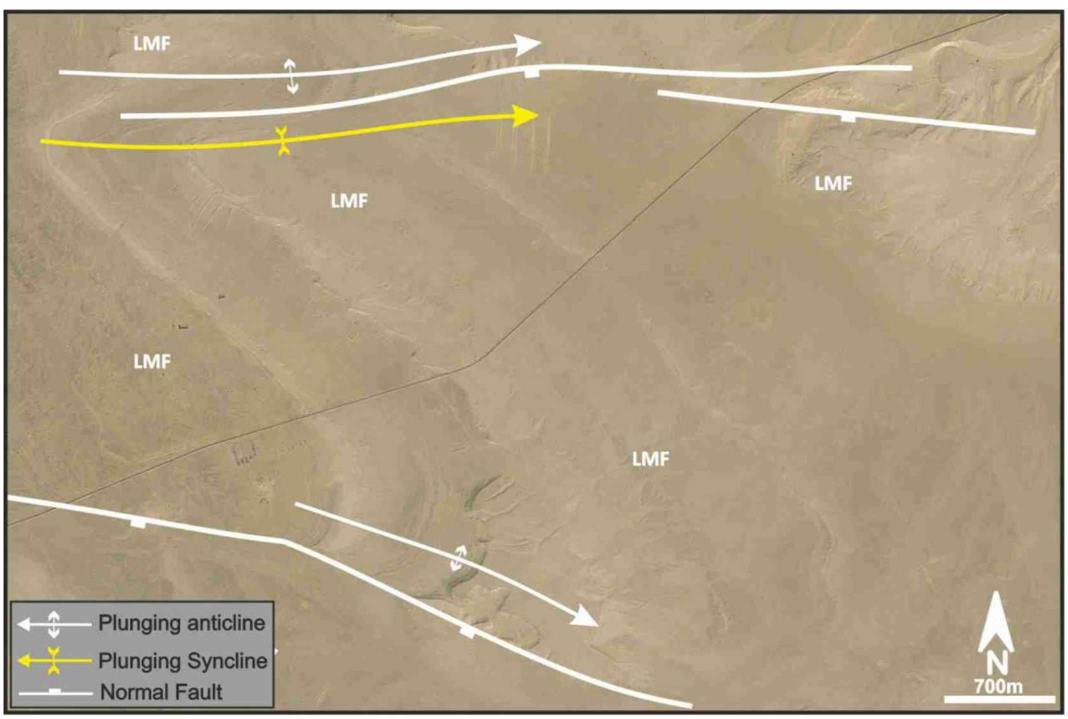

Fig. 10. Google Earth satellite image shows Plunging anticline-syncline dragged along E-W normal fault cut the Lower Miocene sediments and plunged anticline developed in the footwall of NW-SE fault, see Fig. 5 for location.

The central sector (CS) of the G. Um Raqm has less deformation in its structure compared to the mountain's boundaries. This area showcases a variety of structural styles, such as horst, grabens, and step-faults, which are the result of the interaction between NW-SE and WNW-ESE faults (Fig. 5). The deformed beds at this sector are primarily the Oligocene and the lower Miocene strata. The attitudes of beds (i.e. strike and dip amount) have a low range of inclination, ranging from 5° to 11°. The dipping of beds increases near the fault planes. Faults trend NW-SE and WNW-ESE with strike reading between N 290° - N 340°. The detailed mapping of the high-resolution Google Earth images in the central part shows that fault segments are linked in both NW-SE and E-W trends (Fig. 5). The investigated folds in this sector are two plunging anticlines and one plunging syncline (Fig. 10). Their fold-axes are parallel to the orientation of the nearby normal faults. The Lower Miocene sediments occupy their fold cores. The mapped faults are striking E-W and NW-SE. some of them link to form zigzag fault pattern.

The faulted rock units in the southern sector (SS) are composed of the Upper Eocene, the Oligocene, and the Miocene sediments. The mapped faults of this sector have different geometries of horsts, grabens, and step-faults. The mapped folds are also associated to normal faults. Figure 11 shows three anticlines and one plunging syncline. These folds have fold axes parallel to the trends of the overlapped fault segments. The WNW-ESE normal fault juxtaposes the Upper Eocene rocks in the footwall and the Oligocene sediments in the hanging-wall. This fault is characterized by plunging anticline in the footwall that deformed the Upper Eocene sediments (Fig. 11). The other plunging anticline and plunging anticline-syncline are developed between overlapped faults with same dip polarities.

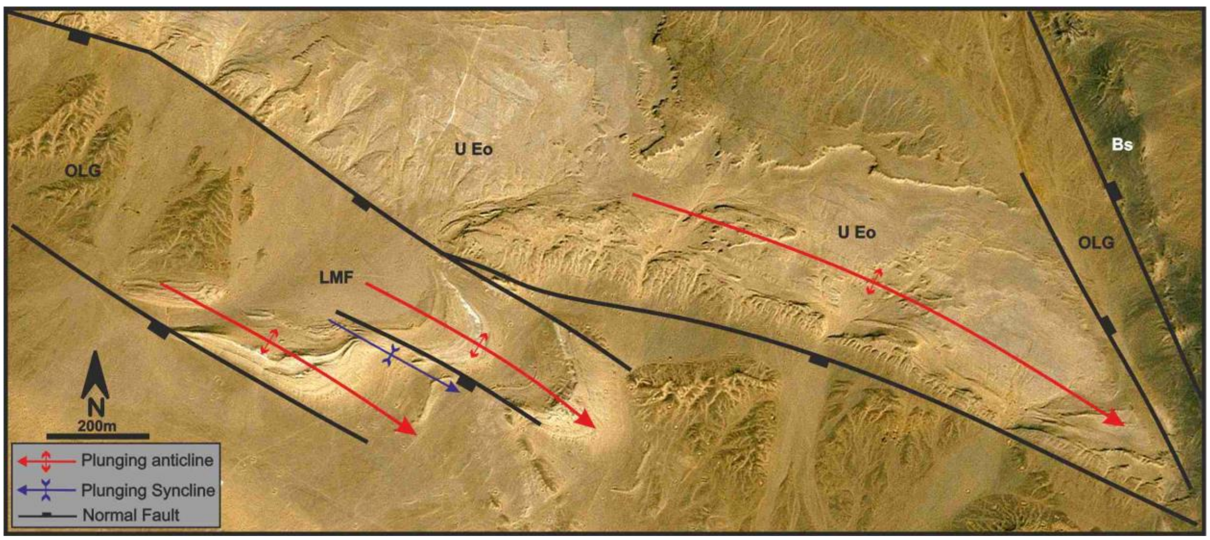

Fig. 11. Google Earth satellite image shows Plunging anticlines and synclines dragged along NW-SE normal faults, see Fig. 5 for location.

6. Discussion

Structural Analysis

Detailed surface structural analysis of the G. Um Raqm revealed that the area is covered by a wide range of brittle and ductile structural forms. The G. Um Raqm is bordered from north and West by left-stepping en echelon normal fault arrays of NW-SE and E-W orientations. These en echelon faults were rejuvenated during the Oligo-Miocene by dextral transtension on the E-W deep-seated basement faults. The total number of mapped faults in the G. Um Raqm is 245 normal faults. These faults are grouped into four main frequency sets in descending order: WNW-ESE, NW-SE, E-W, and NNW-SSE trends (Fig. 12A). Detailed field mapping of the investigated area indicates dip-slip faults with little strike-slip components. The measured faults in the G. Um Raqm area revealed moderate to steep dip angles, usually ranging from 70° to 85°.

The total number of mapped folds in the area is 72. In descending order of frequency, these folds belong to the following four main sets: NNW-SSE, WNW-ESE, E-W, and NW-SE trends (Fig. 12B). Based on the structural analysis of the mapped folds, the followings can be suggested: 1] these folds were formed as fault-related folds by the drag of ductile beds along the normal fault plane. Anticlines are present in the footwalls, and synclines are dragged in the hanging-walls (Fig. 6 & 10). 2] The mapped folds formed between the overlapped normal faults with fold axes parallel to the fault attitude indicate that these folds are transfer folds (Fig. 7 & 11). The area is highly deformed by a wide range of transfer zones that encountered ductile deformation of beds between the fault terminations, similar to some insights along the Cairo-Suez District discussed by (Henaish, 2018a; Henaish, 2023). There are soft-linking folds were formed in synthetic transfer zone (e.g. Fig. 11, 1B), conjugate convergent transfer zone as relay graben (e.g. Fig. 6, 1C), and conjugate divergent transfer zone as relay horst (e.g., Fig. 6, 7, 1D).

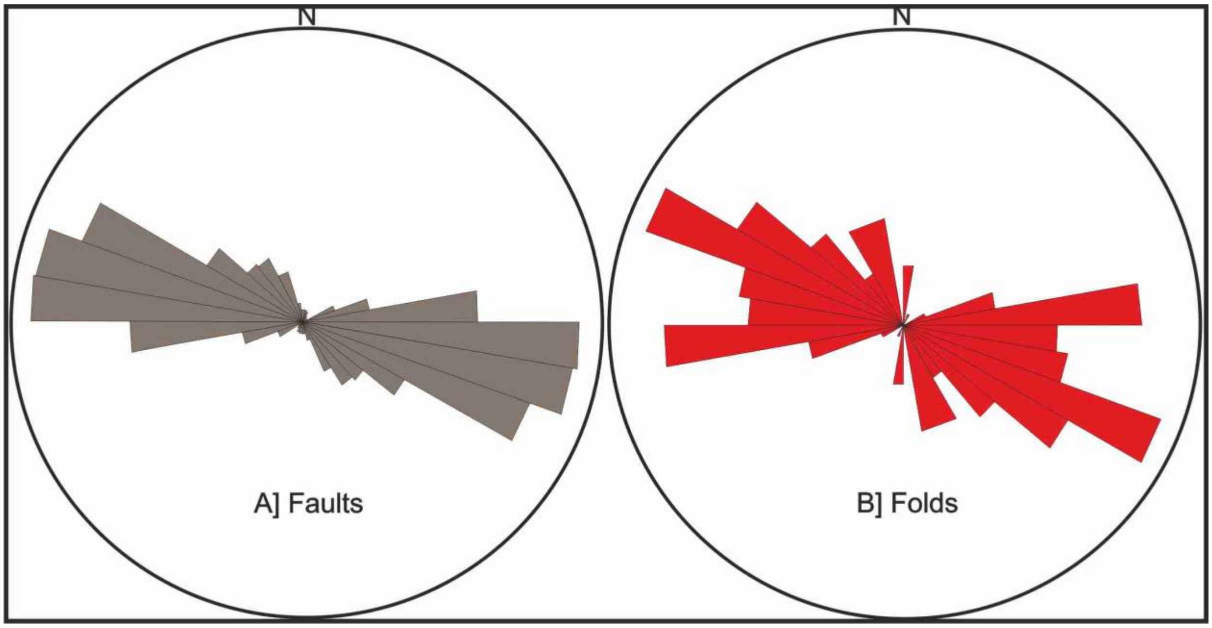

Fig. 12. Rose diagram shows A) the main fault trends, and B) the main fold trends in the G. Um Raqm.

7. Summary and conclusions

Detailed structural field mapping of the G. Um Raqm at the central northern part of the Cairo-Suez District was carried out to illustrate the different types of fold geometries that formed due to extensional fault propagation. Additionally, the work was achieved to define the internal structural geometry of the G. Um Raqm block using field data, high-resolution Google Earth images, and Landsat-8 satellite images. The exposed rock units in the investigated area are made up of rock units that range in age from the Late Eocene to the Middle Miocene. Structurally, the G. Um Raqm appears as a rhombic-shaped block which is delineated from northern and southern borders by left-stepping en echelon E-W and NW-SE trending normal faults, respectively. All mapped folds are related to normal faults and are defined as fault-related folds (i.e. drag folds) or soft-linking folds developed in transfer zones.

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