

## LINKAGE STYLE OF RIFT-ASSOCIATED FAULT ARRAYS: INSIGHTS FROM CENTRAL CAIRO-SUEZ DISTRICT, EGYPT

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**Abstract:** The Cairo-Suez District, Egypt, is well known with its structural complexity which controlled the distribution of rock units as well as the configuration of many fault blocks. The present study deals with the structural architecture of Gebel Abu Treifiya SW, central part of Cairo-Suez District. The study area is represented by several fault blocks which are studied in detail in the present work. The exposed rock units are represented by the Middle Eocene and Upper Eocene rock units; also, Oligo-Miocene basalts are evident. Fieldwork and measurements revealed the presence of three main fault trends represented by NW-SE, WNW-ESE and NNW-SSE. In addition, the majority of the mapped faults are steeply dipping, having a dip values range from 65° to 80°. Interaction and linkage of rift-related normal faults has been studied and categorized depending on the geometry of linked faults as well as the mechanical stratigraphy of the encountered beds. The results revealed five types of transfer zones which belong to soft-linked or hard-linked faults. The findings of this research are valuable for understanding the geometry of different types of transfer zones at the subsurface or other outcrops related to rift tectonics.

**Keywords:** Rift-related structures, Transfer zones, Cairo-Suez District, Fault linkage, Relay ramps, Linking folds

### 1. INTRODUCTION

The Cairo-Suez District (CSD) is considered as one of the most attractive places at the north Eastern Desert (Fig. 1) for geologists due to its deformation history and its outcropping geological structures (e.g. Moustafa et al., 1985; Moustafa & Abd-Allah, 1991; Maqbool et al., 2014; Hagag, 2016; Attwa & Henaish, 2018; Henaish & Attwa, 2018, Henaish, 2018a, b). Regionally, the importance of CSD is due to its structural complexity as it represents a segment of the Tethyan passive continental margin in the East Mediterranean region, which is located between the Gulf of Suez rift and the Nile Delta.

The CSD is a well-known locality of various normal fault geometries and styles of linkage of fault arrays (e.g. Moustafa, 2002; Henaish & Attwa, 2018; Henaish, 2018a). The locations of fault interaction are termed transfer zones (e.g. Morley et al., 1990; Fossen & Rotevatn, 2016) where strain is transferred or relayed from one structure to another. Transfer zones symbolize significant structural elements that

connect fault segments. Transfer structures include the formation and growth of folds as well as the development of fractures and fault populations in any tectonic regime. In particular, transfer zones are considered to be important, from petroleum geology perception, as they are complimentary to form different modes of structural traps (e.g. Fossen & Rotevatn, 2016; Henaish, 2018a). In addition, from engineering point of view, transfer structures initiate major engineering and environmental hazards (e.g. Attwa & Henaish, 2018).

Structurally, the CSD can be subdivided into two major sectors relative to Cairo-Suez road (Fig. 1). The northern CSD, which is located north of Cairo-Suez road, is portrayed by the existence of Cretaceous, Eocene, Oligocene and Miocene outcrops that are affected by faulting and folding (e.g. G. Shabraweet; G. Oweibed; G. Umm Raqm; G. Hamza). On the other hand, the southern CSD, which is located south of Cairo-Suez road, is characterized by the occurrence of several remarkable Eocene fault blocks (e.g. G. Ataqa; G. Abu Treifiya; G. Qattamiya; G. Abu Shama).

The study area is situated at the southern central division of the CSD and forms a part of the north Eastern Desert, Egypt (Fig. 1). While checking the names of the main Gebels and Wadis of CSD from topographic maps (e.g. U.S. Army map Service, 1956; Egyptian Survey, 1989) and geological maps (e.g. CONOCO, 1987) of Egypt, the author found two Gebels at the southern CSD which have the same name (i.e. G. Abu Treifiya). As one of these Gebels is represented at the study area, it was renamed herein according to its location relative to the other Gebel as G. Abu Treifiya SW (Moustafa A.R., personal communication) in order to avoid confusion. The area under investigation extends from latitude 29° 39' 00" N to 29° 54' 00" N and longitude 31° 39' 00" E to 31° 55' 30" E. It includes many Gebels namely; G. Sid El-Na'am, G. Abu Treifiya SW, G. Ghreibun, G. Um Rihyat and the easternmost part of G. Abu Shama.

The aim of this paper is to figure out the structural architecture of Gebel Abu Treifiya SW area and to highlight linkage style of fault segments and modes of transfer zones at the study area. The study was accomplished via detailed surface geological

field mapping of approximately 847 km<sup>2</sup> area. Landsat Thematic Mapper images scale 1:50,000 were used for observing regional structures. Also, high resolution Google Earth images were used in both 2D and 3D perspectives to show up different styles of fault relays.

## 2. STRUCTURAL SETTING AND REGIONAL GEOLOGICAL FRAMEWORK OF CAIRO-SUEZ DISTRICT

The CSD represents a division of the unstable shelf area, which occupies the larger part of northern Egypt. It extends for 120 km in an E-W direction from Cairo City towards Suez City and it is dominated by E to ENE and NW to WNW oriented faults. The structural framework of CSD has evolved from different tectonic episodes related to the movements between the African, Eurasian and Arabian plates (e.g. Meshref, 1990). During Jurassic-Early Cretaceous, North Africa and Arabia have encountered rifting that formed the Tethyan passive continental margin of the

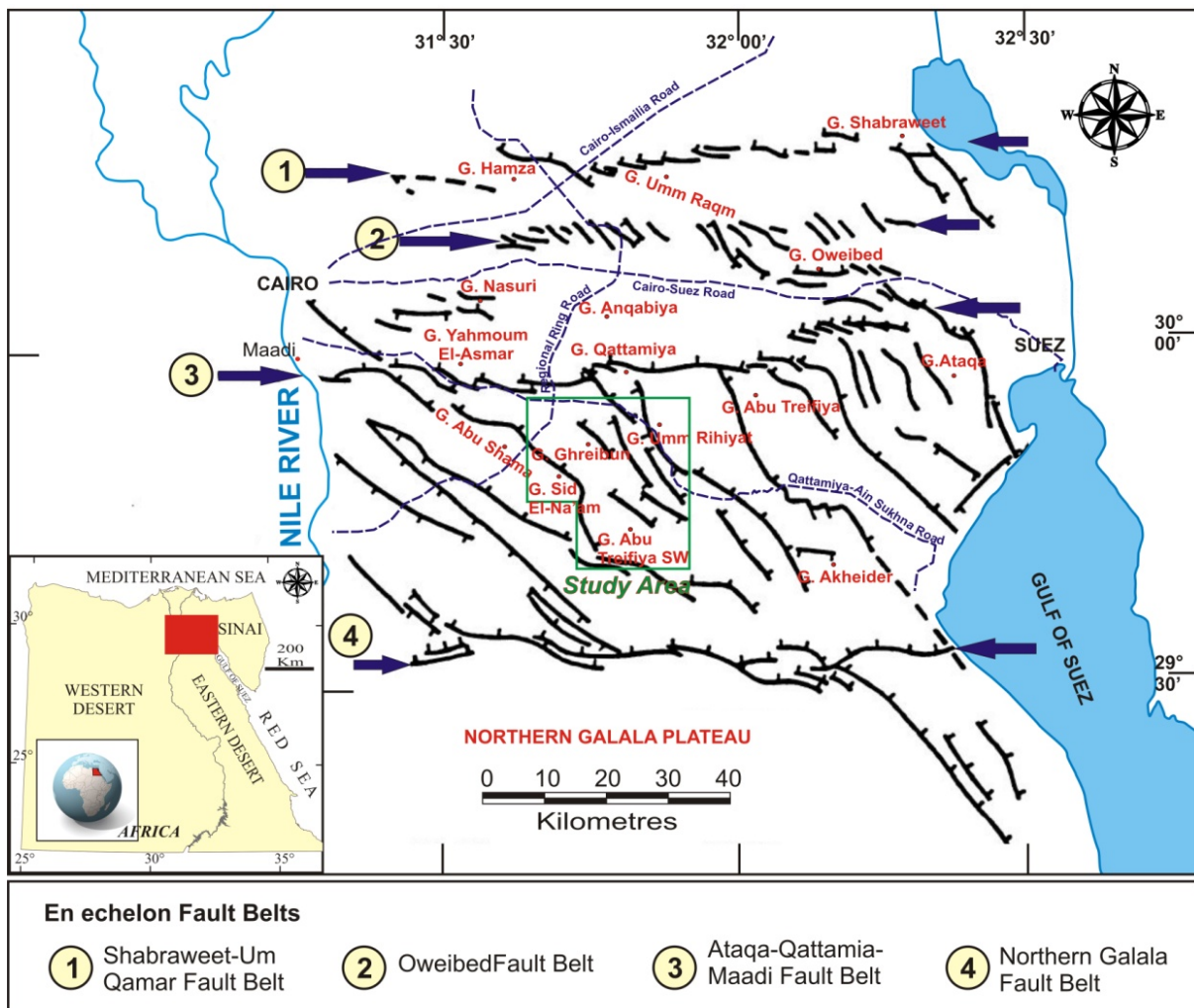


Figure 1. Simplified structural map of CSD and the location of the study area (modified after Moustafa et al., 1998).

East Mediterranean region (e.g. Guiraud & Bosworth, 1997) which led to the reactivation of E-W deep seated faults along CSD. In Late Cretaceous time, most of the E-W oriented faults have reactivated by right-lateral movements (Guiraud & Bosworth, 1999).

The CSD experienced a phase of extension accompanying the opening of the Gulf of Suez rift at the Late Oligocene to Early Miocene times which continued to the post-Miocene time. This rifting phase is characterized by basaltic eruptions as well hydrothermal solutions through fault zones. As the Gulf of Suez rift was unable to extend north of the Suez City, the throw on the faults in the northern part of this Miocene rift was transferred into the CSD (Moustafa & Abd-Allah, 1992) through the deep-seated E-W oriented faults. This led to their rejuvenation by dextral transtension that formed E-W elongated belts of left-stepped en echelon normal faults (Moustafa et al., 1998) in addition to NW-SE oriented normal faults. Moustafa et al., (1998) defined four en echelon fault belts that affect the CSD namely; (i) Shabraweet-Um Qamar, (ii) Oweibed, (iii) Ataqa-Qattamiya-Maadi and (iv) North Galala fault belts. The NW-SE oriented normal faults were linked with E-W fault belts forming a distinguishable zigzag pattern.

The abovementioned tectonic episodes affected the distribution of rock units along CSD, which range in age from Cretaceous to Recent. Sallam et al., (2015) concluded that faulting movements played the most significant role shaping the distribution, lateral facies changes and unconformities between the different rock units at CSD.

### 3. LITHOSTRATIGRAPHIC SETTING

The stratigraphic succession is represented in the study area by the Middle Eocene as well as Upper Eocene rock units (Fig. 2). Also, basalts are found in the study area, which were allocated by Meneisy & Abdel Aal (1984), using K/Ar method, to the late Oligocene-Lower Miocene (Aquitainian; 22±2 Ma.). Additionally, Wadi floors are covered with Quaternary sediments. The exposed rock units (Fig. 2) in the study area are described below from oldest to youngest.

#### 3.1. Gebel Hof Formation

This formation was introduced by Farag & Ismail (1959) in Gebel Hof (Helwan area) to describe 120 m thick section of alternations of white, chalky limestone and hard dolomitic limestone bands. At the study area, the Gebel Hof Formation comprises thin-bedded, white to yellowish, limestone as well as chalky limestone and dolomite bands. It underlies the Observatory Formation and the outcropped thickness

of this Formation ranges from 10-20 m. Based on paleontological studies, a Bartonian age was suggested for the Gebel Hof Formation (e.g. Boukhary et al., 2002).

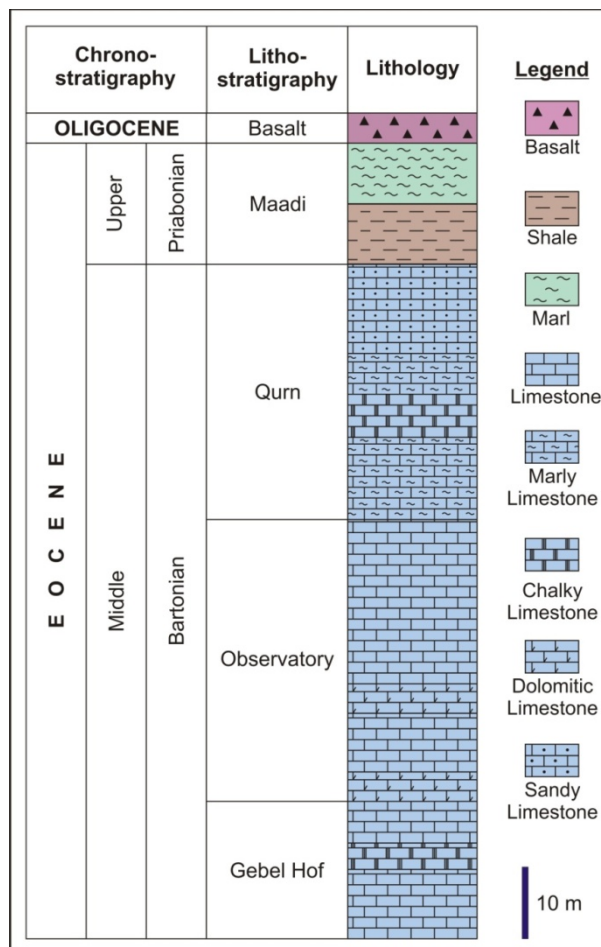


Figure 2. Stratigraphic column of the exposed rock units at the study area (modified after Sallam et al., 2015).

#### 3.2. Observatory Formation

The Observatory Formation was proposed by Farag & Ismail (1959) at East Helwan area to describe about 80 m of marly limestone section. In the study area, this formation consists of white, nummulitic limestone with the abundance of dolomitic limestone intercalations at the middle part. The Observatory Formation overlies the Gebel Hof Formation and underlies the Qurn Formation and ranges in thickness between 45-60 m. Based on fossil content, a Bartonian age was assigned for the Observatory Formation (Sallam et al., 2015).

#### 3.3. Qurn Formation

The Qurn Formation was introduced by Farag & Ismail (1959) in the Qurn area, east of Helwan. They described about 97 m thick section of chalky

and marly limestone alternating with sandy marls. In the study area, this formation is composed of marly and chalky limestones with the abundance of sandy limestone beds at the top. The Qurn Formation overlies the Observatory Formation and underlies the Maadi Formation and its thickness ranges from 25-35 m. Based on the studied foraminiferal species by Sallam et al. (2015), a Bartonian age was assigned for the Qurn Formation.

### 3.4. Maadi Formation

The Priabonian Maadi Formation was proposed by Said (1962) at Gebel Mokattam area to describe a clastic section with minor carbonate beds rich in oysters. In the study area, this formation is composed of marls intercalated with sandy marl beds and shales. The Maadi Formation overlies the Qurn Formation and ranges in thickness from 10-20 m.

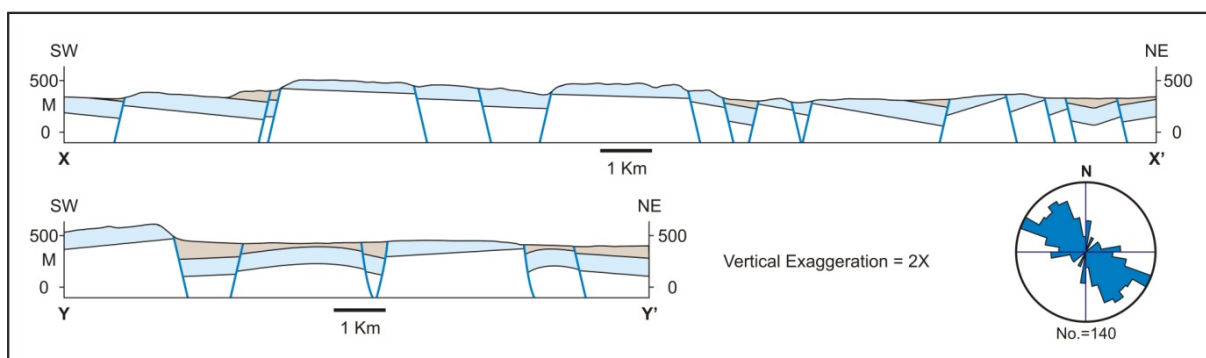
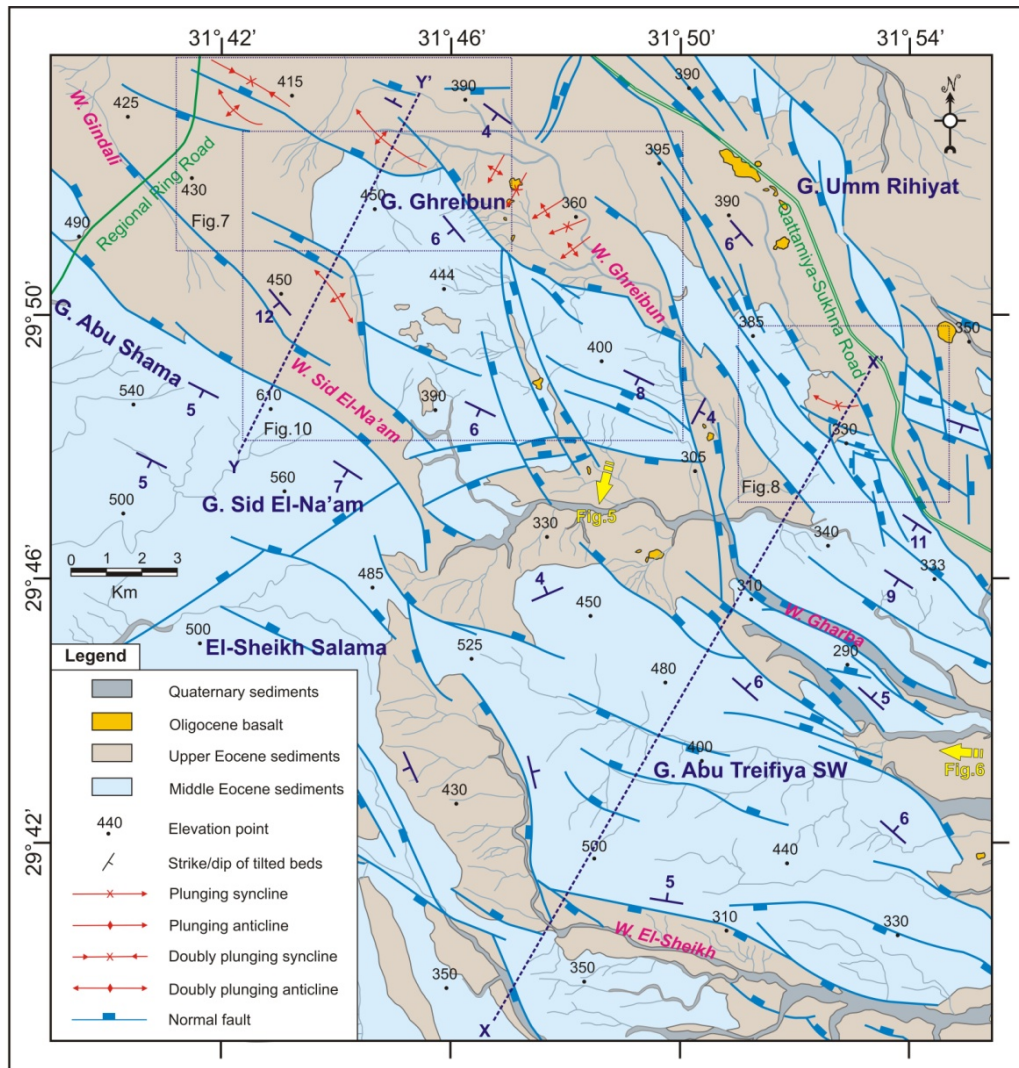


Figure 3. Geological map with structural cross-sections representing the structural setting of the study area and a rose diagram representing the main fault trends.

## 4. STRUCTURAL SETTING

The area under investigation comprises several NW-SE trending fault blocks namely; Abu Shama-Sid El-Na'am fault block, Ghreibun fault block, Um Rihyat fault block and Abu Treifiya SW fault block (Fig. 3). These fault blocks are forming low to moderate topographic ridges with elevations that range between 300-650 m. Moreover, such fault blocks are separated by structural controlled wadis that have the same trends of the nearby faults (e.g., Wadi Gindali, Wadi Sid El-Na'am, Wadi Gharaba, Fig. 3). Most of the bordering cliffs are in fact fault scarps that were modified latter by erosive agents. The measured dip values of bedding planes are gentle ( $5^{\circ}$ - $12^{\circ}$ ) except near the fault planes where it shows a relatively moderate dip values reaching  $25^{\circ}$ .

The study area represents a distinctive instance of rift-related fault systems where it is intensely cut up by normal faults. Extensional structures in the form of step faults as well as horst-graben faulting styles are the main structural style shaping the study area. In addition, fractures are frequent in the Middle Eocene limestones, especially, near fault surfaces. Folds are predominant in the northern part of the study area affecting the Upper Eocene sediments (Maadi Formation).

The mapped faults have both straight and curved traces. The traced fault segments are belonging to three major sets oriented in a descending order of frequency: NW-SE, WNW-ESE and NNW-SSE (Fig. 3). In addition, five subordinate fault trends are represented in the study area in a descending order of frequency by NNE-SSW, ENE-WSW, E-W and NE-SW orientations. Most of the investigated NW, WNW, and NNW trending faults are normal. However, some ENE trending faults show oblique-slip with a major normal dip-slip component.

The measured dip data of many fault surfaces revealed a steep dip angle that usually averages from  $65^{\circ}$ -  $80^{\circ}$ . Additionally, the mapped fault segments have measured lengths that range from 1-12 Km (Fig. 3). Moreover, most of the deduced fault throws at the investigated area revealed values that range between 40-100 m (Fig. 3). However, the maximum deduced fault throw measures about 350 m along Abu Shama-Sid El-Na'am bounding fault, where the younger Upper Eocene sediments are juxtaposed at the hanging-wall against the Middle Eocene sediments at the footwall (Fig. 3).

## 5. RESULTS AND DISCUSSION

The origin and array of faults in the study area are associated with the tectonics of the Gulf of Suez

rift. Observations from outcrop data as well as interpreted fault arrays revealed the recognition of five different types of normal fault styles of linkage in the mapped area (Fig. 4). Descriptions of each of these types of transfer zones and representative examples from the mapped area are given in the following sections.

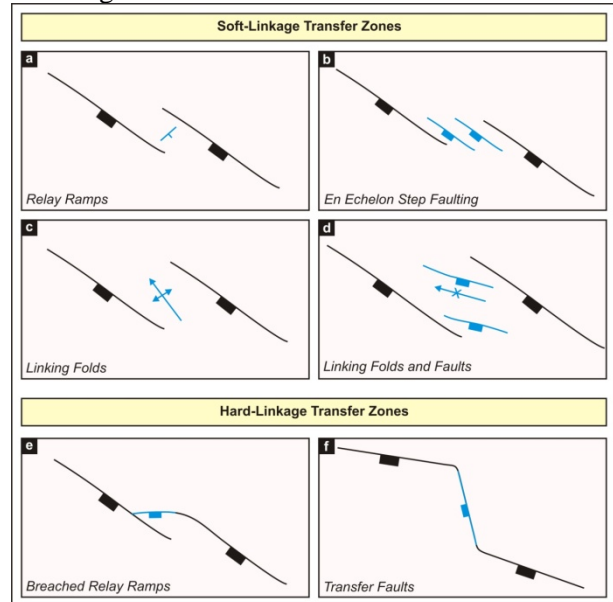


Figure 4. Different types of transfer zones (blue symbols) in the mapped area.

### 5.1. Soft-Linkage Transfer Zones

#### 5.1.1. Relay Ramps

The first type of soft-linking structures is represented by a relay ramp (e.g. Peacock & Sanderson, 1991) between the terminations of normal faults that have the same dip polarity (Fig. 4a). Several relay ramps are well developed in the northern part of G. Abu Treifiya SW (Fig. 5) as well as the eastern part of G. Sid El-Na'am (Fig. 3) between the ends of the NW-SE and NNW-SSE striking faults. Such relay ramps affect the Middle Eocene sediments and have dip angles of  $4^{\circ}$ - $8^{\circ}$  with dip direction that makes an acute angle to the strike of the overlapped faults.

#### 5.1.2. En Echelon Step Faulting

This type of transfer zones is made up of arrays of en echelon normal faults that have the same dip polarity (i.e. step faulting, Fig. 4b). At G. Abu Treifiya SW, this kind of transfer zones is well distinguished (Fig. 6) and is represented by en echelon faults affecting the Middle Eocene rocks that exist between two overlapped NW-SE striking normal faults. In addition, such en echelon faults have strikes that are parallel or sub-parallel to the overlapped faults.

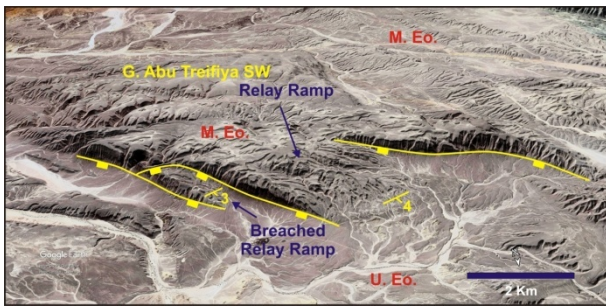


Figure 5. Google Earth satellite images (© 2019 DigitalGlobe) in 3D view showing a relay ramp formed between overlapped left-stepped en echelon normal faults and a breached relay ramp. View looking is represented by a yellow arrow (Fig. 3) towards the northern part of G. Abu Treifiya SW.

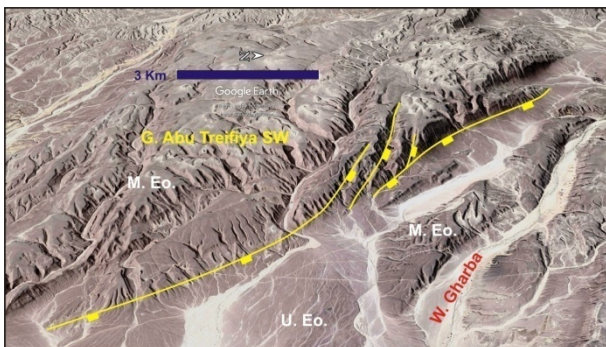


Figure 6. Google Earth satellite images (© 2019 DigitalGlobe) in 3D view showing a transfer zone that is represented by an en echelon fault pattern. View looking is represented by a yellow arrow (Fig. 3) towards the eastern part of G. Abu Treifiya SW.

## 5.2. Hard-Linkage Transfer Zones

### 5.2.1. Breached Relay Ramps

In general, such type of transfer zones is formed as displacement increased on the relay by the propagation of either footwall or hanging-wall fault segment at the base or the top of the ramp. Hence, the overlapped fault segments are linked together (Fig. 4e). There are three end-member types of breached ramp geometries (Fig. 9) that can be surfaces as well as subsurface data (e.g. Fossen & Rotevatn, 2016), forming by 1) single-tip breaching, 2) double-tip breaching, and 3) mid-ramp breaching. In the northern part of the G. Abu Treifiya SW area, a breached relay ramp is well portrayed where two NW-SE striking normal faults are linked together enclosing a ramp with  $4^\circ$  dip value with dip direction that makes an acute angle to the strike of the overlapped faults (Fig. 5). Also, in the northern G. Ghreibun, a breached relay ramp is represented where two NW-SE striking normal faults are linked together enclosing a dragged ramp in the form of a NW-plunging anticlinal fold (Fig. 7). On the map view (Fig. 4e), the shape of the connected fault is curved

which means that this ramp is a single-tip breaching type (Fig. 9b). It can be figured out by one fault tip being arrested while the other tip is bending and finally linking with the other fault (e.g. Fossen & Rotevatn, 2016, Fig. 9b).

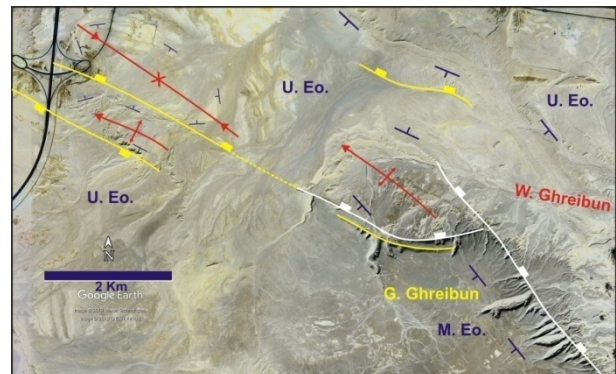


Figure 7. Google Earth satellite images (© 2019 DigitalGlobe) showing the linking folds type in G. Ghreibun between the overlapped normal faults (yellow lines). Relay ramps in the form of linking folds can undergo breaching as shown between the overlapped white faults (for location, see Fig. 3).

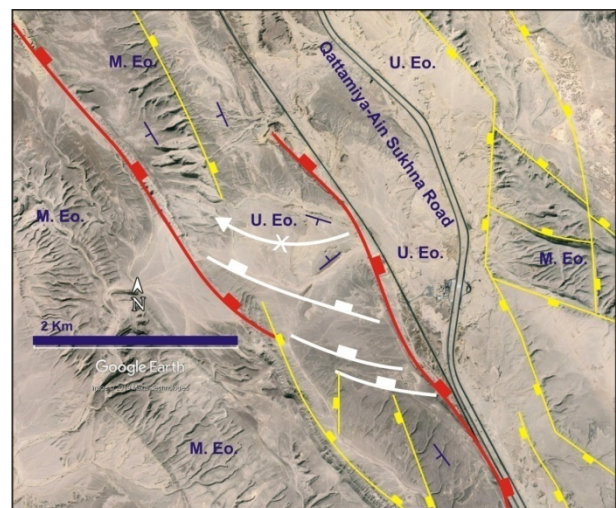


Figure 8. Google Earth satellite images (© 2019 DigitalGlobe) showing the linking folds type which is accompanied by the formation of faults (red lines) at south G. Um Rihyat (for location, see Fig. 3). Note: some faults are not shown on the satellite image for simplification (see Fig. 3 for all mapped faults).

### 5.2.2. Transfer Faults

Transfer faults (Fig. 4f) are common in the eastern and western scarps of G. Ghreibun forming a distinguishable zigzag pattern (Fig. 10). In the eastern scarp it is represented by a NNW-SSE striking fault that link two under-lapped NW-SE normal faults (Fig. 10). In the western scarp the transfer fault is striking N-S where it links two under-lapped NW-SE oriented normal faults (Fig. 10). The transfer faults in both localities have the same dip polarity of the

under-lapped faults. The presence of transverse folds along the strike of the transfer fault of the eastern scarp indicates that this fault has a listric geometry (e.g. Moustafa, 2002).

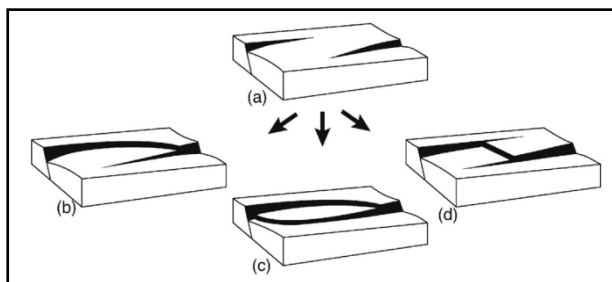


Figure 9. Patterns of relay ramp breaching. a) Unbreached relay ramp. b) Single-tip (upper-ramp) breach. c) Double breach. d) Mid-ramp breach (after Fossen & Rotevatn, 2016).

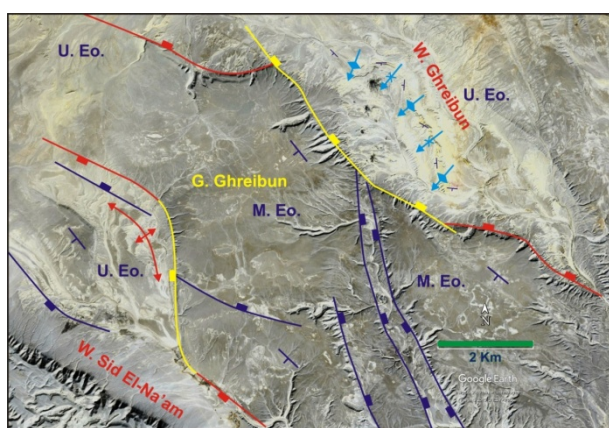


Figure 10. Google Earth satellite images (© 2019 DigitalGlobe) showing the transfer fault (yellow faults) linking type at both eastern and western scarps of G. Ghreibun (for location, see Fig. 3).

## 6. CONCLUSIONS

The present study dealt with the structural setting of the G. Abu Treifiya SW area, central CSD, Egypt. Based on satellite image interpretations and field studies in G. Abu Treifiya SW it is concluded that its current structural setting was controlled by the Oligo-Miocene as well as post-Miocene rift tectonics. The lithostratigraphic setting is represented by the Middle Eocene rock units represented by the Gebel Hof, Observatory and Qurn formations which are overlain by the Upper Eocene Maadi Formation. Bedding planes have dip values that range from 5°-12° and locally reaches 25° near fault planes.

Structurally, the area is mainly represented by rift-related normal faults which have steep dip angles and mean orientations of NW-, WNW- and NNW-trends. Structural analysis of fault arrays and linkage styles of hard- or soft-linked fault segments revealed five categories of transfer zones namely; relay ramps,

en echelon step faulting, linking folds, breached relay ramps and transfer faults. There is a vast agreement of similarity in the structural setting of G. Abu Treifiya SW area to that of other localities at CSD (e.g. G. Ataq, G. Akheidr, G. Umm Raqm). In addition, it is important to understand style of linkage different types of transfer zones that would be helpful to correlate with subsurface- and/or outcrop data related to rift regimes.

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