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Folding style as indicator for strike-slip fault zone deformation in Gebel Sufr El Dara area, Eastern Desert, Egypt

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ABSTRACT

Folds within fault zones are useful kinematic indicators in different tectonic settings. Detailed surface mapping and structural analysis of Gebel Sufr El Dara area, southwest Gulf of Suez rift, Egypt, demonstrate the presence of ENE-oriented asymmetric folds. This folding affected just the pre-rift rocks of the Paleozoic and Upper Cretaceous sediments. The syn-rift Early-Middle Miocene rock unit is not affected by this folding event. The kinematic analysis of this Cretaceous folding indicated that it was formed as a result of dragging within an ENE-oriented strike-slip fault zone. Palinspastic restoration showed that this folding event was commenced following the deposition of the Upper Cretaceous Matulla Formation as showed from the unconformity surface at the top of this formation. The culmination of this movement was active during the Campanian-Maastrichtian time as specified from growth folding where the thickness of this formation decreases towards the crestal part of the anticline of the folds.

1. Introduction

The kinematic history of Gebel Sufr El Dara area is complicated and controversial. As far as the authors are aware, the conventional fault-related kinematic indicators such as slickenlines and tension gashes are nearly absent. Therefore, it was important to find other kinematic indicators to interpret the deformation history of this area.

Folds in fault zones are ordinary structures that have a diversity of geometries and origins. These folds can offer important natural means to recognize the initiation and evolution of structures during the faulting process. The folds can be used to distinguish the sense of shear within the fault zone based on the geometry and rheology of the folded surfaces.

The folds within fault zones are represented by drag folds related to the sense of shear in the fault zone. These asymmetrical drag folds are possibly one of the mainly dependable kinematic indicators used for determining sense of shear within fault zones.

Gebel Sufr El Dara has well exposed rocks for studying the geometry of fault zones related folds. The intentions of this paper are to determine the geometry and kinematics of Gebel Sufr El Dara folding and its significance as a kinematic indicator. In order to get to this target, a detailed mapping using the satellite image of the area of scale 1:40,000, and scale of 1:10,000 whenever needed for more specified mapping of the key parts of the study area. This is substantiated by detailed field mapping to check and correct the positions of geological contacts and structures traced on the satellite images as well.

The Suez rift, where the study area is located (Figure 1A), is an intra-continental rift basin that initiated in the Late Oligocene to Early Miocene as the northwest extension of the Red Sea rift (Garfunkel and Bartov, 1977; Patton et al., 1994, Schütz, 1994; McClay et al., 1998; Bosworth and McClay, 2001; Sakran et al., 2016; Moustafa and Khalil, 2020). The Suez rift includes a number of rift blocks that extends more than a few tens of kilometers in length and width and comprises a group of smaller tilted fault blocks. It is dominated by NNW to NW-oriented faults bounding tilted fault blocks (Figure 1B). The Gulf of Suez was divided by Moustafa (1976) into three dip provinces (half-grabens). The northern and southern dip provinces are dominated by a SW dip polarity of the fault blocks, while the central dip province is characterized by a NE dip polarity. Structurally complex transfer zones divide these provinces (e.g., Moustafa, 1995), (Figure 1B).

Several exposed rift blocks on the eastern and western sides of the Gulf of Suez belong to the three half grabens stated previously. Gebel Sufr El Dara is located at the southwestern onshore part of the Gulf of Suez rift. It represents a tilted fault block situated at the central part of the Gharamul rift block (Figures 1B and 1C).

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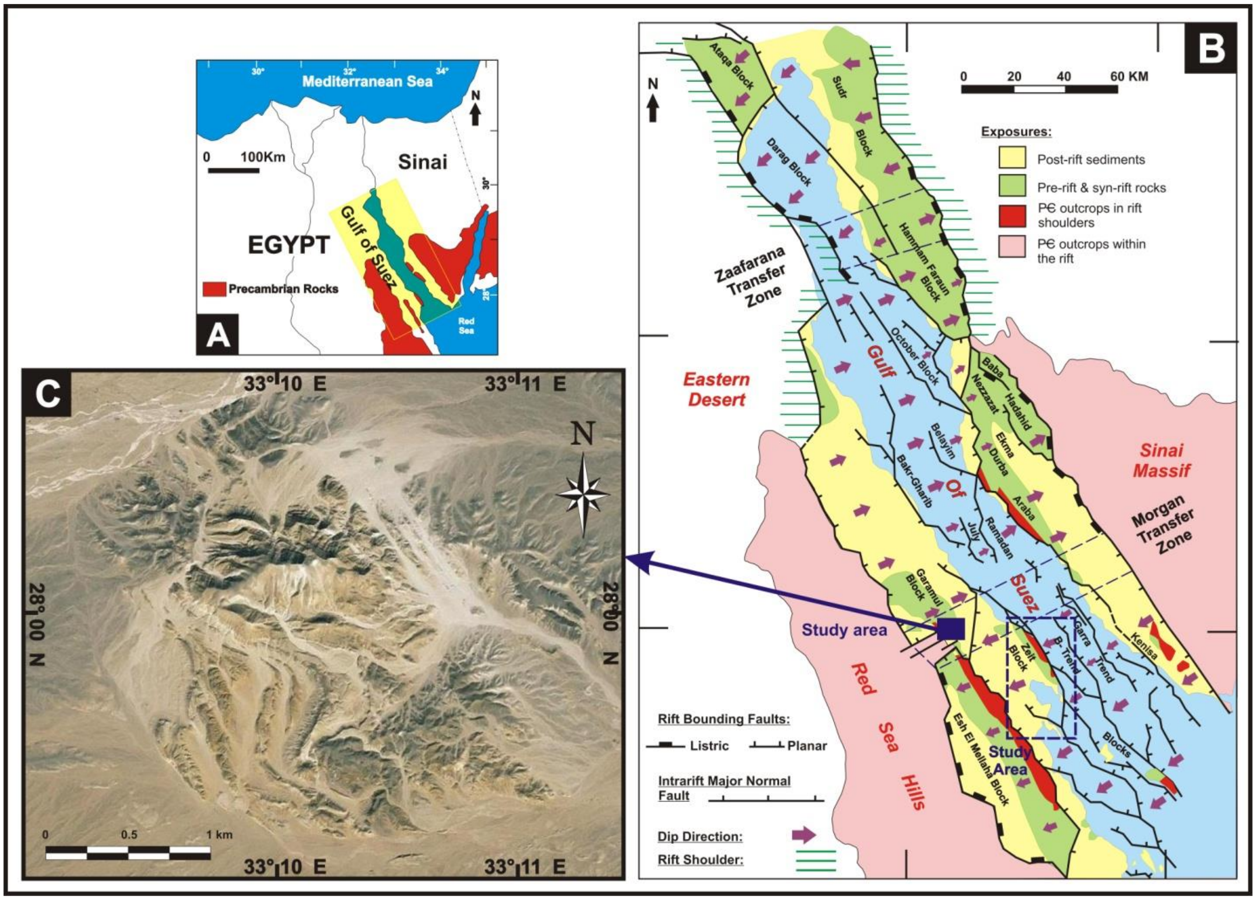

Figure 1: (A) Regional map showing northeastern Egypt and the location of the Gulf of Suez. (B) Map of the Gulf of Suez rift showing the tilted rift blocks, major normal faults and location of Gebel Sufr El Dara (after Moustafa, 2002). (C) Satellite image of Gebel Sufr El Dara.

Stratigraphy

The stratigraphy of the Gulf of Suez has been discussed by several workers. Studies have been oriented towards the facies and thicknesses of the different sedimentary sequences which have been affected by its complicated history. The stratigraphic setting of the Gulf of Suez basin is characterized by three major depositional stages relative to the rifting events Said (1962 and 1990), which are: pre-rift phase (Precambrian to Eocene); syn-rift phase (Early-Middle Miocene) and post-rift phase (Late Miocene to Recent). The pre-rift and syn-rift phases comprise significant hydrocarbon source and reservoir rocks while the post-rift phase is important due to its evaporitic seal. The main sedimentary successions were deposited under different structural settings on the Precambrian basement complex with different inter-and intraformational unconformities and hiatuses of diverse magnitudes. Essential works are those of Moon and Sadek (1923); Sadek (1959); Ghorab (1961); Said (1962, 1971 and 1990); Abdallah and Adindani (1963); Abdallah et al., (1963); Ismail (1991); Darwish (1992); Darwish and El Azabi (1993 and 1995); Sallam et al., (2015).

The measured stratigraphic section in the study area revealed that the outcropped rocks differ in age from Late Ordovician to Recent, (Figure 2). The oldest exposed pre-rift rock unit is represented by the Late Ordovician Naqus Formation (Said, 1971). It reaches 40 m thick and comprises medium to coarse-grained pale earthy yellow to brownish yellow sandstones. Sandstones of this formation are often well-sorted, massive, laminated, and occasionally cross-bedded of fluviatile regime. It represents a regressive marine cycle which terminated in the development of continental facies. The Naqus Formation is uncomformably overlain by the Cenomanian Raha Formation (Ghorab, 1961). It is around 60 m thick and composed of alterations of sandstones and shales of greenish gray to dark green color, but infrequently brown with ledges of limestone yielding microfossils and macrofossils (Exogyra olisponensis) and dissected by numerous gypsum veins. The recorded oyster beds in this formation indicate a shallow marine environment. The Raha Formation is conformably overlain by the Turonian Wata Formation (Ghorab, 1961), which attains 85 m thick and composed of fossiliferous white to yellowish white limestone and varicolored fissile sandy shale.

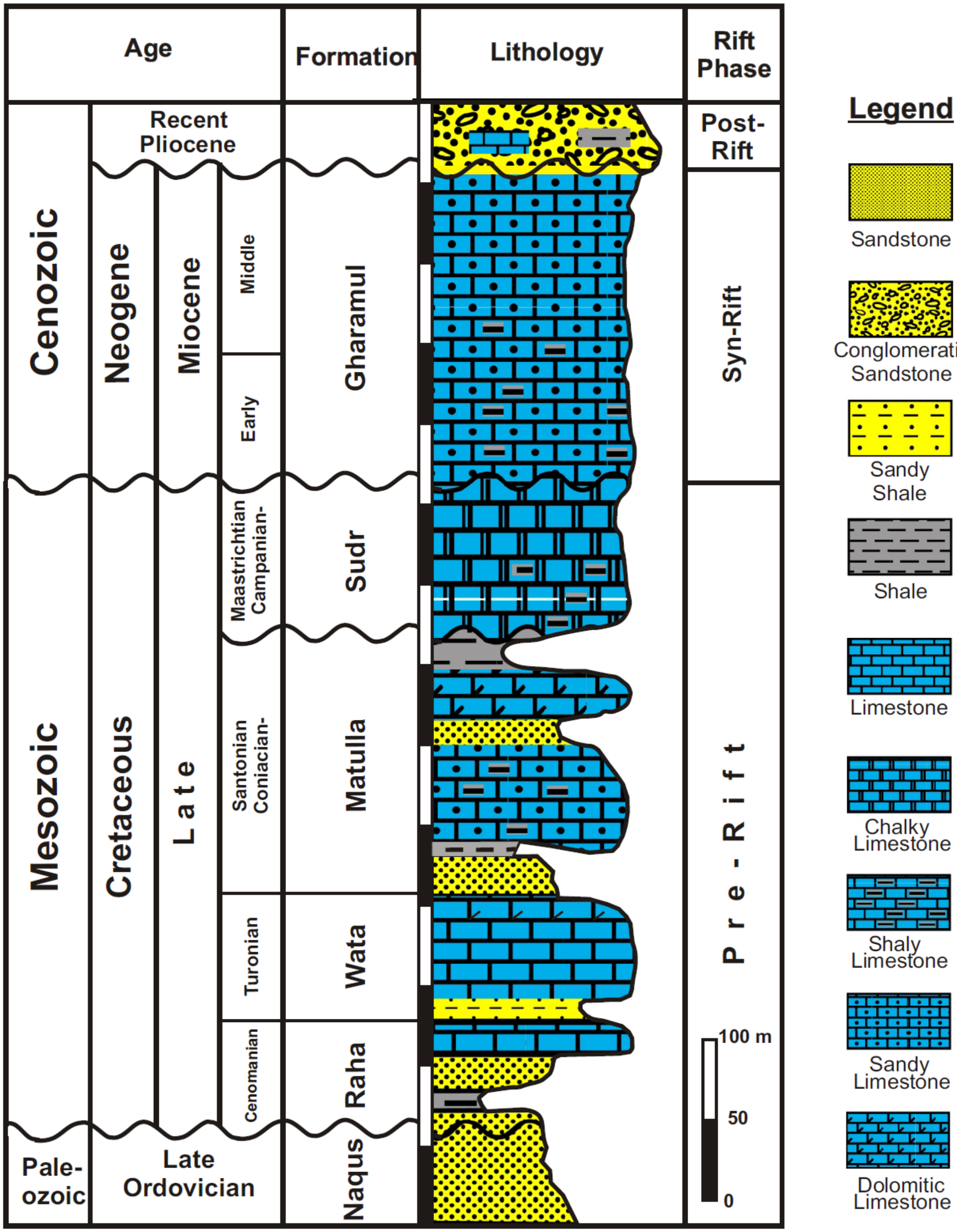

Figure 2: Measured stratigraphic section of Gebel Sufr El Dara.

The Wata Formation was deposited in a broad shallow intertidal-subtidal environment. It is overlain by the Coniacian-Santonian Matulla Formation (Ghorab, 1961). The Matulla Formation reaches 160 m thick and comprises cross-bedded, varicolored, fossiliferous sandstones, earthy to dark green gypsifirous shales and hard, fractured, unfossiliferous, yellow to yellowish brown dolomitic limestone. This formation was deposited in shallow marine environment. It is unconformably overlain by the Campanian-Maastrichtian Sudr Formation (Ghorab, 1961), which attains 100 m thick. The Sudr Formation is composed of massive, thick bedded, chalky limestone yielding microfossils (e.g. planktonic foraminifera) and macrofossils (Pychnodonta vesicularis). It shows deposition in deep marine environment.

The Sudr Formation is unconformably overlain by the syn-rift succession, Early-Middle Miocene, Gharamul Formation (Ghorab and Marzouk, 1967) which attains 250 m, thick. It is composed mainly of massive argillaceous limestone, interbedded with thinly-laminated algal stromatolite in parts. The argillaceous limestone is yellow to yellowish brown, moderately hard and sandy with chert concretion and bands interbeds, highly fossiliferous with corals, bivalves, small-sized gastropods, coralline red algae, algal stromatolites. The lithologic characteristics, faunal content and sedimentary structures of the Gharamul Formation, all indicate deposition in a restricted, shallow marine shelf (intertidal to shallow subtidal) environment under warm, arid climatic conditions.

Post-rift succession is represented by the post Miocene sequence which consists of shale, sandstone and few limestone beds and overlies uncomfortably the Early-Middle Miocene Gharamul Formation. Quaternary gravel terraces and wadi alluvium deposits cover the topographic low land.

Descriptive Analysis

Gebel Sufr El Dara is generally a tilted fault block restricted to the west by a major southwest dipping normal fault. The block is dipping generally towards NE direction (Figure 3). The pre-rift succession of Gebel Sufr El Dara is folded by two major folds, which are ENE-plunging anticline and syncline (Figure 4). The two folds extend for a distance of 1.3 Km in a N-S direction normal to the fold traces. The southern limb of the synclinal fold shows a series of small-scale folds restricted to the shaly beds of the Matulla Formation. The dip measurements collected from the Naqus, Raha, Wata and Matulla formations showed that the northern limb of the anticline is dipping at a range of 30°- 40° towards the NE direction whereas the southern limb is dipping at a range of 20°- 35° towards the SW direction. The southern limb of the syncline is dipping at 18° towards the NE direction. The interlimb angle of the anticlinal fold is 42° and for the synclinal fold is 28°. The Sudr Formation shows more gentle dip angles of the three limbs that range from 15° to 25°.

The pre-rift sequence is highly affected by faulting (Figure 3). It is dissected by three NW-SE striking normal faults (F1, F3 and F5), two NNW-SSE striking normal faults (F2 and F4), a NW-SE striking reverse fault (F7), an E-W striking reverse fault (F8), two WNW-ESE striking reverse faults (F6 and F9), and one small-scale left-lateral strike slip fault (F17).

The small-scale folds and reverse faults of NW, WNW and NE orientations are recorded in the shaly beds of the Matulla Formation. The reverse faults are oriented parallel to their accompanying folds. These structures are most probably related to the shale deformation (Figure 5).

The syn-rift Early-Middle Miocene Gharamul Formation is dissected by several normal faults striking WNW-ESE (F10), and NW-SE (F12, F13, F14, F15 and F16). It forms a WNW-ESE large-scale double plunging synclinal fold (Figure 6). The fold is asymmetrical fold where the northern limb of the anticline is dipping at an average of 20° towards the SSE direction and the southern limb is dipping at a range of 8°-15° towards the NNE direction.

Kinematic Analysis

The mapped folds in Gebel Sufr El Dara can be classified into three categories:

1. Large-scale ENE-oriented folds affecting the pre-rift sequence including Naqus, Raha, Wata and Matulla formations.

2. Small-scale folds of different orientations (NW, WNW and NE) restricted to the shaly layers of the Matulla Formation.

3. A gentle WNW-ESE oriented fold affected the syn-rift Gharamul Formation.

As aforementioned, the main objective of this paper is to determine the kinematics and mechanism of the large-scale ENE-oriented folds of the first category. The ending geometry, symmetry and orientation of these folds are used as kinematic indicators to find out the sense of movement along the associated faults. These folds are characterized by the asymmetric and is characterized by an anticlinal fold axis that trending 75° and plunging 25° towards the ENE direction. The synclinal fold axis is trending 62° and plunging 15° towards the ENE (Figure 7).

A symmetrical drag folds commonly occur in the interior of faults zones; these are very useful in evaluating the sense of simple shear movement during faulting. The vergence of asymmetric folds commonly reflects the sense of movement along associated faults. The asymmetrical folds when viewed downplunge, can be described as S-shaped or Z-shaped. The clockwise rotation that typifies asymmetric, Z-shaped drag folds reflect right-handed movement. The counterclockwise rotation that characterizes asymmetric S-shaped drag folds reflects left-handed movement.

The above-mentioned characteristics reveal that these folds may be related to right-lateral fault zone deformation rather than to pure compression. Such folds are described by many authors (Carey, 1962; Graham, 1978; Manz and Wickham, 1978; Simpson and Schmid, 1983; White et al., 1986; Carreras and Casas, 1987; Choukroune et al., 1987; Bjornerud, 1989; Suppe and Medwedeff, 1990; Hanmer and Passchier, 1991; Hudleston and Lan, 1993; Passchier, 2001; Grasemann and Stüwe, 2001; Grasemann et al., 2003; Carreras et al., 2005).

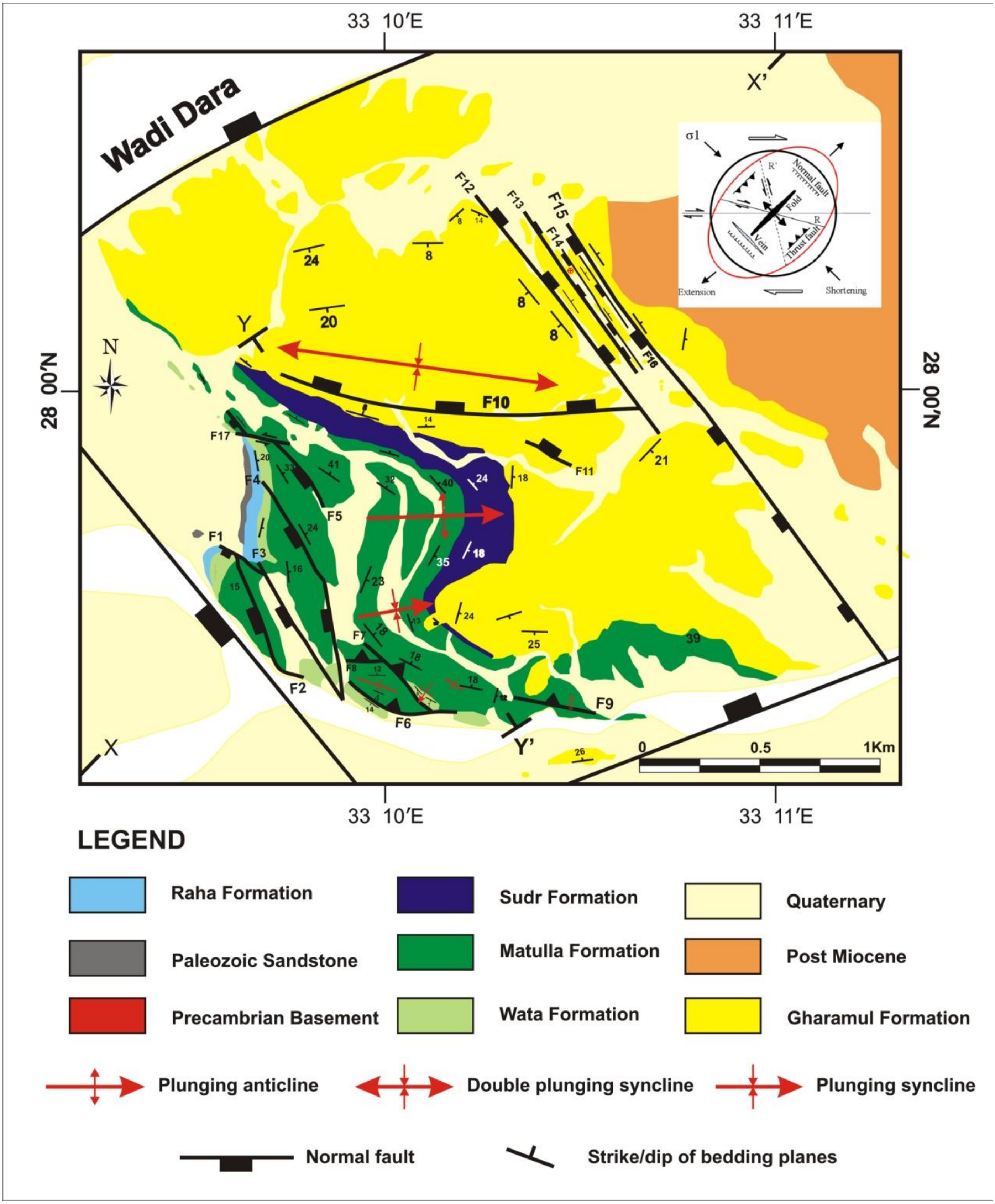

Figure 3: Constructed geological map of Gebel Sufr El Dara.

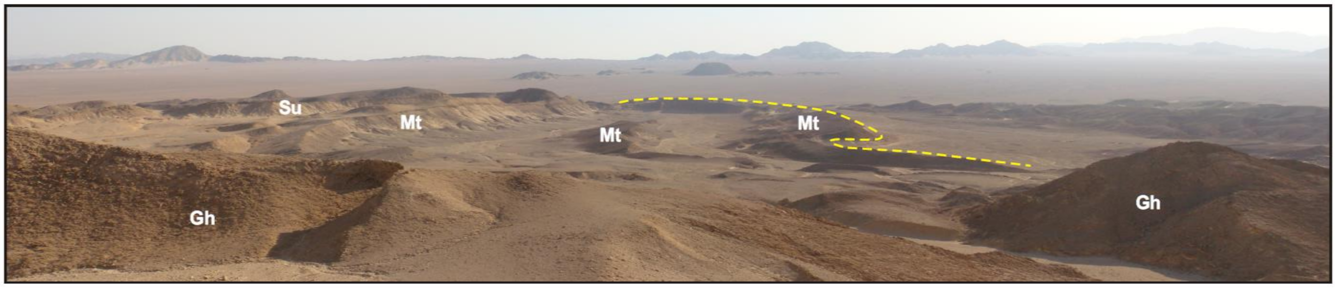

Figure 4: Panorama showing the folding affecting the Upper Cretaceous sediments of Gebel Sufr El Dara.

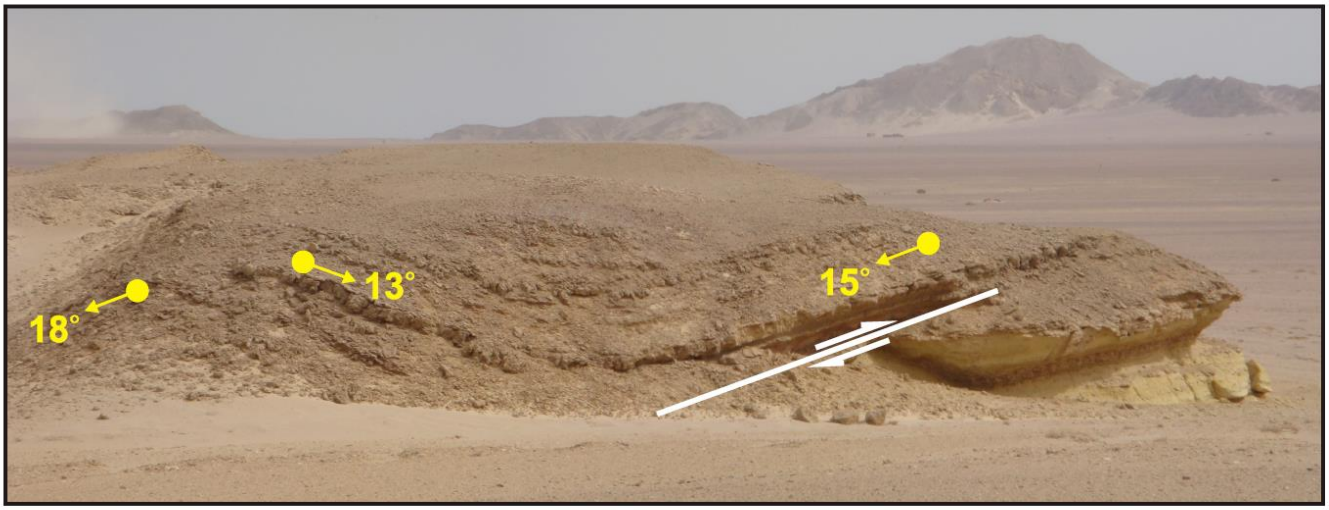

Figure 5: Folding in the form of small-scale anticline and syncline folds. The syncline fold is associated with a small-scale reverse fault affecting the shaly beds of the Matulla Formation.

Figure 6: General view of the synclinal fold affecting the Gharamul Formation (Gh) of Gebel Sufr El Dara, looking towards the ESE direction.

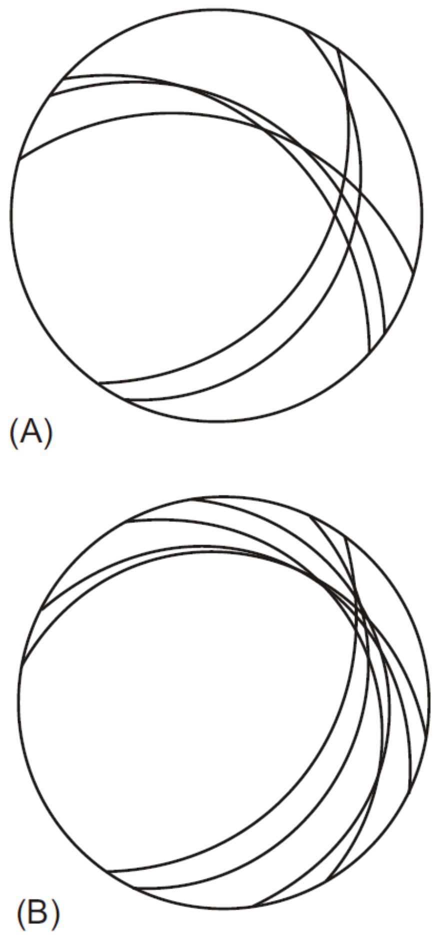

Figure 7: Stereoplot of the (A) anticline and (B) syncline folds of Cretaceous folding.

In order to construct the kinematic history of Gebel Sufr El Dara folding, two cross-sections were constructed and palinspastically restored (Figure 8) and used to build schematically the palinspastic maps of the Gebel Sufr El Dara folding during its different stages of formation (Figure 8). The method used is the overlay manual restoration method. It is assumed that the deformation is a rigid body deformation without significant internal strain. Any change in the dimension of the restored block is supposed to be related to the effect of compaction. The kinematic history of the normal faults related to the Gulf of Suez rifting is not considered in this restoration.

The restoration to the top of the Matulla Formation is schematically represented in Figure 8. According to the paleogeographic map of the Coniacian-Santonian Matulla Formation (Guiraud and Bosworth, 1999) it is supposed that the primary dip during the deposition of this formation was 5° towards the north direction (Figure 8A).

The initial stage of the folding was formed after the deposition of the Matulla Formation as indicated from the unconformity surface at the top of the Matulla Formation as well as the insignificant variation in the thickness of this formation in the study area as well as the neighboring areas. As mentioned in the foregoing, this folding is related to right-lateral simple shear deformation (Figure 8B).

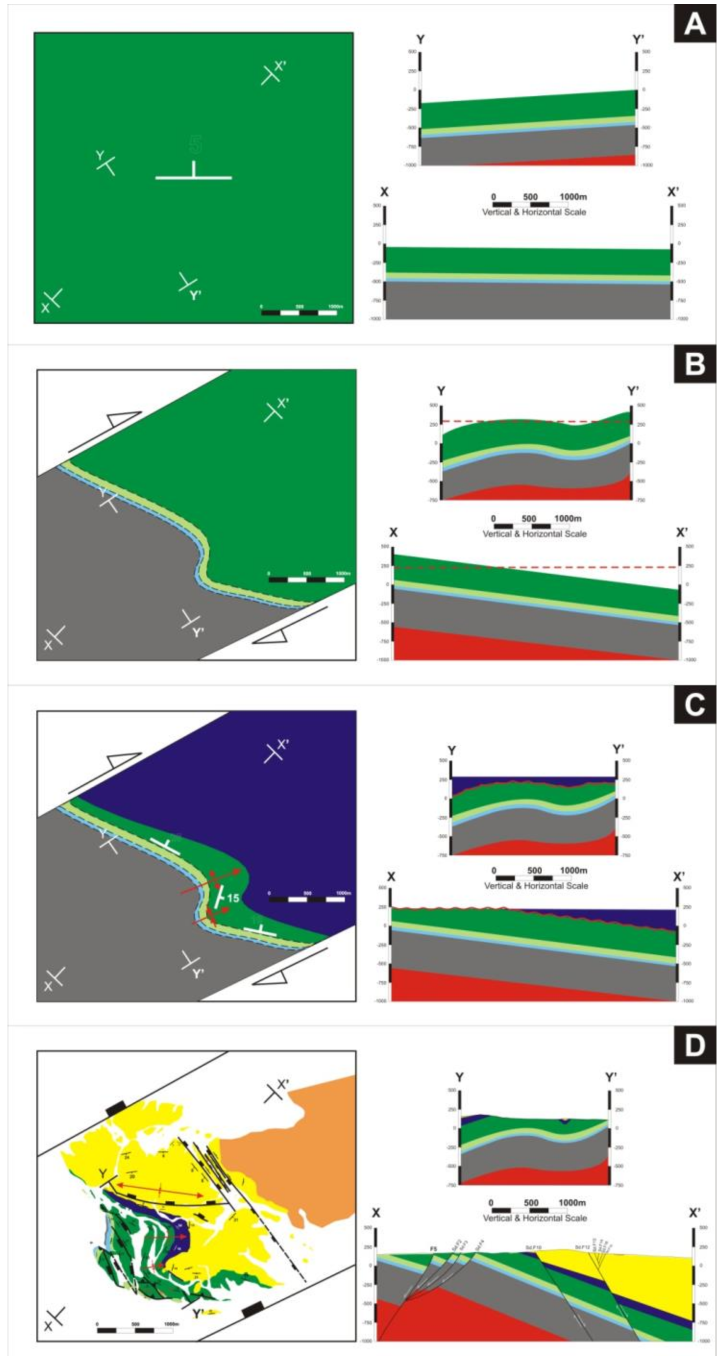

Figure 8: (A) Restoration to the top of the Matulla Formation showing a gentle 5° dip towards the North. (B) Palinspastic construction during the initial stage of folding. The dashed lines represent a proxy for the erosion surface after the folding event. (C) Restoration to the top of the Sudr Formation showing the growth folding and the angular unconformity between the Matulla and Sudr formations. (D) The final stage after the rifting event. Dashed lines in maps B and C represent that the associated formations are still not outcropped. For legend see Figure 3.

The restoration to the top of the Sudr Formation revealed that there is a general decrease in the thickness of this formation towards the crestal part of the anticlinal fold. This feature characterizes growth folds that were developed during deposition. This may indicate that the culmination of the right-lateral movement was active during the Campanian-Maastrichtian (the time of deposition of the Sudr Formation), (Figures 8C and 8D).

Discussion and Conclusions

Moustafa and Fouda (1988) interpreted the sense of movement on the fault zone affecting Gebel Sufr El Dara as a left-lateral movement. Their interpretation based on the small-scale reverse faults and their associated folds affecting the Matulla Formation. However, according to the present study these small-scale reverse faults and their associated small-scale folds were non-tectonic structures formed as a result of deformation of the shaly beds of the Matulla Formation. For that reason, these structures cannot be used as kinematic indicators. Also, their interpretation was based on the NW-SE reverse faults that according to the detailed field investigation were not found. Instead, the detailed field study revealed that these NW-SE reverse faults are normal faults.

In conclusion, the present study revealed that the folding of Gebel Sufr El Dara indicates dragging within an ENE-oriented right-lateral strike-slip fault zone bounding Gebel Sufr El Dara. The small-scale reverse faults and their associated small-scale folds were a result of shale deformation of the shaly beds of the Matulla Formation.

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