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Structural setting and tectonic evolution of the northern Hammam Faraun Block (Wadi Wasit-Wadi Wardan area), eastern side of the Suez rift

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ABSTRACT

The Wadi Wasit-Wadi Wardan area (the northern part of the Hammam Faraun Block) lies on the eastern side of the Suez rift between oppositely-tilted half grabens. Detailed field mapping of the block indicates that the pre-rift and syn-rift rocks are deformed by N- to WNW-oriented normal faults and subordinate folds related mainly to the movement on nearby faults. The block can be divided structurally into three NNW-oriented sub-blocks, the middle one of which is a large graben, whereas the eastern one defines a rollover on the downthrown side of the listric rift-bounding fault.

Seven deformations affected the Hammam Faraun Block, the earliest of which (D1, Early Eocene) was associated with pre-rift "Syrian arc" folding. Oligocene deformation (D2) affected the southernmost part of the block and is probably related to the local uplift at the late stages of "Syrian arc" deformation. Early opening in the Suez rift (D3) was associated with basaltic volcanicity conformable with the underlying pre-rift rocks. Deformations D4 through D6 are directly related to continued opening and evolution of this rift. The D4 event is related to the change from slow to rapid subsidence. A mid-rift (Mid-clysmic) event (D5) led to structural reorganization of the rift associated with uplift of the rift shoulder and deposition of fan conglomerates at the footslopes of fault scarps. Mild, late rift faulting marks the D6 event. Quaternary movements of a local nature (D7) formed minor normal faults and are probably related to local, non-tectonic readjustment above subsurface faults.

The tectonic events of the Hammam Faraun Block indicate the transition from "Syrian arc" folding (related to the convergence between Africa and Eurasia due to the closure of the Neotethys) to the early stages of crustal separation between Africa and Arabia (leading to the opening of the Suez and ancestral Red Sea rifts). The onset of rifting is marked by a phase of Early Miocene volcanicity. Rift tilting followed this volcanicity and is related to the displacement on the listric normal faults at the rift boundary. Half grabens of the rift are marked by major, conjugate, steeply dipping breakaway faults at both sides. A listric fault marks one side and a planar fault marks the other side of each

INTRODUCTION

The Hamman Faran Block lies in the northeastern part of the Suez rift in west-central Sinai. It is elongated in the NW direction for about 65 km and extends from the Markha plain to Wadi Wardan (Fig. 1). This rift block is one of several exposed on the eastern side of the Gulf of Suez. It lies at the transition between the NE-dipping blocks to the south and the SW-dipping blocks to the north.

LOCATION OF THE HAMMAM FARAUN BLOCK IN THE SUEZ RIFT

The Suez rift is a currently inactive continental rift between the Sinai microplate ond the African plate. Both the Suez rift and the Red Sea formed a continuous, NW oriented continental rift at the early stages of separation between Africa and Arabia. The opening of the Suez rift started in the Oligocene (Robson 1971), Oligo-Miocene (Garfunkel & Bartov 1977), or Early Miocene (Moustafa 1993). Sea floor spreading in the Red Sea started in the Pliocene (Cochran 1983) when the movement on the Dead Sea Transform aborted extension in the Suez rift. The latter was left as a failed arm as indicated by the lack of significant post-Miocene extension.

Like other rift basins, e.g. the East African rifts: (Rosendahl *et al.* (1986); Morley *et al.* (1990); and the NE Brazilian rift system (Matos 1992)), the Suez rift includes several half grabens of opposite tilt directions (Moustafa 1993). Three half grabens exist in the Suez rift and occupy its northern, central, and southern parts. SW dip characterizes the northern and southern half grabens whereas NE dip characterizes the central half graben (dip provinces of Moustafa 1976). Each half graben includes several rift blocks tilted in the same direction as their parent half

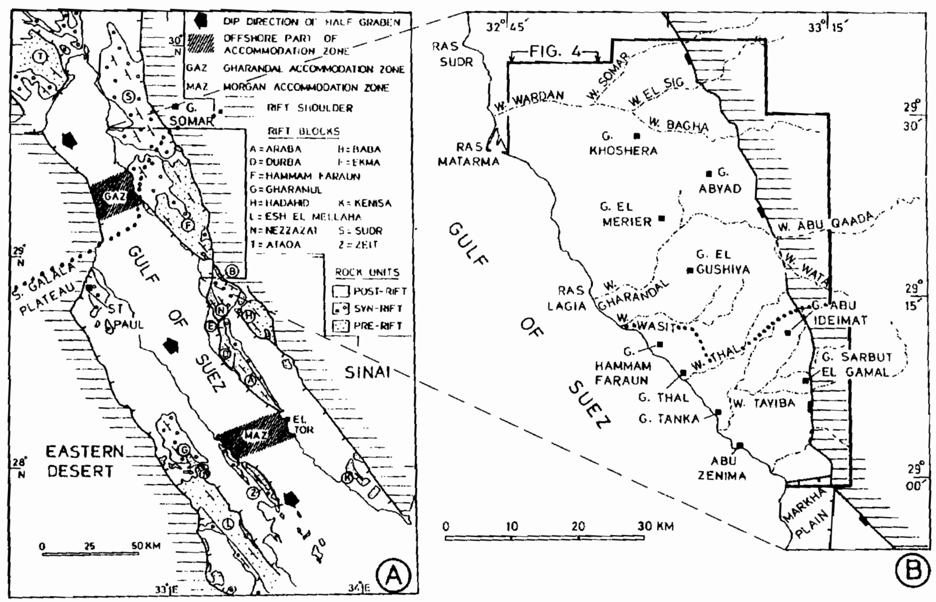


Fig. 1. (a) Location map of the Hamman Faraun Block and its relationship to other rift blocks and the half

graben. A rift block is defined as an area with a group of second-order (relatively small) fault blocks which is separated from adjacent rift blocks by major faults (Moustafa 1993).

Significant parts of the three half grabens of the Suez rift are exposed on the eastern and western sides of the Gulf of Suez, namely in west Sinai and the Eastern Desert of Egypt respectively (Fig. 1a). The SW-dipping Sudr Block is exposed on the north-eastern side of the Gulf of Suez and is the easternmost rift block of the northern half graben. Also, the Araba, Durba, Ekma, Nezzazat, Baba, and most of the Hammam Faraun Blocks are NE-dipping rift blocks exposed on the east side of the Gulf of Suez and belong to the central half graben. The Gharamul Block is another NE-dipping rift block that belongs to the central half graben and is exposed on the western side of the Gulf of Suez at Gebel Gharamul. The Kenisa Block that lies on the southeast side of the Gulf of Suez, as well as the Zeit and Esh El Mellaha Blocks which lie on the southwest side of the Gulf of Suez, are SW-dipping rift blocks that belong to the southern half graben. Excellent exposures of these rift blocks on both sides of the Gulf of Suez offer good opportunities for studying the structural characteristics and tectonic evolution of the rift. Such surface studies are important for hydrocarbon exploration in the offshore part of the Gulf of Suez where subsurface information depends on the quality of seismic reflection data. Seismic information about rocks and structures underlying the syn-rift evaporites are always difficult to obtain due to the seismic energy attenuation and multiples created by these evaporites.

OBJECTIVES OF THE PRESENT STUDY

In their study of the structural setting of the Hammam Faraun Block, Moustafa & Abdeen (1992) mapped the southern part of the block (from the Markha plain to Wadi Wasit). The present study is directed toward mapping the northern part of the block from Wadi Wasit to Wadi Wardan in order to study the structural setting and tectonic evolution of the whole block and its relationship to the surrounding rift blocks, especially the Sudr Block which lies to the north of Wadi Wardan (Fig. 1). In this direction, the dip changes from NE in most of the Hammam Faraun Block to SW in the Sudr Block. The structural data collected during the mapping of the present study as well as those of Moustafa & Abdeen (1992) are the basis for the structural analysis and interpretation given in this paper. Field mapping at a scale of 1 : 40,000 was accomplished for an area of about 1700 km^2. The geologic map was compiled on a topographic base of scale 1 : 50,000 and was later reduced to the scale shown in Plate 1. Structural cross sections of the mapped area are shown in Plate 2.

STRATIGRAPHY

The mapped rocks of the Hammam Faraun Block include pre-rift (Pre-Miocene), syn-rift (Miocene), and post-rift (Quaternary) sequences (Fig. 2). A recent compilation of the stratigraphy of the Suez rift is given by Darwish & El-Araby (1993).

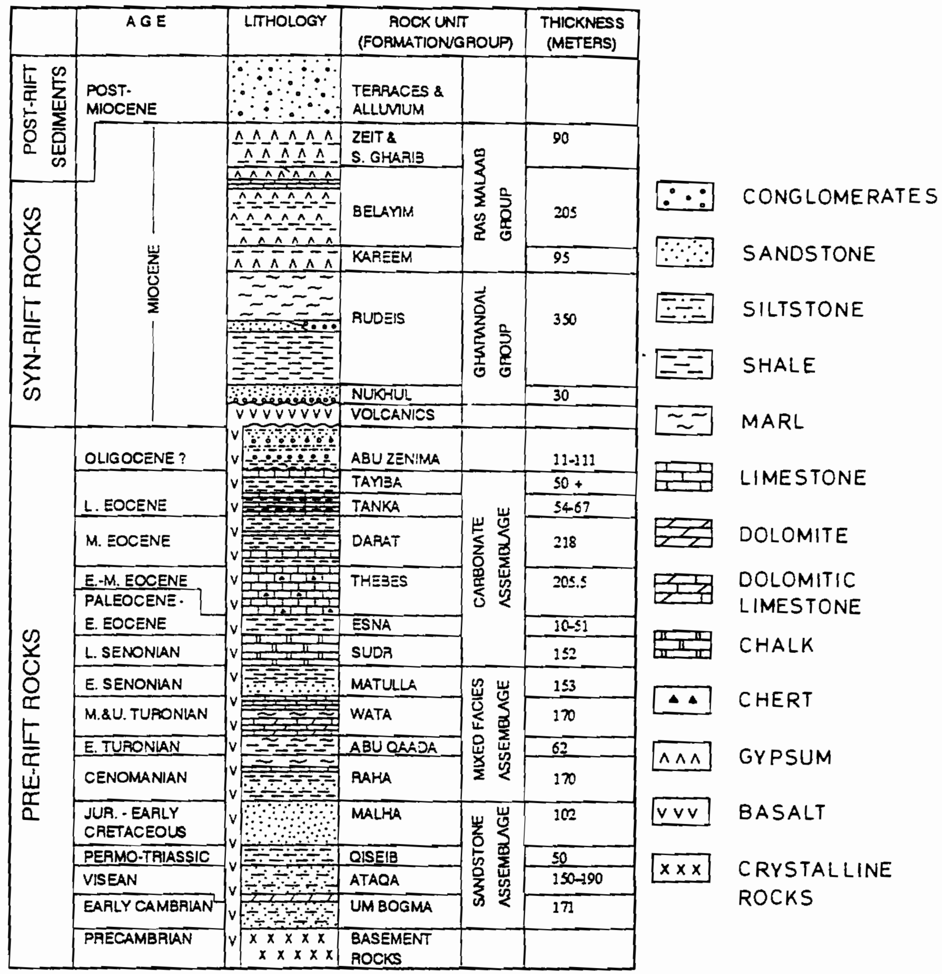


Fig. 2. Composite stratigraphic section of the Hammam Faraun Block based on the results of the present mapping and those of Moustafa & Abdeen (1992).

from base to top, into a sandstone assemblage, a mixed facies assemblage, and a carbonate assemblage.

(A) Sandstone assemblage

The sandstone assemblage includes Paleozoic sandstone (Um Bogma and Ataqa Formations), a Permo-Triassic siltstone unit (Qiseib Formation), as well as a Jurassic-Lower Cretaceous sandstone unit (Malha Formation).

The Um Bogma and Ataqa Formations (Said 1962) are 361 m thick. The Um Bogma Formation consists of a sandstone unit capped by a thin dolomite-limestone section. The sandstones are fluvial to near-shore marine (Klitzsch & Wycisk 1987) has a Visean age (Klitzsch & Wycisk 1987, Klitzsch 1990) and is composed of sandstone interbedded with thin kaolinitic claystone and carbonaceous shale with abundant plant remains (Ball 1916). A 20 m thick olivine basalt sill of wide geographic distribution in the rift (Moustafa & Yousif 1993) occurs near the top of this formation in Um Bogma area and is 178 ± 12 Ma old (Weissbrod 1969) or 233–243 Ma old (Moussa 1987; Roufaiel *et al.* 1989).

The Qiseib Formation (Permo-Triassic age, Abdallah *et al.* (1963)) is made up of brick-red and purple siltstone. It is 327 m thick (Weissbrod 1969) in Wadi Budra (about 12 km southeast of the Hammam Faraun Block) but decreases in thickness northwards to about 50 m on the rift shoulder against the southern part of the Hammam Faraun Block.

The Malha Formation (Jurassic-Early Cretaceous age, Abdallah *et al.* (1963)) consists of white kaolinitic sandstone with some commercial kaolinite beds. It is 102 m thick in Gebel El Akhal (Plate 1), Haight (unpublished data).

(B) Mixed facies assemblage

The mixed facies assemblage includes the Raha (Cenomanian), Abu Qaada and Wata (Turonian), and Matulla (Lower Senonian) Formations (Ghorab 1961).

Akarish (1990) subdivided the Cenomanian-Turonian section of Gebel Hideib El Gamal (see Plate 1 for location) into the Raha, Abu Qaada, and Wata Formations. The Raha Formation (Cenomanian) consists of shale, marl, limestone, and dolomite with sandstone beds at the base. The Abu Qaada Formation (Lower Turonian) consists of varicolored shales and marls with a few limestone beds. The Wata Formation (Middle and Upper Turonian) is composed of a lower cliff-forming, massive dolomitic limestone unit, a middle soft shale and marl unit, and an upper well-bedded limestone and chalky limestone unit. The cumulative thickness of the Raha, Abu Qadda, and Wata Formations exceeds 302 m on the Tih scarp (47 km ESE of Gebel Hamman Faraun), Haight (unpublished data) and is 375 m thick at Gebel El Akhal (Fournier, unpublished data).

The Matulla Formation (Early Senonian age, Ghorab (1961)) includes a basal sandstone and siltstone unit (58 m thick) and an upper shale unit (95 m thick).

(C) Carbonate assemblage

The mixed facies assemblage is overlaid by a thick Late Senonian to Oligocene carbonate unit (limestone and chalk with some claystone, siltstone, and a few sandstone beds). This assemblage includes, from base to top, the Sudr Formation, Esna Shale, Thebes Formation, Darat Formation, Tanka Formation, Tayiba Formation, and Abu Zenima Formation.

The Sudr Formation (Late Maastrichtian age, Ghorab (1961)) is made up of snow-white massive chalk. It includes a thin conglomerate bed with fish and shell fragments at the base (Haight, unpublished data).

The Esna Shale (Paleocene-Early Eocene age) is made up of greensish gray shale. It is 51 m thick at Wadi Matulla, the southern part of the Hammam Faraun Block (Moustafa & Abdeen 1992), but decreases in thickness to 10 m in the northern part of the mapped area.

The Thebes Formation is Early-Middle Eocene and includes a lower unit (140 m equivalent to both the Darat and Khaboba Formations of Viotti & El-Dermerdash (1969).

The Tanka Formation (Tanka Beds of Hume *et al.* 1920) is made up of thin, interbedded, white, chalky limestone and yellow marl and marly limestone. This formation had Middle Eocene (El Heiny & Morsi 1986) or Late Eocene age (Viotti & El-Demerdash 1969; Strougo & Hamza 1989; Abul-Nasr 1990). It is 54 m thick in the mapped area, 67 m thick in Wadi Thal, and completely eroded in the southernmost part of the Hammam Faraun Block (Wadi Nukhul area).

An upper Eocene section (Tayiba Formation) is well exposed in the northernmost part of the Hammam Faraun Block at El Haleifiya area (Plate 1) and was reported before by Farag & Shata (1957) and Strougo & Hamza (1989). It is at least 60 m thick and is made up of highly fossiliferous brown to reddish-brown claystone with several limestone ledges. The Upper Eocene beds of El Haleifiya area belong to the "Red Beds" unit of Hume *et al.* (1920) and Moon & Sadek (1923, 1925) which was named the Tayiba Formation by Abul-Nasr (1990) following Youssef & Abdelmalik (1972).

The Abu Zenima Formation (Hanter 1965) unconformably overlies the Tayiba Formation, Tanka Formation, or older Eocene units. Its age is Oligocene (Ansary 1955) or questionable Oligocene (Viotti & El-Demerdash 1969). It consists of red fluvial sandstone and claystone with several conglomerate beds and was informally named the "Clastic Red Beds" by Abul-Nasr (1990) to differentiate it from the Upper Eocene Tayiba Formation. Its thickness changes from 111 m in the southernmost part of the Hammam Faraun Block to 11 m in its northern part.

SYN-RIFT ROCKS

Syn-rift (Miocene) rocks in the Hammam Faraun Block include early rift volcanics in addition to clastics and evaporites.

(A) Miocene volcanics

Syn-rift basalts in the Hammam Faraun Block occur as dikes, sills, and flows. They have been dated as Early Miocene by the K–Ar method (22–24 Ma old; Steen 1984; Moussa 1987) and are abundant in the southern part of the block (Moustafa & Abdeen 1992).

Two main basalt dikes exist in the east-central part of the mapped area and join together to the south of Wadi Abu Qaada. They are oriented WNW–ESE to NW–SE and NNE–SSW where the former dike continues outside the mapped area (Bartov *et al.* 1980, Geologic Map of Egypt 1981). A third dike, orinted NNE–SSW, occurs to the west of Gebel El Ratama, while a basalt sill exists northwest of Gebel El Gushiya and a 10 m thick basalt flow is found south of the mouth of Wadi Wasit.

(B) Miocene clastics

The Miocene clastics represent the lower syn-rift sedimentary unit in the Hamman Faraun Block. It includes the Nukhul Formation at the base which

Thiebaud & Robson (1979) equated these three units with the Rudeis Formation (EGPC 1964).

About six kilometers SE of the southern side of Gebel El Gushiya, a downlapping unit of chert conglomerate occurs in the stratigraphic position of the Miocene Grits (Fig. 3). These conglomerates downlap the Miocene Clays and their forests show westward current direction, i.e. toward the axis of the Miocene rift. Similar conglomerates were reported at the southern end of Gebel El Gushiya (Sadek 1959), and others were mapped at Gebel El Iseila (Moustafa & Abdeen 1992), Wadi Baba (Moustafa 1987), and Wadi Sudr (Patton *et al.* 1994). All these conglomerates were deposited close to the eastern rift bounding fault during the deposition of the Rudeis Formation. They could have been deposited as submarine fan deltas (Einsele 1992) similar to the Gilbert-style deltas (Gilbert 1891) in a restricted marine setting, Gilbert-style lacustrine deltas, or subaerial alluvial fans or wedges. They mark a major tectonic event in the history of the Suez rift (the mid-clysmic event of Garfunkel & Bartov 1977).

(C) Miocene evaporites

A relatively thick section of Miocene evaporites overlies the Miocene clastics of the Hammam Faraun Block and consists of several thick gypsum beds interbedded with green marls and claystone. Close to the top of this section is a 50 m thick white, porous, highly fossiliferous limestone unit (Nullipore rock of Moon & Sadek (1923)). Thiebaud & Robson (1979) applied the EGPC's (1964) Miocene units nomenclature to this evaporites section.

POST-RIFT DEPOSITS

Post-rift deposits in the Hammam Faraun Block are Quaternary in age and include alluvial deposits and gravel terraces.

STRUCTURES

The Hammam Faraun Block is dissected by a large number of normal faults. Folding also plays a role in the structural deformation of this block, though its effect is not as significant as that of the faults.

FAULTS

A total of 370 normal faults have been mapped in the Hammam Faraun Block (Fig. 4). Some of these faults form the western, southern, and eastern boundaries of the block whereas others occur within the block itself. The Hammam Faraun Fault bounds the block on the southwest and extends northwestward to Ras Lagia (Plate 1 & Fig. 5). According to Patton *et al.* (1994), the Hammam Faraun Fault extends offshore in the same direction for some distance before it dies out. The maximum amount of throw on this fault is 4800 m (Moustafa & El Shaarawy 1987). It consists of several segments oriented NW and NNW (Plate 1 and Figs. 4 & 5). Another major fault forms the southern boundary of the Hammam Faraun Block (the Markha Fault) and generally trends N80°E. It consists of several segments oriented ENE, E–

Fig. 3. (a)

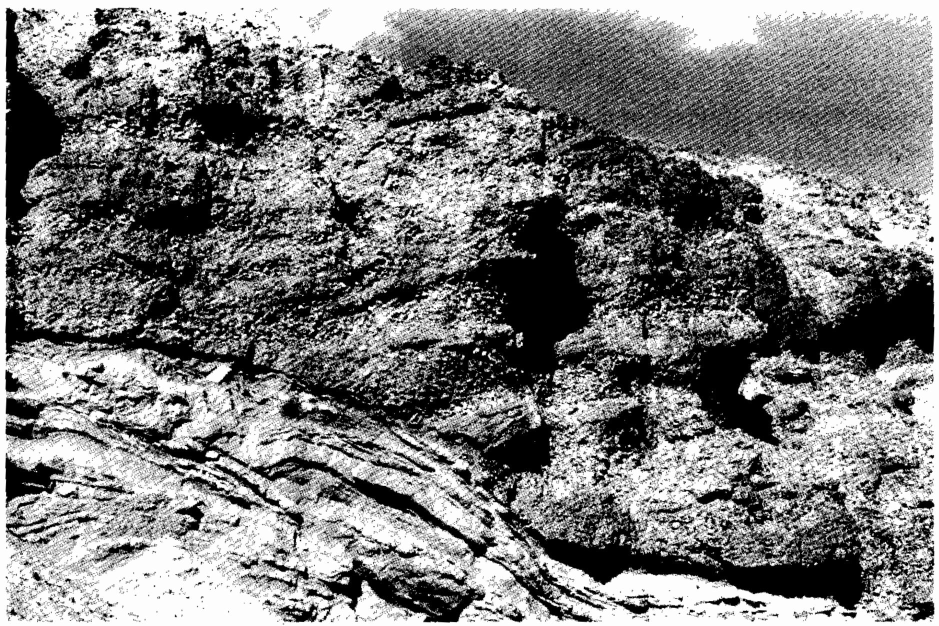


Fig. 3. (b)

Fig. 3. (a) Field photograph of downlapping Miocene fan conglomerates overlying the lower Rudeis

Fig. 3. (c)

Fig. 3. (c) Close-up view of the easternmost part of the Miocene conglomerate of the same area where it overlies the Miocene clays (lower Rudeis) and is itself overlaid by beds of the Miocene marls (upper Rudeis). Notice the slight angular discordance between the conglomerate beds and the underlying claystone beds in the lower left-hand part of the photo.

southeastern part of the block (Moustafa & Abdeen 1992). The rift-bounding fault is discontinuous and is divided into two parts, one in the southeastern part of the block and the other in the northeastern part. The east-central part of the block that lies to the northwest of Ras Um Maghrab is not bounded by a down-to-the-west fault but by a west-facing monocline (Plate 1 and Figs. 4 & 5). The throw on the northeastern part of the rift-bounding fault has a maximum amount of 1250 m (Fig. 5 & Plate 2, cross section B–B′). The rift-bounding fault consists of several segments oriented NW to NNW and N–S to NNE (Plate 1 and Figs. 4 & 5).

In addition to the major fault segments forming the eastern, southern, and southwestern boundaries of the Hammam Faraun Block, many faults dissect the block itself into smaller tilted fault blocks (Fig. 5). The largest throw on these intra-block faults is 1100 m in the southernmost part of the block (north of the Markha Fault) and 800–900 m on the westernmost fault of the Gebel Abyad tilted fault blocks (Fig. 5 and Plate 2, westernmost fault in cross section B–B′). The major intra-block faults divide the northern part of the Hammam Faraun Block (north of Wadi Gharandal-Wadi Abu Qaada) into three large, NNW oriented fault blocks. These are a NE-tilted block on the east, a central graben, and a SW-tilted block on the west. They form a large crustal rollover on the downthrown side of the listric rift-bounding fault in the northern part of the mapped area (Plate 2; cross sections A–A′, B–B′, and C–C′). These three fault blocks are equivalent to parts of the eastern, central, and

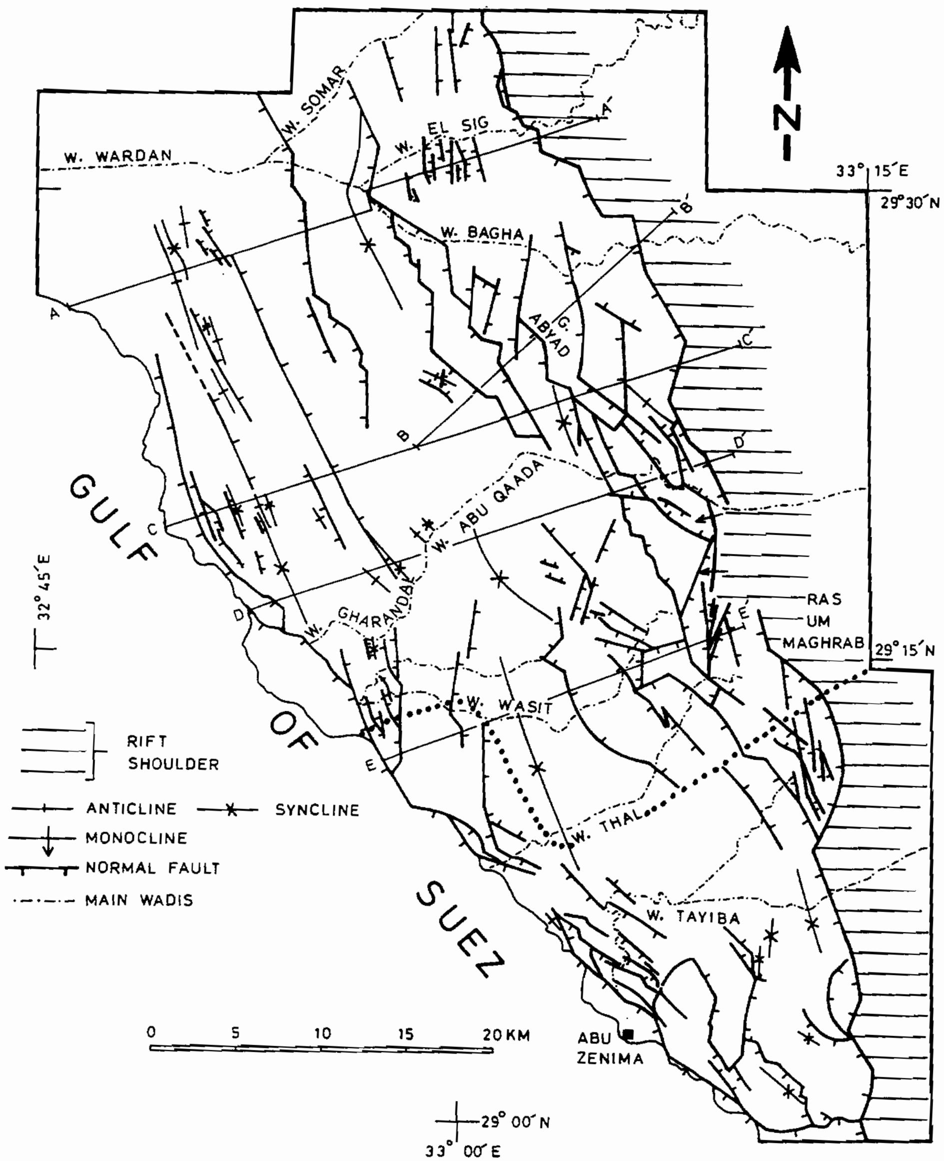


Fig. 4. Simplified structural map of the Hammam Faraun Block. Dotted line separates the area mapped in the present study (Plate 1) from that mapped by Moustafa & Abdeen (1992), sosuth of the line. Cross sections A–A′ through E–E′ are shown in Plate 2.

Detailed structural study of the Hammam Faraun Block (Plate 1 and Figs. 4 & 5) indicates that the faults of the N0–60°W set belong to several subsets including a NNW–SSE subset (most common) as well as NW–SE and N–S subsets. A few faults are also oriented NNE–SSW but are too few to make a distinctive peak in Fig. 6. The

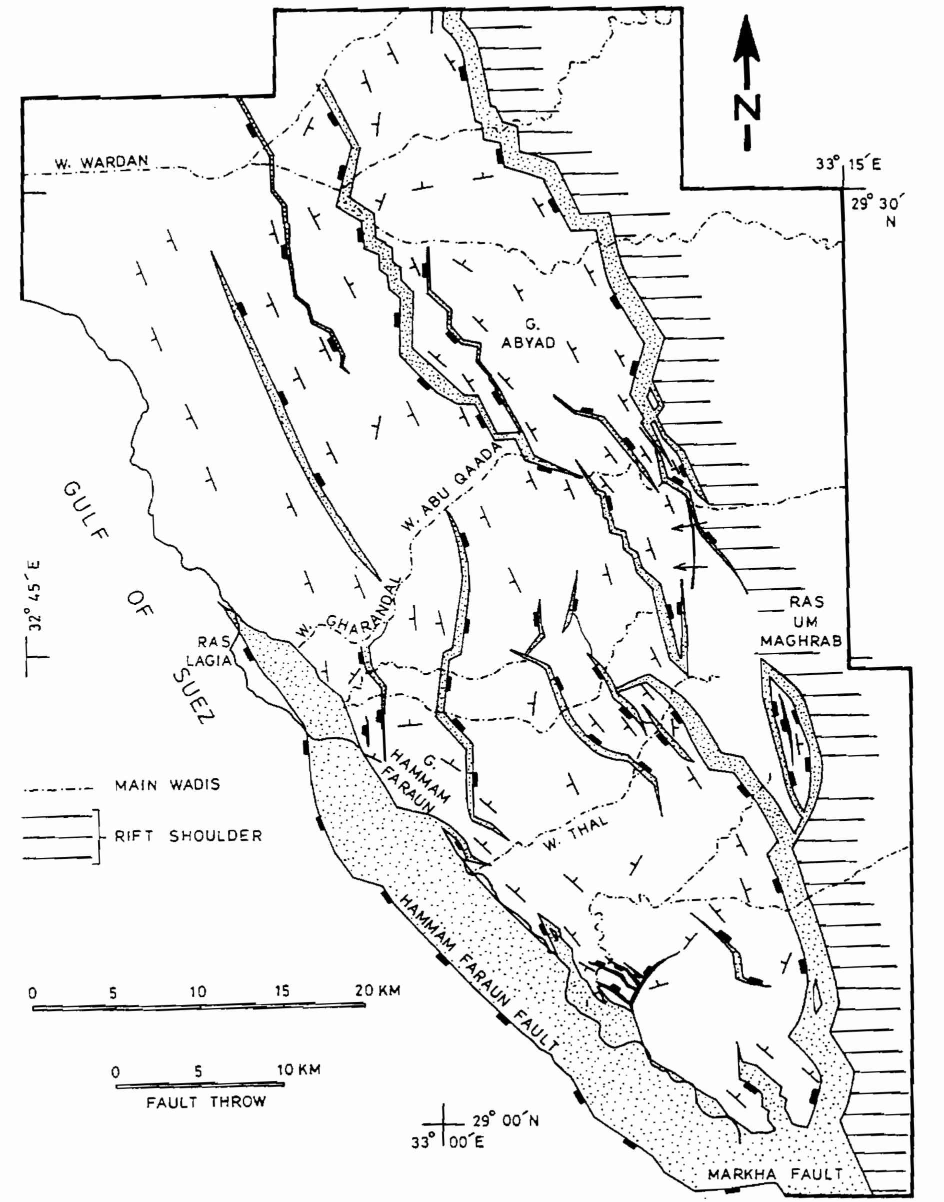


Fig. 5. Main faults dissecting the Hamman Faraun Block (throw equal to or exceeding 200 m). The spacing of the two lines marking each fault is proportional to its throw according to the fault-throw bar scale shown beside the map.

Most of the faults mapped in the blcok show pure dip-slip (normal) displacement but a few show a subordinate strike-slip component. The latter mainly include the listric as indicated by the NE dip of the downthrown block against this fault (e.g. Plate 2, cross sections A–A′ and B–B′ as well as Moustafa & Abdeen's 1992 cross sections).

FOLDS

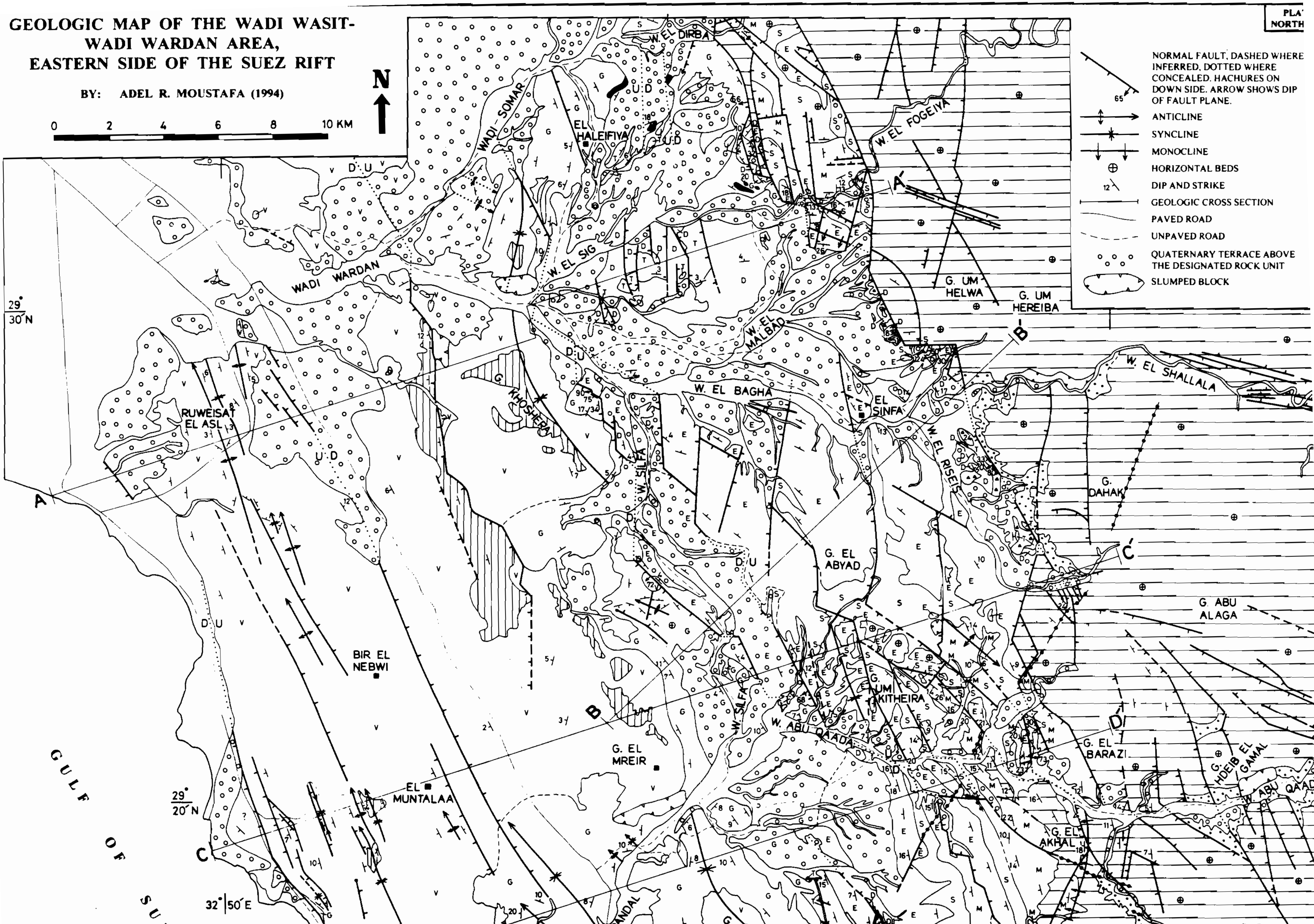
As indicated in the last section, the northern part of the mapped area (north of Wadi Gharandal-Wadi Abu Qaada) is a large crustal rollover on the downthrown side of the listric rift-bounding fault. Smaller folds in the Hammam Faraun Block are not as abundant as faults. Only 19 synclines, 11 anticlines, and 12 monoclines have been mapped (Fig. 7). The mapped anticlines and synclines are open and have gentle flank dips of about 5–8°. Those in the northwestern part of the block (from the Asl anticline to the Nebwi syncline, Fig. 7) are relatively tighter and their flanks are narrow compared to their length. All the anticlines and synclines of the Hammam Faraun Block are oriented NNW and NW (Fig. 7, inset) and range in length from 0.9–13.8 km. The synclines are longer than the anticlines. Six synclines and one anticline are the most prominent and longest folds of the block (Table 1).

The origin of the prominent folds of Table 1 as well as the other smaller folds of the Hammam Faraun Block is directly related to the movement on nearby faults. These folds affect ductile Miocene sediments (Plate 1) and are formed by drag on nearby major normal faults. Synclines are formed by drag on the downthrown sides, whereas anticlines are formed by drag on the upthrown sides of the faults (Plate 1 & Fig. 4). This interpretation might contradict the currently accepted notion among geologists working in extensional terrains where surface folds would infer ramps and flats in deep detachments (Gibbs 1984). Borehole data and seismic reflection profiles in the offshore areas of the Gulf of Suez show many examples where small folds affecting the ductile Miocene rocks are formed by drag on nearby normal faults or by draping over rejuvenated faults in the underlying pre-Miocene section (Eggertson & Moustafa, unpublished data). The same relationship between small surface folds in the Miocene rocks and the movement on normal faults underlying them in the subsurface was discovered by Thiebaud & Robson (1979) through the correlation of borehole data. The close parellelism between the folds and faults of the Hammam Faraun Block (cf. Fig. 6 and the rose diagram of Fig. 7) adds evidence to the effect of drag on the formation of the folds. Two folds between Gebel Abyad and Wadi Abu Qaada (Plate 1 and Fig. 7) affect pre-rift rocks and are related to the change in dip between the northern and central half grabens of the Suez rift. These two folds act like "twist zones" (Colletta *et al.* 1988) within the accommodation zone that separates these two half grabens (Moustafa, in press).

Steep limbs of monoclines mapped in the Hammam Faraun Block have dips that reach a maximum of 26°. Some of these monoclines lie between the ends of normal faults dipping in the same direction and represent synthetic transfer zones (Morely *et al.* 1990). The most prominent monocline lies at the rift boundary in the upstream area of Wadi El Sig (Plate 1 and Fig. 7) and has a southwest dip of about 26°. It lies between two N- to NNE-trending normal faults and form a synthetic transfer zone or a strike ramp (Morely *et al.* 1990) between them. Other monoclines are formed by

GEOLOGIC MAP OF THE WADI WASIT-WADI WARDAN AREA, EASTERN SIDE OF THE SUEZ RIFT

BY: ADEL R. MOUSTAFA (1994)



STRUCTURAL CROSS SECTIONS OF THE WADI WASIT-WADI WARDAN AREA, EASTERN SIDE OF THE SUEZ RIFT

BY: ADEL R. MOUSTAFA (1994)

PLATE 2

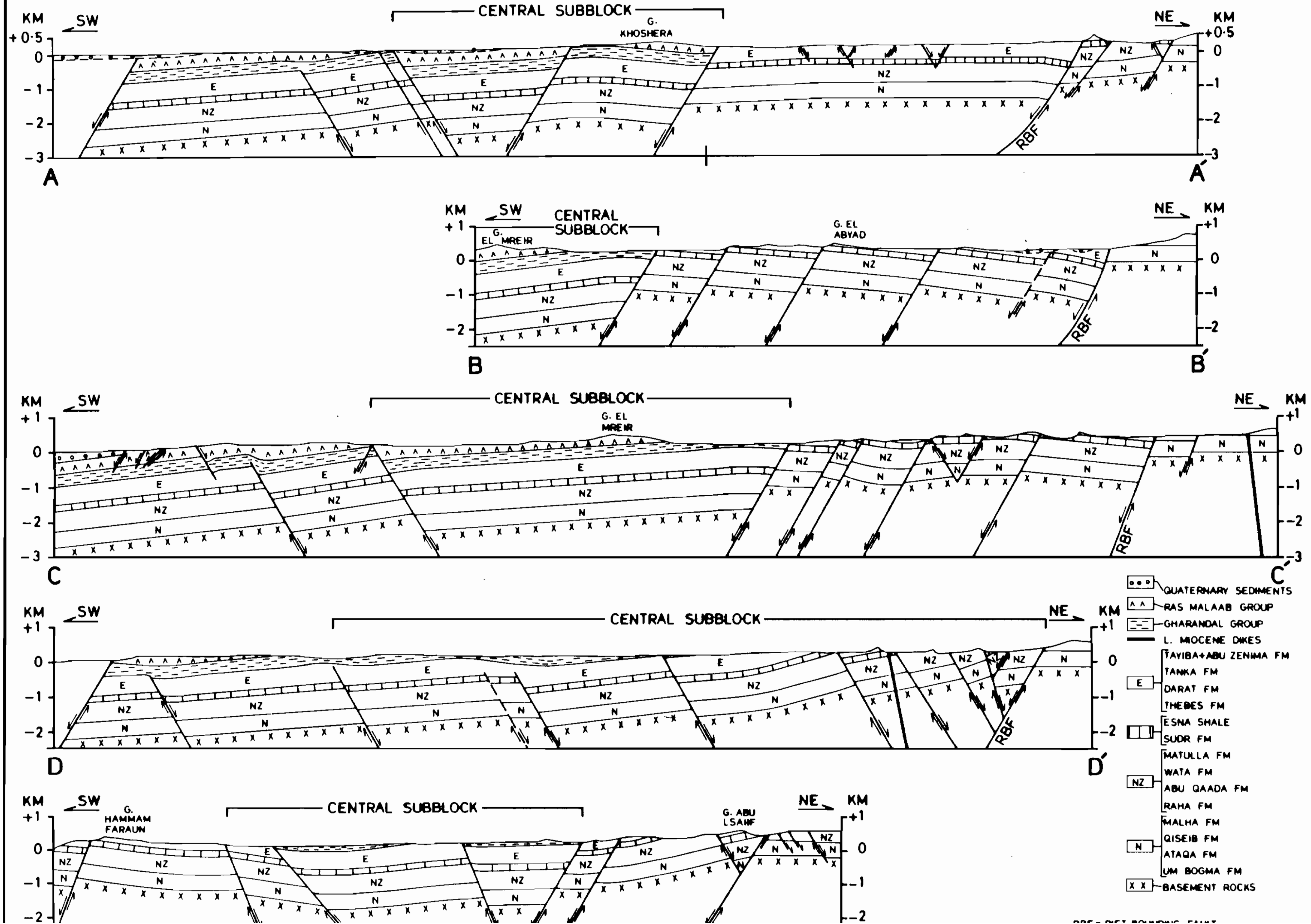


Table 1. Prominent folds of the Hammam Faraun Block

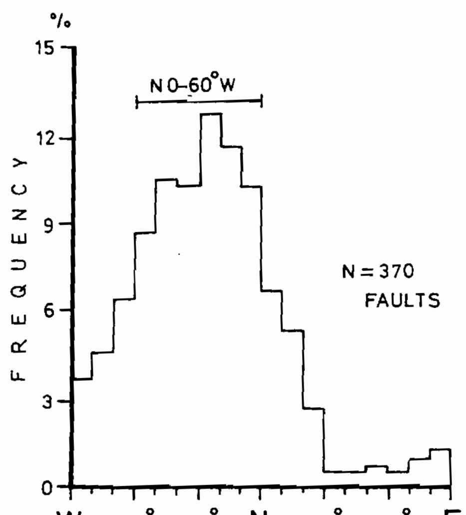
Fold name	Symbol in Fig. 7	Length (km)	Orientation
Asl Anticline	AA	8	N18°W
Gushiya Syncline	GS	10	N10–44°W
Nebwi Syncline	NS	7	N20°W
Khoshera Syncline	KS	12.5	N12°E to N25°W
Thal Syncline	TS	13.8	N18°W
Sarbut El Gamal Syncline	SGS	5.3	N14°W
Gharandal Syncline	GDS	5.3	N38°W

STRUCTURAL SETTING

In their structural study of the southern part of the Hammam Faraun Block, Moustafa & Abdeen (1992) subdivided this part of the block into small sub-blocks of different tilt directions. The study of the northern part of the block in the present work allows the subdivision of the whole block into three main structural sub-blocks based on the bounding faults and structural elevations, instead of different tilt directions. These sub-blocks are called the western, central, and eastern sub-blocks (Fig. 8) and are oriented NNW–SSE, parallel to the long axis of the Hammam Faraun Block. The eastern and western sub-blocks have structurally higher elevations than the intervening (central) sub-block which represents a large elongated graben extending along the central part of the Hammam Faraun Block.

WESTERN SUB-BLOCK

The western sub-block is bounded on the east by the large NNW–SSE–oriented graben of the central sub-block. The northern part of this sub-block (Nebwi-Asl area)



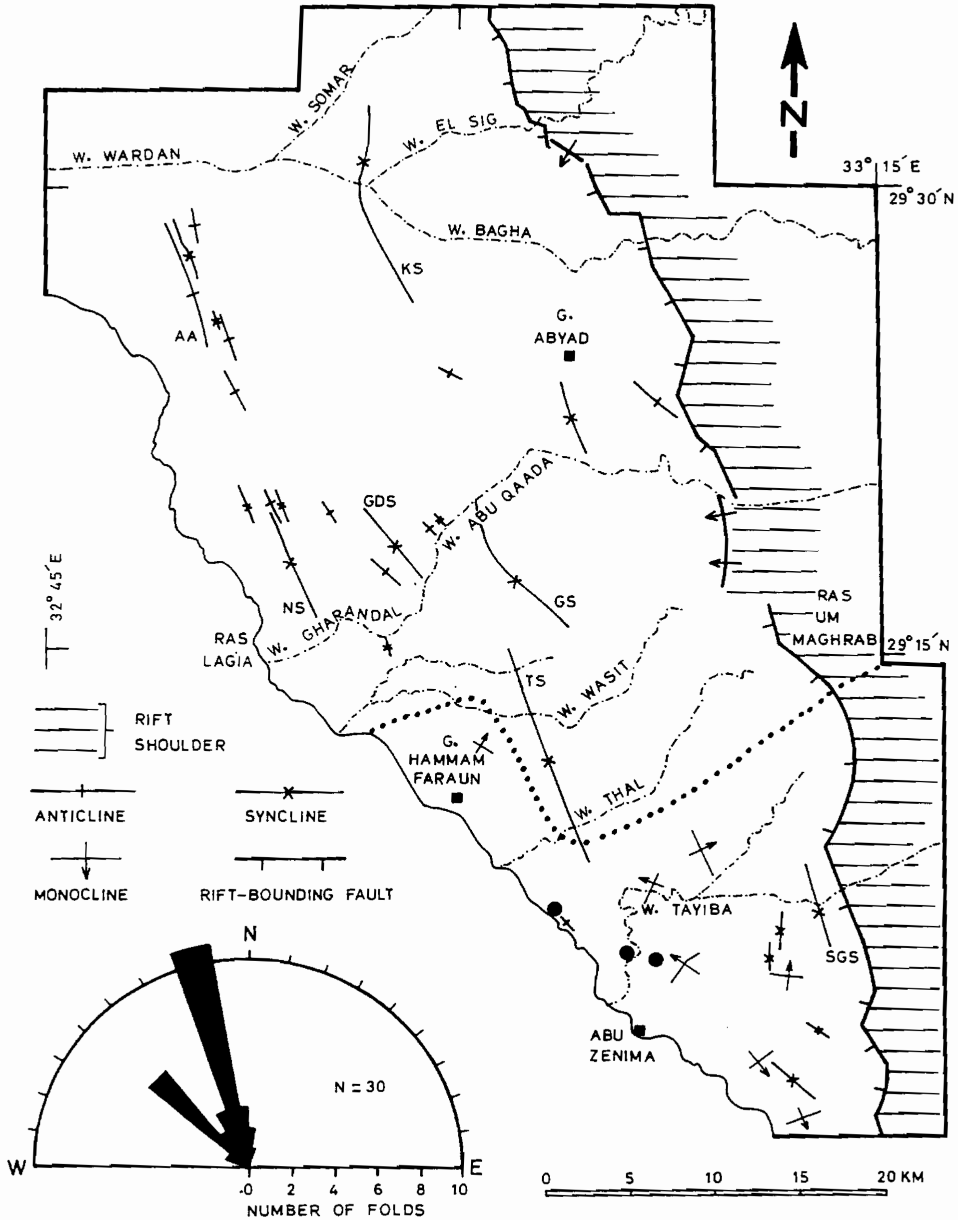


Fig. 7. Folds of the Hammam Faraun Block. Main folds in the map are designated AA (Asl anticline), GDS (Gharandal syncline), GS (Gushiya syncline), KS (Khoshera syncline), NS (Nebwi syncline), SGS (Sarbut El Gamal syncline), and TS (Thal syncline). Three small monoclines north and northwest of Abu Zenima

is a gentle SW dipping homocline that belongs to the northern half graben of the Suez rift. This homocline has a gentle (SW) dip of about 2–8° (Plate 2, southwestern parts of cross sections A–A′, C–C′, and D–D′). A complete stratigraphic section is preserved in this homocline and is dissected by a few NNW–SSE-oriented normal faults and affected by a number of narrow folds in the Miocene evaporites (Fig. 7).

To the south of Wadi Wasit, the western sub-block is a major NNW-oriented horst tilted at about 10° NE (Plate 2, southwestern part of cross section E–E′). This part of the sub-block includes Gebels Hammam Faraun and Thal and belongs to the NE dipping half graben of the Suez rift. The change in dip from SW (north of Wadi Gharandal) to NE (in Gebels Hammam Faraun and Thal) takes place in the vicinity of Wadi Wasit in the Gharandal accommodation zone (Moustafa, in press).

No consistent dip can be assigned to the extreme southwastern part of the western sub-block (Abu Zenima area, south of Wadi Tayiba) where bedding is either horizontal or dipping toward the SW (at about 10–25°) or NW (at about 10°). These anomalous dip directions were attributed by Moustafa & Abdeen (1992) to a change in the geometry of the rift-bounding fault at depth as well as to drag on the upthrown side of the Hammam Faraun Fault.

CENTRAL SUB-BLOCK

The central sub-block is the largest in the Hammam Faraun Block. It is separated from the rift shoulder by the eastern sub-block except in the east-central and southeastern parts of the area. where the eastern sub-block is missing. It is also abutted on the south by the Wadi Nukhul area of the eastern sub-block (Fig. 8).

The central sub-block structurally has the shape of a large graben roughly oriented NNW–SSE (Fig. 8 and Plate 2). The throw of the eastern boundary faults of this sub-block locally exceeds that of the western boundary faults. The western boundary of the sub-block is delineated by three left-stepping en echelon faults (fig. 8). The throws of these faults decrease from north to south, where they are 550 m in the north (Plate 2, southwestern part of cross section A–A′) and only 150 m in the south (the area west of Gebel Sarbut El Gamal). The eastern boundary of this graben is locally defined by the rift shoulder. In the northern part of the central sub-block, the eastern boundary fault has a throw ranging from 200 to 900 m, whereas in the area lying west of the Gebel Abu Ideimat, the throw on the east-bounding fault is about 1100 m.

The central sub-block is generally tilted to the SW though a few small areas with a NE dip exist too. Due to the graben structure of this subarea, a complete syn-rift section is preserved and is exposed at Gebels Khoshera, El Mreir, El Gushiya, and Sarbut El Gamal (Plate 1).

EASTERN SUB-BLOCK

In contrast to the western and central sub-blocks, the eastern sub-block is discontinuous and is represented in the northeastern, east-central, and southernmost parts of the Hammam Faraun Block. It generally has a NE tilt direction toward the rift

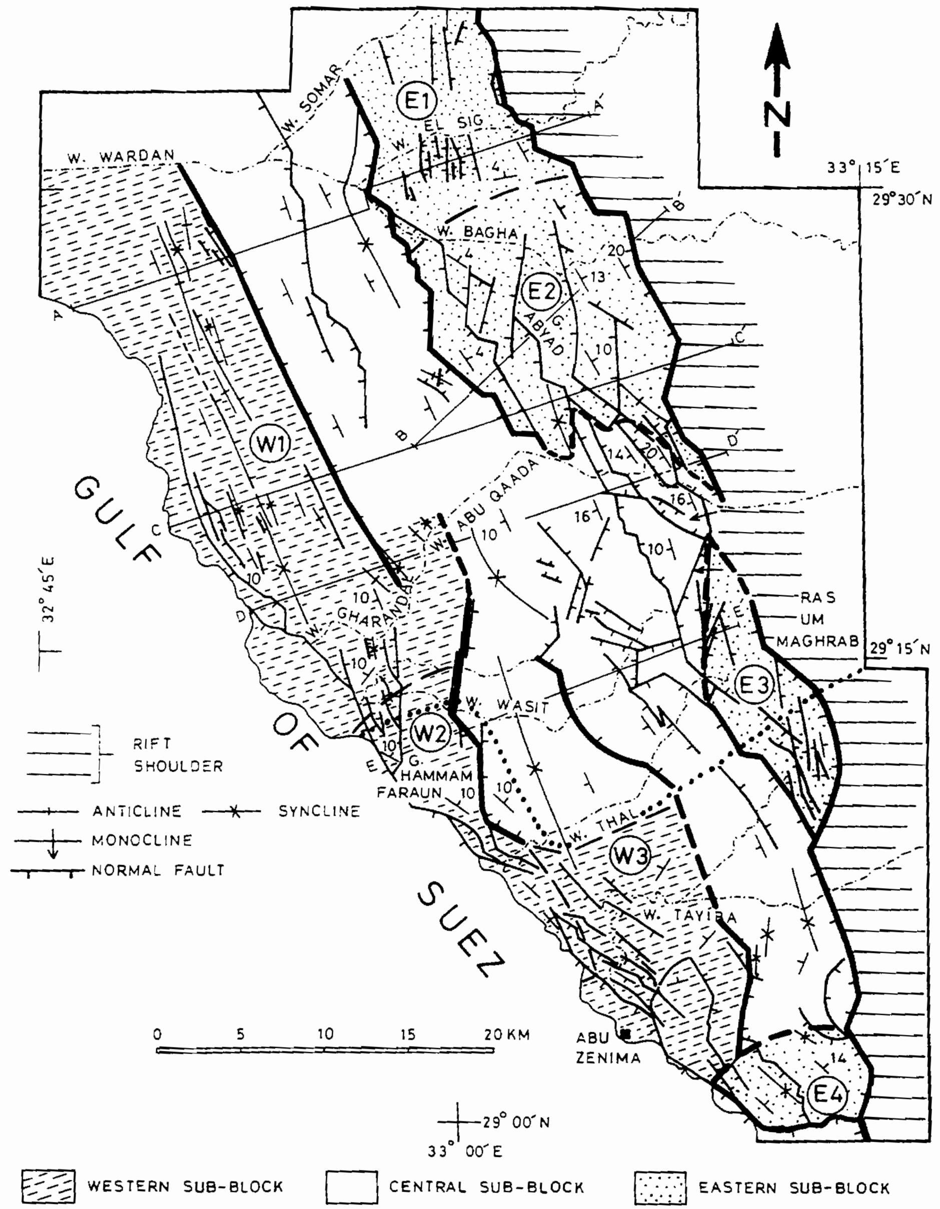


Fig. 8. Structural sub-blocks of the Hammam Faraun Block. Four areas in the eastern sub-block are labeled E1 (Haleifiya), E2 (G. Abyad), E3 (Abu Ideimat), and E4 (W. Nukhul). Three areas in the

Qaada) includes two areas of different tilt directions. These are the Haleifiya area to the north and the Gebel Abyad area to the south (Fig. 8). The Haleifiya area has a northward plunging anticlinal structure where the easternmost part dips NE toward the rift-bounding fault, the western part dips SW, and the central and southern parts dip northward. On the other hand, the Gebel Abyad area has a predominant NE dip toward the rift-bounding fault (Plate 2, cross section B–B′). The dip angle in this area increases as one approaches the rift-bounding fault, The dip angle is about 4° in the westernmost part of the Gebel Abyad area and reaches a maximum of 24° close to the rift bounding fault (Plate 1). The overall structure of the Gebel Abyad area is a rollover anticline (Hamblin 1965; Bruce 1973) on the downthrown side of a major listric normal fault (rift-bounding fault). This rollover anticline is dissected into several fault blocks by southwestward and westward dipping normal faults (cross section B–B′, Plate 2).

The Abu Ideimat area is also a segment of the eastern sub-block (Fig. 8). Horizontal bedding characterizes the western part of this area but the eastern part dips NE against the rift-bounding fault forming a well-defined rollover anticline (Moustafa & Abdeen 1992; Moustafa 1993). The Wadi Nukhul area lies in the extreme southern part of the Hammam Farun Block (Fig. 8) and has a predominant NE dip against the rift-bounding fault. This area is considered here to belong to the eastern sub-block due to its similarity to the Gebel Abyad and Abu Ideimat areas in being tilted to the NE, and lies on the easternmost side of the Hammam Faraun Block.

It can generally be stated that the eastern sub-block is characterized by a predominant NE dip and juxtaposition against the rift-bounding fault. The NE dip of this sub-block is attributed to the listric nature (Shelton 1984) of the rift-bounding fault.

DEFORMATION HISTORY

Several stratigraphic and structural features in the Hammam Faraun Block help decipher its history of deformation. Seven phases of deformation are evident in its history. Some of these phases pre-date the opening of the Suez rift, whereas the others are associated with the opening and evolution of the rift.

EARLY EOCENE DEFORMATION (D1)

The earliest recognizable tectonic event in the Hammam Faraun Block (D1) is Early Eocene and is indicated by a change in the facies of the Thebes Formation. The cherty limestone found to the south abruptly changes in the central and northern parts of the block to an area dominated by conglomerate beds. These conglomerates are most abundant at Gebels Thal and Hammam Faraun, where thick beds are made up of calcirudites cemented by lime-mud and include several syn-depositional slump folds. The Eocene facies of Gebels Thal and Hammam Faraun were considered by Abul-Nasr (1987) to represent slope deposits. Similar conglomerates in the Eocene rocks exist at the same latitude on the other side of the Gulf of Suez in the St. Paul area (see Fig. 1a for location). The conglomerates of this area, as well as those of the Gebel northern Egypt and reached its zenith at the Late Cretaceous. Some of the folds related to this deformation stood high above sea level in the Late Cretaceous and Early Tertiary periods (Moustafa 1988; Moustafa & Khalil 1989). Subsurface and surface study of the northern part of the Suez rift led Moustafa & Khalil (1995) to draw the southernmost boundary of "Syrian arc" folding and related deformation as an arcuate line extending from the southern side of Gebel Somar (about 50 km NNE of Gebel Hammam Faraun) to the nothern scarp of the South Galala Plateau (see Fig. 1a for locations), i.e. close to the sites of slope conglomerate deposits of Gebels Thal and Hammam Faraun.

OLIGOCENE DEFORMATION (D2)

The second deformation (D2) recognized in the Hammam Faraun Block is Oligocene in age and was associated with the deposition of the Abu Zenima Formation. A parallel nonconformity is recognized between the Abu Zenima Formation and the underlying rocks in several localities in the southern part of the Hammam Faraun Block and is related herein to erosion preceding the deposition of the Abu Zenima Formation. Various hiatuses related to this nonconformity are recognized and, in general, these hiatuses are large in the southernmost part of the block. Thus, the Abu Zenima Formation directly overlies the Darat Formation in the southernmost part of the Hammam Faraun Block (Wadi Nukhul area), the Tanka Formation in Wadi Tayiba and Wadi Wasit, and the basal part of the Tayiba Formation at Gebel Tanka (see Fig. 1b for location).

Limestone boulders in some conglomerate beds of the Abu Zenima Formation in the Wadi Nukhul area are thought to have been derived from Eocene and Upper Cretaceous rocks (Moustafa & Abdeen 1992). These boulders indicate significant relief during the Oligocene, attributed by Moustafa & Abdeen (1992) either to a fall in sea level or to Oligocene faulting. Patton *et al.* (1994) considered the Abu Zenima Formation to have been deposited in initial rift sag in the Hammam Faraun Block. The missing sections below the Abu Zenima Formation indicate some tectonic relief in the southern part of the Hammam Faraun Block and argues against the presence of an early rift sag in this area. On the other hand, Moustafa & Khalil (1994) recognized a post-Middle Eocene to pre-Miocene deformation in central Sinai that led to the development of wrench-related folds. They attributed this deformation to continued closure of the Eastern Mediterranean basin. It is believed that this deformation is contemporaneous with the D2 deformation of the present study and is responsible for the tectonic relief and erosion in the southern part of the Hammam Faraun Block before the deposition of the Abu Zenima Formation. The D2 deformation is also contemporaneous with the early stage of the extension and opening in the Red Sea (Bohannon *et al.* 1989).

EARLY MIOCENE DEFORMATION (RIFT INITIATION), D3

Basalt flows overlying the Abu Zenima Formation as well as basalt dikes and sills intruded in the Eocene and older rocks characterize the Hammam Faraun Block and

Field evidence indicates that the volcanics of the study area are older than the Miocene sediments as the latter are not intruded, baked, or colored by these volcanics. K–Ar absolute dating indicates that these volcanics are 22–24 Ma old (Steen 1984; Moussa 1987), i.e. Early Miocene. They mark the onset of rifting in the Gulf of Suez area. Moussa (1987) indicated that these volcanics have a subalkaline (tholeiitic) to alkaline affinity and were intruded in an intraplate, tensional environment. Many dikes in the Hammam Faraun Block are oriented NW indicating NE tensional stresses at the early phase of rift opening. Other dikes have different orientations such as the long NNE–SSW oriented dike that extends from the NE side of Gebel El Gushiya (Plate 1). This dike, as well as that oriented NW–SE in the Wadi Wata area (Plate 1) enclose an acute angle of about 75°. The bisector of this angle is oriented N15°W–S15°E. These two dikes are interpreted here to have been intruded along conjugate shear fractures formed under the effect of shortening in the N15°W–S15°E direction and lengthening in the N75°E–S75°W direction.

Basalt flows in the Wadi Tayiba area are conformable with the underlying Oligocene and Eocene rocks indicating no rift-related tilting or doming prior to or associated with their extrusion. Moustafa & Yousif (1993) indicated that block rotation on the downthrown side of listric normal faults at the Suez rift boundary started only after an early stage of horst-graben faulting. Early rift alkaline volcanics in the Red Sea are also conformable with the underlying pre-rift rocks (see Bohannon *et al.* (1989) for more details).

TECTONIC SUBSIDENCE IN THE RIFT (D4)

(A) Slow subsidence

The lowermost Miocene sediments (the Nukhul Formation) are the earliest rift sediments in the Hammam Faraun Block and are represented by polymictic basal conglomerates at the base, including boulders and pebbles of basalt, chert, and limestone. Wherever the base of the Miocene sedimentary section is exposed, it becomes clear that these conglomerates have a limited geographic distribution and are absent in some parts of the Hammam Faraun Block, e.g. Gebel Sarbut El Gamal and Gebel Gushiya. These conglomerates are well-developed in the southwestern part of the Hammam Faraun Block, e.g. the mouth of Wadi Tayiba, the Tayiba Oasis, and the eastern side of Gebel Hammam Faraun. Such local development of the Nukhul conglomerates is controlled by local structures (furnishing local basins of deposition), local dip directions (where the conglomerates occupy down-dip areas), and/or old topography (like old wadis).

Angular discordance between the Nukul Formation and the underlying pre-rift sediments indicates rift tilting prior to and during the deposition of these early rift clastics. Tilting in the Suez rift is related to the displacement on major listric normal faults bounding the deep sides of the half grabens of the rift. Each half graben in the Suez rift is bounded by two major breakaway faults: a major listric normal fault at one side and another conjugate normal fault at the other side (Fig. 9). The latter fault is planar and is not responsible for block tilting in the half graben. The exposed tips of detachment) is responsible for block rotation in the rift, whereas the other is antithetic to it. They intersect at depth in middle crustal levels where the antithetic fault offsets the main detachment. The Red Sea and Gulf of Aden detachments are different from the breakaway faults bounding the half grabens of the Suez rift. Those in the Suez rift have steeper dip and only one of them is listric. The difference between the Red Sea-Gulf of Aden and the Suez rift boundary faults is probably related to the increased extension and rotation in the former areas where rocks dip 60° (Bohannon 1989).

Tectonic subsidence in the Suez rift was slow during the deposition of the Nukhul Formation (Steckler *et al.* 1988). Uplift of the rift shoulders at or slightly after the onset of rifting was documented by Omar *et al.* (1989) and was attributed to small-scale convection beneath the rift (Steckler 1985; Buck 1986). It may also be attributed to tectonic unloading by breakaway fault.

(B) Rapid subsidence

The thin sequences of the Nukhul Formation are overlaid by the claystones of the Rudeis Formation which were deposited in a relatively deep-water environment related to an increased rate of tectonic subsidence. According to Steckler *et al.* (1988), approximately one third to one-half of the extension in the rift occurred during this phase of rapid subsidence. Block rotation in the rift was continuous during the deposition of the claystones of the Rudeis Formation as indicated by a decrease in the amount of dip upward in the section.

MID-CLYSMIC EVENT (D5)

The relatively deep-water claystones of the lower part of the Rudeis Formation are followed by the Miocene Grits (Asl Member) which indicate a significant change in the regimen of deposition. This change is more evident where the Asl Member grades laterally into downlapping fan delta conglomerates. These conglomerates downlap the Miocene claystones and show current direction toward-the-axis of the Miocene rift (Fig. 3). Conglomerates similar to those mapped to the southeast of Gebel El Gushiya were also reported in the southern part of the Hammam Faraun Block at Gebel El Iseila and partly at Gebel Sarbut El Gamal (Moustafa & Abdeen 1992). These conglomerates are made up of chert cobbles and pebbles derived from the chert beds of the Thebes formation. Similar conglomerates in Gebel Abu Alaqa (about 20 km SE of the Hammam Faraun Block) were given the name Abu Alaqa Group by Garfunkel & Bartov (1977). They were also recognized in the Baba Block (Moustafa 1987), and Wadi Sudr (Patton *et al.* 1994) where they downlap Miocene claystones of the Lower Rudeis Formation. The conglomerates in the six mentioned localities (Wadi Sudr, Gebel El Gushiya, Gebel El Iseila, Gebel Sarbut El Gamal, Wadi Baba, and Gebel Abu Alaqa) exist in close proximity to the rift shoulder and/or other major faults (Fig. 10) and indicate contemporaneous uplift and erosion of the rift shoulder. They were derived by erosion of the Thebes Formation on the rift shoulder and/or other structurally high areas inside the rift.

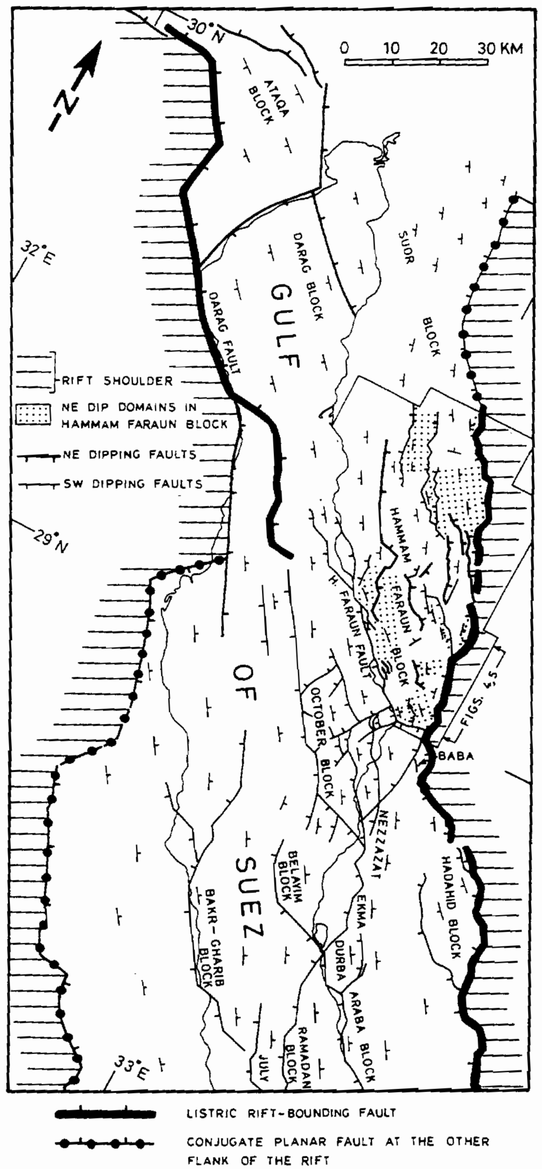


Fig. 9. Regional structural map of the northern and central half grabens of the Suez rift showing major conjugate breakaway faults bounding the two sides of each half graben (slightly modified after Moustafa, in press). Major faults within these half grabens and dip directions are also shown.

where these wadis intersect the rift-bounding fault or major normal faults within the rift (Fig. 10). As indicated above, these conglomerates resulted from the mechanical weathering of the chert beds of the Thebes Formation on the rift shoulder and/or

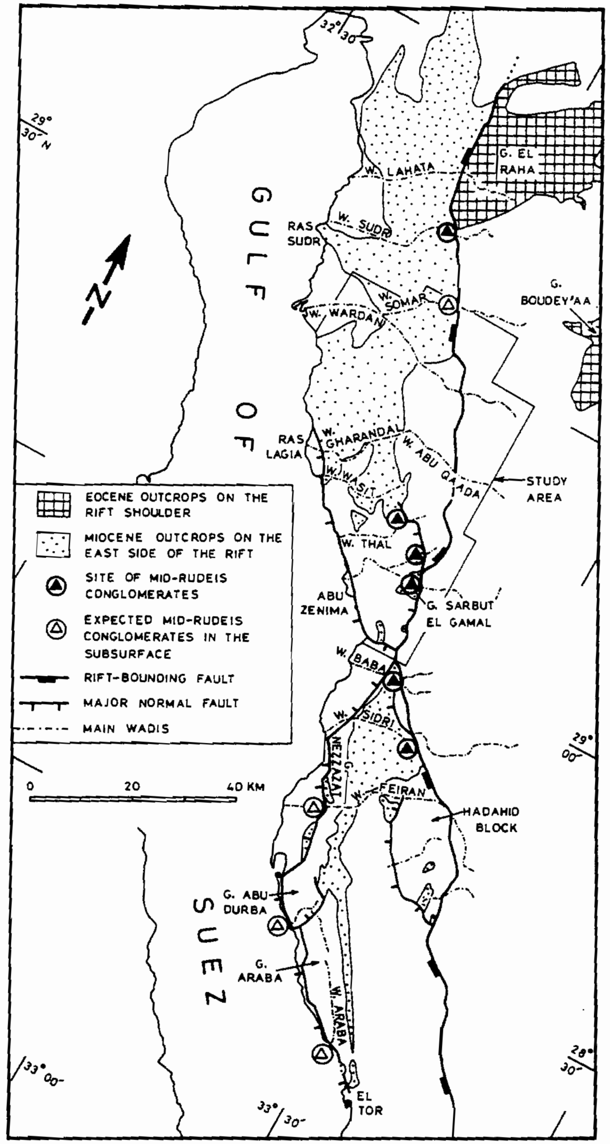


Fig. 10. Location of Miocene mid-Rudeis fan conglomerates in the eastern part of the Suez rift.

normal faults in the rift. As the main wadis crossed the scarps of these faults, the coarse (gravel) fraction of their load was deposited on the downthrown side at the footslopes of the fault scarps forming the fan delta conglomerates similar to the Gilbert-style deltas. Based on these facts, similar fans are also expected to exist in the subsurface in at least four other localities lying at the intersection of main wadis with the rift-bounding fault or major normal faults in the rift (Fig. 10). The four proposed

3. The intersection of the northern branch of Wadi Araba with the Gebel Abu Durba fault, and
4. The intersection of the southern branch of Wadi Araba with the Gebel Araba fault.

Although Wadi Lahata (the northernmnost part of the rift, Fig. 10) is a major wadi traversing the rift shoulder into the rift, no mid-Rudeis conglomerates are expected to exist along this Wadi because the Thebes Formation in the upstream area of this wadi (on the rift shoulder) is still preserved in Gebel El Raha indicating that there was no supply of gravels in that wadi at the mid-Rudeis time. Such a relationship between main wadis, outcrop of the Thebes Formation (source of gravels) on the rift shoulder, major faults, and the location of mid-Rudeis fan conglomerates in the rift, is important in locating stratigraphic traps and should be taken into consideration by petroleum geologists working in the Suez rift. Areas where rift-parallel (NW–NNW-oriented) faults join transfer (N–NNE-oriented) faults may also represent suitable sites ("box corners") for the deposition of mid-Rudeis coarse clastics inside the rift. Although none of these sites show mid-Rudeis fan conglomerates in the mapped area (Plate 1), they may be potential areas of coarse clastics in other parts of the rift.

The conglomerates in the middle part of the Rudeis Formation mark a tectonic event (D5) referred to as the mid-Rudeis or mid-clysmic event (17 Ma old) by Garfunkel & Bartov (1977). It is a major event (Evans 1988) that led to tectonic reorganization of the rift. Major faults were rejuvenated during this event, e.g. the western boundary fault of the Hadahid Block (Moustafa & El-Raey 1993) as well as the Hammam Faraun Fault which is indicated by faulted claystones of the Lower Rudeis Formation at the mouth of Wadi Tayiba. New faults were also created at the mid-clysmic event, for example those dissecting the lower Rudeis claystones of Gebel Sarbut El Gamal. Moustafa (1993) believes that the mid-clysmic event had more effect on the central part of the rift than its eastern and western (onshore) areas as indicated by increased amounts of throw on the faults toward the axis of the rift.

POST-MIOCENE (POST-EVAPORITES) DEFORMATION (D6)

A structural deformation of post-evaporites age is also recognized in the Hammam Faraun Block and is indicated by:

1. Minor faults dissecting the Miocene evaporites, e.g. between Wadi Gharandal and Ruweisat El Asl (Plate 1).
2. Folding of the Miocene evaporites due to displacement on nearby normal faults (e.g. Gebel Khoshera Syncline) or due to draping over rejuvenated faults in the subsurface (e.g. Gebel Gushiya Syncline and many of the folds between Wadi Gharandal and Wadi Warden, Plate 1).
3. Gentle tilting of the Miocene evaporites in areas not associated with folding, e.g. Gebel El Mreir and northwestern part of the western sub-block.

QUATERNARY MOVEMENTS (D7)

The presence of a late structural event of Quaternary age in the Hammam Faraun Block is indicated by NW–NNW oriented minor normal faults dissecting Quaternary terraces to the east and west of Ruweisat El Asl area (Plate 1). The displacement on these faults is only for a few meters. The faults lying to the east of Ruweisat El Asl area overlie a major normal fault underneath the Quaternary terraces (cf. cross section A–A′, Plate 2). It is believed that this Quaternary deformation is not related to tectonic subsidence in the rift but probably reflects local adjustment above subsurface faults.

DISCUSSION

The deformation history of the Hammam Faraun Block shows the transition from "Syrian arc" (Late Cretaceous-Early Tertiary) folding in northern Egypt to the early stages of crustal separation on both sides of the Suez rift. "Syrian arc" folding proceeded by NW–SE shortening in northern Egypt as a result of the closure of Neotethys. This deformation reached its zenith in the Late Cretaceous and continued less stongly into the Early Tertiary (Moustafa 1988; Moustafa & Khalil 1989). Moustafa & Khalil (1994) indicated that the last stage of "Syrian arc" deformation is of post-Middle Eocene to pre-Miocene age and had a local effect on some areas of northern Egypt.

The NW–SE shortening that affected northern Egypt during the "Syrian arc" folding ceased at the early stages of rifting and was replaced in the Early Miocene by extension in the NE–ENE direction (Lyberis 1988; Moustafa 1993). Early Miocene basic igneous dikes were intruded orthogonally to the direction of rift extension, that is, NW to NNW. Two long basalt dikes in the northern part of the Hammam Faraun Block probably indicate the transition from NW–SE shortening (related to "Syrian arc" deformation) to NE–ENE extension at the early rift opening. These two dikes are the NW–SE-oriented dike that is locally occupied by Wadi Wata and the NNE–SSW-oriented dike extending from Gebel El Gushiya toward the rift shoulder (Plate 1). These two dikes are thought to have been intruded along conjugate shear fractures formed by NNW–SSE shortening and ENE–WSW extension. These strain directions probably represent the latest stage of shortening associated with the "Syrian arc" folding and the earliest stage of extension associated with the opening of the Suez rift. Later on, shortening ceased during the main stages of rift opening which proceeded by pure extension.

The onset of rifting in the Suez rift is marked by the early Miocene volcanicity which is relatively widespread in the Hammam Faraun Block compared with other parts of the rift. Block rotation in the rift as a result of displacement on its listric boundary faults followed this phase of volcanicity. The northern part of the Hammam Faraun Block (the area north of Wadi Gharandal-Wadi Abu Qaada) lies between the listric boundary faults of the northern and central half grabens of the Suez rift (Fig. 9). This part of the block is rolled over on these two listric normal faults leading to its broad anticlinal structure. This area, therefore, represents an overrelations compared to other parts of the rift. This part of the block is dominated by Early Miocene volcanics conformable with the underlying pre-rift rocks.

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الوضع التركيبي والتطور التكتوني لشمال كتلة حمام فرعون (منطقة وادي وسيط ـ وادي وردان)، الناحية الشرقية لأخدود السويس

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خلاصة

تقع منطقة وادي وسيط ـ وردان (الجزء الشمالي لكتلة حمام فرعون) بالناحية الشرقية لأخدود السويس بين نصفي أخاديد متعاكسة الميل. أوضح المسح الحقلي التفصيلي أن الصخور الأقدم من الأخدود وتلك المزامنة له مقطوعة بصدوع عادية اتجاهها شمال إلى غرب شمال غرب ومطوية بعدد من الطيات الصغيرة المصاحبة لحركة الصدوع القريبة. وتنقسم كتلة حمام فرعون إلى ثلاثة قطاعات تتجه شمال شمال غرب يمثل القطاع الأوسط منها كتلة خسيفة كبيرة بينما يمثل القطاع الشرقي طية دورانية كبيرة على جانب المرمى السفلي للصدع المقوس الذي يحد الأخدود.

وقد تأثرت كتلة حمام فرعون بسبعة مراحل للتشوه أقدمها (رقم 1) لها علاقة بطي «القوس السوري». وقد تسبب التشوه الثاني (رقم 2) في رفع الجزء الجنوبي من كتلة حمام فرعون في عصر الأوليجوسين أثناء المراحل الأخيرة للطي بالقوس السوري. وقد صاحب المراحل الأولى لفتح أخدود السويس (مرحلة رقم 3) تكوين بركانيات بازلتية متوافقة مع الصخور الأقدم منها. وحدثت مراحل التشوه الرابعة والخامسة والسادسة أثناء الفتح المستمر للأخدود فكان الأخدود يهبط في المرحلة رقم 4 أما في المرحلة رقم 5 فقد تمت اعادة ترتيب الأخدود بنائيا وأرتفعت الأطراف المتاخمة له مما أدى إلى تعريتها وترسيب رواسب حصوية خشنة عند سفوح منحدرات الصدوع. وفي أثناء المرحلة رقم 6 حدث تصدع بسيط في أواخر عهد الأخدود. وقد كان التشوه محليا وغير تكتونيا أثناء المرحلة رقم 7 في الحقب الرباعي وأدى إلى تكوين صدوع عادية صغيرة.

توضح المراحل التكتونية لكتلة حمام فرعون الأنتقال من مراحل الطي المصاحب للقوس السوري (نتيجة أقتراب أفريقيا من أوراسيا وقفل بحر التيثس الجديد) إلى المراحل الأولى لأنفصال الجزيرة العربية عن أفريقيا وفتح أخاديد البحر الأحمر وخليج السويس. وتميز بداية فتح أخدود السويس فترة نشاط بركاني في الميوسين المبكر تلتها حركات دوران بالأخدود نتيجة الأزاحة على صدوع مقوسة عند حافته. وتتميز كل من أنصاف الأخاديد بمنطقة خليج السويس يصدعين متزاوجين كبيري الميل (يحد كل منهما الحافتين) يكون أحدهما مقوسا والآخر غير