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Internal structure and deformation of an accommodation zone in the northern part of the Suez rift

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Abstract—Detailed structural study of the eastern (onshore) part of the Gharandal accommodation zone that separates the northern (SW-dipping) and central (NE-dipping) half grabens of the Suez rift helped\decipher the internal structure and deformation of accommodation zones of continental rifts. This 60 km-wide zone is affected by pure normal faulting. The NE-dipping faults of the northern half graben extend southward into the accommodation zone where they interfinger with SW-dipping faults extending from the central half graben. These two sets of rift-parallel faults form several horsts and grabens in the accommodation zone. Areas dipping parallel to the northern or southern half grabens form several intermixing dip domains in the accommodation zone. Smaller-scale accommodation of dip between these dip domains proceeds by the development of rift-parallel folds (twist zones).

In contrast to the southern accommodation zone of the Suez rift, the internal structure of the Gharandal accommodation zone is believed to be representative of accommodation zones in regions (a) unaffected by pre-rift structures lying at high angles to the rift; and (b) experiencing relatively small extension. Accommodation zones in areas having pre-rift structures lying at high angle to the rift have relatively narrow width and are characterized by transverse, strike-slip faults. Strike-slip movement on these faults is related to the torsional strain resulting from the opposite tilt directions and transport of fault blocks of adjacent half grabens.

INTRODUCTION

Stretching of the continental crust (e.g. at passive continental margins and continental rifts) proceeds by displacement on normal faults (both planar and listric) and block tilting. Such regions are characterized by structural asymmetry portrayed by half grabens of opposite tilt directions. Gently dipping detachment faults (or zones) occur at depth where normal faults bounding the tilted blocks sole down (Wernicke & Burchfiel 1982, Wernicke 1985). Several detachment faults dipping in the same direction may also exist under broad areas of tilted fault blocks (Lister *et al.* 1986). These detachment surfaces penetrate most of the crust (Allmendinger *et al.* 1983) or the entire lithosphere (Wernicke 1985). Field mapping, drilling and geophysical studies of several rift basins indicate changes in the tilt directions of adjacent half grabens (e.g. Moustafa 1976, Bosworth 1985, Rosendahl *et al.* 1986, Morley 1988, Ebinger 1989, Matos 1992). Such changes in the tilt directions of half grabens are accompanied by a reversal in the dip of detachment surfaces (Bosworth 1985).

Literature on non-detachment models of continental rifts is also extensive. Kusznir & Egan (1989) and Kusznir *et al.* (1991) proposed that extension in the upper crust occurs on an array of planar faults, separating fault blocks which behave mechanically as interacting flexural cantilevers. Motion on upper crustal faults initiates an isostatic response and causes a flexural subsidence of hangingwall blocks and flexural uplift of footwall blocks. At basin margins, the flexural cantilever model predicts that the footwalls to the basin itself will be elevated above their initial datum and perhaps subject to erosion. Marginal uplift is completely a mechanical response to faulting with perhaps a small thermal component involved and, therefore, remains largely unrecovered during thermal cooling of the basin. The geometry of many extensional fault systems was also approximated to that of a set of 'rotating dominoes' (Emmons & Garrey 1910, Thompson 1960, Morton & Black 1975, Wernicke & Burchfiel 1982, Mandl 1987, Davison 1989). The domino model can be considered a geometric simplification of the flexural cantilever model. This model is consistent with observations made within many extended basins like the northern North Sea (Barr 1987, 1991, White 1990, Yielding 1990, Roberts *et al.* 1993), the Aegean Sea (Barr 1987) and the Gulf of Suez (Jackson *et al.* 1988). Fault blocks (represented by 'dominoes' in the 'domino model') are suggested to take up extension by rigid-body rotation. Westaway & Kusznir (1993), on the other hand, proposed that the general cause of tilting fault blocks is vertical shear rather than rigid-body rotation. Basin margins can not be analyzed by using the 'domino model', as these margins can not rotate freely as a rigid block.

Whether detachment or non-detachment (planar faults) models are applicable to the Suez rift is difficult to adopt without a detailed study tailored for this purpose. Excellent outcrops of the eastern and western parts of the rift indicate that the rift-bounding faults are not associated with footwall tilting (e.g. figs. 3 and 5 in Moustafa 1993 and fig. 20 in Patton *et al.* 1994). The rift-bounding faults of the Suez rift are, therefore, assumed to be listric and detach at depth. On the other hand, faults within the rift itself may generally be considered planar and the 'domino model' or vertical shear model

(Westaway & Kusznir 1993) may be applicable to these intra-rift faults, except for a few cases where tilting of the hangingwall exceeds that of the footwall (e.g. Esh El Mellaha Fault in the southwestern part of the rift; fig. 6 in Moustafa & El-Raey 1993).

Transfer (also called accommodation) zones exist between adjacent half grabens of different tilt directions and represent the areas through which throw is transferred from the breakaway fault of one half graben to that of the next. Transfer zones show a wide range of deformation including either discrete faults affected by normal slip, diagonal slip, or strike-slip (Chorowicz & Sorlien 1992) or wide complex zones of pure normal faulting, transtension (Maler 1990, Boccaletti *et al.* 1992, Lacombe *et al.* 1993), or broad warping ('twist zones', Colletta *et al.* 1988). The term transfer zone (Gibbs 1984, Morley *et al.* 1990) is used for zones of variable scale represented by a single fault or a broad area. A single fault acting as a transfer zone may link two outcrop-scale normal faults (e.g. Moustafa & Abdeen 1992), basins of different amounts of extension or different polarity (e.g. Tari *et al.* 1992), or areas of different block rotation (e.g. areas with planar faults vs areas with listric faults; Karson & Rona 1990). On the other hand, transfer zones covering a broad area exist between half grabens of opposite tilt directions or even between extended parts of the crust characterized by different structural styles (e.g. areas with horsts and grabens vs areas with tilted fault blocks; Souriot & Brun 1992). These zones help transfer the throw from one half graben to the next. They are also known as accommodation zones (Bosworth 1985, Rosendahl *et al.* 1986).

Although accommodation zones are documented in several studies of continental rifts (e.g. Moustafa 1976, Crossley 1979, Gibbs 1984, Harding 1984, Bosworth 1985, Rosendahl *et al.* 1986, Burgess *et al.* 1988, Colletta *et al.* 1988, Morley 1988, Moustafa & Fouda 1988, Coffield & Schamel 1989, Ebinger 1989, Faulds *et al.* 1990, Morley *et al.* 1990, Nelson *et al.* 1992), their internal structure and mechanism of accommodation of change in the tilt directions of adjacent half grabens are not well understood. The term 'accommodation zone' will preferably be used in this study instead of transfer zone as the paper deals with the accommodation of tilt direction from one half graben to the next. The main objective of the present study is aimed at understanding the internal structure and deformation of accommodation zones through the study of the northern accommodation zone of the Suez rift. Also, a comparison between the styles of deformation of the northern and southern accommodation zones of this rift is made here to understand the factors controlling the deformation in accommodation zones.

STRUCTURAL SETTING OF THE SUEZ RIFT

Extension of the continental Suez rift was initiated during the early stages of separation of Arabia from Africa. The rift represents the northern arm of the Red Sea and extends for about 300 km in a north-northwest direction toward Suez city. It is dominated by north-northwest–northwest oriented tilted fault blocks. Pre-rift (pre-Miocene) and syn-rift (Miocene) rocks dip at an average angle of about 10–15° but locally increase to as much as 45° in the southern part of the rift. The dip direction of fault blocks changes from north to south along the rift, from southwest to northeast and back to southwest defining three tilt-block domains in three geographically successive half grabens (dip provinces of Moustafa 1976). These are called the northern, central and southern half grabens (Fig. 1). Two accommodation zones exist between these half grabens and extend transversely across the rift.

The Suez rift can arbitrarily be divided into three longitudinal (NW–SE oriented) zones, the middle of which is occupied by the Gulf of Suez itself whereas the eastern and western zones are exposed in western Sinai and the Eastern Desert of Egypt respectively. Excellent exposures of pre-rift and syn-rift rocks in the eastern and western zones of the rift offer good opportunities for studying the structural geology of the rift.

The three half grabens of the Suez rift include several rift blocks. A rift block is defined as an area with a group of second-order (relatively small) fault blocks and is separated from adjacent rift blocks by major faults. The exposed rift blocks in the eastern part of the rift (in western Sinai) belong mainly to the northern and central half grabens (Fig. 2) whereas limited exposures of SW dipping rocks in the extreme southwestern part of Sinai belong to the southern half graben (Moustafa & Helmy 1985). The Araba, Durba, Ekma, Nezzazat and Baba blocks (Fig. 2) belong to the central (NE-dipping) half graben of the rift whereas the Sudr block belongs to the northern (SW-dipping) half graben. Each of these blocks has a consistent direction of dip. The Hammam Faraun block occupies an intermediate location between the NE dipping blocks to the south and the SW-dipping blocks to the north (Fig. 2). Moustafa (1976) delineated the accommodation zone that separates the northern and central half grabens of the Suez rift (his Galala–Zenima hinge zone) through the middle of the Hammam Faraun block, some distance to the south of where it should be. Moustafa & Abdeen (1992) mapped the southern part of the Hammam Faraun block and noticed local changes in the dip direction. Similar changes in dip direction also characterize the nearby offshore area (Khalil 1994) as well as the northern part of the Hammam Faraun block (area lying north and northeast of Gebel Hammam Faraun itself). It is evident that most of the Hammam Faraun block represents the eastern (onshore) part of the accommodation zone between the northern and central half grabens. This accommodation zone is herein called the Gharandal accommodation zone after Wadi Gharandal that drains the middle part of the Hammam Faraun block and exists within the accommodation zone itself.

Excellent exposures in the Hammam Faraun block offer a good opportunity for studying the nature of deformation and internal structure of the Gharandal

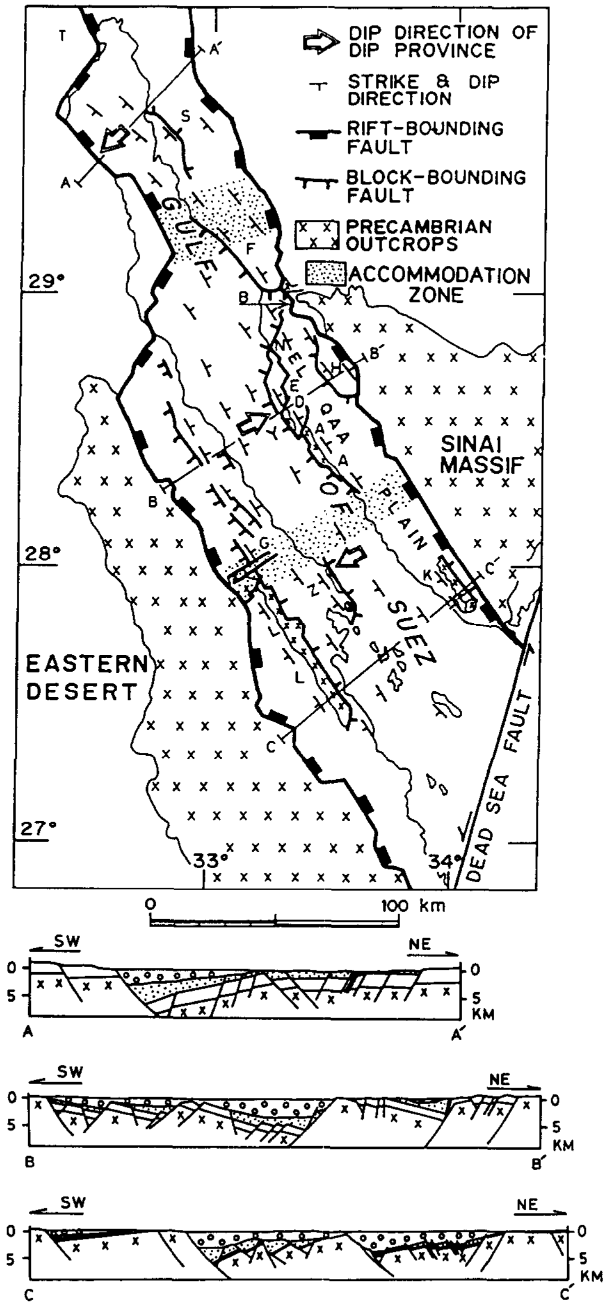


Fig. 1. Dip provinces (half grabens) and rift blocks in the Suez rift (see Fig. 2 for the names of these rift blocks). Width and location of the accommodation zones are approximate. Structural cross sections through the three half grabens are after Patton *et al.* (1994). Symbols designate: basement rocks (crosses), pre-rift sediments (blank), syn-rift clastics (stippled), and syn-rift evaporites and post-rift sediments (circles).

accommodation zone. The northern part of the block (area extending from Wadi Wasit to Wadi Wardan) was mapped in the field in the present study on a scale of 1:40,000 and is about 1700 km^2 in size. The mapping results of this area, as well as those of the southern part of the block (Moustafa & Abdeen 1992), form the core of the present study of the Gharandal accommodation zone.

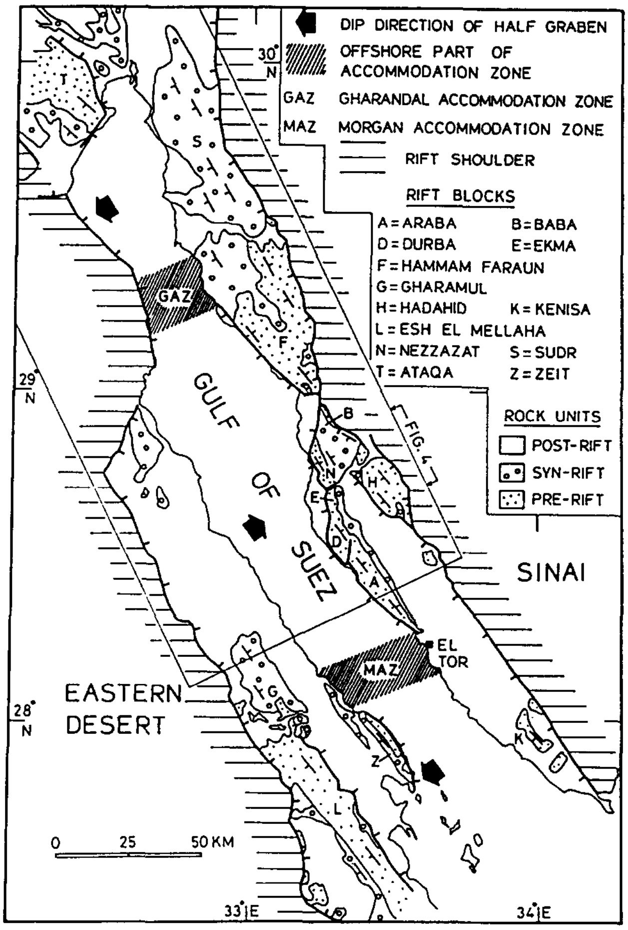


Fig. 2. Simplified map showing pre-rift and syn-rift rocks exposed on both sides of the Suez rift (modified after Garfunkel & Bartov 1977). Notice that most of the rocks on the eastern side of the rift belong to the northern and central half grabens.

GEOLOGIC SETTING OF THE HAMMAM FARAUN BLOCK

The Hammam Faraun block includes a complete section of pre-rift and syn-rift rocks. Pre-rift (pre-Miocene) sedimentary rocks overlie the Precambrian igneous and metamorphic basement rocks and have a cumulative thickness of about 2000 m. They are overlain by a complete syn-rift (Miocene) section that reaches a thickness of about 800 m (Fig. 3). Corresponding Miocene sediments in the Gulf of Suez itself are much thicker and represent faster rates of deposition in the gulf. Post-rift sediments are mainly Quaternary in age and occupy the topographically low areas in the form of wadi alluvium and small, relatively thin alluvial terraces.

Pre-rift rocks are intruded by basalt dikes and sills of Early Miocene age (22–24 Ma old; Steen 1984, Moussa 1987) marking the onset of rifting (Moustafa 1993). Basalt flows of the same age also exist in the southern part of the block (Moustafa & Abdeen 1992). The syn-rift (Miocene) sedimentary section of the Hammam Faraun block includes a basal clastics unit and an upper evaporites unit (Sadek 1959, Thiebaud & Robson 1979) which includes a white porous limestone unit near its top (Nullipore rock of Sadek 1959), Fig. 3.

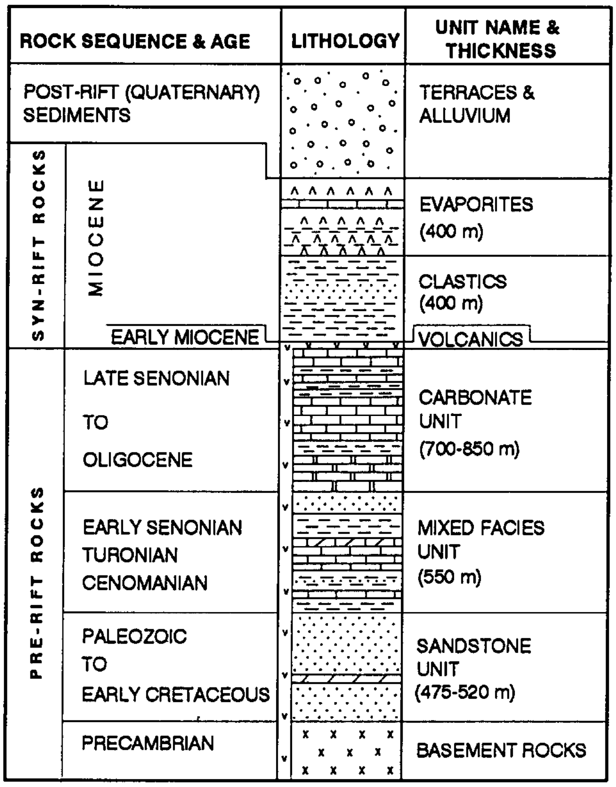


Fig. 3. Simplified stratigraphic section of the Hammam Faraun block.

As already stated, the Hammam Faraun block occupies an intermediate location between the NE-dipping rift blocks of the central half graben of the Suez rift and the SW-dipping blocks of the northern half graben. The NE-dipping rift blocks of the central half graben are bounded by major SW-dipping faults (Fig. 4). Such faults are clearly seen on the western (updip) side of each of the Nezzazat, Ekma, Durba, Araba, Baba and Hadahid blocks (Fig. 4). Offshore structures also portray the same relations, as in the October (Lelek *et al.* 1992), Belayim and Bakr–Gharib, as well as the Ramadan and July blocks (Abdine 1981); Fig. 4. Each of these rift blocks has a predominant NE dip and is bounded on its updip side by a major SW-dipping normal fault. As an example, the major fault bounding the western (updip) side of the October block has a down-to-the-southwest throw equal to about 1220 m (Lelek *et al.* 1992).

The SW-dipping rift blocks of the northern half graben are bounded by down-to-the-northeast faults. The number of rift blocks in this half graben is, however, small compared with the central half graben. This is probably related to the fact that the northern part of the rift was affected by a smaller amount of extension compared with the central and southern parts (Colletta *et al.* 1988). The SW dip is predominant in the Sudr block and its offshore extension, the Darag block and the Ataqa block (western onshore area of the Gulf of Suez; Fig. 4). The NE-dipping faults bounding these blocks exist on the western side of the Darag block (Darag Fault of Moustafa & El Shaarawy (1987) whose throw is equal to 5400 m), the northeastern (updip) side of the Ataqa block, as well as the updip side of the Darag block (also marking the western side of the Sudr block; Fig. 4).

The Hammam Faraun block is elongated in a northwest–southeast direction for about 65 km (Fig. 5). The width of the block changes from 13 km in the south to 32 km in the north. It is bounded on the east by the rift-bounding fault which consists of several segments oriented north-northwest and north-northeast linked together in a zigzag pattern. In the east-central part of the block (west and northwest of Ras Um Maghrab; Fig. 5), the block is separated from the rift shoulder by a SW-facing monocline instead of a down-to-the-southwest

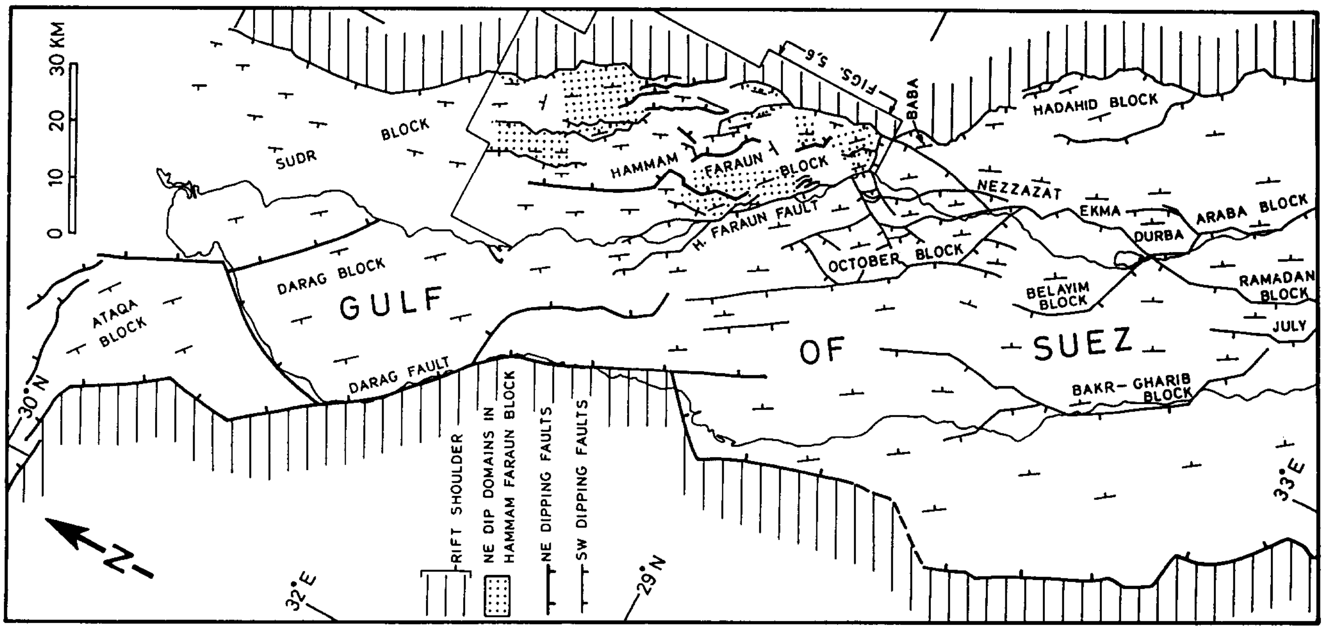


Fig. 4. Structural map of the northern part of the Suez rift showing the SW-dipping rift blocks of the northern half graben, most of the NE-dipping rift blocks of the central half graben and the intervening areas of the Gharandal accommodation zone. Offshore data are compiled from Moustafa & El Shaarawy (1987), Lelek *et al.* (1992) and Patton *et al.* (1994). See Fig. 9 for the sources of onshore data and Fig. 2 for location.

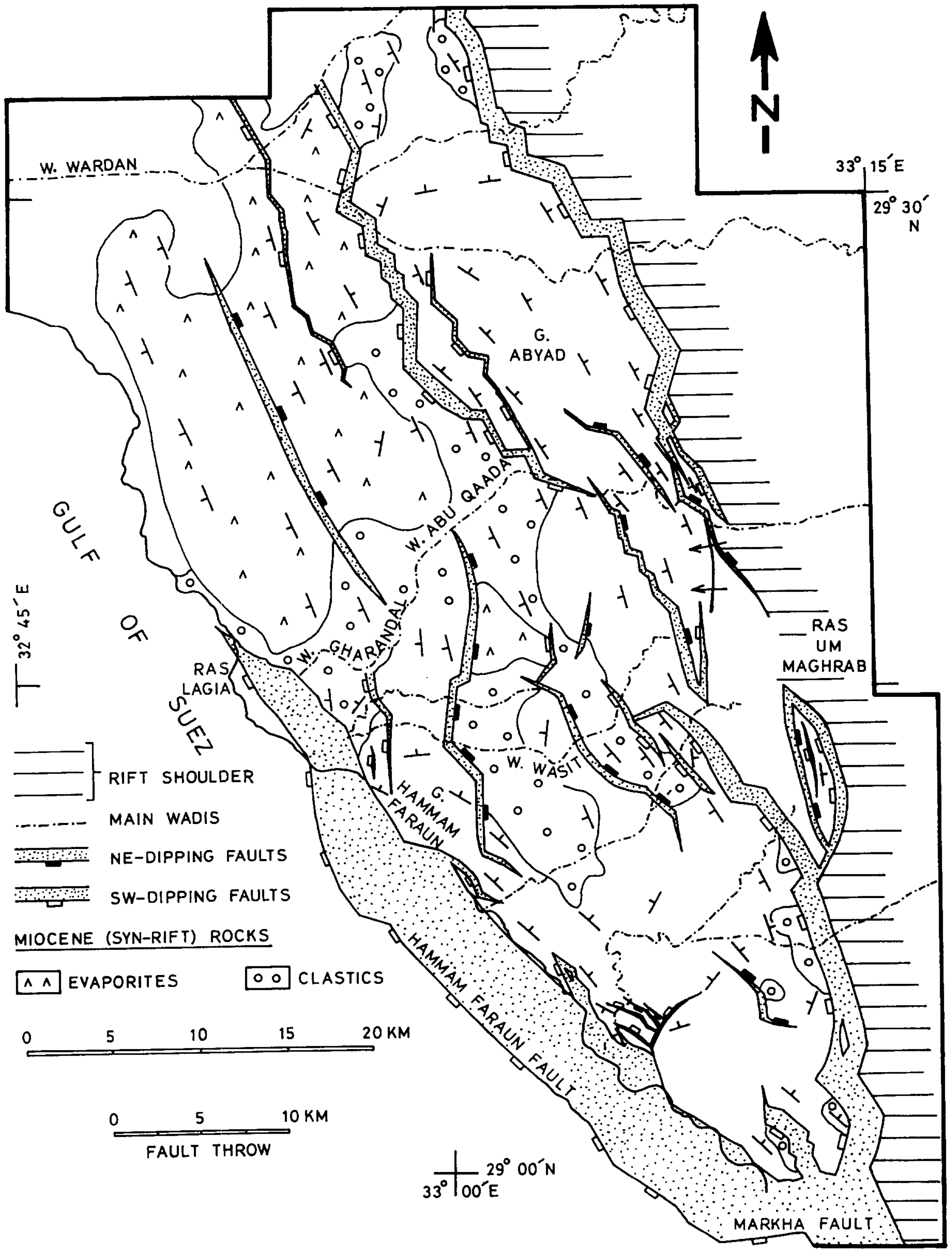


Fig. 5. Faults dissecting the Hammam Faraun block. Faults with throw amount equal to or exceeding 200 m are marked by double lines whose spacing is proportional to the amount of throw according to the indicated bar scale of throw. Fault throws were determined by field mapping except for the Hammam Faraun Fault whose throw was determined by Moustafa & El-Shaarawy (1987) using surface and subsurface data. Present-day fault traces coincide with the footwall segments of each double line shown. Distribution of syn-rift (Miocene) rock units is also shown. See Fig. 4 for location.

fault. Horizontal bedding characterizes the rift shoulder, whereas the downthrown rocks close to the rift-bounding fault generally have a NE dip, indicating a listric nature for this fault. Other faults in the block itself are most probably planar as their hangingwall and footwall blocks are parallel. The throw of the rift-bounding fault of the Hammam Faraun block has a maximum value of 1850 m in its extreme southeastern part, whereas in the northeastern part of the block, the throw decreases to 1050 m (Fig. 5).

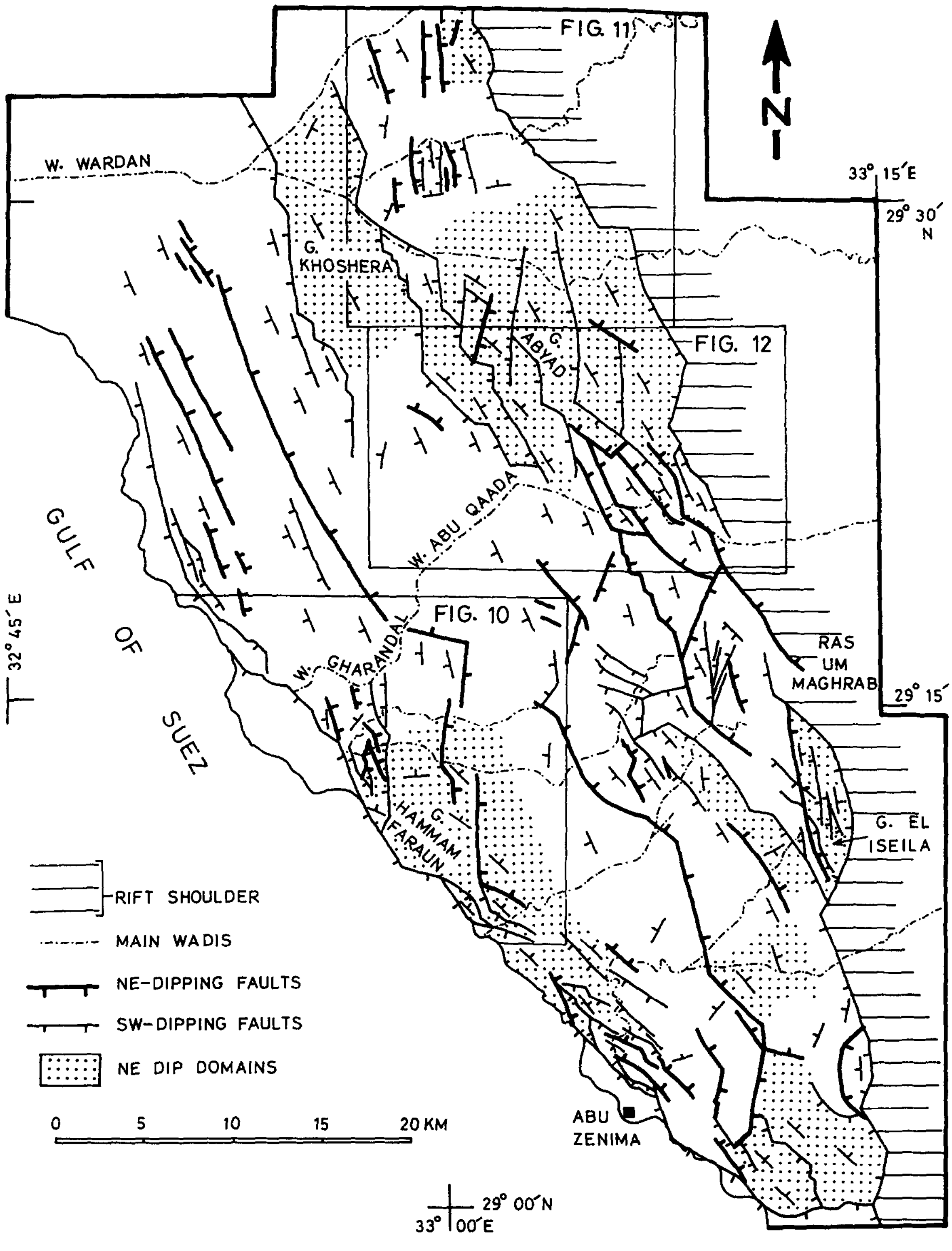


Fig. 6. Dip domains in the Hammam Faraun block and their relationship to the NE- and SW-dipping faults. See Fig. 4 for location.

The western edge of the Hammam Faraun block is marked by a major, northwest–southeast oriented normal fault with downthrow toward the southwest (the Hammam Faraun Fault of Moustafa & El Shaarawy 1987, whose throw is 4800 m). This fault controls the coastline of the Gulf of Suez in several places and extends as far north as the downstream area of Wadi Gharandal (Fig. 5). According to Patton *et al.* (1994), the Hammam Faraun Fault extends offshore northwestwards for about 20 km in the same direction before it dies out.

The southern edge of the Hammam Faraun block is marked by an east–west oriented major normal fault (Markha Fault, Fig. 5) whose throw is equal to about 3500 m (Moustafa 1993). The boundary between the Hammam Faraun block and the Sudr block that lies to the north is not marked by a major fault. This boundary is roughly located at Wadi Wardan. The Hammam

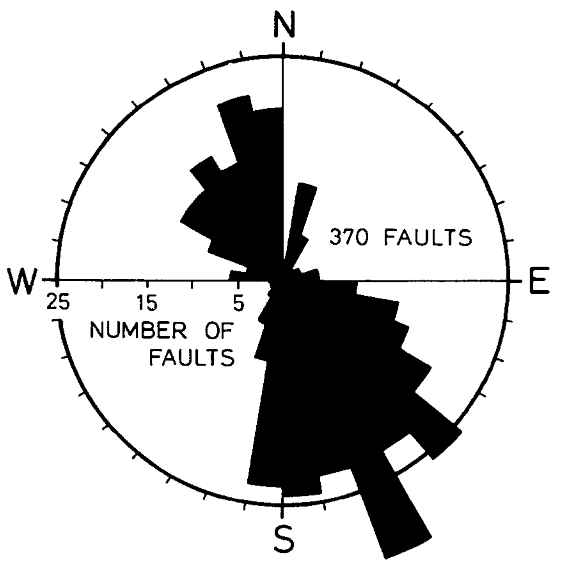


Fig. 7. Rose diagram of the mapped faults of the Hammam Faraun block. Fault strikes are plotted at 90° less than their dip direction, i.e. faults plotted in the northwest quadrant have NE dip and so on.

Faraun block itself is highly dissected by a large number of normal faults oriented mainly north-northwest–northwest and north-northeast–north–south. The maximum amount of throw on these intra-block faults is 650 m (Fig. 5).

The pre-Miocene and Miocene rocks of the Hammam Faraun block have NE or SW dip direction at angles ranging from 4 to about 20°. Several dip domains characterize the block. The NE dip domains exist in the southernmost part of the block, including the coastal area extending from Gebel Hammam Faraun to the vicinity of Abu Zenima, Gebel El Iseila and its neighborhood, the area surrounding Gebel El Abyad and Gebel Khoshera (Fig. 6). The SW dip domains exist in the rest of the block and generally seem to be dominant in the northwestern and central parts of the block (Fig. 6).

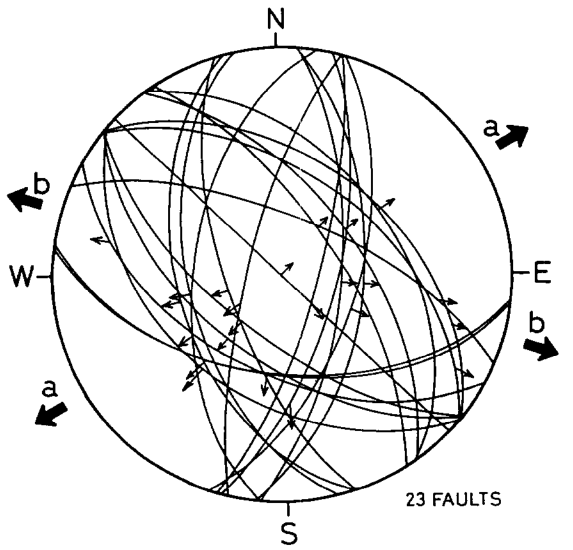


Fig. 8. Lower hemisphere, equal area projection of 23 fault surfaces in the Hammam Faraun block and their slickenside lineations (small arrows). Heavy arrows (a and b) represent two different directions of extension. See text for details.

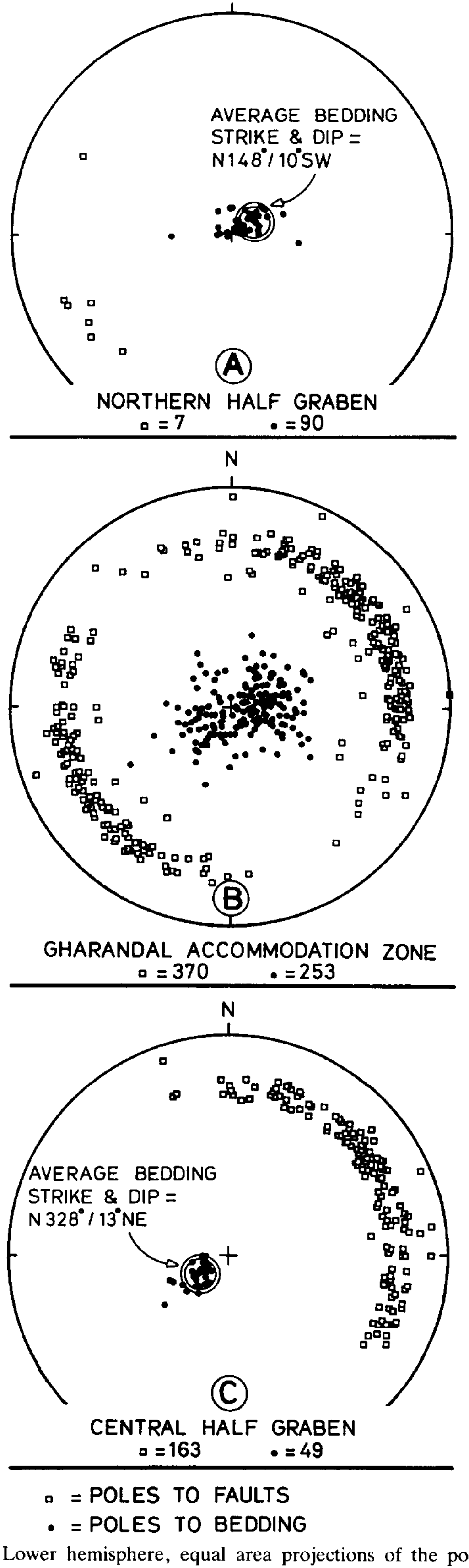


Fig. 9. Lower hemisphere, equal area projections of the poles of bedding and fault planes in the northern half graben (A), Gharandal accommodation zone (B) and the central half graben (C). Center of double circle in diagrams (A) and (C) represents average pole to bedding. Data for the northern half graben are from Sadek (1926), Bowles & Chata (1946), Iskander (1946) and Moustafa & El Shaarawy (1987). Data for the accommodation zone are from the field mapping of the present study as well as Moustafa & Abdeen (1992). Data for the central half graben are from Chenet *et al.* (1984), Moustafa (1987), Moustafa & Khalil (1987), Lelek *et al.* (1992), Moustafa (1993) and Patton *et al.* (1994).

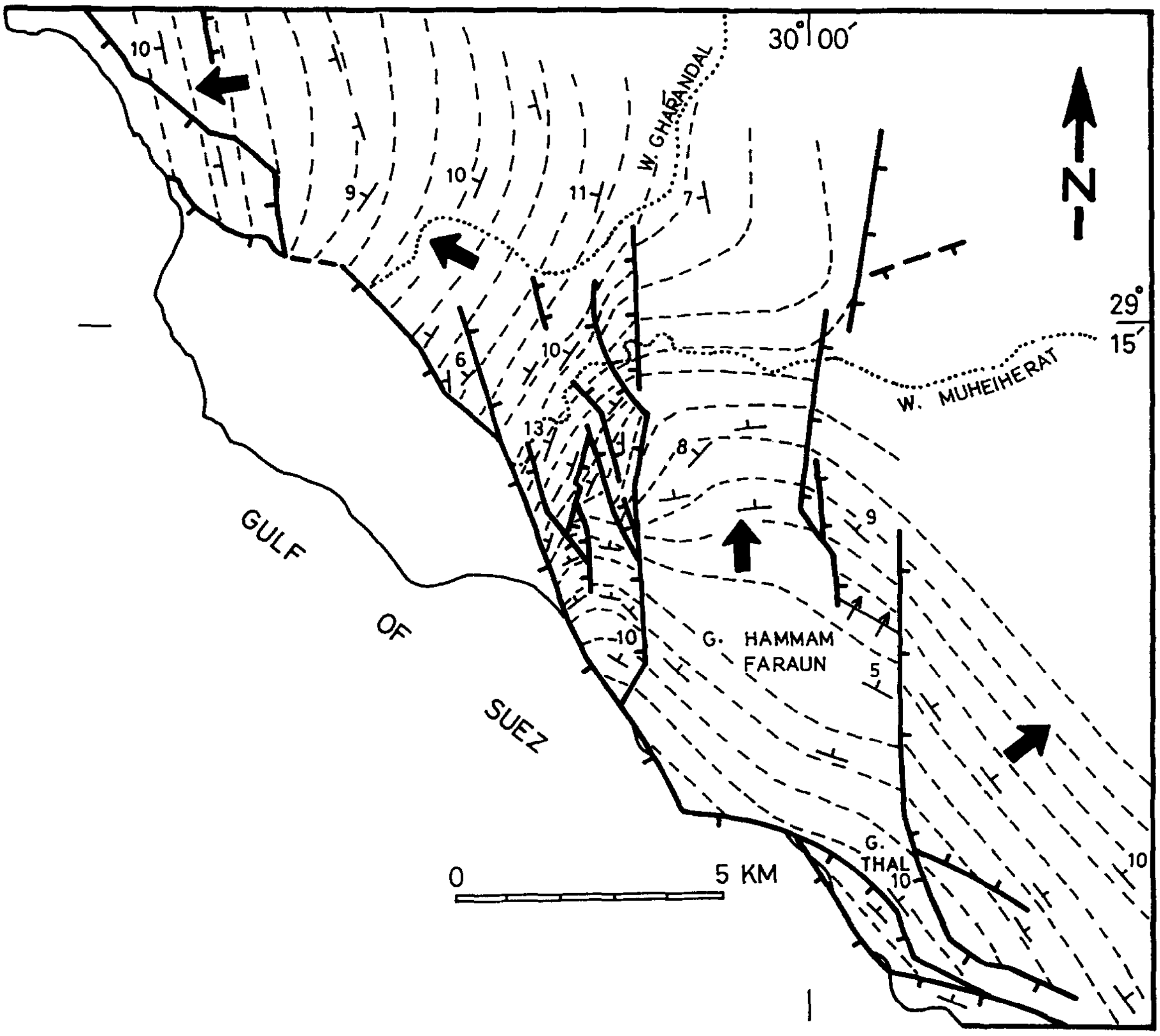


Fig. 10. Small-scale accommodation of dip in Gebel Hammam Faraun and its vicinity. Thick, short arrows show the predominant dip directions. Dashed lines are structural form lines. See Fig. 6 for location and text for details.

The NE dip domains are dissected by SW-dipping faults, whereas the SW dip domains are dissected by NE dipping faults (Fig. 6). A complete Miocene section (including both clastics and evaporites) is preserved in some of the areas having SW dip compared with areas having NE dip where an incomplete Miocene section exists (Fig. 5).

The Gharandal accommodation zone

The accommodation zone between the northern and central half grabens of the Suez rift extends across the northern part of the rift and encompasses most of the Hammam Faraun block in its onshore part as well as the area lying between the Darag and October blocks in its offshore part (Fig. 4). Northwest–Southeast oriented faults in the northern half graben dip toward the northeast, whereas those in the central half graben dip toward the southwest. The NE- and SW-dipping faults of these two half grabens branch and interfinger in the accommodation zone (Fig. 4). In the offshore part of the accommodation zone, the NE-dipping Darag Fault extends southeastward from the northern half graben and also the SW-dipping Hammam Faraun Fault extends northwestward from the central half graben. These two faults overlap before they die out in the accommodation zone (Fig. 4). A small graben is formed between the overlapping segments of these two faults. Seismic reflection profiles indicate that pre-rift and syn-rift rocks in this graben show a gradual change in dip, from NE dip in the southern part of the graben to SW dip in its northern part (Moustafa & El Shaarawy 1987) forming a graben-type 'twist zone' like that described by Colletta *et al.* (1988). Other NE- and SW-dipping faults southwest of this graben interfinger in a similar way (Fig. 4).

In the onshore part of the accommodation zone, a total of 370 faults were mapped, most of which are oriented north-northwest–south-southeast (Figs. 5 and 6). The NE- and SW-dipping faults coexist in the accommodation zone, though SW-dipping faults are more abundant (Fig. 7). Most of the mapped faults consist of several segments oriented north-northwest–south-southeast northwest–southeast, north–south and north-northeast–south-southwest which are joined together in a characteristic zigzag pattern (Figs. 5 and 6). The north-north west-south-southeast and northwest–southeast oriented faults are parallel and sub-parallel to the rift axis and their throw is transferred from one to the other through the north–

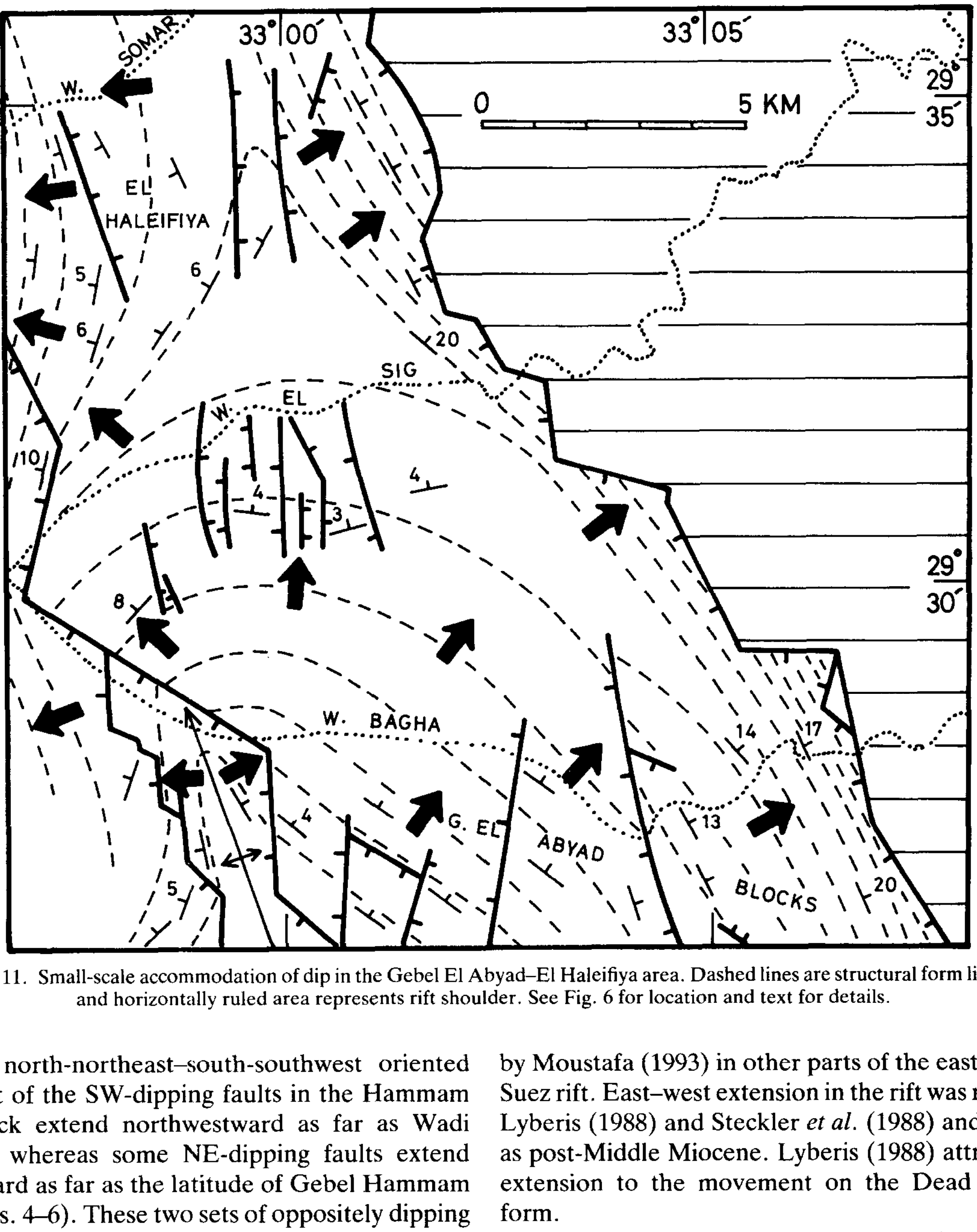


Fig. 11. Small-scale accommodation of dip in the Gebel El Abyad–El Haleifiya area. Dashed lines are structural form lines and horizontally ruled area represents rift shoulder. See Fig. 6 for location and text for details.

south and north-northeast–south-southwest oriented faults. Most of the SW-dipping faults in the Hammam Faraun block extend northwestward as far as Wadi Gharandal, whereas some NE-dipping faults extend southeastward as far as the latitude of Gebel Hammam Faraun (Figs. 4–6). These two sets of oppositely dipping faults enclose some horsts and grabens where they coexist (Fig. 5).

Slickenside lineations on the surfaces of some of the north-northwest–south-southeast oriented (rift-parallel) faults indicate pure dip-slip (normal) movement. On the other hand, diagonal slickensides are found on other faults and indicate normal dip-slip components in addition to right- or left-lateral strike-slip components (Fig. 8). Right-lateral strike-slip components characterize some of the northwest–southeast and west-northwest–east-southeast oriented faults, whereas right- and left-lateral strike-slip components characterize some of the north-northeast–south-southwest oriented faults (Fig. 8). The sense of slip on the mapped faults is compatible with predominant east-northeast–west-southwest oriented extension (arrow a in Fig. 8). Slickenside lineations on a few number of faults also indicate another direction of extension oriented east-southeast–west-southwest (arrow b in Fig. 8). The latter extension direction was also reported by Moustafa (1993) in other parts of the east side of the Suez rift. East–west extension in the rift was reported by Lyberis (1988) and Steckler *et al.* (1988) and was dated as post-Middle Miocene. Lyberis (1988) attributed this extension to the movement on the Dead Sea transform.

With regard to the bedding attitudes in the onshore part of the accommodation zone, NE dip characteristic for the central half graben of the Suez rift can be followed in the Hammam Faraun block, where it dominates most of the southern part of the block. It can also be followed further north in the vicinity of Gebel El Abyad and Gebel Khoshera (Fig. 6). On the other hand, SW dip characteristic for the northern half graben of the rift dominates the northwestern part of the Hammam Faraun block. It also exists between the NE-dipping areas east of Gebel Hammam Faraun (Fig. 6). Therefore, it is obvious that NE and SW dip domains intermix in the onshore part of the accommodation zone. Only north and south of the accommodation zone is one able to recognize a single predominant direction of dip. This is reflected in the stereonet data from the area (Fig. 9). The attitudes of faults also show similar relations in the study area. Faults dip NE in the northern half graben, SW in the central half graben, and both NE and SW in the Gharandal accommodation zone (Fig. 9).

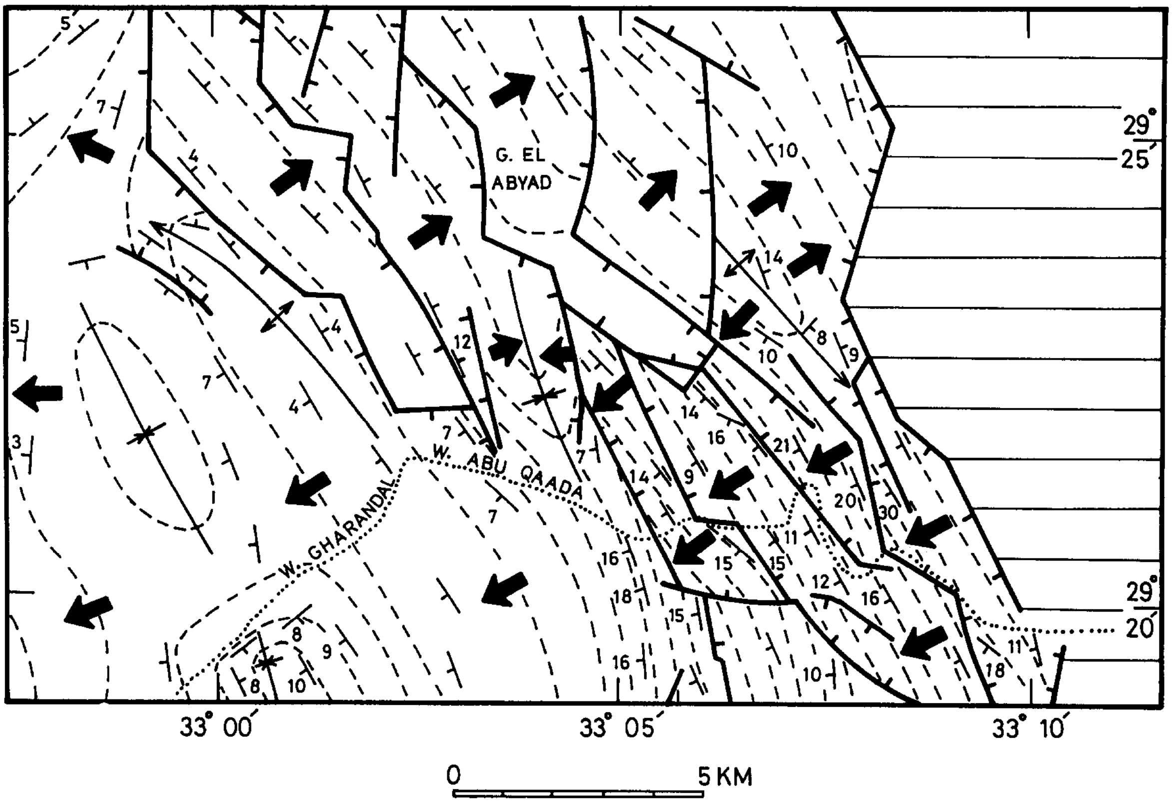


Fig. 12. Small-scale accommodation of dip on both sides of Wadi Abu Qaada. Dashed lines are structural form lines and the horizontally ruled area represents the rift shoulder. See Fig. 6 for location and text for details.

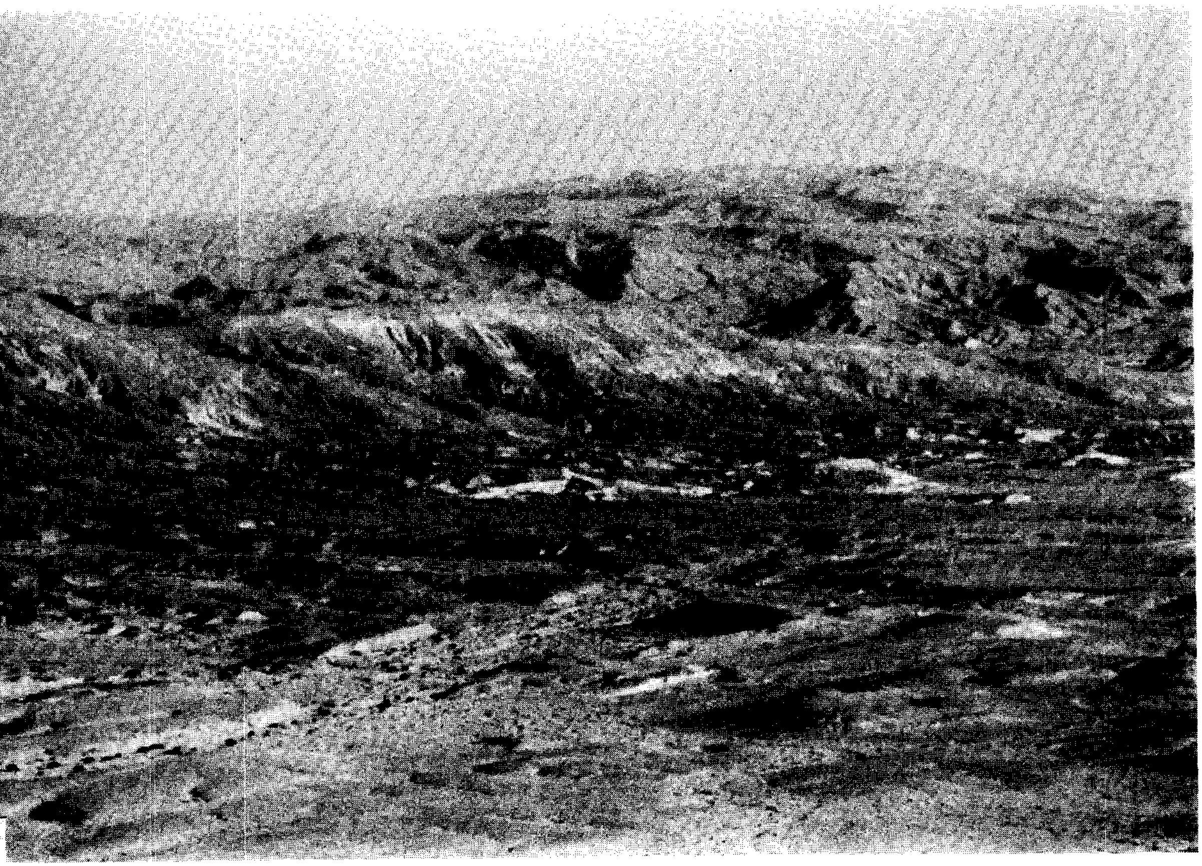
Detailed mapping of the onshore part of the accommodation zone reveals the fact that the change in dip from the northern half graben to the central half graben is not through the development of a single large 'twist zone'. On the contrary, the presence of several intermixed dip domains and the interfingering of oppositely dipping faults are the real characteristics of the onshore part of the Gharandal accommodation zone.

Small-scale accommodation of different tilt directions

Smaller-scale accommodation of dip between the different dip domains within the Gharandal accommodation zone itself is also evident from the detailed surface information of the present study. The NE-dipping rocks in the southwestern part of the Hammam Faraun block (area extending from Abu Zenima to Gebel Hammam Faraun) are followed northwestward (along strike) by SW-dipping rocks in the northwestern part of the block (downstream area of Wadi Gharandal and farther to the northwest; Fig. 6). The change in dip is clear in the northeastern and northwestern sides of Gebel Hammam Faraun. Detailed field mapping of this area reveals the change in dip from 10°NE on the east side of Gebel Hammam Faraun to 10°SW to the northwest of Wadi Gharandal (Fig. 10). The change in dip direction is gradual and proceeds through a change in the strike of the beds from northwest–southeast (in the NE-dipping area) to west–east (with northward dip) and back to southeast–northwest (in the SW-dipping area). Such a change in the bedding attitude defines a northward plunging anticline (or 'twist zone') whose hinge area is dissected by several longitudinal (N–S) normal faults (Fig. 10).

A similar example of small-scale accommodation of dip exists in the northern part of the Hammam Faraun block between the NE-dipping rocks of Gebel El Abyad and the SW-dipping rocks of El Haleifiya area (Fig. 11). The NE dip of the Gebel El Abyad blocks is accommodated to the SW dip of the El Haleifiya area in the same way as in Gebel Hammam Faraun (Fig. 10), where a northward plunging anticline is formed and its hinge area is also dissected by several longitudinal (north–south) normal faults (Fig. 11). In both the Gebel Hammam Faraun and the Abyad–Haleifiya areas, the longitudinal normal faults form horsts and grabens.

A third example of small-scale accommodation of dip exists on both sides of Wadi Abu Qaada (Figs. 12–14). To the south of Wadi Abu Qaada are SW-dipping rocks which locally extend to the north and northwest of the wadi (Fig. 12). These rocks dip at angles ranging from 7 to 21° and locally reach a maximum of 30°. The NE-dipping rocks are dominant in the vicinity of Gebel El Abyad (north of Wadi Abu Qaada) where dip angles range from 4 to 14°. The accommodation of NE and SW dips in this part of the Gharandal accommodation zone proceeds through the development of three northwest–southeast oriented folds to the north of Wadi Abu Qaada. These folds developed between the oppositely dipping rocks. A southeastward plunging anticline exists in the eastern part of this locality, a northwest–southeast oriented syncline exists to the south of Gebel El Abyad,



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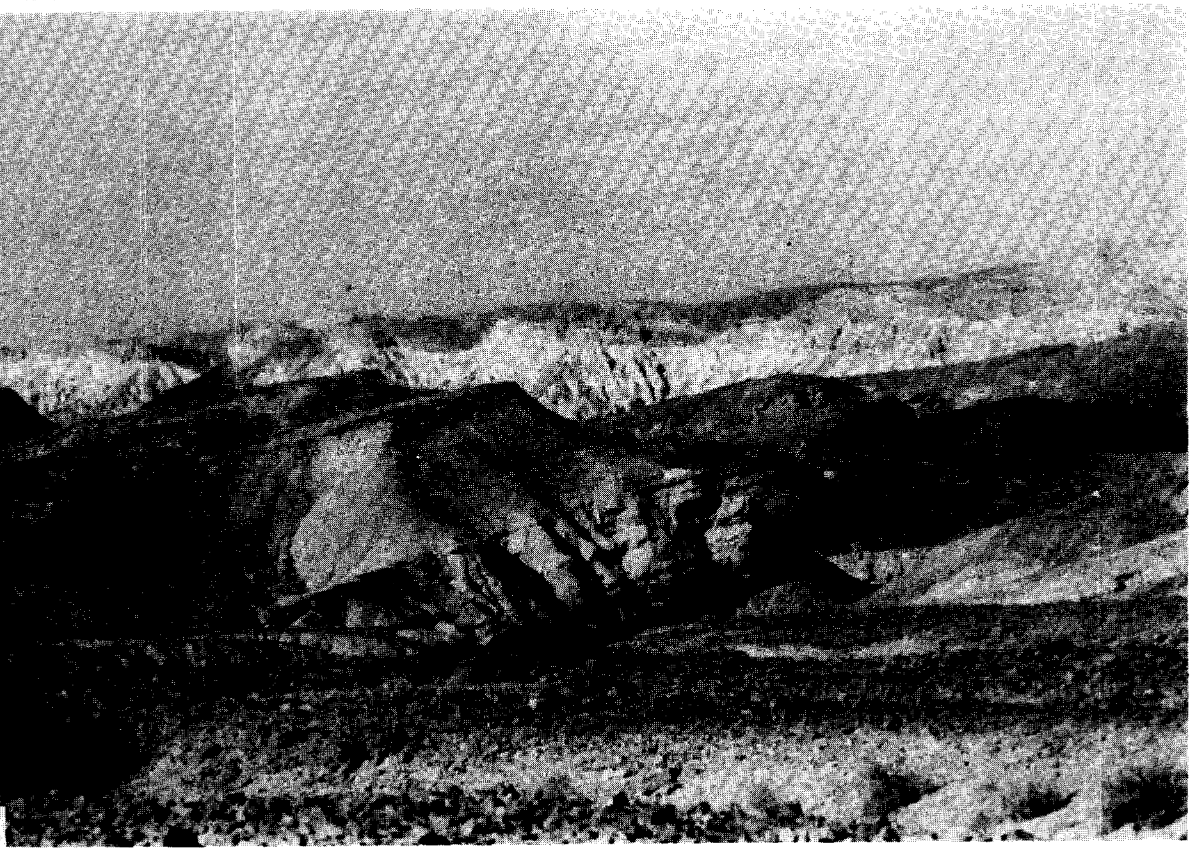

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Fig. 13. Oppositely tilted dip domains on both sides of Wadi Abu Qaada (aligned across the middle part of the photograph from left to right). Rocks south of the wadi (in the background) dip 16–18°SW, whereas those north of the wadi (in the foreground) dip 4–5°NE.

Fig. 14. Oppositely tilted dip domains on both sides of Wadi Abu Qaada. White and light gray outcrops in the background represent NE-dipping Upper Senonian–Eocene rocks of Gebel El Abyad, whereas those in the foreground represent SW-dipping Lower Senonian rocks.

and a northwestward plunging anticline exists to the north of Wadi Gharandal (Fig. 12). These folds exist only where the oppositely dipping beds meet. Folding disappears where a single dip direction becomes dominant. Faulds *et al.* (1990) mapped comparable open–tight folds in the accommodation zone of the central Black Mountains (northwest Arizona) and southern Eldorado Mountains (southern Nevada), Basin and Range region.

DISCUSSION

The results of the present study of the onshore part of the Gharandal accommodation zone indicate that this zone is broad (about 60 km wide) and characterized by intermixing dip domains and interfingering conjugate normal faults forming several horsts and grabens. Rift-parallel faults generally show pure dip-slip normal displacement. Transverse strike-slip faults parallel to the elongation of the accommodation zone are lacking.

In contrast to the Gharandal onshore area, the Morgan (Moustafa 1976) accommodation zone that lies between the central and southern half grabens of the Suez rift (Fig. 2) is narrower (maximum width 20 km; Moustafa & Fouda 1988) and includes several transverse strike-slip faults. These show the effect of torsional strain related to the opposite tilt directions of the fault blocks on both sides of the accommodation zone. Transverse faults orthogonal to the rift were mapped in the western onshore part of the Morgan accommodation zone (Moustafa & Fouda 1988, Coffield & Schamel 1989) and in the offshore area (North Zeit transfer zone; Colletta *et al.* 1988). Intermixing dip domains are not clear in the western onshore part of the Morgan accommodation zone. The frequent transverse faults in this accommodation zone (or at least in its western onshore part) were attributed to the effect of pre-rift structures (Moustafa & Fouda 1988). The contrast between the onshore parts of each of the Morgan and Gharandal accommodation zones can be attributed mainly to the presence of pre-rift structures in the former area.

Lister *et al.* (1986) realized a difference in the internal structure of the accommodation zones of passive continental margins and continental rifts. At passive continental margins (where extension is greater), a few transverse, discrete strike-slip faults exist. These are absent in continental rifts (like the East African rifts) where extension is less (Lister *et al.* 1986). Lister *et al.* (1986) attributed such changes in the internal structure of accommodation zones to the difference in the amounts of extension in these two tectonic settings. In regions of relatively small extension, dispersed faulting throughout the accommodation zone adjusts along-strike changes in normal fault geometry. On the other hand, in regions of large extension like passive continental margins, broad accommodation zones are dissected by transverse strike-slip faults. Detailed study of such transverse strike-slip faults in accommodation zones indicates the effect of torsional strain resulting from the opposite tilt directions and transport of tilted fault blocks away from the breakaway faults in adjacent half grabens (Chapin 1978, Moustafa & Fouda 1988, Coffield & Schamel 1989, Faulds *et al.* 1990).

The southern part of the Suez rift experienced greater extension than its northern part (Colletta *et al.* 1988, Richardson & Arthur 1988, Patton *et al.* 1994). According to Colletta *et al.* (1988), the amount of extension in the Suez rift is 5 km (10%) in the north and 20 km (26%) in the south; according to Patton *et al.* (1994), it is 10–16 km in the north and 30 km in the south. Despite the southward increase in extension in the Suez rift, the presence of a broad deformed zone with superimposed transverse strike-slip faults is not evident in the southern (Morgan) accommodation zone of the rift. Structures mapped in this accommodation zone (Moustafa & Fouda 1986) indicate the rejuvenation of pre-rift structures by strike-slip movement, whereby transverse strike-slip faults dominate a relatively narrow accommodation zone. On the other hand, no transverse strike-slip faults dissect the mapped part of the northern (Gharandal) accommodation zone which experienced relatively smaller extension. Therefore, the Suez rift does not lend support to (neither disproves) Lister *et al.*'s (1986) model of the development of transverse strike-strike faults in accommodation zones with increased extension.

CONCLUSIONS

Detailed study of the Gharandal accommodation zone reveals the internal structure and deformation of accommodation zones of continental rifts. In this part of the Suez rift, where extension is relatively small, the accommodation zone is dominated by intermixing dip domains characteristic of the two half grabens lying on both sides of the accommodation zone. Rift-parallel faults of the two half grabens dip in opposite directions. They extend into the accommodation zone, where they interfinger (before they die out), forming several horsts and grabens. Small-scale accommodation of opposite dip directions between the dip domains in the accommodation zone itself takes place by gradual changes in the strike and dip direction of the beds from one dip domain to the other leading to the development of some rift-parallel folds (twist zones) between the dip domains.

Comparison of the internal structure of the onshore parts of the northern (Gharandal) and southern (Morgan) accommodation zones of the Suez rift clearly indicate the effect of pre-rift structures on the width and internal structure of accommodation zones. Where pre-rift structures exist at high angle to the rift (e.g. western onshore part of the Morgan accommodation zone), the accommodation zone is relatively narrow and dominated by transverse strike-slip faults. Strike-slip movement on these faults is related to the torsional strain resulting from the opposite tilt directions of adjacent half grabens. On the other hand, where pre-rift structures are missing (e.g. eastern onshore part of the Gharandal accommodation zone), or do not lie at high

angle to the rift, the accommodation zone is relatively broad and is dominated by intermixing dip domains and several horsts and grabens formed by rift-parallel faults extending from adjacent half grabens of opposite tilt directions.

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