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Controls on the development and evolution of transfer zones: the influence of basement structure and sedimentary thickness in the Suez rift and Red Sea

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Abstract—Detailed field mapping of the northern part of the Gebel Um Hammad-Gebel Duwi area on the western margin of the Red Sea indicates oppositely dipping rift blocks separated by a 60-km long, WNW–ESE-oriented, reactivated pre-rift fault of Late Precambrian age parallel to the Najd fault system of the Arabian–Nubian Shield. This fault forms the Sudmain transfer zone between the oppositely tilted half-grabens in the northwestern Red Sea region and is associated by a SE-plunging syncline. This pre-rift fault was reactivated by dextral transtension during the Late Oligocene rift opening.

Compared to the transfer zones of the Suez rift, the Sudmain transfer zone is narrower. The Gebel Sufr El Dara transfer zone (between the southern and central half-grabens of the Suez rift) is 20 km wide and is also controlled by pre-rift faults oriented ENE–WSW. The latter were reactivated by left-lateral slip during the rift opening. On the other hand, the Gharandal transfer zone (northern part of the Suez rift) is 40–60 km wide and is not affected by the pre-rift faults in the Precambrian basement, perhaps owing to the large thickness of pre-rift sedimentary rocks in this area. The location of the Gharandal transfer zone was controlled by a NE–SW-oriented 'Syrian arc' fold. This study suggests that the northward increase in the width of transfer zones as well as the northward decrease in the length of half-grabens in the Suez–northern Red Sea rift system are related to the corresponding increase in the thickness of pre-rift Phanerozoic sedimentary section from about 400 m in the south to about 1800 m in the north.

INTRODUCTION

Transfer zones exist between adjacent half-grabens of different tilt directions and represent the areas through which throw is transferred from the bounding fault of one half-graben to that of the next. Transfer zones of rift basins show a wide range of deformation including either discrete faults affected by normal slip, oblique-slip or strike-slip (Chorowicz and Sorlien, 1992), or wide complex zones of pure normal faulting, transtension (Maler, 1990; Boccaletti *et al.*, 1992; Lacombe *et al.*, 1993), or broad warping (Colletta *et al.*, 1988). The term transfer zone (Gibbs, 1984; Morley *et al.*, 1990) is used for zones of variable scale from a single fault to a broad area. A single fault acting as a transfer zone may link two normal faults (e.g. Moustafa and 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 and 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 and 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 transfer 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 and Fouda, 1988; Coffield and Schamel, 1989; Ebinger, 1989; Faulds *et al.*, 1990; Morley *et al.*, 1990; Nelson *et al.*, 1992; Gawthorpe and Hurst, 1993; Patton *et al.*, 1994), their internal structure and the reversal in tilt directions of adjacent half-grabens are not well understood. The objective of this study is to unravel the nature of the transfer zone in the northwestern Red Sea region, its internal geometry, style of deformation and relationship to pre-rift structures in the area. The results allow direct comparison of the transfer zone with others of the Suez rift, thereby improving our understanding of the primary controls on their development which may have wider relevance to other rift systems in which similar transfer zones develop.

The Tertiary opening of the Suez and ancestral Red Sea rifts led to the creation of a series of down-faulted blocks that extend northwestwards from the southern end of the Red Sea to Suez city (at the northern tip of the Gulf of Suez). Although most of the areas of these rift zones are presently below sea level, some portions crop out along the rift flanks. Onshore exposures of the Suez rift are located on both sides of the Gulf of Suez (in western Sinai and the northeastern part of the Eastern Desert of Egypt) with an average width of about 25–30 km (Fig. 1). Onshore exposures of the Red Sea ancestral rift in Egypt are located in the narrow coastal strip (about 5 km wide) where syn-rift sediments are located, as well as in the Safaga–Quseir region where both syn-rift sediments and tilted fault blocks are present (Fig. 1a).

The Suez rift is divided into three half-grabens of opposite tilt directions separated by two transfer zones

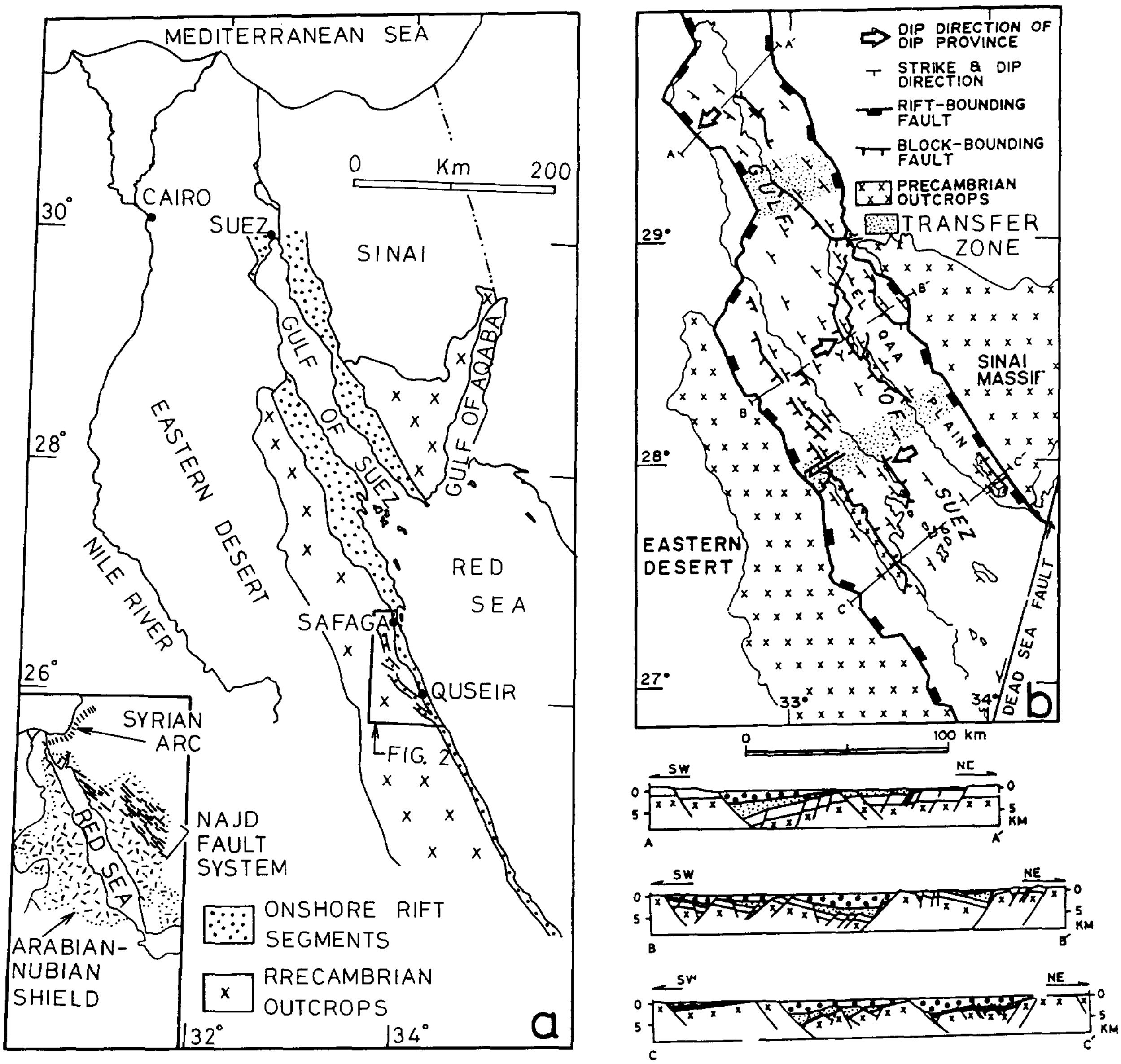

Fig. 1. (a) Location map of the Suez rift and the northwestern part of the Red Sea showing the contrast in the width of the onshore parts of these two rift zones. Inset shows the location of the Najd fault system, Syrian arc and the Arabian–Nubian Shield. (b) Dip provinces (half-grabens) and transfer zones of the Suez rift. 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).

('hinge zones'; Moustafa, 1976). The northern and southern half-grabens have a SW dip whereas the central half-graben has a NE dip (Fig. 1b). Similar relations are also evident in the northwestern Red Sea where a number of rift blocks, with tilt directions alternating along strike, are exposed in the Safaga–Quseir region (Fig. 2). A rift block is defined as a large area (several tens of kilometres in length) that includes several smaller (second-order) fault blocks (a few kilometres in length and width) and is separated from other rift blocks by major faults with throws up to a few kilometres (Moustafa, 1993). Pre- and syn-rift sedimentary sequences are preserved in these blocks in the Safaga–Quseir region and are surrounded by Precambrian basement exposures. The dominant dip directions of the blocks are to the NE or SW, although other dip directions locally exist and may be related to the movements and drag on nearby faults oriented oblique to the rift-parallel faults (Fig. 2).

Five rift blocks with a predominant SW dip direction are located in the northern part of the Safaga–Quseir region. These are (from north to south) the Gebel Um Tagher, Mohamad Rabah, Gebel Gassus, Um El Huetat and Gebel Wasif blocks (Fig. 2). They have an average dip of 18° (Fig. 3a). Six other rift blocks with a NE dip are located in the southern part of the area. These are (from north to south) the Gebel Um Hammad-Gebel Duwi, Anz-Ambagi, Gihania, Gebel Atshan, Zug El Bahar and Gebel Hamadat blocks (Fig. 2). They have an average dip of 19° (Fig. 3b). Syn-rift rocks in the coastal area of the Quseir–Safaga region have a consistent NE dip (Fig. 2) as

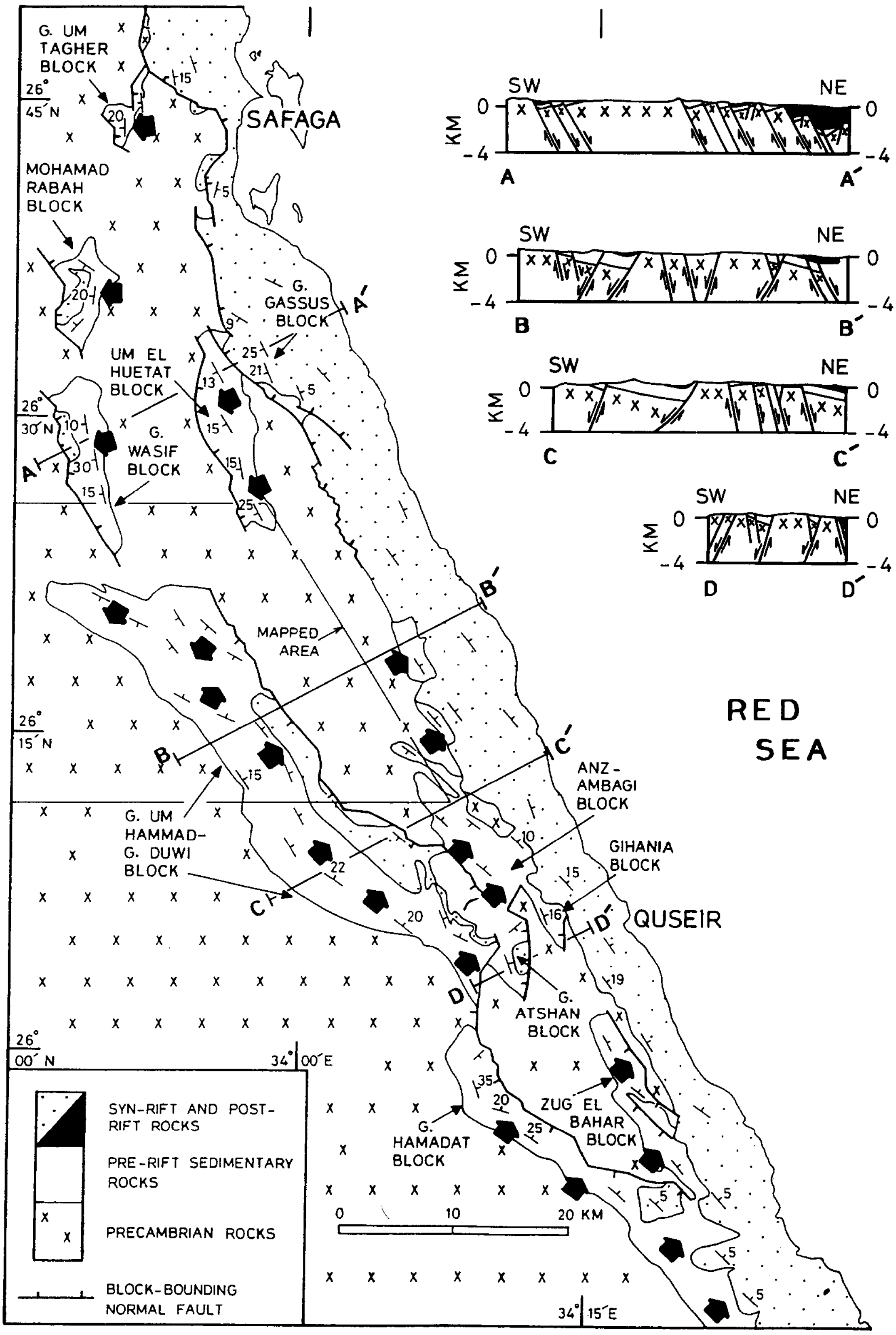

Fig. 2. Tilted fault blocks in the Safaga–Quseir region compiled from Abd El-Razik (1967), Greene (1984), Jarrige *et al.* (1986), Roussel *et al.* (1986) and Thiriet *et al.* (1986). Short bold arrows show dominant dip direction of pre-rift sedimentary rocks. Cross-sections are after Jarrige *et al.* (1986) and Thiriet *et al.* (1986).

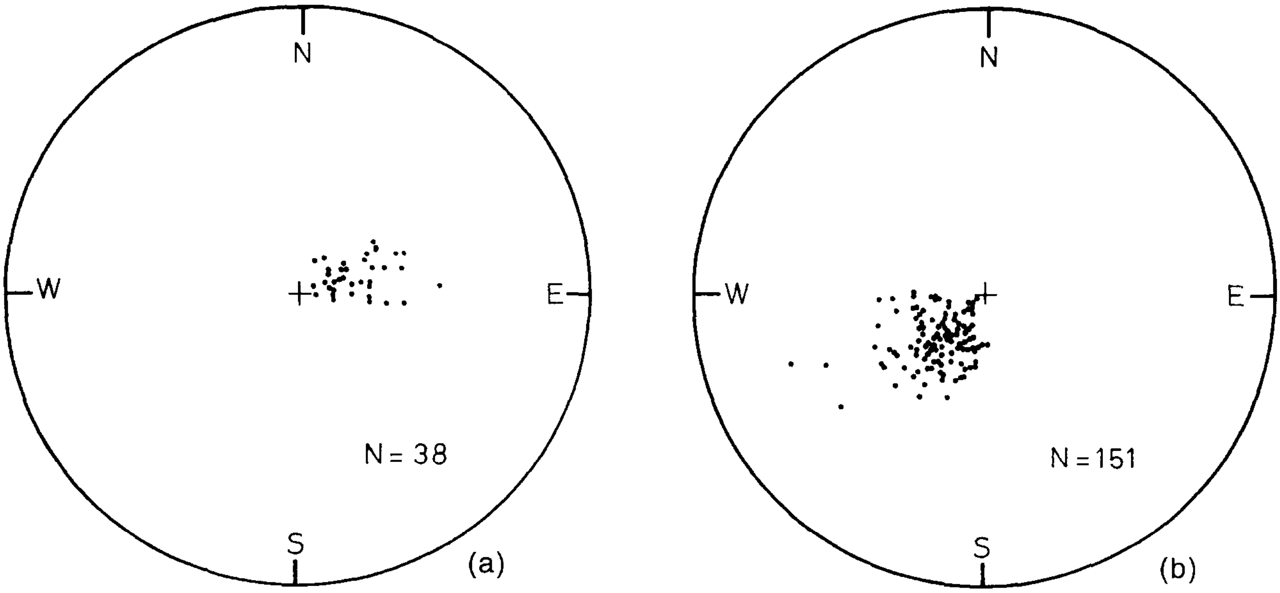

Fig. 3. Lower-hemisphere, equal-area projections of the bedding attitudes of the rift blocks in the Quseir–Safaga region. (a) Northern rift blocks (namely: Gebel Um Tagher, Mohamad Rabah, Gebel Gassus, Um El Huetat and Gebel Wasif blocks). (b) Southern rift blocks (namely: Gebel Hamadat, Zug El Bahar, Gebel Al Atshan, Gihania, Anz-Ambagi and Gebel Um Hammad-Gebel Duwi blocks). Bedding attitudes in the northernmost part of the Gebel Um Hammad-Gebel Duwi block as well as those related to drag on nearby faults in the other blocks are not represented. Sources of data are Issawi *et al.* (1969), Greene (1984), Jarrige *et al.* (1986), Roussel *et al.* (1986), Thiriet *et al.* (1986) and the present mapping.

they are rotated toward the axis of the Red Sea (Jarrige *et al.*, 1990).

The Gebel Um Hammad-Gebel Duwi rift block is the longest and widest block in the Quseir–Safaga region. This block extends for about 50 km in a NW–SE direction and has an average width of about 8.5 km. The northernmost part of this block dips to the SW (Fig. 2), like the northern part of the Quseir–Safaga region. This part of the Gebel Um Hammad-Gebel Duwi Block also includes the zone where the dip direction changes from NE (in the southern rift blocks) to SW (in the northern blocks). An area of approximately 780 km^2 was mapped at a scale of 1:40,000 in the Gebel Um Hammad-Gebel Duwi Block.

STRATIGRAPHY

Basement rocks of the area include Precambrian igneous and slightly metamorphosed sediments (Abdeen *et al.*, 1992). They are overlain by a 430-m thick Late Cretaceous–Middle Eocene sedimentary section (Fig. 4). This sedimentary section includes a predominantly clastic section of four rock units developed on a stable shelf (Nubia Sandstone, Quseir Variegated Shale, Duwi Formation and Esna Shale) overlain by a carbonate section ascribed to the Lower–Middle Eocene Thebes Formation (Youssef, 1949; Strougo and Abul-Nasr, 1981). The Esna Shale has been divided into several units by other workers (Abd El-Razik, 1967; Issawi *et al.*, 1969; Greene, 1984).

A thin section of syn-rift lacustrine sediments (Oligocene Nakheil Formation; El Akkad and Dardir, 1966)

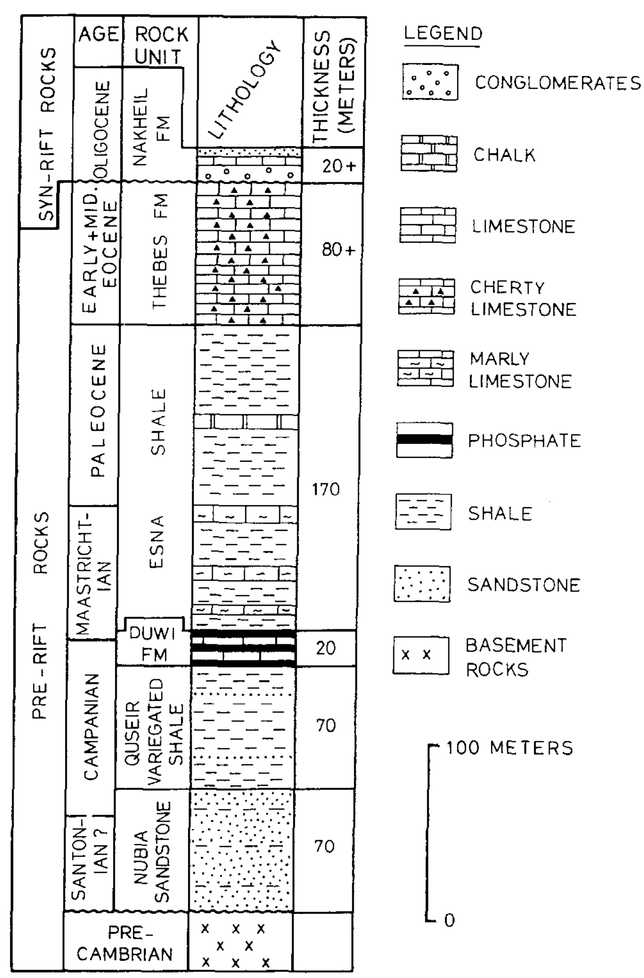

Fig. 4. Composite stratigraphic section of the study area. Age of Cretaceous and Paleocene rocks is modified after Youssef (1957).

overlies the Thebes Formation in the mapped area and consists of yellow–brown iron-stained limestone and rounded chert–pebble conglomerate locally overlain by sandstone. The chert pebbles are derived from the Thebes Formation and retain their originally rounded shape before transportation (Said, 1990, p. 353). Miocene syn-rift sediments are found in other parts of the Safaga–Quseir region (Jarrige *et al.*, 1986; Roussel *et al.*, 1986; Thiriet *et al.*, 1986) but not in the mapped area.

The stratigraphic section can be divided into three mechanical units. The Precambrian basement rocks and the overlying Nubia Sandstone form a brittle unit at the base of the section. This unit is overlain by a fairly thick ductile unit made up of the shales of the Quseir Variegated Shale and Esna Shale. The thin limestone–phosphate unit of the Duwi Formation lies within this ductile shale unit. The limestones of the Thebes Formation as well as the overlying rocks of the Nakheil Formation form a competent unit at the top of the stratigraphic section of the study area. This mechanical–stratigraphic subdivision clearly influenced the style of structural deformation of the rift, as indicated in the next sections.

STRUCTURAL SETTING

Pre- and syn-rift sedimentary rocks are exposed in the northern part of Gebel Um Hammad extending northward to Wadi El Saqi and Gebel Abu Aqarib (Fig. 5). These exposures define large structural blocks down-faulted against Precambrian rocks. The sedimentary rocks have average dips of 13° toward the SW and NE. They are also cut by several NNW–SSE-oriented normal faults, in addition to a few faults of other orientations. Most of the NNW–SSE-oriented normal faults dip toward the ENE (Fig. 6). Fault surfaces are well exposed in the area. Planar segments of these fault surfaces are generally exposed over relatively short distances and indicate that their dip angles range from 50° to 84°. Fault zones with well-developed breccia are generally thin and do not exceed a few tens of centimetres in width. Dragged beds exist on the down-thrown sides of major faults.

A very long WNW–ESE-oriented fault traverses the area and trends diagonally across basement and sedimentary outcrops, hereafter termed the 'Master Fault'. This fault has a relatively wide brecciated zone (several metres thick). It also has an apparent normal slip toward the NNE. The total length of this fault is 60 km defined as a continuous fault on Landsat images. In the northwestern part of the mapped area, the 'Master Fault' juxtaposes pre-rift sedimentary rocks and Quaternary deposits against Precambrian basement rocks. At that locality, the fault is well exposed over a fairly long vertical distance showing a planar fault surface dipping at an angle of 54° toward the NNE. In the central part of the mapped area (northwest of Wadi Sudmain), the 'Master Fault' occupies a very wide zone and splays into two WNW–ESE-oriented faults (Fig. 5). Further to the southeast (outside the boundaries of the mapped area), the 'Master Fault' dips SSW (i.e. in the opposite direction) at an angle of 85° (Abdeen, 1995). The Phanerozoic sedimentary outcrops lying to the north of this fault in the mapped area have a consistent SW dip direction against the fault, whereas those lying south of it have both NE and SW dip directions (Fig. 5). These two areas are called herein the Saqi and Sudmain blocks, respectively, after Wadi El Saqi and Wadi El Sudmain which exist in these blocks.

The Saqi Block is elongated in the WNW–ESE direction, parallel to the 'Master Fault' that bounds it on the south side. Pre-rift sedimentary rocks in this block have a predominant SW to SSW dip at an angle of about 13° (Fig. 7). In the northeastern part of the block, these rocks dip southwestward against a set of NNW–SSE-oriented normal faults which have average dip separation distances ranging from 100 to 200 m (estimated from structural cross-sections). Most of these faults dip ENE forming a group of 'domino-like' fault blocks (Fig. 8, cross-section A–A′). Toward the southern and western parts of the block, the rocks slightly change their dip direction to the SSW (against the 'Master Fault', Fig. 7). Two fault-drag synclines (Ragan, 1973) form along the southern part of the Saqi Block in the pre-rift rocks of the hanging wall of the 'Master Fault' (Figs 7 & 8, cross-sections A–A′ and B–B′) and parallel to it. The dip separation distance on the western part of the 'Master Fault' in the Saqi Block is 650–750 m and decreases to about 400 m on the eastern part in the same block (Figs 7 & 8).

The Sudmain Block lies to the south of the 'Master Fault' and includes sedimentary rocks dipping generally toward the NE at an angle of about 13°. This block is bounded on the east and west by NW–SE-oriented normal faults (Fig. 7). The dip separation distance on the western fault ranges from 200 to 250 m toward the NE, whereas the dip separation distance on the eastern (SW-dipping) fault (Nakheil Fault) is greater and ranges from 1000 m on its northern part (Fig. 8, cross-section C–C′) to 1300 m on its southern part. The Nakheil Fault extends further to the southeast for about 50 km along the eastern side of the Gebel Um Hammad-Gebel Duwi Block (Fig. 2). A large SE-plunging fault-drag syncline forms on the down-thrown side of the Nakheil Fault in the pre- and syn-rift rocks (Figs 7 & 8). Although the rocks of the Sudmain Block show a predominant NE dip direction against the Nakheil Fault, SW-dipping rocks exist in the northernmost part of the block. These SW-dipping rocks form a southeastward gently plunging syncline at their junction with the NE dipping rocks of the rest of the block (Fig. 7). A few NNW–SSE-oriented normal faults dipping parallel to the Nakheil Fault dissect the middle part of the Sudmain Block and have small dip separation distances equal to 30–50 m (Fig. 8, cross-section C–C′). Some oppositely dipping normal faults also dissect the western part of the block (Fig. 7).

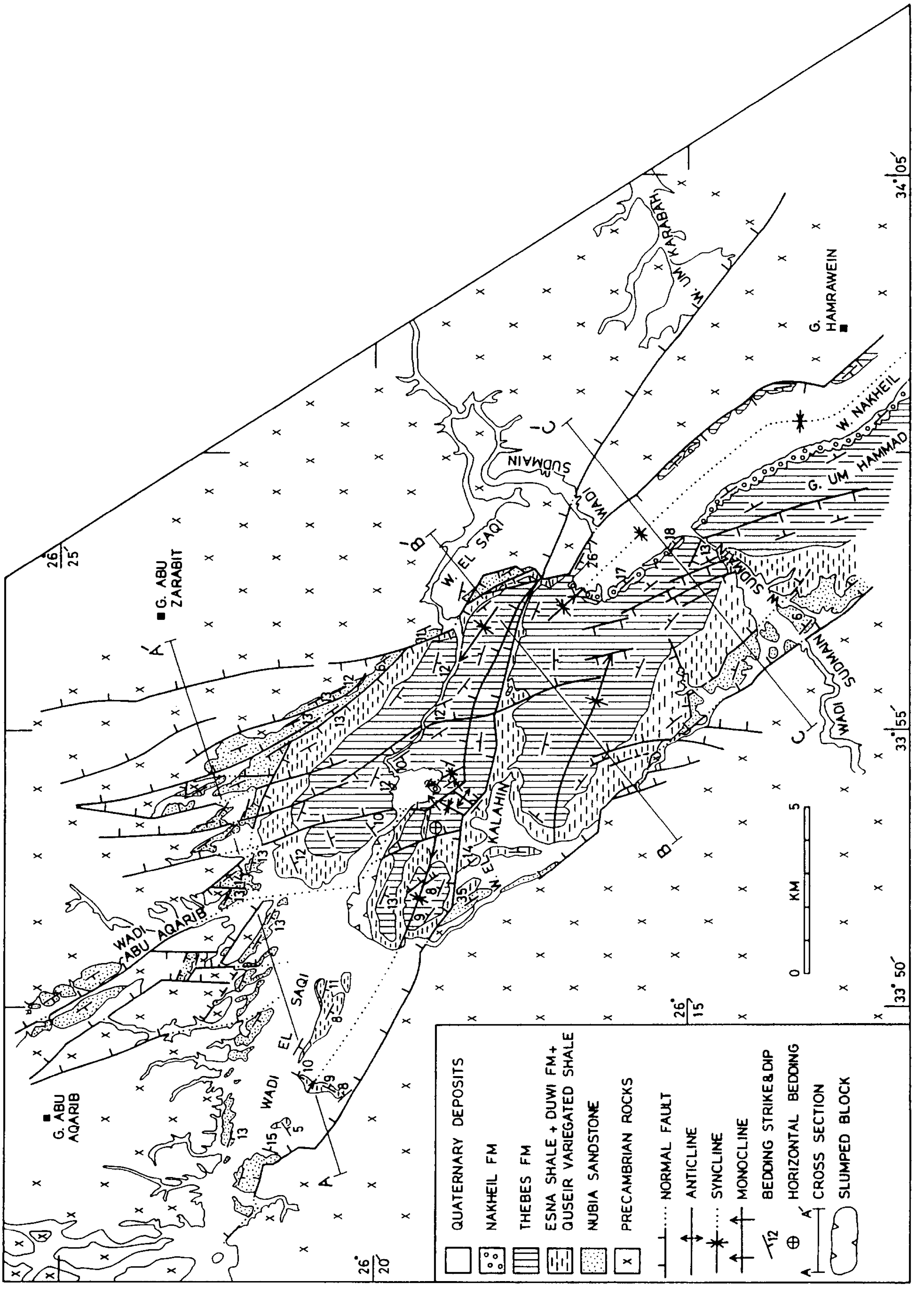

Fig. 5. Simplified geological map of the study area. Cross-sections A–A′, B–B′ and C–C′ are shown in Fig. 8. Notice the extension of the WNW–ESE-oriented 'Master Fault'; for some distance beyond the limits of the Saqi and Sudmain blocks.

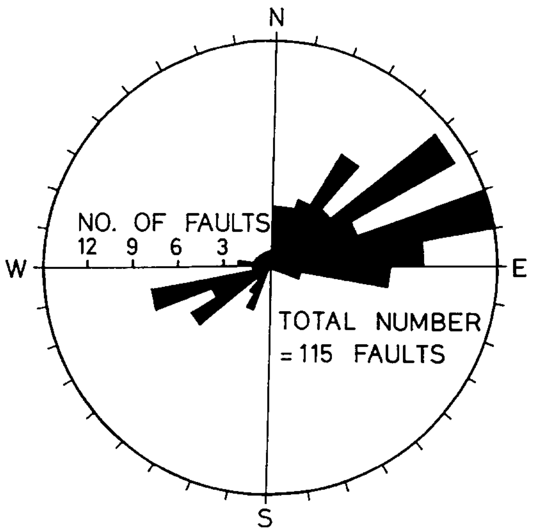

Fig. 6. Rose diagram of the dip directions of the faults mapped in the study area. Notice that the NE-dipping faults are dominant.

STRUCTURAL ANALYSIS

The Saqi and Sudmain blocks are tilted fault blocks bounded by major faults on their down-dip sides, namely the 'Master Fault' and the Nakheil Fault, respectively. These two blocks belong to two half-grabens of opposite tilt directions. Because of the lack of knowledge of the pre-rift attitudes in the areas bounding these two blocks, it is not clear whether the 'Master Fault' and Nakheil Fault are listric normal faults or major planar faults within a larger half-graben complex. Although the exposed uppermost parts of these two faults are planar, it is not possible to assume that the unexposed parts are planar too.

The opposite tilt directions of the Saqi and Sudmain blocks form a SE-plunging syncline in the northernmost part of the Sudmain Block. In addition to this syncline, the 'Master Fault' is also part of the transfer zone between the two blocks and represents a major structural boundary between the two half-grabens to which the two blocks belong. This fault not only separates the two blocks but also extends beyond their limits (Fig. 7). The mapping by Abdeen *et al.* (1992) of the Wadi Queih–Wadi Sudmain area reveals the presence of NW–SE- to WNW–ESE-oriented faults of Late Precambrian age, one of which is the 'Master Fault' of the present study. Regional magnetic anomaly maps of the northwestern Red Sea region (Meshref, 1990) show a probable south-eastward continuation of the 'Master Fault' into the offshore area. According to Abdeen *et al.* (1992), the

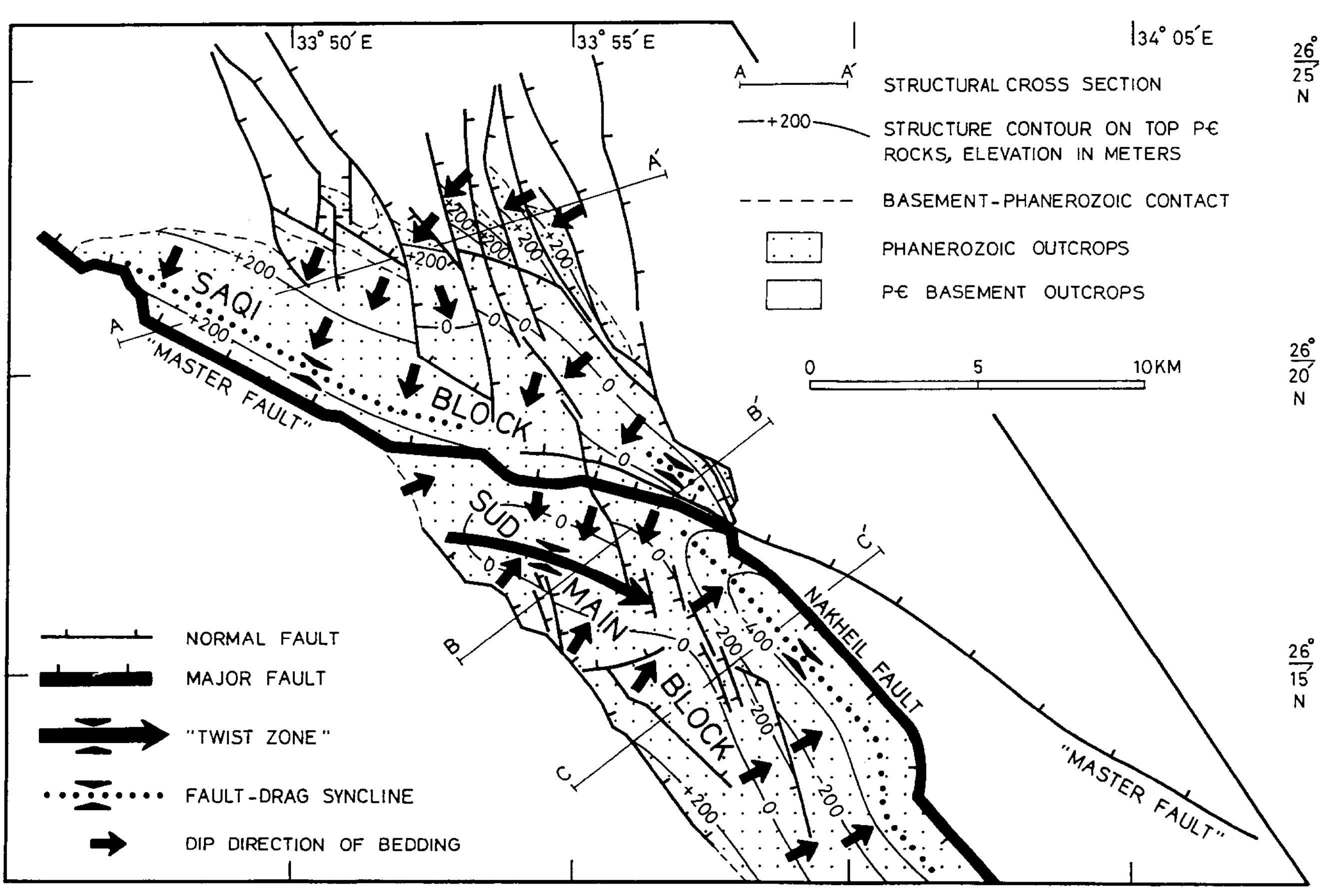

Fig. 7. Simplified structural map of the mapped area. Cross-sections A–A′, B–B′ and C–C′ are shown in Fig. 8. Structural contours of the top of the Precambrian are extrapolated from geological boundaries mapped in the field after subtracting the thickness of the overlying sedimentary rocks.

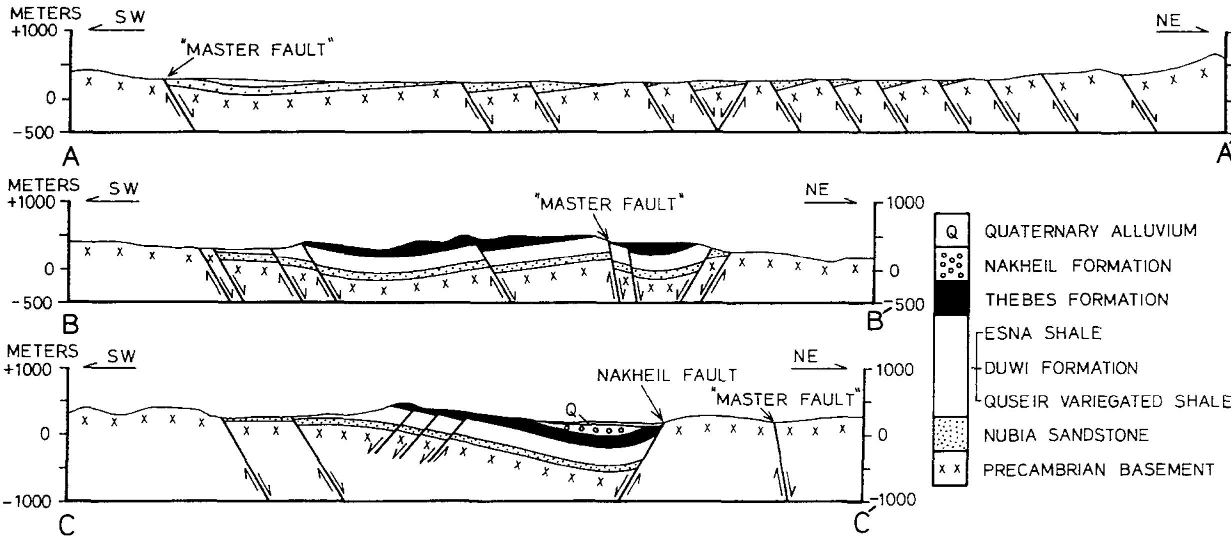

Fig. 8. Structural cross-sections of the mapped area. See Figs 5 and 7 for location.

NW–SE- to WNW–ESE-oriented faults in the Wadi Queih–Wadi Sudmain area (which include among them the 'Master Fault' of the present study) belong to the left-lateral strike-slip faults the Najd fault system of the Arabian–Nubian Shield (Moore, 1979; Stern, 1985) (Fig. 1a, inset). Slickenside lineations on the fault surfaces of the Wadi Queih–Wadi Sudmain area show both left- and right-lateral strike-slip displacements on the same faults. Left-lateral slip on these faults is consistent with second-order structures of Precambrian age whereas right-lateral slip is related to post-Precambrian reactivation of the same faults (M. Abdeen, personal communication). Oblique slickensides showing right-lateral slip on the 'Master Fault' south of Wadi El Sudmain trend N289° and plunge 56° where the fault surface strikes N305° and dips 85°SW (Abdeen, 1995). It is proposed in the present study that the right-lateral slip on the 'Master Fault' probably indicates its reactivation in the Late Oligocene (i.e. at the time of rifting in the northern Red Sea).

The model proposed for the structural deformation of the study area takes into account that the 'Master Fault' is a pre-existing (Late Precambrian) fault that dissected the continental crust of the northwestern Red Sea region before the rift opening. Rift opening during the Late Oligocene in response to ENE–WSW-oriented extension, orthogonal to the NNW–SSE-oriented normal faults of the mapped area (Figs 6 & 7), led to the development of several tilted rift blocks in the Quseir–Safaga region. Rift blocks in the northern part of this region have a SW dip whereas those in the south have a NE dip. Oppositely tilted rift blocks are juxtaposed against each other in the mapped area (Fig. 5). The same extension during the rift opening also reactivated some of the Late Precambrian, pre-existing, left-lateral strike-slip faults of the Najd fault system, among which is the 'Master Fault', by dextral transtension (see also Jarrige *et al.*, 1990). The diagonal slickensides mentioned above lend good support to the sense of slip on the 'Master Fault'. The 'Master Fault' acted as the major fault bounding the Saqi Block on the south and also as a sharp transfer zone between the two half-grabens to which the Saqi and Sudmain blocks belong. The segment of the 'Master Fault' joining the Nakheil Fault and the westernmost end of the Saqi Block acts like ridge–ridge transform faults offsetting spreading ridges at divergent plate boundaries (Wilson, 1965). This fault has dextral slip but shows a sinistral offset of the Saqi and Sudmain rift blocks. The transfer zone between the Saqi and Sudmain blocks includes, in addition to the 'Master Fault', the SE-plunging syncline in the northernmost part of the Sudmain Block. As the change in dip of the strata in the mapped area does not coincide with the location of the 'Master Fault', it is assumed that the change in dip and the development of the SE-plunging syncline slightly preceded the upward propagation of the 'Master Fault' through the pre-rift Phanerozoic sedimentary rocks during its rift-related reactivation.

COMPARISON WITH THE SUEZ RIFT

The Sudmain transfer zone has a relatively narrow width compared to transfer zones in the nearby Suez rift (e.g. Patton *et al.*, 1994). The Sudmain transfer zone is controlled by a pre-rift, WNW–ESE-oriented fault ('Master Fault') and also controls the change in tilt directions of adjacent half-grabens by the formation of a SE-plunging syncline (wavelength of 5 km) in the northern part of the Sudmain Block. The maximum width of this transfer zone is taken to be the width (wavelength) of this syncline. The Sudmain transfer zone clearly shows the effect of pre-rift structures on the width and orientation of transfer zones of continental rifts.

The Suez rift includes three main half-grabens of opposite tilt directions. Each of these half-grabens is bounded on the down-dip side by a listric normal fault. Evidence for the listric nature of these bounding faults is indicated by the presence of non-tilted pre-rift sedimentary rocks on the rift shoulders juxtaposed against tilted rocks in the three half-grabens. Two main transfer zones exist between the half-grabens of the Suez rift (Moustafa, 1976; Patton *et al.*, 1994). These are the Galala-Zenima (Moustafa, 1976) or Gharandal (Moustafa, 1996a) transfer zone in the north, and the Morgan (Moustafa, 1976) or Gebel Sufr El Dara (Moustafa and Fouda, 1988) transfer zone in the south (Fig. 9). The Gharandal transfer zone is 40–60 km wide and lies between the northern and central half-grabens of the Suez rift (Fig. 10). The location of this transfer zone is controlled by the Wadi Araba structure which is a large NE–SW-oriented, pre-rift fold of Late Cretaceous–Early Tertiary age that belongs to the 'Syrian arc system' (Moustafa and Khalil, 1995). On the other hand, Moustafa and El Shaarawy (1987) indicated the presence of a NW–SE-oriented pre-rift fault in this area which had no direct effect on the transfer zone. The Darag Fault and the Hammam Faraun Fault are parts of this pre-rift fault. Both of the Darag and Hammam Faraun faults line up when one reconstructs them to pre-rift positions by taking out the extension along each of them. They also line up with a Precambrian lineament outside the rift in southwest Sinai (Moustafa and El Shaarawy, 1987). According to those authors, this NW–SE-oriented pre-rift fault belongs to the Najd fault system. Patton *et al.* (1994) considered the Gharandal transfer zone to be controlled by the Darag-Hammam Faraun Fault but detailed surface mapping (Moustafa, 1996a,b) and subsurface study (Moustafa and Khalil, 1995) indicate that the Wadi Araba fold controls this transfer zone, whereas the Darag-Hammam Faraun Fault traverses the transfer zone diagonally with no direct effect on it.

The deformation of the Gharandal transfer zone proceeded by pure normal faulting without strike-slip movements (Moustafa, 1996a). Northeast-dipping faults of the northern half-grabens extend southward into the transfer 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 transfer zone. According to the nomenclature of Morley *et al.* (1990), this transfer zone is a convergent conjugate transfer zone. It has a broad anticlinal structure lying between the overlapping ends of the major listric normal faults bounding the northern and central half-grabens of the Suez rift (Moustafa, 1996b) (Fig. 10).

The western (onshore) segment of the Gebel Sufr El Dara transfer zone is 20 km wide and dominated by strike-slip faults (Fig. 11). It does show the effect of

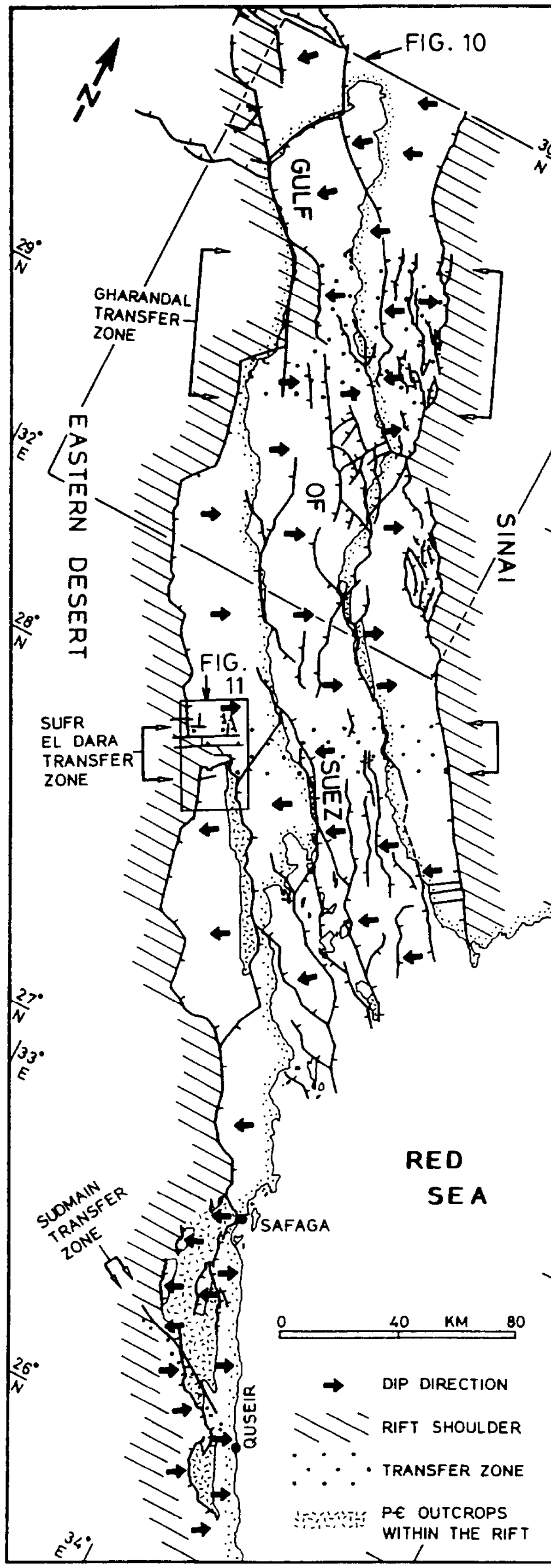

Fig. 9. Simplified structural map of the Suez rift–northern Red Sea region compiled from Issawi *et al.* (1969), Greene (1984), Jarrige *et al.* (1986), Roussel *et al.* (1986), Thiriet *et al.* (1986), Moustafa (1987, 1996b), Moustafa and El Shaarawy (1987), Moustafa and Khalil (1987, 1995), Moustafa and Fouda (1988), Lelek *et al.* (1992), Moustafa and Abdeen (1992), Moustafa and El-Raey (1993), Patton *et al.* (1994) and the present mapping.

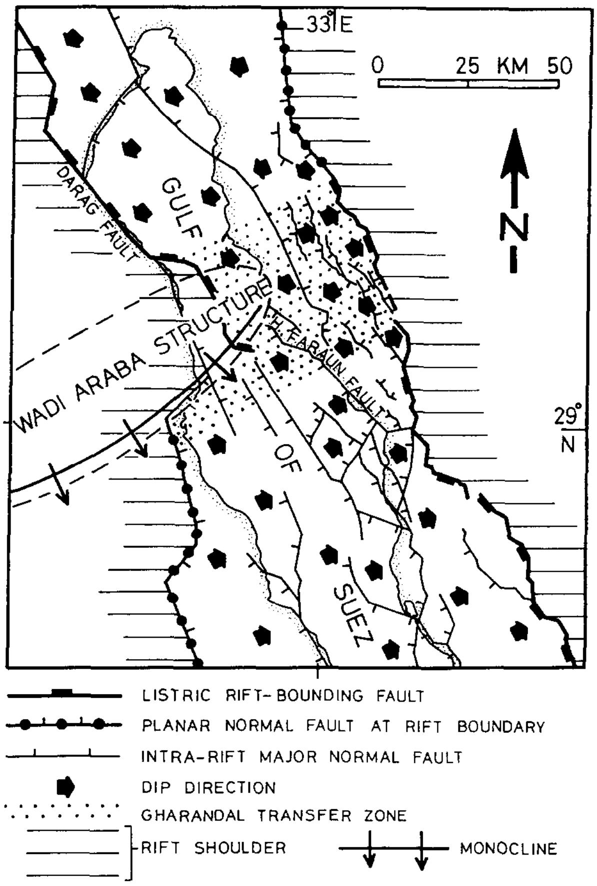

Fig. 10. Detailed structural map of the northern and central parts of the Suez rift showing the Gharandal transfer zone and its relationship to the Wadi Araba 'Syrian arc' fold. Compiled after Moustafa and Khalil (1995) and Moustafa (1996a,b).

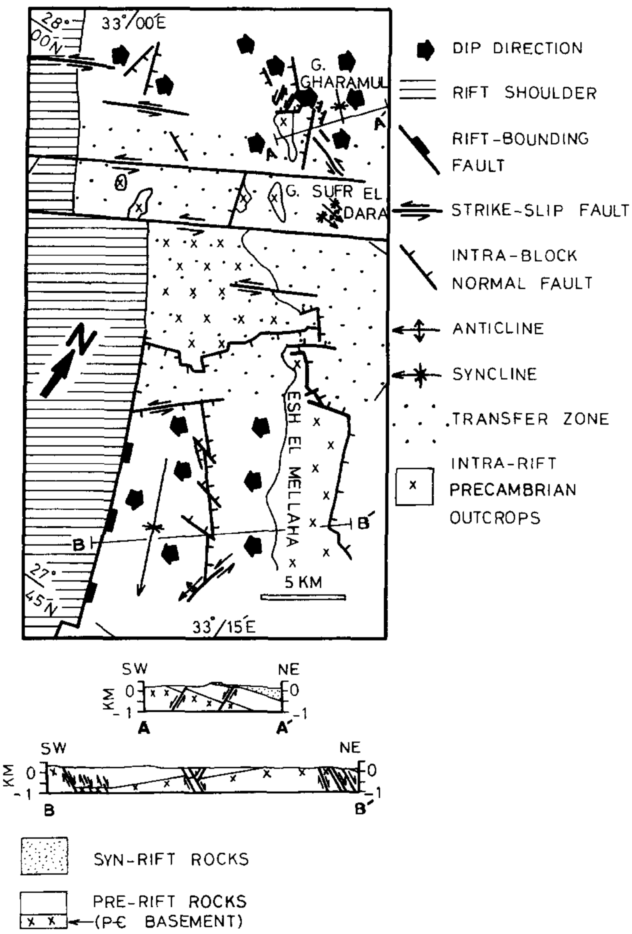

Fig. 11. Simplified geological map of the onshore part of the Sufr El Dara transfer zone (after Moustafa and Fouda, 1988). See Fig. 9 for location.

transverse pre-rift structures on its development and orientation (Moustafa and Fouda, 1988), at least in this surface segment of the transfer zone. ENE–WSW-oriented pre-rift faults in this part of the Suez rift controlled the location, orientation and style of deformation of this transfer zone. The transfer zone inherited its ENE–WSW orientation from the pre-existing faults and the latter were reactivated by left-lateral strike-slip movement due to the opposite directions of rotation of the fault blocks which lie to the north and south of them and belong to the central and southern half-grabens of the Suez rift. Left-lateral strike-slip movement in this transfer zone led to the local development of NW–SE-oriented folds and thrusts as well as some strike-slip faults representing second-order wrench structures (Moustafa and Fouda, 1988) (Fig. 11).

DISCUSSION

It is clear from the last sections that there are three transfer zones in the Suez rift and the northern Red Sea. The southern two transfer zones (Sudmain and Gebel Sufr El Dara) are controlled by pre-rift faults whereas the northern (Gharandal) transfer zone is not controlled by such faults but by a 'Syrian arc' fold. These three transfer zones also show a remarkable contrast in their widths which increase northward (Fig. 12). The Sudmain transfer zone is 5 km wide, the Gebel Sufr El Dara transfer zone is 20 km wide and the Gharandal transfer zone is 40–60 km wide. Another significant observation is the length of each of the half-grabens bounded by these transfer zones. It is evident that these half-grabens increase in length southward (Fig. 9). The northern half-graben of the Suez rift that lies north of the Gharandal transfer zone is 65 km long, the central half-graben that lies between the Gharandal and Gebel Sufr El Dara transfer zones is 120 km long, and the southern half-graben that lies between the Gebel Sufr El Dara and Sudmain transfer zones is 210 km long (Fig. 9).

The fact that the deformation of the Gharandal transfer zone was free from the influence of pre-rift faults should not be attributed to the absence of such faults in this part of the rift. Surface geological studies of the Precambrian basement rocks in northern Egypt, as well as subsurface (geophysical) studies, proved that the Precambrian basement rocks of this part of north Egypt are affected by a large number of ENE–WSW- to E–W-oriented faults (Youssef, 1968; Orwig, 1982), in addition

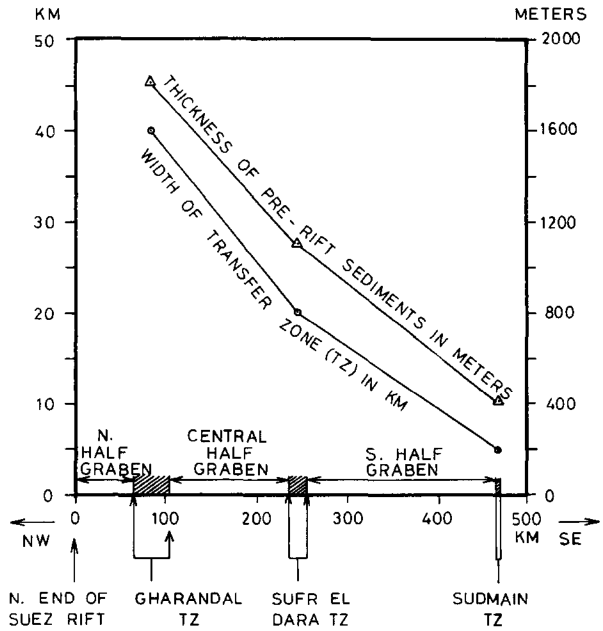

Fig. 12. Diagrammatic representation of the relationship between the length of half grabens in the Suez rift–northern Red Sea region, the width of transfer zones and the thickness of the pre-rift sedimentary section overlying the Precambrian basement. See text for details.

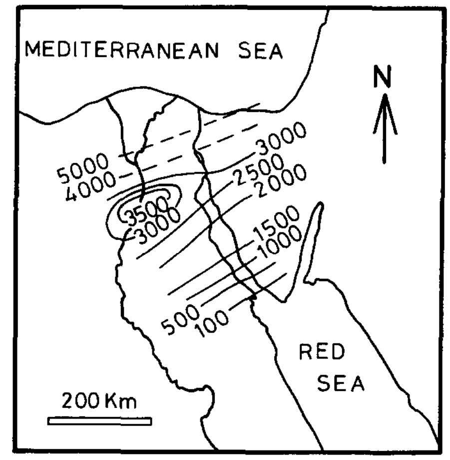

Fig. 13. Isopach map of the pre-rift sedimentary rocks (Paleozoic–Eocene) in the Gulf of Suez area and the northern Eastern Desert compiled from Beleity *et al.* (1986) and May (1991). Contour values are in metres.

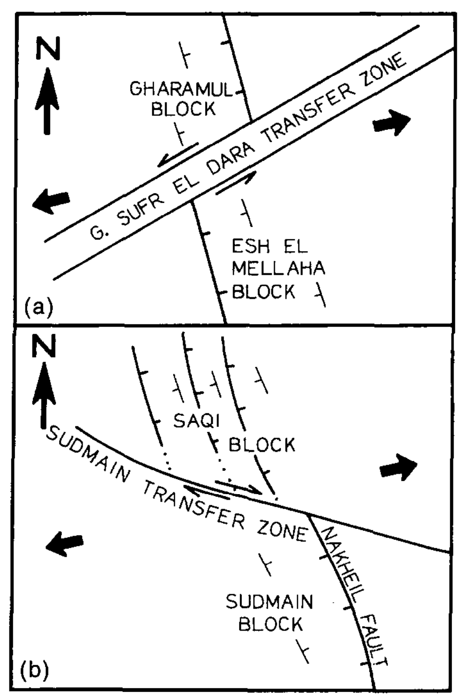

Fig. 14. Sketches showing the opposite sense of strike-slip movement on (a) the Gebel Sufr El Dara and (b) the Sudmain transfer zones depending on the relationship between the orientation of the pre-rift faults in these zones and the direction of extension (bold arrows).

to the NW–SE-oriented Darag-Hammam Faraun Fault. Beleity *et al.* (1986) indicated that ENE–WSW- to E–W-oriented faults controlled the thickness of Paleozoic sediments in the Gulf of Suez area, i.e. these faults are most probably of pre-Paleozoic age. On the other hand, the thickness of the pre-rift Phanerozoic sedimentary section may well account for the passive role of the deep-seated Precambrian faults in the structural deformation of the Gharandal transfer zone and their active role in the central and southern parts of the rift. This sedimentary section progressively increases in thickness northward in the Suez rift area (Fig. 13). The pre-rift sedimentary section of the Suez rift and northern Red Sea shows a remarkable relationship between northward thickening, from 410 m in the vicinity of the Sudmain transfer zone to 1110 m in the vicinity of Gebel Sufr El Dara transfer zone (Moustafa and Fouda, 1988) and reaching 1810 m in the vicinity of the Gharandal transfer zone (Moustafa, 1996b), and transfer zone width (Fig. 12). It is proposed here that as the thickness of the sedimentary section increases, the influence of Precambrian basement faults on the deformation of the sedimentary cover becomes less important and their effect on the transfer zones of continental rifts is thereby limited. Also, as the sediments increase in thickness, half-grabens tend to decrease in length and vice versa. This perhaps draws attention to an important relationship between length, width and sedimentary thickness (down to the basal detachment) of half-grabens.

Another observation regarding the reactivation of pre-rift faults in transfer zones is the sense of strike-slip movement on these faults. The sense of strike-slip movements as faults are reactivated during the rift opening depends on the orientation of these faults relative to the direction of extension in the rift (e.g. sinistral strike-slip movement on the Gebel Sufr El Dara transfer zone vs dextral strike-slip movement on the Sudmain transfer zone) (Fig. 14).

A final point worth discussing is the nature of the major faults in the Suez rift and northern Red Sea area (i.e. planar or subplanar fault geometry vs listric fault geometry with a basal detachment; e.g. Wernicke and Burchfiel, 1982; Wernicke, 1985; Lister *et al.*, 1986). Kusznir and 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 hanging-wall 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 a completely mechanical response to faulting with perhaps a small thermal component involved, and, therefore, remains largely unrecovered during thermal cooling of the basin. Excellent outcrops in the Suez rift and northern Red Sea area may help check the applicability of the detatchment or non-detachment (planar fault) models. The Darag Fault represents the western rift-bounding fault of the northern half-graben of the Suez rift (Fig. 10). Horizontal attitude characterizes the pre-rift sedimentary rocks in the footwall block of this fault (North Galala Plateau). Similar pre-rift rocks in the hanging wall of the same fault dip at about 12–15°SW (toward the fault). Similar relations also exist at the eastern rift-bounding fault of the central half-graben of the Suez rift. These two areas indicate that the rift-bounding faults on the down-dip sides of the northern and central half-grabens of the Suez rift are not associated with footwall tilting (e.g. Moustafa, 1993, figs 3 & 4; Patton *et al.*, 1994, fig. 20). It is assumed, therefore, that the rift-bounding faults of the northern and central half-grabens of the Suez rift are listric and detach at depth. On the other hand, the pre-rift sedimentary section in the footwalls of the rift-bounding faults in the southernmost part of the Suez rift and the northern Red Sea area is eroded and Precambrian crystalline rocks are exposed. Roberts and Yielding (1991) indicated that adjacent to large faults at the margins of the North Sea–mid-Norway rift, the pre-rift footwall sequence is completely eroded as a result of uplift predicted by the flexural cantilever basin model. Applying the same concept to the southernmost part of the Suez rift and the northern Red Sea area is not easy because one may attribute rift shoulder uplift in these areas to thermal uplift related to seafloor spreading in the Red Sea. Therefore, it is not possible to adopt the detachment or non-detachment models for the rift-bounding faults in the southern Suez rift and northern Red Sea area. On the other hand, the non-detachment (planar) fault model may be applicable to most of the intra-rift faults in the Suez rift and northern Red Sea area where both footwall and hanging-wall blocks are tilted (e.g. Jackson *et al.*, 1988).

CONCLUSIONS

(1) In the Suez–northern Red Sea rift system the effect of pre-rift faults in the Precambrian basement on transfer zones depends on the thickness of the pre-rift Phanerozoic sedimentary section.

(2) The length of half-grabens in this region is inversely proportional to the thickness of the pre-rift sedimentary section.

(3) Transfer zones affected by pre-rift faults are oriented parallel to these faults. The latter are reactivated by oblique-slip movement, the sense of strike-slip component depends on the orientation of these faults relative to the direction of rift extension.

(4) The effect of the thickness of the pre-rift sedimentary section on the width of transfer zones and thereby the dimensions of structures in such zones may have a direct effect on the nature and size of potential hydrocarbon traps in such zones.

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