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Structural and stratigraphic evolution of the Gulf of Suez Rift, Egypt: a synthesis

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ABSTRACT

The structural and stratigraphic development of the Gulf of Suez Rift reflects the interplay of five principal factors: (1) the presence of pre-existing fault systems, penetrative fabrics and basement terrane boundaries, (2) eustatic sea-level changes, (3) changes in basin connectivity to the Mediterranean Sea and Indian Ocean, (4) rapid changes in African intra-plate stress fields, and (5) activation of the Levant-Aqaba transform plate boundary. The Gulf of Suez Rift initiated in the late Oligocene, probably propagating northwards, and intersecting a major east-west structural boundary of late Eocene age at the latitude of Suez city. North of Suez, extension was more diffuse but mostly focused on the Manzala Rift that is presently buried beneath the Nile delta. Earliest syn-rift, mainly continental sediments (Chattian-Aquitanian) consisted of red beds containing minor basalts. Marine Oligocene strata are presently only proven from the southernmost Gulf, at the juncture with the northern Red Sea. By the Aquitanian, a shallow to marginal marine environment prevailed in most of the rift. The prolonged Burdigalian sea-level rise enabled marine waters to flow freely between the Mediterranean Sea and the Gulf of Suez, resulting in deposition of thick *Globigerina* shales and deep-water carbonates. During the Langhian and early Serravallian, rapid eustatic sea-level changes resulted in pronounced facies changes within the rift. During the late Serravallian significant fall in sea-levels, the Mediterranean water connection was either completely or intermittently blocked, leading to deposition of evaporites in the central and southern Gulf sub-basins. Thick halite sections accumulated in the late Miocene, and later loading resulted in the formation of salt diapirs and salt walls. Normal marine conditions were re-established during the Pliocene, but waters were then provided by the Red Sea-Gulf of Aden connection to the Indian Ocean, and a permanent land-barrier separated the Gulf of Suez from the Mediterranean. Analysis of fault geometries, fault kinematics and sedimentation patterns indicate that rift-normal extension predominated throughout the Oligocene to early middle Miocene evolution of the rift. In the middle Miocene, the Levant-Gulf of Aqaba transform boundary was established, linking the Red Sea Rift plate boundary to the convergent Bitlis-Zagros plate boundary. This resulted in a dramatic decrease in extension rates across the Gulf of Suez and a clockwise rotation of stress fields in Sinai. During the late Pleistocene, the intra-Gulf of Suez extension direction rotated counter-clockwise to N15°E.

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RÉSUMÉ

Évolution structurale et stratigraphique du rift de Suez, Égypte : une synthèse.

L'évolution structurale et stratigraphique du rift de Suez est contrôlée par cinq facteurs principaux : (1) la présence de systèmes de failles préexistantes, de structures pénétratives et de limites de blocs de socle, (2) les variations eustatiques, (3) les changements dans les relations du bassin avec la Méditerranée et l'océan Indien, (4) les changements rapides du champ de contrainte dans la plaque africaine et (5) l'apparition de la frontière transformante Levant-Aqaba. Le rift de Suez apparaît à l'Oligocène supérieur. En se propageant probablement vers le nord, il a recoupé une limite structurale majeure orientée est-ouest, d'âge Éocène supérieur, à la latitude de la ville de Suez. Au nord de Suez, l'extension est plus diffuse et essentiellement localisée dans le rift de Manzala, actuellement enfoui sous le delta du Nil. Les plus anciens dépôts syn-rift, principalement des sédiments continentaux (Chattien-Aquitanien), sont constitués de niveaux rouges, avec des intercalations de basaltes. L'Oligocène marin a été mis en évidence uniquement à l'extrémité sud du Golfe, à la jonction avec la Mer Rouge. À l'Aquitanien, un environnement marin de faible profondeur s'installe dans la majeure partie du rift. La transgression marine burdigalienne permet une communication entre la Méditerranée et le golfe de Suez, permettant le dépôt d'épaisses séries de marnes à *Globigerina* et de carbonates d'eau profonde. Pendant le Langhien et le Serravalien inférieur, de rapides variations eustatiques induisent des changements de faciès à l'intérieur du rift. Au Serravalien supérieur, d'appréciables chutes du niveau marin ont amené le dépôt d'évaporites dans les parties centrales et méridionales du rift. Pendant cette période, la liaison avec la Méditerranée était, soit intermittente, soit interrompue. La charge induite par les épaisses accumulations d'halites du Miocène supérieur a entraîné la formation de diapirs et de murs de sel. Les conditions marines normales ont été rétablies au cours du Pliocène, mais l'alimentation en eau provenait de la Mer Rouge et du golfe d'Aden, reliés à l'océan Indien. À partir de cette période, une barrière permanente s'établit entre le golfe de Suez et la Méditerranée. L'analyse de la géométrie et de la cinématique des failles ainsi que l'étude de la sédimentation montrent que l'extension perpendiculaire au rift prédomine, de l'Oligocène au début du Miocène moyen. Au Miocène moyen, le système transformant faille du Levant-golfe d'Aqaba est actif, reliant le rift de la Mer Rouge à la frontière convergente Bitlis-Zagros. Ce changement majeur dans la cinématique régionale a entraîné un considérable ralentissement du taux d'extension dans le golfe de Suez et une rotation horaire du champ de contrainte dans le Sinaï. Pendant le Pléistocène supérieur, l'extension dans le golfe de Suez subit une rotation dans le sens anti-horaire, jusqu'à une direction N15°E.

INTRODUCTION

The Late Cainozoic Gulf of Suez Basin is one of the best exposed and studied examples of a continental rift. Several recent models of rift geometry and evolution have relied heavily on data and concepts derived here (e.g., BOSWORTH, 1994; BOSENCE, 1998). The Gulf of Suez was the first rift basin in which large-scale, along-axis segmentation into sub-basins by accommodation zones was clearly recognized (MOUSTAFA, 1976). It has served as one of the premier models for Miocene carbonate platform development (JAMES *et al.*, 1988; BURCHETTE, 1988; CROSS *et al.*, 1998), and is recognized as a superb example of the interplay between sedimentation and extensional fault development (GAWTHORPE *et al.*, 1997). Recent studies evaluated the relative roles of hard- and soft-transfer in intra-basin fault linkage, and the significance of pre-rift structures in controlling the style of linkage (MCCLAY *et al.*, 1998; MCCLAY & KHALIL, 1998; YOUNES & MCCLAY, 1998). The Gulf of Suez is also one of the best examples of the integration of outcrop and subsurface data to enhance hydrocarbon exploration and exploitation (GAWTHORPE *et al.*, 1990; PATTON *et al.*, 1994).

Despite these positive and important developments, we believe that two issues have not been satisfactorily addressed. First, no comprehensive analysis and integration of all areas of the rift has been published, in spite of abundant new stratigraphic and structural data for parts of the basin (e.g., RICHARDSON & ARTHUR, 1988; HUGHES *et al.*, 1992; PATTON *et al.*, 1994; BOSWORTH, 1995; MCCLAY *et al.*, 1998). Specifically, the major differences in the tectonostratigraphic histories of the southern and central rift basins have never been adequately addressed. Second, despite the use of many aspects of outcrop and subsurface geology of this basin as a model for other rift settings, this extrapolation has not considered all the dominant factors that controlled overall evolution of the Gulf. Some of these factors, such as the activation of the Levant-Aqaba transform boundary, are actually specific to the geographical and temporal position of the basin, and may make some aspects of this rift unsuitable for a general model.

This paper considers these neglected issues by integrating a detailed structural and stratigraphic study of a large part of the exposed eastern and western shoulders of the Gulf of Suez Rift (Fig. 1) with extensive subsurface interpretation covering most of the southern Gulf, and selected areas in the central and northern sub-basins.

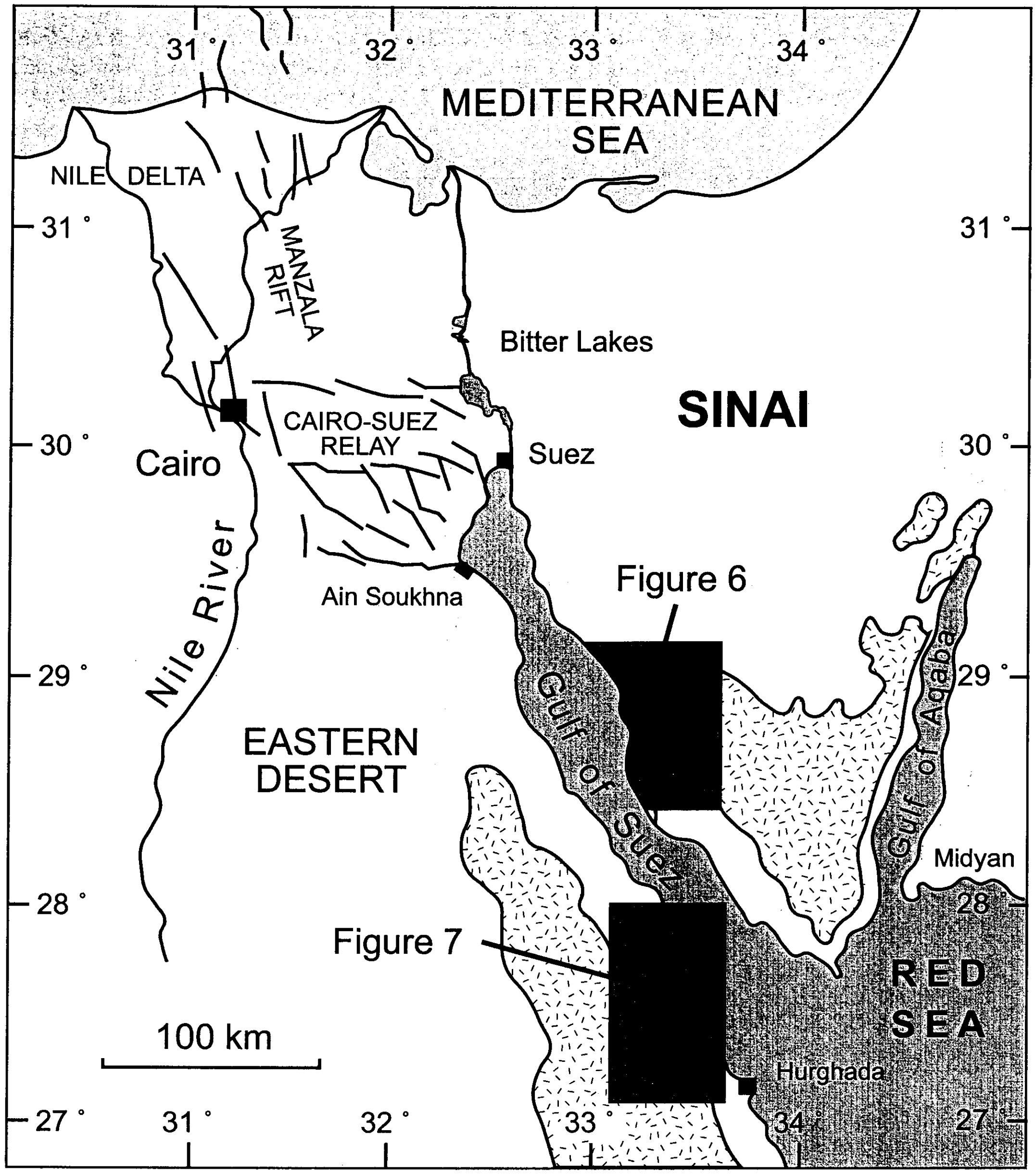

FIG. 1.— Location of the Gulf of Suez and eastern and western field study areas. Basement is shown with stipple pattern. The Gulf of Suez Rift is linked to extension in the Nile delta-Bitter lakes region (Manzala Rift) via the Cairo-Suez relay.

FIG. 1.— Localisation du golfe de Suez et des zones d'étude. Le socle apparaît en hachures. Le rift de Suez est relié à la zone d'extension du delta du Nil et du lac Amer (Manzala rift) via la zone de relais Le Caire-Suez.

PLATE TECTONIC SETTING OF THE GULF OF SUEZ RIFT

The Late Cainozoic Gulf of Suez is the northern termination of the Gulf of Aden-Red Sea rift system (Fig. 2) which developed as a result of the northeastward separation of the Arabian from the African plate (MCKENZIE *et al.*, 1970; COLEMAN, 1974, 1993; COCHRAN, 1983; GIRDLER & SOUTHREN, 1987;

HEMPTON, 1987; JOFFE & GARFUNKEL, 1987). Two contrasting models have been postulated for the early (late Oligocene-early Miocene) evolution of the Red Sea-Gulf of Suez rift system. The first model invokes regional northeastward extension, approximately normal to the present NW trend of the rift. In this model, the Red Sea-Gulf of Suez rift system formed by anticlockwise rotation of Arabia away from Africa about a pole of rotation located in the central or south central Mediterranean Sea (MCKENZIE *et al.*, 1970; FREUND, 1970; LE PICHON & FRANCHETEAU, 1978; MORGAN, 1990; MESHREF, 1990). Extension decreases westwards along the Gulf of Aden and northward along the Red Sea, consistent

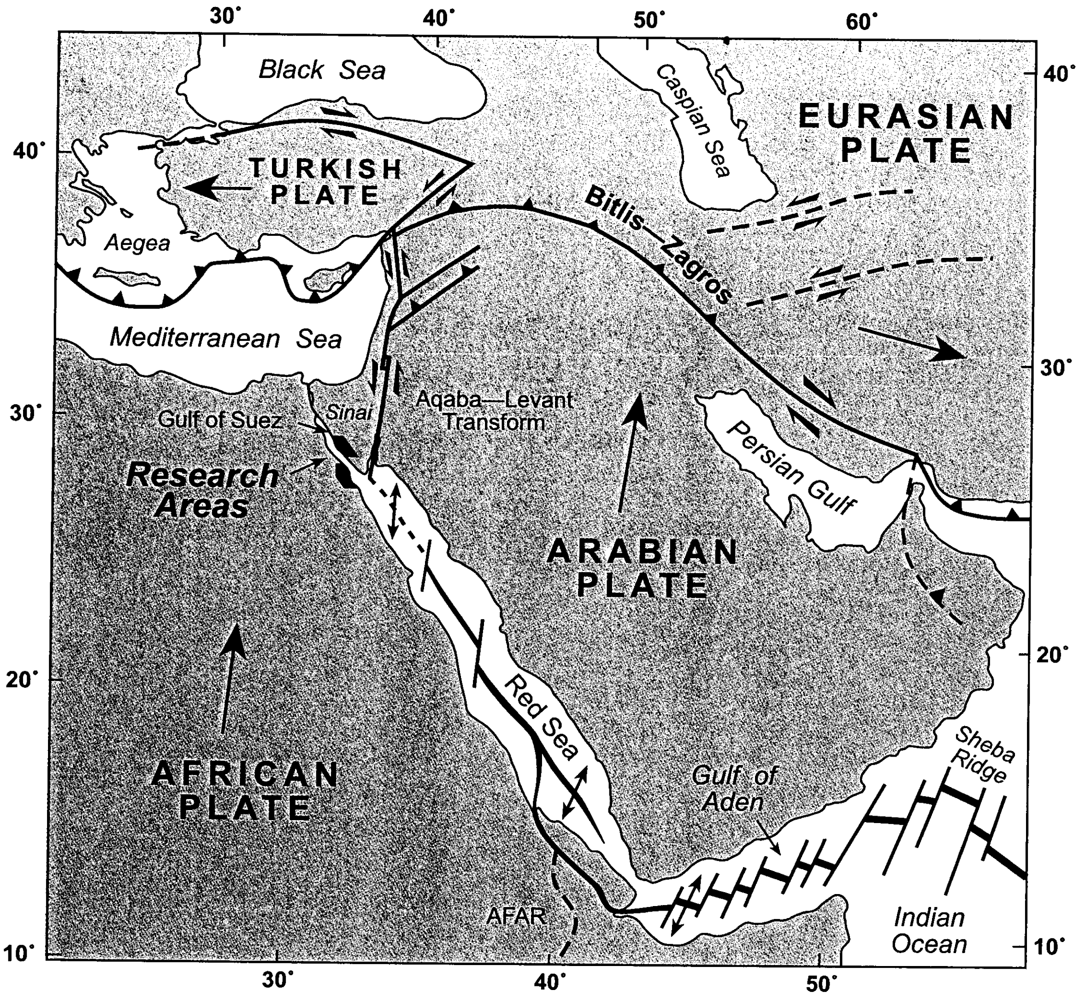

FIG. 2.— Plate tectonic setting of the Gulf of Suez (modified from HEMPTON, 1987; JOFFE & GARFUNKEL, 1987; Afar region after ABBATE *et al.*, 1995).

FIG. 2.— Cadre géodynamique du golfe de Suez (modifié d'après HEMPTON, 1987 ; JOFFE & GARFUNKEL, 1987 ; ABBATE et al., *1995 pour la région des Afars).*

with, and constraining the Arabian pole of rotation. In the Red Sea, the amount of extension decreases northwards into the Gulf of Suez. There is general agreement that magnetic anomalies in the central and southern Red Sea axis (below latitude 24°N) were generated by sea-floor spreading that began in the early Pliocene (~4.5 Ma; COCHRAN, 1983; GIRDLER & SOUTHREN, 1987; COLEMAN, 1993). Some interpretations also invoke an earlier phase of sea-floor spreading, for example in the early Miocene (23-15 Ma; GIRDLER & SOUTHREN, 1987). The Gulf of Suez attained stretching factors of $\beta=2$ (GAULIER *et al.*, 1988), but remained floored by continental crust (FREUND, 1970; JOFFE & GARFUNKEL, 1987). By the late middle Miocene, rifting became subdued in the Gulf of Suez and the opening of the Red Sea was linked to sinistral strike-slip displacements along the Gulf of Aqaba-Dead Sea transform fault system

(Fig. 2) (QUENNELL, 1958; FREUND, 1970; BEN-MENAHEM *et al.*, 1976; STECKLER *et al.*, 1988; ABDEL KHALEK *et al.*, 1993). Displacement along the Gulf of Aqaba-Dead Sea transform system accumulated in two periods with approximately 65 km occurring in the middle Miocene to Pliocene and 40 km in the Pliocene to Quaternary (FREUND, 1970; BARTOV *et al.*, 1980; EYAL *et al.*, 1981; QUENNELL, 1984; HEMPTON, 1987; JOFFE & GARFUNKEL, 1987; EYAL, 1996).

In contrast to the above simple model of northeastward movement of the Arabian plate away from the African plate, several authors have suggested that initial opening of the Red Sea-Gulf of Suez rift system was characterized by strike-slip faulting and pull-apart tectonics. Based on outcrop structural and stratigraphic analyses, JARRIGE *et al.* (1986, 1990) and MONTENAT *et al.* (1986a, 1988) inferred that NW-SE compression along the proto-rift axis induced NNE-SSW ("Aqaba" trend) sinistral and ESE-WNW ("Duwi" trend) dextral reactivation of pre-existing basement fabrics to produce rhombic, weakly subsident sub-basins. MAKRIS & RIHM (1991) and RIHM & HENKE (1998), using geophysical data, hypothesized the existence of basins floored by oceanic-type crust immediately offshore from Egypt and Sudan along the western Red Sea margin. They proposed that this oceanic crust formed during early sinistral strike-slip motion parallel to the axis of the Gulf of Suez, producing highly extended pull-apart basins along a transform plate boundary. In the MAKRIS-RIHM-HENKE model, plate reorganization at about 22 Ma produced more northeastward directed extension slightly oblique to the main NW-trending rift axis, and a shift to the present extensional configuration of the Red Sea margins. In the JARRIGE-MONTENAT model, the shift to approximately rift-normal triaxial or radial extension (with σ_3=N70-80°E) occurred during the late Burdigalian.

STRUCTURAL AND STRATIGRAPHIC FRAMEWORK OF THE GULF OF SUEZ

The NW-trending Gulf of Suez is about 300 km long, and the complete rift basin, including the on-shore border fault systems, varies in width from about 50 km at its northern end to about 90 km at its southern end where it merges with the Red Sea (Fig. 3). This has been traditionally referred to as the "Clysmic" rift, after the ancient Roman settlement of Clysma that occupied the present site of the city of Suez (HUME, 1921; ROBSON, 1971). The rift is characterized by a zigzag fault pattern, composed of N-S to NNE-SSW, E-W and NW-SE striking extensional fault systems both at the rift borders and within the rift basins (GARFUNKEL & BARTOV, 1977; JARRIGE *et al.*, 1986; MORETTI & CHÉNET, 1987; COLLETTA *et al.*, 1988; MESHREF, 1990; MOUSTAFA, 1993; PATTON *et al.*, 1994; SCHUTZ, 1994; BOSWORTH, 1995; MONTENAT *et al.*, 1998; MCCLAY *et al.*, 1998; Fig. 3).

There are three distinct depocentres within the Gulf of Suez: the Darag Basin at the northern end, the central basin or Belayim Province in the middle, and the southern Amal-Zeit Province (Fig. 3). Each sub-basin is asymmetric, bounded on one side by a major NW-trending border fault system with large throws (4-6 km in general) together with a dominant stratal dip direction toward the border fault system. Structurally complex accommodation zones, oblique to the rift trend, separate the three depocentres (MOUSTAFA, 1976; BOSWORTH, 1985; COFFIELD & SCHAMEL, 1989; Fig. 3). The accommodation zones appear to be wide (up to 20 km) areas of complexly faulted blocks of variable dips and interlocking 'flip-flop' conjugate fault systems. COLLETTA *et al.* (1988) interpreted that the change in rift geometry across the Morgan accommodation zone (Fig. 3) is accomplished principally by a major, through-going oblique transfer fault. However, this is not supported by outcrop (MOUSTAFA & FOUDA, 1988; COFFIELD & SCHAMEL, 1989) or subsurface data (PATTON *et al.*, 1994; BOSWORTH, 1995).

Within each of the three main half-graben there are second-order sub-basins formed by individual fault blocks, each of which has its own characteristic syn-rift stratigraphy. Many detailed, local descriptions have been given for outcrops in the central (GARFUNKEL & BARTOV, 1977; SELLWOOD & NETHERWOOD, 1984; SCOTT & GOVEAN, 1985; PATTON *et al.*, 1994; MCCLAY *et al.*, 1998) and southern basins (EVANS & MOXON, 1988; MONTENAT *et al.*, 1988, 1998; DARWISH & EL-AZABI, 1993; BOSWORTH, 1995; BOSWORTH *et al.*, 1998). Unfortunately, the syn-rift strata of the northern Darag Basin are poorly exposed, although some well data have been published (e.g., FAWZY & ABDEL AAL, 1986).

Figure 4 shows the summary stratigraphy from the eastern side of the Gulf of Suez where the most complete stratigraphic section is exposed (MCCLAY *et al.*, 1998; KHALIL, 1998). This is taken as typical

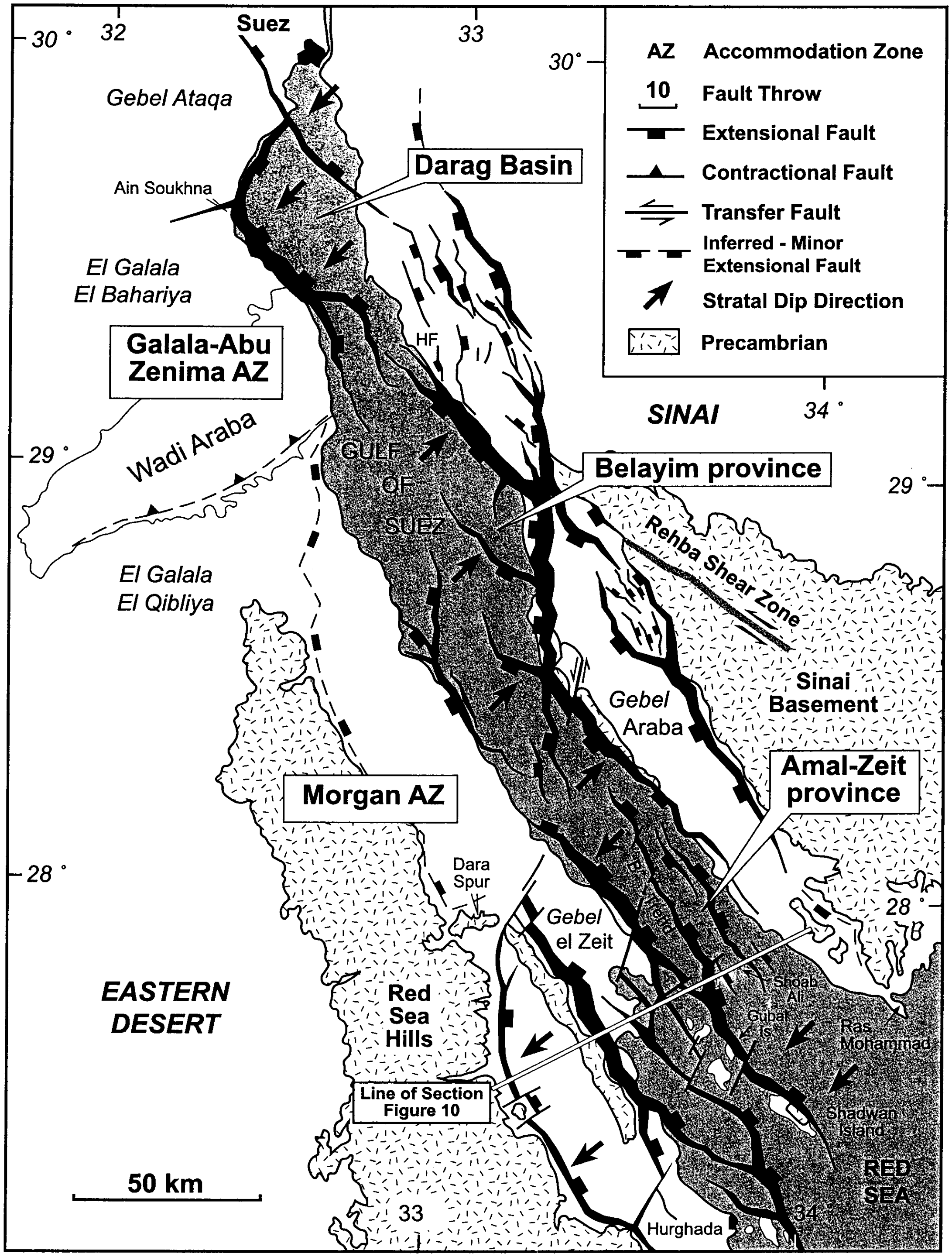

FIG. 3.— Tectonic map of the Gulf of Suez Rift. HF = Hammam Faraun (modified from S. KHALIL, pers. comm., 1998).

FIG. 3.— Carte tectonique du rift de Suez. HF = Hammam Farum (modifié d'après S. KHALIL, comm. pers., 1998).

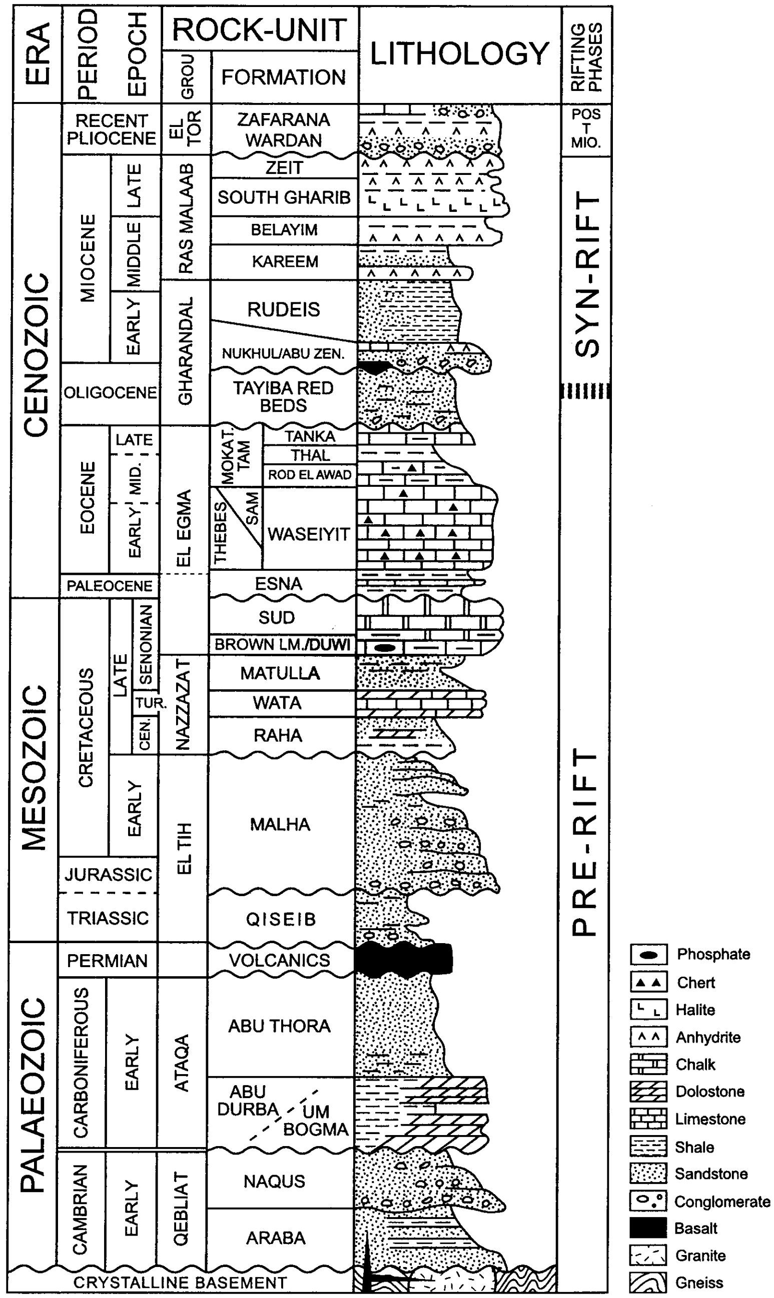

FIG. 4.— Generalized stratigraphy of the Gulf of Suez Basin (after DARWISH & EL ARABY, 1993).

FIG. 4.— Stratigraphie synthétique du bassin du golfe de Suez (d'après DARWISH & EL ARABY, 1993).

of most of the Gulf of Suez (cf. PATTON *et al.*, 1994; BOSWORTH *et al.*, 1998; MONTENAT *et al.*, 1998), although thickness, facies and local formation names vary as discussed below (Fig. 5). Based on observed stratigraphic and structural relationships, Late Cainozoic rifting along the northern Red Sea and the Gulf of Suez appears to have commenced during the late Oligocene (Chattian).

We have mapped in detail the principal exposures of pre- and syn-rift strata along the central eastern and southern western margins of the Gulf of Suez (Figs 6, 7). Subsurface data are principally derived from the *Proceedings* of the Egyptian General Petroleum Corporation Conferences and other publications noted below. We also refer to unpublished mapping in the northern Gulf and Cairo-Suez district, and published and ongoing mapping along the northern Red Sea margin (BOSWORTH *et al.*, 1998; YOUNES & MCCLAY, 1998). The following sections summarize the pre-rift and syn-rift stratigraphy of the Gulf of Suez.

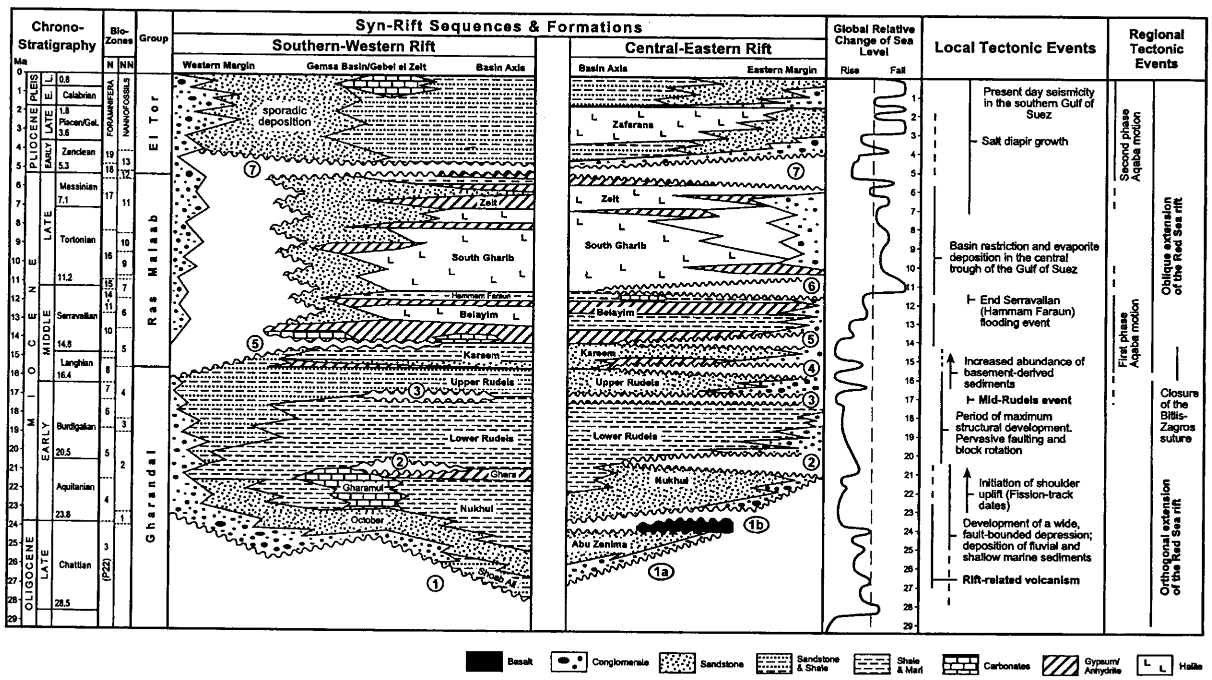

FIG. 5.— Syn-rift stratigraphy of the Gulf of Suez (southern and central basins) and correlation with local and regional tectonic events. Circled numbers indicate major unconformities: **1**, base rifting, divided into base Abu Zenima formation (1a) and base Nukhul formation (1b) in the central rift; **2**, base lower Rudeis; **3**, mid-Rudeis or mid-Clysmic; **4**, base Kareem (not major in the south); **5**, base Belayim; **6**, base south Gharib (not major in the south); **7**, base Pliocene.

*FIG. 5.— Stratigraphie syn-rift du golfe de Suez (bassins central et méridional) et corrélation avec les événements tectoniques locaux et régionaux. Les chiffres cerclés indiquent les discordances majeures : **1**, base du rifting, divisée entre la base de la formation d'Abu Zenima (1a) et la base de la formation de Nukhul (1b) dans la partie centrale du rift ; **2**, base du Rudeis inférieur ; **3**, Rudeis moyen ou Clysmic moyen ; **4**, base Kareem (peu importante dans le sud); **5**, base Belayim ; **6**, base de south Gharib (peu importante dans le sud) ; **7**, base du Pliocène.*

BASEMENT AND PRE-RIFT STRATA

The pre-rift stratigraphy shows relatively simple variations along the length of the Gulf of Suez, with a general southwards thinning of most of the marine units. An exception to this trend is the continental Lower Cretaceous Malha formation, which thickens toward the south. Local uplift and erosion due to far-field compressional events are recognized, as for example in the Late(?) Devonian (early Hercynian deformation; BELEITY *et al.*, 1988; PATTON *et al.*, 1994). Upper Palaeozoic strata may have been deposited in a trough that occupied roughly the same position as the northern Gulf of Suez (GUIRAUD *et al.*, 2001). However, general Mesozoic and Early Cainozoic facies and thickness trends do not display any changes that can be attributed to "proto" Gulf of Suez tectonics (GARFUNKEL & BARTOV, 1977; GUIRAUD *et al.*, 2001). Locally, as in the vicinity of Gebel el Zeit and Esh el Mellaha (see below), there are Cretaceous and Eocene age faults that introduce minor variations in thickness of the pre-rift strata (BOSWORTH, 1995; GUIRAUD & BOSWORTH, 1997).

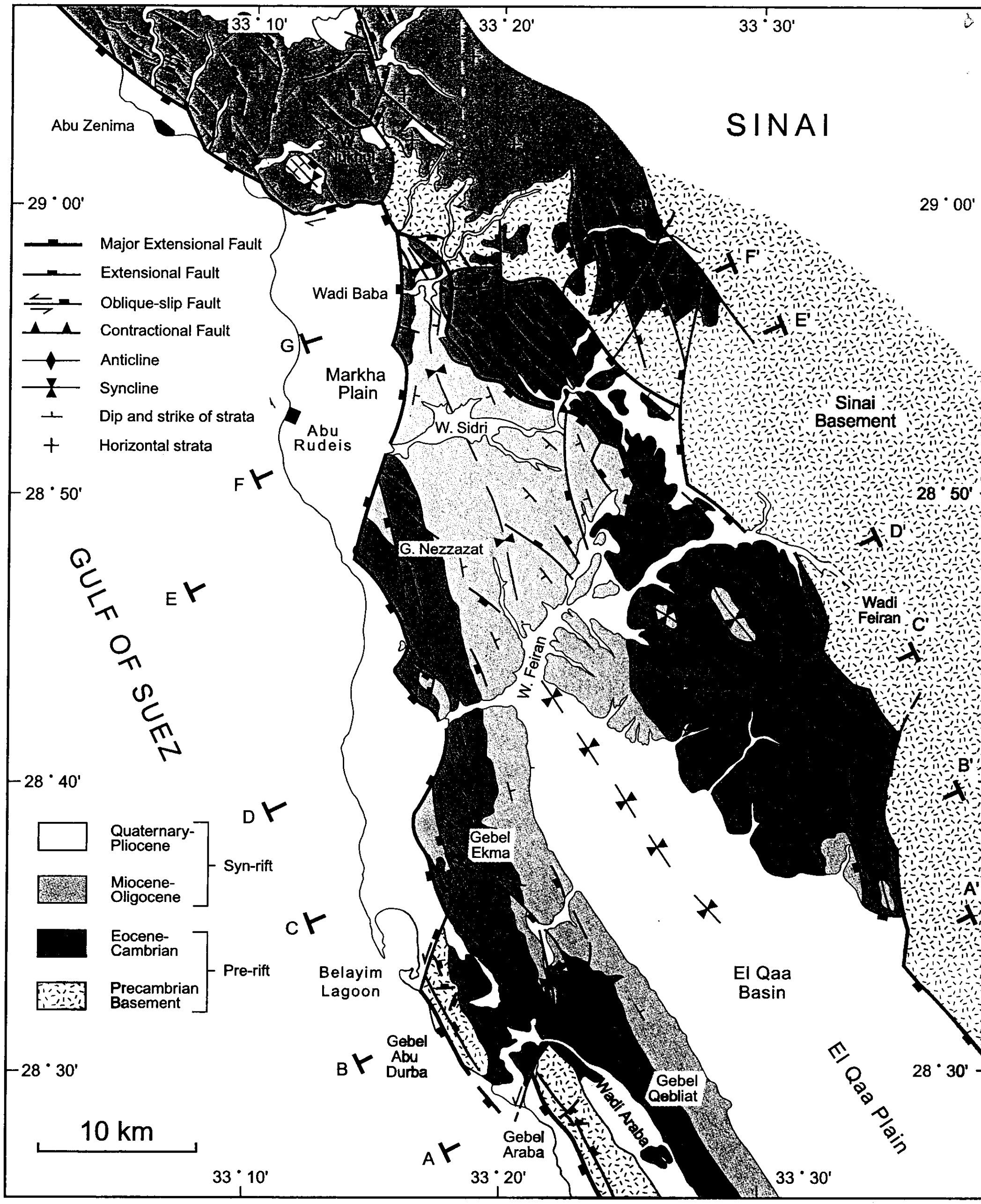

FIG. 6.— Surface geologic map of the central eastern margin of the Gulf of Suez Rift (after MCCLAY *et al.*, 1998). Locations of cross-sections of figure 9 are labelled as A-A' to G-G'.

FIG. 6.— Carte géologique de la marge orientale centrale du rift du golfe de Suez (d'après MCCLAY et al., *1998). Localisation des coupes de la figure 9 : de A-A' à G-G'.*

BASEMENT

The oldest rocks of the Gulf of Suez region are Precambrian gneisses, volcanics and metasediments deformed and metamorphosed during the Panafrican orogeny, which terminated about 550 Ma (e.g., STERN, 1981, 1994; STOESSER & CAMP, 1985; KRÖNER, 1984, 1993). These units were intruded by synand post-tectonic granites and granodiorites, ranging in age from 700 to 500 Ma (GREENBERG, 1981; HASSAN & HASHAD, 1990).

Basement rocks are found in the cores of tilted fault blocks in the central and southern Gulf of Suez and also form the mountainous rift flanks of Sinai on the eastern margin and the Red Sea hills on the southwestern margin of the Gulf (Figs 1, 3). Erosion of the basement provided siliciclastic detritus to the rift, as metamorphic and igneous clasts are found in proximal deposits from the early Miocene to the present-day.

The basement of the Gulf of Suez exhibits a number of strong pre-rift fabrics (faults, joints, dikes, and shear zones) that have clearly influenced the Late Cainozoic rifting (ROBSON, 1971; GARFUNKEL & BARTOV, 1977; JARRIGE *et al.*, 1986; YOUNES *et al.*, 1998; YOUNES & MCCLAY, 1998; BOSWORTH *et al.*, 1998; MONTENAT *et al.*, 1998), as will be discussed below.

EARLY PALAEOZOIC STRATA

The metamorphic and granitoid pre-rift basement was extensively peneplained prior to deposition of the Cambrian clastics of the Araba and Naqus formations of the Qebliat Group (Fig. 4; HASSAN, 1967; SAID, 1971; EL BARKOOKY, 1992). These two distinctive red and white sandstone units are up to 130 m and 380 m thick, respectively. To the north of the Belayim area, on the eastern margin of the Gulf of Suez, Cambrian sequences are developed in a marine facies whereas to the south they are more continental.

LATE PALAEOZOIC STRATA

The Cambrian sandstones are conformably overlain by the Carboniferous Umm Bogma dolomitic strata that attain a thickness of 40 m (KOSTANDI, 1959; KLITZSCH, 1990). Somewhat impoverished foraminiferal microfaunas with Tethyan affinities indicate a middle Visean age (BRENCKLE & MARCHANT, 1984; KORA, 1986). To the south, in the Abu Durba area, the Umm Bogma passes laterally into the fossiliferous black shales and mudstones of the Abu Durba Formation (HASSAN, 1967; EL BARKOOKY, 1992). The Umm Bogma and Abu Durba formations are overlain by up to 200 m of brown, shallow marine sandstones of the Abu Thora Formation (WEISSBROD, 1969; KORA, 1984). These Carboniferous sandstones are intruded and capped by Permian basalts.

TRIASSIC, JURASSIC AND EARLY CRETACEOUS STRATA

Overlying the Carboniferous sandstones are thin, poorly fossiliferous strata of the Triassic Qiseib and the Jurassic to Lower Cretaceous Malha formations of the El Tih Group (BARAKAT *et al.*, 1988a; DARWISH, 1992). The Qiseib Formation (ABDALLAH *et al.*, 1963; BARAKAT *et al.*, 1988a) is Permo-Triassic in age, is about 300 m thick, and consists of unfossiliferous red beds which are in places clearly continental with well-developed palaeosols and in other areas are shallow marine, with bi-directional (tidal) cross-stratification. The Malha Formation (ABDALLAH *et al.*, 1963) varies in thickness from 30 to more than 150 m in the central Gulf and consists of white to pale yellow and pink, clean quartzose, cross-bedded fluvial sandstones. In the southern Gulf, the Malha Formation attains a maximum thickness of 400 m (R. WINN JR., *in* BOSWORTH, 1995).

LATE CRETACEOUS STRATA

The Upper Cretaceous sections (Fig. 4) consist of shallow marine strata that exhibit decreasing thickness from north to south (KERDANY & CHERIF, 1990; DARWISH, 1994). The Cenomanian Raha Formation is a succession of shales, sandstones and limestones, 80 to 100 m thick (GHORAB, 1961). The overlying 100 m thick Turonian Wata Formation (GHORAB, 1961) contains a thicker limestone which serves as a useful marker across the central and northern Gulf. The shales and sandstones of the 120 to 170 m thick Coniacian-Santonian Matulla Formation (GHORAB, 1961) are locally glauconitic and decrease in thickness south of Wadi Belayim. The Campanian to Maastrichtian Duwi (Brown

Limestone) and Sudr chalk formations (YOUSSEF, 1957; GHORAB, 1961) consist of 6 to 70 m of phosphatic, cherty and organic-rich limestones at the base, overlain by snow-white, hard, poorly-bedded chalk and chalky limestones that attain 100-140 m in thickness. The Brown Limestone is the richest oil source rock of the Gulf of Suez. The total thickness of Upper Cretaceous strata is about 500 m.

PALAEOCENE AND EOCENE STRATA

The grey Esna Shale Formation (BEADNELL, 1905; SAID, 1960) forms a prominent marker unit that overlies the Sudr chalk (Fig. 4). It varies in thickness from less than one metre in some places along the northeastern rift flank to about 35 m on the central eastern rift margin. The Palaeocene-Eocene boundary is found within the upper 3 m of the Esna shale (SAID, 1990; ZICO *et al.*, 1993). Overlying the Esna are the characteristic light buff weathering early Eocene limestones of the Thebes and Waseiyit formations. The composite thickness of the Eocene on the eastern side of the Gulf is more than 500 m.

There are two distinctive facies suites characterizing the Eocene sequences in the central and northern Gulf of Suez region. The Nile Valley facies is well developed south of the Feiran-Belayim area and is represented by the Thebes Formation (70 to 130 m of well-bedded, grey/white limestone with abundant chert in certain horizons; SAID, 1960) and the Samalut Formation, a thick-bedded, highly fossiliferous limestone 90 to 110 m thick (BISHAY, 1966). In some places, local outcrops of the middle-upper Eocene Mokattam Formation occur (SAID, 1990). The central Gulf of Suez facies is found between Wadi Feiran in the south and Wadi Sudr in the north. This facies suite includes the Waseiyit (early to middle Eocene), Rod El Awad, Thal (middle Eocene) and Tanka (late Eocene) formations (DARWISH & EL ARABY, 1993). In the southern Gulf, the thickness of the Eocene is greatly diminished. Only the Thebes formation is present, with thickness of generally 30-60 m. In the northernmost Gulf, at Gebel Ataqa, the lower Eocene is absent and the middle Eocene Suez Formation unconformably overlies Late Cretaceous strata (AKKAD & ABDALLAH, 1971; SAID, 1990). The distribution, sedimentary characteristics and boundary relationships of the Eocene formations are discussed in detail by e.g., MOON & SADEK (1923), VIOTTI & EL DEMERDASH (1969), BARAKAT *et al.* (1988a), ABUL NASR (1990) and SAID (1990).

LATE EOCENE-OLIGOCENE TRANSITION

The Tayiba Formation (HUME *et al.*, 1920) is a succession of red and white sandstones and siltstones which, based on stratigraphic position, are considered to be late Eocene-early Oligocene in age (HERMINA *et al.*, 1989; ABUL NASR, 1990). This formation is dominated by fluvial sandstones and poorly developed palaeosols. In the northern regions of the eastern margin of the Gulf of Suez, the lower part of the Tayiba red beds are found to contain shallow marine fossils (ABUL NASR, 1990). The Tayiba Formation is only locally exposed near Wadi Tayiba on the eastern margin of the Gulf of Suez. It passes upwards into the latest Oligocene-earliest Miocene syn-rift red beds of the Abu Zenima Formation. Strata of similar facies, and possibly the same age, are found overlying the Thebes Formation on the northernmost western margin of the Red Sea, as at Gebel Duwi.

SYN-RIFT STRATA

The latest Oligocene-Miocene syn-rift stratigraphy, shown in figure 5, was constructed using both onshore exposures and offshore well data, and illustrates both across- and along-strike variations within the basin. Syn-rift strata lie unconformably on a variety of pre-rift strata that range in age from Oligocene to Precambrian basement, as for example in the tilted fault blocks of the southern Gulf of Suez (ROBSON, 1971; EVANS, 1988; EVANS & MOXON, 1988). Structural control on deposition of syn-rift strata along the margins of the Gulf of Suez produced complex facies relationships, both along-strike and down-dip, particularly in the vicinity of active extensional faults (LAMBIASE & BOSWORTH, 1995; GAWTHORPE *et al.*, 1997; MCCLAY *et al.*, 1998; BOSWORTH *et al.*, 1998; PLAZIAT *et al.*, 1998b; KHALIL, 1998). The coarser-grained proximal syn-rift deposits give way to finer-grained deeper water facies in the central sections of the rift. Below a *résumé* of the main characteristics of the syn-rift sequences is given.

LATE OLIGOCENE-EARLIEST MIOCENE

The earliest recognized syn-rift deposits are the red beds of the late Oligocene-early Miocene (Chattian-Aquitanian) Abu Zenima Formation (HANTAR, 1965; SELLWOOD & NETHERWOOD, 1984; PLAZIAT *et al.*, 1998b; Figs 4, 5). This is a succession of red and white sandstones and siltstones with a basal conglomerate that contains basalt pebbles. The Abu Zenima Formation overlies the Tayiba red beds and is itself capped near Abu Zenima (Fig. 6) by a basaltic flow dated at 22 Ma (K-Ar; PLAZIAT *et al.*, 1998b). Other dikes and flows are dated by whole-rock K-Ar at 27 Ma and 24-21 Ma (STEEN, 1984; MENEISY, 1990; PLAZIAT *et al.*, 1998b). The basaltic flows are locally underlain by altered and weathered volcanic ash. In the northern Gulf, along the western coast north and south of Ain Soukhna (Fig. 3), a few highly altered basaltic dikes are present. One of these at southern Gebel Ataqa was dated at 25.7±1.7 Ma (K-Ar; BOSWORTH, unpublished data). These basic rocks are the only exposed rift-related igneous activity found in the Gulf of Suez. The Abu Zenima Formation is unconformably overlain by shallow marine strata of the Aquitanian Nukhul Formation (MCCLAY *et al.*, 1998; PLAZIAT *et al.*, 1998b).

No strata lithologically and stratigraphically equivalent to the Abu Zenima Formation outcrop in the southern Gulf of Suez. However, along the western margin of the Red Sea, south of Hurghada (Figs 1, 3), reddish siltstones, sandstones and conglomerates, immediately overlying the pre-rift sequence on the down-thrown side of major extensional faults, are interpreted to be of probable late Oligocene-earliest Miocene age (BOSWORTH *et al.*, 1998). These strata have been assigned to the Ranga Formation (GINDY, 1963; ISSAWI *et al.*, 1971) and are the basal part of Group A of MONTENAT *et al.* (1986a, 1988). At Gebel Duwi near Quseir, basal syn-rift conglomerates, sandstones, and lacustrine sediments are referred to the Nakheil Formation (AKKAD & DARDIR, 1966). In the subsurface, it is also possible that the basal member of the Nukhul Formation of the southern Gulf (Shoab Ali member; see below) correlates to the Abu Zenima Formation.

MIOCENE SYN-RIFT STRATA

The Miocene syn-rift series in the Gulf of Suez were deposited in near-shore and marine environments and range from coarse conglomeratic fan deltas adjacent to active border fault systems to more distal marls and evaporites in the central regions of individual sub-basins (Fig. 5). During the early rifting stages, individual extensional fault blocks along the rift margins developed their own sub-basins, each with its own stratigraphy. Hence, in different marginal fault blocks, the earliest syn-rift deposits vary in age and overlie different pre-rift strata as a result of different amounts and timing of extension, rotation, uplift, erosion and subsidence below the erosional base-level. In any particular sub-basin, the lowermost syn-rift deposits are commonly coarse clastics which, based on lithostratigraphic correlations, are generally assigned to the Nukhul Formation, but may in fact be diachronous and highly variable in age.

Below we summarize the general characteristics of the syn-rift strata, keeping in mind limitations outlined above and that more detailed research is ongoing (e.g., GAWTHORPE *et al.*, 1997). The best outcrops of syn-rift strata occur on the eastern margin of the Gulf of Suez from Wadi Baba to Gebel Ekma (Fig. 6). The following descriptions are primarily based upon our work in this area (MCCLAY *et al.*, 1998; KHALIL, 1998), supplemented by observations from Gebel el Zeit in the south (Fig. 7).

Nukhul Formation

The Aquitanian-Early Burdigalian Nukhul Formation (Figs 4, 5) is the first marine syn-rift sequence and in its type section in Wadi Nukhul (Fig. 6) is a succession of mainly shallow marine deposits which include calcareous conglomerates, sandstones and marls (EGYPTIAN GENERAL PETROLEUM CORPORATION STRATIGRAPHIC COMMITTEE, 1964; SCOTT & GOVEAN, 1985). Red palaeosols are locally present, indicating episodic exposure. In places the Nukhul Formation unconformably overlies the Abu Zenima red beds. The lowest beds of the Nukhul Formation are cross-bedded sandstones and conglomerates. Up-section, the calcareous sandstones are wave-rippled and siltstones contain marine fauna (pelecypod fragments). These beds are overlain by pale green calcareous mudstones that abruptly give way to a unit of cross-bedded calcareous lower and upper shoreface sandstones. Other exposures are composed of massive or horizontally stratified gravelly, coarse calcareous sandstones with angular chert fragments, pebbles of white Thebes limestones and broken pieces of oyster shells. In outcrops along the western margin of the rift, the basal syn-rift conglomerates are sometimes referred to the Abu Gerfan Formation (GHORAB & MARZOUK, 1967; NATIONAL STRATIGRAPHIC SUB-COMMITTEE OF THE GEOLOGICAL SCIENCES OF EGYPT, 1974; DARWISH & EL-AZABI, 1993).

Along the eastern margin of the Gulf, true Aquitanian-age Nukhul deposits are probably restricted to Wadi Nukhul (Fig. 6). Coarse basal clastics in other fault blocks are probably lower Burdigalian in age (i.e. time equivalent to lowermost Rudeis Formation). Aquitanian Nukhul strata also occur at Gebel el Zeit (Fig. 7), where they include channelised submarine sandstones, near-shore chert-cobble conglomerates and various carbonate shelf and slope facies (BOSWORTH *et al.*, 1998). Here the Nukhul facies distribution was directly controlled by the position and timing of movement of cross- and rift-parallel faults (WINN *et al.*, in press). The different Nukhul lithologies at Gebel el Zeit include abundant chert clasts of Eocene and Late Cretaceous origin. However, cobbles of Malha Formation sandstone, and rarely, basement-derived granites, are also present indicating more extensive early rift erosion than at Wadi Nukhul.

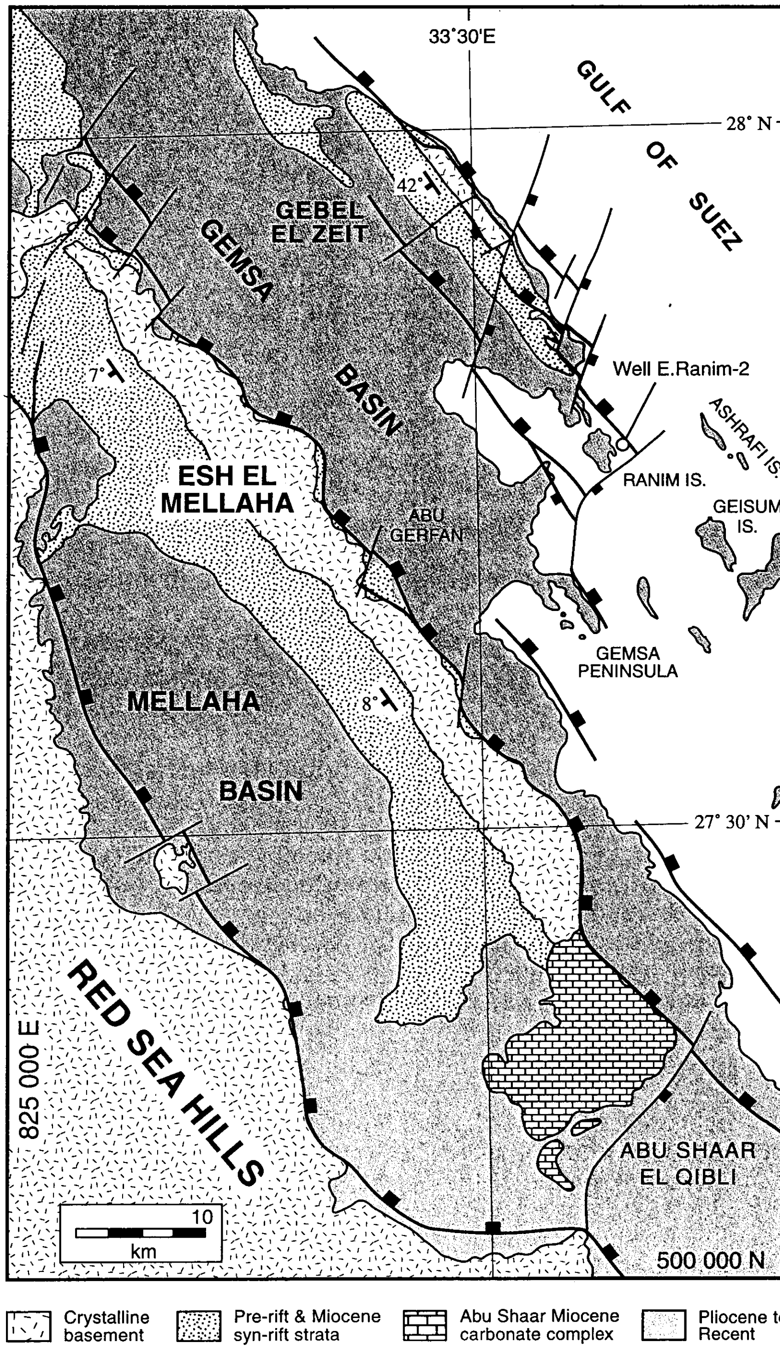

FIG. 7.— Surface geologic map of the southern western margin of the Gulf of Suez Rift (after BOSWORTH, 1995). Faults in the offshore and areas of Pliocene to Recent cover are projected to the surface.

FIG. 7.— Carte géologique de la marge sud-ouest rift du golfe de Suez (d'après BOSWORTH, 1995). Les failles en mer et dans les secteurs recouverts de sédiments pliocènes à récents sont projetées sur la surface.

In the southern Gulf of Suez subsurface, four Nukhul Formation members have been defined based on well penetrations at Shoab Ali field (Figs 3, 4; SAOUDI & KHALIL, 1986). The basal unit, the Shoab Ali Member, consists of sandstone with intercalated red shale and occasional coaly carbonaceous material. The unit is unfossiliferous at Shoab Ali, although a well east of Ranim Island (Fig. 7) has yielded Aquitanian-age microfossils from grey shales and limestones immediately overlying the interbedded reddish siltstones, sandstones and shales of the basal Nukhul strata. The Shoab Ali member is in turn overlain by the laterally interfingering Ghara anhydrite and marl, the October sandstone and conglomerate, and the Gharamul reefal limestone members (SAOUDI & KHALIL, 1986). Given the presence of Aquitanian age Nukhul strata at Gebel el Zeit and in the nearby subsurface, and based on the above discussion of lithologic variation within the Abu Zenima and Nukhul formations, it is clear that a distinction between these two formations is, in a regional sense, rather artificial.

Rudeis Formation

The early to earliest middle Miocene Rudeis Formation (EGYPTIAN GENERAL PETROLEUM CORPORATION STRATIGRAPHIC COMMITTEE, 1964) is much more widespread in the eastern Gulf outcrops than the Nukhul Formation. The Rudeis is divided into two parts by the "mid-Rudeis" or "mid-Clysmic" event, which produced a sharp facies change from a lower, fine-grained marl and sandstone succession to an upper, glauconitic and fossiliferous coarse sandstone succession (GARFUNKEL & BARTOV, 1977; BELEITY, 1984; Fig. 5).

In general, Lower Rudeis deposits consist of marls containing thin sandstones. However, in places, on the corners of tilted fault blocks, shallow marine reefal carbonates rest directly on tilted mid-Eocene nummulitic limestones (e.g., in the Gebel Araba and Gebel Abu Durba fault blocks; Fig. 6). In the southern Gulf, submarine channels cut locally into the Lower Rudeis section, and were later back-filled by turbidite sands and debris flows. In outcrop, the best example of this occurs in the central area of Gebel el Zeit, where the preserved channel thickness exceeds 50 m, down-cutting through the Nukhul Formation and underlying Malha sandstone, and includes in its basal unit large boulders of Malha Formation sandstone (LAMBIASE & BOSWORTH, 1995). In the subsurface, clastics transported through these channels are interpreted to have accumulated in submarine fan complexes near the basin axes.

The deposits formed after the mid-Rudeis event are extensive, coarse syn-rift sediments along the central eastern margin of the rift (Fig. 5). The best exposed area of these coarse conglomeratic sediments is in Wadi Sidri (Fig. 6), where conglomerate deposition persisted from Rudeis Formation times through to the Kareem Formation. Here the coarse clastics, known as the Abu Alaqa conglomerates (GARFUNKEL & BARTOV, 1977), are mostly poorly sorted, matrix- or clast-supported, with a crude stratification suggesting deposition in shelf-type fan deltas (GAWTHORPE *et al.*, 1990). In the lower parts of this Upper Rudeis succession, the clasts are mainly Eocene and upper Cretaceous limestones, whereas Palaeozoic and Mesozoic sandstones, followed by Precambrian basement, occur higher up section in conglomerates of the Kareem Formation.

Kareem Formation

The middle Miocene Kareem Formation overlies the Rudeis Formation (Fig. 5; EGYPTIAN GENERAL PETROLEUM CORPORATION STRATIGRAPHIC COMMITTEE, 1964). Locally, the Kareem rests unconformably on top of the Lower Rudeis Formation, in which case the mid-Rudeis event demarcates the boundary between these two formations. At the basin margin in the central eastern Gulf of Suez, conglomerates of the Abu Alaqa Group continued to develop. Shelly calcarenites and patch reef limestones make up most of the exposed sections, with a subordinate proportion of polymict conglomerates. In exposures near the coast in the Hammam Faraun area (Fig. 3), the appearance of the first middle Miocene evaporites denotes the abrupt facies change and basin restriction during early Kareem Formation time (Rahmi Member). This is followed by open marine dark grey shales (Shagar Member), a well-defined middle Miocene marker unit in the subsurface offshore sequences. In some areas the Kareem facies appears to have developed earlier at the basin margins than in the open basin and, accordingly, it is considered to be time transgressive from the latest early Miocene to the middle Miocene. As discussed below, onset of Kareem deposition is interpreted to reflect local uplift due to renewed block rotation in the southern Gulf region. This suggests that the boundary between the Rudeis and Kareem formations was a period of complex interaction between eustacy and local tectonism.

Belayim Formation

The Kareem Formation is unconformably overlain by late middle Miocene deposits referred to the Belayim Formation (EGYPTIAN GENERAL PETROLEUM CORPORATION STRATIGRAPHIC COMMITTEE, 1964; Figs 4, 5). In outcrop, the Belayim Formation consists of anhydrite, commonly overlain by a regional shale marker known as the Hammam Faraun. In the subsurface, anhydrite, halite, and conglomeratic sandstone predominate in the lower-middle part (Baba, Sidri and Feiran members) and shale and limestone in the uppermost part (Hammam Faraun Member; RICHARDSON & ARTHUR, 1988). The limestones are locally a reefal, primarily composed of red-algal (*Lithothamnium*) "Nullipore" rock (SELLWOOD & NETHERWOOD, 1984). This facies is extensively developed on most of the crests of subsurface fault blocks in the central Gulf.

In the southern Gulf of Suez, middle Miocene carbonate platforms and reefs developed directly on top of tilted basement fault blocks of the Esh el Mellaha range (Abu Shaar; JAMES *et al.*, 1988; BURCHETTE, 1988; CROSS *et al.*, 1998) and in the subsurface beneath Gubal Island (BOSWORTH *et al.*, 1998; Figs 3, 5 and 7). At Gubal Island and further south at Safaga, these carbonates contain Serravallian foraminifera (BOSWORTH *et al.*, 1998), and are therefore generally correlative with the upper Kareem and Belayim formations. In outcrop, based on lithologic correlations, these carbonates have been assigned to the Gharamul Formation (DARWISH & EL-AZABI, 1993). This is inappropriate, as the next higher "outcrop" unit, the Gemsa Formation, contains Burdigalian shales at its base at Gebel el Zeit and elsewhere (Rudeis Formation of subsurface terminology). For these and other reasons, the NATIONAL STRATIGRAPHIC SUB-COMMITTEE OF THE GEOLOGICAL SCIENCES OF EGYPT (1974) outcrop terminology is unworkable and is not followed in our field mapping.

South Gharib and Zeit formations

The South Gharib and Zeit formations are known principally from the subsurface and highly leached outcrops north of Hammam Faraun (Fig. 3) and along the southwestern margin of the rift (Fig. 7; SAID & EL HEINY, 1967; HASSAN & EL DASHLOUTY, 1970; GEZEERY & MARZOUK, 1976; ORSZAG-SPERBER *et al.*, 1998). In wells, the two formations may exceed 3 km in thickness (e.g., Gemsa and Central basins, southern Gulf of Suez; BOSWORTH, 1995). The South Gharib Formation is composed primarily of halite whereas the Zeit is comprised of halite, anhydrite, and lesser mudstone interbeds (Fig. 5). The uppermost strata of the Zeit Formation have been dated as late Miocene (stage not distinguished) based on ostracods and calcareous nannoplankton (EL-SHAFY, 1992).

PLIOCENE

In the Gulf of Suez, the Pliocene forms part of the El Tor Group (Fig. 4). At the rift margins it is characterized by gravels and sands (Wardan or Shukheir formations), whereas in the subsurface a section of clastics and thin evaporites overlie the late Miocene Zeit Formation (FAWZY & ABDEL AAL, 1986; Fig. 5). In the subsurface of the central Belayim Province, a thickness of more than 1000 m of this lower clastic/evaporite sequence is encountered in wells. It is overlain by evaporites of the Zaafarana Formation which is dominated by anhydrite at the base, salts in the middle, followed by pisolitic limestones and pebbly sandstones at the top (Figs 4, 5). In the southern Gulf, evaporites are locally present in the basal Pliocene section, but are absent from the late Pliocene.

As noted by FAWZY & ABDEL AAL (1986), the Pliocene/Pleistocene boundary is nearly impossible to pick, due to the lack of age-specific faunal control. TAVIANI (1998) has pointed out that many assignments of strata outcropping in the Gulf of Suez-northern Red Sea to the "Pliocene" are either incorrect or without palaeontologic support. In the central basin of the southern Gulf the undifferentiated Pliocene-Recent section reaches a thickness of about 1500-2000 m (BOSWORTH, 1995; BOSWORTH *et al.*, 1998), accounting for about one third of the total rift-fill.

QUATERNARY DEPOSITS

Quaternary deposits cover flat and topographically low areas as well as the coastal plains surrounding the present-day marine gulf. Quaternary alluvium and wind-blown sands cover the wadi floors. On the coastal plains, these deposits include loose to moderately consolidated coarse clastics, derived from the older pre-rift rocks that form the surrounding topographic highs. Along the central eastern margin of the Gulf of Suez, these coarse clastics mainly form coastal fan deltas. In addition, a series of raised beaches develop at different altitudes, ranging from a few meters on the coastal plains up to more than 90 m on the marginal coastal ranges (e.g., Hammam Faraun, Abu Durba, Gebel Araba, Gebel el Zeit and el Galala el Bahariya; GARFUNKEL & BARTOV, 1977). Many of these raised beaches include patchy coral reefs and oyster banks (ABU KHADRAH & DARWISH, 1986; PLAZIAT *et al.*, 1998a). Mapping and dating of these shoreline deposits along Gebel el Zeit and the offshore islands of the southern Gulf of Suez has shown that flexural uplift along individual, large extensional fault systems continues to the present (BOSWORTH & TAVIANI, 1996).

TECTONIC EVOLUTION OF THE GULF OF SUEZ RIFT

SIGNIFICANCE OF PRE-RIFT STRUCTURES

BASEMENT FAULTS AND FABRICS

The crystalline basement of the central Gulf of Suez predominantly consists of highly foliated granitic gneisses that have a dominant NW-trending fabric, minor metasediments, and at least three phases of syn-kinematic to post-kinematic granitoids that form semi-circular to oblate outcrop patterns. In the southern Gulf, at South Gebel el Zeit, Esh el Mellaha and the subsurface of Zeit Bay, Late Proterozoic calc-alkaline volcanic flows and pyroclastics of the Dokhan Group are also important (EL WAZEER *et al.*, 1992). The granitoids are largely unfoliated except for syn-kinematic intrusions which have plastic shear zones along their margins. Regional basement fabrics are readily observable on Landsat Thematic Mapper images and aerial photographs and include N- and NW-trending Panafrican foliations in the basement gneisses, pervasive NE- to ENE-trending vertical to sub-vertical mafic to andesitic post-Panafrican to Early Cambrian dikes, N-S fracture zones that offset some of the granitic intrusions, and NW-trending basement shear zones that are parallel the Najd Shear Zone system of the Arabian Craton (YOUNES & MCCLAY, 1998; MCCLAY & KHALIL, 1998).

The oldest fabrics are the Panafrican metamorphic foliations in the basement gneisses. On Sinai, the basement on the rift shoulder is cut by the NW-trending Rehba Shear Zone (Figs 3, 8) that parallels the Najd system in Saudi Arabia. The Rehba Shear Zone is characterized by a 200 m wide zone of cataclasites and is itself intruded by NE-trending rhyolitic and andesitic dikes. The basement gneisses and the granitoids are also cut by N-S fault systems that in places show dextral offset of the granitoid contacts by as much as 3 km. All of these pre-existing Pre-Cambrian to Early Cambrian fabrics were reactivated during the Late Cainozoic rifting of the Gulf of Suez (EL TARABILI & ADAWY, 1972; GARFUNKEL & BARTOV, 1977; JARRIGE *et al.*, 1986; PATTON *et al.*, 1994; YOUNES *et al.*, 1998). In particular, the zigzag pattern of the rift border fault and intra-rift fault systems results from reactivation and hard-linkage of the NW-trending shear zones and foliation fabrics via the N-S and NNE-SSW fault fabrics. MCCLAY & KHALIL (1998) demonstrated that in the Gebel Abu Durba area, *en échelon* NW-trending, SW-dipping extensional faults developed first in the rifting sequence, and were subsequently linked by reactivation of NNE-SSW fabrics.

All basement lithologies of the Eastern Desert-Gulf of Suez-Sinai region are also cut by pervasive, systematic joint systems (EL-SHAZLY *et al.*, 1979; ZAHRAN & ISMAIL, 1988; BOSWORTH, 1995; YOUNES *et al.*, 1998). At Gebel el Zeit and Esh el Mellaha, main basement joint sets pre-date deposition of basal Palaeozoic(?) sandstones, and themselves are locally intruded by Panafrican dike material (YOUNES *et al.*, 1998; A. YOUNES, unpublished data). The best developed joint sets strike N45°W,

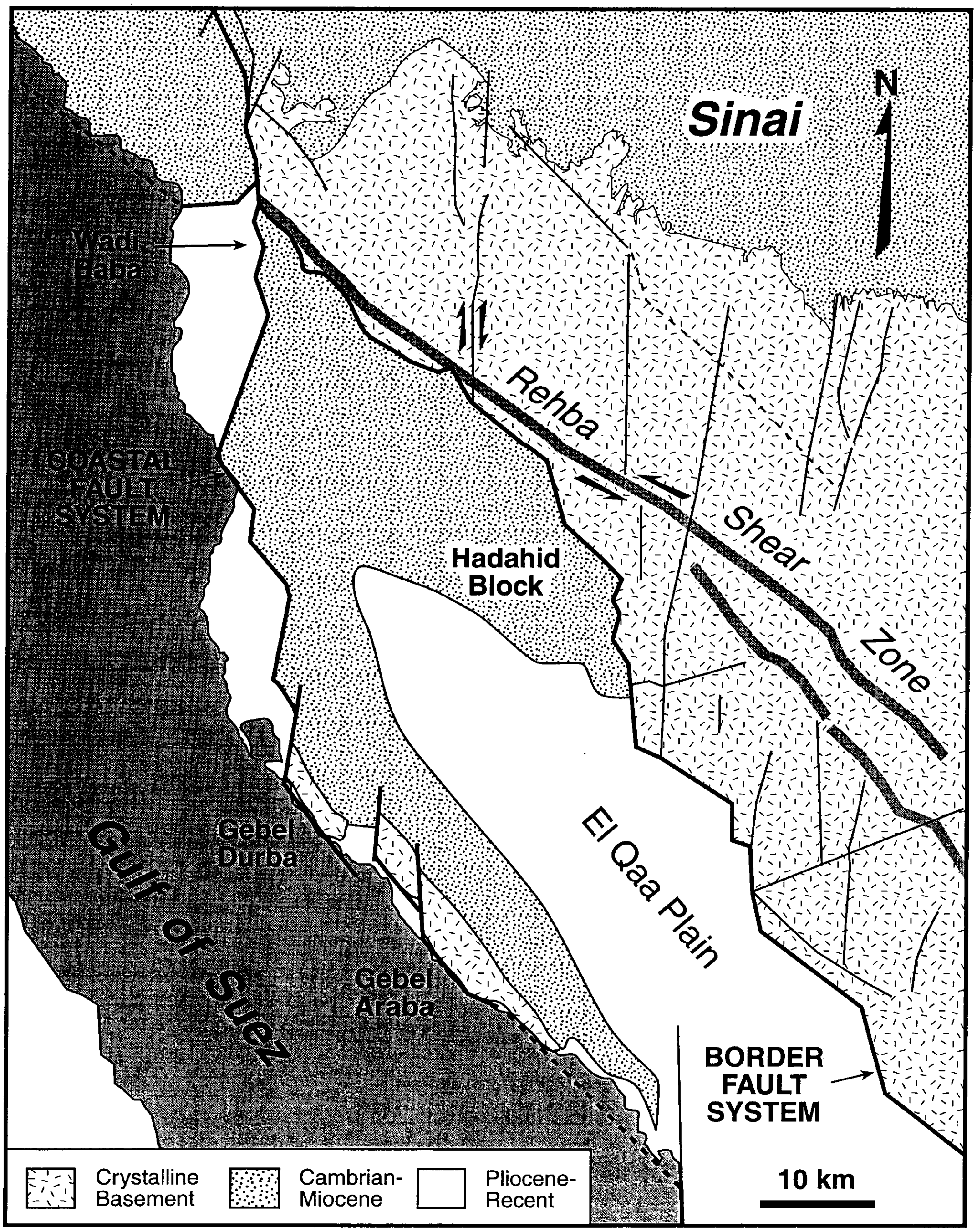

FIG. 8.— Basement fabric map of the central eastern margin of the Gulf of Suez (after YOUNES & MCCLAY, 1998). The position of the rift bounding fault east of the Hadahid Block is interpreted to have been controlled by the presence of the Pan-African Rehba Shear Zone. Jogs in syn-rift faults reflect the interplay between N-S and NW-SE basement fabrics.

FIG. 8.— Carte structurale du socle de la marge centre orientale du golfe de Suez (d'après YOUNES & MCCLAY, 1998). La position de la faille bordière du rift à l'est du bloc de Hadahid est interprétée comme contrôlée par la présence de socle panafricain de Rehba. Les décalages le long des failles syn-rifts représentent les interactions entre les accidents de socle N-S et NW-SE.

parallel to the Gulf of Suez rift axis, and N55°E, normal to the rift axis. Locally, a N25°E set is also present. After removing Late Cainozoic rotation of the basement fault blocks, these joint sets restore to vertical. In outcrop, mesoscale extensional and cross-faults with throws of a few meters are commonly oriented parallel to the rift-parallel and rift-normal joints. These faults are younger than the regional joint sets, and are mostly part of the Gulf of Suez syn-rift fault system, although a few may be Late Cretaceous in age (see below). Adjacent to the faults, younger fracture sets are developed that decrease in frequency away from the fault surfaces (YOUNES *et al.*, 1998). These faults also restore to approximately vertical orientations. Similarly, when restoring large basement blocks to pre-rift attitudes in the southern Gulf, the main rift-trend faults tend to restore to very steep dips, often ~80° (e.g., BOSWORTH, 1995). The effect of these geometric fault relationships can also be seen in outcrop at the northern end of the basement range at Gebel el Zeit. There, the basal pre-rift sandstone dips 42° SW. The main block-bounding extensional fault is exposed, with basement in the footwall and Belayim Formation/mega-fault breccia in the hanging wall (BOSWORTH, 1995, his Fig. 6). The dip of the fault is approximately 40° NE, resulting in a cut-off angle for the pre-rift strata of 82°. We interpret these pre-rift joint/syn-rift fault relationships to indicate that the Gulf of Suez extensional faults and interlinking cross-faults have, at least on the mesoscale, reactivated and precisely followed the basement joints.

TETHYAN/ALPINE STRUCTURES

In addition to the role played by basement structures in the subsequent development of the Late Cainozoic rift, faults that originated during Mesozoic and Early Cainozoic deformations exerted lesser, but nonetheless important influence on the orientation of syn-rift structures. The most important of these deformations occurred during the Santonian and late Eocene phases of regional compression and transpression. Both were related to events occurring to the north in the Tethyan-Alpine domains.

Santonian age deformation is the most widespread and best documented compressional event on the African plate (GUIRAUD *et al.*, 1987; GUIRAUD & BOSWORTH, 1997; GUIRAUD, 1998), although its manifestations are generally less dramatic than those of the Permo-Triassic Cape fold belt and Karoo basins of southern Africa (e.g., JOHNSON *et al.*, 1997). The Santonian event occurred at about 84 Ma, the time of a significant change in the relative motion between the African and Eurasian plates (SAVOSTIN *et al.*, 1986). This resulted in right-lateral transpression along the southern margin of the Tethys Ocean, and initiated the major phase of deformation within the Syrian Arc fold belt. Large ENE-WSW to NE-SW trending folds of this age are present in the northern sub-basin of the Gulf of Suez, both in outcrops of the rift shoulders and in the subsurface beneath the syn-rift fill (SADEK, 1926; SAID, 1962; MOUSTAFA & KHALIL, 1995). The northern accommodation zone of the rift, extending from the Galala Plateau to Abu Zenima (Fig. 3), is located at the intersection of the Late Cainozoic rift with the large Wadi Araba, south-verging anticline (LAMBIASE & BOSWORTH, 1995). In detail, the eastern, SW-dipping border fault of the central half-graben follows a series of Late Panafrican shear zones (Fig. 8). The border fault apparently propagated northward until it intersected the asymmetrical basement horst block that underlies the Wadi Araba Anticline. This horst block acted as an abutment, restricting further propagation of the border fault system. North of this fold/basement horst, the border fault reappeared as a NE-dipping structure, forming the eastern boundary of the northern Darag half-graben (Fig. 3).

Late Cretaceous structures also play a role in localising faults at smaller scales. At Gebel el Zeit and Esh el Mellaha, faulting of several ages has been identified: (1) post-Albian/pre-Senonian E-W strike-slip faults; (2) late Coniacian/earliest Santonian ENE-WSW strike-slip faults; and (3) late Santonian NNW-SSE normal, E-W strike-slip, and NNE-SSW reverse faults (BOSWORTH, 1995; GUIRAUD & BOSWORTH, 1997). The late Santonian faults are most abundant, but all of these fabrics have in places been reactivated, and were particularly important in the localisation and development of cross-faults during hard-linkage of rift-parallel normal faults.

Further north, within the Syrian Arc, folding and faulting continued locally and episodically during the Campanian and Maastrichtian, and in some places, early Eocene deformation is reported. However in the central and southern Gulf of Suez, no Eocene faulting has been firmly established (cf. RIVA *et al.*, 1992). During the late Eocene, a new pulse of deformation occurred across much of North Africa, corresponding to a significant phase of shortening in the Alpine fold belt in Europe (GUIRAUD *et al.*, 1987) and in Greece and Turkey (A.H.F. ROBERTSON, pers. comm.). The renewal of NW-SE compressional stresses produced right-lateral strike-slip faulting and associated folding in E-W belts in northern Egypt and along the Egypt-Sudan border. Prominent late Eocene E-W fault zones extend from Cairo to near Suez and Ain Soukhna (Fig. 1), probably in part reactivating Syrian Arc structures. During the late Oligocene development of the Gulf of Suez Rift, the Cairo-Suez fault zones are interpreted to have again moved as right-lateral strike-slip faults (PATTON *et al.*, 1994). Seismic data indicate that a large, N- to NNW-trending extensional basin of Oligocene to late Miocene age lies buried beneath the present-day Nile Delta fan. Extensional features also underlie the northern projection of the Gulf of Suez into the Bitter Lakes region (Fig. 1), and continue offshore into the Mediterranean continental margin (Y. MART, pers. comm.). We interpret the Cairo-Suez fault zones as large-scale relays, connecting the Darag half-graben with a more diffuse zone of extension to the north that includes the Bitter Lakes region and Manzala Rift basin. The Cairo-Suez relay area was also the focus for the extrusion of the largest volumes of late Oligocene/early Miocene basalt flows temporally associated with the Gulf of Suez Rift. In the Cairo area, these basalts have been radiometrically dated ($^{40}Ar/^{39}Ar$) as 23.64±0.035 Ma (KAPPLEMAN *et al.*, 1992) and approximately 22.5 Ma (2 samples with inconclusive plateau ages of 22.6 and 22.4 Ma; LOTFY *et al.*, 1995). Kinematic data from oblique- and strike-slip faults that were synchronous with, to slightly post-dating, the extrusion of the basalts, give an average extension direction of N10°E (BOSWORTH, unpublished data). The E-W Cairo-Suez Fault Zone behaved similarly to a "leaky transform" under the influence of the regional NE-SW directed early Gulf of Suez extensional stress field.

SUBSIDENCE MODELS AND REGIONAL EXTENSION ESTIMATES

The Gulf of Suez Rift basin is generally very well-suited to subsidence modelling. In comparison to many rift settings, the syn-rift fill is marked by good palaeontologic age control. The combination of abundant well data for basin depocentres and good outcrop along significant stretches of the rift shoulders allows back-stripping techniques to be applied both at individual localities and for reasonably well-constrained regional cross-sections (STECKLER, 1985; ANGELIER, 1985; EVANS, 1988; RICHARDSON & ARTHUR, 1988; STECKLER *et al.*, 1988). The major uncertainties encountered in these studies are: (1) the precise age of Abu Zenima-Nukhul Formation (estimates of early subsidence rates and the age of onset of rifting are not tightly constrained in these published studies); (2) the water depths (considerable differences of opinion have been presented, but this probably does not impact the first-order conclusions of these studies); (3) the depositional thicknesses of the evaporite section (due to flowage of the halite bodies within the Belayim to Zeit section, estimating original rock-unit thicknesses is extremely difficult; no good data are available for how far salt flowed laterally during formation of the Gulf of Suez salt swells and diapirs); and (4) the age of the South Gharib-Zeit formations. The top of the Belayim formation is known to be Foraminifera Zone N14 (end Serravallian) and the base Pliocene (generally an unconformity) can usually be picked, but the section between these two points is only defined palaeontologically as late Miocene (cf. EL-SHAFY, 1992).

Keeping these difficulties in mind, the subsidence studies noted above are in general agreement about the main evolutionary scheme of the rift: (1) total and tectonic subsidence rates during deposition of the Nukhul Formation were fairly low; (2) rapid subsidence appeared at ~20-19 Ma, during deposition of the Lower Rudeis Formation; (3) a major break in subsidence occurred at ~16 Ma (mid-Clysmic event; discussed below), within the upper part of the Rudeis Formation, but the nature of this break is highly variable from well to well; (4) subsidence rates abruptly slowed at ~15-14 Ma; (5) tectonic quiescence persisted until sometime in the late Miocene (~11 Ma; EVANS, 1988 or ~6 Ma; RICHARDSON & ARTHUR, 1988), when a new pulse of tectonically-driven subsidence occurred; and (6) from about 5 Ma to the present-day, tectonic subsidence rates again dropped but have not completely dissipated.

Based on these subsidence studies, estimates of total regional horizontal extension have been computed, and can be compared with similar estimates derived from structural restorations (reviewed in PATTON *et al.*, 1994 and BOSWORTH, 1995). In general, extension estimates calculated from subsidence analysis are about 50-100% larger than those based on structural/mechanical techniques. For example, COLLETTA *et al.* (1988) restored regional cross-sections and obtained 4-5 km of extension in the Darag Basin and ~20 km in the southern Gulf. RICHARDSON & ARTHUR's (1988) subsidence study yielded 5-10 km and 30-40 km of extension for each of these areas, respectively. Utilising more recent well and seismic control, and taking into consideration small-scale faulting not resolvable on seismic images, newly published structural estimates for extension are ~16 km for the northern Gulf (PATTON *et al.*, 1994) and ~35 km for the southern Gulf (BOSWORTH, 1995). These new studies largely reconcile the two approaches. They also confirm the general decrease in extension from south to north, and are compatible with the most commonly advocated requirements of Africa-Arabia-Sinai plate reconstructions (e.g., FREUND, 1970; COCHRAN, 1981, 1983; JOFFE & GARFUNKEL, 1987).

BASIN EVOLUTION

Our interpretation of the structural evolution of the Gulf of Suez Rift is heavily dependent on the following types of data: (1) timing and geometry of active fault systems; this strongly relies on observations from robust outcrop exposures, as on the central eastern Gulf margin and at Gebel el Zeit (Figs 6, 7), and formation isopach maps based on exploratory drilling (e.g., FAWZY & ABDEL AAL, 1986); (2) kinematics of stratigraphically-dated faults; age-constrained fault kinematic data for most of the intra-rift fill are unfortunately very limited — both in terms of areas and time intervals. We will discuss this aspect of previous published interpretations in some detail due to its importance to tectonic reconstructions; (3) interplay between structures and syn-tectonic sediments; these data are also heavily weighted to outcrop examples. We will attempt to draw upon the information that is now available for both the central and southern Gulf; and (4) new refinements in the palaeontologic dating of key stratigraphic intervals; this information has resulted from both recent exploratory drilling in the Gulf and detailed outcrop studies.

RIFT INITIATION (CHATTIAN-AQUITANIAN)

The evidence for the timing of the onset of rifting in the Gulf of Suez can be summarized as follows. (1) Reworked Chattian age foraminifera have been identified in the basal Nukhul Formation of a well drilled at Hurghada (EL SHINNAWI, 1975). This proves that late Oligocene marine strata were deposited in the area of the southern Gulf. It is not known, however, whether these marine strata were deposited in a fault-bounded rift basin, or a proto-rift sag. (2) Benthic foraminifera of Chattian age (planktonic zones N2 and N3 of BLOW (1969), equivalent to P22 zone of BERGGREN *et al.* (1995), or ~27-24 Ma) have been found in carbonates of the early syn-rift Musayr Formation along the northern Saudi Arabian Red Sea margin at Midyan (DULLO *et al.*, 1983; BAYER *et al.*, 1988; PURSER & HÖTZL, 1988). These carbonates are in turn underlain by undated redbeds of the Sharik Formation, which are also potentially syn-rift deposits. In a pre-rift configuration, the Midyan region restores to a position essentially adjacent to Hurghada. (3) The oldest syn-rift strata exposed along the Egyptian Red Sea coast, the northern, central and southern Suez coasts, and drilled in the Gulf of Suez subsurface, are unfossiliferous, but are intruded by basaltic dikes or overlain by flows that yielded K-Ar dates between 27 and 20 Ma (STEEN, 1984; ROUSSEL, 1986; MENEISY, 1990; BOSWORTH, 1995; PLAZIAT *et al.*, 1998b; Gebel Ataqa date given above). As shown for the southern Red Sea Saudi Arabian and Yemeni margins, these volcanic rocks suffer extensively from contamination by crustal fluids and surface alteration by ground water, and therefore the K-Ar dates must be treated with a great deal of caution (CHAZOT *et al.*, 1998). (4) Equivalent volcanics intruding and interbedded with continental strata along the Cairo-Suez Fault Zone give $^{40}Ar/^{39}Ar$ dates of 23.6 to 22.4 Ma (see above). These data are assigned considerably more significance than the K-Ar dates. 5) Marine strata of the early Aquitanian planktonic zone N4 (BLOW, 1969; = zone M1 of BERGGREN *et al.*, 1995) are well-documented in the Nukhul formation in the southern Gulf of Suez, at least as far north as the northern termination of Gebel el Zeit (BOSWORTH, 1995, and discussion above).

Based on these stratigraphic data, the onset of rifting is no younger than 27-25 Ma for the latitude of Hurghada (mid-Chattian faunas), 25-23 Ma for the central Gulf (local K-Ar dates and stratigraphic relationships), and ~23.5 Ma for the northern Gulf and Cairo-Suez relay zone ($^{40}Ar/^{39}Ar$ dates). This interpretation is compatible with the general observation that the basal strata of the Nukhul Formation, the Shoab Ali Member, appear to pinch-out north of its type locality in the southern Gulf of Suez (SAOUDI & KHALIL, 1986; MESHREF & KHALIL, 1992; PATTON *et al.*, 1994). However, these are only minimum ages for the onset of rifting. These ages are compatible with a period of Chattian-Aquitanian rift propagation toward the north, which serves as our working hypothesis until older syn-rift strata (if any) are proven to occur in any of the rift sub-basins.

Initial rifting began at or near sea-level as evidenced by the deposition of Chattian marine sediments in the south and the rapid transition from the Abu Zenima red beds to the shallow marine Nukhul Formation in the central Gulf. There is no stratigraphic or other evidence for any significant regional crustal doming or uplift prior to rifting (GARFUNKEL & BARTOV, 1977; STECKLER, 1985). However, apatite fission-track studies suggest that a phase of basement unroofing began on the rift shoulder of the southern Red Sea of Egypt and in a small area of the northwestern Gulf of Suez at ~34 Ma (Eocene-Oligocene transition; STECKLER & OMAR, 1994; OMAR & STECKLER, 1995). OMAR & STECKLER interpret this as part of a regionally synchronous, Red Sea rift system pulse of extension. However, no definitive stratigraphic or structural evidence is available to ascertain the relationship between this older "rift event" and the Red Sea-Gulf of Suez extension *sensu stricto* that began several million years later. It is more likely that this brief pulse of denudation was related to the late Eocene strike-slip faulting (Tethyan/Alpine fabric) discussed above.

EARLY CRUSTAL EXTENSION (AQUITANIAN)

The first major phase of extension was marked by the development of domino-style tilted (rotational) fault blocks with growth of the Nukhul Formation syn-rift strata in the hanging walls of the active extensional faults. Major depocentres developed along what are now the margins of the rift, including the El Qaa, Mellaha, and Gemsa basins (Figs 9, 10). Rifting developed by initial formation of segmented NW-trending extensional faults that rapidly became linked by the N to NNE fault systems (e.g., KHALIL & MCCLAY, 1998; KHALIL, 1998), thus forming the characteristic zigzag or rhomboidal fault pattern of the Gulf of Suez (Figs 11, 12).

Several interpretations of palaeostress fields have been proposed for the early Miocene initial extension (Fig. 13). ANGELIER (1985) suggested a relatively simple scenario in which Gulf of Suez extension remained approximately rift-normal throughout the evolution of the basin. LYBERIS (1988) envisioned initial NNE-SSW extension, followed by several stress-field rotations during the late early Miocene to Pliocene. JARRIGE *et al.* (1990) elaborated a very different interpretation, in which the rift formed during NNW-SSE compression under a strike-slip stress regime. The problem is that very few, stratigraphically-constrained, fault kinematic indicators of Chattian-Aquitanian age have been found in outcrop. At South Gebel el Zeit (BOSWORTH, 1995, his Fig. 7), numerous 150-160° striking syn-depositional small-scale faults are present. These are extensional faults, compatible with a rift-normal minimum stress, but no slip-direction indicators are preserved. In general, we observe similar geometric relationships throughout the rift: i.e. earliest Miocene fault patterns that are compatible with, but do not necessarily prove, rift-normal extension.

Near the end of Nukhul deposition, extensive carbonate platforms, in part reefal, and carbonate slopes developed on the crests of fault blocks in the southern Gulf of Suez (BOSWORTH *et al.*, 1998). The Nukhul carbonate units seal many previously active cross and rift-parallel faults. This is the first of several fault-system reorganizations that occurred during the extensional history of the basin. Topographic relief during the Aquitanian was variable. For the central eastern margin of the rift, sedimentologic studies suggest that very little topography was present during the early Miocene (SELLWOOD & NETHERWOOD, 1984). At Gebel el Zeit, the presence of boulders of sandstone and chert within deeply incised, steep-walled Nukhul channels and the rare occurrence of basement clasts have been interpreted to indicate considerable, local uplift (BOSWORTH *et al.*, 1998; WINN *et al.*, in press). There is no definitive stratigraphic evidence, however, of significant rift shoulder uplift during the Aquitanian.

MAIN PHASE OF RIFT SUBSIDENCE AND ONSET OF RIFT SHOULDER UPLIFT (BURDIGALIAN)

Subsidence rates in the Gulf of Suez reached their maximum during the Burdigalian between 19 and 16 Ma (STECKLER, 1985; MORETTI & COLLETTA, 1987; MORETTI & CHÉNET, 1987; EVANS, 1988; RICHARDSON & ARTHUR, 1988; STECKLER *et al.*, 1988). During this period, it appears that the Suez Rift was linked with the northern Red Sea (GARFUNKEL & BARTOV, 1977; MART & HALL, 1984), and the

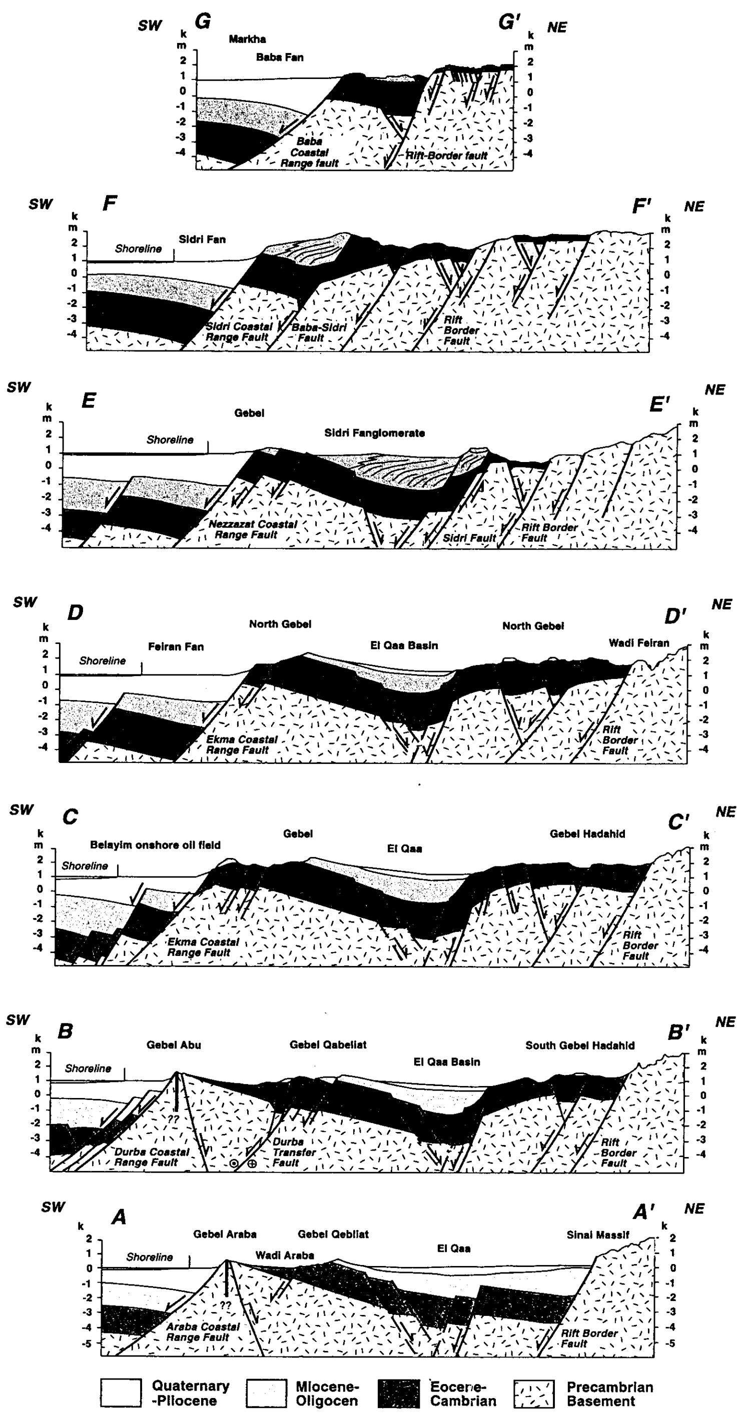

FIG. 9.— Cross-sections through the central eastern margin of the Gulf of Suez (after MCCLAY *et al.*, 1998). See figure 6 for locations.

FIG. 9.— Coupes à travers la marge centre orientale du golfe de Suez (d'après MCCLAY et al., *1998). Voir localisations sur la figure 6.*

general stratigraphic framework of the two areas is similar (TEWFIK & AYYAD, 1984; MILLER & BARAKAT, 1988). Stratigraphic sequences that developed during this main phase of extension show major variations across and between adjacent fault blocks. Key erosional unconformities (sequence boundaries) developed and bound major stratigraphic packages (Fig. 5). These sequence boundaries indicate major extensional tectonic events, causing rotation of the fault blocks and influencing the accommodation space, sediment sources, input points and sediment distributions within sub-basins of the rift (GAWTHORPE *et al.*, 1990, 1997).

By the early Burdigalian, the fault pattern that underpins the final rift geometry of the Gulf of Suez was generally well-established (Figs 12, 13). As during the Aquitanian, precisely constrained fault kinematic data are lacking during the Burdigalian. Nevertheless, fault geometries indicate that rift-normal extension probably persisted through this main subsidence phase, in agreement with the interpretation of ANGELIER (1985).

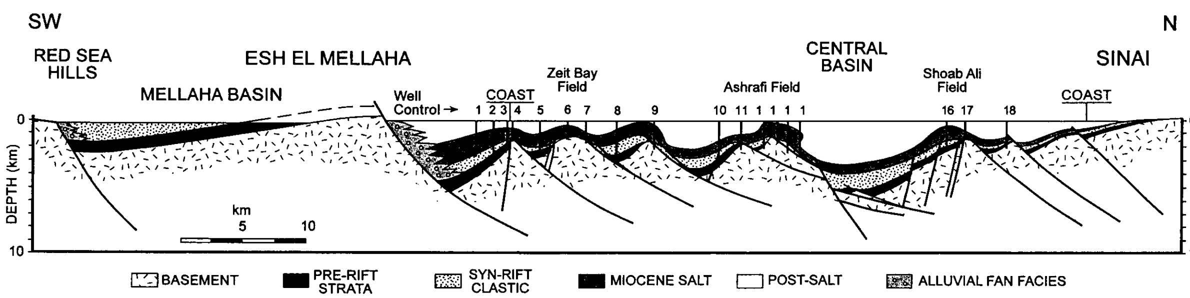

FIG. 10.— Regional cross-section through the southern Gulf of Suez (after BOSWORTH, 1994). See figure 3 for location.

FIG. 10.— Coupe régionale du golfe de Suez méridional (d'après BOSWORTH, 1994). Voir localisation sur la figure 3.

MID-RUDEIS (MID-CLYSMIC) EVENT (LATE BURDIGALIAN)

The first major influx of coarse clastics into the eastern marginal sub-basins of the central rift occurred after a major, intra-Burdigalian unconformity (unconformity 3 on Fig. 5) that has received considerable attention in the literature (GARFUNKEL & BARTOV, 1977; see discussion *in* PATTON *et al.*, 1994). This is a widespread unconformity, across which the fine-grained *Globigerina* marls of the lower Rudeis are overlain by limestone conglomerates, in places focused in channels and canyons that cut deeply into the underlying strata (both syn-rift and locally pre-rift). The Upper Rudeis is spectacularly developed as large, gravelly fan-deltas which formed at the mouths of ancestral drainage systems. These marginal conglomerates are found adjacent to active major faults along the eastern margin of the Gulf (Wadi Homur, Wadi Baba, Wadi Sidri and Wadi Feiran; Fig. 6). A progressive erosion, or unroofing/exhumation history, of the rift flank is evident from the clast types found in the upper parts of the fanglomerate successions (i.e. an inverted clast stratigraphy; GARFUNKEL & BARTOV, 1977; SELLWOOD & NETHERWOOD, 1984). Continued and renewed phases of extension on faults along this eastern margin of the rift are indicated by syn-depositional unconformities within the conglomerate sequences. In contrast to the coarse clastic deposition in the immediate hanging walls of active faults, finer-grained clastics (sandstones and silts) are found onlapping the uplifted footwalls of some fault blocks (DOLSON *et al.*, 1996). These sand sequences form important syn-rift reservoirs in the eastern Gulf of Suez (e.g., October field).

The duration and local significance of the Mid-Rudeis event are extremely variable. In some areas, Kareem formation strata of Langhian to Serravallian age are found resting directly on Lower Rudeis strata, and the Mid-Rudeis and base-Kareem unconformities merge. Due to its occurrence during the main rifting phase, it is often referred to as the "mid-Clysmic" event. GARFUNKEL & BARTOV (1977) observed that numerous faults die out or diminish at the Mid-Rudeis unconformity, and hence inferred a significant structural reorganization, similar to that described above for the end-Nukhul carbonates. LYBERIS (1988) inferred an ~45° clockwise rotation of the regional stress field to ENE extension during the late Burdigalian (Fig. 14). JARRIGE *et al.* (1990) interpreted the Mid-Clysmic event to correspond to the end of strike-slip faulting and the onset of the main phase of approximately rift-normal (N70-80°E) extension (see also MONTENAT *et al.*, 1986a). In contrast, no significant break in Rudeis deposition is observed in many basinal wells of the southern Gulf of Suez. EVANS (1988) reports the occurrence of an intra-Rudeis conglomerate horizon at Gebel el Zeit, but based on our field observations and palaeontologic data, the Mid-Rudeis event cannot be discerned in most sections exposed at Gebel el Zeit.

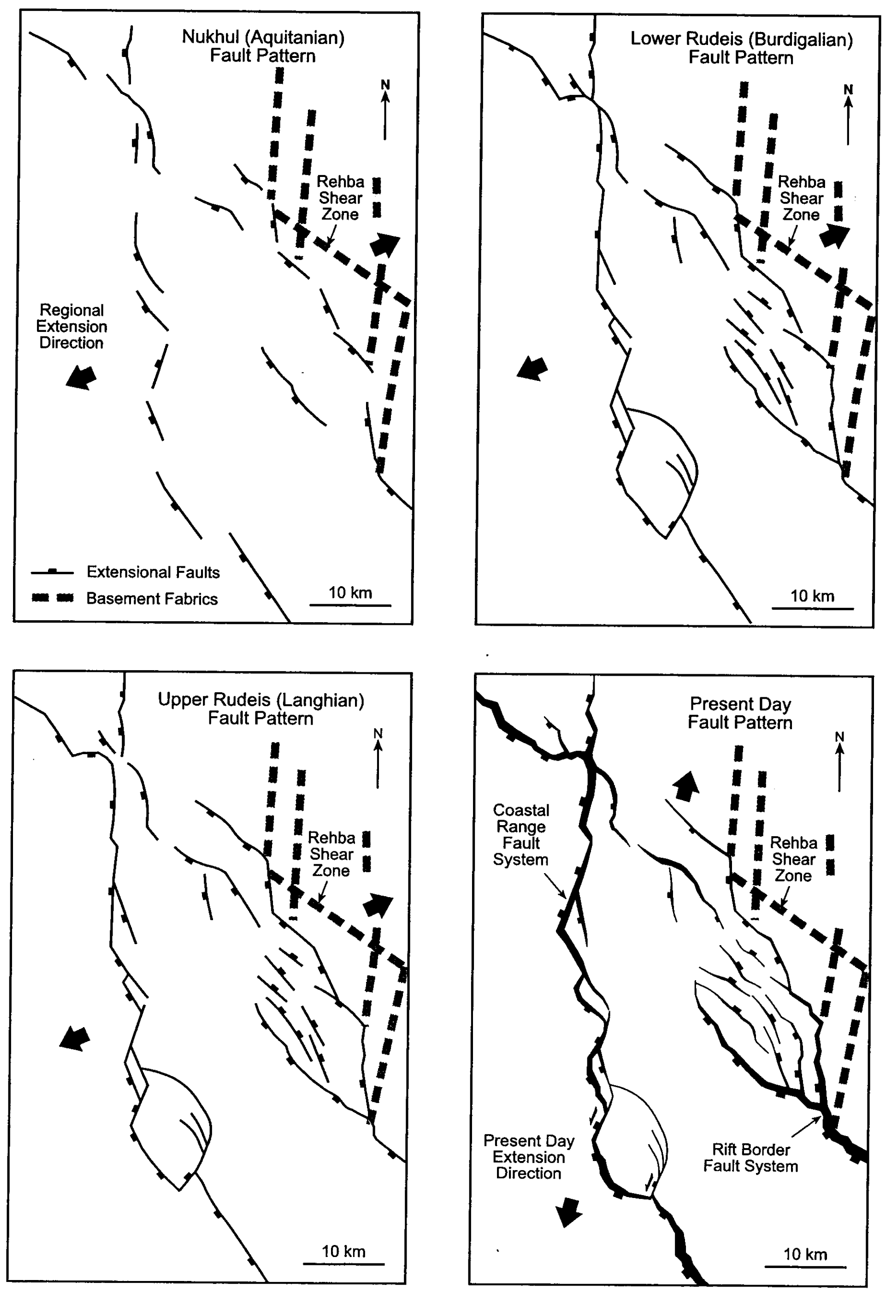

FIG. 11.— Fault activity maps for the central eastern margin of the Gulf of Suez (after KHALIL & MCCLAY, 1998). Based on interpretation of the area shown in figure 6.

FIG. 11.— Cartes des failles actives dans la marge centre orientale du golfe de Suez (d'après KHALIL & MCCLAY, 1998.) Basées sur l'interprétation du secteur localisé sur la figure 6.

According to PATTON *et al.* (1994), the Mid-Rudeis event is most plausibly related to the onset of significant transform movement along the Gulf of Aqaba and a decrease in extension rates across the Gulf of Suez. Several lines of evidence, however, contradict this interpretation: (1) using stratal rotation as a proxy for extension, the principal decrease in extension rates observed in dipmeter logs and outcrops of the southern Gulf (i.e. near the Gulf of Aqaba) occurred after deposition of the Kareem Formation, during the late Serravallian (BOSWORTH *et al.*, 1998); (2) in the southern Gulf, there is

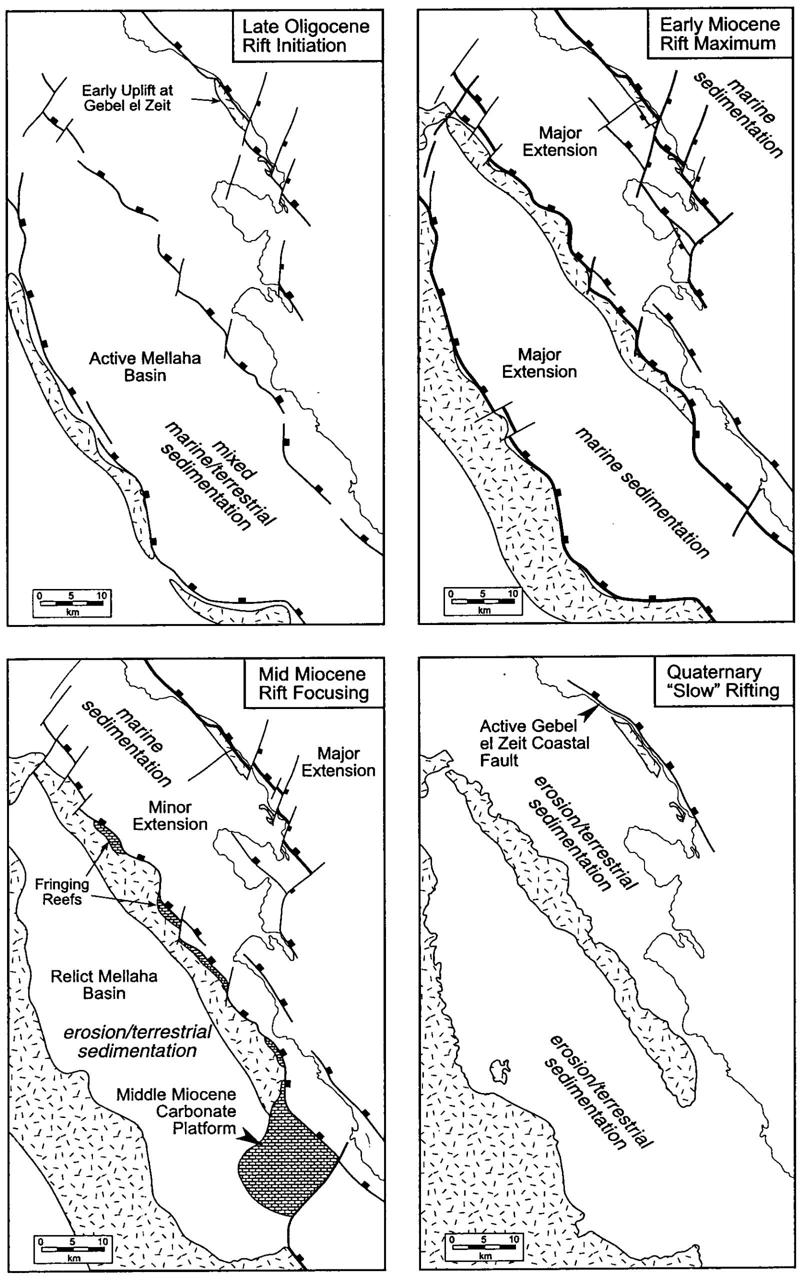

FIG. 12.— Fault activity maps for the south western margin of the Gulf of Suez based on interpretation of the area shown in figure 7. Fault movement and associated basin subsidence were progressively focused toward the axis of the rift through time, culminating in the present-day, narrow Gulf of Suez marine basin.

FIG. 12.— Cartes des failles actives dans la marge méridionale occidentale du golfe de Suez basées sur l'interprétation du secteur localisé sur la figure 7. Le mouvement des failles et la subsidence associée dans les bassins se circonscrivent progressivement à la partie axiale du rift, pour se limiter actuellement à l'étroit bassin marin du golfe de Suez.

generally greater angular discordance and more missing section at the base Belayim unconformity than at the Mid-Rudeis unconformity; (3) quantitative subsidence analyses show a more consistent sudden drop in subsidence rates at the end of Kareem deposition than across the Mid-Rudeis unconformity (e.g., EVANS, 1988; RICHARDSON & ARTHUR, 1988); and (4) new age constraints on the timing of Gulf of Aqaba strike-slip deformation from northern Sinai indicate that development of the transform boundary occurred in the middle Miocene (EYAL, 1996). These data suggest that the Mid-Rudeis unconformity, and associated uplift of blocks long the central eastern margin of the rift, were related to tectonic activity older than the initial movement along the Gulf of Aqaba.

END MAIN PHASE RIFTING (LATE BURDIGALIAN-SERRAVALLIAN)

As discussed above, following the Mid-Rudeis tectonic event, deposition changed to predominantly coarse clastics and associated reefal limestones along the central eastern margin of the basin. Although *Globigerina* marls continued to be deposited along the basin axis, the Upper Rudeis there also contains significant quantities of clastic material in submarine fans. At approximately the Burdigalian-Langhian transition, a brief pulse of evaporite deposition occurred in many sub-basins, associated with very localized sandstones. This change in deposition marks the base of the Kareem formation, and may reflect a complex interplay between eustatic and tectonic effects detailed in a following section. Subsidence rates were generally lower during Upper Rudeis and Kareem deposition than during the Lower Rudeis; yet, these strata still belong to the main phase of Gulf of Suez extension.

Based on our field observations, no major change in fault geometries or fault kinematics occurred following the Mid-Rudeis event (Fig. 12b, c). We cannot definitively rule out the late Burdigalian stress field adjustment advocated by LYBERIS (1988), but note that the absolute age-constraints are very limited. Our interpretations are not compatible, however, with a major shift from strike-slip rift initiation (pull-apart basins) to ENE-extensional faulting (horst and graben formation), as postulated to have occurred at the Mid-Rudeis (Mid-Clysmic) event by the GENEBAS mapping program (e.g., JARRIGE *et al.*, 1986, 1990; MONTENAT *et al.*, 1988, 1998). Two of the principal field areas studied by this group were Gebel el Zeit-Esh el Mellaha and Abu Rudeis-Abu Durba, which also form the core of our own field mapping and the basis for the model we present here. A reconciliation of the two models is discussed below.

INITIATION OF AQABA TRANSFORM, FORMATION OF EVAPORITIC BASIN AND UPLIFT OF MARGINAL BASINS (LATE SERRAVALLIAN-MESSINIAN)

Based on structural restorations, extension is interpreted to have continued at a slower rate from the Serravallian to the Messinian (GARFUNKEL & BARTOV, 1977), with concomitant slower subsidence (e.g., STECKLER *et al.*, 1988). Many workers (EVANS, 1988; RICHARDSON & ARTHUR, 1988; STECKLER *et al.*, 1988; BOSWORTH *et al.*, 1998) interpret the dramatic decrease in tectonic subsidence during the Serravallian as resulting from a shift of the Sinai-Africa plate boundary to the Gulf of Aqaba-Dead Sea Transform. With the onset of sinistral strike-slip motion along the Gulf of Aqaba fault system, the Gulf of Suez was effectively isolated from further extension, thus causing its abortion. Based on subsidence modelling, STECKLER *et al.* (1988, their table 1) interpreted the late Burdigalian (Rudeis), early Serravallian (Kareem) and late Serravallian (Belayim) opening rates in the vicinity of Hurghada (Sinai triple junction) to be approximately 0.48, 0.18 and 0.05 cm/yr, respectively. Extension continued in the northern Red Sea and is still active (COCHRAN, 1983; MART & HALL, 1984; MARTINEZ & COCHRAN, 1988). Stratigraphic sequences developed during this stage in the rift evolution are characterized by the thick evaporites (up to 3 km) of the Belayim, South Gharib and Zeit formations (HASSAN & EL-DASHLOUTI, 1970; ROBSON, 1971). Major evaporite deposition began during the late Serravallian and continued until the Pliocene (RICHARDSON & ARTHUR, 1988; ORSZAG-SPERBER *et al.*, 1998). These evaporites consist mainly of sulphates along the basin margins and halite in its central parts with shale intercalations containing biotas displaying Mediterranean affinities. At least parts of these evaporite sequences were deposited in deep water (ORSZAG-SPERBER *et al.*, 1998).

It is generally agreed that during this period tectonism in combination with the effects of a globally falling sea-level (HAQ *et al.*, 1987) played an important role in developing restricted and isolated basins

(PATTON *et al.*, 1994; BOSWORTH *et al.*, 1998; ORSZAG-SPERBER *et al.*, 1998; PLAZIAT *et al.*, 1998b). Two specific mechanisms contributed to this. First, the main phase of early Miocene extension drove flexural uplift of rift flanks, particularly after the late Burdigalian Mid-Rudeis event (see above) and continuing through the late Miocene. Marginal fault blocks, such as the Mellaha, Gemsa, and El Qaa sub-basins, were affected by this uplift (Figs 12, 13). This resulted in a decrease of water depths and severely restricted water circulation, favouring deposition of gypsum as selenite (RICHARDSON & ARTHUR, 1988; ORSZAG-SPERBER *et al.*, 1998). Some fault blocks, such as Esh el Mellaha, were

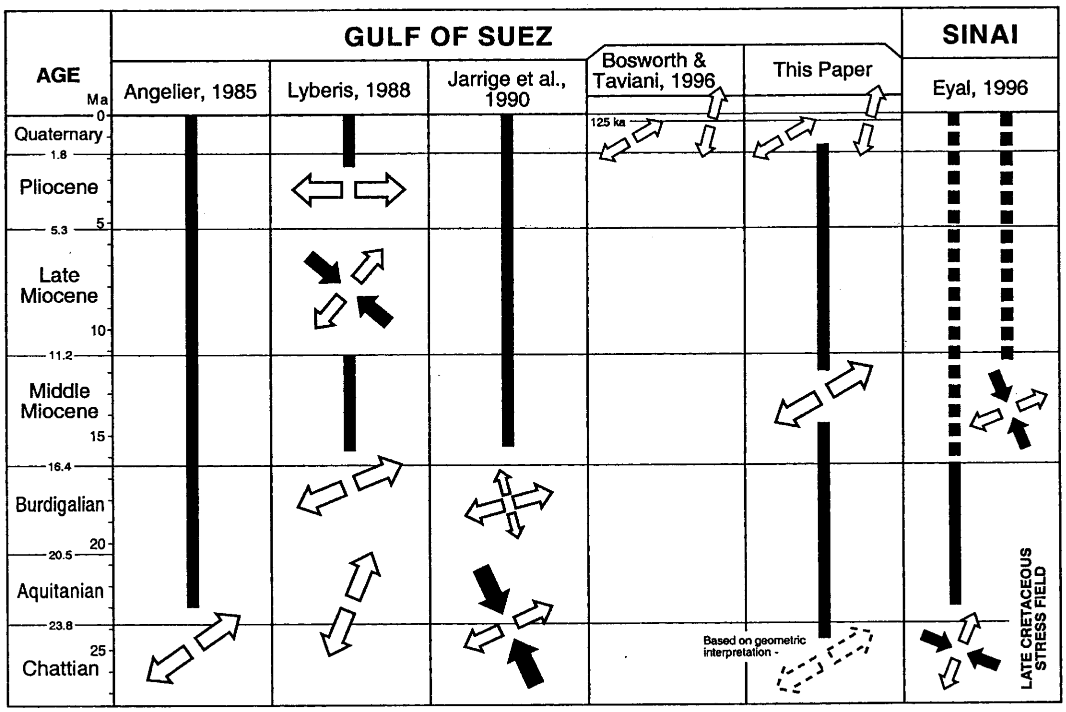

FIG. 13.— Summary of palaeostress interpretations for the Gulf of Suez and the adjacent Sinai micro-plate. Heavy solid lines show duration of interpreted stress field. The various interpretations of Chattian to Burdigalian stress fields in the Gulf of Suez are largely based on fault kinematic data that lack age control. Geometric data presented in this paper, which must be treated with caution, support approximate rift-normal extension (dashed arrows). In the northern Sinai, EYAL (1996) interpreted that two stress fields have operated concurrently or intermittently since the middle Miocene (heavy dashed lines). Kinematic data supporting our middle Miocene and Quaternary interpretations are given in figure 14.

FIG. 13.— Résumé de l'interprétation des paléocontraintes dans le golfe de Suez et la microplaque Sinaï adjacente. Les traits épais indiquent la durée proposée du champ de contrainte. Les différentes interprétations des champs de contraintes du Chattien au Burdigalien dans le golfe de Suez sont largement basées sur les données cinématiques de failles peu contraintes en âge. Les données géométriques présentées dans cet article doivent être considérées avec précaution, elles plaident pour une extension sub-perpendiculaire au rift (flèches en tirets). Dans le nord du Sinaï, EYAL(1996) décrit deux champs de contraintes concurrents ou intermittents depuis le Miocène moyen (tirets épais). Les données cinématiques appuyant notre interprétation du Miocène moyen au Quaternaire sont présentées sur la figure 14.

uplifted to the extent that continental environments were established, with erosion or non-deposition predominating, forming relict basins (BOSWORTH, 1994). Second, onset of left-lateral strike-slip faulting along the Aqaba-Levant trend was accompanied by a reorientation of the stress field in northern Sinai (EYAL, 1996) and, by the late Miocene, also in the Gulf of Suez (LYBERIS, 1988; Fig. 13). Interpretations infer NW-SE to NNW-SSE directed compression. However, we are not aware of any published middle to late Miocene stress field data for the northernmost Gulf-Bitter Lakes region. Nevertheless, it is possible that NW-SE compressional stresses were also present in this area, causing reactivation of ENE-trending Syrian Arc structures as positive uplifts, either at Wadi Araba (PATTON *et al.*, 1994) or further north.

In addition to the thick evaporitic sequences, the Serravallian in the southern Gulf of Suez is also noted for carbonate reefs and platforms located at the crests of fault blocks and along the western rift margin (e.g., at Esh el Mellaha; CROSS *et al.*, 1998; Fig. 12). Comparable to the Nukhul, the Serravallian carbonates and their laterally equivalent evaporites seal many cross- and rift-trend faults. BOSWORTH *et al.* (1998) suggested that the extensive development of Aquitanian (Nukhul) and Serravallian (Kareem-Belayim) carbonate platforms reflects a waning of tectonic activity, linkage of small fault blocks into larger, stable blocks, and correspondingly a decrease in siliciclastic input for topographic highs.

Some fault kinematic data are available from Serravallian age rocks caught in sliver blocks along the NE-dipping border faults of Gebel el Zeit and Esh el Mellaha (Fig. 14). Geologic relationships suggest that the period of movement recorded by these faults is late middle to late Miocene in age, with an extension direction of N40-60°E. These data are in agreement with most fault kinematic analyses for this period of the rift history, generally inferring rift-normal extension (ANGELIER, 1985; LYBERIS, 1988; JARRIGE *et al.*, 1990).

LATE-RIFT RENEWED SUBSIDENCE (PLIOCENE-RECENT)

A second period of significant subsidence followed deposition of the Gulf of Suez evaporite sequence. As noted above, there is uncertainty when this new phase of subsidence began, largely due to the lack of reliable palaeontological control. After the Messinian eustatic sea-level lowstand, there was a change from restricted conditions with little clastic input to more rapid deposition of thick sequences of Pliocene clastics. In excess of 1000 m of post-Miocene sediments accumulated in several depocenters of the central and southern Gulf of Suez (BUTLER *et al.*, 1984; BOSWORTH, 1995; ORSZAG-SPERBER *et al.*, 1998). In the northern two basins of the gulf (i.e. north of the Morgan accommodation zone, Fig. 3), Pliocene clastic (with evaporites) sequences are only little affected by extensional faulting whereas in the southern basin (Amal-Zeit Basin, Fig. 3) Pliocene strata are affected by extensional faults and by salt tectonics (diapirs and salt walls; ORSZAG-SPERBER *et al.*, 1998).

This phase of tectonic subsidence and minor extension in the southern Gulf of Suez is probably kinematically linked to continuing extension in the northern Red Sea and a second phase of sinistral strike-slip movements along the Aqaba-Dead Sea transform fault system. During this period almost all subsidence was focused along the rift axis, corresponding approximately with the modern marine Gulf of Suez Basin. Minor subsidence occurred within the Gemsa Basin, whereas the Esh el Mellaha and el Qaa basins along the rift margins (Figs 6, 7) experienced slight uplift, similar to other relict basins along the Egyptian and Saudi Arabian coasts of the Red Sea Rift (BOSWORTH, 1994).

QUATERNARY TECTONICS

Microearthquakes and some teleseismic events continue to occur along a few major normal faults in the southern Gulf of Suez, indicating that horizontal extensional stresses are still present in this region (DAGGETT *et al.*, 1986; JACKSON *et al.*, 1988). Pleistocene age extensional faults, joints, and open extension gashes are evident at Gebel el Zeit, Ras Mohammad, and elsewhere in the Gulf (BOSWORTH & TAVIANI, 1996). At Gebel el Zeit, coral terraces Uranium-series dated as ±125 ka (Eemian, the last interglacial period; ANDRES & RADTKE, 1988; REYSS *et al.*, 1993; CHOUKRI *et al.*, 1995) now lie as much as 18 m above present-day sea-level (BOSWORTH & TAVIANI, 1996). Sea-level during the Eemian is known to have been ~6 m higher than at present (e.g., AHARON & CHAPPELL, 1986; BARD *et al.*, 1990). Hence, approximately 12 m of tectonic uplift has occurred at Gebel el Zeit in the past 125 ka. Near Hurghada, Holocene reef-flats, dated at 3.9-5.5 ka are up to 0.5 m above present-day mean sea-level (DULLO & MONTAGGIONI, 1998), and at Gebel el Zeit a Holocene reef, dated at ~5.6 ka, is 2 m above sea-level (PLAZIAT *et al.*, 1998a). These data support the contention that the Gebel el Zeit bounding fault remains active. Based on their analysis of neotectonic data for the southern Gulf of Suez region, BOSWORTH & TAVIANI (1996) estimated the present-day extension rate for the vicinity of Gebel el Zeit to be 0.08-0.12 cm/yr (intermediate between Kareem and Belayim rates of STECKLER *et al.*, 1988). Elsewhere in the Gulf of Suez and the northern Red Sea, extensive dating of coral terraces indicates stability during the late Pleistocene (PLAZIAT *et al.*, 1998a).

Fault kinematic and other structural data from Quaternary strata older than the Eemian terraces in the southern Gulf of Suez indicate that during the early Pleistocene-early late Pleistocene, extension was oriented N60°E, normal to the rift axis (Fig. 14). During the late Pleistocene, but prior to 125 ka, the extension direction rotated to NNE-SSW (Fig. 14). Borehole breakout data from exploratory wells in the southern Gulf indicate that the present-day minimum horizontal stress direction remains ~N15°E (BOSWORTH & TAVIANI, 1996). In the central/northern Gulf, breakout data indicate that the minimum stress is aligned ~N-S; this orientation continues to the Mediterranean coastal area (BOSWORTH, unpublished data).

Along the Sinai/Gulf of Aqaba margin, the present-day stress field is producing E-W extension, manifested by dip-slip, N-S striking extensional faults that cut basement and pre-rift strata (LYBERIS, 1988) and Recent alluvial fans (BOSWORTH, unpublished data; SEHIM, unpublished data). Along the eastern margin of Aqaba in Saudi Arabia, Eemian reefs are uplifted 20 m above sea-level, with older Pleistocene reefs at elevations of ~98 m (DULLO, 1990; DULLO & MONTAGGIONI, 1998). Major earthquakes in this region, however, are generated along the axis of the Gulf of Aqaba in a sinistral strike-slip mode, with fault planes striking NNE. These two local stress fields are coeval and partition deformation between the onshore (E-W extension) and offshore (sinistral wrenching). This is an intriguing situation that warrants further study.

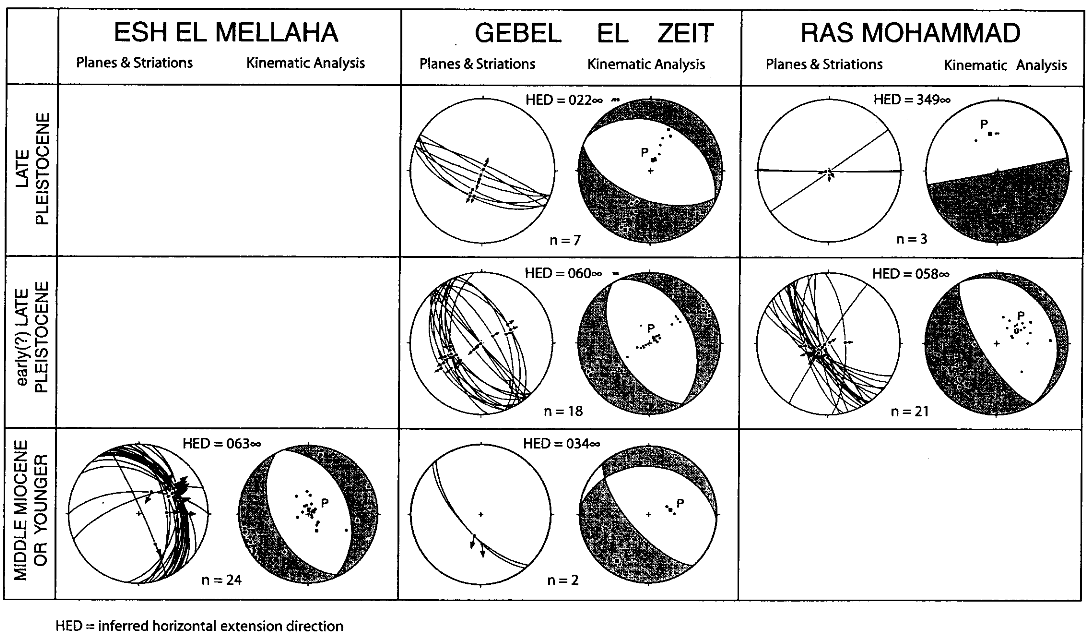

FIG. 14.— Fault slip data, lower hemisphere projections (P = compression axis; T = tension axis). Kinematic analysis based on MARRETT & ALLMENDINGER (1990). No kinematic indicators have been found on faults that could be dated as late Oligocene or early Miocene. In part after BOSWORTH & TAVIANI (1996).

FIG. 14.— Populations de failles à stries. Projections de l'hémisphère inférieur (P = axe de compression ; T = axe de tension). Analyse cinématique basée sur MARRETT & ALLMENDINGER (1990). Aucun indicateur cinématique n'a été trouvé sur les plans de failles, qui pourraient être datés l'Oligocène supérieur ou du Miocène inférieur. En partie d'après BOSWORTH & TAVIANI (1996).

EUSTATIC AND LOCAL SEA-LEVEL CHANGES

Differentiating between the effects of global, eustatic sea-level changes and those imparted by local, tectonic phenomenon is a fundamental problem in sequence stratigraphic analysis (e.g., VAIL *et al.*, 1991; UNDERHILL, 1991; CHRISTIE-BLICK & DRISCOLL, 1995). As the Gulf of Suez rift was connected to either the Mediterranean Sea or Indian Ocean during most of its history, it provides a good example of the interplay between tectonics and eustacy in a developing continental rift system.

The long-term fall in sea-level at the end of the early Oligocene (HAQ *et al.*, 1987) manifested itself by the final retreat of Eocene epeiric continental seas from Northeast Africa and the establishment of continental, yet near-sea-level conditions in the proto-Gulf of Suez region. This low-stand in sea-level is recorded by the patchy deposits of the pre-rift Tayiba Formation and the early syn-rift Abu Zenima formation and Shoab Ali Member of the Nukhul Formation (Fig. 5). After a period of moderately rising sea-levels, during which *Globigerina* marls were deposited over much of the Gulf of Suez rift basin, sea-levels dropped again during the Serravallian. This corresponded to the widespread deposition of evaporite series in the Gulf of Suez that terminated with the early Pliocene cyclical rise in sea-levels.

At the scale of short-term eustatic curves, there is generally still disagreement concerning the absolute magnitudes of sea-level fluctuation and the precise timing of truly "global" events. However, several correlations between published short-term eustatic curves (e.g., HAQ *et al.*, 1987) and the Gulf of Suez stratigraphy seem to be valid. The rapid rise in sea-level at the end of the Chattian (~25-24 Ma) corresponds with the rapid establishment of marine conditions over much of the Gulf of Suez/Red Sea rift system during deposition of the Nukhul Formation. A short-term period of lower sea-level during the late Aquitanian (~21-19 Ma) is reflected by the deposition of the thin, but aerially extensive Ghara Member evaporite section and prolific shallow-water Gharamul Member carbonates within the upper part of the Nukhul Formation. These late Aquitanian units are observed from the Gulf of Suez to the northern Red Sea, at least as far south as the southern Egyptian coastal plain (MONTENAT *et al.*, 1986a, b; PURSER *et al.*, 1990). During the Burdigalian slow rise in sea-levels, the main body of Rudeis marl and shale was deposited. During the Langhian and Serravallian, several short-lived, abrupt drops in global sea-level have been inferred (HAQ *et al.*, 1987). In the Gulf of Suez, this corresponds with the complex depositional facies of the Kareem and Belayim formations.

During the late Serravallian falling sea-levels, Belayim gypsum (now anhydrite) and localized halite were deposited. The onset of the main period of massive halite deposition in the Gulf of Suez basin followed immediately the late Serravallian (Foraminifera zone N14; ~11.5 Ma) Hammam Faraun shale (Fig. 5). This corresponds to the beginning-Tortonian short term sea-level drop, interpreted to represent the absolute lowest sea-level for the Cainozoic (HAQ *et al.*, 1987). The Hammam Faraun shale was probably the last time that the Gulf of Suez was connected by an open sea way to the Mediterranean. During the Tortonian and Messinian low-stands in global sea-levels, the supply of water to the Gulf was sufficient only to feed the evaporitic basin, but insufficient to re-establish normal marine conditions. During the early Zanclean (~5 Ma), sea-level rose abruptly and marine waters of the Indian Ocean invaded the entire Red Sea-Gulf of Suez Basin (RICHARDSON & ARTHUR, 1988; HUGHES & BEYDOUN, 1992; HUGHES *et al.*, 1992).

From the late Zanclean to the Recent, global sea-levels fluctuated considerably (HAQ *et al.*, 1987). In the Gulf of Suez, this accounts, in combination with continued tectonic activity, for: (1) the preservation of Pliocene gravel terraces at various elevations, reflecting basin-wide base level changes (GARFUNKEL & BARTOV, 1977; ABU KHADRAH & DARWISH, 1986; BOSWORTH & TAVIANI, 1996); (2) post-Miocene marine oolitic sands at Gebel el Zeit at elevations up to 200 m above MSL; and (3) Pleistocene coral reef terraces at Gebel el Zeit at elevations up to 42 m above MSL (see discussion above).

DISCUSSION

BASIN GEODYNAMICS

The Gulf of Suez is an example of a high-strain failed rift, with regional ß factors approaching 2 near the junction with the northern Red Sea (STECKLER *et al.*, 1988; PERRY & SCHAMEL, 1990; BOSWORTH, 1995). At the onset of rifting, the main border fault or break-away for the southern Gulf half-graben was positioned at the present basement scarp of the Red Sea Hills (Figs 3, 7 and 13a). In the Central Gulf, the border of the rift was controlled by the Precambrian Rehba Shear Zone east of the Hadahid Block (Figs 3, 6, 8 and 12a). By the end of the early Miocene, the Red Sea border fault was abandoned and the Esh el Mellaha range acted as the rift shoulder (BOSWORTH, 1995; Fig. 13c). The Esh el Mellaha fault similarly became inactive in the Pliocene, and the youngest fault movements in the southern Gulf are focused along the modern marine basin (Fig. 13d). Interpretation of seismic events (JACKSON *et al.*, 1988) and structural relationships (BOSWORTH, 1994) suggest that these young faults are part of a new, higher-angle, planar and largely non-rotational fault system (Fig. 10). Similarly, Pliocene to Recent fault movement and subsidence in the Central Gulf have occurred southwest of Gebels Nezzazat, Ekma, Abu Durba and Araba, within the basin axis (Figs 6, 12d). These faulting histories, and the resultant subsidence patterns (cf. MORETTI & COLLETTA, 1987; MORETTI & CHÉNET, 1987), indicate that through time extension focused toward the rift axis — i.e. the rift developed by crustal necking. Correspondingly, the rift margins and the marginal fault blocks underwent flexural uplift such that early marine syn-rift sediments are now exposed above sea-level. Syn-rift flexural and footwall uplift has affected the marginal domino fault blocks of Gebels el Zeit, Abu Durba and Araba such that their pre-rift basement cores are now exposed at elevations up to 680 m above sea-level.

The rift flanks of the Gulf of Suez are strongly uplifted and exhumed (cf. GARFUNKEL, 1988). Elevations on average exceed 1000 m and on Sinai exceed 2600 m. Fission track dating on samples from the Precambrian basement on the western (OMAR *et al.*, 1989) and eastern sides of the Gulf (KOHN & EYAL, 1981) generally show that there must have been about 5 km of uplift/exhumation. The main phase of uplift is interpreted to have commenced at about 22 Ma, a few million years after the initiation of extension. The regional heat flow is considerably higher than would be expected simply from passive lithospheric stretching (MORGAN *et al.*, 1985), and uplift of the rift margins of the Gulf of Suez is significantly in excess of that predicted by purely extensional lithospheric thinning (STECKLER, 1985). There is no convincing evidence that rifting was preceded by major doming (see discussion above). Two mechanisms may contribute to the additional rift margin uplift. First, thermal thinning of the Gulf of Suez lithosphere may have been enhanced due to proximity to the asthenospheric upwelling beneath the Red Sea rift axis (STECKLER, 1985). Upward displacement of the asthenosphere-lithosphere boundary beneath extensional basins is an important, general cause of their uplift (e.g., ZIEGLER, 1996). Second, the rift lithosphere has lateral strength and flexes like an elastic beam during loading (e.g., WEISSEL & KARNER, 1989; KUSZNIR & EGAN, 1990). Extensional crustal thinning across the rift exerts a negative load on the lithosphere, causing flexural isostatic uplift of the rift flanks. This uplift increases the rate of erosional unloading of the elevated flanks, in turn enhancing flank uplift (KUSZNIR & ZIEGLER, 1992). Flexural isostasy produces permanent topographic uplift, consistent with the amplitude and wavelength of the topography found around the Gulf of Suez as modelled by WILLACY (1996).

Uplift of the rift flanks has important consequences for the provenance of clastic sediments supplied into the Gulf of Suez Rift basins (MCCLAY *et al.*, 1998). Presently, the uplifted rift margins to the north of the Galala-Abu Zenima accommodation zone (Fig. 3) predominantly expose Eocene and Cretaceous carbonates of the pre-rift sequence. As a result, most of the syn-rift sediments in this northern area are carbonate clastics-marls and calcarenites, generally with poor reservoir characteristics. In contrast, to the south of the accommodation zone, the uplifted rift flanks expose siliciclastics of the lower pre-rift section as well as the basement granites and gneisses (Fig. 6). Correspondingly, syn-rift clastics in the central and southern rift basins contain significant siliciclastic reservoirs (e.g., in the Belayim, October, Ramadan and Morgan fields).

RIFT INITIATION

We have discussed above two general models for the initiation of rifting in the Gulf of Suez: (1) rift normal extension, or (2) various configurations of rift parallel compression and strike-slip faulting. The present paper documents the geometry and timing of faulting and syn-tectonic sedimentation within the Gulf of Suez, but we have also examined outcrops along the northwestern Red Sea margin (BOSWORTH *et al.*, 1998; YOUNES & MCCLAY, 1998) and interpret its tectonic history to have been similar. Our main observations regarding rift initiation are: (1) strike-slip kinematic indicators have not been found along major block-bounding faults of the southern, central and northern Gulf of Suez; (2) all significant populations of fault kinematic indicators, whether from major bounding fault complexes or smaller-scale faults, and of all ages, are compatible with ENE-WSW to NNE-SSW extension, with no evidence for significant rift parallel shortening; and (3) no major change in fault orientation occurs across the proposed tectonic break (i.e. the Mid-Rudeis event) as advocated in most of the strike-slip interpretations (e.g., JARRIGE *et al.,* 1986, 1990; MONTENAT *et al.*, 1986a, 1988).

We agree with the observation of JARRIGE *et al.* (1986) and MONTENAT *et al.* (1986a) that the early syn-rift faults extensively reactivated pre-existing basement fabrics, and that, in many cases, this produced oblique-slip and strike-slip faulting on segments of faults oriented oblique or normal to the rift axis. The various basement breaks linked, however, into border faults that were essentially parallel to the present rift axis (Figs 3, 6). This occurred within an approximately rift normal, regional extensional stress field. Under such conditions, observations of local fault kinematics or geometries will not reliably reproduce the stress field that was applied to the large-scale rift system.

The presence of extensive pre-rift zones of weakness at high angles to the regional extension direction resulted in fault geometries in which rift-parallel faults are normally linked by cross faults, rather than by ductile zones of overlap or fault relays. This preference for "hard" linkage rather than "soft" linkage distinguishes the Gulf of Suez from other segments of the Red Sea rift system, as, for example, along the Yemeni margin where numerous fault relays are observed (DAVISON *et al.*, 1994).

CONCLUSION

The structural and stratigraphic development of the Gulf of Suez Rift reflects the interplay of five principal factors: (1) the presence of pre-existing fault systems, penetrative fabrics and basement terrane boundaries, (2) eustatic sea-level changes, (3) changes in basin connectivity to the Mediterranean Sea and Indian Ocean, (4) rapid changes in African intra-plate stress fields, and (5) configuration of the Levant-Aqaba transform plate boundary. Due to excellent surface exposures and abundant subsurface data, it is tempting to use the Gulf of Suez for formulating general models of continental rifting. However, this should be done within the context of these factors, which have varying applicability to other rift settings.

The Gulf of Suez Rift initiated in the late Oligocene, in conjunction with the rifting of the Red Sea basins to the south. Integration of radiometric and palaeontologic data suggests that extensional faulting commenced in the southern Gulf-northernmost Red Sea area by 27-25 Ma, and in the northern Gulf-Suez-Cairo area by ~23.5 Ma. The rift probably propagated toward the north, intersecting a major east-west structural boundary of late Eocene age at the general latitude of Suez city. North of Suez city, extension was more diffuse but mostly focused in the Manzala Rift basin that is presently buried beneath the modern Nile Delta. Earliest syn-rift sediments (Chattian-Aquitanian) generally consist of continental red beds associated with volumetrically minor basaltic volcanics. Marine Oligocene strata are only proven from the southernmost Gulf, at the juncture with the northern Red Sea. The most extensive basalt extrusions occurred in the area of linkage between the northern Gulf of Suez Darag Basin and the Manzala Rift, and to a lesser extent, on the central-eastern margin of the Gulf.

Following the late Aquitanian sea-level lowstand, the prolonged Burdigalian sea-level rise enabled marine waters to flow freely between the Mediterranean Sea and the Gulf of Suez, resulting in deposition of the thick Rudeis and Kareem shales and deep-water carbonates. During the Langhian and early Serravallian, rapid eustatic sea-level changes resulted in pronounced facies changes within the rift. During the late Serravallian period of significant sea-level fall, connections between the Gulf and the Mediterranean were either completely or intermittently blocked, leading to deposition of evaporites in the central and southern Gulf sub-basins. Thick halites accumulated during the late Miocene, and later loading resulted in the development of salt diapirs and walls. This had profound effects on post-Miocene depositional patterns and the style of intra-sediment faulting. Conditions returned to normal marine during the Pliocene, but waters were now provided by the Red Sea-Gulf of Aden connection to the Indian Ocean, whilst a permanent land-barrier separated the Gulf of Suez from the Mediterranean.

Analysis of fault geometries, fault kinematics and sedimentation patterns indicate that the late Oligocene earliest phase of rifting involved NE-SW directed extension. Reactivation of pre-existing NNE-trending basement structures, however, caused the development of local N10-20°E transfer faults and rhombic basin geometries, sometimes interpreted as pull-apart basins. There is no convincing evidence for significant Oligocene-age strike-slip faulting parallel to the axis of the Gulf of Suez. In the southern Gulf, the initial dip of syn-rift extensional faults was generally very steep, involving the reactivation of well-developed, vertical, tectonic joints of Late Precambrian to Early Palaeozoic age. As rifting progressed, N10-20°E transfer faults were locally abandoned and younger rift-normal transfer faults predominated. In the southern Gulf, rift-parallel extensional faults were progressively rotated to shallower dips, locally to less than 25°. During the middle Miocene, the Levant-Gulf of Aqaba transform boundary was established, linking the Red Sea Rift plate boundary to the convergent Bitlis-Zagros plate boundary. This resulted in a dramatic drop in extension rates across the Gulf of Suez and clockwise rotation of stress fields in Sinai and within the Gulf. The middle Miocene shift in relative plate movement vectors may also have caused slight compression across North Sinai and the Bitter lakes region, leading to minor uplift, accentuating the effects of generally falling sea-levels, and shutting-off the marine connection to the Mediterranean. During the late Pleistocene, the intra-Gulf extension direction rotated counter-clockwise to N15°E (present-day extension direction). Estimates of present-day extension rates across the tectonically active southern Gulf of Suez are in close agreement with regional plate tectonic requirements.

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REFERENCES

ABBATE, E., PASSERINI, P. & ZAN, L., 1995.— Strike-slip faults in a rift area: transect in the Afar Triangle, East Africa. *Tectonophysics*, **241**: 67-97.

ABDALLAH, A.M., ADINDANI, A. & FAHMY, N., 1963.— Stratigraphy of the Lower Mesozoic rocks, western side of the Gulf of Suez, Egypt. *Paper- Geological Survey of Egypt, Mineral Resources Department,* **27**: 1-23.

ABDEL KHALEK, M.L., ABDEL WAHED, M. & SEHIM, A., 1993.— Wrenching deformation and tectonic setting of the Northwestern part of the Gulf of Aqaba. Geodynamics and sedimentation of the Red Sea-Gulf of Aden Rift system. *Special Publication- Geological Survey of Egypt,* **1**: 409-445.

ABU KHADRAH, A.M. & DARWISH, M., 1986.— On the occurrence of raised beach sediments in the Hammam Faraun area, Sinai, Egypt. *Arabian Gulf Journal of Scientific Research,* **4**: 159-175.

ABUL NASR, R.A., 1990.— Re-evaluation of the Upper Eocene rock units in west central Sinai, Egypt. *Ain Shams University, Earth Science Serie,* **4**: 234-247.

AHARON, P. & CHAPPELL, J., 1986.— Oxygen isotopes, sea-level changes and the temperature history of a coral reef environment in New Guinea over the last 10^5 years. *Palaeogeography, Palaeoclimatology, Palaeoecology,* **56**: 337-379.

AKKAD, M.K. & ABDALLAH, A.M., 1971.— Contribution to the geology of Gebel Ataqa area. *Annals- Geological Survey of Egypt,* **1**: 21-42.

AKKAD, M.K. & DARDIR, A., 1966.— Geology and phosphate deposits of Wassif-Safaga area. *Paper- Geological Survey of Egypt,* **36**: 1-35.

ANDRES, W. & RADTKE, U., 1988.— Quartäre Strandterrassen an der Küste des Gebel Zeit (Golf von Suez/Ägypten). *Erdkunde,* **42**: 7-16.

ANGELIER, J., 1985.— Extension and rifting: the Zeit region, Gulf of Suez. *Journal of Structural Geology,* **7**: 605-612.

BARAKAT, M.G., DARWISH, M. & EL BARKOOKY, A.N., 1988a.— Lithostratigraphy of the Post Carboniferous - Pre Cenomanian clastics in west central Sinai and Gulf of Suez, Egypt. *In*: *Proceedings of 8th Exploration Conference, Cairo, November, 1986*. Vol. 1. Egyptian General Petroleum Corporation, Cairo: 380-405.

BARAKAT, M.G., DARWISH, M. & EL OUTEFI, N.S., 1988b.— Eocene tectono-stratigraphy and basin evaluation in the Gulf of Suez Petroliferous Province. *In*: *Proceedings of 9th Exploration Conference, Cairo, November, 1988.* Egyptian General Petroleum Corporation, Cairo: 1-22.

BARD, E., FAIRBANKS, R.G. & HAMELIN, B., 1990.— U-Th ages obtained by mass spectrometry in corals from Barbados: sea-level during the past 130,000 years. *Nature,* **346**: 456-458.

BARTOV, Y., STEINITZ, G., EYAL, M. & EYAL, U., 1980.— Sinistral movement along the Gulf of Aqaba - its age and relation to the opening of the Red Sea. *Nature*, **285**: 220-221.

BAYER, H.-J., HÖTZL, H., JADO, A.R., ROSCHER, B. & VOGGENREITER, W., 1988.— Sedimentary and structural evolution of the northwest Arabian Red Sea margin. *Tectonophysics,* **153**: 137-51.

BEADNELL, H.J.L., 1905.— The relations of the Eocene and Cretaceous systems in the Esna - Aswan reach of the Nile Valley. *Quarterly Journal of the Geological Society of London,* **61**: 667-678.

BELEITY, A.M., 1984.— The composite standard and definition of paleo events in the Gulf of Suez. *In*: *Proceedings of 6th Exploration Seminar, Cairo, March 1982*. Vol. 1. Egyptian General Petroleum Corporation and Egypt Petroleum Exploration Society, Cairo: 181-198.

BELEITY, A.M., GHONEIM, M., HINAWI, M., FATHI, M., GEBALI, G. & KAMEL, M., 1988.— Paleozoic stratigraphy, paleogeography and paleotectonics in the Gulf of Suez. *In*: *Proceedings of 8th Exploration Conference, Cairo, November, 1986*. Vol. 1. Egyptian General Petroleum Corporation, Cairo: 96-116.

BEN-MENAHEM, A., NUR, A. & VERED, M., 1976.— Tectonics, seismicity and structure of the Afro-Eurasian junction - the breaking of an incoherent plate. *Physics of the Earth and Planetary Interiors,* **12**: 1-50.

BERGGREN, W.A., KENT, D.V, SWISHER, C.C. III & AUBRY, M.-P., 1995.— A Revised Cenozoic geochronology and chronostratiraphy. *In*: W.A. BERGRENN, D.V. KENT, M.P. AUBRY & J. HARDENBOL (eds), Geochronology, time scales and global stratigraphic correlation. *SEPM, Special Publication*, **54**: 129-212.

BISHAY, Y., 1966.— *Studies on the Larger Foraminifera of the Eocene (the Nile Valley between Assiut and Cairo and SW Sinai.* Ph.D. Thesis, Alexandria University, Alexandria, Egypt.

BLOW, W.H., 1969.— Late Middle Eocene to Recent planktonic foraminiferal biostratigraphy. *In*: R. BRONNIMAN (ed.), *Proceedings of First International Conference on Planktonic Microfossils, Geneva, 1967*. Vol. 1. Brill, Leiden: 199-421.

BOSENCE, D.W.J., 1998.— Stratigraphic and sedimentological models of rift basins. *In*: B.H. PURSER & D.W.J. BOSENCE (eds); *Sedimentation and Tectonics of Rift Basins: Red Sea-Gulf of Aden*. Chapman and Hall, London: 9-25.

BOSWORTH, W., 1985.— Geometry of propagating continental rifts. *Nature*, **316**: 625-627.

BOSWORTH, W., 1994.— A Model for the three-dimensional evolution of continental rift basins, north-east Africa. *In*: H. SCHANDELMEIER & R.J. STERN (eds), Geology of Northeast Africa (Part 2). *Geologische Rundschau*, **83**: 671-88.

BOSWORTH, W., 1995.— A High-strain rift model for the southern Gulf of Suez (Egypt). *In*: J.J. LAMBIASE (ed.), Hydrocarbon Habitat in Rift Basins. *Special Publications- Geological Society of London*, **80**: 75-112.

BOSWORTH, W. & TAVIANI, M., 1996.— Late Quaternary reorientation of stress field and extension direction in the southern Gulf of Suez, Egypt: evidence from uplifted coral terraces, mesoscopic fault arrays and borehole breakouts. *Tectonics*, **15**: 791-802.

BOSWORTH, W., CREVELLO, P., WINN JR., R.D. & STEINMETZ, J., 1998.— Structure, sedimentation, and basin dynamics during rifting of the Gulf of Suez and northwestern Red Sea. *In*: B.H. PURSER & D.W.J. BOSENCE (eds), *Sedimentation and Tectonics of Rift Basins: Red Sea-Gulf of Aden*. Chapman and Hall, London: 77-96.

BRENCKLE, P.L. & MARCHANT, T.R., 1984.— Calcareous microfossils form the Um Bogma Formation (Lower Carboniferous) of the Lower Nubia Group at Gebel Nukhul, Sinai, Egypt. *In*: *Proceedings of 6th Exploration Seminar, Cairo, March 1982*. Vol. 1. Egyptian General Petroleum Corporation and Egypt Petroleum Exploration Society, Cairo: 302-309.

BURCHETTE, T.P., 1988.— Tectonic control on carbonate plarform facies distribution and sequence development: Miocene, Gulf of Suez. *Sedimentary Geology*, **59**: 179-204.

BUTLER, M., SELLWOOD, B.W. & THURLEY, B., 1984.— Recent alluvial fans of the Baba Plain, implications for deposition in the Gulf of Suez region. *In*: *Proceedings of 6th Exploration Seminar, Cairo, March 1982*. Vol. 1. Egyptian General Petroleum Corporation and Egypt Petroleum Exploration Society, Cairo: 252-268.

CHAZOT, G., MENZIES, M.A. & BAKER, J., 1998.— Pre-, syn- and post-rift volcanism on the south-western margin of the Arabian plate. *In*: B.H. PURSER & D.W.J. BOSENCE (eds), *Sedimentation and Tectonics of Rift Basins: Red Sea-Gulf of Aden*. Chapman and Hall, London: 50-55.

CHOUKRI, A., REYSS, J.-L. & PLAZIAT, J.-C., 1995.— Datations radiochimiques des hauts niveaux marins de la rive occidentale du Nord de la mer Rouge au moyen de radioles d'oursin. *Comptes Rendus de l'Académie des Sciences, Paris*, **321** (IIa): 25-30.

CHRISTIE-BLICK, N. & DRISCOLL, N.W., 1995.— Sequence stratigraphy. *Annual Review of Earth and Planetary Sciences*, **23**: 451-478.

COCHRAN, J.R., 1981.— The Gulf of Aden: structure and evolution of a young ocean basin and continental margin. *Journal of Geophysical Research,* **86**: 263-288.

COCHRAN, J.R., 1983.— A Model for development of the Red Sea. *AAPG Bulletin*, **67**: 41-69.

COFFIELD, D.Q. & SCHAMEL, S., 1989.— Surface expression of an accommodation zone within the Gulf of Suez rift, Egypt. *Geology*, **17**: 76-79.

COLEMAN, R.G., 1974.— Geologic background of the Red Sea. *In*: C.A. BURKE & C.L. DRAKE (eds), *The Geology of Continental Margins*. Springer, Berlin: 743-751.

COLEMAN, R.G., 1993.— *Geologic Evolution of the Red Sea.* Oxford University Press, Oxford Monographs on Geology and Geophysics 24, Oxford: 1-186.

COLLETTA, B., LE QUELLEC, P., LETOUZY, J. & MORETTI, I., 1988.— Longitudinal evolution of the Suez rift structure (Egypt). *Tectonophysics*, **153**: 221-233.

CROSS, N.E., PURSER, B.H. & BOSENCE, D.W.J., 1998.— The Tectono-sedimentary evolution of a rift margin coarbonate platform: Abu Shaar, Gulf of Suez, Egypt. *In*: B.H. PURSER & D.W.J. BOSENCE (eds), *Sedimentation and Tectonics of Rift Basins: Red Sea-Gulf of Aden*. Chapman and Hall, London: 271-295.

DAGGETT, P.H., MORGAN, P., BOULOS, F.K., HENNIN, S.F., EL-SHERIF, A.A., EL-SAYED, A.A., BASTA, N.Z. & MELEK, Y.S., 1986.— Seismicity and active tectonics of the Egyptian Red Sea margin and the northern Red Sea. *Tectonophysics*, **125**: 313-24.

DARWISH, M., 1992.— Facies developments of the Upper Paleozoic - Lower Cretaceous sequences in the Northern Galala Plateau and evidences for their hydrocarbon reservoir potentiality, Northern Gulf of Suez, Egypt. *In*: *Proceedings of 1st International Conference on Geology of the Arab World*. Vol. 1. Cairo University, Cairo: 75-214.

DARWISH, M., 1994.— Cenomanian-Turonian sequence stratigraphy, basin evolution and hydrocarbon potentialities of Northern Egypt. *In*: *Proceedings of 2nd International Conference on Geology of the Arab World*. Vol. 3. Cairo University, Cairo: 315-362.

DARWISH, M. & EL ARABY, A., 1993.— Petrography and diagenetic aspects of some siliciclastic hydrocarbon reservoirs in relation to rifting of the Gulf of Suez, Egypt. Geodynamics and sedimentation of the Red Sea-Gulf of Aden Rift System. *Special Publication- Geological Survey of Egypt*, **1**: 155-187.

DARWISH, M. & EL-AZABI, M., 1993.— Contributions to the Miocene sequences along the western coast of the Gulf of Suez, Egypt. *Egyptian Journal of Geology*, **37**: 21-47.

DAVISON, I., AL-KADASI, M., AL-KHIRBASH, S., AL-SUBBARY, A.K., BAKER, J., BLAKEY, S., BOSENCE, D.W.J., DART, C., HEATON, R., MCCLAY, K., MENZIES, M., NICHOLS, G., OWEN, L. & YELLAND, A., 1994.— Geological evolution of the southeastern Red Sea Rift margin, Republic of Yemen. *Geological Society of America, Bulletin*, **106**: 1474-1493.

DOLSON, J., EL-GENDI, O., CHARMY, H., GATHALLA, M. & GAAFAR, I., 1996.— Gulf of Suez rift basin sequence models. Part A: Miocene sequence stratigraphy and exploration significance in the Greater October field area, northern Gulf of Suez. *In*: *Proceedings of 16th Exploration Conference, Cairo, November, 1996*. Vol. 1. Egyptian General Petroleum Corporation, Cairo: 1-8.

DULLO, W.C., 1990.— Facies, fossil record, and age of Pleistocene reefs from the Red Sea (Saudi Arabia). *Facies*, **22**: 1-46.

DULLO, W.C. & MONTAGGIONI, L., 1998.— Modern Red Sea coral reefs: a review of their morphologies and zonation. *In*: B.H. PURSER & D.W.J. BOSENCE (eds), *Sedimentation and Tectonics of Rift Basins: Red Sea-Gulf of Aden*. Chapman and Hall, London: 583-594.

DULLO, W.C., HÖTZL, H. & JADO, A.R., 1983.— New stratigraphical results from the Tertiary sequence of the Midyan area, NW Saudi Arabia. *Newsletters on Stratigraphy*, **12**: 75-83.

EGYPTIAN GENERAL PETROLEUM CORPORATION STRATIGRAPHIC COMMITTEE, 1964.— *Oligocene and Miocene Rock Stratigraphy of the Gulf of Suez Region*. Egyptian General Petroleum Corporation Consultative Stratigraphical Committee, Cairo: 1-142.

EL BARKOOKY, A.N., 1992.— Stratigraphic framework of the Paleozoic in the Gulf of Suez Region, Egypt. *In*: *1st International Conference on the Geology of the Arab World*. Cairo University, Cairo.

EL TARABILI, E. & ADAWY, N., 1972.— Geologic history of the Nukhul-Baba area, Gulf of Suez, Egypt. *The American Association of Petroleum Geologists, Bulletin, Tulsa Okla*, **56**: 882-902.

EL WAZEER, F., ISMAIL, F. & STANDEN, E., 1992.— Fracture geometry and hydrocarbon productivity in the basement rocks of the Zeit Bay field - Gulf of Suez, Egypt. *In*: *Proceedings of 10th Petroleum Exploration and Production Conference, Cairo, November, 1990*. Vol. 1. Egyptian General Petroleum Corporation, Cairo: 579-605.

EL-SHAFY, A.A., 1992.— Miocene-Pliocene boundary in the Gulf of Suez-Region, Egypt. *Proceedings of 10th Petroleum Exploration and Production Conference, Cairo, November, 1990*. Vol. 1. Egyptian General Petroleum Corporation, Cairo: 213-232.

EL-SHAZLY, E., EL-KASSAS, I. & MOUSTAFA, M., 1979.— Comparative fracture analysis and its relation to radioactivity in the pink granite of Um Had pluton, Central Eastern Desert, Egypt. *Egyptian Journal of Geology*, **23**: 95-110.

EL-SHINNAWI, M.A., 1975.— Planktonic foraminifera from the Miocene Globigerina Marl of Hurgada-well-134, Eastern Desert, Egypt. *In*: *Proceedings of 4th African Colloquium Micropalaeontology, Addis Abeba, 1972*. Addis Abeba University, Addis Abeba: 199-224.

EVANS, A.L., 1988.— Neogene tectonic and stratigraphic events in the Gulf of Suez rift area, Egypt. *Tectonophysics*, **153**: 235-247.

EVANS, A.L. & MOXON, I.W., 1988.— Gebel Zeit chronostratigraphy: Neogene syn-rift sedimentation atop a long-lived paleohigh. *In*: *Proceedings of 8th Exploration Conference, Cairo, November, 1986*. Vol. 1. Egyptian General Petroleum Corporation, Cairo: 251-265.

EYAL, M., EYAL, Y., BARTOV, Y. & STEINITZ, G., 1981.— Tectonic development of the western margin of the Gulf of Elat (Aqaba) rift. *Tectonophysics*, **80**: 39-66.

EYAL, Y., 1996.— Stress field fluctuations along the Dead Sea rift since the Middle Miocene. *Tectonics*, **15**: 157-170.

FAWZY, H. & ABDEL AAL, A., 1986.— Regional study of Miocene evaporites and Pliocene - Recent sediments in the Gulf of Suez. *In*: *Proceedings of 7th Exploration Seminar, Cairo, March, 1984*. Egyptian General Petroleum Corporation and Egypt Petroleum Exploration Society, Cairo: 49-74.

FREUND, R., 1970.— Plate tectonics of the Red Sea and Africa. *Nature*, **228**: 453.

GARFUNKEL, Z., 1988.— Relation between continental rifting and uplifting: evidence from the Suez rift and northern Red Sea. *Tectonophysics,* **150**: 33-49.

GARFUNKEL, Z. & BARTOV, Y., 1977.— The Tectonics of the Suez rift. *Israel Geological Survey, Bulletin,* **71**: 1-44.

GAULIER, J.M., LE PICHON, X., LYBERIS, N., AVEDIK, F., GELI, L., MORETTI, I., DESCHAMPS, A. & HAFEZ, S., 1988.— Seismic study of the crust of the northern Red Sea and Gulf of Suez. *Tectonophysics*, **153**: 55-88.

GAWTHORPE, R.L., HURST, J.M. & SLADEN, C.P., 1990.— Evolution of Miocene footwall-derived coarse-grained deltas, Gulf of Suez, Egypt: implications for exploration. *AAPG Bulletin*, **74**: 1077-1086.

GAWTHORPE, R.L., SHARP, I., UNDERHILL, J.R. & GUPTA, S., 1997.— Linked sequence stratigraphic and structural evolution of propagating normal faults. *Geology*, **25**: 795-798.

GEZEERY, M.N. & MARZOUK, I.M. (eds), 1976.— Miocene rock stratigraphy of Egypt, the stratigraphic sub-committee of the National Committee of Geological Sciences of Egypt, 1974. *Egyptian Journal of Geology*, **18**: 1-69.

GHORAB, M.A., 1961.— Abnormal stratigraphic features in Ras Gharib oil field. *In*: *3rd Arabian Petroleum Congress, Alexandria*. Alexandria University, Alexandria: 1-10.

GHORAB, M.A. & MARZOUK, I.M., 1967.— *A Summary Report on the Rock-Stratigraphic Classification of the Miocene Non-Marine and Coastal Facies in the Gulf of Suez and Red Sea Coast.* General Petroleum Company, Cairo, Unpublished Report, E. R. 601.

GINDY, A.R., 1963.— Stratigraphic sequence and structures of a post-lower Eocene section in Wadi Gasus el Bahari, Safaga district, Eastern Desert. *United Arab Republic Bulletin of the Faculty of Sciences, Alexandria University,* **5**: 71-87.

GIRDLER, R.W. & SOUTHREN, T.C., 1987.— Structure and evolution of the northern Red Sea.*Nature*, **330**: 716-721.

GREENBERG, J.K., 1981.— Characteristics and origin of Egyptian younger granites. *Geological Society of America, Bulletin*, **92**: 1224-1232, 11749-11840.

GUIRAUD, R., 1998.— Mesozoic rifting and basin inversion along the northern African Tethyan margin: an overview. *In*: D.S. MCGREGOR, R.T. MOODY & D.D. CLARK-LOWES (eds), Petroleum Geology of North Africa. *Special Publications-Geological Society of London*, **132**: 217-229.

GUIRAUD, R. & BOSWORTH, W., 1997.— Senonian basin inversion and rejuvenation of rifting in Africa and Arabia: synthesis and implications to plate-scale tectonics. *Tectonophysics*, **282**: 39-82.

GUIRAUD, R., BELLION, Y., BENKHELIL, J. & MOREAU, C., 1987.— Post-Hercynian tectonics in Northern and Western Africa. *In*: P. BOWDEN & J. KINNAIRD (eds), African Geology Reviews. *Geological Journal*, **22**: 433-466.

GUIRAUD, R., ISSAWI, B. & BOSWORTH, W., 2001.— Phanerozoic history of Egypt and surrounding areas. *In*: P.A. ZIEGLER, W. CAVAZZA, A.H.F. ROBERTSON & S. CRASQUIN-SOLEAU (eds), Peri-Tethys Memoir 6: Peri-Tethyan Rift / Wrench Basins and Passive Margins. *Mémoires du Muséum national d'Histoire naturelle*, **186**: 469-509.

HANTAR, G., 1965.— Remarks on the distribution of Miocene sediments in the Gulf of Suez region. *In*: *5th Arabian Petroleum Congress, Cairo*. Cairo University, Cairo: 1-13.

HAQ, B.U., HARDENBOL, J. & VAIL, P.R., 1987.— Chronology of fluctuating sea levels since the Triassic. *Science,* **235**: 1156-1167.

HASSAN, A.A., 1967.— A New Carboniferous occurrence in Abu Durba-Sinai, Egypt. *In*: *6th Arabian Petroleum Congress, Baghdad, II.* Bagdad University, Bagdad: 1-8.

HASSAN, F. & EL-DASHLOUTY, S., 1970.— Miocene evaporites of Gulf of Suez region and their significance. *The American Association of Petroleum Geologists Bulletin,* **54**: 1686-1696.

HASSAN, M.A. & HASHAD, A.H., 1990.— Chapter 12, Precambrian of Egypt. *In*: R. SAID (ed.), *The Geology of Egypt.* Balkema, Rotterdam: 201-245.

HEMPTON, M., 1987.— Constraints on Arabian plate motion and extensional history of the Red Sea. *Tectonics*, **6** (6): 687-705.

HERMINA, M., KLITZSCH, E. & LIST, F.K., 1989.— *Stratigraphic Lexicon and Explanatory notes to the Geological Map of Egypt, 1:500,000.* Conoco Inc., Cairo: 1-263.

HUGHES, G.W. & BEYDOUN, Z.R., 1992.— The Red Sea-Gulf of Aden: biostratigraphy, lithostratigraphy and paleoenvironments. *Journal of Petroleum Geology*, **15**: 135-156.

HUGHES, G.W., ABDINE, S. & GIRGIS, M.H., 1992.— Miocene biofacies development and geological history of the Gulf of Suez, Egypt. *Marine and Petroleum Geology,* **9**: 2-28.

HUME, W.R., 1921.— Relations of the northern Red Sea and associated Gulf areas to the "rift" theory. *Proceedings of the Geological Society of London*, **77**: 96-101.

HUME, W.F., MADGWICK, T.G., MOON, F.W. & SADEK, H., 1920.— Preliminary geological report on the Gebel Tanka area. *Petroleum Research Bulletin,* **4**: 1-16.

ISSAWI, B., FRANCIS, M., EL-HINNAWI, M. & EL-DEFTAR, T., 1971.— Geology of Safaga-Quseir coastal plain and of Mohamed Rabah area. *Annals of Geological Survey of Egypt*, **1**: 1-19.

JACKSON, J.A., WHITE, N.J., GARFUNKEL, Z. & ANDERSON, H., 1988.— Relations between normal-fault geometry, tilting and vertical motions in extensional terrains: an example from the southern Gulf of Suez. *Journal of Structural Geology,* **10**: 155-170.

JAMES, N.P., CONIGLIO, M., AISSAOUI, D.M. & PURSER, B.H., 1988.— Facies and geologic history of an exposed Miocene rift-margin carbonate platform; Gulf of Suez, Egypt. *AAPG Bulletin*, **72** (5): 555-572.

JARRIGE, J.J., OTT D'ESTEVOU, P., BUROLLET, P.F., THIRIET, J.-P., ICART, J.C., RICHERT, J.-P., SEHANS, P., MONTENAT, C. & PRAT, P., 1986.— Inherited discontinuities and Neogene structure: the Gulf of Suez and northwestern edge of the Red Sea. *Philosophical Transactions of the Royal Society of London,* **317** (A): 129-139.

JARRIGE, J.J., OTT D'ESTEVOU, P., BUROLLET, P.F., MONTENAT, C., PRAT, P., RICHERT, J.-P. & THIRIET, J.-P., 1990.— The Multistage tectonic evolution of the Gulf of Suez and northern Red Sea continental rift from field observations. *Tectonics*, **9**: 441-465.

JOFFE, S. & GARFUNKEL, Z., 1987.— Plate kinematics of the circum Red Sea: a re-evaluation. *Tectonophysics*, **141**: 5-22.

JOHNSON, M.R., VAN VUUREN, C.J., VISSER, J.N.J., COLE, D.I., WICKENS, H.DE.V., CHRISTIE, A.D.M. & ROBERTS, D.L., 1997.— The Foreland Karoo basin, South Africa. *In*: R.C. SELLEY (ed.), *African Basins. Sedimentary Basins of the World.* Elsevier, Elsevier Science 3, Amsterdam: 269-317.

KAPPELMAN, J., SIMONS, E.L. & SWISHER III, C.C., 1992.— New age determinations for the Eocene-Oligocene boundary sediments in the Fayum Depression, northern Egypt. *Journal of Geology*, **100**: 647-667.

KERDANY, M.T. & CHERIF, O.H., 1990.— Chapter 22: Mesozoic. *In*: R. SAID (ed.), *The Geology of Egypt.* Balkema, Rotterdam: 407-438.

KHALIL, S.M., 1998.— *Tectonic Evolution of the Eastern Margin of the Gulf of Suez, Egypt.* Ph.D. Thesis, Royal Holloway, University of London, London, United Kingdom: 1-349.

KHALIL, S.M. & MCCLAY, K., 1998.— Structural architecture of the eastern margin of the Gulf of Suez: field studies and analogue modelling results. *In*: *Proceedings of 14th Exploration Conference, October, 1998.* Vol. 1. Egyptian General Petroleum Corporation, Cairo: 201-211.

KLITZSCH, E., 1990.— Chapter 21: Paleozoic. *In*: R. SAID (ed.), *The Geology of Egypt* Balkema, Rotterdam: 393-406.

KOHN, B.P. & EYAL, M., 1981.— History of uplift of the crystalline basement of Sinai and its relation to opening of the Red Sea as revealed by fission track dating of apatites. *Earth and Planetary Science Letters*, **52**: 129-141.

KORA, M., 1984.— *The Paleozoic Outcrops of Um Bogma Area, Sinai.* Ph.D. Thesis, Mansoura University, Mansoura, Egypt: 1-233.

KORA, M., 1986.— Lower Carboniferous microfauna from Um Bogma Formation, Sinai. *Mansoura Scientific Bulletin*, **13**: 127-150.

KOSTANDI, A.B., 1959.— Facies maps of the study of the Paleozoic and Mesozoic sedimentary basins of the Egyptian region. *In*: *UAR 1, Arabian Petroleum Congress Cairo, Congress 2.* Cairo University, Cairo: 54-62.

KRÖNER, A., 1984.— Late Precambrian plate tectonics and orogeny: a need to redefine the term Pan-African. *In*: J. KLERKX & J. MICHOT (eds), *African Geology*. Musée royal de l'Afrique centrale, Tervuren: 23-28.

KRÖNER, A., 1993.— The Pan African belt of northeastern and Eastern Africa, Madagascar, southern India, Sri Lanka and East Antarctica: terrane amalgamation during the formation of the Gondwana supercontinent. *In*: U. THORWEIHE & H. SCHANDELMEIER (eds), *Geoscientific Research in Northeast Africa*. Balkema, Rotterdam: 3-9.

KUSZNIR, N.J. & EGAN, S.S., 1990.— Simple-shear and pure-shear models of extensional sedimentary basin formation: application to the Jeanne d'Arc Basin, Grand Banks of Newfoundland. *In*: A.J. TANKARD & H.R. BALKWILL (eds), Extensional Tectonics of the North Atlantic Margins. *AAPG Memoir*, **46**: 305-322.

KUSZNIR, N.J. & ZIEGLER, P.A., 1992.— The Mechanics of continental extension and sedimentary basin formation: a simple-shear/pure-shear flexural cantilever model. *Tectonophysics*, **215**: 117-131.

LAMBIASE, J.J. & BOSWORTH, W., 1995.— Structural controls on sedimentation in continental rifts. *In*: J.J. LAMBIASE (ed.), Hydrocarbon Habitat in Rift Basins. *Special Publications- Geological Society of London*, **80**: 117-144.

LE PICHON, X. & FRANCHETEAU, J., 1978.— A Plate tectonic analysis of the Red Sea - Gulf of Aden area. *Tectonophysics*, **46**: 369-406.

LOTFY, H.I., VAN DER VOO, R., HALL, C.M., KAMEL, O.A. & ABDEL AAL, A.Y., 1995.— Palaeomagnetism of Early Miocene basaltic eruptions in the areas east and west of Cairo. *Journal of African Earth-Sciences*, **21**: 407-419.

LYBERIS, N., 1988.— Tectonic evolution of the Gulf of Suez and the Gulf of Aqaba. *Tectonophysics*, **153**: 209-220.

MAKRIS, J. & RIHM, R., 1991.— Shear controlled evolution of the Red Sea: pull apart model. *Tectonophysics*, **198**: 441-466.

MARRETT, R. & ALLMENDINGER, R.W., 1990.— Kinematic analysis of fault-slip data. *Journal of Structural Geology,* **12**: 973-986.

MART, Y. & HALL, J., 1984.— Structural trends in the northern Red Sea. *Journal of Geophysical Research*, **89**: 352-364.

MARTINEZ, F. & COCHRAN, J.R., 1988.— Structure and tectonics of the northern Red Sea: catching a continental margin between rifting and drifting. *Tectonophysics*, **150**: 1-32.

MCCLAY, K. & KHALIL, S., 1998.— Extensional hard linkages, eastern Gulf of Suez, Egypt. *Geology*, **26**: 563-566.

MCCLAY, K.R., NICHOLS, G.J., KHALIL, S., DARWISH, M. & BOSWORTH, W., 1998.— Extensional tectonics and sedimentation, eastern Gulf of Suez, Egypt. *In*: B.H. PURSER & D.W.J. BOSENCE (eds), *Sedimentation and Tectonics of Rift Basins: Red Sea-Gulf of Aden*. Chapman and Hall, London: 223-238.

MCKENZIE, D.P., DAVIES, D. & MOLNAR, P., 1970.— Plate tectonics of the Red Sea and east Africa. *Nature*, **226**: 243-248.

MENEISY, M.Y., 1990.— Chapter 9: Vulcanicity. *In*: R. SAID (ed.), *The Geology of Egypt* Balkema, Rotterdam: 157-172.

MESHREF, W.M., 1990.— Chapter 8: Tectonic Framework. *In*: R. SAID (ed.), *The Geology of Egypt*. Balkema, Rotterdam: 113-155.

MESHREF, W.M. & KHALIL, B., 1992.— Evidence for northerly propagation in Suez Rift. *In*: *Proceedings of 10th Petroleum Exploration and Production Conference, Cairo, November, 1990*. Vol. 1. Egyptian General Petroleum Corporation, Cairo: 55-76.

MILLER, P.M. & BARAKAT, H., 1988.— Geology of the Safaga Concession, northern Red Sea, Egypt. *Tectonophysics*, **153**: 123-136.

MONTENAT, C., OTT D'ESTEVOU, P. & PURSER, B., 1986a.— Tectonic and sedimentary evolution of the Gulf of Suez and northwestern Red Sea: a review. *In*: C. MONTENAT (ed.), *Ecological Studies on the Gulf of Suez, the Northwestern Red Sea Coasts, Tectonic and Sedimentary Evolution of a Neogene Rift.* Institut géologique Albert de Lapparent, Documents et Travaux 10, Paris: 7-18.

MONTENAT, C., ORSZAG-SPERBER, F., OTT D'ESTEVOU, P., PURSER, B.H. & RICHERT, J.P., 1986b— Étude d'une transversale de la marge occidentale de la mer Rouge: le secteur de Ras Honkorab-Abu Ghusun. *In*: C. MONTENAT (ed.), *Ecological Studies on the Gulf of Suez, the Northwestern Red Sea Coasts, Tectonic and Sedimentary Evolution of a Neogene Rift.* Institut géologique Albert de Lapparent, Documents et Travaux 10, Paris: 145-170.

MONTENAT, C., OTT D'ESTEVOU, P., PURSER, B., BUROLLET, P., JARRIGE, J., SPERBER, F., PHILOBBOS, E., PLAZIAT, J.-C., PRAT, P., RICHERT, J., ROUSSEL, N. & THEIRIET, J., 1988.— Tectonic and sedimentary evolution of the Gulf of Suez and the northern western Red Sea. *Tectonophysics*, **153**: 166-177.

MONTENAT, C., OTT D'ESTEVOU, P., JARRIGE, J.-J. & RICHERT, J.-P., 1998.— Rift development in the Gulf of Suez and the north-western Red Sea: structural aspects and related sedimentary processes. *In*: B.H. PURSER & D.W.J. BOSENCE (eds), *Sedimentation and Tectonics of Rift Basins: Red Sea-Gulf of Aden.* Chapman and Hall, London: 97-116.

MOON, F.W. & SADEK, H., 1923.— Preliminary geological report on Wadi Gharandal area. *Petroleum Research Bulletin,* **9**: 1-40.

MORETTI, I. & CHÉNET, P.Y., 1987.— The Evolution of the Suez rift: a combination of stretching and secondary convection. *Tectonophysics,* **133**: 229-234.

MORETTI, I. & COLLETTA, B., 1987.— Spatial and temporal evolution of the Suez Rift subsidence. *Journal of Geodynamics*, **7**: 151-168.

MORGAN, P., 1990.— Chapter7: Egypt in the tectonic framework of global tectonics. *In*: R. SAID (ed.), *The Geology of Egypt.* Balkema, Rotterdam: 91-111.

MORGAN, P., BOULOS, F.K., HENNIN, S.F., EL SHERIF, A.A., EL SAYED, A.A., BASTA, N.Z. & MELEK, Y.S., 1985.— Heat flow in eastern Egypt, the thermal signature of a continental break up. *Journal of Geodynamics,* **4**: 107-131.

MOUSTAFA, A.M., 1976.— *Block faulting of the Gulf of Suez. Presented at 5th Exploration Seminar.*Unpublished Report, Egyptian General Petroleum Company, Cairo: 1-19.

MOUSTAFA, A.R., 1993.— Structural characteristics and tectonic evolution of the east-margin blocks of the Suez rift. *Tectonophysics*, **223**: 381-399.

MOUSTAFA, A.R. & FOUDA, H.G., 1988.— Gebel Sufr el Dara accommodation zone, southwestern part of the Suez rift. *Ain Shams University Earth-Sciences Serie*, **2**: 227-39.

MOUSTAFA, A.R. & KHALIL, M.H., 1995.— Superposed deformation in the northern Suez rift, Egypt: relevance to hydrocarbons exploration. *Journal of Petroleum Geology,* **18**: 245-266.

NATIONAL STRATIGRAPHIC SUB-COMMITTEE OF THE GEOLOGICAL SCIENCES OF EGYPT, 1974.— Miocene rock stratigraphy of Egypt. *Egyptian Journal of Geology*, **18**: 1-69.

OMAR, G.I. & STECKLER, M.S., 1995.— Fission track evidence on the initial rifting of the Red Sea: two pulses, no propagation. *Science*, **270**: 1341-1344.

OMAR, G.I., STECKLER, M.S., BUCK, W.R. & KOHN, B.P., 1989.— Fission-track analysis of basement apatites at the western margin of the Gulf of Suez rift, Egypt: evidence for synchroneity of uplift and subsidence. *Earth and Planetary Science Letters*, **94**: 316-28.

ORSZAG-SPERBER, F., HARWOOD, G., KENDALL, A. & PURSER, B.H., 1998.— A Review of the evaporites of the Red Sea-Gulf of Suez rift. *In*: B.H. PURSER & D.W.J. BOSENCE (eds), *Sedimentation and Tectonics of Rift Basins: Red Sea-Gulf of Aden.* Chapman and Hall, London: 409-426.

PATTON, T.L., MOUSTAFA, A.R., NELSON, R.A. & ABDINE, S.A., 1994.— Tectonic evolution and structural setting of the Suez Rift. *In*: S.M. LANDON (ed.), Interior rift basins. *AAPG Memoir,* **59**: 7-55.

PERRY, S.K. & SCHAMEL, S., 1990.— The Role of low-angle normal faulting and isostatic response in the evolution of the Suez rift, Egypt. *Tectonophysics*, **174**: 159-173.

PLAZIAT, J.-C., BALTZER, F., CHOUKRI, A., CONCHON, O., FREYTET, P., ORSZAG-SPERBER, F., RAGUIDEAU, A. & REYSS, J.-L., 1998a.— Quaternary marine and continental sedimentation in the northern Red Sea and Gulf of Suez (Egyptian coast): influences of rift tectonics, climatic changes and sea-level fluctuations. *In*: B.H. PURSER & D.W.J. BOSENCE (eds), *Sedimentation and Tectonics of Rift Basins: Red Sea-Gulf of Aden.* Chapman and Hall, London: 537-573.

PLAZIAT, J.-C., MONTENAT, C., BARRIER, P., JANIN, M.-C., ORSZAG-SPERBER, F. & PHILOBBOS, E., 1998b.— Stratigraphy of the Egyptian syn-rift deposits: correlations between axial and peripheral sequences of the north-western Red Sea and Gulf of Suez and their relations with tectonics and eustacy. *In*: B.H. PURSER & D.W.J. BOSENCE (eds), *Sedimentation and Tectonics of Rift Basins: Red Sea-Gulf of Aden.* Chapman and Hall, London: 211-222.

PURSER, B.H. & HÖTZL, H., 1988.— The Sedimentary evolution of the Red Sea rift: a comparison of the northwest (Egyptian) and northeast (Saudi Arabian) margins. *Tectonophysics*, **153**: 193-208.

PURSER, B.H., PHILLOBOS, E.R. & SOLIMAN, M., 1990.— Sedimentation and rifting in the NW parts of the Red Sea: a review. *Bulletin de la Société géologique de France*, **6**: 371-84.

QUENNELL, A.M., 1958.— The Structural and geomorphic evolution of the Dead Sea rift. *Quarterly Journal of the Geological Society of London,* **114**: 1-24.

QUENNELL, A.M., 1984.— The Western Arabian rift system. *In*: J.E. DIXON & A.H.F. ROBERTSON (eds), *The Geological Evolution of the Eastern Mediterranean*. Blackwell Scientific Publishers, Oxford: 775-788.

REYSS, J.-L., CHOUKRI, A., PLAZIAT, J.-C. & PURSER, B.H., 1993.— Datations radiochimiques des récifs coralliens de la rive occidentale du Nord de la mer Rouge, premières implications stratigraphiques et tectoniques. *Comptes Rendus de l'Académie des Sciences, Paris*, **317** (II): 487-492.

RICHARDSON, M. & ARTHUR, M.A., 1988.— The Gulf of Suez-northern Red Sea Neogene rift: a quantitive basin analysis. *Marine and Petroleum Geology*, **5**: 247-270.

RIHM, R. & HENKE, C.H., 1998.— Geophysical studies on early tectonic controls on Red Sea rifting, opening and segmentation. *In*: B.H. PURSER & D.W.J. BOSENCE (eds), *Sedimentation and Tectonics of Rift Basins: Red Sea-Gulf of Aden.* Chapman and Hall, London: 29-49.

RIVA, E., COLLETTA, B., GRUNEISEN, P. & MORETTI, I., 1992.— Western Sinai (Egypt): evidence of a pre-rift compressional event during Upper Cretaceous time. *In*: *Proceedings of 10th Petroleum Exploration and Production Conference, Cairo, November, 1990.* Vol. 1. Egyptian General Petroleum Corporation, Cairo: 724-739.

ROBSON, D.A., 1971.— The Structure of the Gulf of Suez (Clysmic) rift, with special reference to the eastern side. *Journal of the Geological Society, London*, **127**: 247-276.

ROUSSEL, N., 1986.— *Dynamique sédimentaire des séries miocènes de la région de Quseir (Égypte), bordure NW de la mer Rouge*. Thèse 3ème cycle, Université de Paris-Sud, Orsay, France: 1-191.

SADEK, H., 1926.— The Geography and geology of the district between Gebel Ataqa and El-Galala El-Bahariya (Gulf of Suez). *Geological Survey of Egypt, Paper*, **40**: 1-120.

SAID, R., 1960.— Planktonic foraminifera from the Thebes Formation, Luxor. *Micropaleontology*, **6**: 277-286.

SAID, R., 1962.— *The Geology of Egypt*. Elsevier, Amsterdam: 1-377.

SAID, R., 1971.— The Explanatory notes to accompany the Geological Map of Egypt. *Geological Survey of Egypt, Paper,* **56**: 1-123.

SAID, R., 1990.— Chapter 24: Cenozoic. *In*: R. SAID (ed.), *The Geology of Egypt.* Balkema, Rotterdam: 451-486.

SAID, R. & EL HEINY, I., 1967.— Planktonic foraminifera from the Miocene rocks of the Gulf of Suez region. *Contributions for Cushman Foundation for Foraminiferal Research*, **18**: 14-26.

SAOUDI, A. & KHALIL, B., 1986.— Distribution and hydrocarbon potential of Nukhul sediments in the Gulf of Suez. *In*: *Proceedings of 7th Exploration Seminar, Cairo, March 1984*. Vol. 1. Egyptian General Petroleum Corporation, Cairo: 75-96.

SAVOSTIN, L.A., SIBUET, J.C., ZONENSHAIN, L.P., LE PICHON, X. & ROULET, M.J., 1986.— Kinematic evolution of the Tethys belt from the Atlantic Ocean to the Pamirs since the Triassic. *Tectonophysics*, **123**: 1-35.

SCHUTZ, K., 1994.— Structure and Stratigraphy of the Gulf of Suez, Egypt. *In*: S.M. LANDON (ed.), Interior Rift Basins. *AAPG Memoir*, **59**: 57-95.

SCOTT, R.W. & GOVEAN, F.M., 1985.— Early depositional history of a rift basin: Miocene in the western Sinai. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **52**: 143-58.

SELLWOOD, B.W. & NETHERWOOD, R.E., 1984.— Facies evolution in the Gulf of Suez area: sedimentation history as an indicator of rift initiation and development. *Modern Geology*, **9**: 43-69.

STECKLER, M.S., 1985.— Uplift and extension at the Gulf of Suez: indications of induced mantle convection. *Nature*, **317**: 135-139.

STECKLER, M.S & OMAR, G.I., 1994.— Controls of erosional retreat of the uplifted rift flanks at the Gulf of Suez and northern Red Sea. *Journal of Geophysical Research*, **99**: 12119-12173.

STECKLER, M.S., BERTHELOT, F., LYBERIS, N. & LE PICHON, X., 1988.— Subsidence in the Gulf of Suez: implications for rifting and plate kinematics. *Tectonophysics*, **153**: 249-170.

STEEN, G., 1984.— Radiometric age dating of some Gulf of Suez igneous rocks. *In*: *Proceedings of 6th Exploration Seminar, Cairo, March 1982.* Vol. 1. Egyptian General Petroleum Corporation and Egypt Petroleum Exploration Society, Cairo: 199-211.

STERN, R.J., 1981.— Petrogenesis and tectonic setting of Late Precambrian ensimatic volcanic rocks, Central Eastern Desert of Egypt. *Precambrian Research*, **16**: 195-230.

STERN, R.J., 1994.— Arc assembly and continental collision in the Neoproterozoic East African orogen: implications for the consolidation of Gondwanaland. *Annual Reviews of Earth and Planetary Sciences*, **22**: 319-351.

STOESSER, D.B. & CAMP, V.E., 1985.— Pan-African microplate accretion of the Arabian shield. *Geological Society of America, Bulletin*, **96** (7): 817-826.

TAVIANI, M., 1998.— Post-Miocene reef faunas of the Red Sea: glacio-eustatic controls. *In*: B.H. PURSER & D.W.J. BOSENCE (eds), *Sedimentation and Tectonics of Rift Basins: Red Sea-Gulf of Aden.* Chapman and Hall, London: 574-582.

TEWFIK, N. & AYYAD, M., 1984.— Petroleum exploration in the Red Sea shelf of Egypt. *In*: *Proceedings of 6th Exploration Seminar, Cairo, March 1982*. Vol. 1. Egyptian General Petroleum Corporation and Egypt Petroleum Exploration Society, Cairo: 159-180.

UNDERHILL, J.R., 1991.— Controls on late Jurassic seismic sequences, Inner Moray Firth, UK North Sea: a critical test of a key segment of Exxon's original global cycle chart. *Basin Research*, **3**: 79-98.

VAIL, P.R., AUDEMARD, F., BOWMAN, S.A., EISNER, P.N. & PEREZ-CRUZ, C., 1991.— The Stratigraphic signatures of tectonics, eustasy and sedimentology: an overview. *In*: G. EINSELE, W. RICKEN & A. SEILACHER (eds), *Cycles and Events in Stratigraphy*. Springer, Berlin: 617-659.

VIOTTI, C. & EL DEMERDASH, G., 1969.— Studies in Eocene sediments of Wadi Nukhul area, east coast, Gulf of Suez. *In*: *Proceedings of 3rd African Micropaleontological Colloquium, Cairo*. Vol. 3. National Information and Documentation Centre, Cairo: 403-423.

WEISSBROD, T., 1969.— The Paleozoic of Israel and adjacent countries. Part 2: The Paleozoic outcrops in southwestern Sinai and their relation with those of southern Israel. *Israel Geological Survey, Bulletin*, **48**: 1-32.

WEISSEL, J.K. & KARNER, G.D., 1989.— Flexural uplift of rift flanks due to mechanical unloading of the lithosphere during extension. *Journal Geophysical Research*, **94**: 13919-13950.

WILLACY, C., 1996.— *Thermo-Mechanical Modelling of Extensional Fault Systems*. Ph.D. Thesis, Royal Holloway, University of London, London, England: 1-352.

WINN JR., R.D., CREVELLO, P.D. & BOSWORTH, W. in press.— Lower Miocene Nukhul Formation, Gebel el Zeit, Egypt: model for structural control on early syn-rift strata and reservoirs, Gulf of Suez. *AAPG Bulletin*.

YOUNES, A.I. & MCCLAY, K.R., 1998.— Role of basement fabric on Miocene rifting in the Gulf of Suez-Red Sea. *In*: *Proceedings of 14th Petroleum Conference, Cairo, October, 1998*. Vol. 1. Egyptian General Petroleum Corporation, Cairo: 35-50.

YOUNES, A.I., ENGELDER, T. & BOSWORTH, W., 1998.— Fracture distribution in faulted basement blocks: Gulf of Suez, Egypt. *In*: M.P. COWARD, T.S. DALTABAN & H. JOHNSON (eds), Structural Geology in Reservoir Characterization. *Special Publications- Geological Society of London*, **127**: 167-190.

YOUSSEF, M.I., 1957.— Upper Cretaceous rocks in Kosseir area. *Bulletin of Institute Desert Egypte*, **7**: 35-54.

ZAHRAN, I. & ISMAIL, F., 1988.— Similarity in composition and tectonic style between basement exposed in Gebel el Zeit and Zeit Bay subsurface. *In*: *Proceedings of 8th Exploration Conference, Cairo, November, 1986*. Egyptian General Petroleum Corporation, Cairo: 183-205.

ZICO, A., DARWISH, M. & EWEDA, S., 1993.— Late Cretaceous-Early Tertairy stratigraphy of the Themed area, East Central Sinai, Egypt. *Neues Jahrbruch für Geologie und Paläontologie, Monatshefte*, **3**: 135-149.

ZIEGLER, P.A., 1996.— Geodynamic processes governing development of rifted basins. *In*: F. ROURE, N. ELLOUZ, V.S. SHEIN & I. SKVORTSOV (eds), *Geodynamic Evolution of Sedimentary Basins*. Technip, Paris: 19-67.