Petroleum geology and potential hydrocarbon plays in the Gulf of Suez rift basin, Egypt

A. S. Alsharhan

AUTHOR

A. S. ALSHARHAN ~ *Faculty of Science, United Arab Emirates University, P.O. Box 17551, Al-Ain, United Arab Emirates; sharhana@emirates.net.ae*

A. S. Alsharhan is professor of geology and dean of the Faculty of Science at the United Arab Emirates University. He holds a Ph.D. (1985) in petroleum geology from the University of South Carolina. He has authored and published more than 80 scientific articles. He coauthored *Sedimentary Basins and Petroleum Geology of the Middle East* (1997) with A. E. Nairn and *Hydrogeology of an Arid Region: Arabian Gulf and Adjacent Areas* (2001) with Z. Rizk, A. E. Nairn, D. Bakhit, and S. Al-Hajari. He co-edited *Quaternary Deserts and Climate Change* (1998) with K. W. Glennie, G. Whittle, and C. Kendall and *Middle East Models of Jurassic/Cretaceous Carbonate Systems* (2000) with R. W. Scott. His research interests include Holocene coastal sabkhas of the Arabian Gulf region and the geology and hydrocarbon habitats of the Middle East and North Africa. He is a member of the AAPG, SEPM, International Association of Sedimentologists, and Geological Society of London.

ABSTRACT

The Gulf of Suez in Egypt has a north-northwest–south-southeast orientation and is located at the junction of the African and Arabian plates where it separates the northeast African continent from the Sinai Peninsula. It has excellent hydrocarbon potential, with the prospective sedimentary basin area measuring approximately 19,000 km^2, and it is considered as the most prolific oil province rift basin in Africa and the Middle East. This basin contains more than 80 oil fields, with reserves ranging from 1350 to less than 1 million bbl, in reservoirs of Precambrian to Quaternary age. The lithostratigraphic units in the Gulf of Suez can be subdivided into three megasequences: a prerift succession (pre-Miocene or Paleozoic–Eocene), a synrift succession (Oligocene–Miocene), and a postrift succession (post-Miocene or Pliocene–Holocene). These units vary in lithology, thickness, areal distribution, depositional environment, and hydrocarbon importance. Geological and geophysical data show that the northern and central Gulf of Suez consist of several narrow, elongated depositional troughs, whereas the southern part is dominated by a tilt-block terrane, containing numerous offset linear highs.

Major prerift and synrift source rocks have potential to yield oil and/or gas and are mature enough in the deep kitchens to generate hydrocarbons. Geochemical parameters, sterane distribution, and biomarker correlations are consistent with oils generated from marine source rocks. Oils in the Gulf of Suez were sourced from potential source rock intervals in the prerift succession that are typically oil prone (type I), and in places oil and gas prone (type II), or are composites of more than one type (multiple types I, II, or III for oil prone, oil and gas prone, or gas prone, respectively).

The reservoirs can be classified into prerift reservoirs, such as the Precambrian granitic rocks, Paleozoic–Cretaceous Nubian sandstones, Upper Cretaceous Nezzazat sandstones and the fractured Eocene Thebes limestone; and synrift reservoirs, such the Miocene sandstones and carbonates of the Nukhul, Rudeis, Kareem, and Belayim formations and the sandstones of South Gharib, Zeit, and

post-Zeit. The majority of oil fields in the region incorporate multiple productive reservoirs. Miocene evaporites are the ultimate hydrocarbon seals, whereas the shale and dense limestones of the prerift and the synrift stratigraphic units are the primary seals. Structural, stratigraphic, and combination traps are encountered in the study area. The Gulf of Suez is the most prolific and prospective oil province in Egypt, and any open acreage, or relinquished area, will be of great interest to the oil industry.

INTRODUCTION

The Gulf of Suez is bounded by long. 32°10' and 34°E and lat. 27° and 30°N (Figure 1) and is known to be a Clysmic Gulf (Robson, 1971), a rejuvenated, slightly arcuate northwest-southeast–trending taphrogenic depression. It is an intracontinental, late Oligocene rifted basin but was originally formed during the early Paleozoic as a narrow embayment of the Tethys that was intensively rejuvenated during the rifting phase of the great East African rift system in the Paleogene (see also Bosworth et al., 1998; Montenat et al., 1998; Jarrige et al., 1990). The Gulf runs in a northwest-southeast direction and forms an elongated graben measuring about 320 km in length, with width ranging between 30 and 80 km, and water depth only 40–60 m. It is bounded by two major sets of marginal faults. Paleozoic–Tertiary strata and huge Precambrian basement blocks are exposed on both sides of the Gulf of Suez.
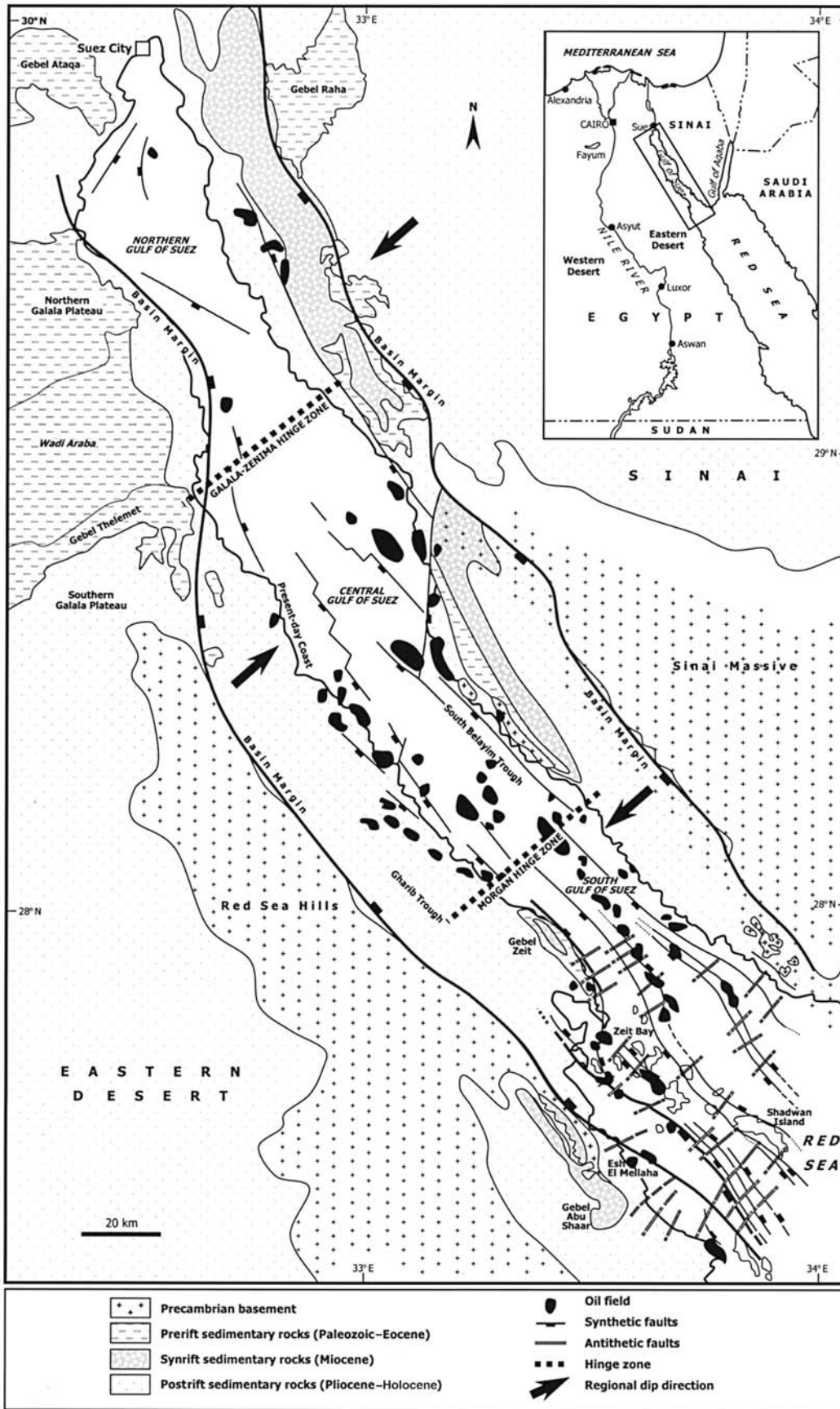
Surface hydrocarbons are uncommon and found only in the southern part of the Gulf of Suez. Asphaltic impregnations have been found in alluvial sands, and seeps exist mainly in Pliocene and Pleistocene limestones. Oil was first found in the Gulf of Suez in 1886, when crude oil seeped into tunnels that had been dug to extract sulfur in the Gemsa area, on the western coast of the Gulf of Suez (Schlumberger, 1995). Subsequently, drilling was conducted close to the surface oil seeps in the west coastal strip of the southern Gulf of Suez, resulting in the discovery of the Gemsa oil field in 1907, the first oil discovery in the Middle East and Africa. Oil also was found in 1918, when the Anglo Egyptian Oil Com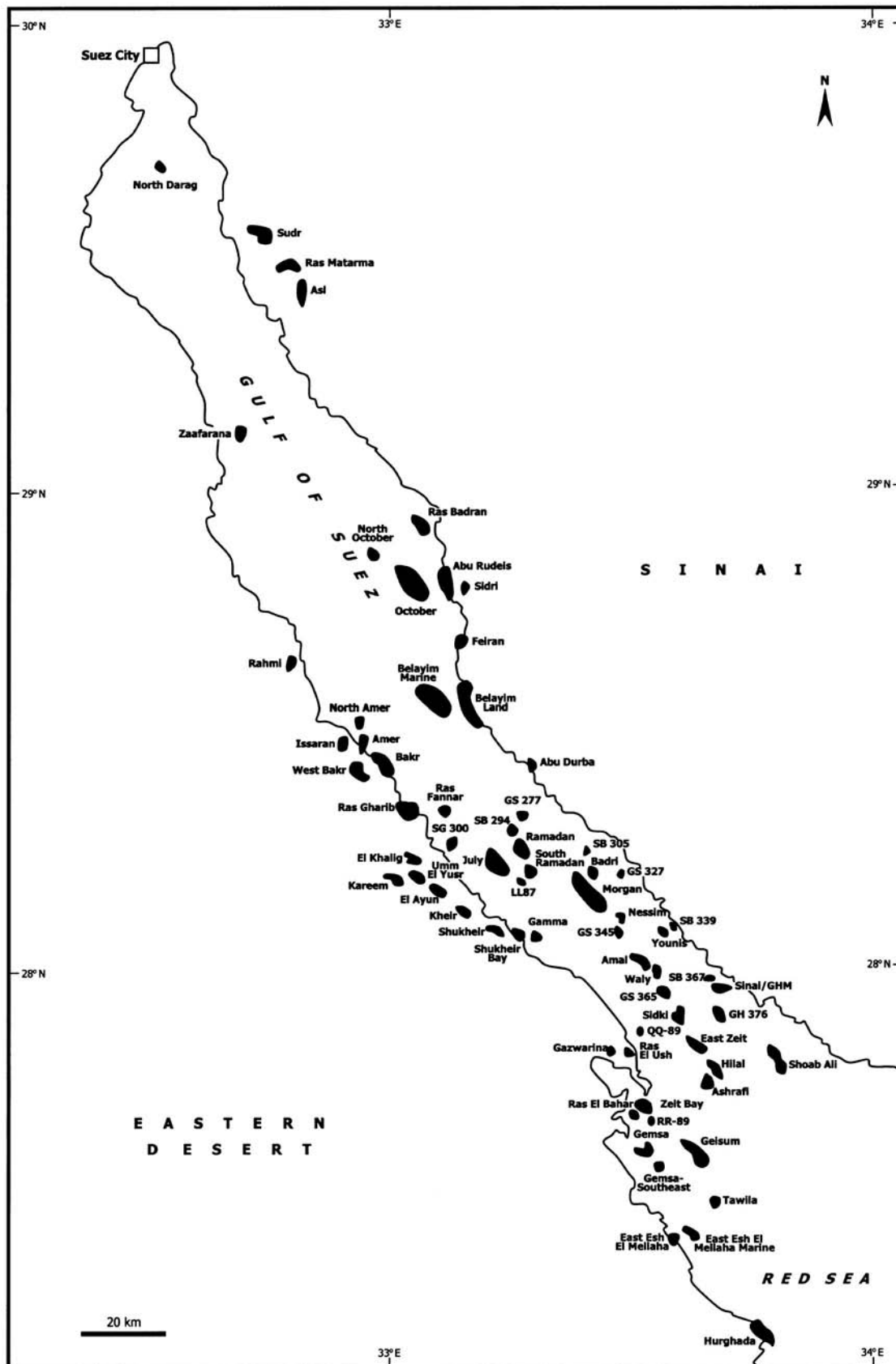pany drilled near an oil seep on the eastern side of the Gulf of Suez and discovered the noncommercial Abu Durba oil field. Ras Gharib was the field providing the first commercial oil and is the most prolific in the area. It was discovered in 1938 on the western side of the Gulf of Suez by the Standard Oil Company of Egypt. Drilling ceased during the Second World War and recommenced in 1946. The exploration activity in the Gulf of Suez and in Egypt has been affected by changes in the political environment and has passed through several phases of activity. From 1970 onward, the Egyptian government encouraged foreign oil companies, leading to continuous and intensive exploration. At present, the Gulf of Suez oil basin has more than 1000 exploration wells, resulting in 240 oil discoveries in more than 80 oil fields (Figure 2), with reserves from 1350 to less than 1 million bbl, in reservoirs ranging in age from Precambrian to Quaternary. The purpose of this article is to illustrate the comparative influences of geology, hydrocarbon potential, and tectonism on hydrocarbon generation, migration, and accumulation within the basin and to clarify the controls on hydrocarbon occurrences and hydrocarbon potential in the Gulf of Suez onshore and offshore regions.

LITHOSTRATIGRAPHY

The stratigraphy, age, and lithological characterization of rock units described in this article from the Gulf of Suez region (i.e., western Sinai Peninsula, offshore the Gulf, and Eastern Desert) relies on data from measured stratigraphic sections and subsurface cores, electric logs tied to microfaunal and palynological studies of ditch samples, and rock thin sections. These data are incorporated with reference to previous studies, such as Sadek (1959), Abdallah et al. (1963), Egyptian General Petroleum Corporation Stratigraphic Committee (1964), Issawi (1973), Mazhar et al. (1979), Beleity (1982), Webster (1982), Sellwood and Netherwood (1984), Beleity et al. (1986), Barakat et al. (1986, 1988), Darwish (1992), Darwish and El-Araby (1993), and Alsharhan and Salah (1994, 1995). The lithostratigraphic units in the study area range from Precambrian to Holocene in age and have been divided into three

Figure 1. Tectonic setting and major tectonic developments. Successive group of tilt blocks with regional dips. The homogeneous tilt provinces are separated by tectonic boundaries (transform faults), which are the effects of Aqaba faults that acted as strike-slip faults during the early stage of the rift structuration (compiled from Jarrige et al. [1990]; Alsharhan and Salah [1994, 1995]; and Montenat et al. [1998]). Insert figure shows location map of Egypt and Gulf of Suez study area.

	Precambrian basement
	Prerift sedimentary rocks (Paleozoic–Eocene)
	Synrift sedimentary rocks (Miocene)
	Postrift sedimentary rocks (Pliocene–Holocene)

	Oil field
	Synthetic faults
	Antithetic faults
	Hinge zone
	Regional dip direction

Figure 2. Major oil fields in the Gulf of Suez.

major sequences relative to the Miocene rifting event: postrift lithostratigraphic units (post-Miocene units), synrift lithostratigraphic units (Miocene units), and prerift lithostratigraphic units (pre-Miocene units). These units vary in thickness and other facies attributes within the Gulf of Suez. A generalized lithostratigraphic scheme of the study area is given in Figure 3 and Tables 1, 2, and 3.

PRERIFT LITHOSTRATIGRAPHIC UNITS

The prerift stratigraphic sequence is composed of strata ranging from Precambrian to upper Eocene and contains sand, shale, and carbonate facies that were laid down under terrestrial and marine-platform environments (Table 1). This period of sedimentation was affected by major unconformities representing nondeposition or erosion at different geologic times, as shown in Figure 3.

Basement rocks have been penetrated by about 200 wells in the southern Gulf of Suez at depths ranging from 1000 to 5000 m (3000 to 15,000 ft) and are interpreted to be granitic rocks on the basis of petrophysical and structural similarities with their surface exposures (Salah and Alsharhan, 1998). The basement is highly weathered and intensively fractured in response to the tectonic activity in this area.

The term "Nubian sandstone" is applied to the Paleozoic–Lower Cretaceous clastic section that lies unconformably on the Precambrian basement complex (see also Pomeyrol, 1968). Pollens and spores have been used to determine geologic ages of the Nubian sandstone succession.

The distribution of these strata in the Gulf of Suez varies widely. In the southern part, the strata range in thickness from 25 to 430 m. In the northern Gulf of Suez, the strata reach their maximum thickness of about 700 m in the western part of the basin, whereas in the central Gulf of Suez the thickness increases toward the east and reaches almost 915 m. The strata also are exposed along the western and eastern flanks of the Gulf of Suez and have thicknesses ranging from 305 to 1065 m.

SYNRIFT LITHOSTRATIGRAPHIC UNITS

Interbedded Oligocene limestones, sandstones, and shales are present in the southern Gulf of Suez, where they rest unconformably on the Eocene rocks. Red bed strata known as Tayiba red beds were deposited in the late Oligocene and are sporadically distributed, having accumulated during the early stages of rifting in the central and northern Gulf of Suez regions. The Miocene sequences were previously subdivided into two main groups, the Gharandal and Ras Malaab (Table 2).
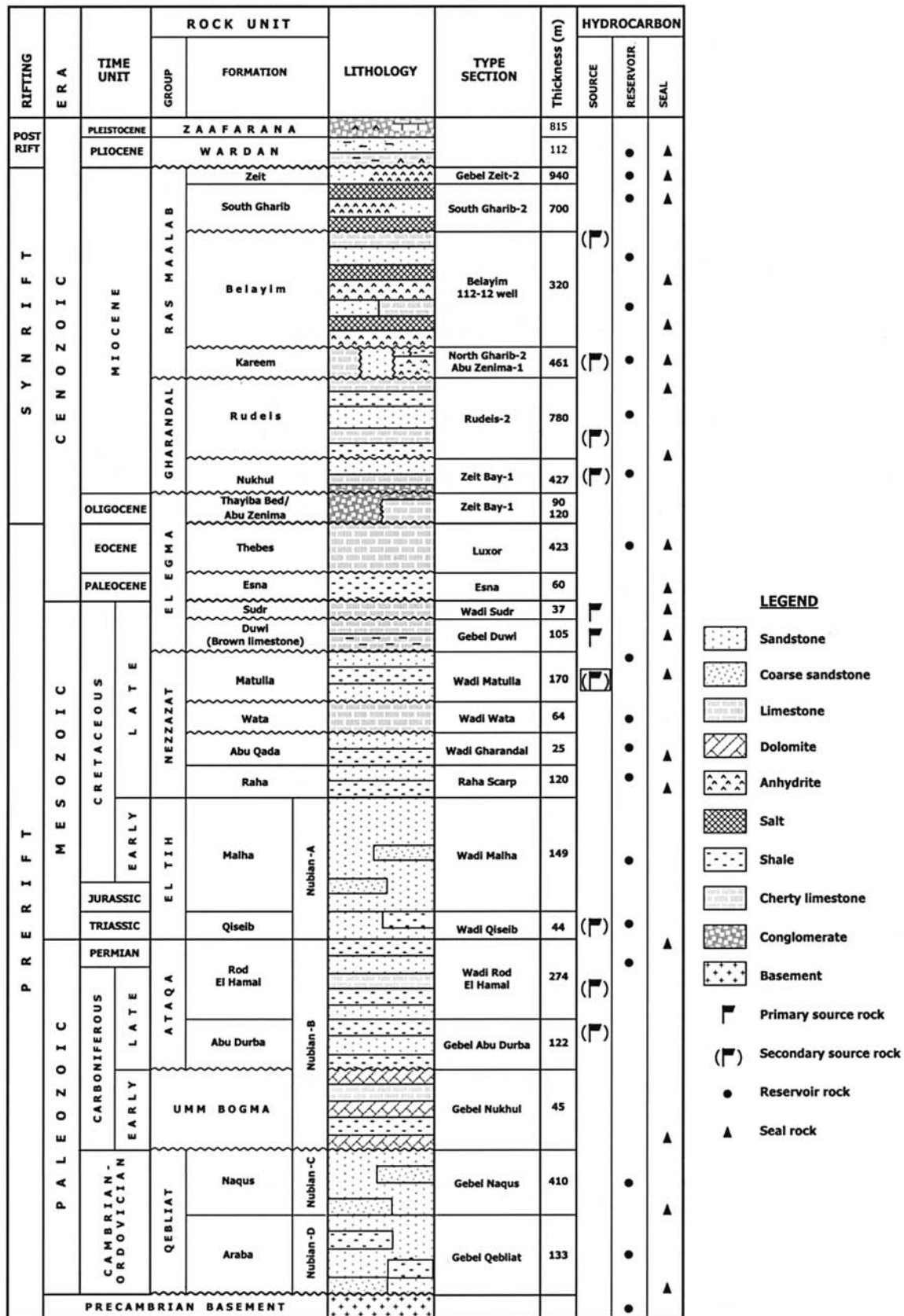
The term "Gharandal" was introduced by the Anglo Egyptian Oil Company (1949, cited in Said [1962]) to describe the strata that lie beneath the Miocene evaporites in the area between Ayun Musa and Lagia on the Sinai side of the Gulf of Suez. The rocks were divided into two formations: the Nukhul and the Rudeis. The term "Ras Malaab" was first introduced to describe surface exposures at the entrance to Wadi Gharandal. As the name "Gharandal" was already reserved for the underlying clastic group, the closest geographic name, "Ras Malaab," was chosen for this group by the Egyptian General Petroleum Corporation (1964). This group was redefined and subdivided by the Egyptian General Petroleum Corporation (1974) into the Zeit, South Gharib, Belayim, and Kareem formations, in descending order.

POSTRIFT LITHOSTRATIGRAPHIC UNITS

The postrift sedimentary fill of the Gulf of Suez is Pliocene–Holocene in age (Table 3). The thickness and lithology of these strata show marked variations from one area to another. Generally, the post-Miocene strata consist of sands and sandstones, shales, and/or limestones. The sand and sandstones and minor shales are predominant in marginal areas, whereas limestones and minor shales are well developed in the central parts, and carbonate with thin streaks of anhydrite occupies the southern part. The strata were deposited in a shallow to deep marine setting. The thickness of this succession ranges from 15 to greater than 1525 m in some of the southern offshore wells.

STRUCTURE AND TECTONISM

The present-day Gulf of Suez rift, together with the Red Sea oceanic basin and the Aqaba–Dead Sea transform systems, comprise the Sinai triple junction, which initiated during the northeasterly movement of Arabia away from Africa. The age of such movements is mainly Neogene (Fichera et al., 1992). The rifting commenced in the pre-Miocene, with the maximum tectonic subsidence, accompanied by magmatic events,

RIFTING	ERA	TIME UNIT	ROCK UNIT GROUP	FORMATION	LITHOLOGY	TYPE SECTION	Thickness (m)	HYDROCARBON SOURCE	RESERVOIR	SEAL
POST RIFT	CENOZOIC	PLEISTOCENE		ZAAFARANA			815			
		PLIOCENE		WARDAN			112		●	▲
SYNRIFT	CENOZOIC	MIOCENE	RAS MAALAB	Zeit		Gebel Zeit-2	940		●	▲
				South Gharib		South Gharib-2	700	(⌐)	●	▲
				Belayim		Belayim 112-12 well	320		● ●	▲ ▲
			GHARANDAL	Kareem		North Gharib-2 Abu Zenima-1	461	(⌐)	●	▲ ▲
				Rudeis		Rudeis-2	780	(⌐)	●	
				Nukhul		Zeit Bay-1	427	(⌐)	●	▲
PRERIFT		OLIGOCENE	EL EGMA	Thayiba Bed/ Abu Zenima		Zeit Bay-1	90 120			
		EOCENE		Thebes		Luxor	423		●	▲
		PALEOCENE		Esna		Esna	60			▲
				Sudr		Wadi Sudr	37	⌐		▲ ▲
	MESOZOIC			Duwi (Brown limestone)		Gebel Duwi	105	⌐		▲
		CRETACEOUS LATE	NEZZAZAT	Matulla		Wadi Matulla	170	(⌐)	●	▲
				Wata		Wadi Wata	64		●	
				Abu Qada		Wadi Gharandal	25		●	▲
				Raha		Raha Scarp	120		●	▲
		EARLY	EL TIH	Malha (Nubian-A)		Wadi Malha	149		●	
		JURASSIC								
		TRIASSIC		Qiseib		Wadi Qiseib	44	(⌐)	●	▲
		PERMIAN	ATAQA	Rod El Hamal		Wadi Rod El Hamal	274	(⌐)	●	
	PALEOZOIC	CARBONIFEROUS LATE		Abu Durba (Nubian-B)		Gebel Abu Durba	122	(⌐)		
		CARBONIFEROUS EARLY		UMM BOGMA		Gebel Nukhul	45			▲
		CAMBRIAN-ORDOVICIAN	QEBLIAT	Naqus (Nubian-C)		Gebel Naqus	410		●	▲
				Araba (Nubian-D)		Gebel Qebliat	133		●	▲
		PRECAMBRIAN BASEMENT							●	▲

LEGEND

- Sandstone
- Coarse sandstone
- Limestone
- Dolomite
- Anhydrite
- Salt
- Shale
- Cherty limestone
- Conglomerate
- Basement
- ⌐ Primary source rock
- (⌐) Secondary source rock
- ● Reservoir rock
- ▲ Seal rock

Figure 3. Lithostratigraphy and hydrocarbon distribution in the Gulf of Suez.

occurring in the late Oligocene–early Miocene (Gandino et al., 1990). Subsidence may have continued until the late Neogene. The interpretation of the phases of tectonic subsidence and their periods and structural stages during the late Tertiary are shown in Figures 4 and 5. The Suez rift was initiated between 24 and 21 Ma, that is, latest Oligocene to earliest Miocene (Evans, 1990). Rifting was caused by tensional stresses transmitted through the lithosphere, accompanied by an upwelling of hot asthenosphere. Both the crustal extension and tectonic subsidence of the axial trough reached their maximum development between 19 and 15 Ma (Steckler et al., 1988). Between 20 and 17 Ma, the flanks of this basin began to rise because of heating effects (Steckler, 1985). By 15 Ma, the movement along the Aqaba–Dead Sea transform fault had begun (Bartov et al., 1980). By 5 Ma, this transform fault replaced the Gulf of Suez as the primary plate boundary between the African and Arabian plates (Evans, 1990). Several unconformities interrupt the sedimentary record, with major ones in the Paleozoic, Triassic–Jurassic, Oligocene, and late Miocene (Messinian). These basinwide unconformities formed primarily in response to regional tectonic adjustments associated with different rift phases of the Gulf of Suez (Dolson et al., 2001).

The Gulf of Suez occupies the northern end of the Red Sea rift (Said, 1962) and is separated from it by the Aqaba transform faults. The Suez rift is bounded by the Sinai massif on the east and the Red Sea hills of the Eastern Desert of Egypt on the west and constitutes a large depression, lying below sea level in its axial part only. This extensional tectonic basin is approximately 60 to 80 km wide and contains a sedimentary prism about 3–5 km thick, with fill ranging in age from Miocene to Holocene (James et al., 1988).

The Gulf of Suez represents a typical interior basin. The evolution of this basin is illustrated in Figure 6 in stages from the Paleozoic to the Holocene and is characterized by tectonic extensional episodes producing tension block faulting (horst and graben) and block subsidence (see also Kingston et al., 1983). Thus the Gulf of Suez has developed in a series of distinct evolutionary stages. (1) In the first stage, Paleozoic terrestrial clastics were deposited over Precambrian crystalline basement with minor tectonic movements. The Hercynian epeirogeny folded and uplifted the Paleozoic deposits. The hiatus caused by these movements is evident in the thinning or absence of sedimentation in many parts of the Gulf of Suez, where Cenomanian strata rest unconformably on Carboniferous strata. (2)

The second stage occurred during the Permian–Triassic to Jurassic and is characterized by local subsidence and minor transgression, leading to deposition of fluvio-marine red shales and sandstones. (3) The third stage dates from the Early Cretaceous and involved rifting of the continental crust, under tension, to produce a system of grabens via block faulting. Depressions were later filled with nonmarine sandstone and shale. (4) During the fourth stage, which extended from the middle Cretaceous to the Miocene, normal faulting continued and the graben system gradually subsided to form a deep basin. Early and middle Alpine movements occurring in this stage had significant effects on the structure of Mesozoic and Paleogene strata and gave rise to a series of folds in areas of tectonic compression. Marine waters invaded the basin and deposited a range of different sedimentary facies, varying with location in the basin. Marine sandstone and shallow marine limestone, including reefal limestone, were deposited on structural highs, whereas shale and globigerinal marl accumulated in the low areas. The last strata of this stage were thick salt deposits. (5) During the fifth and final stage of rift evolution, the interior fracture system widened during the Pliocene–Holocene, the basin fill was uplifted at the rift margins because of continued block faulting, and nonmarine wedge-top strata (mainly sandstone) penetrated the basin. Within-basin faulting is generally not evident in this stage, and sedimentary accumulation in the basin was accommodated by sag.

Garfunkel and Bartov (1977) modeled the stresses operating during development of the Suez rift (Figure 7). The north-south and northwest-southeast orientations of faults imply a preexisting grid of fractures that were reactivated during subsidence of the rift. In Garfunkel and Bartov's (1977) model, the fracture grid was established by a stress regime intermediate between the north-northwest–south-southeast compression, associated with the Syrian Arc System, and east-northeast–west-southwest extension, which occurred during the time of advanced rifting. Most of the normal faults in the Gulf of Suez are not straight but show curved or zigzag traces. Dips of the faults tend to be toward the center of the rift, but this pattern is only modestly dominant (Garfunkel and Bartov, 1977).

The geometry of the basinal fault system is typical for those of extensional settings, and the Gulf of Suez can be considered as a failed rift. Generally, the Gulf of Suez is subdivided into three tectonic provinces (from north to south, the Ataqa, Gharib, and Zeit).

Table 1. Prerift Lithostratigraphic Units in the Gulf of Suez

Age	Group	Formation		Thickness (m)	Lithology	Depositional Setting	Contacts
Cambrian–Ordovician	Qebliat	Araba	Nubia D	130	Interbedded fine to medium-grained colorless yellowish white sandstones and gray to greenish-gray mudstones	Shallow marine	Rests unconformably over the Precambrian basement
	Qebliat	Naqus	Nubia C	410	Thick and massive pebbly and cross-bedded sandstones	Continental	Unconformably overlain by the Umm Bogma Formation
Early Carbonifeorus		Umm Bogma	Nubia B	45	Interbedded fossiliferous, highly calcareous marl and dolomite	Shallow marine	Unconformably overlies Naqus Formation and is overlain by the Abu Durba Formation
Late Carboniferous–Permian	Ataqa	Abu Durba		120	Fossiliferous black shale with thin carbonate streaks	Marine	Rests unconformably on the Rod El Hamal Formation
	Ataqa	Rod El Hamal		275	Interbedded sandstones and shale with streaks of carbonates in the upper part	Shallow marine	Overlies the Abu Durba Formation and is unconformably overlain by the Qiseib Formation
Triassic	El-Tih	Qiseib	Nubia A	50	Interbedded ferruginous sandstone red beds and variegated shale with some limestone in the basal part	Continental deposits with marine influence in the lower part	Rests unconformably on the Rod El Hamal Formation
Jurassic–Early Cretaceous	El-Tih	Malha		150	White to gray sandstones	Continental deposits passing into shallow marine in the upper part of the section	Conformably overlies the Qiseib Formation
Cenomanian	Nezzazat	Raha		50	White sandstone and light to dark gray shale interbeds, with minor thin marl streaks	Shallow marine	Rests conformably on the Malha Formation and conformably overlain by the Abu Qada Formation

Cenomanian–early Turonian	Nezzazat	Abu Qada	25	Sand and shale interbeds, with some thin carbonate streaks	Shallow marine	Unconformably overlain by the Wata Formation
Late Turonian	Nezzazat	Wata	100	Dense dolomite, fossiliferous carbonates with minor streaks of shale, and muddy limestone with minor sandstone	Moderately shallow marine shelf or possibly lagoon	Unconformably overlain by the Matulla Formation
Early Campanian	Nezzazat	Matulla	120–240	Sandstones and shale interbeds with occasional carbonate streaks and, near the middle part of the formation, an interval of oolitic grainstone extends regionally	Delta plain and interdistributary bay, with high-energy oolitic shoal formed by the constant ebb and flood of water in a subtidal setting	Unconformably overlain by the Duwi Formation
Late Campanian–early Maastrichtian	El-Egma	Brown limestone	15–105	Limestone with interbeds of highly calcareous shale. The lower part of the succession contains chert, while the upper part is more argillaceous	Marine outer sublittoral	Conformably overlies the Matulla Formation
	El-Egma	Duwi	50	Hard, highly argillaceous, cherty, phosphatic limestone with thin interbeds of shale and marl	Deep marine	Overlain unconformably by the Sudr Formation and overlies unconformably the Matulla Formation
Maastrichtian	El-Egma	Sudr (Sudr Chalk)	140	Chalky limestone, with thin interbeds of chalk and argillaceous limestone	Deep marine	Unconformably overlain by the Esna Formation
Late Paleocene	El-Egma	Esna (Esna Shale)	60	Soft fossiliferous shale with interbeds of limestone	Marine outer sublittoral to upper bathyal	Unconformably overlain by the Thebes Formation
Early–middle Eocene	El-Egma	Thebes	60	Massive fossiliferous limestone, flints (bands and concretions), and thin interbeds of marl	Marine outer sublittoral	Overlain unconformably by the Oligocene Tayiba red beds or by the lower Miocene Nukhul Formation

Table 2. Synrift Lithostratigraphic Units in the Gulf of Suez

Age	Group	Formation	Member	Thickness (m)	Lithology	Depositional Setting	Contacts
Oligocene	El-Egma	Abu Zeneima		120	Interbedded limestones, sandstones, and shales commonly with a reddish color	Continental	Rests unconformably on the Eocene Thebes Formation and unconformably overlain by the lower Miocene Nukhul Formation
Late Oligocene	El-Egma	Tayiba red bed		90	Variegated sandstone and shale interbeds	Continental	Rests unconformably on the Eocene Thebes Formation and unconformably overlain by the lower Miocene Nukhul Formation
Aquitanian (early Miocene)	Gharandal	Nukhul	Shoab Ali	330	Sandstones: well sorted to fairly well sorted, subrounded and porous. Fine to medium grained becoming coarser toward the base. The sand also contains streaks of shales which are barren of fauna	Fluviatile	Unconformably overlies the Thebes Formation and is conformably overlain by the lower Rudeis Formation
			Ghara	200	White, dense anhydrite with thin beds of gray marl	Shallow marine lagoon	Unconformably overlain by the lower Rudeis Formation
			Gharamul	165	Reefal limestone	Shallow marine	This member represents the marginal equivalent of both the Ghara and October members. It unconformably overlies the coarse detrital sand of the Shoab Ali Member and is unconformably overlain by the Rudeis Formation
			October	160	Limestone boulder conglomerates, with sandstone matrix and relatively thick beds of porous sandstones	Fluviatile to shallow marine	Unconformably overlies the Eocene and conformably underlies the lower Rudeis Formation

Burdigalian–Langhian	Gharandal	Rudeis	Yusr	85	Quartzarenites and sublitharenites	The sandstone deposited as valley and basin fills in a preexisting topography. It forms narrow, eastward-prograding tongues that accumulated in linear structural depressions and grabens	Conformably overlies the Nukhul Formation and is unconformably overlain by the Kareem Formation
			Safra	75	Shales, with sandstone units and minor carbonates intercalated in the lower part	Transgressive marine shale with narrow discontinuous tongues of sandstone and carbonates accumulated in structural troughs	
			Ayun	160	The lower part is medium to very coarse grained, poorly sorted sandstone. The upper part is dominated by shale	The sandstone influx and accumulation was controlled by fault valleys and graben. The shale was deposited during a period of relative tectonic quiescence	
Middle–late Miocene	Ras Malaab	Kareem	Rahmi	165	Thin beds of anhydrite intercalated with sands, shales, and carbonates	Shallow marine to partly open marine, with local lagoonal conditions	Unconformably overlies the Rudeis Formation
			Shagar	300	Interbedded shales, limestones, and sandstones	Deep inner to shallow outer sublittoral	
	Ras Malaab	Belayim	Baba	15–80	Anhydrite with thin interbeds of shale and salt	Shallow marine lagoon	Unconformably overlain by the Sidri Member
			Sidri	13	Shale that is locally dolomitic, with greater abundance of coarse sand along the western and eastern onshore area	Inner neritic to littoral marine	Unconformably overlain by the Feiran Member
			Feiran		Thick evaporates (anhydrite, salt, and some polyhalite), with minor shale and sandstone	Shallow marine lagoon	Unconformably overlain by the Hammam Faraun Member

Table 2. Continued

Age	Group	Formation	Member	Thickness (m)	Lithology	Depositional Setting	Contacts
Middle–late Miocene	Ras Malaab	Belayim	Hammam Faraun	90	Interbedded shale, sandstone, and carbonate with occasional thin beds of anhydrite	Open marine in the central part of the basin, and tidal flat to intertidal in the marginal areas	Unconformably underlies the Ras Gharib evaporites
	Ras Malaab	South Ras Gharib		45–2285	Thick evaporite (salt with anhydrite) with thin intercalations of shales and sands	Restricted, subsiding saline basin	Unconformably overlain by the Zeit Formation
	Ras Malaab	Zeit		25–945	Interbedded anhydrite, gypsum, and shale with some thin salt streaks. Locally in the marginal areas, it contains some thin intercalations of sandstones and limestones	Deep semirestricted to lagoonal setting	Unconformably overlain by post-Miocene deposits

The three provinces are separated by two north-north-east–south-southwest major accommodation faults or hinge zones. Each province has its own structural and stratigraphic history. The accommodation faults include a zone of fault rotation in the Gulf of Suez, called the Galala-Zenima hinge zone (Figure 1). This fault separates the northern province of the Gulf of Suez, with a basin floor generally dipping southwest, from the central province, with a northeast-dipping basin floor. Another similar zone is called the Morgan hinge zone, which separates the central and southern provinces, the latter with dips toward the southwest (Figure 1). Meshref and Khalil (1990) calculated 5.1 and 14 km of widening in the northern and central provinces of the Gulf of Suez, respectively, representing an increase of 11 and 17%, respectively, in the initial basin width. Clearly the northern province of the Gulf of Suez has suffered less extension than the central province.

Interpretation of geological and geophysical data indicates that the Gulf of Suez consists of elongated troughs containing several submarine ridges (elongated structural highs). Both troughs and highs have the same trend as the Gulf of Suez (northwest-southeast). These highs are dissected by some high-angle discordant elements that trend northeast-southwest and east-northeast–west-southwest. These later elements are viewed as cross faults that segment the highs. The distinctive structural and stratigraphic features within the subbasins of the rift vary in both the northern and central provinces of the Gulf, and even within the same province. The stratigraphic succession and depth to basement also varies from one structural high to another and also within the same high (Rashed, 1990; Saoudy, 1990). The temperature gradient is in agreement with the proposed dog-leg model for the Suez rift. Figure 8 shows that the major troughs along the rift axis are associated with a high temperature gradient (reaching 2°F/100 ft or more). This may be explained by the axis of the rift being associated with thin crust and upwelling of hot mantle by convection (Meshref, 1990).

The Gulf of Suez basin axis has apparently shifted progressively eastward with time, probably due to the evolution of the deep structural detachment below this asymmetric rift (Ahmed, 1972). This asymmetry has led to subsidence of former reefal and clastic coastlines in the eastern part of the Gulf, and their subsequent burial beneath impermeable basinal mudrocks, whereas similar units were uplifted and exposed in the west. The Miocene sequence forms a broadly fining-upward se-

Table 3. Postrift Lithostratigraphic Units (Pliocene–Pleistocene Strata) in the Gulf of Suez

Group	Formation	Thickness (m)	Lithology	Depositional Setting	Contacts
	Ashrafi	1300	Fossiliferous and sandy limestone, intercalated with minor streaks of crystalline and cryptocrystalline anhydrite and gray to greenish calcareous shale	Shallow marine	It underlies the fine sediment of recent deposits, well developed in the south and showing a narrow extension into the central part of the Gulf of Suez
	El Tor	1100	Thick coarse to very coarse subangular to subrounded sand and sandstone, with some traces of mafic and feldspar fragments. The sandstone is intercalated with streaks of tan brown shales, cryptocrystalline limestones, and anhydrite	Alluvial deposits	The formation underlies the fine sediment of recent deposits, well developed in the central Gulf of Suez
Darag	Wardan	112	Sandstone and shale intercalations with some streaks of limestone and occasional anhydrite near the base and the top	Shallow marine	Conformably underlies the Zaafarana Formation and well developed in the northern part of the Gulf of Suez
	Zaafarana	815	Evaporite and shale and sandstone intercalations with minor streaks of limestone and salt	Shallow marine lagoon	The formation underlies the fine clastic sediments of recent deposits well represented in the northern sector of the Gulf of Suez

quence passing gradually upward into evaporites (Cofield and Smale, 1987). The thickness of the individual units varies greatly because of the irregular topography of the underlying block-faulted early Miocene, which has elevations ranging from 19 to 890 m.

The first stage of rifting produced a graben about 50–70 km wide. Some upper Eocene and Oligocene conglomerates found in the Gulf area are continuous with lower Miocene conglomerates. In the early Miocene, the conglomerates were followed by organic-rich shales and marls containing abundant foraminifera and exceeding 2 km in stratigraphic thickness in parts of the basin. These fine-grained deposits provide the potential source rock for most of the oil in the Gulf of Suez. In the late early Miocene the rift became more restricted, and a partly evaporitic sequence was deposited (Fichera et al., 1992; Ibrahim, 1992).

The middle Miocene witnessed a renewed episode of rift faulting. The central line of the original rift became a deep trough. Many tilted fault blocks developed, from which the lower Miocene beds were stripped by erosion. The Gulf was effectively cut off from free circulation of Mediterranean water, and a sequence of evaporites more than 2 km thick was deposited over most of the basin. Salt deposition dominated along the central axis of the rift, whereas anhydrite is the principal evaporite in the marginal areas (Fawzy and Abd El Aal, 1984). This evaporite sequence provides the seal for many of the oil fields in the Gulf. Sand derived from the uplands of the Sinai Peninsula and the Egyptian Eastern Desert was deposited in the rift as deltas and alluvial fans. Clastic deposition was intermittent throughout the Miocene, and the sands are interbedded with shales and evaporites as far as the center of the Gulf.

In the Pliocene, the Gulf of Suez became essentially tectonically quiescent. There were repeated incursions of marine water from the Red Sea, as at the present time, but the Pliocene deposits are not significantly petroliferous. Pliocene alluvial fan and playa deposits covered the evaporitic basin to a thickness of more than 3 km in the deeper fault troughs. Subsidence and graben evolution continued during the Pliocene, mainly in the central part of the basin. Under

Figure 4. The relationship between tectonic subsidence rates, types, and periods and climate and sea level changes during the Neogene in the Gulf of Suez (compiled and modified from Griffin [1999] and Bosworth et al. [1998]). Smaller V symbols represent periods of rapid basin subsidence, for example, the Burdigalian; larger V symbols represent modest rates of basin subsidence, for example, in the Serravallian.
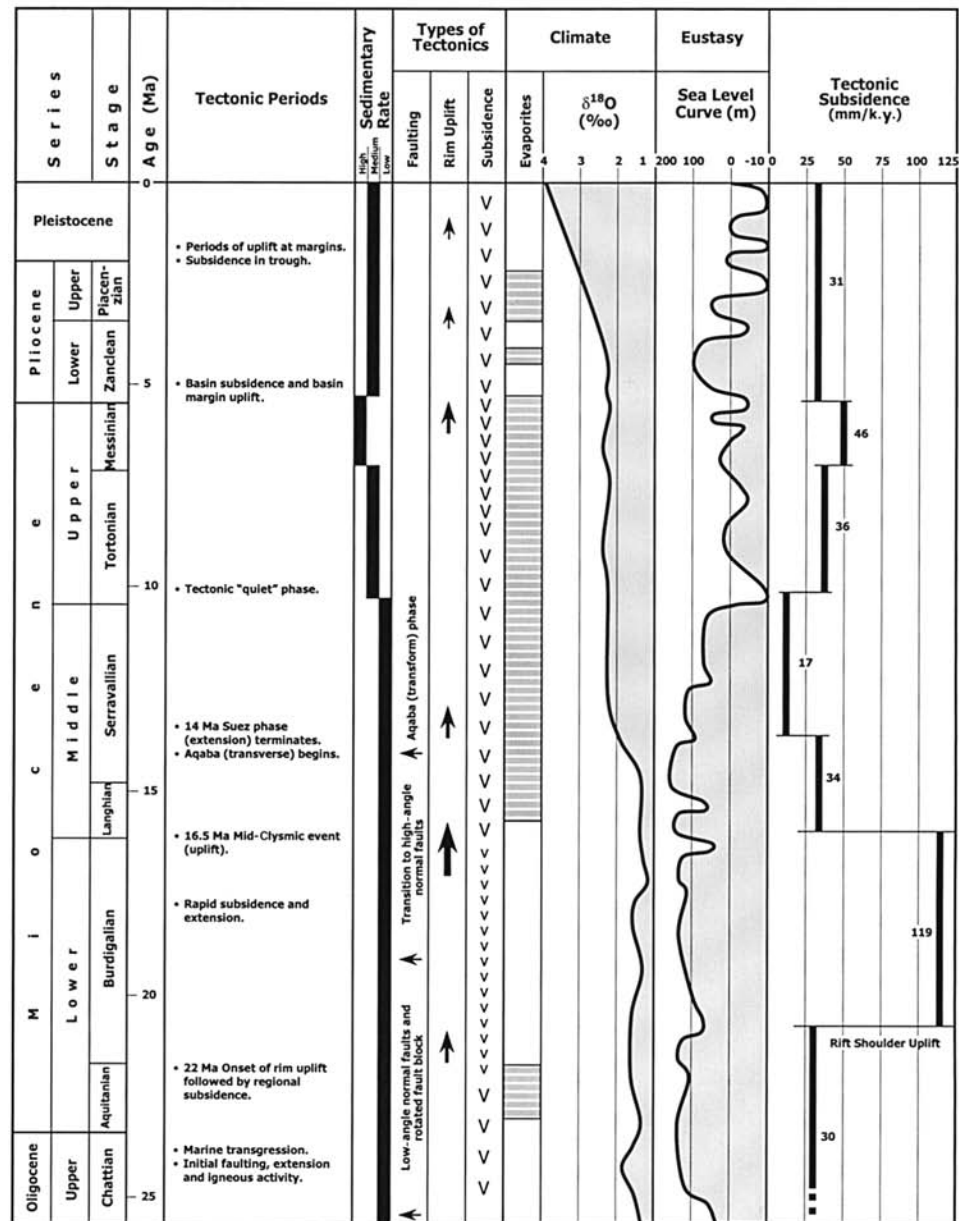
the accumulated weight of Pliocene strata, the Miocene salt flowed upward into broad salt pillows and ridges. These salt structures commonly obscure the deeper prospective characteristics.

HYDROCARBON HABITAT

The hydrocarbon potential of the study area is generally high because (1) rifting tended to produce both restricted and open marine settings favorable to source rock accumulation; (2) relatively high geothermal gradients helped convert organic matter in the source rocks to hydrocarbons; (3) subsequent rotational faulting and marginal uplifting produced clastic systems served by the mature shield terranes and formed shoal areas where porous reef buildups and dolomitized limestones—potential reservoirs—could develop; (4) rotational faulting of these units produced structural traps, which were sealed by onlapping basinal mudrocks or evaporites during later thermal subsidence of the rift; (5) all faults in the Gulf of Suez are normal faults. The trapping structures of the numerous oil fields are horsts or tilted fault blocks. The intervening grabens contain thick accumulations of basinal shales and marls, producing favorable conditions for rich
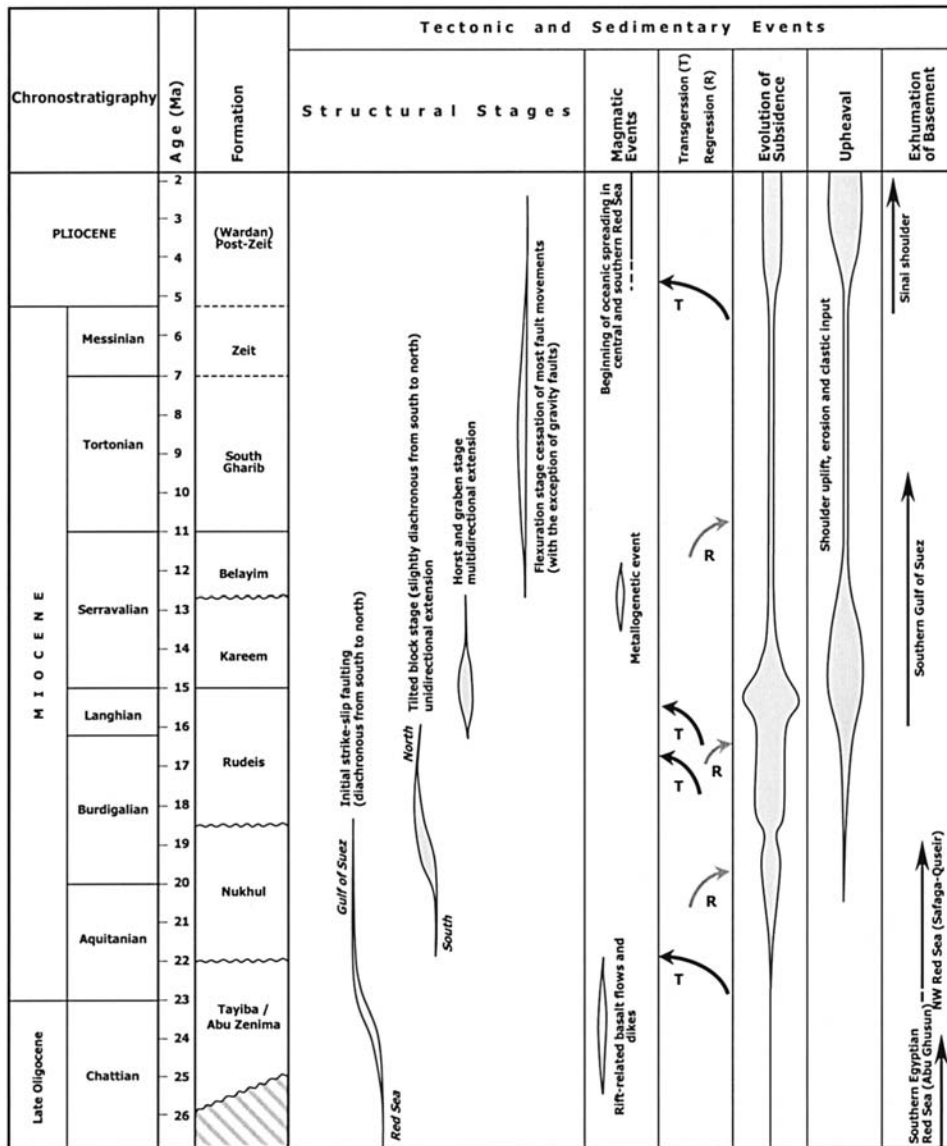
Figure 5. Chronodiagram of tectonic, sedimentary, and magmatic events that characterize the Gulf of Suez and northwestern Red Sea evolution (modified from Montenat et al., 1998).

source rock deposition and a suitable maturity regime for generation of hydrocarbons; (6) thick accumulations of the evaporites, mainly of Miocene age, contain much salt, which has formed broad salt swells and pillows in the deeper parts of the basin, and provide excellent seals; and (7) reservoirs are characterized by a relatively active water drive and good to excellent porosity and flow capacity (exceptions to the water drive rule are Umm al Yusr and July fields in the Rudeis reservoirs). A summary chart of hydrocarbon habitat (source rocks, seals, and reservoirs) and types of traps are shown in Tables 4 and 5, and their distribution relative to the formations and geologic ages is shown in Figure 3.

Source Rock Potential

The source rock potential of the Gulf of Suez has been studied by many authors, such as Rohrback (1982), Barakat (1982), Shaheen and Shehab (1984), Atef (1988), Mostafa (1993), Mostafa et al. (1993), and Alsharhan and Salah (1994, 1995), and these studies are considered here.

Potentially rich source rock intervals have been identified on the basis of total organic carbon (TOC) content and pyrolysis result (S_2) within the Gulf of Suez. In stratigraphic ascending order these are the Upper Cretaceous carbonates (Brown Limestone and Sudr Chalk); the Eocene Thebes, lower Miocene

Figure 6. Development stages of the Gulf of Suez, as an example of a typical interior fracture rift basin (stages 3–5 modified from Kingston et al. [1983]).
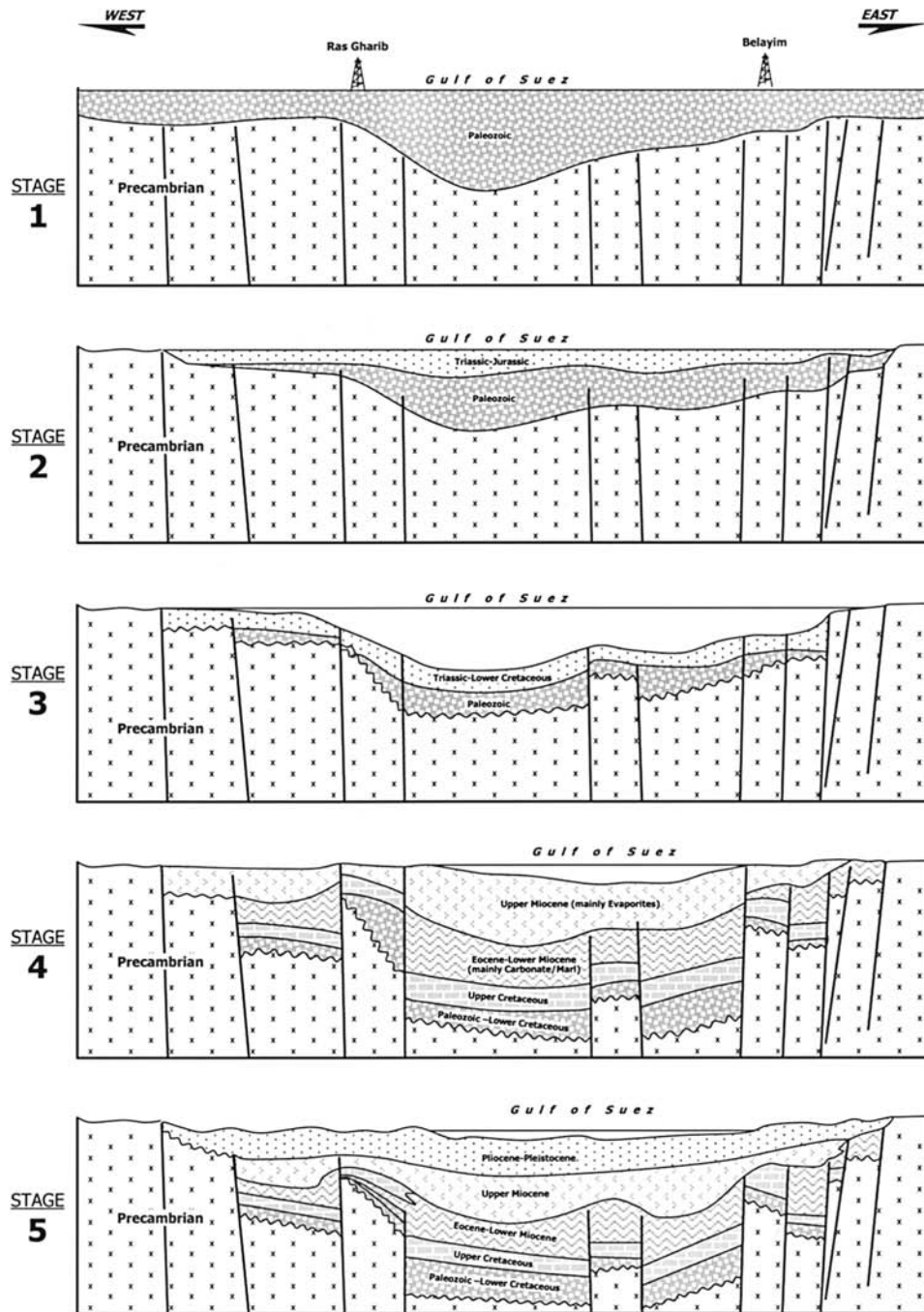
Rudeis, and middle Miocene Kareem formations; and the Hammam Faraun Member of the Belayim Formation. The Upper Cretaceous Brown Limestone carbonates (with an average TOC of 3.5%) and the Eocene Thebes Formation (average TOC 3.2%) are the prerift deposits formed during the Tethyan transgression across northeastern Africa. The Rudeis Formation (average TOC 2.5%), and the Kareem Formation and Hammam Faraun Member (average TOC 1.5%, rang-

ing from 0.20 to 1.5%) are synrift deposits. In terms of TOC content of well-preserved source rocks, the synrift sequence is more important than the prerift (Figure 9). Figure 10 shows that the prerift source intervals are typically oil prone (type I) and in places oil and gas prone (type II). The synrift source rocks are of multiple types that may be oil prone, oil and gas prone, or gas prone (types I, II, and III, respectively, of Tissot and Welte [1984]). There is also a minor contribution from
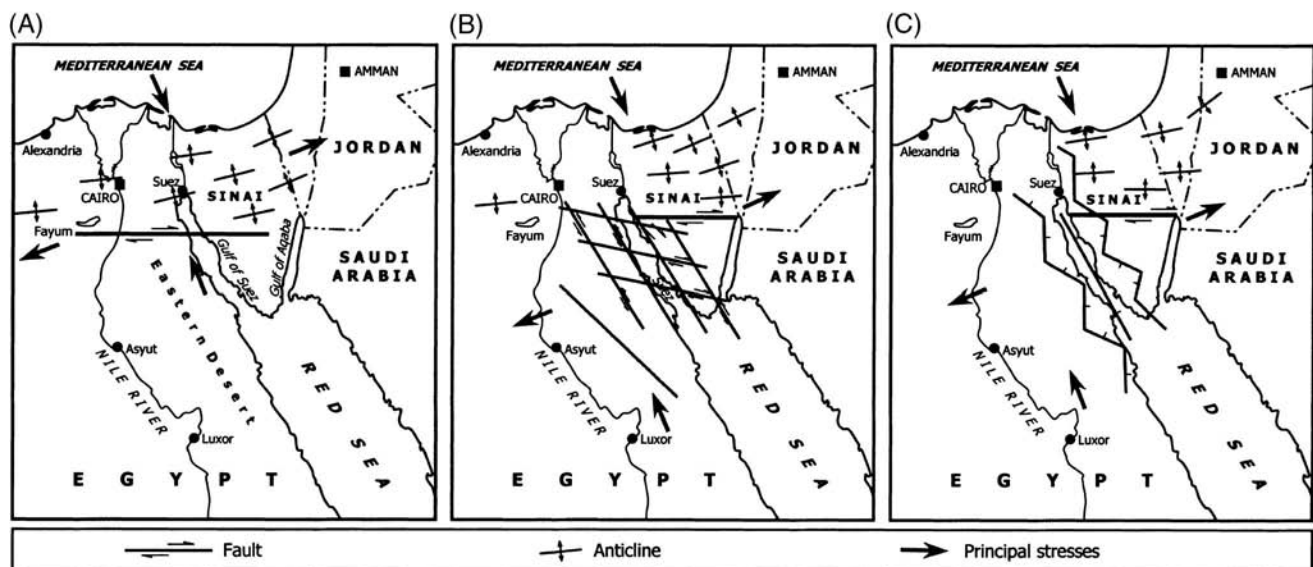
Figure 7. Model for stresses operating during development of the Suez rift (modified from Garfunkel and Bartov, 1977). (A) Prerifting; (B) embryonic rifting; (C) advanced rifting.

postrift Quaternary carbonates and shales. Rock-Eval pyrolysis data from different oil samples in the Gulf of Suez were analyzed and show that samples from the Brown Limestone and the Thebes and Matulla formations contain more than 2% TOC and high hydrogen index (HI) values (HI 300–675), with low oxygen index (OI) values (OI 15–100), of type I/II and type III kerogens (Figure 11). The available geochemical parameters indicate the presence of organic-rich source rocks within several stratigraphic sequences. The source rocks in the Gulf of Suez are mature to highly mature and contain type II and II-I kerogen, which are capable of hydrocarbon generation. The threshold for oil generation occurred during the late Miocene or Pliocene between 10 and 4 Ma.

Postrift Source Unit (Post-Miocene)

The source potential of the Quaternary strata has been studied by Barakat (1982) and Alsharhan and Salah (1998). Based on the geochemical analyses of the TOC content and the results of pyrolysis (S_2) reported by these authors and others on the Quaternary shales and carbonates covering most of the Red Sea and the southern sector of the Gulf of Suez, the organic-rich shaly intervals are considered to have fair source potential (TOC and S_2 values average 1.0% and 4 kg/ton, respectively). The HI of the Quaternary shales and carbonates ranges between 50 and 350, indicating that a gas-prone source rock is present (type III of Tissot and Welte [1984]).

Synrift Source Units (Miocene)

Three Miocene intervals have been identified as having rich potential source units: the Rudeis, Kareem, and Belayim formations. The Rudeis Formation is very rich in the deep basins where its main constituent is marly shale. It yields an average TOC value of 1.5–2.2%. The Rudeis Formation is extensively developed and is believed to be a major source rock in the study area.

On the basis of the available geochemical data, the Belayim and Kareem formations are generally fair to rich source rocks. The average TOC of the Belayim and Kareem formations in the Gulf of Suez is 1.3 and 1.1%, respectively (Barakat, 1982). Both formations are widely distributed in the Gulf of Suez and are believed to have fair hydrocarbon source potential over much of the study area.

The lower Miocene Rudeis Formation is an oil-prone (type I) and oil- and gas-prone (type II) source rock. The middle Miocene Kareem and Belayim formations are multiple types that may be oil prone, oil and gas prone, or gas prone (types I, II, III). The pre-Miocene rich source rocks are typically oil prone (type I) and in places oil and gas prone (type II).

Prerift Source Units (Pre-Miocene)

The pre-Miocene source rocks are the Thebes-Esna shale interval, Brown Limestone–Sudr carbonate interval (upper Senonian), and the shales of the lower Senonian Matulla Formation. The available
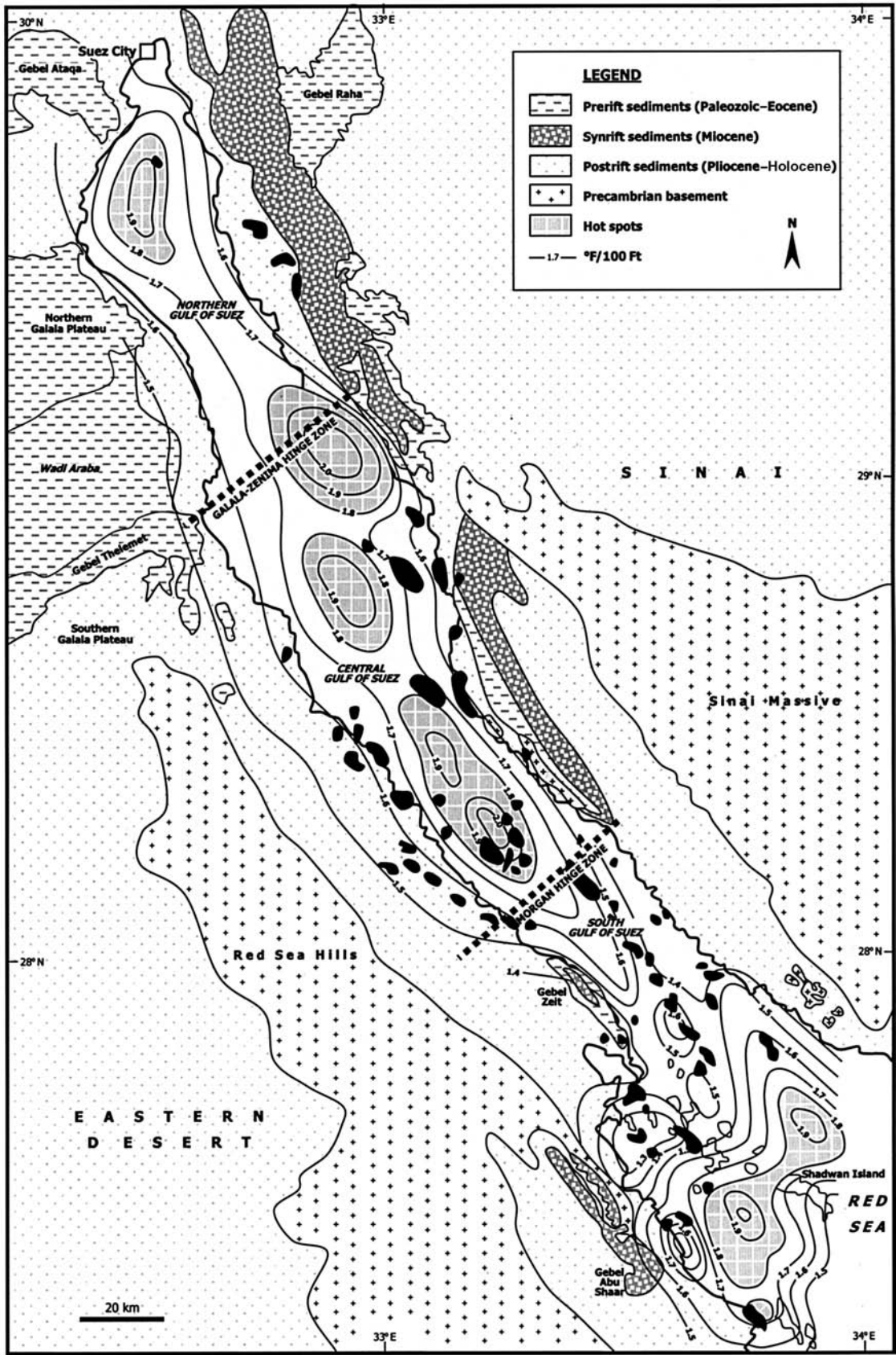
Figure 8. Geothermal gradient and hot spot areas in the Gulf of Suez.

Table 4. Hydrocarbon Habitat Summary for the Gulf of Suez

Cap Rocks		Reservoir Rocks		Source Rocks	
Lateral	Vertical	Secondary	Primary	Secondary	Primary
Zeit Formation (evaporite) South Gharib Formation (evaporite) Rudeis Formation (mudstone)	Zeit Formation (evaporite) South Gharib Formation (evaporite) Belayim Formation (Feiran and Baba members) (evaporite) Kareem Formation (Shagar Member) (mudstone) Rudeis Formation (mudstone) Thebes Formation (Limestone) Esna Formation (shale) Sudr Formation (chalk) Duwi Formation (carbonate)	Post-Zeit (sandstone) Zeit Formation (clastic) South Gharib Formation (clastic) Hammam Faraun Member (reefal carbonate) Hammam Faraun Member (clastic) Sidri Formation (clastic) Kareem and Rudeis formations (reefal carbonate) Rudeis Formation (fractured limestone) Nukhul Formation (reefal carbonate) Thebes Formation (limestone) Wata Formation (clastic) Raha Formation (clastic) Nubian sandstone (Araba, Naqus, Qiseiba and Malha formations) Fractured and weathered basement	Belayim Formation (clastic) Kareem Formation (clastics: deltaic and turbidite sands) Rudeis Formation (clastics: shallow-marine and turbidites) Nukhul Formation (clastics: shallow-marine)	Belayim, Kareem, Rudeis, and Nukhul formations (Miocene); Matulla Formation (lower Senonian); Abu Qada (Cenomanian); Rod El Hamal (Carboniferous)	Brown limestone, Duwi and Sudr formations (upper Senonian); Thebe Formation (Eocene)

Table 5. Hydrocarbon Traps and Trapping Mechanisms in the Gulf of Suez

Structural				Combination				Stratigraphic			
Crests of tilted blocks (e.g., Ramadan, October, Belayim, and Morgan fields)	Draping over fault-block boundaries (Belayim Marine and Belayim Land fields); Twist zone–subtle trap (e.g., South Ramadan field)	Fault-controlled closures (intersection of several longitudinal-Clysmic-faults) (e.g., Ramadan field)	Faulted structure (e.g., Hilal, East Zeit, Ramadan, October, Geisum, Shoab Ali, and Ras Budran fields)	Four-way dip closure (e.g., Belayim Marine and Zeit Bay fields)	Reefal buildup on block crests (e.g., RR89, Ras Gharib, Ras Bakr, and Gemsa fields)	Fractured limestone on faults (e.g., Shoab Ali, Ras Matarma, Asl, and Sudr fields)	Truncation below unconformity (e.g., Ras Gharib and July fields)	Onlap pinch-out (e.g., Abu Rudeis, Ekma, and Ras Bakr fields)	Updip pinch-out of sand lenses (e.g., Umm El Yusr and El Ayun fields)	Reefal buildups over block crests (e.g., Ras Gharib, Gemsa, and Ras Bakr fields)	Weathered and fractured basement (e.g., Shoab Ali, Zeit Bay, and Hurghada fields)

geochemical data for these intervals indicate that the Thebes-Esna shale interval is considered a fair to rich source unit, with average TOC values ranging between 1.40 and 1.70%.

The upper Senonian carbonates (Brown Limestone, locally known as the Duwi and Sudr formations) are the richest and most important source rocks in the northern and central provinces of the Gulf of Suez. This accords with other studies by Rohrback (1982) and Alsharhan and Salah (1994, 1995) that the Brown Limestone and Sudr formations are the primary source rocks of the Gulf of Suez. The average TOC of this interval in the study area is 1.7%, with a maximum recorded TOC value of 16%.

The richness of the Matulla Formation is readily apparent from the TOC values, available only from the GS24-1 and GS195-1 wells, where these recorded values are 1.38 and 1.16%, respectively, indicating fair to rich source rocks (Alsharhan and Salah, 1995).

Source Rock Maturity

The Gulf of Suez rift basin is characterized by heterogeneity of crustal thickness. Several hot spots have given rise to localized source kitchens even at shallow depths, especially in the southernmost Gulf of Suez and northern Red Sea. The average geothermal gradient of the northern and central sectors of the Gulf of Suez basin is 1.55°F/100 ft, whereas it averages 1.75°F/100 ft in the southern part (Alsharhan and Salah, 1994, 1995).

The geothermal gradient estimated for most of the drilled exploratory wells in the Gulf of Suez was calculated from the available drillstem tests, electric logs, and temperature surveys, after correcting the bottom-hole temperature (Figure 8). These corrected readings were used to calculate the time-temperature index on the burial history diagrams and discussed in Alsharhan and Salah (1994, 1995). The major source kitchens and probable migration pathways of hydrocarbons are shown in Figure 12. The synrift and prerift source kitchens (primarily Miocene) are the East and West Shadwan Island and Gemsa troughs and the East Ghara, East Zeit, Darag, South Darag, October, South Belayim, and Gharib troughs, respectively. In the Gemsa trough, the depth to basement reaches more than 4600 m in places, at which the prerift source rocks are effectively in the gas generation window. The Shadwan and Ghara prerift source kitchens extend to the Precambrian basement and range in depth from 2900 to 4000 m. At these depths the prerift
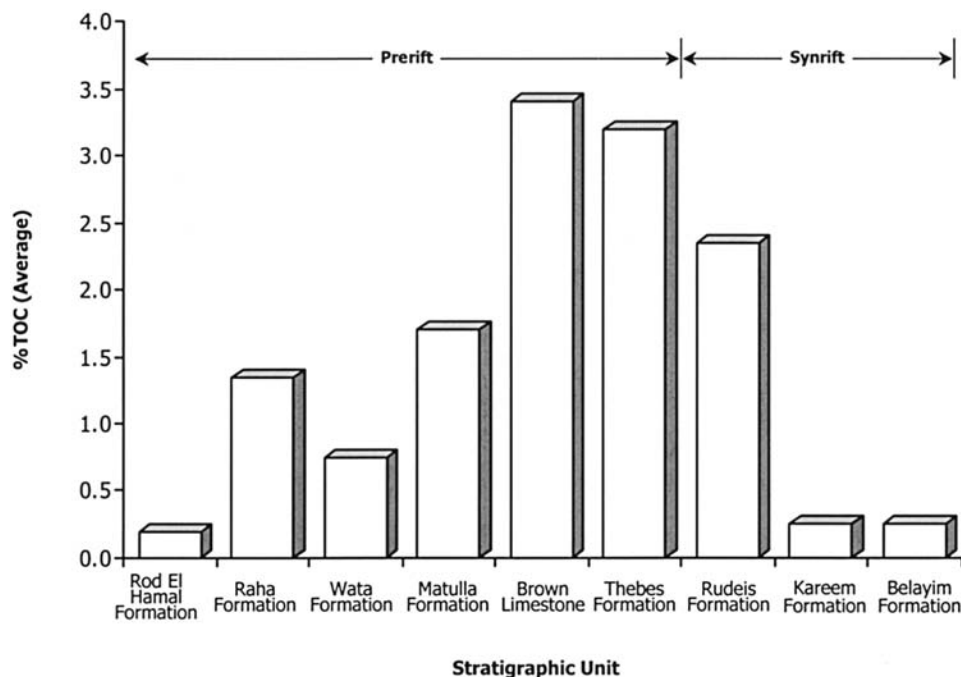
Figure 9. Average organic carbon content (% TOC) for Upper Cretaceous, Eocene, and Miocene formations in the Gulf of Suez.

sources lie within the oil generation window. The oil generation threshold is believed to have been established at 10 Ma for the prerift sources and around 4 Ma for the synrift sources (mainly Miocene) in the southern Gulf of Suez. The depth to the level of onset of oil generation ranges in the area from about 2290 to greater than 3660 m and decreases southward within the study area.

In the Darag trough, the basement is as deep as approximately 7000 m, at which prerift source rocks are within the gas generation window or below it. The oil generation threshold rates from approximately 9 Ma for the prerift sources and around 3 Ma for the synrift sources (mainly Miocene). The depth to the onset of oil generation ranges from about 2280 to greater than 3650 m for this trough.

Oil Groups

Multiple analytical parameters of oil samples, collected from both Miocene and pre-Miocene reservoirs, and several extracts from offshore and onshore areas of the Gulf of Suez were used to compare the genetic relations of these oils with the analytical parameters for oils from the whole Gulf of Suez, described by Rohrback (1982), Mostafa (1993), and Alsharhan and Salah (1994, 1995). These analyses include liquid chromatograph separation, gas chromatography, gas chromatography–mass spectroscopy (GC-MS), and
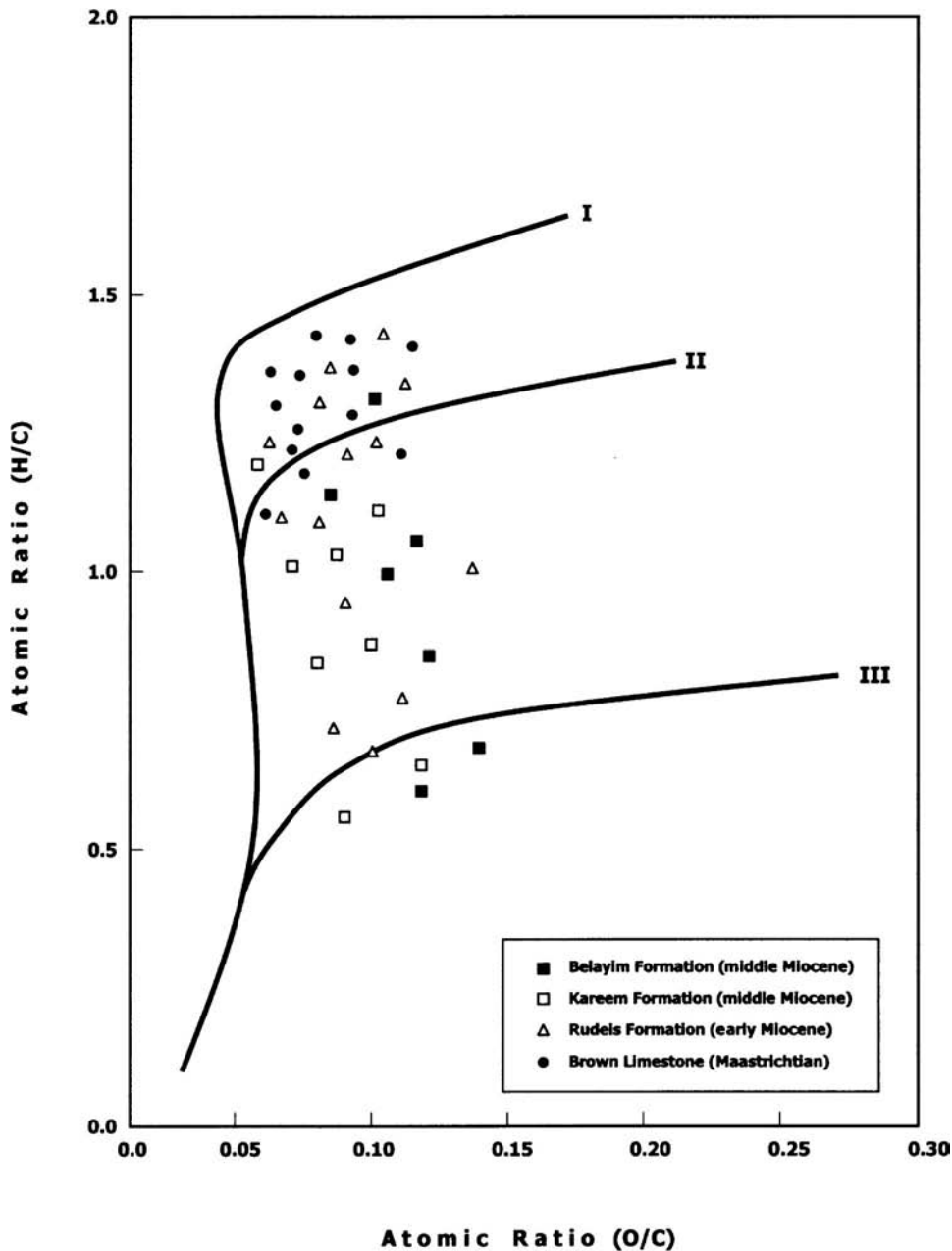
stable isotope mass spectroscopy. The Gulf of Suez oils are interpreted to be of a single genetic family, suggesting the same or similar source rocks of marine origin. Crude oils and their geochemical analyses are shown in Table 6.

Based on geochemical analyses and interpretation, the oil families in the Gulf of Suez can be classified into groups (see also Barakat, 1982; Rohrback, 1982; Mostafa, 1993; Mostafa et al., 1993; Alsharhan and Salah, 1994, 1995; Wever, 2000) as summarized in the following sections. The different number of classified groups is due to different analytical techniques, oil samples (numbers and distributions), and localities. Moreover, all the samples and group numbers are distinguished by biomarker distribution (gammacerane), gross composition, pristane/phytane ratios, carbon reference index, and sulfur content.

Group I Oil

The source rock for group I oil is the Cenomanian Raha Formation, confined to northeast fields such as Asal, Ras Matarma, and Sudr. These oils have been generated at an early stage of thermal maturity. The oil is 20° API, has about 2% sulfur, $\delta^{13}C$ values for saturates around –27‰, and n-alkane distribution with pristane dominant over phytane. The lower C_{35}/C_{34} homohopane ratios are less than 1, suggesting a less reducing marine environment for the source rock.

Figure 10. Van Krevelen diagram showing source rock types in the Gulf of Suez.

Legend:
■ Belayim Formation (middle Miocene)
□ Kareem Formation (middle Miocene)
△ Rudeis Formation (early Miocene)
● Brown Limestone (Maastrichtian)

Group II Oil

The group II oils show good correlation with the source rocks of the Brown Limestone and the Thebes Formation. Sulfur-rich kerogen in these two source rocks might be the source material for the high sulfur (poor-quality) oils of this group. Oils have been generated at lower temperature than the oils of the other groups. The oil fields belonging to this group are Ras Budran, October, Abu Rudeis, Belayim Land, and Belayim Marine. The oil is characterized by $\delta^{13}C$ values of satu-

rates ranging between –28.6 and –29.3‰, with low gravity and high sulfur content, and high C_{35}/C_{34} homohopanes, which is consistent with a reducing marine environment.

Group IIA Oil

The group IIA oils originated essentially from the Brown Limestone in the Rahmi, Ras Amr, Ras Bakr, Ras Gharib, and Umm Al Yusr fields. The oils have $\delta^{13}C$ values ranging between –28.8 and –29.7‰ and
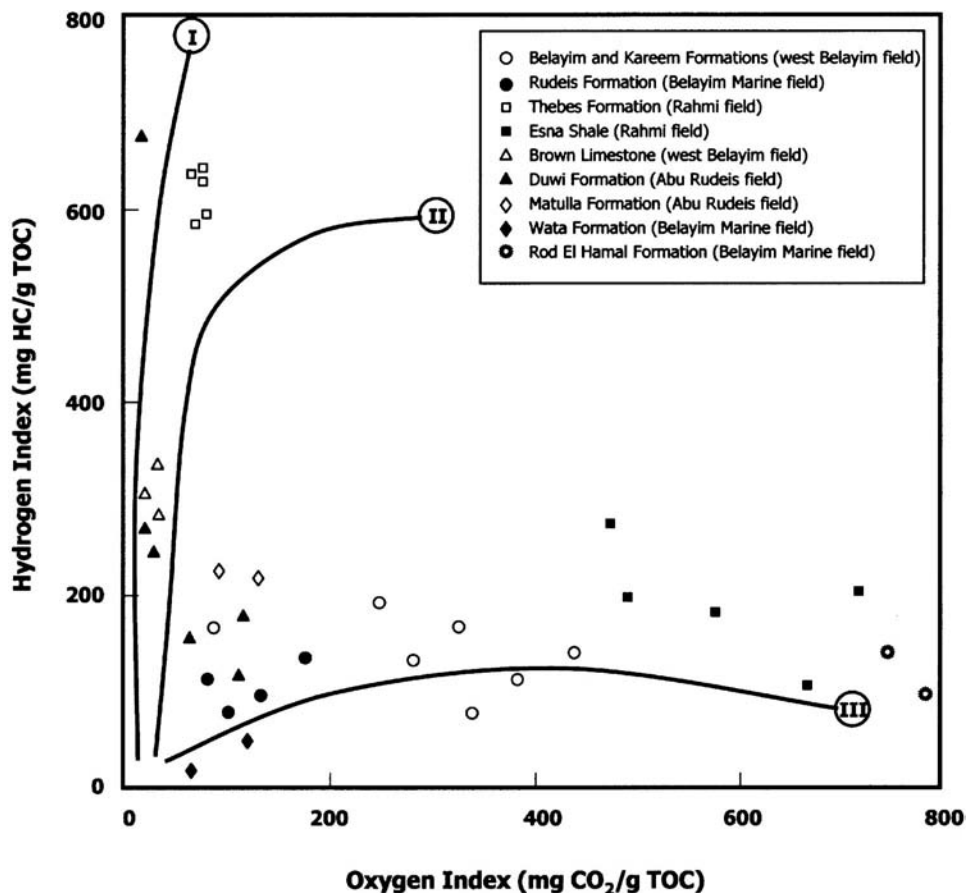
Figure 11. Van Krevelen–type plot of oxygen index and hydrogen index of different formations from different fields in the Gulf of Suez.

high sulfur content and poor quality, with lower API gravity, due to the strong reducing conditions of the source rock.

Group III Oil

The group III oils show a correlation with the Rudeis Formation and the lower Senonian Matulla Limestone. There also may be some contribution of oils generated from the Brown Limestone and the Thebes Formation. The oils belonging to this group are confined to the Ramadan, July, Morgan, Ras Gharra, Shoab Ali, Ashrafi, Ganim, Geisum, Ras Al Bahr, and Ras Shukeir fields. The oil is characterized by a $\delta^{13}C$ range between –28.1 and –29.2‰, medium to high API oil gravity, and low to medium (less than 2%) sulfur content. Pristane/phytane ratios are relatively high (>1). Steranes and terpanes show that the source rocks were deposited under less reducing conditions and have high concentration of C_{28} steranes, due to the variations in phytoplanktonic assemblages, because these source rocks are younger than those for the other oil groups in the Gulf of Suez.

The API gravity of the crude oils can be expected to decrease from south to north in the basin and from the center of the basin to the edges. Thus, oil gravity reaches 39° API in midbasin fields near the southern part of the Gulf of Suez. Crude gravity gradually decreases to 27° API at midbasin fields at the north end and also decreases to as low as 19° API at fields on the shallow basin west and east flanks (Figure 13).

Crude oil samples from some of the producing fields were geochemically investigated by Rohrback (1982), Mostafa (1993), Alsharhan and Salah (1994, 1995), and Wever (2000) to determine the number of genetically related families of oils and to evaluate maturity and migration trends. Multiple analytical parameters used to characterize the petroleum samples include API gravity, sulfur content, and crude oil composition; the distribution of C_{15+} compounds; and specific parameters (liquid chromatographic separation, gas chromatography, GC-MS, and stable isotope mass spectroscopy). Each of these parameters was tabulated and interpreted to determine the genetic relationship(s) between the studied oil samples from
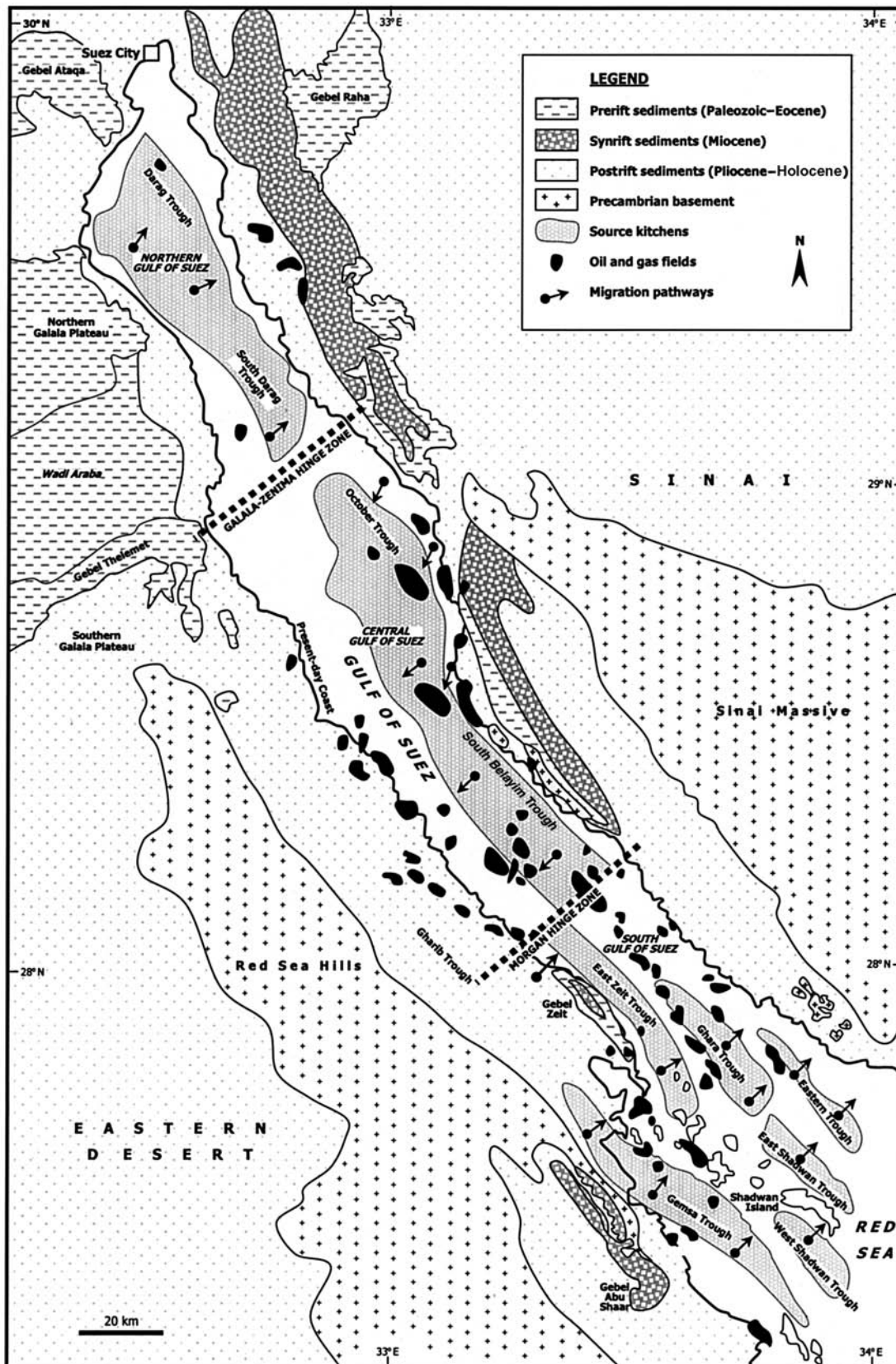
Figure 12. Major source kitchens and migration pathways of hydrocarbons in the Gulf of Suez.

different parts of the Gulf of Suez cited in previous references.

The relationship between API gravity and sulfur content is shown in Figure 14. Little variation exists in the API gravity and sulfur contents of the studied oil samples, which may reflect a common source rock. The high percentage of sulfur (>1%) indicates marine source(s). The general crude oil composition of analyzed oil samples shows no major geochemical differences (Figure 15). This supports the contention that these oils were generated from one source rock or similar source rocks. The distribution of the C_{15+} components (paraffin, naphthene, aromatic, asphalt, and the nitrogen, sulfur, and oxygen compounds) also indicates the same or similar source rocks in these fields (Figure 16). The studied oil samples from this part of the Gulf of Suez reflect a marine origin, show no apparent biodegradation, and display similar carbon isotope ratios (approximately −29‰ for the saturate and −28‰ for the aromatic hydrocarbons) (Figure 17).

RESERVOIR POTENTIAL

The Gulf of Suez is known for its multireservoir character, in that each field contains several productive reservoirs (Tables 4, 7; Figure 3). The reservoirs can be classified into prerift reservoirs and synrift reservoirs (for more details see Khalil and Meshref, 1988; Meshref et al., 1988; Tewfik et al., 1992; Alsharhan and Salah, 1994, 1995).

The Paleozoic sandstones in the Gulf of Suez are characterized by mature, well-sorted strata, which constitute one of the major prerift reservoirs in the Nubian sandstone formations. Net pay thickness reaches greater than 300 m, with known recovery factors of up to 60%. The sandstones have good porosity up to 29%, and permeabilities reached about 400 md.

The Miocene sandstones are the most important reservoir units in the Gulf of Suez, having porosities of 15–35%. Dolomitized reef limestones also have reservoir potential in the Miocene units. These facies were deposited during rotational faulting, as the early Miocene uplifted horsts along the Gulf of Suez margins shed alluvial sands into marine basins. The active faulting provided a topographic relief, which was progressively submerged by a middle Miocene transgression, allowing the development of reefs on local highs (Coffield and Smale, 1987; Smale et al., 1988). Periodic uplift of the horsts probably allowed repeated flushing of the Miocene sandstones by acidic ground waters,

creating secondary porosity by leaching of carbonate cements. At the same time, feldspars were leached to produce kaolinite cements (Coffield and Smale, 1987). The reef limestones, which are also important reservoirs, were probably dolomitized as a result of magnesium enrichment of pore waters due to removal of calcium from seawater by precipitation of the evaporites that cap the dolostones (Heybroek, 1965).

The synrift reservoirs have greater potential in the Gulf of Suez than the prerift (Table 7) because they are better preserved, more broadly distributed, and produce hydrocarbons from several formations.

Prerift Reservoirs

Fractured and Weathered Basement
Oil and gas were first discovered in the fractured basement rocks in 1981 in the QQ89 and RR89 wells (Figure 2). These days the basement is a common reservoir in the Gulf of Suez and represents about 3.2% of production potential, yielding oil/gas in eight fields (Zeit Bay, Shoab Ali, Hilal, Sidki, Geisum, Ashrafi, Hareed, and Esh El Mellaha). Porosity of the basement rocks ranges between 1 and 15%, permeability ranges between 10 and 300 md, and net pay thicknesses range between about 10 and 300 m (Salah and Alsharhan, 1998). The basement is granitic (quartz-diorite, granodiorite, syenogranite, alkali granites, and andesite porphyry) and is cut by mafic and acidic dikes. The reservoir properties depend on crystal disaggregations, caused by weathering of the basement complex, and on tectonic brecciation caused by faulting and fracturing. The reservoir characterization of the Precambrian basement depends mainly on the fractures, the diagenetic processes, and the dip and direction of the dikes and brecciated zones. The topmost section, known as the basement cover, yields the best reservoir potential, resulting from the enlargement of the fractures and their vertical interconnections and the more intensive effect of diagenetic processes.

Nubian Sandstone
The Nubian sandstone (Cambrian–Lower Cretaceous) in the Gulf of Suez is characteristically a mature and well-sorted sandstone. This facies forms one of the major prerift reservoirs and is confined to four formations (the Araba, Naqus, Qiseib, and Malha). Its net pay thickness ranges between 30 and 305 m, with the known recovery factor lying between 15 and 60%. The Nubian sandstone has a maximum-recorded thickness of about 465 m, located in the northern part. It

Table 6. Crude Oil and Bulk Geochemical Compositions in Some Gulf of Suez Fields*

| Field	Crude Oil Composition				C^{15+} Composition					Stable Isotope Ratios				
	API Gravity	% $<C_{15}$	% C_{15+}	% S	Paraffin	Naphthene	Aromatic	NSO	Asphalt	$\delta^{34}S$	$\delta^{13}C$ Saturate	$\delta^{13}C$ Aromatic	$\delta^{13}C$ NSO	$\delta^{13}C$ Asphalt
Amer	21	14.5	86	4.7	9	17	28.5	28.5	16.5	4.4	−28.8	−28	−28	−28
Bakr	13–22	6–17	83–94	4–5.3	6–9	7–17.5	25–27	26–32	20–30	2–4.5	−29.5	−28	−28	−28
Belayim Land	17–23	8–17	83–90	2.2–3.4	6–10.5	12–18.0	23–31	18–33	14–32	1.0–3.5	−29	−28	−28	−28
Belayim Marine	26–28	14–25	75–85	2	11–19	22–25	24–37	14–22	7–16	3.8	−28.8	−28	−27	−28
El Morgan	17–26	20–27	69–78	1.4	14–26	17–38	29–35	5–17	4–15	–	−28.5	−28	–	–
GS 382	30	28	72	1.3	25	26	31	9	10	–	−27	−27	–	–
July	25–33	24–36	63–76	1.2	14–27	22–34	19–34	5.5–28	2–15	0.5	−28.5	−27.5	−27	−27.5
October	26.6	23	77	2	20	23	34	9	14	–	−28.5	−28.8	–	–
Ramadan	20–28.5	21–35	65–78	1.0	20–29	27–32	20–31	7–26	2–11	0.3	−29	−27.5	−27	−28
Ras Gharib	17	18–20	81	2.5	12.5	21	30	23	13	6.5	−29	−28	−27	−28
Rudeis	25	12–21	80–88	2.2	12–18	17–22	25–37	10–30	13–18	2.6	−29	−28	−27	−28
Shaob Ali	33	36	64	1.7	24	25	35	11	5.5	–	−27.5	−27.5	–	–
Shukheir Bay	29	25.5	75	1.3	23	28	32	11	7	–	−28.5	−28	–	–
Shukheir Marine	41	47	53	0.3	25	35	20	12	7	4.0	−29	−25	–	–
Sudr	22	17	83	2.1	16.0–20	23	33–37	3.5–11	16	–	27	−26.5	–	–
Umm El Yusr	21	17	83	3	14	17	39	14	15	–	−29	−28.5	–	–
Wadi Dara Marine	45	42	58	0.4	26	37	21	9	7	5.0	−28.5	−27.5	−27	−27.5
West Bakr	18	12	88	3.7	13	13	41	11	22	–	−29	−28	–	–

*Data compiled from Rohrback (1982) and Alsharhan and Salah (1994, 1995).
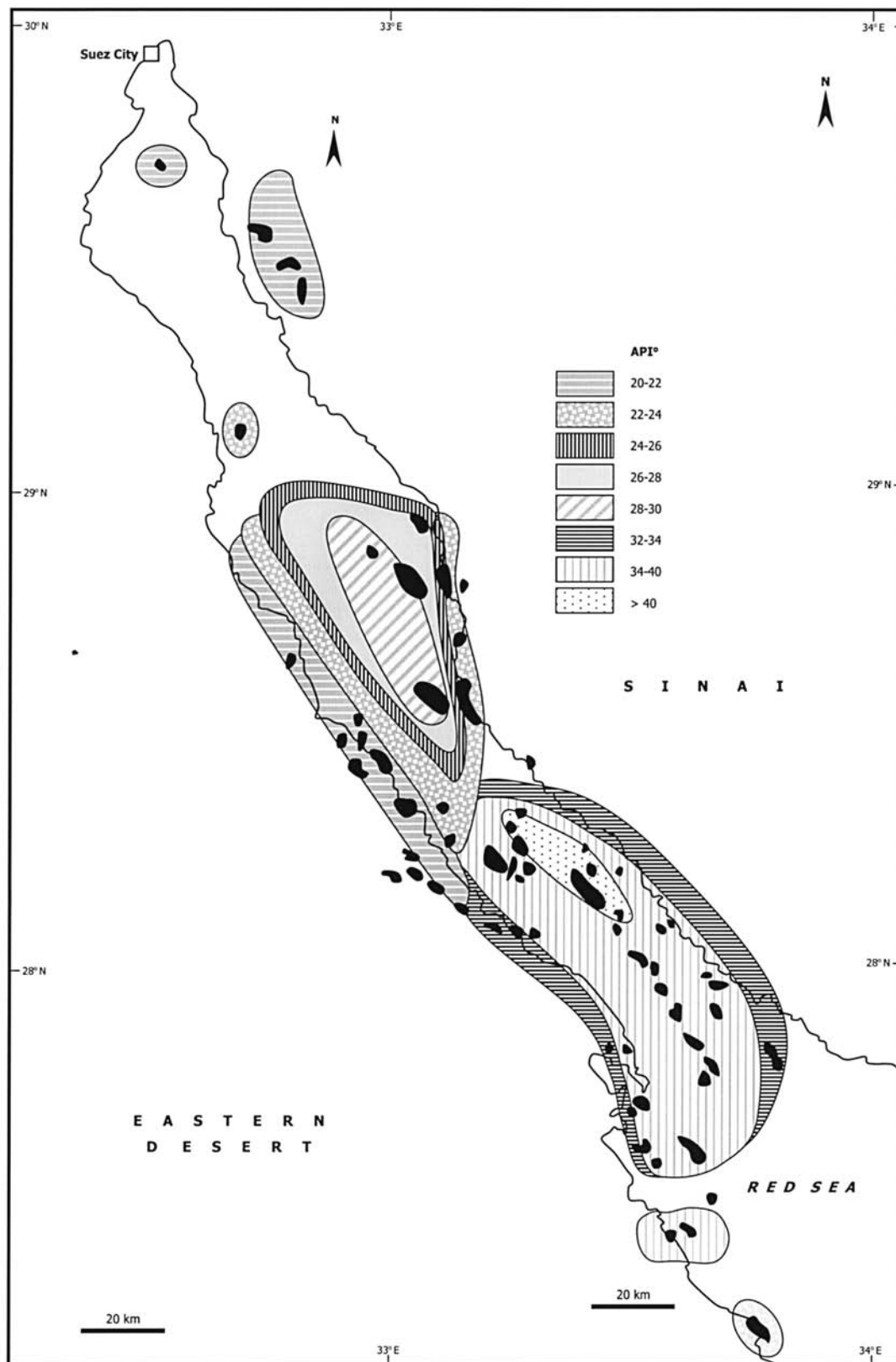
Figure 13. API gravity map of oils in the Gulf of Suez (compiled and modified from Mostafa [1993] and Alsharhan and Salah [1994, 1995]).

Figure 14. API gravity and sulfur content (wt. %) of some oil samples from main producing formations in representative fields.
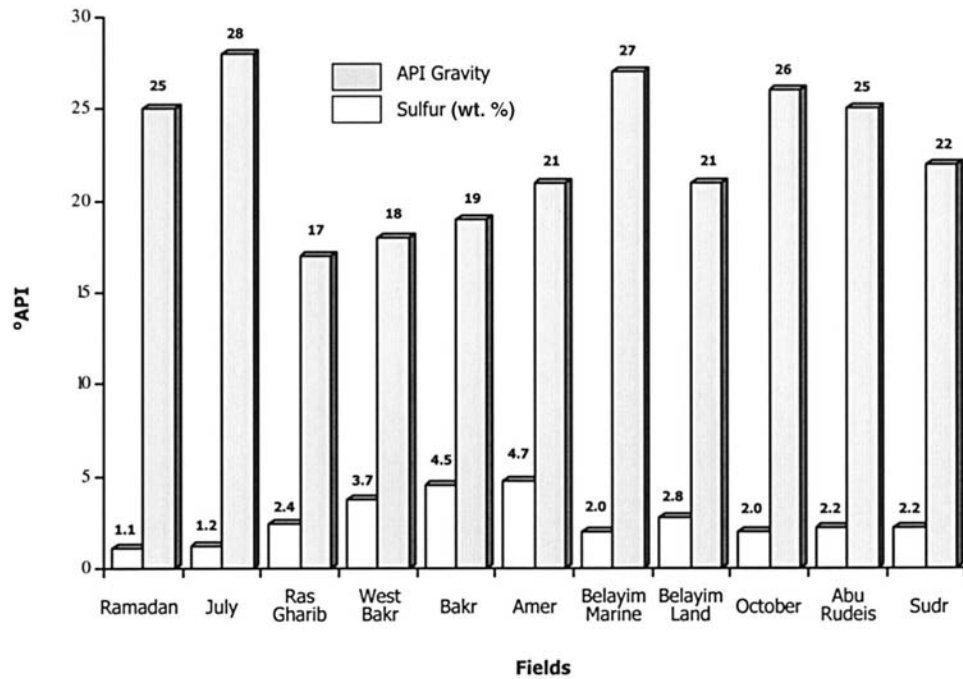
generally thins southward and is absent in most of the wells drilled in the southern Gulf of Suez area. The sandstones yield a porosity ranging from 13 to 29% and permeability from 70 to 400 md. The quality of the reservoir depends on the amount of shale, the diagenetic processes (including secondary silica dissolution and precipitation), and the depth of burial. The Nubian sandstone produces oil in many fields in the area and represents about 17% of production potential in the Gulf of Suez. Most of the Nubian sandstone res-

ervoir is quartzarenite-type with minor reservoirs of quartzwacke type.

The Araba Formation consists of sandstones with kaolinitic, illitic, and calcareous cements and is interbedded with thin siltstone. This sandstone reservoir has an average porosity of 15% and yields hydrocarbons in the Bakr and Ras Gharib oil fields with a net pay zone thickness range of 45 to 450 m.

The Naqus Formation comprises medium to coarse-grained sands and sandstones, with minor clay
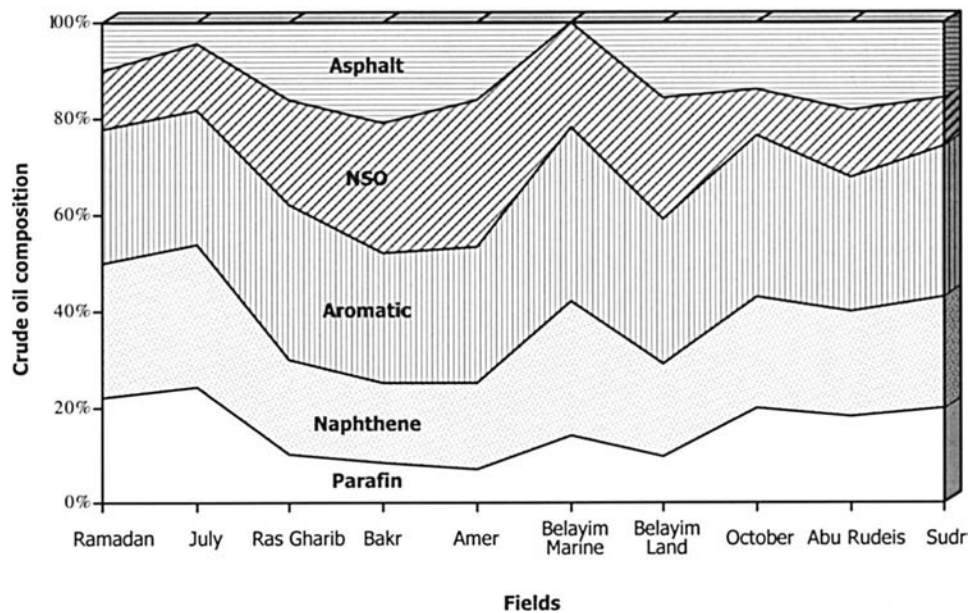
Figure 15. Crude oil composition of some oil samples for major reservoirs in representative fields.
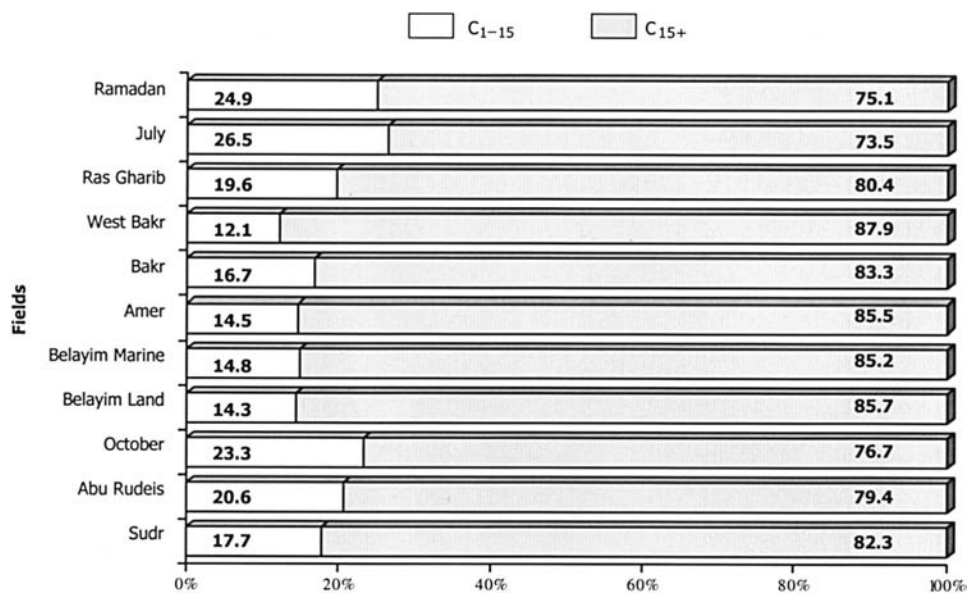
Figure 16. Distribution of C_{15+} components for some oil samples from main producing formation in each field.
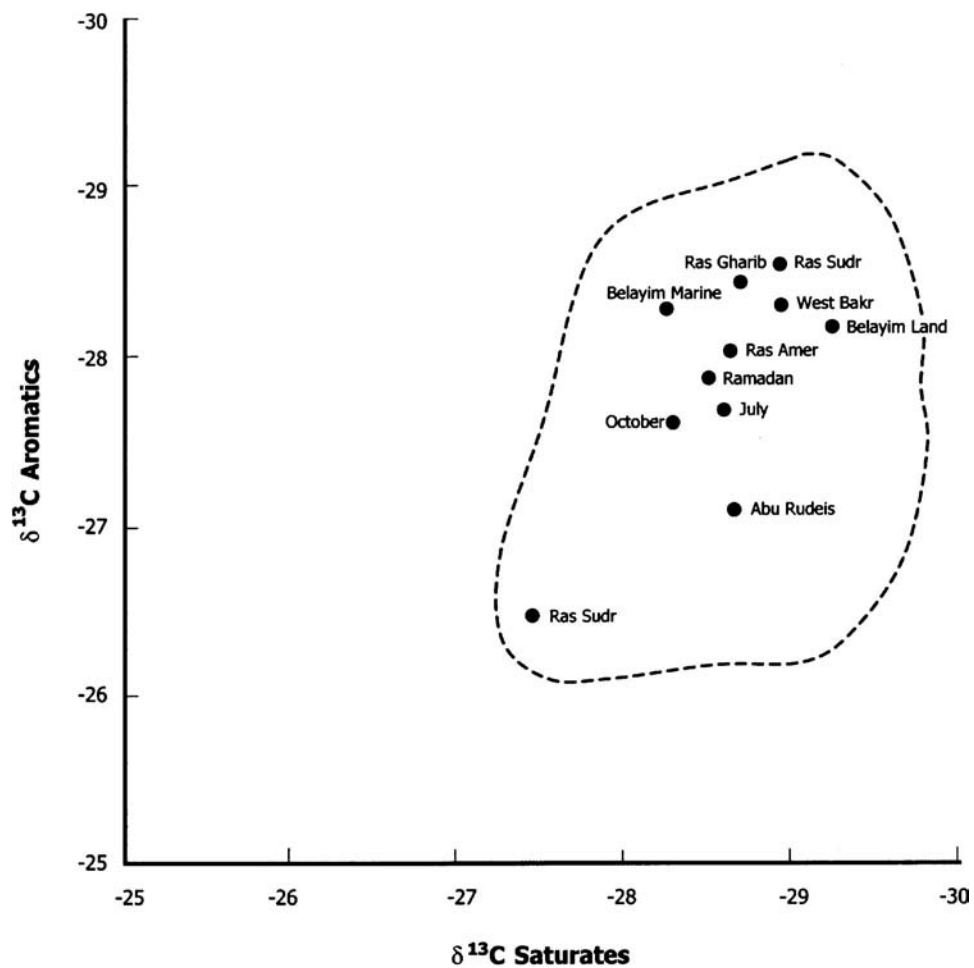
Figure 17. Aromatics/saturates carbon isotopes of some oil samples from main producing formations in representative fields.

and kaolinitic interbeds at the top of the unit. The Naqus sandstone is the main producing reservoir zone in the July, Hurghada, and Ramadan oil fields, with net pay thicknesses of 210, 340, and 230 m, respectively. These sandstones possess an average porosity of 15% and an average permeability of 250 md.

The Qiseib Formation consists mainly of a reddish, fine to coarse-grained, cross-bedded sandstone, with thin interbeds of shale. Petrographically, these sandstones are quartzarenite. The Qiseib Formation tested oil from an 18% porosity sandstone in the North Darag discovery in the northern Gulf of Suez.

The Malha Formation provides the best quality sandstone reservoir in the Gulf of Suez. The sandstones form the main producing reservoir in several oil fields (e.g., Ras Budran, July, October, Feiran, East Zeit, Hilal, Shoab Ali, Ramadan, GS 382, Ras Gharib, and Bakr). The porosity of the Malha Sandstone ranges from 13 to 28%, depending mainly on the depth of burial, kaolinite content, and silica dissolution and/or precipitation. The net pay thickness of the Malha Sandstone varies from one field to another; for example, in the October, Hilal, and GS382 oil fields it is 245, 95, and 30 m, respectively.

Nezzazat Group

The Nezzazat Group includes the Matulla, Wata, Abu Qada, and Raha sandstones, which provide about 1% of production potential, and produces oil from several fields, such as the Belayim Marine, October, Ras Budran, Abu Rudeis/Sidri, Feiran, Bakr, Ras Gharib, Amer, Kareem, July, Ramadan, Sidki, Shoab Ali, Zeit Bay, Geisum, and Bahr fields. Porosity ranges between 15 and 23% and permeability between 100 and 250 md. The quality of the reservoir depends on the depth of the sandstone and the amount of argillaceous matter and/or calcareous cement.

Thebes Formation

The Thebes Formation contributes about 1.1% of production potential and produces from the Sudr, Asal, Ras Matarma, Bakr, West Bakr, Kareem, Rahmi, Issaran, and Shoab Ali fields. It consists of fractured marine carbonates with an average porosity of 13% and net pay thickness of 15–17 m.

Synrift Reservoirs

Nukhul Formation

The Nukhul sandstone is well developed in the Gulf of Suez, but is locally absent, particularly in places that remained structurally high or emergent until later times. The Nukhul Formation thins toward the margins of the Gulf of Suez and reaches its maximum thickness in the central offshore area. It represents about 11.5% of production potential and produces oil from the Rudeis, Sidri, Shoab Ali, GS 173, Zeit Bay, Hilal, Ashrafi, Gemsa SE, and Darag fields and oil and gas from Hareed field. The sandstone is conglomeratic in parts and yields porosities ranging between 17 and 25%. The Nukhul carbonates of reefal origin produce oil from three fields (Al Ayun, Kareem, and Zeit Bay) and oil and gas from the Felefel field. The average porosity of these carbonates is 16%. The net pay thickness of the Nukhul reservoirs in these fields ranges from 20 to 60 m.

Rudeis Formation

The Rudeis reservoirs are present over most of the study area and represent about 20% of production potential in the Gulf of Suez. The Rudeis sandstone has produced oil from fields such as the Shoab Ali, East Zeit, Ashrafi, GH376, Amal, Asal, Belayim Marine, Belayim Land, Al Ayun, July, Kareem, Matarma, Sudr, Morgan, Kheir, and Umm El Yusr and has tested gas from the Felefel field. The net pay thickness of the reservoir ranges between about 15 and 30 m in the south, whereas in the north the range is 20 to 75 m. The porosity ranges between 13 and 26%, and permeability lies between 10 and 1000 md. The Rudeis carbonates are producers of oil in the Zeit Bay, Bahr, Sudr, Asl, and Matarma fields and of gas in the Felefel field, with an average porosity of 16%. These carbonates are particularly well developed in submerged high areas within the lower Miocene basin, such as in the North Bahar area.

Kareem Formation

The sandstones of the Kareem Formation are one of the most important reservoir lithologies in the Gulf of Suez Basin and produce and/or test oil from many oilfields (including Morgan, Belayim Land and Belayim Marine, Amal, Kareem, Badri, Zeit Bay, East Zeit, Shoab Ali, Hilal, Sidki, Geisum, Ashrafi, GH376, Bahr, Warda, Kheir, Hareed, and Esh El Mellaha). Of ten potential reservoir units in the basin, almost 23% of the oil is produced from the Kareem Formation sandstones. Their net pay thicknesses range between 10 and 200 m, porosities range from 7 to 33%, and permeabilities range from 20 to 730 md. Overall reservoir quality depends on the shale content, the importance of diagenetic processes, such as silica

dissolution and precipitation, and the depth of burial. Three major alluvial fans of sand belonging to this formation are recorded in the Gulf of Suez: (1) a northern fan, with 14% average porosity and sediment being derived from Gebel Zeit; (2) an eastern fan, with 25% average porosity and sediment derived from the Sinai massif; and (3) a southern fan, with 20% average porosity and sediment derived from the Esh El Mellaha range. The Kareem carbonate reservoir has good secondary porosity and contains gas in the Felefel field.

Belayim Formation

The Belayim reservoir contains about 10.5% of the oil produced in the Gulf of Suez. The Belayim sandstones (Sidri and Hammam Faraun members) produce oil in the following fields: Belayim Land, Belayim Marine, Ras Fanar, Shukeir, Shoab Ali, Esh El Mellaha, and Morgan. Two component sandy alluvial fans were recorded in the study area, one in the east and the other in the west, which were the main source of clastics for this formation. The Belayim sandstones have an average porosity of 16%, with thicknesses ranging from about 8 to 35 m. The Belayim carbonates are more important in the Gulf of Suez than the Belayim sandstones. The Belayim carbonates are reefal buildups on fault-controlled highs and have porosity ranging between 10 and 19%. The average net pay thickness of the Belayim carbonates is about 9 to 12 m. Oil and gas were produced from the Esh El Mellaha field, oil from the Ras Fanar field, and gas from the Hareed and Felefel fields.

Zeit and South Gharib Formations

The upper Miocene sandstones of the Zeit and South Gharib formations have locally proved potential in the Belayim Land, Belayim Marine, and Ras Fanar oil fields. They are thin (not exceeding 15 m) and possess an average porosity of 18%. The Zeit and South Gharib sandstones have not been recorded as producing zones elsewhere in the Gulf of Suez. The first Miocene reefal limestone, the Ras Gharib Formation, was reported from the Gemsa field by Bowman (1931, cited in El Ayouty, 1990). The oil was present in limestone and dolomitic limestone interbeds within evaporitic sections of this formation.

Postrift Reservoirs

The Quaternary sandstones are included in the reservoir lithologies in the Gulf of Suez and have been found to be oil-bearing only in the Abu Durba field.

The average net pay thickness in this field is 15 m. Sandstone porosities range from 16 to 33%, and their permeabilities range from 20 to 730 md. The good reservoir quality of these strata is a result of shallow depths of burial (<1000 m). The overall reservoir quality depends on the shale content and the importance of diagenetic processes, including silica dissolution and precipitation. Most of the Quaternary clastic strata in the southern and central parts of the Gulf of Suez are derived from eroded basement rocks flanking the Gulf. Erosion of horsts within the Quaternary basin partly contributed to sand accumulation. However, some of these highs have acted as a barrier, effectively preventing the advance of prograding alluvial fans. Most sand bodies are developed adjacent to these highs, and in some places overstep the highs.

SEALS

Horizons of caprock beds (such as shales, evaporites, and dense limestones) are abundant throughout the stratigraphic column in the Gulf of Suez. The Miocene evaporites in the Gulf of Suez may exceed 3 km in thickness and pass laterally from paleohighs into shallow-water carbonates via dolomitic and gypsiferous marls (Heybroek, 1965). The evaporites have provided the essential element for the retention and preservation of oil accumulations. They represent excellent seals for shallow-water limestone reservoirs and were deposited as onlapping anhydritic evaporites during progressive eastward basinal collapse and ongoing late-stage rifting events. Within the synrift sequence, however, the Miocene evaporites are considered to be the ultimate seal for reservoir rocks in the Gulf of Suez (Rashed, 1990). This is particularly true in the southern and central Gulf of Suez, where the evaporites are generally thick, either on the downthrown side of major Clysmic faults or in the downdip direction of uplifted tilted fault blocks. However, the magnitude of throw on the Clysmic faults is a critical factor in the effectiveness of the sealing mechanism (Meshref et al., 1988). A small throw juxtaposes the evaporite section, on the downthrown side, against the Miocene porous section on the uplifted block. A large throw brings the Miocene evaporites in juxtaposition with the pre-Miocene reservoirs on the uplifted block, as shown at the Hilal, Belayim Marine, and Belayim Land fields (Saoudy, 1990).

The Miocene clastic section, such as the Rudeis and Kareem formations, can act as seals especially in areas where some shaly facies have developed. In such

Table 7. Hydrocarbon Habitat, Mode of Migration, and Trapping Mechanism in Miocene Gharandal and Ras Malaah groups

Reservoir		Source Rock	Cap Rock (Seal)	Mode of Migration	Trapping Mechanism	Examples
Formation	Lithology					
Belayim, Kareem, and Rudeis	Sandstone with minor limestones, shale, and anhydrite	Kareem and Rudeis	Mudstone and evaporites vertically and laterally	Sourced across/up faults, then updip with possible direct/vertical migration from interbedded mudstone/ carbonate source beds	3-way dip closed, fault-bounded trap	El Morgan, Badri, and Amal fields
Belayim, Kareem, and Rudeis	Clastics in multireservoir stacked sequence	Rudeis	Individual sands sealed by interbedded mudstone	Lowermost reservoir in direct (erosional) contact with prerift accumulation, vertical, fracture migration within sands	3-way dip, fault closure	Belayim Marine and Shoab Ali fields
Belayim, Kareem, and Rudeis	Sandstones with minor limestone, shale, and anhydrite	Nukhul	Sealed by surrounding mudstones	Sourced by combination of direct access from synrift source and/or vertical/upfault migration from prerift source beds	Stratigraphic pinch-out trap	Umm El Yusr and El Ayun fields
Belayim, Kareem, and Rudeis	Sandstones with thin interbedded anhydrite and intercalated shale	Kareem and Rudeis	Sealed vertically by interbedded mudstone and laterally by change to tighter lithologies	Sourced by cross-fault and updip migration from prerift source beds	Stratigraphic trap formed by lateral facies change to mudstone/ wackestone	Esh Mellaha field

Belayim and Kareem	Sandstones with minor limestones and shale	Kareem	Sealed vertically and laterally by evaporites	Migration vertically through Rudeis and Kareem formations, up faults from prerift and synrift source beds	Fault-bounded horst	GH375 and Kheir fields
Belayim and Rudeis	Carbonate reefal buildup, evaporite with minor shale	Belayim	Sealed by overlying/ draped mudstones or evaporites	Sourced from subcropping prerift and/or upfault/updip contribution	Combination fault block trap and stratigraphic trap	Ras Fanar, Zeit Bay, and Gemsa fields
Rudeis	Sandstones with interbedded shale and limestone	Rudeis	Updip migration sealed by upper part of the Rudeis Formation, both laterally and vertically	Sourced by cross-fault juxtaposition with prerift sediments	Eroded/faulted at mid-Clysmic unconformity to produce geomorphic/faulted trap	July field
Nukhul	Interbedded sandstones with limestone and highly calcareous shale	Nukhul	Sealed both laterally and vertically by Nukhul/Rudeis mudstones	Direct communication with underlying Thebes source beds	Combination onlap/ fault bounded	East Zeit and Hurghada fields
Nukhul	Clastics with minor carbonates and shales	Nukhul	Vertical sealing by overlying tight formations	Sourced by upfault migration	Trapping by hydrocarbons as a result of updip formation of tar mat by biodegradation of earlier generated oil	Ekma and Gazwarina fields
Zeit, South Gharib, Belayim, and Nukhul	Clastics, salt, and anhydrite interbed	Rudeis	Sealed by overlying mudstones/evaporites	Sourced by upfault migration. Spill may be controlled by faults	4-way dip closed (rollover anticline) structure	Belayim Land, Garra Marine, and Shukheir fields

cases, porous intervals within the formation act as reservoirs, whereas the shaly intervals become vertical and/or horizontal seals, depending on the magnitude of the throw of the fault. The Miocene shales also are an important factor in stratigraphic traps, where they confine a body of sandstone as a lateral facies variation.

The prerift Cretaceous carbonates (Brown Limestone and Sudr), the Paleocene Esna Shale, and the Eocene Thebes limestone formations can act as vertical seals over the Cretaceous sandstone reservoirs.

HYDROCARBON ENTRAPMENT

The main trap types are due to rotational faulting and related unconformities. Porous Carboniferous, Cretaceous, and Eocene facies in the footwalls of the basin-edge half grabens have been faulted against and are sourced by middle Miocene marls. Unconformity traps occur in the eroded formations at the tops of horsts and in onlapped Miocene reefs, which cap the horsts. Drape anticlines above buried horsts provide traps in many of the later Miocene reservoirs. Small cross faults, related to transfer faults, cut the horsts to produce prospective trap door structures (Clifford, 1987). The main directions of the fractures affecting these basement rocks are northwest-southeast, northeast-southwest, and east-northeast–west-southwest. Several mechanisms for hydrocarbon entrapment are recorded in the Gulf of Suez. These are structural, stratigraphic, and combination traps, as reported by Meshref et al. (1988), Tewfik (1988), Zahran and Meshref (1988), El Ayouty (1990), Rashed (1990), Saoudy (1990), Hammouda (1992), Alsharhan and Salah (1994, 1995), and Salah and Alsharhan (1998). These are summarized in the following sections and in Table 5.

Structural Traps

In the Gulf of Suez, most oil accumulations are trapped structurally. The following are examples of these traps.

Both the prerift and synrift reservoirs produce oil from fault-related traps where the reservoir is laterally and vertically confined by a down-faulted overlying seal. Hydrocarbons in this type of trap are from either prerift sources across synthetic faults (e.g., October, Belayim Land, Morgan, Geisum, and Shoab Ali fields) or the underlying prerift or synrift sources, as in the Hilal, East Zeit, Ramadan, and Ras Badran fields.

Closures induced by intersection of several Clysmic faults are exemplified by the traps in the Ramadan field, where such intersecting faults determine additional producing compartments. In several fields, such as the Belayim fields, drape over fault-block boundaries produced by differential sediment compaction in synrift formations has generated asymmetrical anticlines overlying a faulted high with hingeline or associated flexures.

In the Belayim Marine and Zeit Bay fields, a four-way dip closure trap has formed as a hanging-wall anticline, related to thrusting of Miocene strata. This trap is sealed vertically by intraformational mudstones or Miocene evaporites, with sources lying across or in the upfault direction from prerift source rocks. Draping over fault-block boundaries created by differential sediment compaction over the crests of blocks is common in synrift formation. Such traps are found in the Belayim Land and Belayim Marine fields. A subtle trap occurs as flat lying areas between two grabens or two horst structures, such as in South Ramadan field.

Stratigraphic Traps

Stratigraphic traps have recently become important targets for hydrocarbon exploration in the Gulf of Suez in general. There are some proven stratigraphic traps at the Ras El Bahar discovery, where the Miocene porous carbonate wedge is sealed vertically and laterally by a facies change to dense carbonate. In the Belayim Land field, Miocene porous sandstone is present as lenses that are sealed vertically and laterally by a facies change to evaporites. Oil sources lie across faults or are located updip from the prerift sections. A stratigraphic trap occurs in well-developed Miocene reefal limestone on the eastern flank of the Ras Gharib field. In the Gemsa field, a basement horst is capped by Miocene and younger strata. In the lower part of the Miocene, a reefal limestone developed, within which oil accumulated. This reefal limestone is surrounded by fossiliferous, organic-rich shales, which also surround the basement horst (Bowman [1931] cited in El Ayouty [1990]).

Truncations below an unconformity are recognized in prerift strata cut by the basal rift unconformity or in Miocene strata cut by the intra-Miocene unconformity, as in the Ras Gharib and July fields. Onlap pinch-out can be seen where the sandstones of the Nukhul Formation are overlain by transgressive shales, on the flanks of tilted blocks in the Ekma,

Ras Bakr, and Abu Rudeis fields. Updip pinch-out of sand lenses within the Kareem and Rudeis formations has developed on the flanks of some structures. These pinch-outs have irregular patterns, and such rapid changes in thickness and lateral facies represent good stratigraphic traps in the Umm El Yusr and El Ayun fields. Some block crests composed of weathered and fractured basement rocks contain oil accumulations in the Shoab Ali, Zeit Bay, and Hurghada fields.

Combination Traps

There are two proven cases of combination traps. (1) In the Shoab Ali, Asl, Sudr, and Ras Matarma fields, the Eocene limestone is both reservoir and source, with an updip contribution from the Upper Cretaceous carbonates and sealed by synrift mudstones. In these fields some of the synthetic faults act as sealing faults. (2) In the RR89 discovery and the Ras Gharib field, a reef reservoir deposited on a fault-controlled high is sealed by Miocene evaporites. The hydrocarbon source was a prerift source rock with a long migration range. These reefs possess very high porosity (up to 30%), as in the Miocene reef complex at Gebel Abu Shaar. Reefal buildups accumulated on the crests of some blocks and have good petrophysical properties due to dolomitization and fracturing. These can be seen in the Ras Bakr field.

SUMMARY FACTORS RESPONSIBLE FOR THE HYDROCARBON POTENTIAL

Several common factors that we believe are important for the development and occurrence of hydrocarbons in the Gulf of Suez rift basin are summarized in the following list.

- Composite maximum thickness of the strata is about 8000 m. The sequence comprises lower Paleozoic sandstone of terrestrial origin and carboniferous shales of marine origin. Mesozoic and Paleocene–Eocene units were essentially uniform in a marine platform environment of mainly carbonates, with subordinate sandstones and shales, Oligocene red beds, Miocene marls, sandstones and evaporites, Pliocene clastics, and Quaternary carbonates.
- Large traps were formed by anticlines over predepositional highs and by reservoir beds within the predepositional highs. The traps commonly have an

areal extent of a few square kilometers and are fault controlled. They accommodate the oil fields formed during the late Tertiary.
- Since the formation of traps (most of them during the Miocene), no later major tectonic events have occurred, except for basaltic extrusions in the Oligocene, before the deposition of the source rocks. After that, minor vertical uplift and strike-slip movements occurred.
- Major disconformities occur within and at the top of the Nubian sandstone during the Permian–Triassic and Jurassic, at the top of the Cretaceous, at the top of the Eocene, at the base of the Gharandal Group, and within the Miocene.
- Significant oil has accumulated in strata ranging in age from Paleozoic to Eocene, but the largest oil accumulations occur in Miocene strata.
- Highly organic-rich marls and shales were deposited during the Late Cretaceous and Miocene. These rocks encase the uplifted blocks, which acted as a major source for giant traps, and filled these with hydrocarbons in highly porous and permeable reservoirs.
- A thick evaporite sequence (up to 2000 m) was deposited during the Miocene. Salt flowage has been an important factor in sealing active faults to prevent oil migration. This thick evaporite sequence was deposited above the reservoirs and forms an effective caprock.
- A higher than normal geothermal gradient is present due to the processes of rifting, crustal thinning, diabase dike intrusions, and thick salt deposits.

POTENTIAL PLAYS

The geologic controls on the distribution of hydrocarbons in the Gulf of Suez are based on the areal extent and richness of potential source rock, tectonic subsidence, and excellent seals (e.g., evaporite) that accelerated hydrocarbon formation and redistribution. Figure 18 represents a typical model of trap mechanism and formation in the southern Gulf of Suez. The following is a summary of potential plays.

- Fractured and karstified limestone reservoirs lie below the Rudeis Limestone unconformity or where there is intense folding in the hanging wall. Hydrocarbons could migrate from surrounding Rudeis source rocks, up faults from prerift strata, and be sealed by surrounding mudstones.
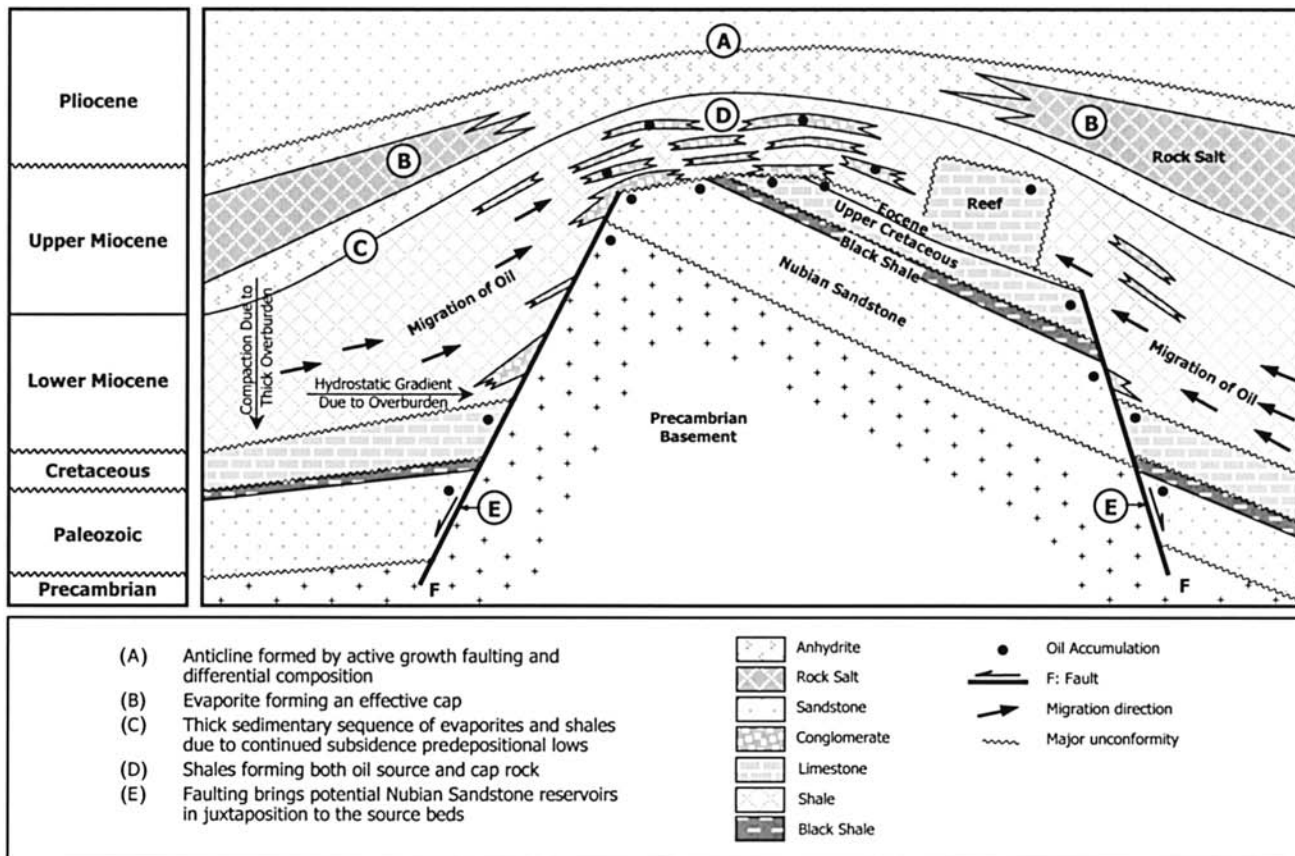
Figure 18. Formation of typical oil field in the Gulf of Suez (modified from O'Connor and Kanes, 1984).

- Belayim reefal buildups have developed as carbonate talus in the hanging wall of major faults. These carbonate reservoirs are sourced by lateral potential sequences or underlying prerift sequences and are sealed by overlying mudstones and laterally by impermeable units in the footwall.
- In the southeast Gulf of Suez, the reservoir in clastics of the lower Belayim Formation and also an intra-evaporite event, which represents a subcrop/unconformity play, could have been sourced by vertical or upfault migration and sealed above and below by mudstones and evaporites.
- Clastic reservoirs in the Zeit and South Gharib formations occur in structural traps formed by salt diapirism/piercement. Hydrocarbons migrated up along faults from deeper sources and were sealed laterally by salts and vertically by evaporites or mudstones.
- There are possibilities for finding new prerift structures near and associated with prominent fault systems with large throws. The prerift reservoirs are not

in contact with the overlying rift source beds unless there are large throws on the faults.
- Prerift reservoirs have not been fully tested by deeper drilling on several older fields. Among these, early discoveries are producing only from the first production encountered, which is commonly synrift (Miocene reservoirs).

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