

Egypt in the Twenty-First Century: Petroleum Potential in Offshore Trends

John C. Dolson, Mark V. Shann,
BP Amoco Corporation, Egypt
Sayed I. Matbouly, Egyptian General Petroleum Corporation
Hussein Hammouda and Rashed M. Rashed,
Gulf of Suez Petroleum Company

ABSTRACT

Since the onshore discovery of oil in the Eastern Desert in 1886, the petroleum industry in Egypt has accumulated reserves of more than 15.5 billion barrels of oil equivalent. An understanding of the tectono-stratigraphic history of each major basin, combined with drilling history and field-size distributions, justifies the realization of the complete replacement of these reserves in the coming decades. Most of the increase in reserves will be the result of offshore exploration.

In addition to the 25 trillion cubic feet already discovered, the offshore Mediterranean may hold 64 to 84 trillion cubic feet and the onshore Western Desert may contribute 15 to 30 trillion cubic feet in new gas resources. Many of the new fields are expected to be in the giant-field class that contains greater than 100 million barrels of oil equivalent. Challenges include sub-salt imaging, market constraints for predominantly gas resources and economic constraints imposed by the high cost of development of the current deep-water gas discoveries that are probably unique worldwide. The offshore Gulf of Suez may yield an additional 1.5 to 3.3 billion barrels of oil equivalent, but it continues to be technologically constrained by poor-quality seismic data. Advances in multiple suppression and development of new 'off-structure' play concepts with higher quality seismic data should result in continual new pool discoveries. Offshore frontier exploration includes the Red Sea rift (currently under reassessment with area-wide 3-D surveys) and the Gulf of Aqaba. Deep-water and sub-salt imaging remain significant challenges to be overcome.

Despite a relatively complex history, the Phanerozoic geological framework of Egypt is extremely prospective for oil and gas. Eight major tectono-stratigraphic events are: (1) Paleozoic craton; (2) Jurassic rifting; (3) Cretaceous passive margin; (4) Cretaceous Syrian Arc deformation and foreland transgressions; (5) Oligocene-Miocene Gulf of Suez rifting; (6) Miocene Red Sea opening; (7) the Messinian salinity crisis; and (8) Pliocene-Pleistocene delta progradation. Each of these events has created multiple reservoir and seal combinations. Source rocks occur from the Paleozoic through to the Pliocene and petroleum is produced from reservoirs that range in age from Precambrian to Pleistocene. The offshore Mediterranean, Gulf of Suez and Red Sea/Gulf of Aqaba contain significant exploration potential and will provide substantial reserve replacements in the coming decades.

INTRODUCTION

In spite of more than 100 years of petroleum exploration, large parts of Egypt remain under-explored. The Gulf of Suez, Nile Delta, offshore Mediterranean and greater Western Desert basins (Figure 1) are the only basins that have been proven to contain economically viable petroleum. At least six sedimentary basins are present in Upper Egypt that have had little or no hydrocarbon exploration activity. However, the hydrocarbon potential of Upper Egypt was shown when, in 1997, Komombo-1 in the Komombo basin tested live oil from Jurassic reservoirs (Dolson et al., 2000).

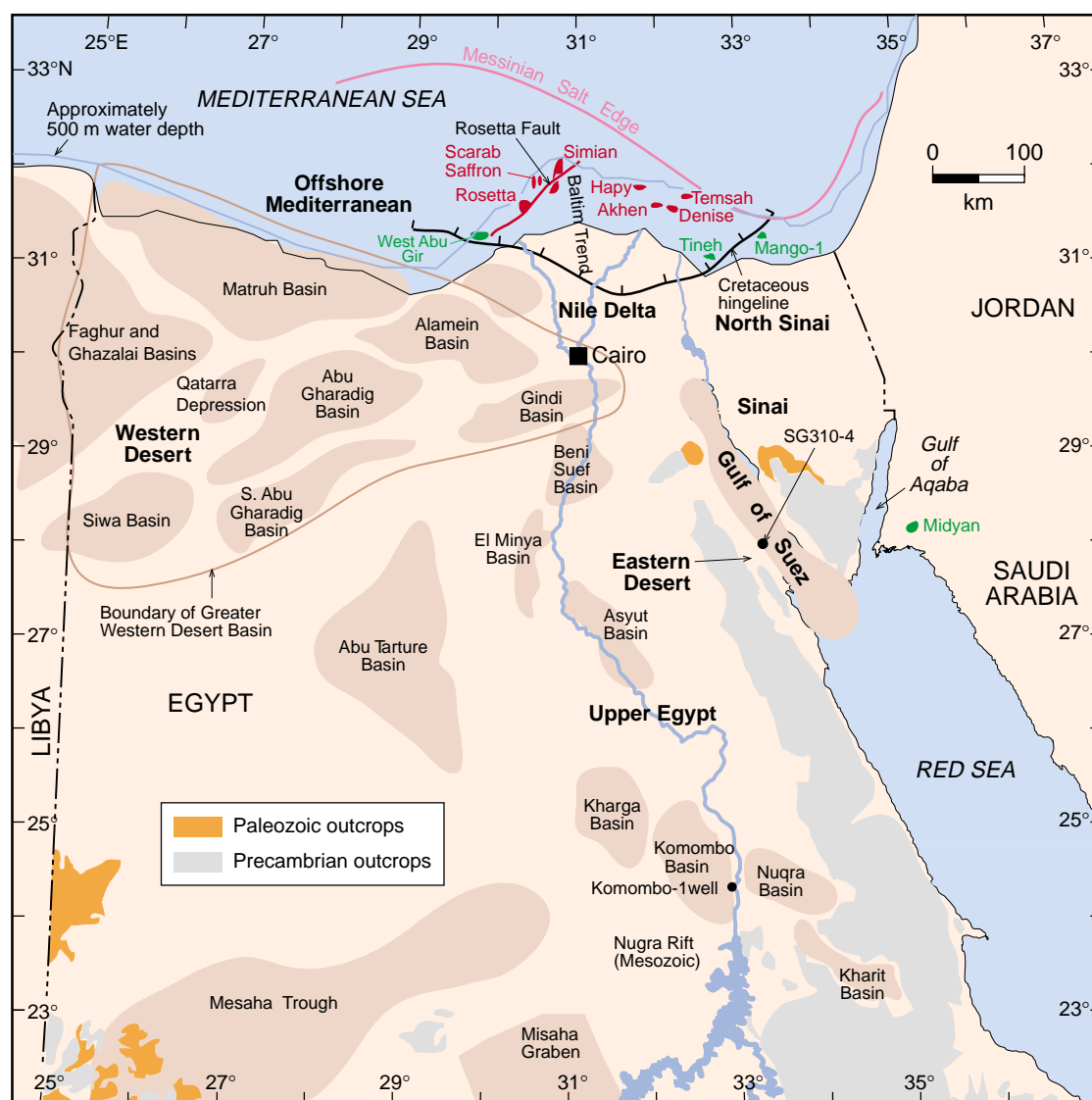


Figure 1: Index map of the sedimentary basins of Egypt (modified from Dolson et al., 2000)

Although Egypt is one-third larger than the state of Texas in the USA, only 1,754 exploratory wells have been drilled in Egypt—an insignificant number compared to the several hundred thousand wells of various kinds drilled in the search and production of oil and gas in Texas. Of the 1,754 wells, only 245 have penetrated to the Precambrian basement. Nevertheless, these exploratory tests have resulted in the discovery of 30 giant oil and gas fields (greater than 100 million barrels of oil equivalent (MMBOE)), seven of which were found in the late 1990s (Table 1). In addition, a substantial number of significant discoveries of up to 100 MMBOE have also been made.

This paper is a shortened version of Dolson et al. (2000) and focuses in more detail on both the onshore and offshore growth potential. It not only summarizes the work of Dolson et al. (2000) but also concentrates on challenges in the development of deep-water hydrocarbon reserves in the Mediterranean, Red Sea and Gulf of Suez petroleum provinces.

We have analyzed Egypt's geological history in the context of eight major tectono-stratigraphic sequences (Figure 2) that have created major petroleum systems. The following are key references that deal with the petroleum systems and geology of Egypt and surrounding areas: Dixon and Robertson (1984); Said (1990); Sadek (1992); Halbouty and El-Baz (1992); Morris and Tarling (1996); MacGregor et al. (1998); Traut et al. (1998); Purser and Bosence (1998) and Wycisk (1994). They provide valuable insights into the major tectonic events that can explain the pattern of unconformity development shown in Figure 2.

Table 1:
Significant Exploratory Tests in the 1990s

WELL	COMPANY	REGION	LAT.	LONG.	YEAR	CLASS	COMMENTS	AGE AT TD	TD (m)
KHARIT-1	Repsol	Upper Egypt	23.5155	34.3507	1998	Dry hole	P & A; established presence of new basin in Egypt	Precambrian	2307.53
KOMOMBO-2 ST	Repsol	Upper Egypt	24.6543	32.8083	1998	Dry hole	P & A; established presence of new basin in Egypt	Precambrian	2651.63
KOMOMBO-3	Repsol	Upper Egypt	24.5995	32.7390	1998	Dry hole	P & A; established presence of new basin in Egypt	Precambrian	1281.32
NUJRA-1	Repsol	Upper Egypt	24.4208	33.4982	1997	Dry hole	P & A; established presence of new basin in Egypt	Precambrian	2549.53
KOMOMBO-1	Repsol	Upper Egypt	24.6665	32.8064	1997	Dry hole	Tested oil in Jurassic; proved viability of new basin in Upper Egypt	Precambrian	2579.00
BENI SUEF-1X	Seagull	Upper Egypt	29.1533	30.8738	1997	Discovery	Oil discovery (Kharita and Bahariya); southernmost Egypt oil extension	Precambrian	3388.60
BENI SUEF-4X	Seagull	Upper Egypt	29.1533	30.8858	1998	Discovery	Oil well in Creataceous; southernmost Egypt oil extension	L. Creataceous	2197.50
BENI SUEF-5X	Seagull	Upper Egypt	29.1532	30.8801	1998	Discovery	Wells Bahariya and Kharita T and A.; southernmost Egypt oil extension	L. Creataceous	2256.63
ASHRAFI SW-3	Agiba	Gulf of Suez	27.7762	33.7089	1998	Discovery	Nubia oil; significant southern extension of pay in Gulf of Suez	Precambrian	1904.91
E.TANKA-3 (ET-A1)	Amocco	Gulf of Suez	28.9845	32.9443	1996	Discovery	New field discovery of downthrown Asl sand trap; IP 10,000 BOPD	Burdigalian	2834.50
GS 18 -2	Gupco	Gulf of Suez	28.8794	33.0264	1994	Discovery	New field discovery of downthrown Asl sand trap; offset flows 15,000 BOPD	Burdigalian	3554.71
RABEH-1	Coplex	Gulf of Suez	27.2229	33.7466	1997	Discovery	6,800 BOPD Nukhul and Matulla (Nezzazat); Significant southern extension of production	Precambrian	
SG 310-4	Gupco	Gulf of Suez	28.2532	33.2251	1998	Discovery	Asl and Hawara formation (Burdigalian); flows 20,000 BOPD	Burdigalian	3230.72
SG 310-6A	Gupco	Gulf of Suez	28.2498	33.2100	1999	Discovery	Asl and Hawara formations; significant small field discovery on new fault block	Burdigalian	4462.05
WARDA	British Gas	Gulf of Suez	29.1900	32.7063	1991	Discovery	40+ MMBO oil field discovery beyond limits of Belayim Salt; topseal from Kareem and Rudeis Fm.	Langhian	2752.21
AKHEN-1	Amoco	Mediterranean	31.9067	31.9213	1996	Discovery	New Serravalian field discovery (350-700 BCF)	Burdigalian	4421.82
BALTIM E-1	IEOC	Mediterranean	31.7748	31.2449	1993	Discovery	New Messinian valley fill trend extension (500-800 BCF)	Serravalian	3911.92
DENISE-1	IEOC	Mediterranean	31.8705	32.0959	1995	Discovery	Pliocene gas discovery (750-900 BCF)	Pliocene	2402.93
EL TEMSAH NW-1	IEOC	Mediterranean	31.8619	32.1233	1996	Discovery	Significant Serravalian pay extension	Burdigalian	4019.81
HAPY-1	Amoco	Mediterranean	31.9197	31.8544	1996	Discovery	Giant Pliocene gas discovery (1,500-2,500 BCF)	Pliocene	1861.93
PFM SW-1"ST"	Petrobel	Mediterranean	31.5506	32.4446	1998	Discovery	Pliocene gas discovery Port Fouad SE (350-500 BCF)	Pliocene	3985.98
ROSETTA-3	British Gas	Mediterranean	31.8408	30.6282	1997	Discovery	Giant Pliocene gas discovery (1,500-2,000 BCF)	Pliocene	1943.92
SAFFRON-1	British Gas	Mediterranean	32.1047	30.5344	1998	Discovery	Giant Pliocene gas discovery (2,000-2,500 BCF)	Pliocene	2374.89
SCARAB-1	British Gas	Mediterranean	32.0474	30.6302	1998	Discovery	Giant Pliocene gas discovery (2,250-2,700 BCF)	Pliocene	2099.97
SIMIAN-1	British Gas	Mediterranean	32.1920	30.7990	1999	Discovery	Giant Pliocene gas discovery (2,500-4,000 BCF)	Pliocene	2264.86
TAO-1	Amoco	Mediterranean	31.6142	32.7733	1997	Discovery	Significant Pliocene gas discovery (250-550 BCF)	Pliocene	2719.90
TUNA-1	IEOC	Mediterranean	31.8961	32.2160	1996	Discovery	Significant Pliocene gas discovery (350-500 BCF)	Pliocene	1259.98
MARAKIA-1	Shell	Mediterranean	31.1871	29.6316	1992	Dry hole	P & A; Tested 9 liters of oil in the Creataceous; Northern Extension of Western Desert Creataceous into offshore Mediterranean	L. Creataceous	4366.96
EL SAGHA-3X	Phoenix	Western Desert	29.7880	30.5814	1995	Discovery	Qarun field discovery, Bahariya (80-100 MMBOE)	L. Creataceous	2936.60
KANAYIS-4	Norsk Hydro	Western Desert	31.0609	27.6718	1992	Discovery	Discovery as gas and condensate from Khatatba (Jurassic) 19.2 MMSCFGD and 1,300 BCPD; 77.3 MMBOE	Jurassic	4765.01
OBA A-3	Shell	Western Desert	31.1273	26.5893	1996	Discovery	Recovered gas/condensate from Paleozoic strata	Carboniferous	4132.89
OBAYID-1	Shell	Western Desert	31.0723	27.0502	1992	Discovery	Giant Jurassic and Lower Creataceous field discovery; (1,700-2,200 BCF)	Jurassic	5038.10
QARUN A-4X	Phoenix	Western Desert	29.7665	30.5977	1995	Discovery	Significant southern extension of Qarun field pay	L. Creataceous	2939.96
S.W.QARUN-1X	Apache	Western Desert	29.7766	30.5226	1996	Discovery	Extension of Qarun field pay	L. Creataceous	3349.89
SHAMS S-1X	Khalda	Western Desert	30.8262	26.9078	1996	Discovery	Discovery gas/condensate in Kharita (380-500 BCF)	Jurassic	4114.60
SHAMS-2X	Repsol	Western Desert	30.8508	26.9284	1997	Discovery	Significant Jurassic discovery (1,000-1,500 BCF)	Jurassic	

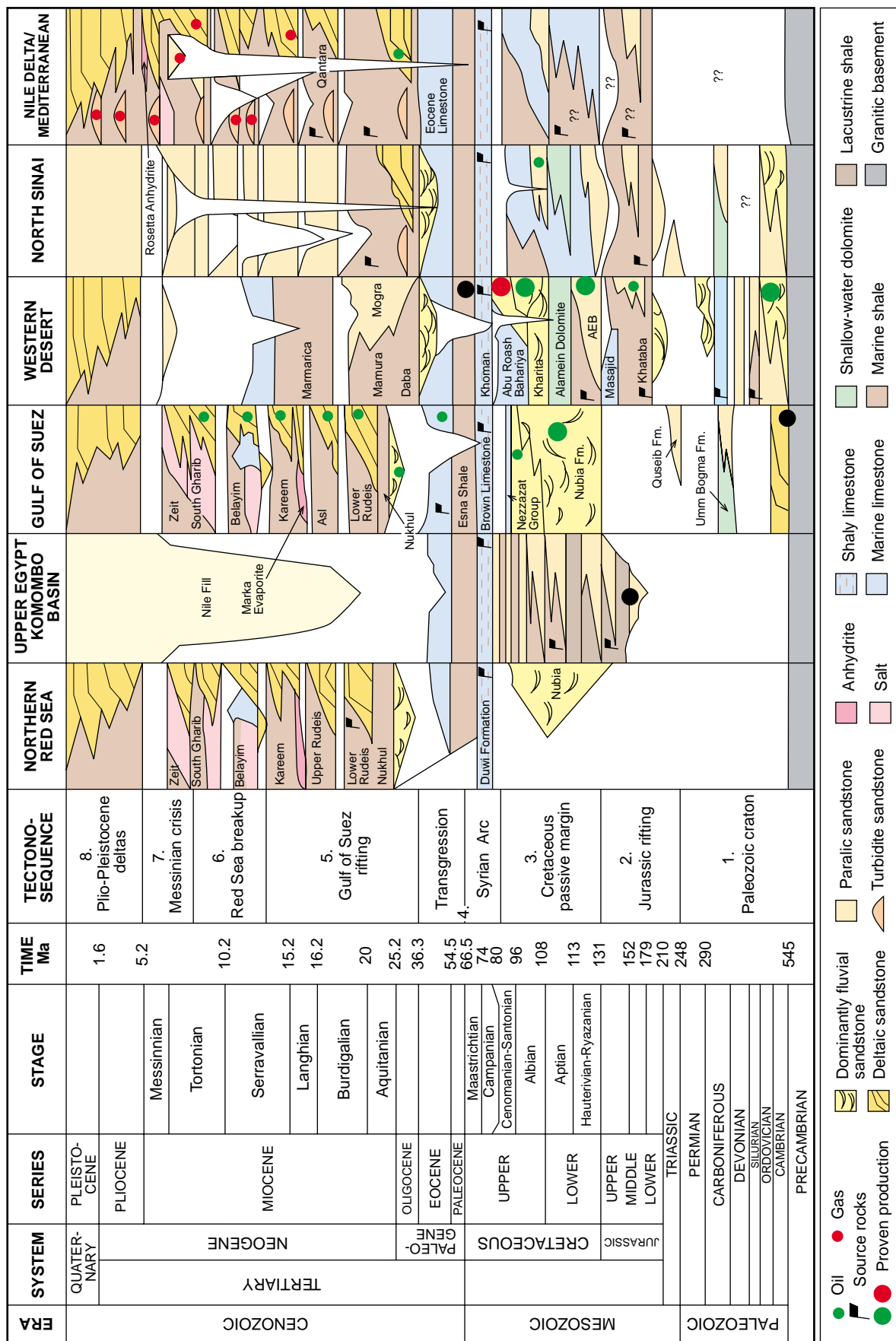


Figure 2: Stratigraphy of Egypt showing major tectono-stratigraphic events (from Dolson et al., 2000).

METHODOLOGY AND PREVIOUS WORK

The 'yet-to-find' numbers of potential giant fields used to postulate a minimum resource doubling for Egypt in the coming decades, is based on the integration of field-size distribution with drilling success statistics interpreted within a petroleum systems context.

An historical exploratory drilling database was made available by the Egyptian General Petroleum Corporation. It was used in conjunction with published field data from about 250 fields (Hegazy, 1992; Moussa and Matbouly, 1994; Matbouly and Sabbagh, 1996) to understand the exploratory drilling history by basin and play type. Post-1990 field-size data from the IHS Energy Group (London) have been added to supplement missing information. Additional reserves data is available from El-Banbi (1999).

The combination of historical drilling information and the fields database has provided field-size distributions for recoverable reserves estimates. From these, the number of 'yet-to-find' giant fields in each basin or trend have been derived on the assumption that field-size distributions follow log-normal trends. This technique of estimating 'yet-to-find' by statistical analysis of log-normal plots for known discoveries follows published work by Capon (1992), Smith and Jones (1992), Root and Attanasi (1993) and Drew and Schuenemeyer (1993). Historical drilling success rates by basin and trend have also been used to assess which plays are 'emerging' in Egypt and which are mature and apparently 'played out'.

Drilling fairways, using nomenclature already established by the Egyptian General Petroleum Corporation, are the Gulf of Suez, Eastern Desert, Sinai, North Sinai, Nile Delta and Western Desert (Figure 1). Exploratory wells are defined in Egypt as any well targeting a new trap as demonstrated by variant pressures, fluid levels, fault blocks, stratigraphic horizons or more than 2 km away from known production wells. Hence, many of the exploratory tests used for statistical analysis in this paper may be viewed in other countries as appraisal or field delineation wells or as deeper pool tests. Gas caps and associated gas in oil fields are not included in the 'yet-to-find' resources estimates.

Age control (Figure 2) is derived from an extensive chronostratigraphic synthesis of the literature, much of which, however, is very general in nature. A more fully annotated reference list is available in Dolson et al. (2000). Structural and stratigraphic synthesis of the Gulf of Suez is taken from Patton et al. (1994) and Schutz (1994). Recent concepts in sequence stratigraphy for the Gulf of Suez Tertiary syn-rift section are covered by Dolson et al. (1996), Ramzy et al. (1996) and Wescott et al. (1996). The chronostratigraphy of the Nile Delta and Mediterranean is taken from Harms and Wray (1990), Moussa and Matbouly (1994) and Harwood et al. (1998), supplemented by unpublished work of BP on the combined structural and stratigraphic evolution of the basin. Higher-resolution age analysis of the Tertiary section in the Western Desert is largely unavailable. Purser and Philobos (1993) and Philobos and Purser (1993) provide chronostratigraphic data from the southern Gulf of Suez and the Red Sea.

TECTONO-STRATIGRAPHIC HISTORY

The tectono-stratigraphic history of Egypt consists of eight major episodes summarized in Figure 2. Each episode has created combinations of reservoir, source and seal facies that control the hydrocarbon prospectivity of each basin.

1. Paleozoic Craton

The Paleozoic succession has been drilled to Precambrian basement in 245 wells in Egypt. This limited well data plus some outcrop exposures (Figure 1), provides control for a much-generalized history of the Paleozoic of Egypt. Prior to Triassic and Jurassic rifting that resulted in the breakup of the Pangea supercontinent, Egypt consisted of a low-relief alluvial plain dipping northward and westward toward cratonic sags developed in Libya and along the proto-Mediterranean. Shallow-marine carbonates and clastics generally increase in thickness northward in Egypt, with dominantly fluvial-alluvial lithofacies present in the south. Most of the lithofacies are light-colored sands, glauconitic sandstones and gray or red shales formed as paleosols or sabkhas, or in well-oxygenated marine environments.

However, shelfal marine black shales of Silurian age are present in the Western Desert where the thickness of the Paleozoic rocks in the Siwa basin exceeds 2,500 m. These potential source rocks are age-equivalents of the Tenzuft Shales of western Libya that are a proven petroleum source rock facies (Hegazy, 1992).

Paleozoic strata are absent from large areas in Egypt due to erosion during Triassic and Jurassic rifting episodes and onlap around pre-existing basement highs. Production from Paleozoic strata has been minimal so far, but there has been little systematic exploration.

2. Jurassic Rifting

From the Late Triassic through Jurassic times, a series of multiple rift basins formed during the breakup of Pangea that eventually resulted in the opening of the proto-Mediterranean Tethyan basin. Jurassic strata are best developed within the northeastern corner of the Western Desert where the syn-rift graben-fill exceeds 2,500 m.

Late Triassic and Early Jurassic strata record an early rift phase of non-marine and shallow-marine sediments that thin progressively southward away from the Tethyan margin. In the south, these strata are predominantly sandstone, red shale and thin beds of anhydrite deposited in rift-bounded fluvial, lacustrine and sabkha environments. Northward toward the proto-Mediterranean, time-equivalent rift-fill lithofacies contain progressively more carbonate and marine shale.

By Middle Jurassic times, fault blocks had fully developed and progressively deeper marine strata were deposited. The predominantly carbonate Masajid Formation contains black marine shales that form locally thick source rocks in the Western Desert. Toward the south, there is a change to progressively more non-marine facies that contain carbonaceous shale and coal of the Khataba Formation, that is a proven source rock facies.

In addition, Taha (1992) and Schull (1988) document the development of other Mesozoic rift basins in Upper Egypt and Sudan that appear to contain predominantly non-marine lacustrine sediments. These basins were probably not physically connected to the Tethyan open-marine rift systems in the Western Desert and North Sinai areas. Repsol successfully proved the presence of three of these basins (Nuqra, Kharit and Komombo, Figure 1) with exploratory wells drilled in the 1990s (Table 1). The NW-orientation of these basins may indicate rifting associated with the breakup of the African-Arabian plate, possibly as far south as Yemen (M. Winfield, personal communication, 1999) in trends that remain poorly understood.

3. Cretaceous Passive Margin

By the Early Cretaceous, an extended period of thermal sag associated with the development of a wide passive margin occurred across the northern margin of the African plate, resulting in a mixed siliciclastic and carbonate system. The AEB Formation is progressively overlain by a pattern of carbonate micrite and oolitic limestone cycles that suggests an episodic series of transgressions and regressions related to regional sea-level oscillations. The AEB Formation contains proven marine carbonate source rocks. Southward, age-equivalent strata in the Nubia Formation generally consist of red shale and coarse-grained reservoir sandstones deposited in fluvial environments.

Continued thermal subsidence throughout the Western Desert was accompanied by southward transgressions across the stable carbonate shelf and resulted in the deposition of additional widespread source rocks in the Kharita and Bahariya formations. Time-equivalent strata to the south are predominantly fluvial (Nubia Formation) and shallow-marine (Raha Formation, Lower Nezzazat Group). The northern margin of the Cretaceous carbonate platform system is in the Nile Delta area where it has been mapped as the Cretaceous hingeline (Figure 1). The carbonate margin crops out in southern Levant as a locally thick carbonate slope-breccia of the Talme Yafe Formation (Bein and Weiler, 1976). To the north of this carbonate margin, deep-marine carbonate and shale were deposited across the offshore Nile Delta and Mediterranean Sea areas.

4. Syrian Arc Deformation and Foreland Transgression

The closing of Tethys between the converging European and African plates occurred during Cenomanian and Turonian times. It resulted in rift-basin inversion throughout the Western Desert to form a series of NE-trending 'Syrian Arc' folds (Moustafa and Khalil, 1990; Moustafa et al., 1998). Carbonates of the Turonian-Santonian Abu Roash Formation show widespread high-frequency cyclicity, and some correlative units (such as the Nezzazat Group in the Gulf of Suez) contain oolitic limestone and grainstone. These rocks can be traced from well to well as far south as the southern end of the Gulf of Suez. At the same time, deep marine shale and limestone were deposited northward of the remnant carbonate margin across the Mediterranean and Nile Delta areas.

By early Campanian time, most of the structural deformation associated with the development of the Syrian Arc had ceased. A major rise in sea level (Haq et al., 1988), resulted in widespread flooding and deposition of source-rich anoxic shelfal shale and limestone of the Khoman Formation and its southern equivalent, the Brown Limestone. Where they were not removed by Tertiary uplift and erosion, these important oil source rocks are present as far south as the northern end of the Red Sea. Continued transgression resulted in the deposition of Paleocene shale (Esna Shale and equivalents) and Eocene cherty carbonate and thinly laminated shale of the Thebes Formation and equivalent strata, which form both source and seal in many petroleum accumulations.

5. Gulf of Suez Rifting and 6. Red Sea Opening

Rifting in the Gulf of Suez began in the Early Oligocene and culminated with the opening of the Red Sea in the Middle Miocene (Serravallian). Biostratigraphic assemblages indicate a full connection between the Mediterranean and Gulf of Suez by early Burdigalian times. By the middle Serravallian, however, the faunal assemblages show only a southern connection with the Indian Ocean as structural uplift across reactivated Syrian Arc structures had closed off the northern end of the Gulf of Suez (Figure 3). This event caused a marked basinward-translation of reservoir facies into the Nile Delta and Mediterranean Sea region. Concurrently, it caused isolation of the Gulf of Suez and parts of the Red Sea and resulted in the widespread deposition of evaporites that provided the ultimate topseals of the Belayim and younger evaporites in those basins.

7. Messinian Crisis

Within the Mediterranean and Nile Delta region, the frequency of development of erosional unconformities in Late Miocene times appears to increase upward stratigraphically, culminating in the Messinian crisis of about 6.7 Ma. Essentially, the late-stage impingement of the African plate against Europe caused the closure of the Straits of Gibraltar and the subsequent desiccation of the basin of the Mediterranean Sea in this tectonic-driven event. Basin-wide lowstand deposits of salt and anhydrite occur throughout the deeper portions of the Mediterranean (see Figure 1 for limits of Messinian salt).

Grand Canyon-scale incisions accompanied the drawdown that occurred concurrent with tectonic uplift in the Nile Delta region. Subsequent flooding and backfilling of these canyons during transgressions has set up numerous estuarine and point-bar deposit combinations and stratigraphic traps.

8. Pliocene-Pleistocene Delta Progradation

The Pliocene section in Upper Egypt and the Gulf of Suez lies well above potential mature source rocks. The presence of intervening shale and evaporite seals has meant that the Pliocene has not been a successful exploration target in these basins. In the Nile Delta and Mediterranean areas, however, Pliocene deltaic sandstones form very significant reservoirs and have become the dominant 'big play' of the 1990s. The Messinian canyons were completely overstepped and infilled by 5.6 Ma, but large volumes of sediment from the Nile Valley continued to prograde into the Mediterranean. As many as

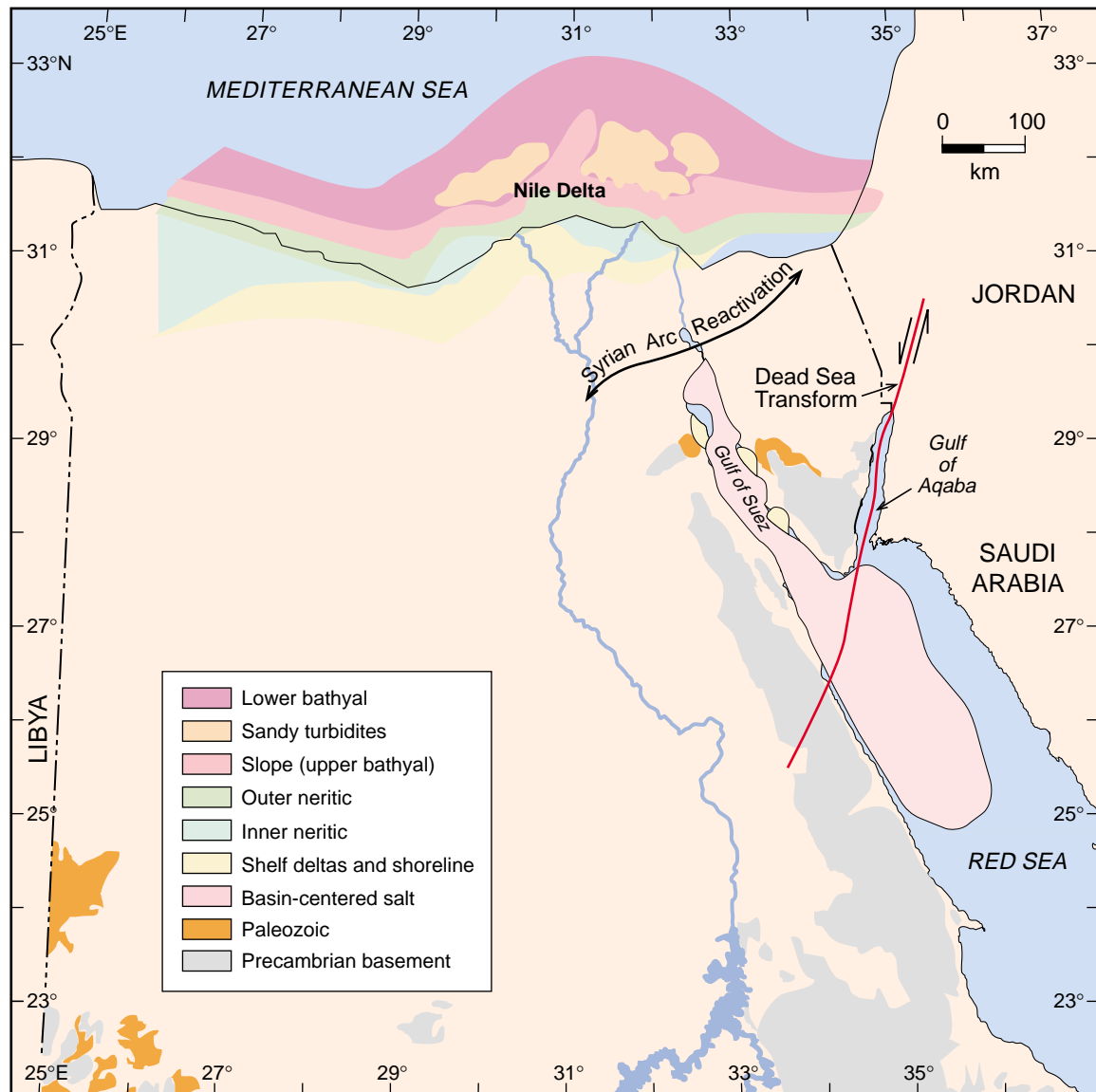


Figure 3: Serravallian (Middle Miocene) paleogeography. Basinward translation of reservoirs occurred in the Nile Delta in a pattern that is generally repeated through to the present, as Syrian Arc structures became reactivated. Concurrently, the Gulf of Suez rift was abandoned as the Gulf of Aqaba opened. Widespread deposition of evaporites (Belayim and younger) in the Gulf of Suez and Red Sea created regional seals to the underlying petroleum systems.

17 sequences have been documented for the Pliocene (Harwood et al., 1998) and the associated facies shifts have formed important reservoir fairways and traps.

A switch in the plate convergence direction toward the northwest from about 5 Ma onward, probably caused the Nile Delta depocenter to tilt downward to the northwest into the present-day basinal low of the Herodotus basin.

DRILLING HISTORY

Exploration drilling continues to significantly increase the number of new field discoveries (Figure 4 and Table 1). The Gulf of Suez petroleum system is in a mature exploration phase, although significant additional potential remains. In contrast, a substantial growth in reserves has occurred in the Western

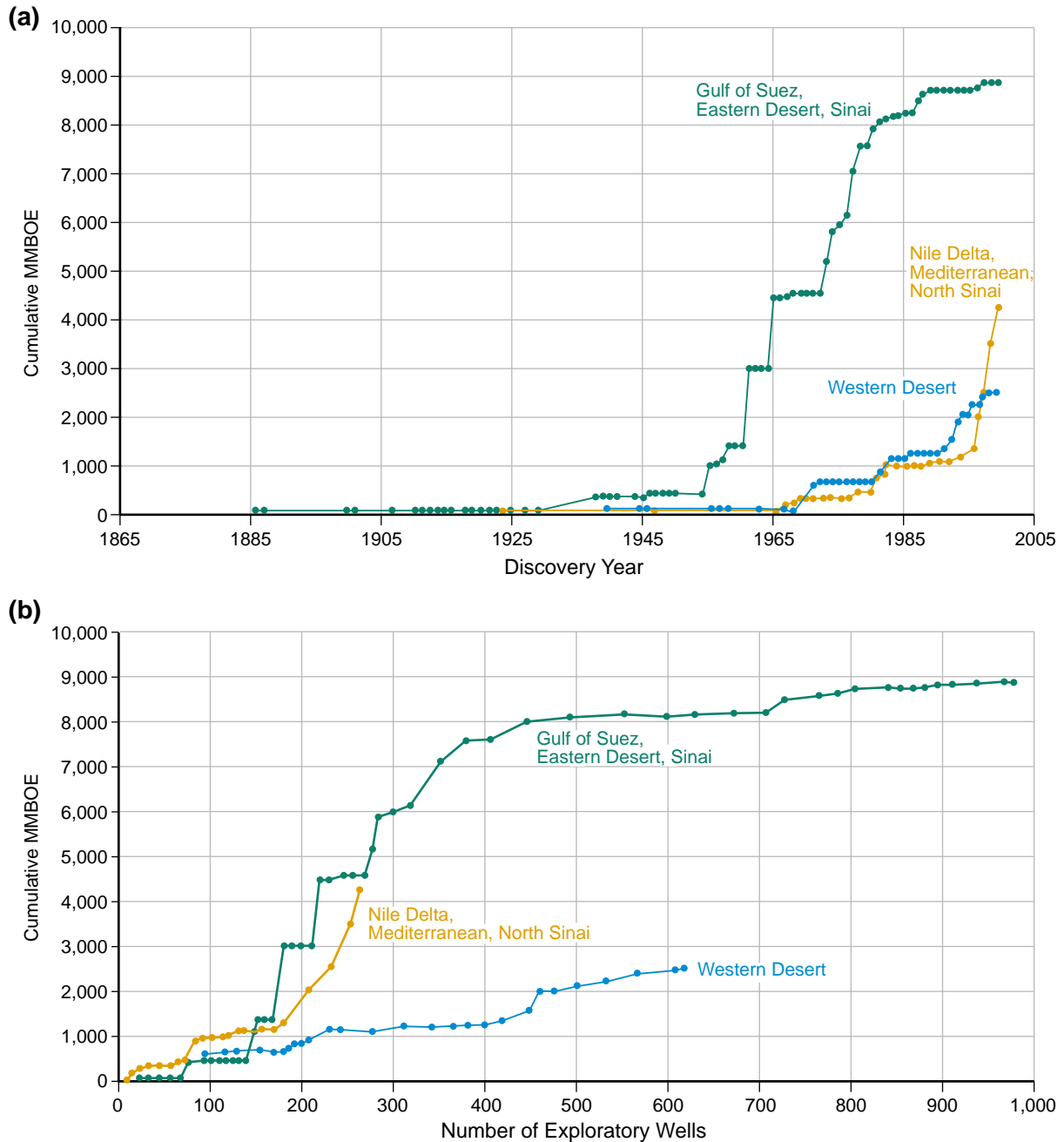


Figure 4: Drilling history by petroleum system (from Dolson et al., 2000). The Gulf of Suez is in a mature phase of drilling, whereas the Nile Delta/Mediterranean system is in a very early phase of exploration and has significant growth potential.

Desert and Mediterranean provinces. This growth has been fueled largely by the awarding of gas rights in both basins in the late 1980s. The ‘cumulative discovery versus time’ data for the offshore Mediterranean is closely paralleling that of the early discovery rate in the Gulf of Suez.

Although drilling statistics do not show significant reserves in Upper Egypt, this area has seen only limited, but significant, exploration activity (five wells) in the 1990s (Table 1). The presence of oil was established with the drilling of the Komombo-1 well by Repsol in 1997, and new resources were found in the Beni Suef basin. A new phase of drilling in the Red Sea may soon be underway. Several companies are completing interpretations of newly acquired 2-D, 3-D, aeromagnetic and gravity data in an attempt to open up new discoveries in this frontier province.

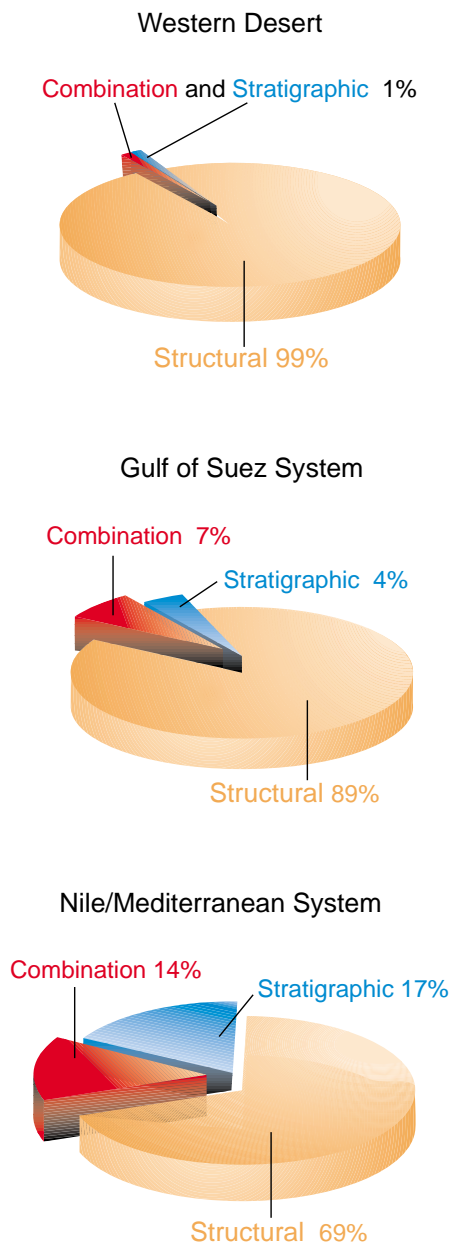


Figure 5: Reserves by trap type (from Dolson et al., 2000).

suggest that the Western Desert will continue to be an attractive exploration target into the future. Extensions into the offshore Mediterranean should also prove attractive.

Gulf of Suez, Eastern Desert and Sinai

The Gulf of Suez is a technologically constrained basin in a mature exploration phase. A multitude of proven play types exist in this basin (Figure 7). The largest fields, such as Belayim Marine, Morgan and July are rotated fault blocks with 3-way and 4-way closures against sealing shales or evaporites. Exploration in synclinal lows for deep-marine turbidite stratigraphic plays remains essentially untested. Exploration in Miocene strata of the Gulf of Suez is complicated by syndepositional movement around fault blocks that has created complicated reservoir distributions.

EXPLORATION POTENTIAL BY PETROLEUM SYSTEM

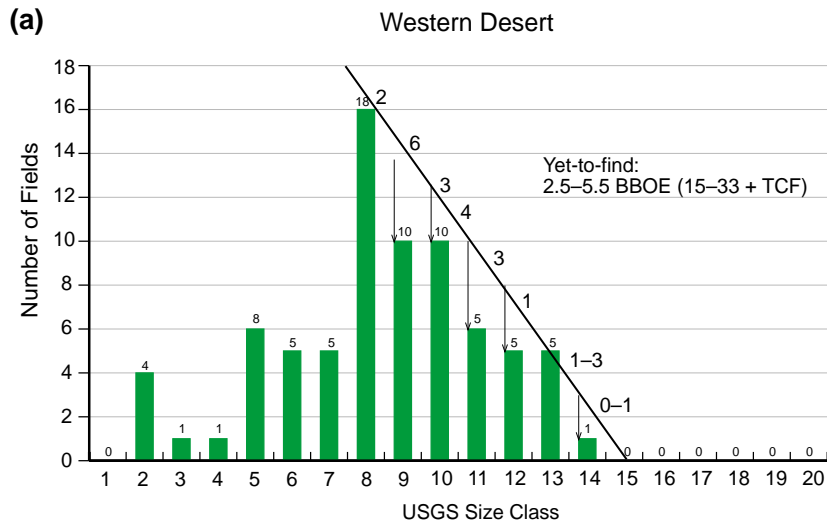
Western Desert

The Mesozoic basins of the Western Desert provide rewarding but difficult exploration opportunities. Pre-Alamein Dolomite seismic imaging is of poor quality and, because of the complex structural history, exploration has been almost exclusively for structural traps (Figure 5). Surface acquisition is also difficult and only recently have widespread 3-D seismic surveys with the potential to decrease risk on future drilling opportunities been shot, and most of them are of local extent.

Nevertheless, the Western Desert field-size distribution shows many small fields but with some potential for 100 MMBOE and larger discoveries (Figure 6a). The interpreted numbers of 'yet-to-find' discoveries shown on Figure 6a are derived by assuming that there is one field left to find larger than Obaiyed, the largest field yet found in the Western Desert. In theory, since the field-size clusters shown are combined in exponential classes on the x-axis, missing field sizes can be estimated from the difference between the diagonal line and the number of fields in each class. The diagonal line is picked by estimating the largest field yet to be found in the trend and then connecting back to the number of the smallest fields. The gaps are theoretical missing field numbers.

Geochemical data presented in Dolson et al. (2000) suggest 159 to 300 billion barrels of oil equivalent (BBOE) hydrocarbons have been generated in the Western Desert basins. This is more than enough volume to justify future reserves of 15 to 33 trillion cubic feet (TCF) of gas remaining to be found. The location of most of these new reserves would almost certainly be in deeper Jurassic and/or Paleozoic objectives, or in new stratigraphic trap concepts drilled in flank and basinal areas.

The field-size distributions and significant reserves growth shown by the strong cumulative finding rate in the 1990s



MMBOE CLASS	USGS CLASS	MMBO MIDPOINT
0.03-0.06	1	0.05
0.06-0.125	2	0.092
0.125-250	3	0.188
0.25-5	4	0.37
0.5-1	5	0.75
1-2	6	1.5
2-4	7	3
4-8	8	6
8-16	9	12
16-32	10	24
32-64	11	48
64-128	12	96
128-256	13	192
256-512	14	384
512-1,024	15	768
1,024-2,048	16	1,536
2,048-4,096	17	3,072
4,096-8,192	18	6,144
8,129-16,384	19	12,288
16,384-32,768	20	24,576

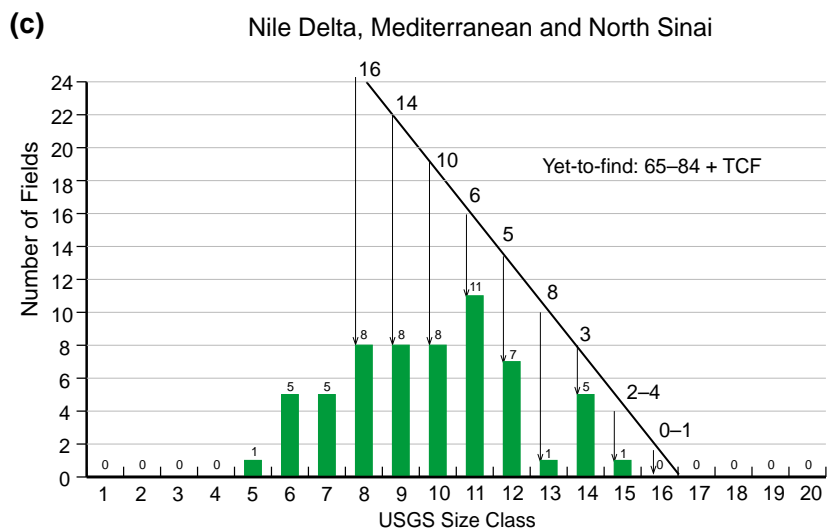
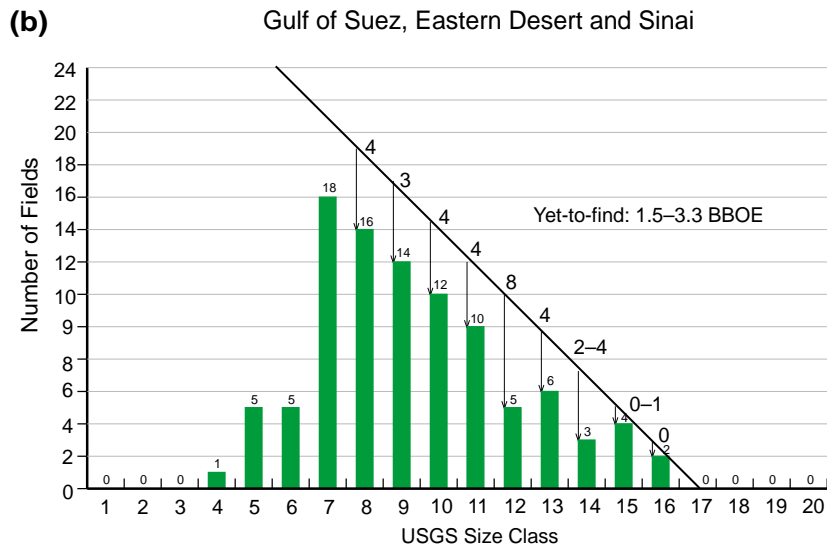


Figure 6: Field-size distribution by petroleum system and speculative 'yet-to-find' numbers of fields by class (from Dolson et al., 2000).

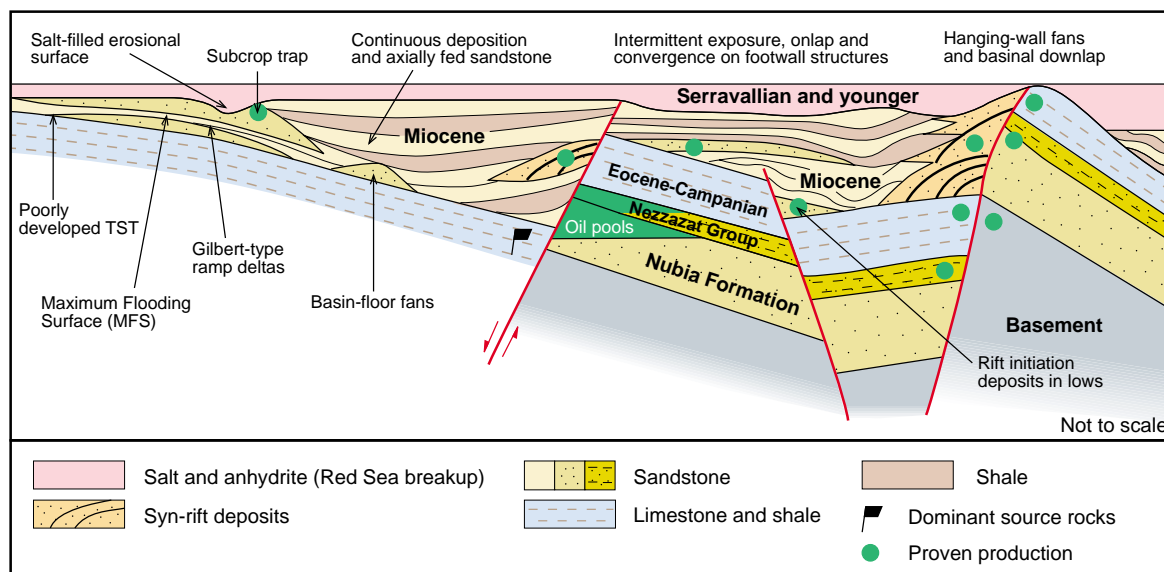


Figure 7: Gulf of Suez rift model with play types. Cretaceous and Eocene source rocks and complex syn-sedimentary depositional patterns in Miocene strata create multiple play types and complex structural geometries (from Dolson et al., 2000).

Despite the mature drilling curve of the Gulf of Suez (Figure 4), the field-size distributions (Figure 6b) indicate a potential for the discovery of several new giant fields and a large number of intermediate-size fields. These data suggest that from 1.5 to 3.3 BBOE may still be discovered, based partly on the assumption that the largest field sizes (classes 15 and 16) have already been found. Given its mature history and dense drilling, most new fields will be under 100 MMBOE in size. However, this basin is exceptionally difficult to explore seismically, with severe multiples masking structural and stratigraphic signatures. Consequently, more structural traps like those of the Warda field (Table 1) are still to be found. As seismic imaging improves, significant new reserves may be found in stratigraphic and combination traps.

Dolson et al. (1997) discussed an exploration 'turn around' in the mid-1990s through the application of integrated technology, 3-D seismic and seismic multiple-suppression techniques in the Gulf of Suez. An example of overcoming difficult seismic imaging problems is the successful step-out exploration in the Gulf of Suez (Figure 8). The SG310-6 and SG310-4 wells flowed 11,000 and 20,000 barrels of oil per day, respectively, from high structural corners that were previously unseen on seismic images. Posting of dipmeters on depth-seismic sections and integration of 3-D mapping and multiple removal allowed accurate mapping of updip traps. Severe multiples that mask traps are the main barrier to future exploration in the Gulf of Suez.

We believe that the extremely difficult seismic imaging makes the Gulf of Suez a technologically limited basin for further growth potential. Continued improvements in seismic image-enhancement will undoubtedly be the key to the discovery of significant new reserves.

Red Sea

The obvious southeastward extension of the Gulf of Suez productive trends has been difficult to prove, with only the discovery of some relatively small fields in highly complicated structural blocks. However, recently acquired 3-D surveys, regional gravity and aeromagnetic data (Figure 9) illustrate the potential of this large geographic area that contains multiple basins and could be the next large offshore resource for Egypt. The opening of the Red Sea was initiated by movement on the Dead Sea transform fault and the consequent formation of the Gulf of Aqaba. The Dead Sea transform extends southwestward into the northern part of the Gebel Duwi area (Figure 9) where it sets up a major structural transfer zone along the Egyptian side of the Red Sea coast.

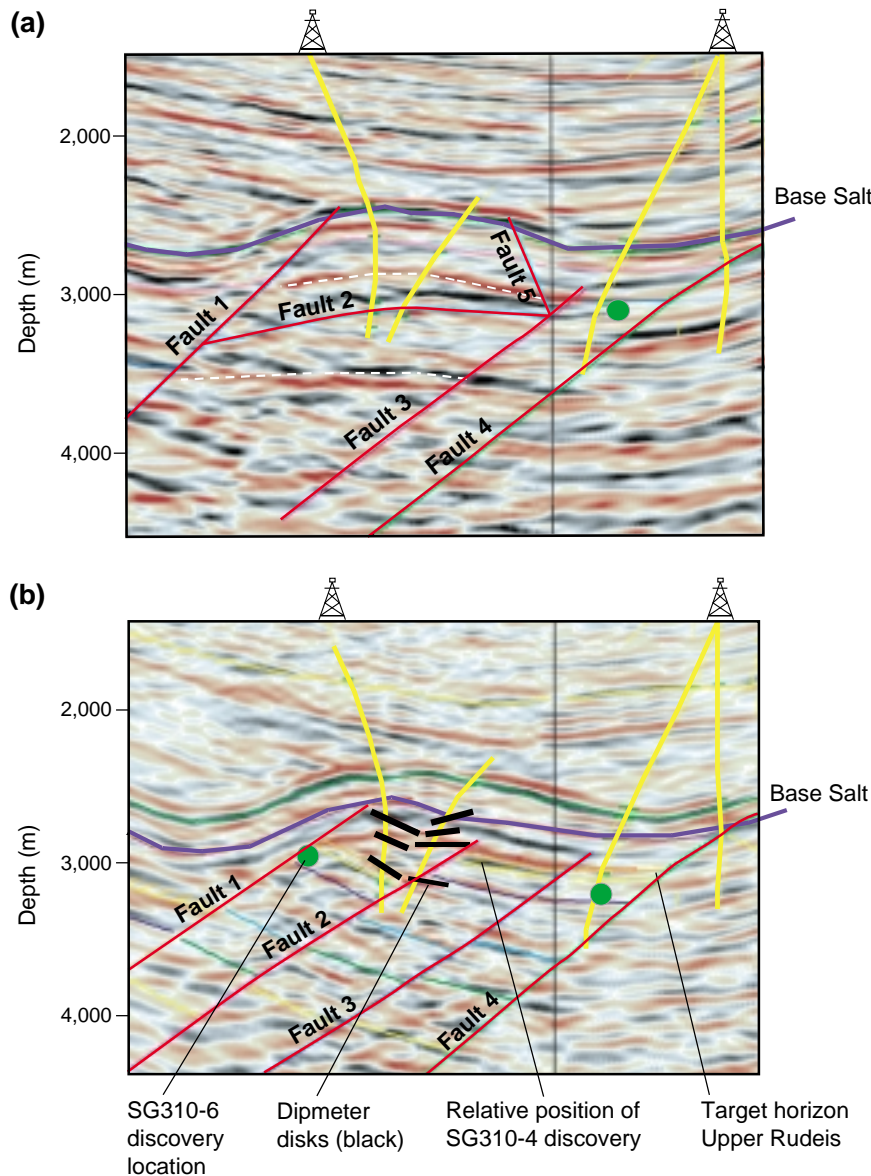


Figure 8: Example of successful step-out exploration in the Gulf of Suez. (a) SG310-6 and SG310-4 discoveries were from high structural corners that were previously not seen on seismic images. (b) Posting of dipmeters on depth-seismic sections and integration of 3-D mapping and multiple removal allowed accurate mapping of updip traps.

Only 12 wells have been drilled in the Red Sea province. Cretaceous source rocks crop out at Gebel Duwi immediately east of the Red Sea Hills (Heath et al., 1998; Khalil et al., 1998), and are likely to be present throughout the graben areas of the Red Sea. Perhaps more significantly, Alsharan and Salah (1997) document a Lower Miocene source rock common to the Midyan field of northwestern Saudi Arabia (Figure 9) and the southern Gulf of Suez. The structural style and proven petroleum system of the Gulf of Suez should continue southward into the Red Sea, although the dominant petroleum product is likely to be gas.

As in the Gulf of Suez, sub-salt seismic imaging poses the greatest challenge to success, and an additional challenge is the water depth of more than 1,000 m. Multiple reservoir and seal combinations should be present in the Red Sea within Tertiary strata and the potential exists for significant future discoveries. In addition, targets drilled off the flanks of the highest structural culminations may also intersect reservoirs in pre-Tertiary strata.

Nile Delta, Mediterranean and North Sinai

Drilling in the Nile Delta, Mediterranean and North Sinai regions occurs within a petroleum system dominated by play trends involving turbidite fans and channels, deformed Pliocene deltaic sandstone,

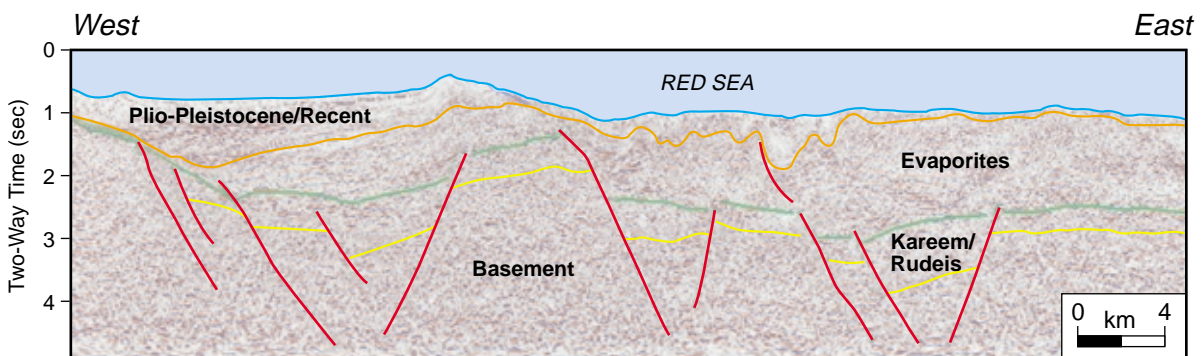
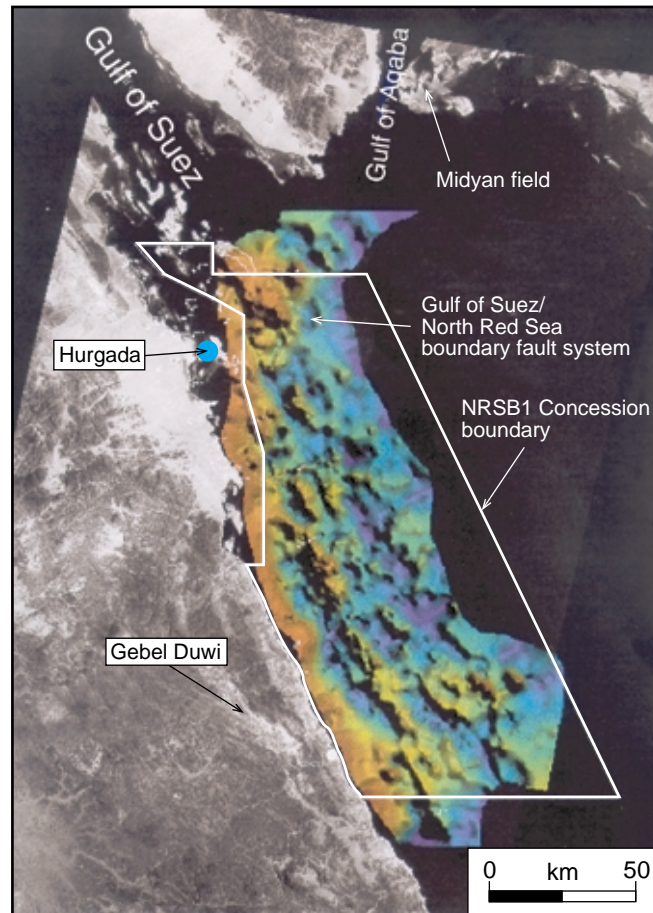


Figure 9: Northern half of Red Sea gravity interpretation and typical W-E section across the NRSB1 Concession (from Dolson et al., 2000; data courtesy of British Gas Egypt and Edison Gas). The Gebel Duwi outcrop contains Cretaceous source rocks and the Midyan field in Saudi Arabia has a Lower Miocene oil source common to fields in the southern Gulf of Suez.

Messinian valley fills, and older Miocene turbidite deposits. Most activity is currently located in the offshore Mediterranean region.

Charge in all three provinces is from Jurassic through Early Miocene strata (Moussa and Matbouly, 1994). North Sinai has had very limited exploratory success as follow-up offsets to initial discoveries were unsuccessful. In contrast, a significant growth is occurring in Tertiary targets of the Nile Delta and Mediterranean regions (Figure 4). Field-size distributions (Figure 6c) indicate a substantial potential for more large-field discoveries. Given the relatively immature exploration history of this petroleum system, the number of 'yet-to-find' resources is difficult to estimate. The assumption in Figure 6c is that at least one field will be found in the 512 to 1024 MMBOE grouping (3.07–6.14 TCF). In addition,

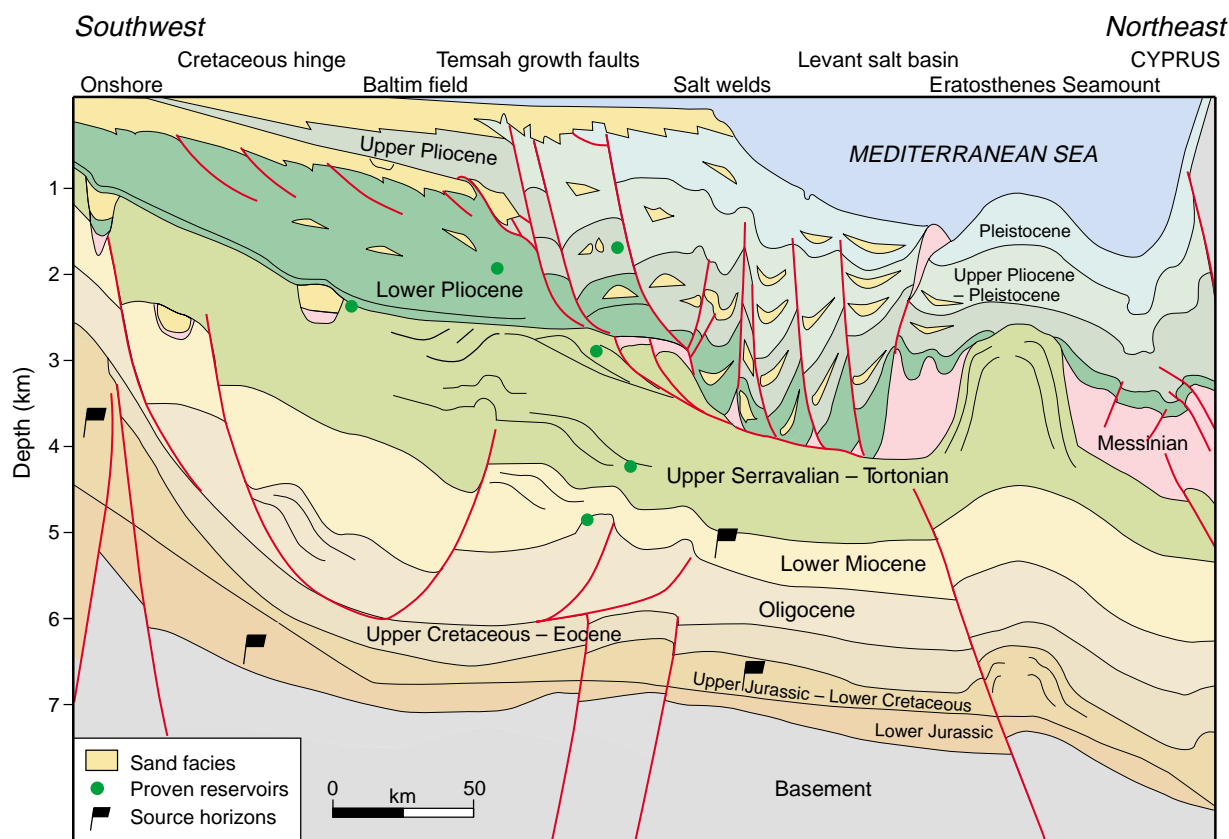


Figure 10: Nile Delta play interpretations based on regional seismic lines. The multiple source, reservoir and seal configuration in a wide variety of traps will create long-term exploration opportunities.

we assume that a minimum of 14 new fields will be found in the 8 to 16 MMBOE class (48–96 billion cubic feet). This conservative small-field estimate is based on not only the size and volume of undrilled parts of this rich hydrocarbon province, but on the large number of seismically derived leads visible from direct hydrocarbon indicators throughout the Pliocene section. The area is geographically about half the size of the Gulf of Mexico’s shelf province and has a similar multi-storied pay potential. A ‘yet-to-find’ value of 65 to 84 TCF may be possible from a comparison with reserves in the Gulf of Mexico and from this simplified statistical approach.

The plays are numerous (Figure 10) and provide a multitude of opportunities in both structural and stratigraphic traps. Historically, the Nile and Mediterranean provinces have shown greater potential for non-structural-trap reserve additions (Figure 5). Tertiary reservoirs are likely to be underlain by the deep-marine equivalent facies of the same Mesozoic source rocks that occur in the Western Desert. Some additional sources have been identified in the prodelta shales of the Early Miocene to Oligocene Qantara Formation (Moussa and Matbouly, 1994).

The best examples of Serravallian turbidite reservoirs on large pre-Messinian structural traps are the greater than 2 TCF Akhen and Tamsah fields (Table 1) (Bertello et al., 1996). Exploration for deep targets such as the Tamsah field has been limited in recent years, as the quality of the seismic data degrades significantly beneath Messinian evaporites and the Pliocene-Pleistocene growth-fault province. In addition, direct detection of hydrocarbons from seismic data is much more difficult and not physically possible in much of the deeper plays. Hence, industry activity has focused recently on the higher-amplitude bearing Messinian and Pliocene strata.

The tectono-stratigraphic events of the Messinian crisis and Pliocene deltaic progradation, set up the ‘big plays’ of the 1990s in Egypt. Gas/condensate traps in canyons related to the Messinian crisis and drawdown, occur mainly in the Baltim trend (see Figure 1) (Dalla et al., 1997). However, Messinian

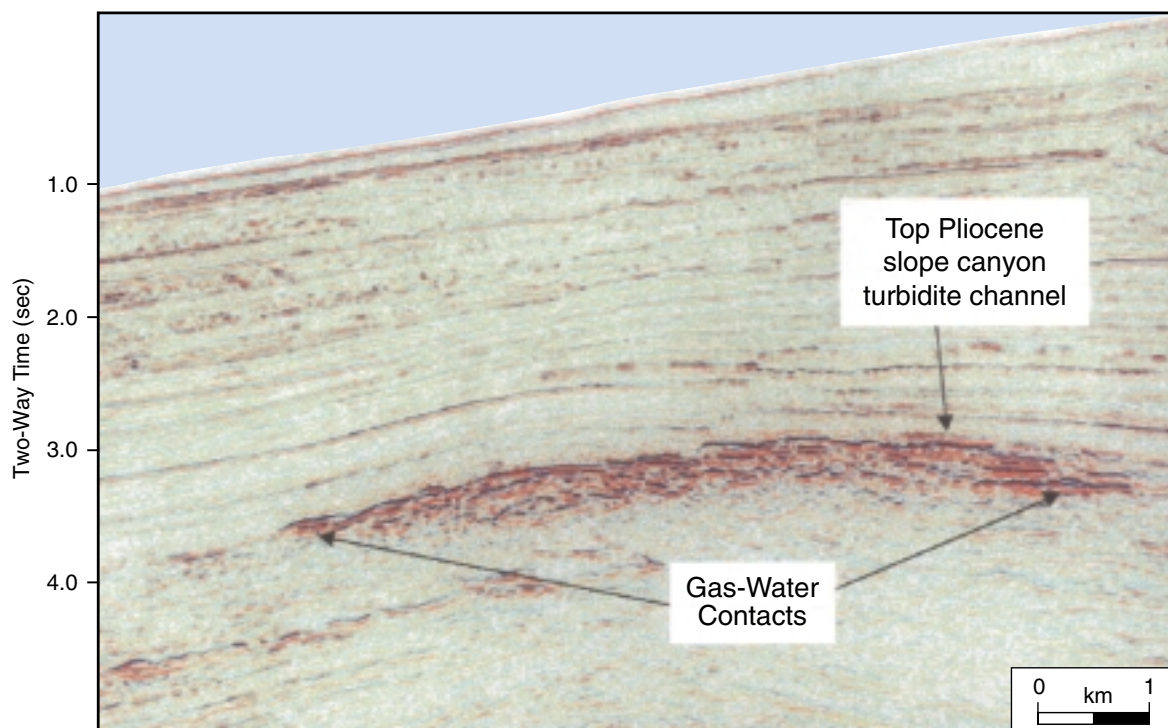


Figure 11: British Gas/Edison Gas Scarab field discovery, offshore Nile Delta: this shelf canyon turbidite channel system is typical of the emerging Pliocene trends in the Delta and Mediterranean Sea.

canyons are not confined to the Baltim trend alone. They occur throughout the Mediterranean region to provide additional exploration opportunities. Exploration for the associated downdip deltas and turbidites has not been undertaken as that play trend exists in the offshore deep water that is untested by drilling.

Pliocene deltaic and turbidite sandstone plays are currently dominating industry activity. The Scarab field (Figure 11) is a trap in shelf canyon, turbidite-channel sandstones. Its discovery was made possible through direct seismic hydrocarbon indicators, such as flat spots at the gas/water contacts. Direct hydrocarbon detection from seismic data has resulted in a 93.5 percent success rate in normally pressured Pliocene trends. This play offers by far the best short-term, large-reserve growth potential, although drilling for gas targets in deep water in front of the Nile Delta (water depths greater than 500 m) has been attempted only recently (Figure 1). Oil has been found on the fringe of the Delta (West Abu Qir, Tineh and Mango fields), and the potential exists for the discovery of oil in other parts of the Nile Delta and Mediterranean region (Moussa and Matbouly, 1994).

One of the major challenges to exploration remains the successful economic exploitation of gas resources in a deep-water setting, as deep-water development programs of gas reservoirs are rare worldwide. The successive giant-field discoveries made in the 1990s in the Mediterranean were in progressively deeper water and further growth is likely to occur in water depths in excess of 500 m (Figure 1). The recently discovered Simian, Saffron and Scarab fields (Table 1) have a complex reservoir architecture in shelf canyon turbidite systems but little is known about how to effectively develop and exploit these resources in a deep-water environment.

SUMMARY

When associated gas and gas-cap reserves are added to the volume of known resources in Egypt, more than 41 TCF of gas and 10 billion barrels of oil have been proven to date. Data presented in this paper suggest that additional resources of up to 100 TCF (16.6 BBOE) may remain to be discovered.

Challenges in offshore exploration are primarily connected with the economics and long-term efficiency of developing and maintaining deep-water gas reservoirs in the Mediterranean and in potential new discoveries in the Red Sea. In addition, serious market constraints may hamper development of the large potential gas reserves if additional export markets are not developed. The Gulf of Suez will remain a predominantly minor contributor in years to come unless significant sub-salt seismic imaging techniques are developed that can exploit hidden structural and stratigraphic traps.

'Yet-to-find' resources are difficult to quantify with any degree of accuracy. However, a very positive future is suggested by the missing field-size distributions shown by the present study. Also to be taken into account is the large areal extent of rich source rocks, the multiplicity of play and basin types, and the relatively small amount of drilling in many of the petroleum provinces. We believe that our data show that Egypt should be able to fully replace its current proven reserves base of 15.7 BBOE in the coming decades.

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ABOUT THE AUTHORS

John C. Dolson is a Senior Geological Associate exploring for hydrocarbons in the Nile Delta basin for BP-Egypt. He has lived in Cairo for six years with additional experience in the Gulf of Suez and Western Desert basins. His interests include sequence stratigraphy, integrated workstation technology and stratigraphic traps. He has over 20 years of experience in petroleum exploration, including the greater Rocky Mountain basins, Anadarko, Cook Inlet, Pre-Caspian and Caspian basins and the Hugoton embayment.



Mark V. Shann is a Geologist with the BP-Egypt Gas Business Unit located in Cairo, Egypt. He has 19 years of worldwide petroleum geology experience with BP, specializing in basin and play analysis, with current emphasis on Middle East regional geology and play concepts. Mark is interested in both the detailed appraisal / early development challenges of discovered petroleum pools as well as the regional play system characterization and focus to exploration strategy.



Sayed Matbouly is the General Manager for Exploration Studies with the Egyptian General Petroleum Corporation in Cairo, Egypt. He has served as the primary editor for many petroleum related books and articles dealing with Egypt and has over 25 years of experience in petroleum exploration. He is interested in all phases of oil and gas field exploration and management and is an active member of the AAPG.



Hussein Hammouda is Manager of Geophysics for the Gulf of Suez Petroleum Company, Cairo, Egypt. He has over 24 years of experience in petroleum exploration and management. He holds a PhD in Applied Geology and an MS in Applied Geophysics. He has interests in sequence stratigraphy, remote sensing and general exploration.



Rashed M. Rashed is the Prospect Generation General Manager for the Gulf of Suez Petroleum Company, Cairo, Egypt. He has worked for the Geological Survey of Egypt, participated in the mapping and economic evaluation of the Red Sea and has been with GUPCO since 1979. He has experience in all of Egypt's basins and, along with the senior author, was a winner of Amoco's Chairman's Award for Team Excellence (1996) and Amoco's Worldwide Chairman's Award for Technology Excellence in the Exploration and Production sector.



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