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Geologic setting and hydrocarbon potential of north Sinai, Egypt

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ABSTRACT

The Sinai Peninsula is bounded by the Suez Canal and Gulf of Suez rift to the west, the transform Dead Sea-Aqaba rift to the east and the Mediterranean passive margin to the north. The stratigraphic section in North Sinai ranges in age from Precambrian to Recent and varies in thickness between 2000 m of mostly continental facies in the south to almost 8000 m of marine facies in the north. Four main tectonic trends reflect the influence of regional tectonic movements on the study area: 1) ENE-WSW-trending normal faults at the Triassic, Jurassic and Early Cretaceous levels; 2) NE-SW-trending anticlines at the Late Cretaceous and Early Tertiary levels; 3) NNW-SSE-trending normal faults at the Oligocene and Early Miocene levels; and 4) NNW-SSE-trending transform faults during the Late Miocene. Several oil and gas fields have been discovered in North Sinai since 1955. The Oligo-Miocene shales, the Early Cretaceous carbonates and the Jurassic fine clastics are rich source rocks yielding oil and gas in deep source kitchens. The sandstones of the Miocene, Oligocene, Cretaceous and Jurassic ages, the Jurassic carbonates and the Cretaceous carbonates form the reservoirs in north Sinai. The intraformational Mesozoic and Cenozoic shales and dense carbonates and the middle Miocene anhydrite form the seals. Structural, stratigraphic and combination traps are encountered in the study area. The north Sinai district has a good oil exploration potential. Only a few plays have been tested.

RÉSUMÉ

La péninsule du Sinaï est limitée par le canal de Suez et le fossé ouest du golfe de Suez, le fossé transformant de la mer Morte-Aqaba à l'est et la marge passive de la Méditerranée au nord. La section stratigraphique dans le Sinaï du nord s'échelonne de Précambrien à Holocène et varie en épaisseur de 2000 m de faciès surtout continentaux dans le sud à près de 8000 m de faciès marins au nord. Quatre tendances tectoniques principales reflètent l'influence des mouvements tectoniques régionaux dans la région étudiée : 1. les directions ENE-OSO des failles normales aux niveaux du Triassique, Jurassique et du Crétacé précoce; 2. les directions NE-SO anticlinales aux niveaux du Crétacé tardif et du Tertiaire précoce; 3. la direction NNO-SSE des failles normales aux niveaux de l'Oligocène et du Miocène précoce; et 4. la direction NNO-SSE des failles transformantes pendant le Miocène tardif. Plusieurs champs pétrolifères et de gaz naturel ont été découverts dans le Sinaï du nord depuis 1955. Les schistes du Oligo-Miocène, les carbonates du Crétacé précoce et les clastiques à grains fins du Jurassique sont de riches roches-mère produisant du pétrole et du gaz dans le cuisines-mère profondes. Les grès d'âge Miocène, Oligocène, Crétacé et Jurassique, les carbonates du Jurassique et les carbonates du Crétacé forment les réservoirs dans le Sinaï du nord. Les schistes intraformationels du Mésozoïque et du Cénozoïque et les carbonates denses et le Miocène moyen déshydratés forment les obturations. Les pièges structuraux, stratigraphiques et une combinaison des deux se trouvent dans la région étudiée. Le district du Sinaï du nord possède de bonne possibilité pour l'exploitation de pétrole. Seuls quelques jeux ont été testés.

Traduit par Marie-Louise Tomas

INTRODUCTION

The Sinai Peninsula, the common part of Africa and Asia, is triangular in shape and occupies an area of almost 60 000 km^2 (Fig. 1). It is separated geographically from Africa by the Suez Canal and the Gulf of Suez rift. The southern sector of the peninsula is occupied by rigid Precambrian basement rocks that reach elevations of 2640 m in Jebel Katherine (Said, 1962) (Fig. 1). The central and northern sectors of the Sinai Peninsula are covered with a northward-draining limestone plateau with a series of northeast-trending anticlinal and synclinal jebels (mountains). These folds, extending from the Western Desert in the west to Jordan and Syria in the east, follow the Syrian Arc System. Generally, the elevation of these jebels decreases northwards to 1090, 890 and 735 m in Jebels

Yelleg, Halal and Maghara, respectively (Fig. 1). These Syrian arc folds sink seawards under a Quaternary coastal plain. Farther north, a broad tract of sand dunes runs parallel to the Mediterranean coast and the Bardwail Sabkha (known as Bardwail Lake) (Fig. 1) and ranging in elevation from 10 to 1000 m.

The study area is located in the northern part of Egyptian Sinai and is delineated by longitudes 32°35' and 34°25' E and latitudes 29°55' and 31°30' N, embracing an area of almost 28 000 km^2 that averages 175 km in length and 150 km in width. The northern part of the study area is located in the offshore Mediterranean (Fig. 1).

The main target of this paper is to describe the geology, hydrocarbon potential and tectonic influence on hydrocarbon generation, migration and accumulation within the north Sinai area. This study covers in detail the geology and hydrocarbon habitat of the onshore and offshore areas of north Sinai. As the authors are aware, most of the previous work was mainly localized or focused on certain geological aspects, *e.g.*, stratigraphy, structure, sedimentology, etc.

XPLORATION HISTORY

In addition to being very close to the prolific Gulf of Suez oil basin in which the first discovery, Gemsa oil field, was made in 1886, north Sinai contains several interesting surface geologic features which made it an attractive exploration prospect. The exploration for oil in Sinai began in 1910 when the Sinai Petroleum Syndicate (SPS) drilled a dry hole Tanka-1 near an oil seep in west Sinai (EGPC, 1986). Since then, the Anglo Egyptian Oil Fields, Standard Oil of Egypt and the Socony Vacuum Oil Company (the Egyptian subsidiaries of Shell, Esso and Mobil, respectively) conducted detailed surface geologic mapping, carried out several gravity and magnetic surveys and drilled several wells in the central and northern Sinai without any success. The drilling ceased during the Second World War (WWII) and attention was focused to the eastern coast of the Gulf of Suez, south of the study area, where three oil fields, Sudr, Asl and Matarma, were discovered between 1945 to 1948 (Fig. 1). During the occupation of Sinai by Israel (1967-1979), the Israeli explorationists conducted several additional gravity, magnetic and seismic surveys over the onshore and offshore parts of north Sinai and drilled 17 wells, resulting in the discovery of Sadot gas field in 1975 (Fig. 1). Since 1979, the Egyptian General Petroleum Corporation (EGPC) launched an exploration program and awarded exploration rights to several western oil companies to explore for hydrocarbons in north Sinai, *e.g.*, Conoco, Amoco, Total, BP, Elf Aquitaine and IEOC (the International Egyptian Oil Company). These resulted in the discovery of the Tineh, Port Fouad, Abu Zakin, Wakar, South Rafah and Mango oil and gas discoveries (Fig. 1). In addition to these discoveries, several wells have encountered good oil and/or gas shows (EGPC, 1986) (Fig. 2).

STRATIGRAPHY

The lithostratigraphic units of the north Sinai district have been defined from examination of measured sections and subsurface cores, electric logs tied to microfaunal and palynological studies of ditch samples and thin sections (Shata, 1956; Said, 1962, 1990; Al Far, 1966; Neev, 1975, 1977; Beyth, 1981; Jenkins *et al.*, 1982; Ammar and Afifi, 1992; Zaghloul and Khidr, 1992; EGPC, 1994). In this study, the lithostratigraphic units in the north Sinai district have been divided into four major sequences which vary in both thickness and facies within the northern and central sectors of the north Sinai area. A lithostratigraphic column of the study area is given in Figure 3.

PALEOZOIC SEQUENCE

The Paleozoic succession has been penetrated mostly in the southern wells in the study area, Nakhl-1, Abu Hamth-1 and El Hamra-1, with an average thickness of 550 m. It is present in the surface exposures at Durba-Araba and Jebel Um Bogma, southwest Sinai. Farther north, the Paleozoic section is assumed to lie at great depths as the well Waker-1 (Fig. 2) was bottomed in the Oligocene rocks at depth of 4733 m. Generally, the thickness of the Paleozoic section increases northwards and there is a greater marine influence on the facies (Fig. 4). This succession is subdivided into the following groups and formations: Qebliate Group (Cambro-Ordovician), represents the oldest Phanerozoic regressive marine facies terminating in a fluviatile facies and includes two formations, the Araba and Naqus (Hassan, 1967); Um Bogma Formation (Lower Carboniferous); Ataqa Group (Upper Carboniferous), proposed by Soliman and El Fetouh (1970), includes two formations, the Abu Durba and Rod El Hamal; and Budra Formation (Permian?)

TRIASSIC TO EARLY CRETACEOUS SEQUENCE

This sequence is the thickest section in the stratigraphic column of the onshore part of the study area as indicated from the well Halal N-1 (Fig. 2), which started in the Upper Cretaceous section and bottomed at 4313 m in the Triassic sediments. It contains potential source, reservoir and seal rocks. It is present on the surface as well as the subsurface and consists of the following units: 1) Arif El Naqa Formation (Triassic), continental clastics and marine limestones exposed in Jebel Arif El Naqa in the southeastern part of the study area with vertebrate bone fragments and plant remains recorded in the upper and lower parts, respectively, is encountered in the Abu Hamth-1, Nakhl-1, El Hamra-1 and Halal N-1 wells (Fig. 2); 2) Maghara Group (Jurassic To Early Cretaceous), shallow shelf limestone and fluvial to continental clastics cover a broad area of north Sinai and extend from the Western Desert of Egypt, through north Sinai, to Negev Desert, Jordan and Syria. In north Sinai, Jurassic rocks are exposed in the cores of several structures (Jebels Maghara, Rizan Aneiza, Minsherah and Arif El Naqa) (Fig. 1) and are encountered in 17 wells in the onshore and offshore parts of the study area. The thickest and most complete section of the

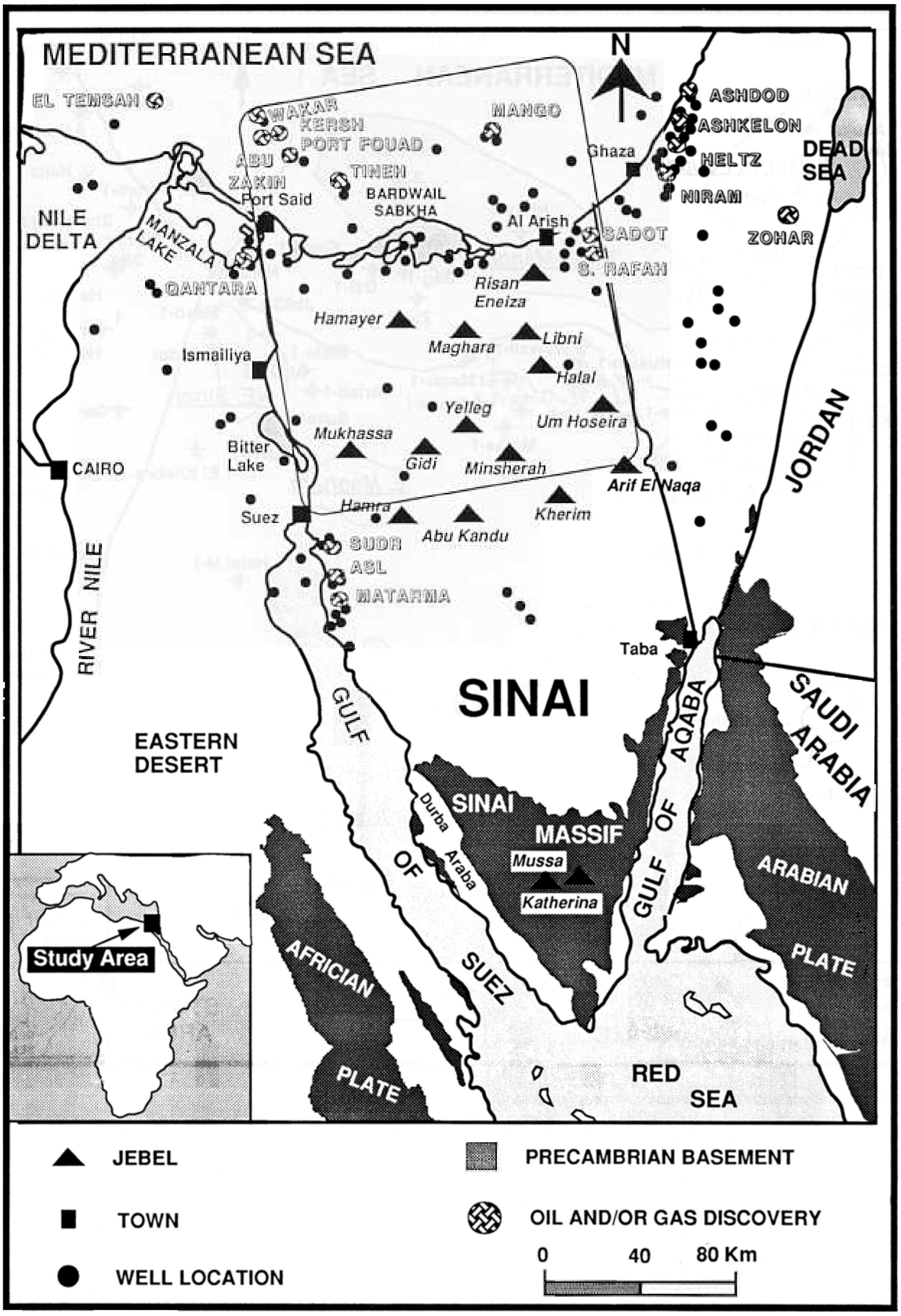

Fig. 1. Generalized geological map and oil fields in northern Sinai.

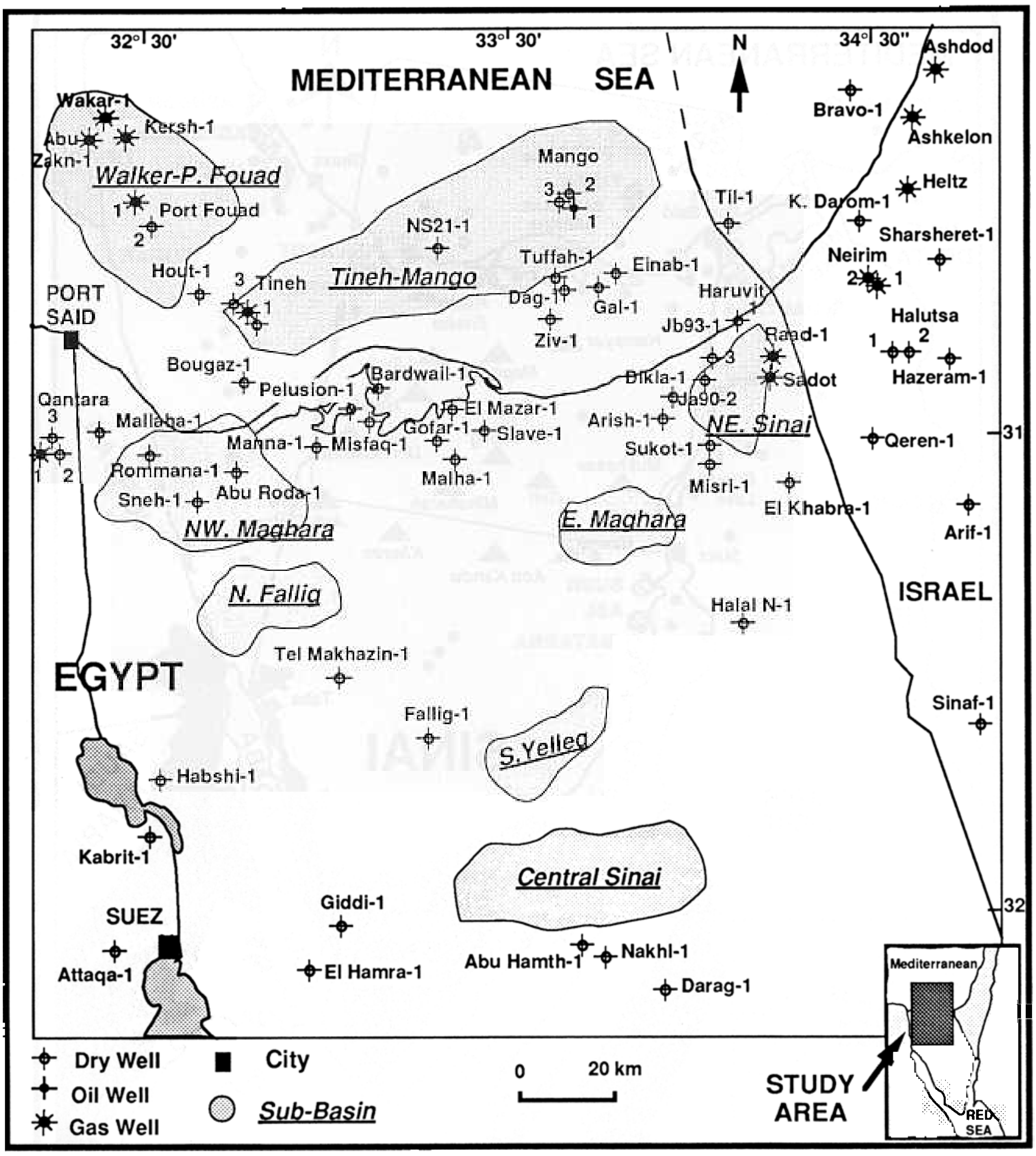

Fig. 2. Well locations and major subbasins in the study area.

Jurassic rocks in north Sinai is that of Jebel Maghara, where it reaches to almost 2000 m (Al Far, 1966), and is used in this study as a reference section. The Maghara Group is subdivided into the following formations, in ascending order: Mashaba Formation (Lower Lias); Rajabiah Formation (Lower Lias); Shusha Formation (Upper Lias); Bir Maghara Formation (Bajocian to Early Bathonian); Safa Formation (Early Bathonian); Masajid Formation; Rakeib Formation (Neocomian to Barramian); and Rizan Aneiza Formation (Aptian to Albian).

Upper Cretaceous to Late Eocene Sequence

This sequence is characterized by the predominance of carbonates in the lithostratigraphic units of the onshore part of the study area several of which are potential reservoirs. It is present on the surface and the subsurface of north Sinai (Fig. 4) and consists of two groups, in ascending order: Nezzazat (Cenomanian to Santonian) with thicknesses of 732, 845 and 945 m in the Jebels Maghara, Arif Al Naqa and Minsherah,

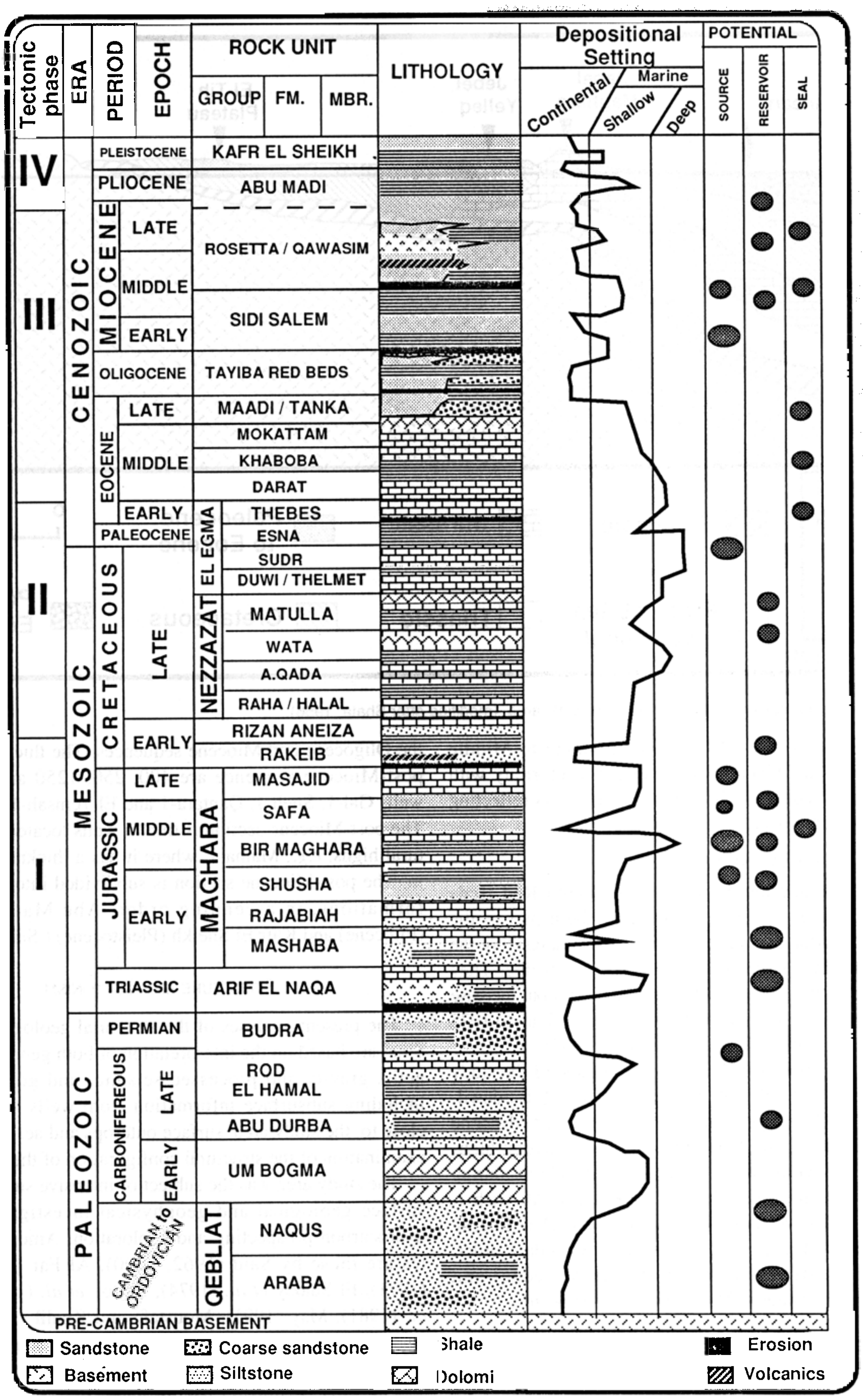

Fig. 3. Generalized stratigraphic column, depositional environments and hydrocarbon potential of the northern Sinai area (modified after several authors).

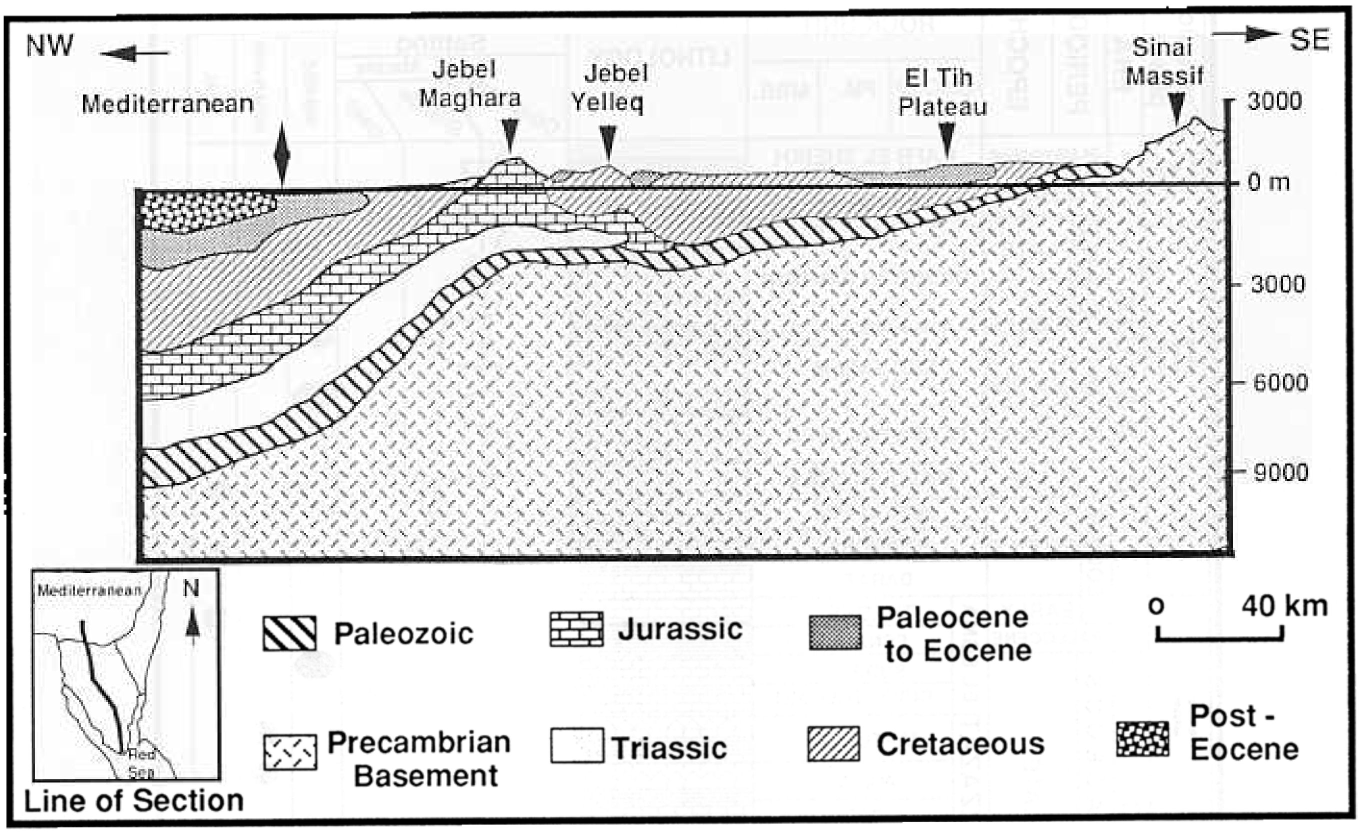

Fig. 4. Schematic cross-section across the north Sinai area. (modified after Shata, 1956).

respectively (Fig. 1), and El Egma (Campanian to Middle Eocene) with various thicknesses, facies and conformity with the overlying and underlying lithostratigraphic units reflecting the influence of tectonism.

Oligocene to Late Miocene Sequence

The Oligocene sediments, known as Tayiba Red Beds (Barakat *et al.*, 1988), are absent in the southern part of the onshore area due to the emergence of this sector as a result of the influence of the early stages of the Gulf of Suez rifting. They average to 90 m in the eastern part of the study area but increase abruptly to the west to an average of 750 m and reach up to 1075 m west of the Suez Canal (Zaghloul and Khidr, 1992).

The Miocene section is well developed in most of the study area and is 1100, 1260 and 1350 m thick in the Gal-1, Bardawil-1 and Sneh-1 wells, respectively. A much thinner Miocene sequence was drilled in wells located over old structural highs (most probably of Syrian Arc trend) that remained highs during the Miocene, as in the wells Slave-1, Gofer-1 and Al-Arish-1, where it reaches 270, 180 and 200 m, respectively. The Miocene section is subdivided into two formations, in ascending order: Sidi Salem Formation (Lower to Middle Miocene) and Qawasim/Rosetta Formation (Middle to Upper Miocene).

Post-Miocene Sequence

The post-Miocene sediments show marked variations from one area to another but generally increase in thickness to the west in the Nile Delta area, following the same trend seen in the Oligocene and Miocene sequences. The thicknesses of the post-Miocene sequence are 400, 250, 1250 and 1700 m in wells Gal-1, Sneh-1, Qantara-1 and El Temsah-1, respectively. The post-Miocene section is thin in wells located on old structural highs, *e.g.*, Malha-1, where it has a thickness of only 88 m. The post-Miocene section is subdivided into the following formations, in ascending order: Abu Madi Formation (Pliocene) and Kafr El Sheikh (Pleistocene) (Said, 1962).

Structure and Tectonism

The present analyses of the structural geology in the north Sinai are based on the interpretation of both geophysical (magnetic, gravity and processed seismic) and geological data, including subsurface information from wells drilled in, and close to, the study area, surface outcrops and aerial photograph examination of the structural configuration of the region.

The study area was the subject of intensive surface and subsurface geological and geophysical investigations during hydrocarbon prospecting and exploration. Among these studies are those by Said (1962, 1990), Al Far (1966), Smith (1971), El Shazly *et al.* (1974), Bartov *et al.* (1980), Eyal *et al.* (1981), May (1991), Moustafa and Khalil (1987), Aal *et al.* (1992) and Aal and Lelek (1994). The results are incorporated in the current study.

The Sinai Peninsula has attracted the attention of many geologists as it is bounded by major tectonic elements. These are the Mesozoic-Early Cenozoic tectonically-active Tethys Sea to the north, the Oligo-Miocene Gulf of Suez rifted basin to the west, and the late Miocene to Recent transform Dead Sea-Gulf of Aqaba rift to the east. Each of these major elements has affected dramatically the structure and tectonic evolution of the north Sinai area, which has been subdivided into four tectonic phases, as follows:

PHASE I: The breakup of north Africa-Arabia in Late Triassic-Liassic time and the opening of the Tethys took place and reactivated ENE-WSW-oriented deep-seated faults. The southern and central sectors of Sinai were uplifted, relative to the northern (onshore and offshore) (Bartov *et al.*, 1980). The influence resulted in the development of a thick wedge of the Early and Middle Mesozoic sediments (Triassic, Jurassic and Early Cretaceous) in the northern sector and its abrupt thinning to the south (Fig. 5). Structurally, this phase was dominated by Jurassic NW-SE left-lateral oblique extension which resulted in ENE- to NE-trending normal faulting (Aal and Lelek, 1994).

PHASE II: During the Late Cretaceous to Early Tertiary (Laramide) time, Africa moved west-northwest relative to Eurasia, which closed the Tethys Sea and produced a right-lateral shear couple between north Africa and Eurasia (Smith, 1971). This shear couple started in the Turonian, climaxed in the Late Cretaceous and decreased into the Early Tertiary, causing the right-lateral rejuvenation of the deep-seated faults in north Egypt (Smith, 1971) (Fig. 5). This tectonic event, known in the Middle East as Syrian arc system, produced a series of asymmetrical NE-trending, doubly-plunging anticlines in the study area, *e.g.*, Jebels Maghara, Yelleq, Halal, Minsherah and Fallig (Fig. 6).

PHASE III: The rifting of the Gulf of Suez, started between 24 and 21 Ma, during the latest Oligocene to the earliest Miocene (Evans, 1990), was caused by ENE-WSW-trending tensional stresses transmitted through the lithosphere, in addition to an upwelling of hot asthenosphere (Hammouda, 1992). Between 20 and 17 Ma, the flanks of this future basin began to be uplifted in response to heating. Both the crustal extension and tectonic subsidence of the axial trough reached their peaks between 19 and 15 Ma. This tectonic phase is very clear in the southern and southwestern parts of Sinai and dominated NNW-trending normal faults (Fig. 6).

PHASE IV: This phase is represented by the Late Miocene to Recent Gulf of Aqaba rifting, which was formed by left-lateral

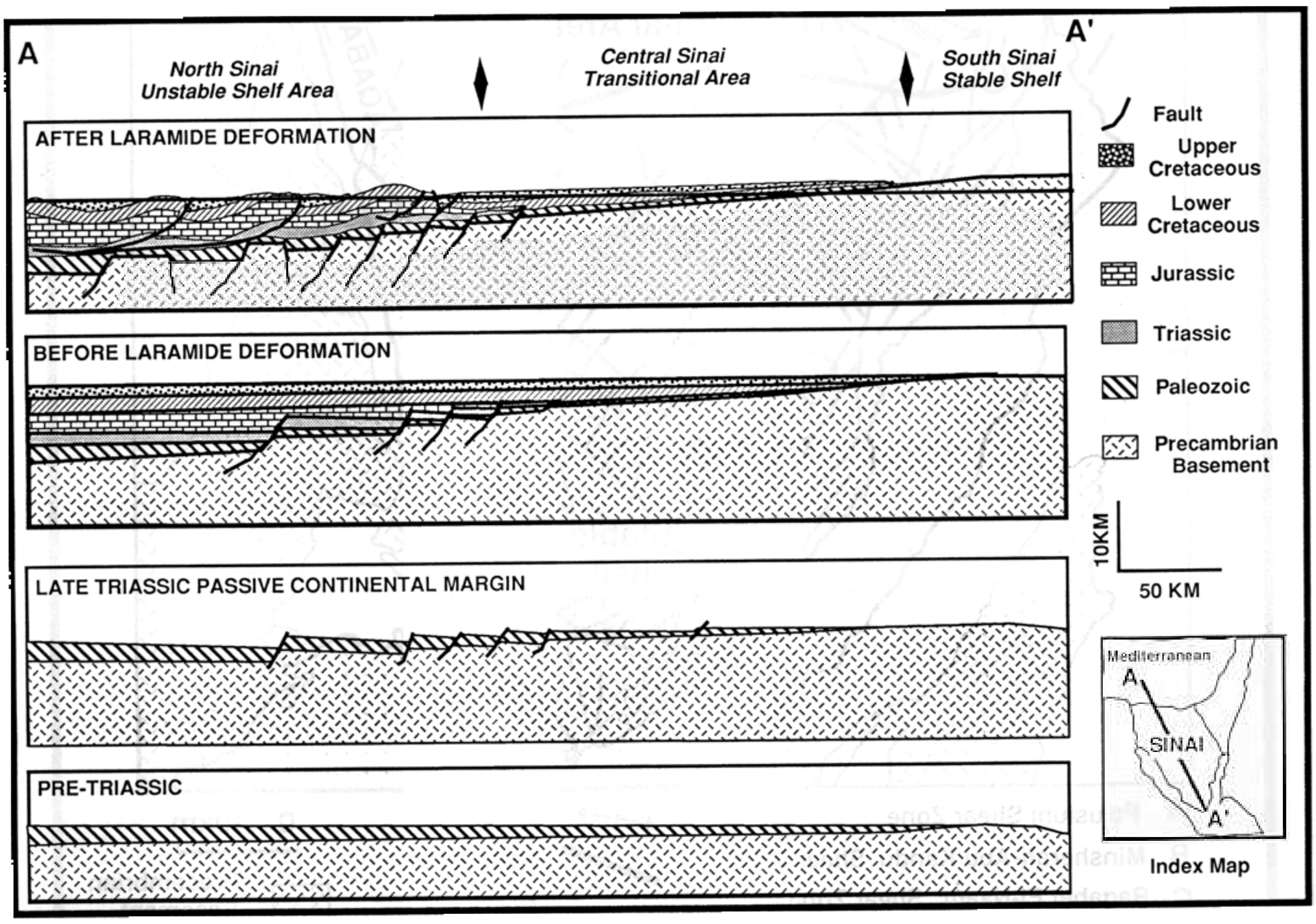

Fig. 5. Evolutionary stages of the study area (modified after Bartov *et al.*, 1980; Moustafa and Khalil, 1987; Aal *et al.*, 1992). See Figure 6 for regional relationships.

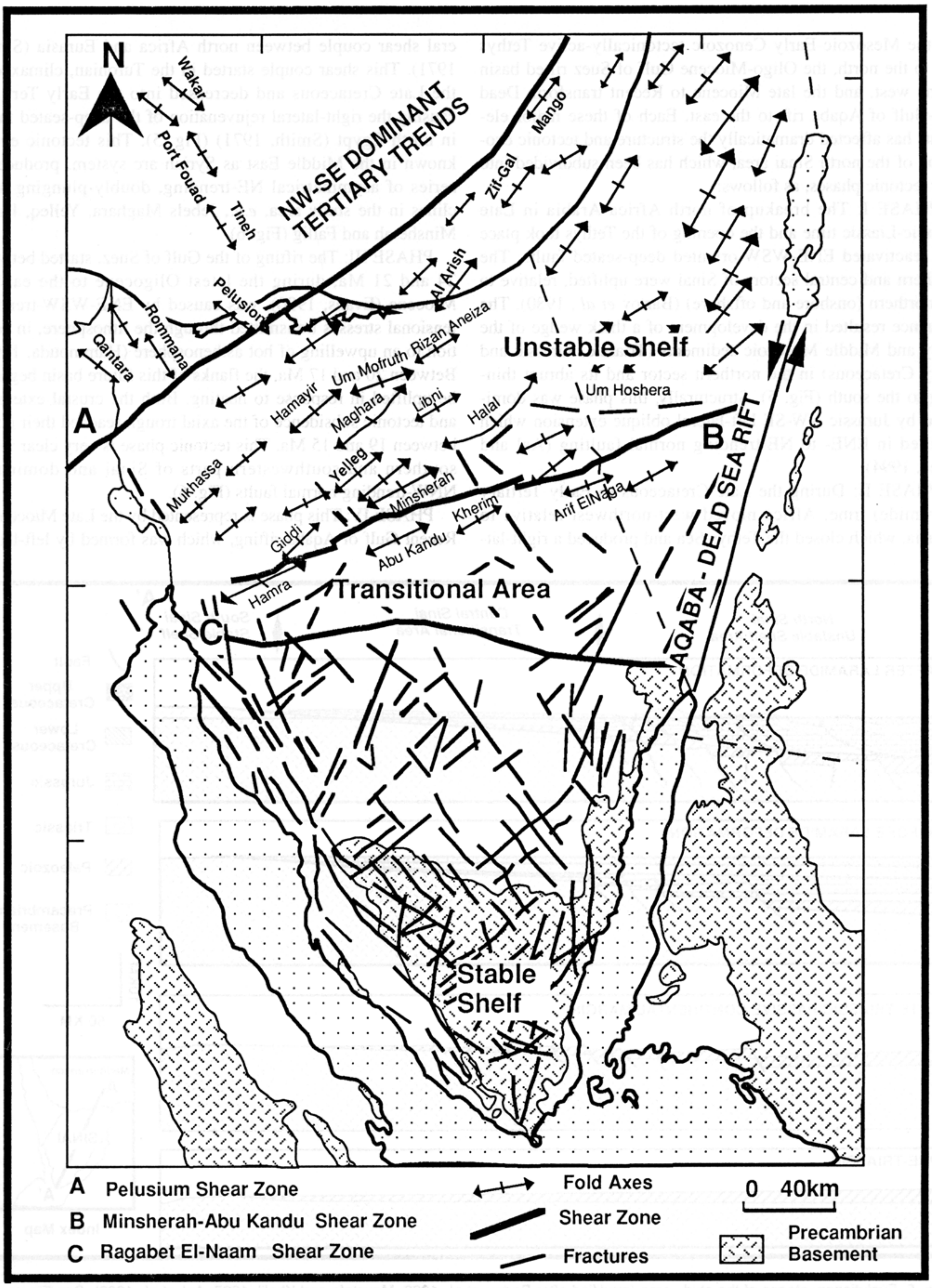

Fig. 6. Major tectonic elements in the northern Sinai District (modified after Neev, 1975).

oblique-slip movement along the Dead Sea (Levant) Shear zone along which approximately 105 km of left-lateral offset has been documented (Eyal *et al.*, 1981). Such tectonism dominated several E-W-trending faults rejuvenated with right-lateral movement, and are observed in central Sinai (Fig. 6).

Magnetic, gravity, seismic, surface and subsurface data from the north Sinai area delineate the geometry of the fault systems in the basin. According to structural setting and regional trends, the Sinai Peninsula can be subdivided into four provinces that are separated by three NNE-SSW- and ENE-WSW-trending major tectonic dislocation "shear zones" (Fig. 6). Moustafa and Khalil (1990) recognized less-extended fold belts and named them as subbelts. The major fold belts are:

a. Ragabet El-Naam Shear Zone, named Central Sinai Shear Zone by some authors, is the most southern belt and is probably a reactivated Paleozoic trend (Beyth, 1981) (Fig. 6). Dominance of E-W- and ENE-WSW-trending wrench faults and folds are interpreted by Aal and Lelek (1994) as a result of pure shear forces. This shear zone separates the southern sector of the Sinai Peninsula, known as the stable shelf area by Said (1962), with the exposed Precambrian basement from the transitional zone.

b. Minsherah-Abu Kandu Shear Zone separates the transitional zone, where both compressive and wrench stresses affected central Sinai and resulted in creating flower structures along prominent right-lateral shear zones (Harding, 1985) and the unstable shelf in north Sinai (Fig. 6). Such flower structures have a remarkable thinning of the sedimentary section along the ENE-trending Jurassic wedge-edge, *e.g.*, Jebel El-Minsherah (Aal and Lelek, 1994).

c. Pelusium Shear Zone, proposed by Neev (1975), trends NE-SW and isolates the offshore structures trending NE-SW from others trending NW-SE (Fig. 6). This hinge zone truncates the Miocene Messinian evaporites and forms their southeastern boundary. Neev (1977) extrapolated the Pelusium line northwest of the Bardwail lagoon until the Western Desert of Egypt. Furthermore, it was traced southwest, through West Africa, to the Atlantic Ocean and, hence, is a transcontinental shear.

The southern part of the unstable shelf area is characterized by the abundance of ENE- and NE-trending, doubly plunging, asymmetric anticlines with relatively gentle dip on their NW flanks (5°-20°) and steeper dips on their SE flank. The latter is vertical, and even overturned in some of the anticlines, and is faulted down to the south by means of NE-SW-trending faults (Moustafa and Khalil, 1987). The north Sinai folds vary in size from 10 km long and 5 km wide (such as Jebels Rizan Aniza and Libni) to 50 km long and 20 km wide, *e.g.*, Jebels Yelleg, Maghara and Halal (Fig. 1). The outcropping folds suffered different degrees of erosion in the core. The maximum recorded erosion is that of Jebel Maghara, where the Lower Jurassic section is exposed, but in other places the Upper Cretaceous sediments are exposed in the core of the fold.

The contrast between the Upper Tertiary clastics and the unconformably underlying Late Cretaceous to Jurassic carbonates permits an acquisition of reliable seismic reflections and, consequently, enables the geophysicists to map the subsurface structures with fair to good reliability. The geophysical data established typically similar structures in the subsurface of the onshore and offshore Sinai to those present on the surface. The most dominant subsurface structure is the NE-SW-trending folds with almost similar sizes as the surface ones (Zaghloul and Khidr, 1992).

Four main types of structures are reported in the north Sinai area: 1) thin-skinned thrust-related features; 2) basement-involved forced folds; 3) flower structures; and 4) pure wrench faults. The distribution and the morphology of these structures depend mainly on the type of the dominant tectonics, *i.e.*, whether compressional or wrench tectonics (Aal and Lelek, 1994).

The interpretation of gravity, magnetic, seismic and well data show that northern Sinai consists of elongated troughs (source kitchens) that contain several high trends (elongated structural highs). Both troughs and highs are trending NE-SW. The age and distinctive structural and stratigraphic features within these subbasins vary from basin to basin. These subbasins are subdivided into onshore and offshore ones, as follows:

Onshore subbasins: These are, from south to north, the Central Sinai, South Yelleq, North Fallig, East Maghara, North Maghara and Northeast Sinai (Fig. 2). The northern onshore subbasins, formed in the Early Jurassic time due to the tectonic activities that affected North Africa, reach down to 5000 m. The most southern ones (Central Sinai and South Yelleq) are Eocene and Late Cretaceous subbasins and range in depth from 1500 to 2000 m. They were formed due to the marine transgression from the north.

Offshore subbasins: Generally, the whole offshore north Sinai area is considered as a deep basin, relative to the onshore area, with two very deep subbasins (Fig. 2): 1) the Walker-Port Fouad Subbasin, where some of the drilled wells bottomed in the Oligocene section at 4700 m, is located at the northwestern part of the study area and 2) the Tineh-Mango Subbasin, extending from the well Tineh-1 (bottomed in the Eocene section at 4200 m), through the NS21-1 well (bottomed in the Cretaceous section at 4500 m), to Mango-1 (bottomed in the Jurassic section at 4650 m).

HYDROCARBON HABITAT

The hydrocarbon potential of the study area is generally promising because the tectonic activity produced favourable conditions for rich source rock deposition and a heat regime placing these source rocks in the hydrocarbon generation window. The different tectonic phases resulted in the development of carbonate and sandstone reservoirs, presence of potential fine clastics, dense carbonates and evaporite seals and several types of trap for accumulation of oil and/or gas.

SOURCE ROCK POTENTIAL

This section aims to evaluate the source rock richness, kerogen type, maturity regime and hydrocarbon (oil and/or gas) composition and correlation. The source rock potential of the northern Sinai has been studied by Abdin and Aal (1992), Aal and Lelek (1994) and Tammam (1994).

1) Source Rock Richness

The geochemical parameters of 12 wells drilled in the onshore and offshore of north Sinai found organic-rich source rocks within four stratigraphic sequences (Fig. 7) with oil and/or gas kerogen type (types II and III) (Fig. 8), as follows:

JURASSIC: The Jurassic section is penetrated in a few wells drilled in the study area. Most of the Jurassic section has been identified as having rich potential source rocks (more than 1.5% TOC) in the Shusha, Bir Maghara, Safa and Masajid formations. The Jurassic shales and carbonates yield an average TOC value of 2.0% and the recorded TOC values are 3.0%, 1.94%, 2.64% and 1.6% in the N. Fallig-1, El-Mazar-1, Misri-1 and Mango-1 wells, respectively (Fig. 7). The available pyrolysis yield (S2) for the Jurassic source rocks are rarely less than 5 kgm/tonne, which matches the TOC readings. In other areas, the Jurassic Masajid and Bir Maghara carbonates have not been analyzed and are described as: a) light brown to black, b) fine-grained, and c) laminated limestones (Oehler, 1984). They show lower formation density and higher gamma ray in comparison with the overlying carbonates (Meyer and Nederlof, 1980). These Jurassic carbonates are considered as typical carbonate source rocks.

LOWER CRETACEOUS: The Lower Cretaceous section is considered to have the most prolific source rocks, especially in the offshore part of north Sinai (Tammam, 1994). The available geochemical data for the shales of the upper part of the Rakeib Formation and shales of Rizan Aneiza Formation show good to excellent source units. The average TOC of this interval in the study area is 1.7%. The maximum recorded TOC value is 5.2% in the well Abu Roda-1 (Fig. 7).

OLIGOCENE: The Oligocene shales are well developed in the western part of the study area and contain total organic carbon up to 7.01% and 6.0% in the wells Abu Roda-1 and Wakar-1, respectively (Fig. 7). Elsewhere, the Oligocene shales contain poor to fair source rock potential in the rest of the offshore and onshore area.

MIOCENE: The Miocene shales follow the same trend of the Oligocene rich shales. The maximum recorded TOC value is 5.37% in the well Abu Roda-1 and the recorded TOC values are 0.6%, 0.4%, 1.2%, 0.8% and 1.0% in the Enab-1, NS21-1, Wakar-1, El-Mazar-1 and Misri-1 wells, respectively (Fig. 7).

2) Kerogen Type

The available hydrogen and oxygen indices of the candidate

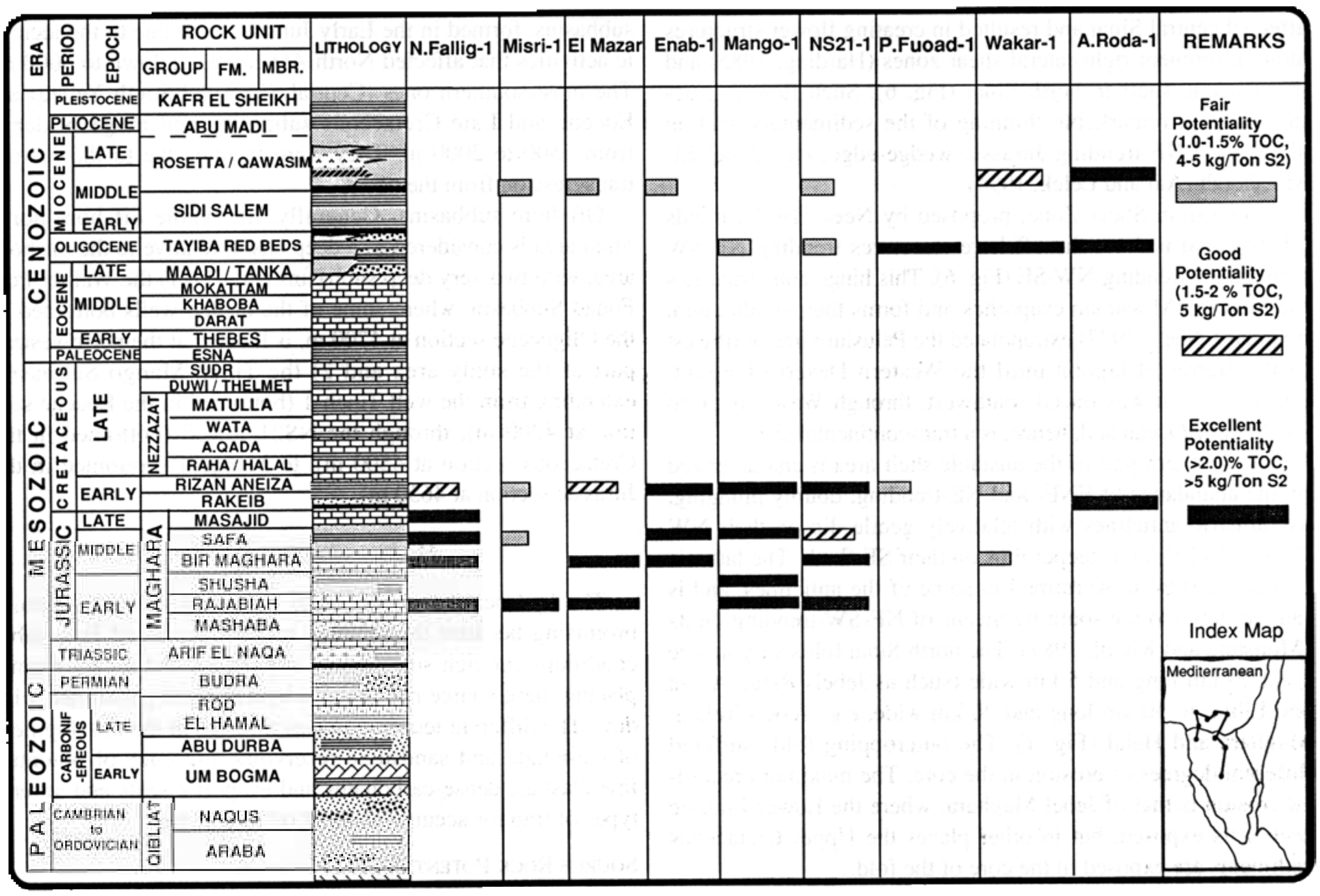

Fig. 7. Source rock richness through stratigraphic column in the northern Sinai area (based on information from EGPC, 1994).

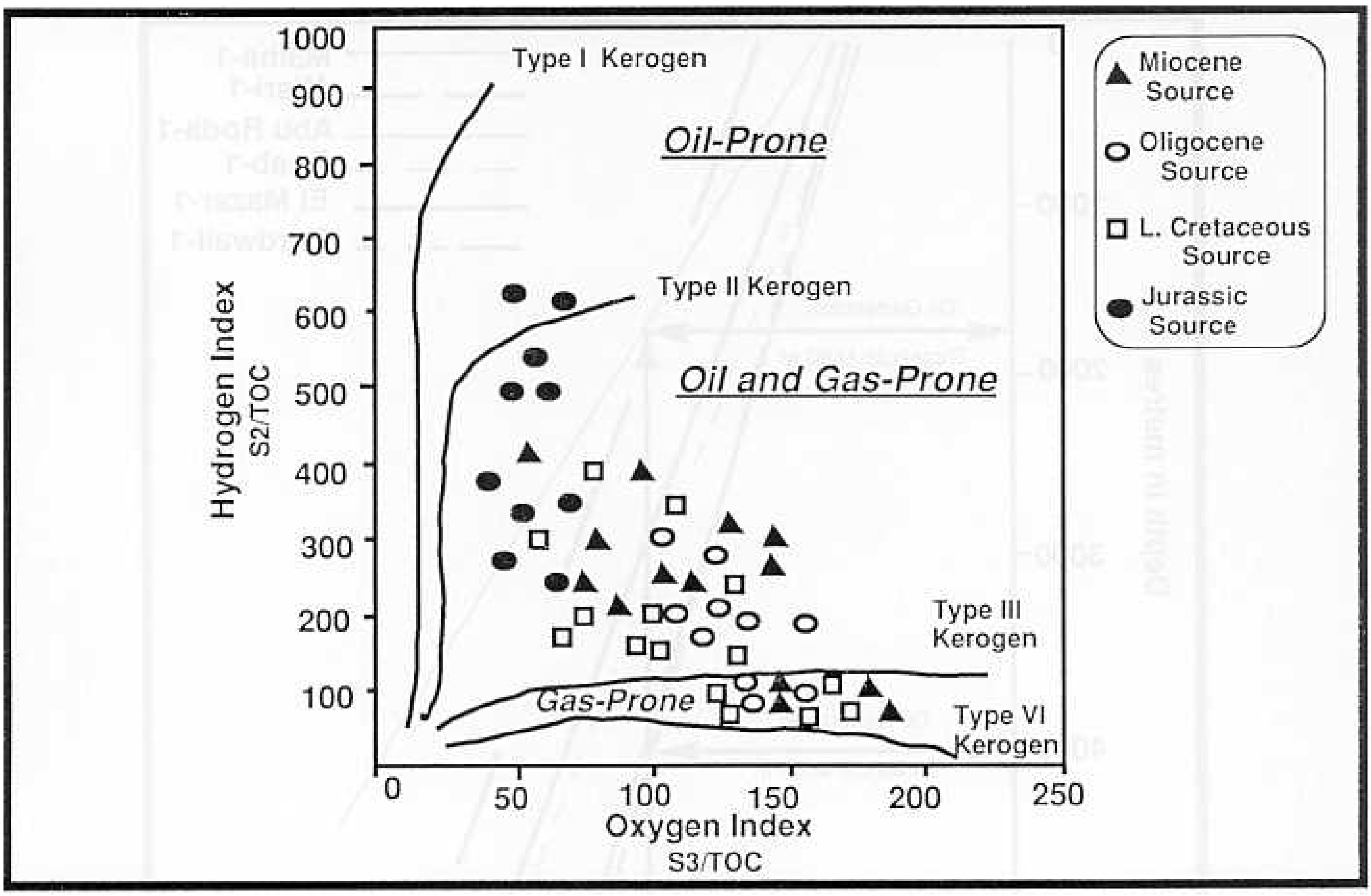

Fig. 8. Source rock types in northern Sinai (modified after Van Krevelen diagram).

source rock units in 13 wells (Fallig-1, Misri-1, Bardawil-1, NS21-1, Mellaha-1, Abu Roda-1, Enab-1, El Mazhar-1, Kersh-1, Mango-1, Teneh-2, Halal-1 and Waker-1) were plotted on Van Krevelen diagram to detect the kerogen type and the most likely-generated hydrocarbons (Fig. 8). The Jurassic source rocks display an oil and gas-prone (type II) kerogen type. The Lower Cretaceous, Oligocene and Miocene rich source rocks are oil and/or gas-prone (types II, III).

3) Source Rock Maturity

Maturity was estimated on the basis of vitrinite reflectance (Ro) and thermal alteration index (TAI) measurements. The available vitrinite reflectance data of six wells was plotted against depth to detect the boundries of the oil generation window (Fig. 9). The time-temperature index proposed by Waples (1985) was calculated first from the combined use of a burial history plot and geothermal gradient data, and then the equivalent isothermal value was estimated for several modelled points (Fig. 10). To substitute for the maturity estimate in undrilled areas (particularly in structurally deeper areas), the depths of the stratigraphic units in these modelled points were estimated from seismic and well data.

The main Jurassic and Lower Cretaceous source kitchens are: the East Maghara, North Maghara, Northeast Sinai and Tineh-Mango troughs. The Jurassic and the Lower Cretaceous source rocks are marginally mature to immature in the Central Sinai and North Fallig troughs. In the Wakar-Port Fouad trough, they are overmature.

The Oligocene and Miocene source kitchens in north Sinai are theWakar-Port Fouad and Tineh-Mango troughs. The Oligocene source rocks are mature in the northern part of the North Maghara trough.

The Waker-Port Fouad trough in the Mediterranean Sea is the deepest kitchen in the study area where the Oligocene reaches to approximately 4700 m (Figs. 1, 2) at parts which place the Jurassic and Lower Cretaceous source rocks in the gas generation window and even deeper. The oil generation threshold (OGT) took place approximately 100 Ma for the Jurassic and Lower Cretaceous sources and around 5 m.y. ago for the Oligocene and Miocene sources (Fig. 10). The depth to the onset of oil generation ranges from about 1800 to over 4100 m (Fig. 9).

4) Oil Study

Tammam (1994) used crude oil samples from the Mango discovery and Aal and Lelek (1994) used fluid inclusion analysis results in Fallig-1 well to geochemically assess the genetic relation(s) between source rocks and hydrocarbons in the north Sinai area. The former concluded that the Mango-1 oil is sourced from the Lower Cretaceous sources, while Aal and

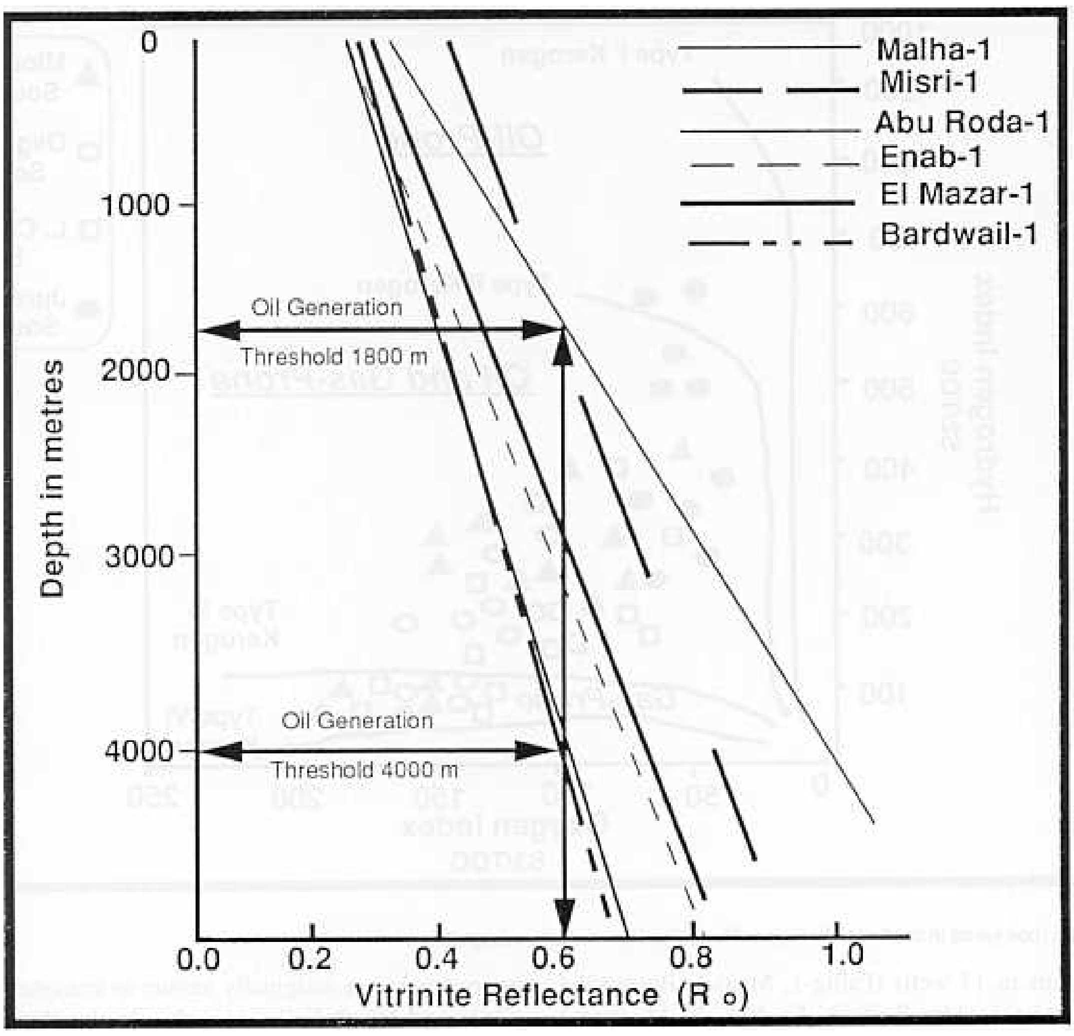

Fig. 9. Depth-vitrinite reflectance curves for some wells in north Sinai area (based on information from EGPC, 1994).

Lelek determined a match between the Jurassic source rocks and the fluid inclusion analysis.

Reservoir Potential

The north Sinai province is known for several stratigraphic units which produce, test and/or show hydrocarbons (oil and/or gas). Some authors found that gas discoveries are generally associated with Tertiary, Miocene and Oligocene sandstones, while oil discoveries are found in Mesozoic carbonates and sandstones. The recent discovery El Temsah (northwest of the study area), producing oil from the Miocene sandstones, and the Zohar and Sadot gas fields (northeast of the study area), producing gas from the Jurassic and Cretaceous, respectively, break the old rule. The potential reservoirs in north Sinai are classified into sandstone and carbonate reservoirs.

Sandstone Reservoirs

The major sandstone reservoirs range in age and characters as described below:

A. Early Jurassic sandstones: These include the sandstones of Mashaba, Rajabiah and Shusha formations. These sandstones are present in the central and northeastern parts of onshore north Sinai and have strong gas shows in the Qeren-1 well (just east of the study area). They have porosities ranging from 15 to 23% in the Halal-1 well and are nominated as good reservoirs by Aal and Lelek (1994). The quality of such reservoirs depends mainly on the depth of the sandstone, the amount of argillaceous matter and/or calcareous cement content.

B. Early Cretaceous sandstones: The Early Cretaceous sandstones range up to 200 m and are fine- to coarse-grained, crossbedded, highly jointed and of high porosity and permeability (Ammar and Afifi, 1992). These sandstones belong to the Rakeib and Rizan Aneiza formations. The sandstones tested oil in the Mango-1 discovery and produced from the Israel Heltz oil field (just northwest of the study area). The net sand thickness in the Mango discovery reaches 35 m with an average porosity of 25%.

C. Oligocene sandstones: These sandstones have good potential over the western offshore and onshore parts of the

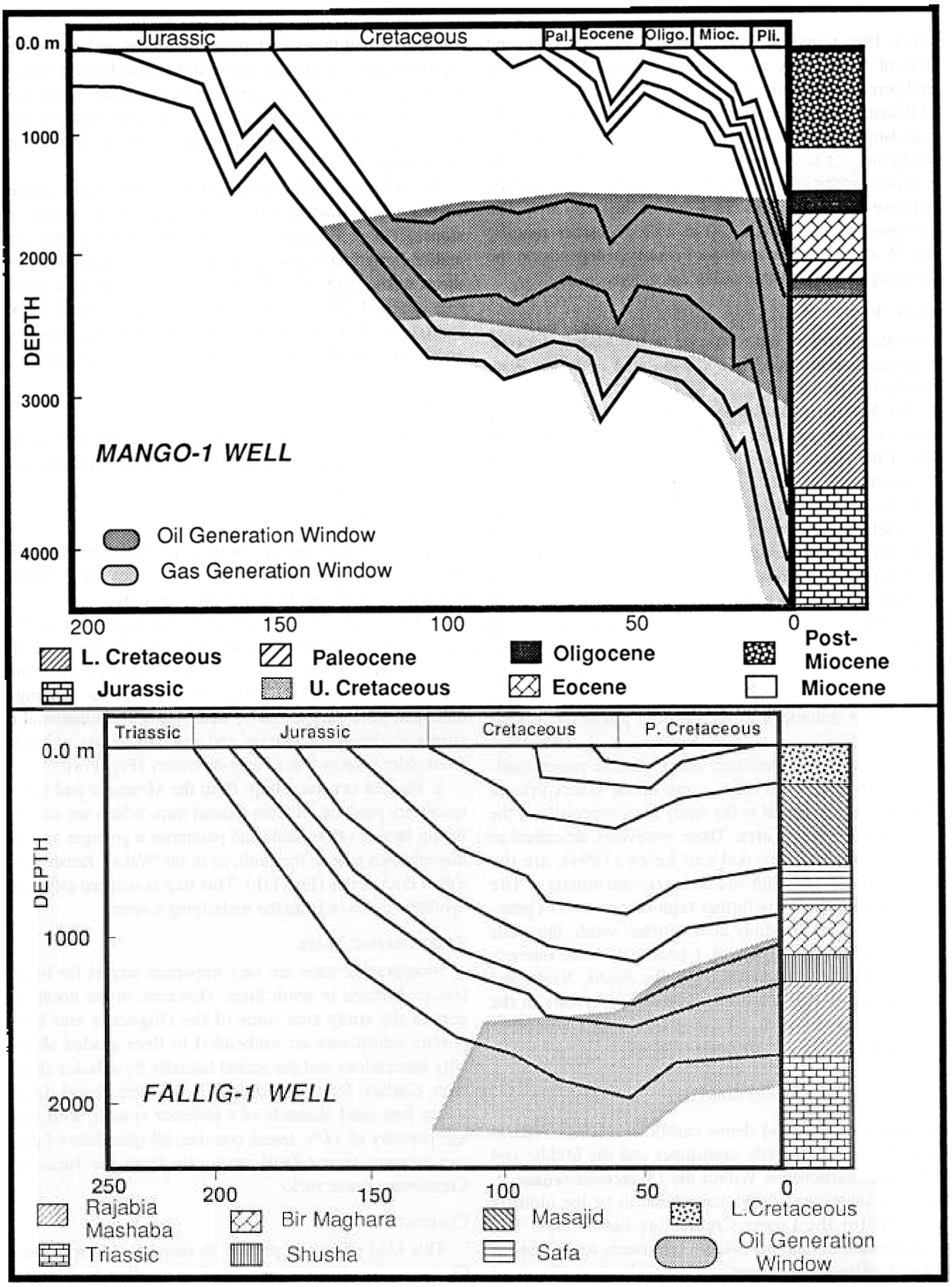

Fig. 10. Burial history plot of modelled points Mango and Fallig (modified after Aal and Lelek, 1994; Tammam, 1994).

study area. They tested oil in Tineh discovery with a net sand thickness of 50 m. They have porosities ranging from 18 to 23% and permeabilities of between 216 to 1729 md.

D. Miocene sandstones: The Sidi Salem, Qawasim and Abu Madi sandstones produce oil and/or gas from seven fields in and nearby the north Sinai area: Port Fouad, Walker, Temsah, Kersh, Qantara, Abu Madi and Naf. These sandstone reservoirs are well developed in the western sector of the study area. The average reservoir thickness is 30 m with porosities ranging between 15 and 25%. The quality of reservoir depends on the amount of argillaceous matter and/or calcareous cement.

Carbonate Reservoirs

Carbonate reservoirs are restricted to the Middle Jurassic Bir Maghara, Late Jurassic Masajid and Late Cretaceous Wata and Matulla formations.

The Bir Maghara limestones have oil shows and were recorded as oil staining in some of the drilled wells in the eastern side of the study area. The porosity of these limestones depends mainly on secondary diagenetic processes.

The Late Jurassic carbonates produced oil from the Heltz field of Israel and have strong oil shows in most of the coastal wells. These carbonates are reefal limestones and were described as good reservoirs by Aal and Lelek (1994).

The Wata and Matulla carbonates are the main reservoir in Sadot gas field and Raad discovery where reefal facies with almost 35 m net pay thickness and average porosity and permeability of 13% and 81 md, respectively, contain 30 billion cubic feet of gas. These carbonates are described as vuggy, microcrystalline dolomites in the onshore jebels by Ammar and Afifi (1992).

In addition to these Mesozoic and Cenozoic major sandstone and carbonate reservoirs, some minor reservoirs are recorded with less potential in the study area, especially in the offshore part of the study area. These reservoirs, described as having good potential by Aal and Lelek (1994), are the Paleozoic sandstones and the Triassic carbonates. The Paleozoic section, deserving further exploration, was not penetrated or exposed in the study area. Farther south, the wells Abu Hamth-1, Nakhl-1 and Darag-1 penetrated some interested Paleozoic rocks. The sandstones of the Araba, Naqus and Abu Durba formations may form potential reservoirs in the southern part of north Sinai. Fair to good porosity was penetrated in the Arif El Naqa carbonates of Halal-1.

Seal Potential

The Jurassic shales and dense carbonates act as vertical seals over the Lower Jurassic sandstones and the Middle and Upper Jurassic carbonates. Within the Cretaceous sequence, the Nezzazat shales are always considered to be the ultimate vertical seal for the Lower Cretaceous sandstones. The Paleocene Esna shale and the Eocene carbonates act as vertical seals over the Upper Cretaceous reservoirs. In areas of normal faulting, the magnitude of throw on the clysmic fault is very critical in the effective sealing mechanism (Meshref *et al.*, 1988). A small throw juxtaposes the shales and dense carbonates of some stratigraphic units on the downthrown side of the fault against the porous carbonates and/or the sandstones of the same unit on the uplifted block. A large throw will bring young seal rocks juxtaposing older reservoirs on the uplifted block (Figs. 11, 12).

The Miocene Sidi Salem and Qawasim shales can act as sealing agents for the Oligocene and Miocene porous sandstones. These Miocene shaly intervals will become vertical and/or horizontal seals, depending on the magnitude of the throw of the fault. The Miocene shales also play an important role in stratigraphic traps where they laterally face a body of sandstone. The Qawasim equivalent Rosetta anhydrite is another seal for the Oligocene and Miocene sandstones.

Trapping Mechanism

The hydrocarbon entrapment in the northern onshore and offshore Sinai can be regarded as structural, stratigraphic and combination traps.

Structural Traps

Structural traps are the most important type in the north Sinai district, where most of the discoveries are in structures (Figs. 11, 12). These traps are represented by:

a. Four-way dip closures: This trap is present as 1) fold core sealed vertically and laterally by the overlying shales and/or dense carbonates and sourced from an older source rock, *e.g.*, Sadot gas field (Fig. 12a); and 2) the hanging wall anticlinal reservoirs sealed vertically by intraformational mudstones or dense carbonates and sourced across or up faults from older sources, *e.g.*, Tineh discovery (Fig. 11a).

b. Faulted structural trap: Both the Mesozoic and Cenozoic reservoirs produce oil from faulted traps which are sealed vertically by one of the seals and juxtapose a younger seal on the downthrown side of the fault, as in the Wakar, Kersh and Abu Zakin discoveries (Fig. 11b). This trap is sourced either across synthetic faults or from the underlying sources.

Stratigraphic Traps

Stratigraphic traps are very important targets for hydrocarbon exploration in north Sinai. However, in the northwestern part of the study area some of the Oligocene and Miocene porous sandstones are embedded in finer graded shaly and silty successions and are sealed laterally by a facies change to finer clastics. Such an example is the Port Fouad discovery where four sand channels of a turbidite system, with an average porosity of 18%, tested commercial quantities of gas. Oil can migrate across faults or updip from the Jurassic and Cretaceous source rocks.

Combination Traps

This kind of trap is present as reefal buildups of the Late Cretaceous carbonates on a fault-controlled high sealed by intraformational mudstones or dense carbonates and charged from Jurassic and/or Early Cretaceous sources.

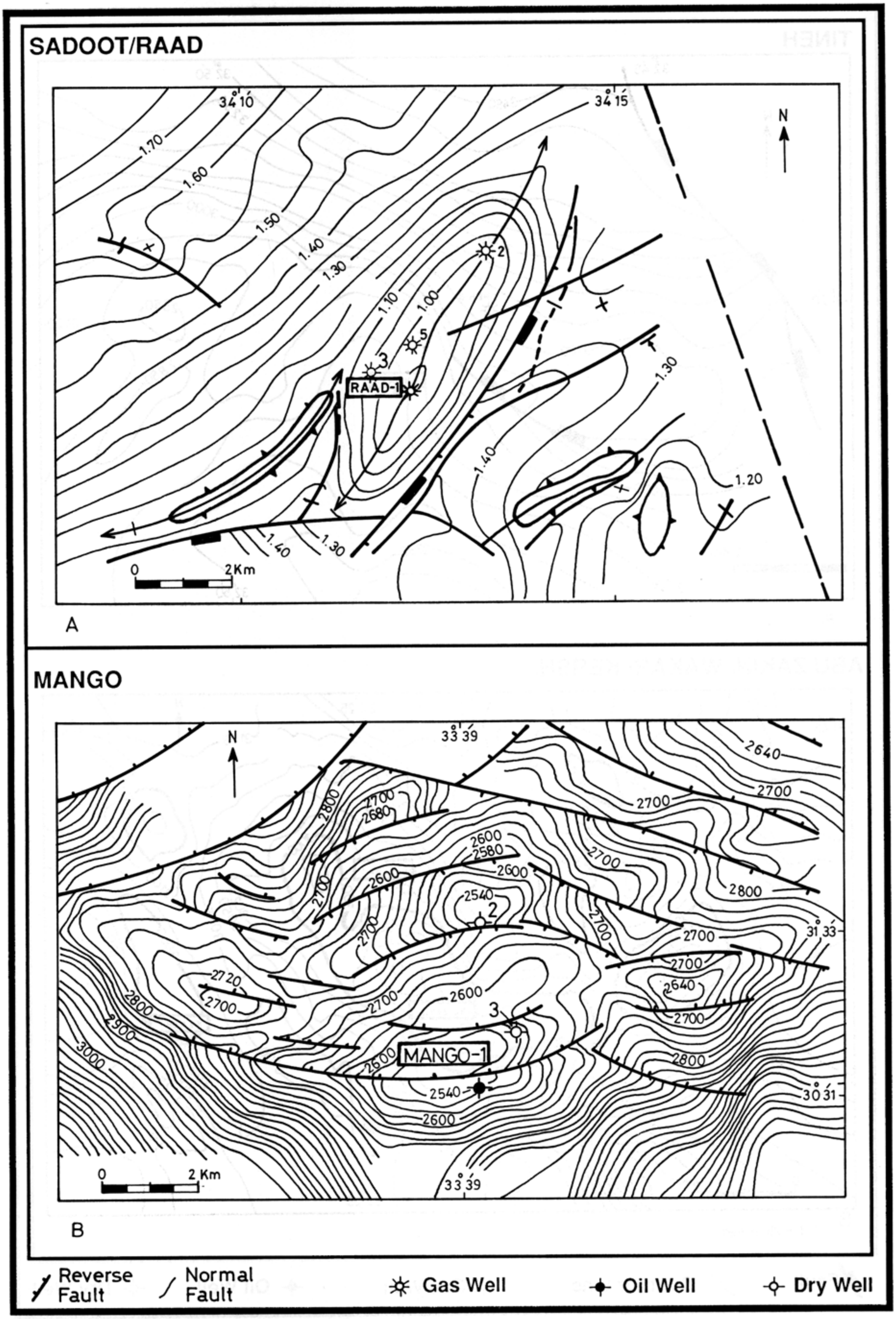

Fig. 11. A. Structure contour map on top Late Oligocene in the Tineh discovery (modified after EGPC, 1994). **B.** Structure contour map on top middle Miocene in the Wakar, Abu Zakin and Kersh discoveries (modified after EGPC, 1994).

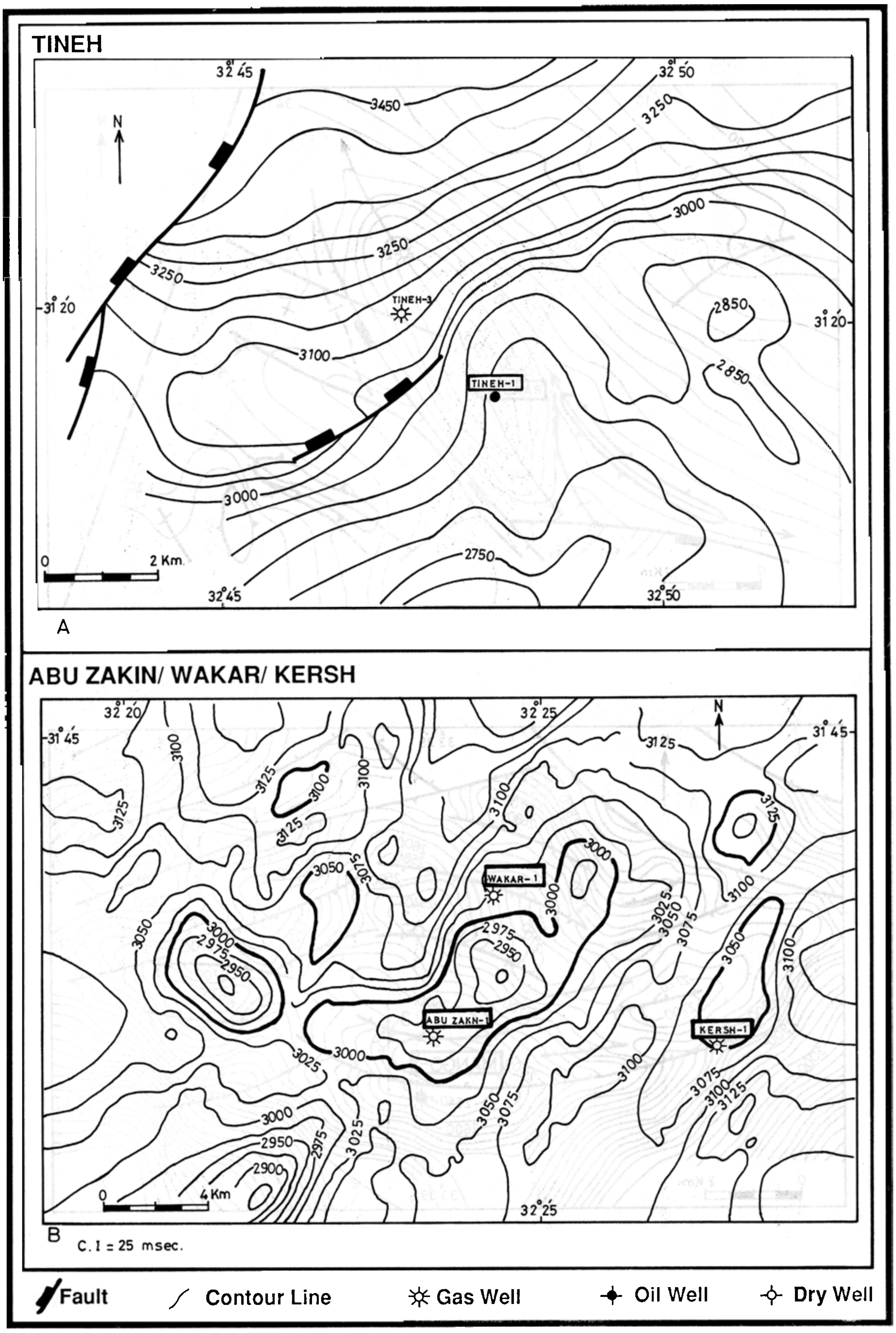

Fig. 12. A. Time map on top Cenomanian in the Sadot and Raad gas fields (modified after EGPC, 1994). **B.** Structure contour map on top Albian in the Mango discovery (modified after EGPC, 1994).

CONCLUSIONS

The Sinai Peninsula, the common part of Africa and Asia, is bounded by the Gulf of Suez rifted basin to the west, the transform Dead Sea-Aqaba rift to the east and the Mediterranean passive margin to the north. The North Sinai lithostratigraphic units range in age from Precambrian to Recent. These units vary in lithology, thickness, areal distribution and depositional settings.

The interpretation of both geological and geophysical data shows four main tectonic trends (normal and transform faults and folds) reflecting the influence of regional tectonic movements on the North Sinai. These trends are: 1) ENE-WSW-trending normal faults, mapped at the Triassic, Jurassic and Early Cretaceous levels; 2) NE-SW-trending anticlines at the Late Cretaceous and Early Tertiary levels; 3) NNW-SSE-trending normal faults at the Oligocene and early Miocene levels; and 4) NNW-SSE-trending transform faults mapped on the Late Miocene.

Three main rich source units: 1) the Jurassic shales; 2) the Early Cretaceous carbonates; and 3) the Oligo-Miocene fine clastics, could yield oil and/or gas and are mature enough in the deep kitchens to generate hydrocarbons. In addition to the Jurassic and Cretaceous carbonates, the sandstones of the Miocene, Oligocene, Cretaceous and Jurassic rocks form the major reservoirs in the north Sinai. The intraformational Mesozoic and Cenozoic shales and dense carbonates and the middle Miocene anhydrite form the seals for hydrocarbons. Trap types include structural, stratigraphic and combination traps.

It is fair to say that the north Sinai remains high in hydrocarbon potential with many untested plays.

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