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Lithostratigraphy, Sedimentology and Hydrocarbon Habitat of the Pre-Cenomanian Nubian Sandstone in the Gulf of Suez Oil Province, Egypt

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ABSTRACT

The Paleozoic-Lower Cretaceous Nubian Sandstone is a thick sequence of up to 1,200 meters of clastic and thin carbonate sediments. In ascending order it is classified into the following groups and formations: Qebliat Group, Umm Bogma Formation, Ataqa Group and El-Tih Group. This sequence is composed mainly of sandstones with shale and minor carbonate interbeds and was deposited in continental and fluviomarine to marine settings. Petrographically, two main facies of Nubian Sandstone can be recognized in the Gulf of Suez: quartzarenite and quartzwackes. Both contain subfacies that are different in their secondary components, cement and matrix types, reflecting their different depositional environments and diagenetic histories. The pre-Cenomanian Nubian Sandstone is one of the most prolific reservoirs in the Gulf of Suez oil province. These sandstones have intervals with good reservoir quality throughout the basin, with net pay thickness of up to 450 meters, and net sand ratios ranging from 60% to 90%. Porosity varies from 10% to 29%, and permeability from 70-850 millidarcies. The quality of the reservoir depends on its shaliness, diagenetic history and the depth of burial (compaction). The Nubian Sandstone still has a high potential as a reservoir, particularly in the northern sector of the Gulf of Suez where few wells have specifically targeted this interval.

INTRODUCTION

This study is focused on the Gulf of Suez Basin, which represents the northern extension of the Red Sea and extends for almost 320 kilometers (km) with an average width of 50 km (Figure 1). This basin constitutes a large depression which lies below sea-level in the axial region (Salah, 1994). The Suez rift trends north northwest-south southeast, separating the African Plate from the Sinai Microplate.

Generally, the Gulf of Suez is subdivided into three sub-provinces relative to the structural dip of the sedimentary cover (Moustafa, 1976). These are separated by two major transfer faults, or "hinge zones". The northern one is called the Zaafarana Hinge Zone and separates the northern sector of the Gulf of Suez with a general dip to the southwest from the central sector of the Gulf of Suez which dips to the northeast. The other hinge zone is known as the Morgan Hinge Zone and separates the central sector from the southern sector which dips again towards the southwest (Figure 1).

The stratigraphic section in the Gulf of Suez ranges in age from Precambrian to Recent and can be classified into two megasequences: pre-rift (pre-Miocene) and syn-rift (Miocene to Recent) (Figure 2).

The essential works on the stratigraphy of the Nubian Sandstone are reviewed in the stratigraphic part of this paper (Barron, 1907; Ball, 1916; Cuviller, 1937; Beats, 1948; Kostandi, 1959; Said, 1962 and 1971; Abdallah et al., 1963; Hassan, 1967; Weissbrod, 1970; Soliman and El-Fetouh, 1970; Mazhar et al., 1979; Issawi and Jux, 1982; Barakat et al., 1986; Beleity et al., 1986; El-Barkooky, 1986; Zahran and Meshref, 1988; El-Araby, 1989; Darwish, 1992).

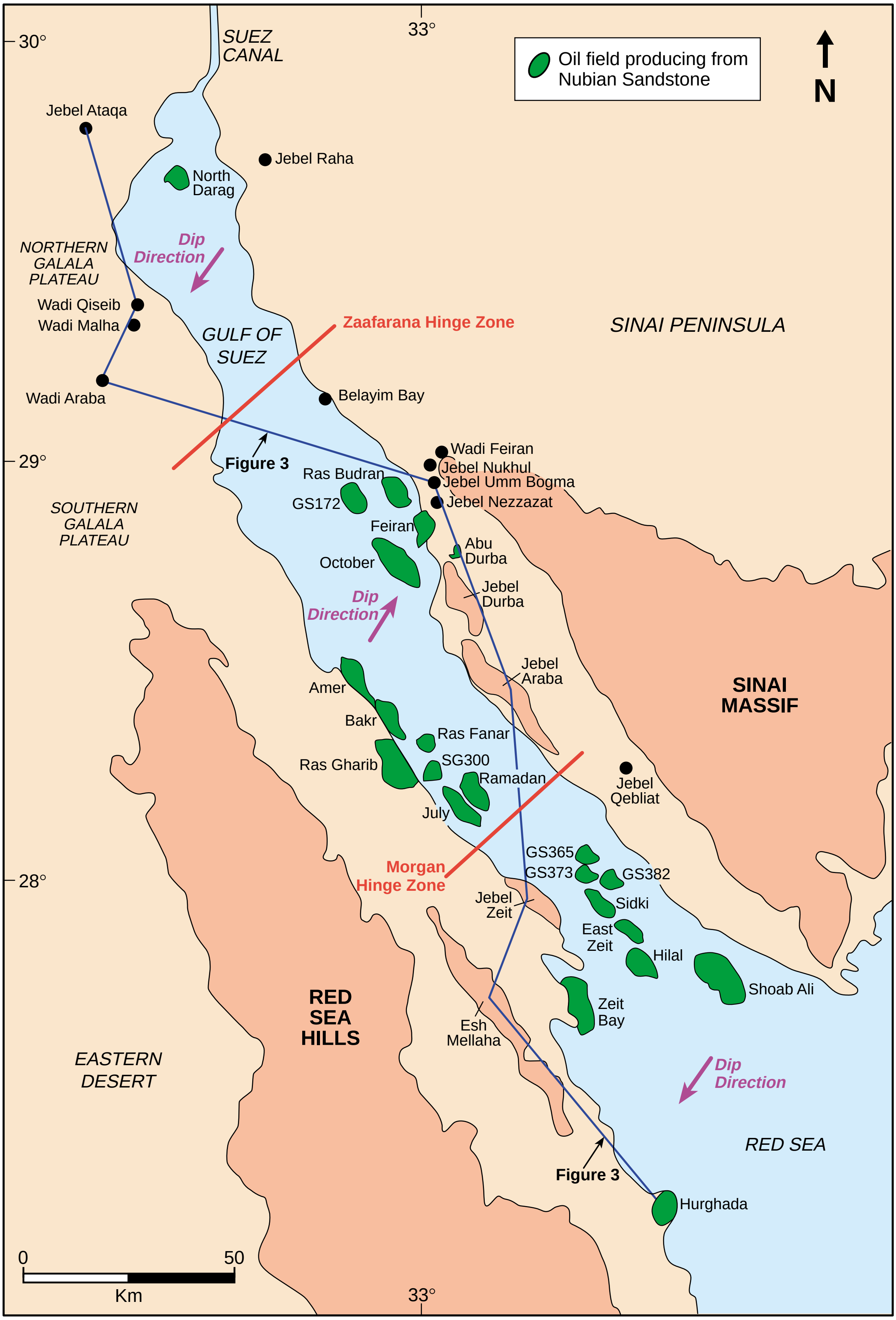

Figure 1: Nearly 20 of the more than 60 oil fields in the Gulf of Suez produce oil from the Nubian Sandstone.

The prolific Gulf of Suez oil basin contains more than 60 oil fields with initial reserves from 1,350 million barrels to less than 1 million barrels, in reservoirs from Precambrian Basement to post-Miocene age. The pre-Cenomanian Nubian Sandstone forms one of the major reservoirs in the Gulf of Suez. It produces oil in Ramadan, July, Ras Gharib, Hurghada, Sidki, October, East Zeit, Feiran, Ras Budran, Hilal, and Ras Fanar oil fields (Figure 1).

The main goal of this paper is to define the surface and subsurface lithostratigraphic units of the pre-Cenomanian Nubian Sandstone, describe its petrographic characteristics and hydrocarbon potential including reservoir, seal, and source potential in the Gulf of Suez oil province.

MATERIALS AND METHOD

The materials used in this study include electric logs, cores from selected intervals, side-wall cores and ditch samples of the Nubian Sandstone. The samples are from the offshore and onshore parts of the southern and central Gulf of Suez and from the Sidki, Hilal, Bakr and Ramadan oil fields (Figure 1). The core samples were first described and studied as hand specimens and then from binocular microscope. Thin sections were made from selected intervals of the studied cores, side-wall cores and ditch samples.

The classification of Pettijohn et al. (1987) was used for the description of the studied samples. The selected samples were impregnated with blue plastic resin to help distinguish porosity types. All thin sections were studied petrographically and the diagenetic processes and products were analyzed and described. This petrographic study aims to determine the facies and sub-facies and the main diagenetic processes of the Nubian Sandstones in the Gulf of Suez. The role of diagenesis is interpreted in relation to pore geometry, size and filling material.

STRATIGRAPHY

For more than one hundred years, the stratigraphic definition of the Nubian Sandstone has been the subject of numerous investigations. All the type sections of the formal stratigraphic rock units of the Nubian Sandstone cropout on both shoulders of the Gulf of Suez (Figure 1).

On the western side of the Gulf, the largely non-marine sandstone sequence termed Nubian Sandstone crops out on the western flank of both the Esh Mellaha Range and Jebel El-Zeit, Southern Galala and Northern Galala Plateaus (Wadis Qiseib and Malha) and Wadi Araba. On the eastern side of the Gulf of Suez, it is exposed in the Durba-Araba area (Jebel Qebliat and Jebel Naqus), Jebel Nukhul, Umm Bogma area, the southern scarp of Jebel El-Tih, Jebel Nezzazat, east of Belayim Bay and near the mouth of Wadi Feiran (Figure 1).

The term "Nubian" was used for the clastic section which lies immediately above the Precambrian Basement complex. Previously, it had been subdivided into four members: Nubian A (Early Cretaceous); Nubian B (Carboniferous); and Nubian C and D (Early Paleozoic). The most relevant studies dealing with the pre-Cenomanian sediments were carried out by El-Barkooky (1992), Darwish and El-Araby (1994) and Alsharhan and Salah (1995) who subdivided this succession into the following groups and formations (in ascending order) and summarized below (Figure 2).

Cambrian to Ordovician (Qebliat Group)

This group is distributed over the whole Gulf of Suez (Figure 3) and represents the oldest regressive marine facies. It was terminated with the development of fluviatile facies (Figure 4a). The Qebliat Group is divided into two formations, Araba and Naqus (Hassan, 1967). It lies unconformably over the Precambrian Basement and is unconformably overlain by the Umm Bogma Formation, in the northern and central portions of the Gulf of Suez, or the Nezzazat Group, in the Southern Gulf of Suez.

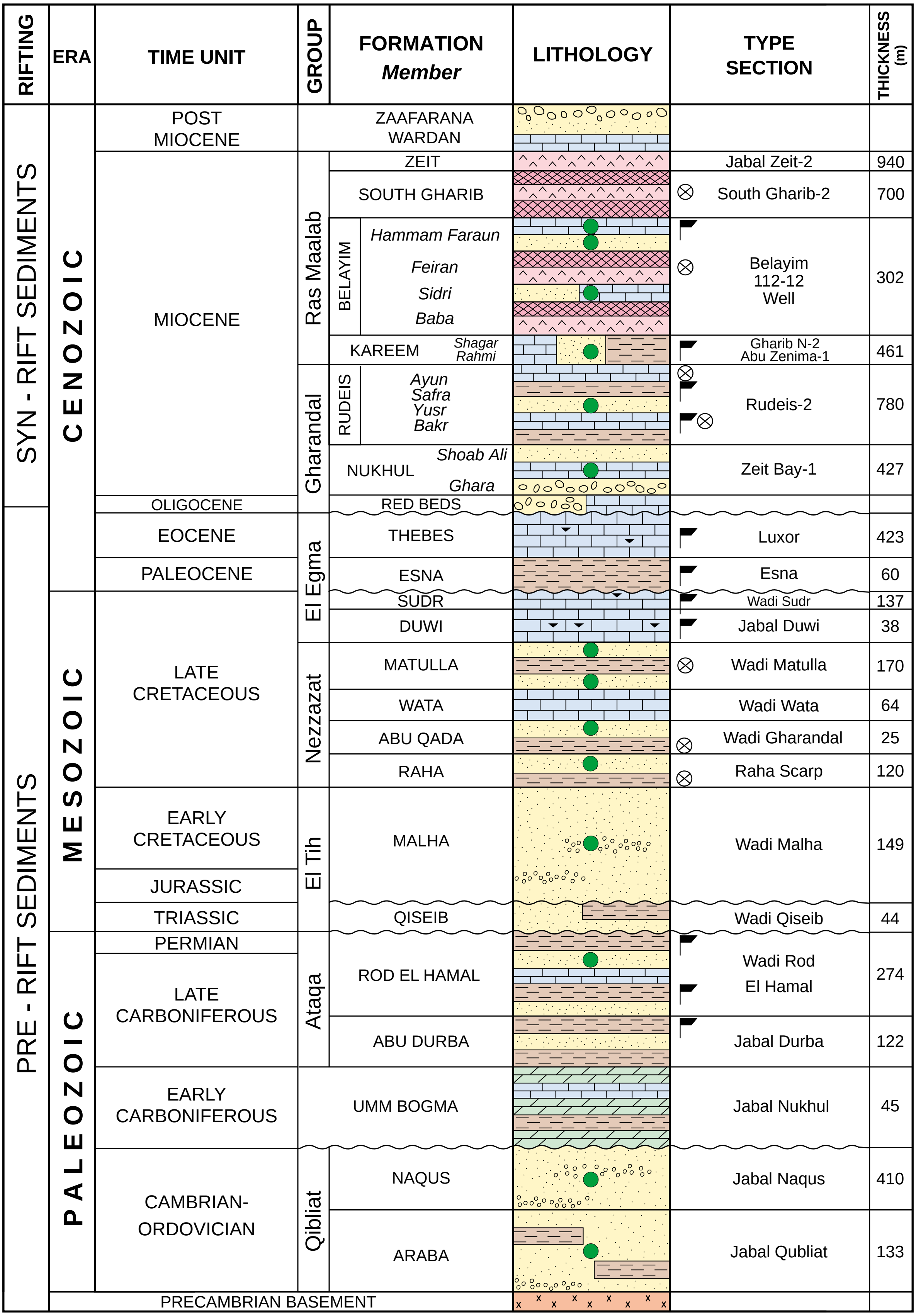

Figure 2: Stratigraphic column of the Gulf of Suez. Oil reservoirs are indicated by green circles (●), source rocks as flags (⚑) and seals as (⊗).

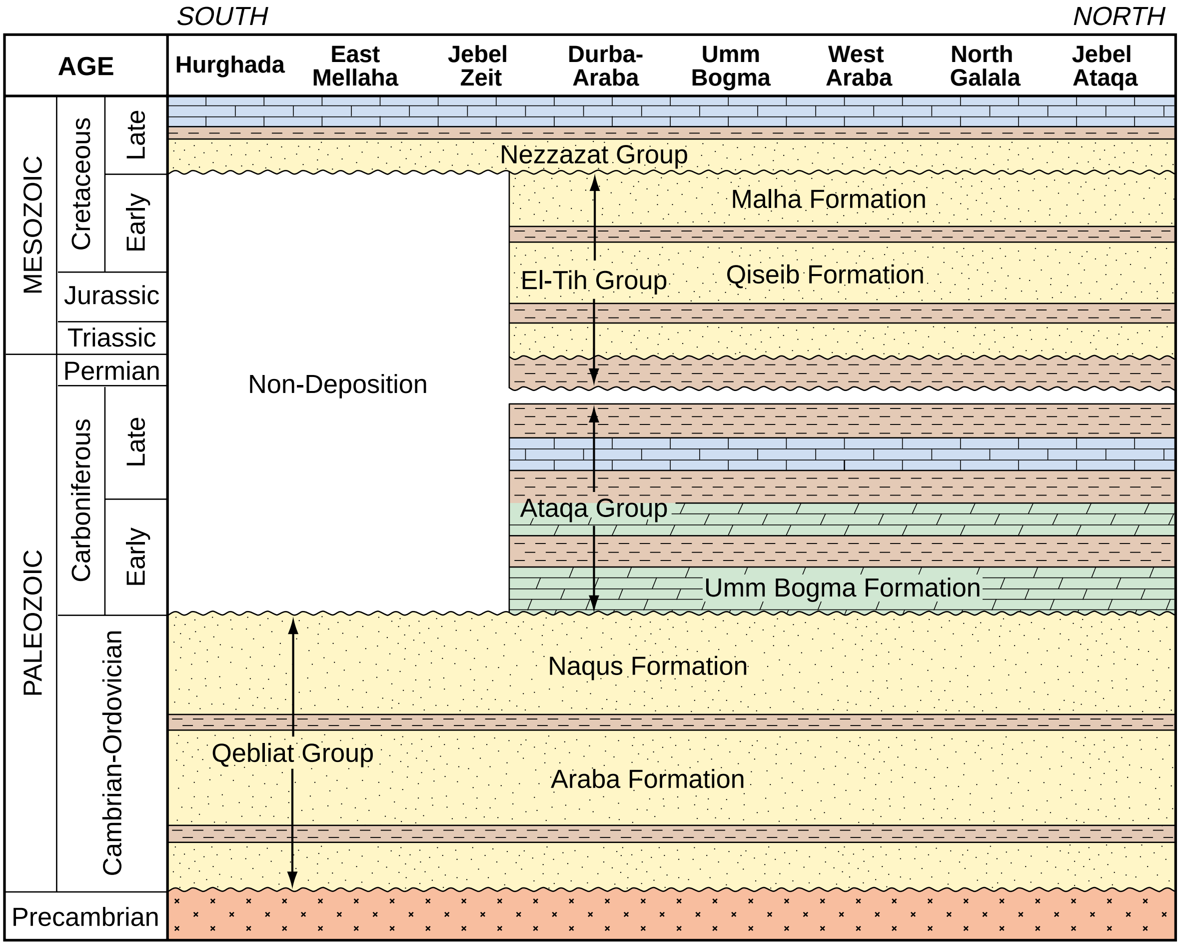

Figure 3: Distribution of the Nubian Sandstone units along the Gulf of Suez.

The Araba Formation is equivalent to the informal Nubian D' and dated as Lower Paleozoic, Cambrian or younger by Issawi (1973). It is recognized on the basis of the presence of traces of *Cruziana* and *Scolithus*. It is dominated by interbedded fine- to medium-grained, colorless to yellowish white sandstones and gray to greenish-gray mudstones. It reaches a thickness of 133 meters (m) at the type section located at Jebel Qebliat, Sinai (Figure 1).

The Naqus Formation is a continental sequence of thick, massive, pebbly, cross-bedded sandstone with minor clay interbeds at the top. It reaches upto 410 m in thickness in the type locality (Jebel Naqus, Durba-Araba area, Sinai). The Naqus Formation has been assigned an Ordovician age on the basis of stratigraphic position, since no fossils are recorded from this unit.

Early Carboniferous (Umm Bogma Formation)

The Umm Bogma Formation, proposed by Kostandi (1959), attains a thickness of 45 m in the type section in the Jebel Nukhul area, Sinai (Figure 1). On the basis of the abundance of *Neospirifer* sp., *Spirifer* sp., *Dielasma* sp., *Products* sp., *Lophophyllidium* sp., *Endothyra* sp. and *Tetraxis* sp., the Umm Bogma Formation is dated as Early Carboniferous. It consists of interbedded fossiliferous, highly calcareous shale and light gray dolomite, deposited in a shallow marine setting (Figure 4b). The Umm Bogma Formation unconformably overlies the Qebliat Group and is overlain by the Abu Durba Formation (Figures 3 and 5) in the central and northern Gulf of Suez, but in the southern Gulf of Suez, the Umm Bogma Formation is absent (Figure 3).

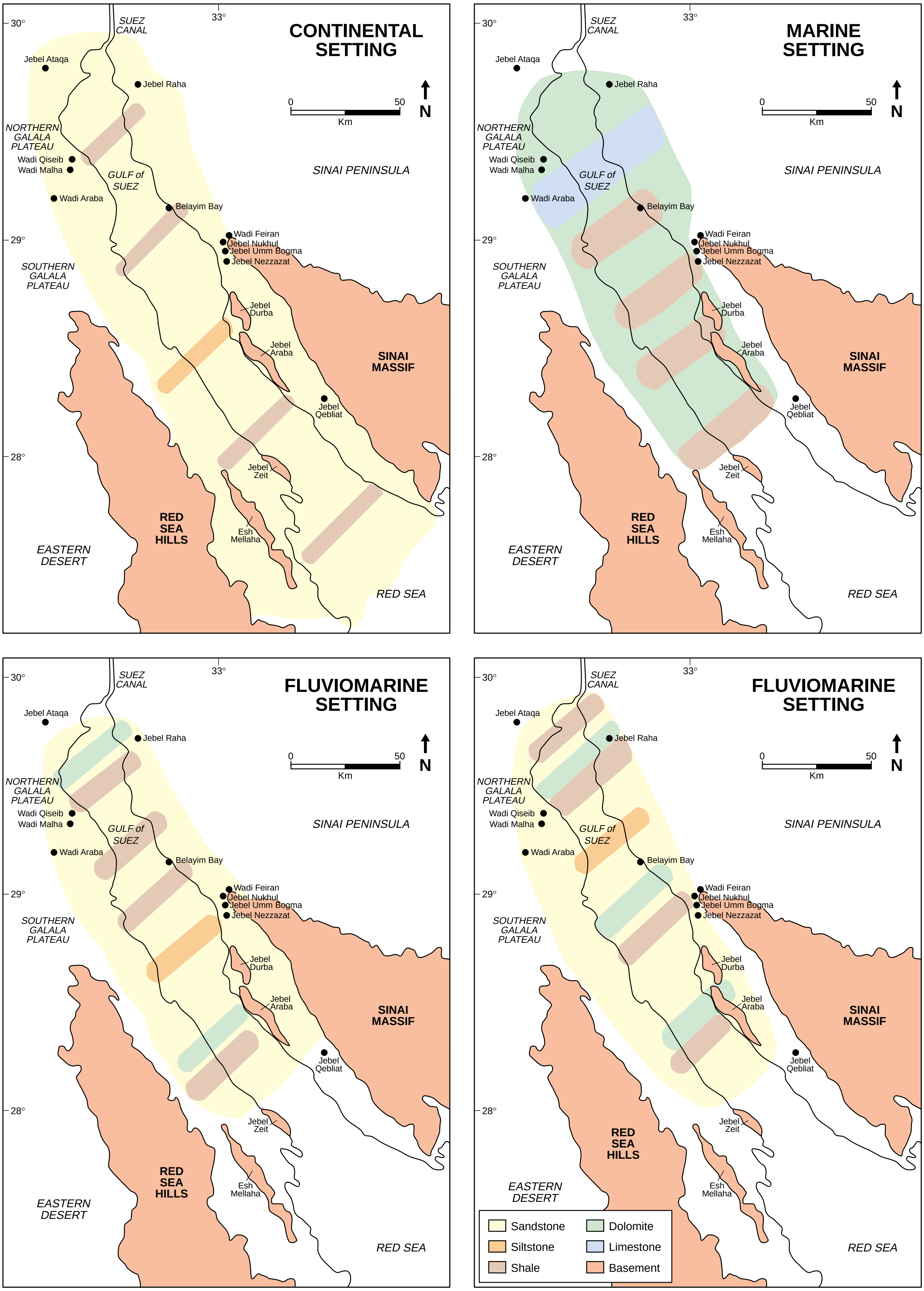

Figure 4: Depositional settings of the Nubian Sandstone units in the Gulf of Suez.

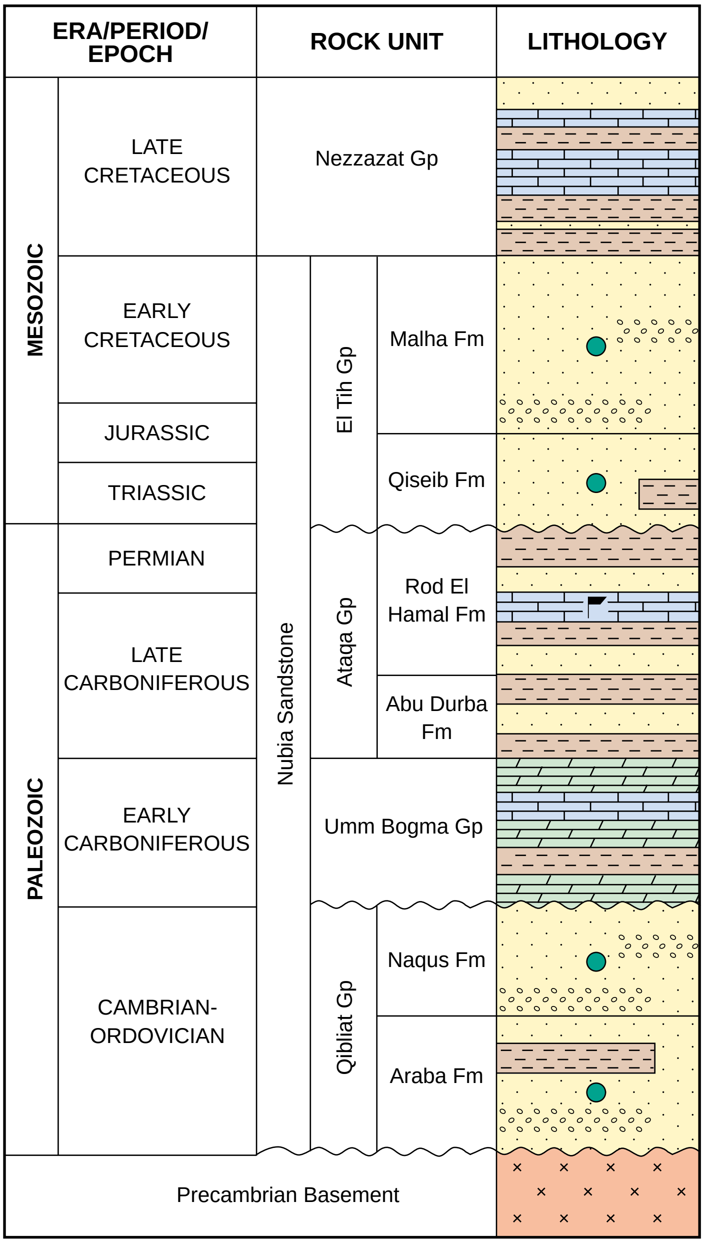

Figure 5: Schematic section showing the stratigraphic development of the Nubian Sandstone along the Gulf of Suez.

Late Carboniferous - Permian (Ataqa Group)

The Ataqa Group was proposed by Soliman and El-Fetouh (1970) and lies conformably to unconformably upon the Umm Bogma Formation. It includes two formations, Abu Durba and Rod El Hamal, that were deposited in a fluviomarine setting (Figure 4c).

The Abu Durba Formation, which lies conformably upon the Rod El Hamal Formation, attains a thickness of 122 m at the type locality in Jebel Abu Durba on the Sinai side of the Gulf of Suez. It is composed mainly of fossiliferous marine black shale with thin carbonate streaks. The formation is rich in *Neospirifer* sp., *Spirifer* sp., *Products* sp., *Bellorophon* sp., *Rhynconella* sp. and crinoidal stems and is dated as Early Carboniferous by Hassan (1967).

The Rod El Hamal Formation reaches a thickness of 274 m at the type section in Wadi Rod El Hamal, Sinai, Gulf of Suez. It consists of interbedded sandstone and shale with streaks of carbonates in the upper part reflecting fluviomarine setting. It overlies the Abu Durba Formation and in turn, is unconformably overlain by the Qiseib Formation of El-Tih Group. The formation is dated as Carboniferous by Beleity et al. (1986) based on the presence of both macro- and microfossils. The macrofossils, described by Abdallah (1965), include *Allerisma* sp., *Spirigerella* sp., *Productus* sp., *Bellorophon* sp., *Tabulipora* cava and pleurophorus. The microfossils, described by Said and Eissa (1969), include *Bigenerina* elongata, *B.* virgilensis, *Textularia* bucheri, *Ammovertella* sp., *Hyperammina* compressa, *Ammodiscus* annularis and *Sphaeroidalis* sp.

Triassic - Early Cretaceous (El-Tih Group)

In the Gulf of Suez, the El-Tih Group was named by Barakat et al. (1986) and was previously called the "Mesozoic Nubian". It unconformably overlies the Rod El Hamal Formation of the Ataqa Group and underlies the Late Cretaceous Nezzazat Group (Figure 5). It includes two formations, the Qiseib and Malha.

The Qiseib Formation reaches a thickness of 44 m at the type locality in Wadi Qiseib, in the Northern Galala Plateau and is composed of interbedded continental, ferruginous, red beds of sandstone and variegated-colored shale, with some marine limestone in the basal part of the unit (as recorded in Wadi Rod El-Hamal). It was dated by Abdallah et al. (1963) as Late Permian-Triassic but was considered to be Triassic by El-Barkooky (1992) and Darwish and El-Araby (1994), based on its stratigraphic position.

The overlying Malha Formation, consists mainly of white to gray, continental sandstone, passing upwards into shallow marine beds (Abdallah et al., 1963). It conformably underlies shales and marls of Cenomanian age and unconformably overlies the Paleozoic and early Mesozoic Nubian (Figure 5). Some plant remains and imprints of *Phlebopteris* sp. and *Otozamites* sp. were recorded in the section which enable it to be assigned to a Late Jurassic-Early Cretaceous age (El-Saadawy and Farag, 1972). The Malha Formation attains a thickness of 149 m in the type locality of Wadi Malha, on the western side of the Gulf of Suez but it reaches 330 m in the southern cliffs of El-Tih Plateau, Sinai (El-Barkooky, 1986).

PETROGRAPHY AND DIAGENESIS

Petrography of the Nubian Sandstone

The Nubian Sandstone in the Gulf of Suez can be classified into two main petrographic groups: quartzarenites and quartzwackes, following the classification of Tucker (1984) and Adams et al. (1984). Different cement types (siliceous, ferruginous and dolomitic) were recorded in the studied Nubian Sandstone.

Quartzarenites

The matrix is mainly composed of an average of more than 90% quartz with a non-quartz content of around <3% (Plate 1a). The latter is represented by heavy minerals (e.g. zircon and tourmaline), mica flakes and clay minerals (especially kaolinite). These are lumped together with siliceous (Plate 1a),

Plate 1 *(facing page)*: (a) Siliceous quartzarenites (Malha Formation, Bakr oil field) (XPL). Subrounded to rounded quartz grains, with point and straight contacts. Note the fractures on the central quartz grain. The intergranular pores are filled with a crypto- to microcrystalline silica cement. (b) Ferruginous quartzarenites (Naqus Formation, Sidki oil field) (XPL). Quartz overgrowth in medium- to fine-grains of quartz. (c) Dolomitic quartzarentes (Naqus Formation, Hilal oil field) (PPL). Subrounded and corroded quartz grains with idiotopic dolomite cement and tourmaline (T) is recorded. (d) Ferruginous quartzwackes (Malha Formation, Bakr oil field) (PPL). Ferruginous cement and dark argillaceous matrix lumped the angular fine quartz grains. (e) Quartzwackes (Malha Formation, Bakr oil field) (PPL). Clusters of fine subangular quartz grains. (f) Quartzarenites (Naqus Formation, Ramadan oil field) (XPL). Quartz overgrowth in an optical continuity with the quartz grains.

PLATE 1

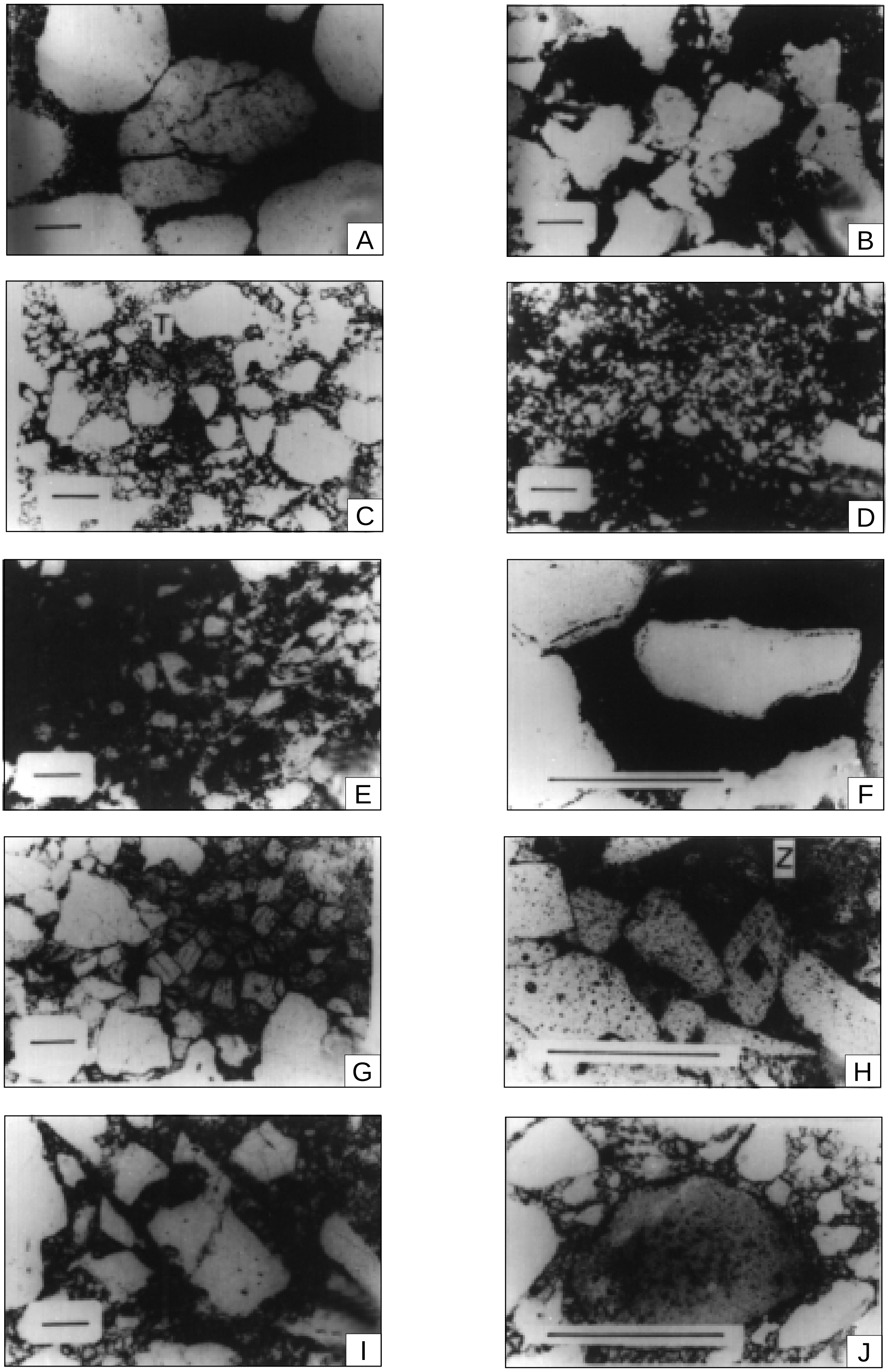

Plate 1 *(continued)*: (g) (Malha Formation, Bakr oil field) (PPL). Zoned and unzoned idiotopic dolomite rhombs, with cloudy center. (h) (Malha Formation, Bakr oil field) (PPL). Macrocrystalline, poikilotopic dolomite rhombs with dark cloudy center. Zircon (z) is recorded. (i) (Naqus Formation, Hilal oil field) (PPL). Fine crystalline ideotopic dolomite rhombs, replaced partically by quartz grain. (j) (Naqus Formation, Ramadan oil field) (XPL). Slightly corroded chert fragment, partially recrystallized to cryptocrystalline quartz grains in the dark gray spots. Bar scale is 200 microns.

ferruginous (Plate 1b) or carbonate (calcite and / or dolomite) cements (Plate 1c). Some quartz grains are embayed by calcite. Long or point contact and concavo-convex contacts are common, caused by pressure solution and compaction (Plate 1a). Examples of these sediments can be seen in samples from the Malha and Naqus formations in the Bakr, Hilal, Ramadan and Sidki oil fields.

Quartzwackes

Here, the term quartzwacke was introduced for any sandstone type with 10% or more matrix and less than 10% detrital feldspars and rock particles. This lithofacies group is represented by samples collected from the Nubian pay zones of the October, Bakr and Hilal oil fields. It is made up of mono-and polycrystalline quartz grains occurring mainly as fine sand, together with coarse sand, reflecting moderate- to poor-sorting. The grains are subangular to subrounded, showing low sphericity and textural submaturity. In these pay zones the porosity is fair to good (about 21%). The majority of the pores are intergranular and have an irregular shape filled with matrix material. The pay zone of the Bakr oil field where the quartzwacke is intercalated with ferruginous quartzarenites, includes an argillaceous matrix and ferregineous cement (Plate 1d and 1e).

Diagenesis of the Nubian Sandstone

The role of diagenesis of the pre-Cenomanian Nubian Sandstone is interpreted on the basis of pore geometry, size and filling material. The depositional environment, composition, textures, pore-fluid composition and migration and burial history are the main factors which affect Nubian sandstone diagenesis (Metwalli et al., 1987). The studied sandstone groups have shown the presence of the following physical and chemical diagenetic processes: compaction, pressure solution, hematite, silica and carbonate cementation, feldspar alteration, replacement, recrystallization and secondary pore fillings.

Compaction and Pressure Solution

The studied quartzarenites exhibit pressure solution features, including concavo-convex contacts and a certain degree of stylolitization. In addition, irregular microfractures are more common (Plate 1a). The compaction of the detrital framework has resulted in close packing which has caused a reduction in porosity.

Hematite Cementation and Pigmentation

Iron oxides are present in the studied sandstones, occurring as cementing material and / or spots and patches filling pore spaces. In addition, quartzarenites exhibit iron oxides as pore filling and grain coatings (Plate 1d).

Silica Cementation

This was observed in the quartzarenites of the studied sandstones. Silica cementation acts as secondary enlargement of the quartz grains forming optically continuous overgrowths which result in euhedral crystals or a mosaic of interlocking overgrowths. The dissolved silica originated from the effective pressures exerted at the contact between quartz grains and this has enhanced the solubility at these points. Another origin for the dissolved silica was the migrating silica-rich solutions in pore waters which have decreased the original porosity (Plate 1f).

Carbonate Cementation and Pore Fillings

These are represented by calcite and / or dolomite recorded in the quartzarenite of the Nubian Sandstone and represent an increase in pH and / or temperature. The carbonate cement and fillings are mainly dolomite (Plate 1g). Dolomite rhombs are found on the quartz grains and cause close-packed textures of crystal mosaics or isolated rhombs. The aggrading recrystallization of the primary dolomite is recorded in the studied sandstone types. The coarse unzoned dolomite rhombs fill the intergranular pore spaces (Plate 1h).

Replacement

Replacement of quartz grains by calcareous cement is recorded in the sandstones of the Hilal, Bakr and Gharib oil fields (Plate 1i). Silica solution and carbonate replacement were controlled by changes in pH, partial pressure of CO_2 and temperature; they typically occur when the pore waters are undersaturated with respect to carbonates.

Recrystallization

This process is represented by recrystallization of amorphous silica and chert to crypto- and microcrystalline quartz, respectively (Plate 1j). The recrystallization process, which is exemplified by the Nubian Sandstone samples from the Hilal and Bakr oil fields, was caused by a rise in temperature, pressure and the type of pore water, since amorphous silica and chert are less stable and tend to be more coarsely crystalline. Accordingly, this process increases the original porosity of the rock seen in the studied formations.

HYDROCARBON POTENTIAL

Reservoir Potential

The pre-Cenomanian Nubian Sandstone forms one of the major pre-rift reservoirs in the Gulf of Suez, having produced and/or tested oil from several oil fields in the Gulf of Suez, including Ramadan, July, Ras Gharib, Hurghada, Sidki, October, East Zeit, Feiran, Ras Budran, Hilal and Ras Fanar (Figure 1). Of ten potential reservoir units in the Gulf of Suez basin, almost 19% of the oil is produced from these Nubian Sandstones (Figure 6). The net pay thickness ranges between about 30 and 450 m, with a known recovery factor of between 15 and 60%. These reservoir rocks have porosities which range from 10 to 29% and permeabilities from 70 to 850 millidarcies (md). The quality of the reservoir depends on its shale contents, the diagenetic processes which may have caused secondary silica dissolution and precipitation, and the depth of burial. Most of the Nubian Sandstone reservoirs are quartzarenites and are confined to four formations (Araba, Naqus, Qiseb and Malha). Quartzwacke-type reservoirs are however recorded in some oil fields, e.g., October, Bakr and Hilal fields.

The Araba Formation consists of sandstones with kaolinitic, illitic and calcareous cement interbedded with thin siltstone. These sandstone reservoirs have an average porosity of 15% and produce from Bakr and Ras Gharib oil fields at depths of 1,150 and 630 m, respectively. The net pay zone thickness of the Araba Formation reservoir in the Ras Gharib oil field ranges between 46 to 450 m.

The Naqus Formation comprises medium- to coarse-grained sands and sandstones with minor clay and kaolinitic interbeds at the top of the unit. The Naqus sandstone is the main producing reservoir zone in July, Hurghada and Ramadan oil fields (Figure 8), at depths of 2,900 m, 525 m and 3,700 m, with net pay thicknesses of 207, 338 and 230 m, respectively. These sandstones yield an average porosity of 15%, and 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 quartzarenitic. The Qiseib Formation tested oil from an 18% porosity sandstone in the North Darag discovery in the northern Gulf of Suez (Figure 1). The Malha Formation provides the best quality sandstone reservoirs in the Gulf of Suez. The sandstones of the Malha Formation forms the main producing reservoir in several oil fields, e.g., Ras Budran, October, Feiran, East Zeit, Hilal, Shoab Ali, Ramadan, GS 382, Ras Gharib and Bakr (Figure 1) at depths ranging between 630 and 3,700 m. 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 thicknesses of the Malha Sandstones at the October, Hilal and GS382 oil fields are 244 m, 94 m and 30 m, respectively.

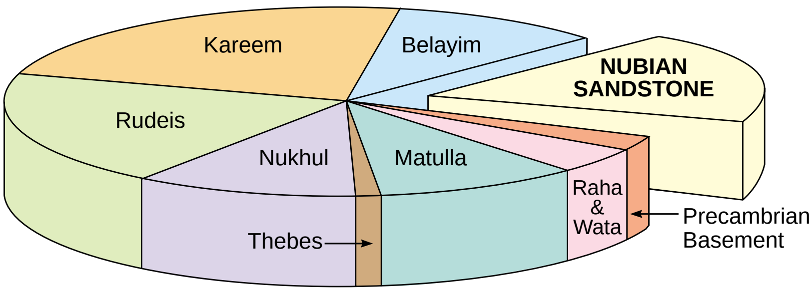

Figure 6: Hydrocarbon potential of the Nubian Sandstone.

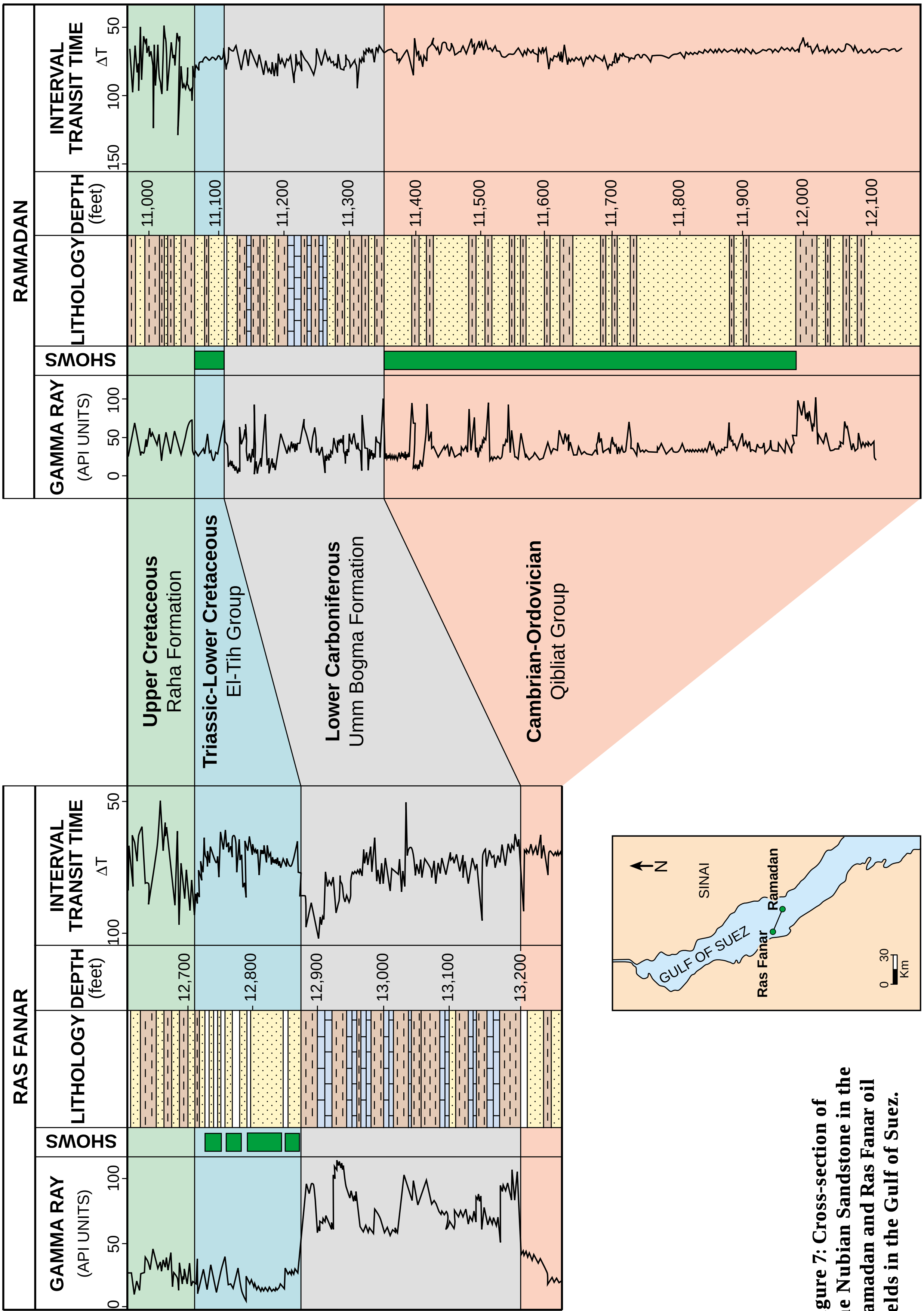

Figure 7: Cross-section of the Nubian Sandstone in the Ramadan and Ras Fanar oil fields in the Gulf of Suez.

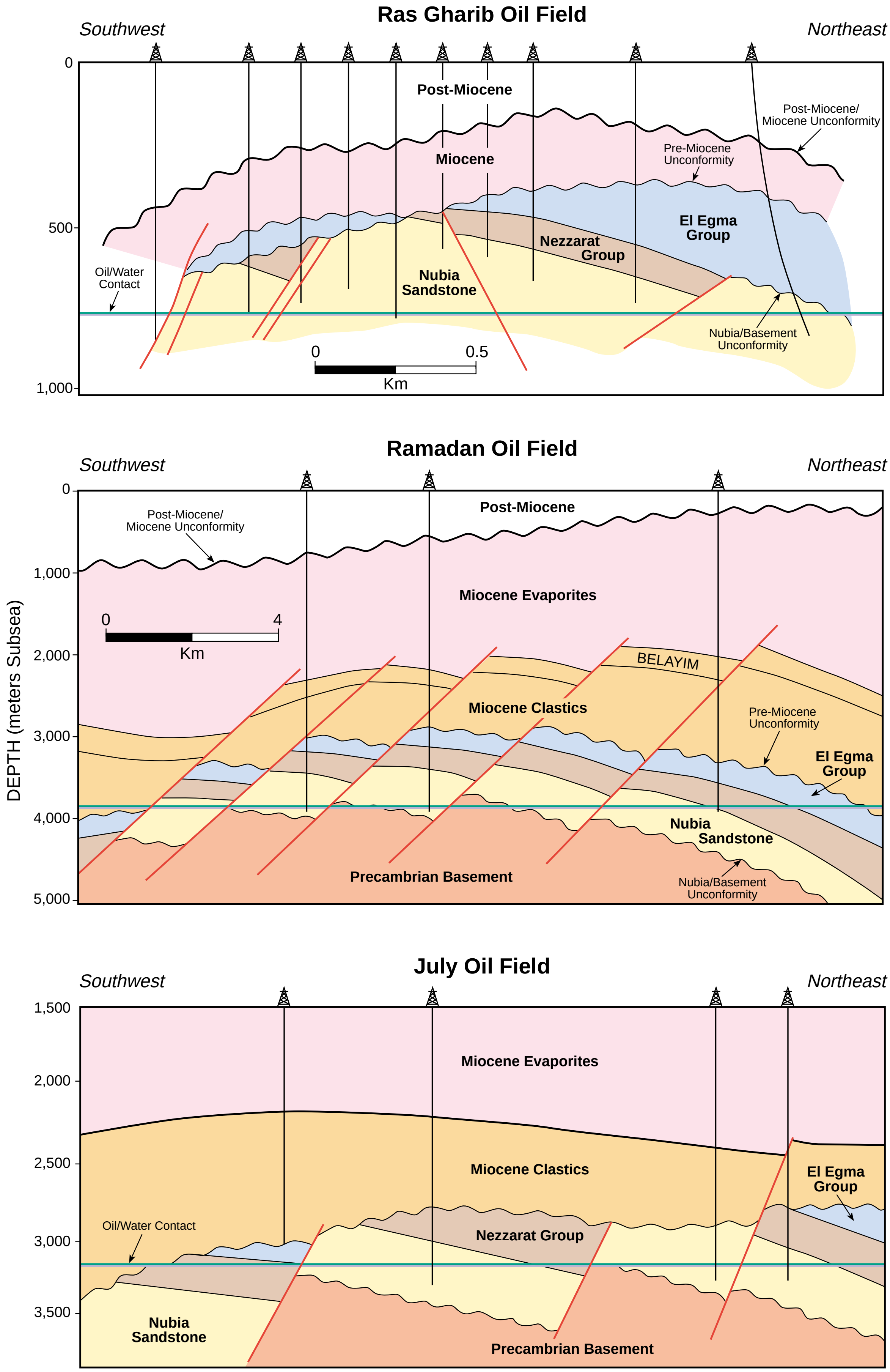

Figure 8: Examples of trapping mechanisms of oil in the Nubian Sandstone in the Gulf of Suez.

Source Potential

The Upper Paleozoic Rod El Hamal Formation represents the source facies within the Nubian Sandstone series. It is made up of shale, dolomitic limestone and thin interbeds of sandstone and is described as fair source rock in the southern Gulf of Suez by Shahin and Shehab (1984) and Salah (1989 and 1994). In the Hurghada oil field, the southernmost field of the Gulf of Suez (Figure 1), the Rod El Hamal Formation (Nubian B) has charged the underlying Lower Paleozoic Nubian Sandstone and the overlying Lower Miocene Conglomerates of the Nukhul Formation, based on the structural configuration of the field (Salah, 1994). As the field was discovered in 1914, no geochemical analysis was undertaken, as such this hypothesis cannot be proven.

Seal Potential

Two formations, Umm Bogma and Abu Durba, form potential vertical seals to the underlying Lower Paleozoic Nubian Sandstone reservoirs. They also form lateral seals when juxtaposing the Lower Cretaceous Nubian sandstone reservoirs are juxtaposed across faults. The Umm Bogma Formation is composed of two major dolomite units at its top and base, separated by marl. The Abu Durba Formation comprises mainly shale with thin dolomitic limestone interbeds (Figure 7).

Trapping Mechanisms

Two sealing mechanisms for hydrocarbon entrapment are known to work for in the Nubian Sandstone in the Gulf of Suez. The fine clastics of the Nezzazat Group and the carbonates of the El Egma Group can act as seals for the Nubian sandstone reservoirs on the down-thrown side of major clysmic faults or on the downdip direction of uplifted tilted fault blocks (Figure 8). However, the magnitude of throw on the clysmic fault is very critical to effective sealing (Salah, 1994). A small throw will juxtapose the Nezzazat Shales on the down-thrown side of the fault against the Nubian porous section on the uplifted block, e.g., Ramadan oil field. A large throw will allow the El-Egma Group and even the Miocene clastics to juxtapose the Nubian reservoirs on the uplifted block as in the Ras Gharib and July oil fields (Figure 8). The Nubian Sandstone is charged in the majority of the oil fields in the Gulf of Suez from the Upper Cretaceous carbonate source rocks (Salah, 1994).

CONCLUSIONS

The Nubian Sandstone is subdivided, in ascending order into the following groups and formations: the Qebliat Group (Araba and Naqus formations), Umm Bogma Formation, Ataqa Group (Abu Durba and Rod El Hamal formations) and El-Tih Group (Qiseib and Malha formations). Two main facies of the Nubian Sandstone are present in the Gulf of Suez basin, these are quartzarenites and quartzwackes.

The pre-Cenomanian Nubian Sandstone is considered to be one of the most prolific reservoirs in the Gulf of Suez oil province. It has produced and/or tested oil from several fields in the basin. The Araba, Naqus, Qiseib and Malha formations form the potential reservoirs within the Nubian facies. The Umm Bogma and Abu Durba formations act as seals; while the Rod El Hamal Formation is a source unit.

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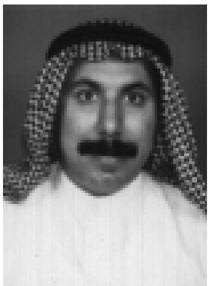

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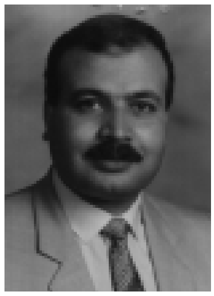

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