CHAPTER ONE

INTRODUCTION

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Introduction

Geologically, Egypt is a part of the North African Craton, which, during its geological history has undergone periodic transgressions from the ancient Tethys situated to the north and northeast of the country. Therefore, it comprises four major geological provinces, which are: The Nubian-Arabian Shield and the Shelf which is subdivided into the Stable Shelf, the Unstable Shelf and the Gulf of Suez-Red Sea Graben.

Geographically, Egypt is made up of seven distinct regions namely, from east to west; Sinai Peninsula, Gulf of Suez, Eastern Desert, Nile Delta and Western Desert, in addition to the territorial water of the Mediterranean and Red Sea.

The Sinai Peninsula covers an area of approximately 61,000 square kilometers. Highly dissected igneous and metamorphic mountains, rise to a height of 2675 m (Gebel Mussa), form the high relief mountainous tip of the peninsula at its southern portion as a part of the Arabo-Nubian massif. The central part of the peninsula consists of subhorizontal Mesozoic and Tertiary sediments, creating the plateaux of Gebel El Tih and Gebel Egma, which are drained by the northerly flowing affluents of Wadi El Arish. North of latitude 30° N, alternating Mesozoic faulted domes, anticlines and synclines (such as Gebel Yelleq 1090 m, Gebel Halal 890 m and Gebel Maghara 735 m) known as the Syrian Arc System, form a contrasting topography of low alluvial plains and high hill masses. Northward, these Syrian Arc structures sink seaward and are hidden under the Quaternary coastal plain and continental shelf deposits due to a series of down-to-basin faults of Neogene age. North of Gebel Maghara and extending nearly to the Mediterranean coast is a broad tract of sand dunes, some of which attain heights of 91 m above sea level. On the Mediterranean coast, the total thickness of the previous deposits exceeds 6000 m.

1.1 Studied area

The present work deals mainly with the study of the Early Paleozoic surface and subsurface rocks in southwestern Sinai. The surface area extends more or less parallel to the Gulf of Suez, and is confined between latitudes 28° 20` North and 28° 35` North and longitudes 33° 10` East and 33° 32` East (Fig. 1.1). To the east, the area is bounded by Gebel Qabeliat ridge which makes the western side of the flat Qa`a plain, to the north by Gebel Abu Durba and Wadi Feiran, to the south by El Tor area (Gebel Hammam Mussa and El Tor Town).

The subsurface sequence consists of a massive sandstone (Paleozoic Sandstone unit I) correlatable with the well known Early Paleozoic Nubian C and D and is represented by core samples from different wells in Ras Budran oil field, which is located in the northern part of the Gulf of Suez approximately 4 km from the east coast and 13 kms northwest from Abu Rudeis town (Fig. 1.2).

1.2 General physiography of the area

The general geomorphic pattern of the studied area is greatly, if not solely, controlled by its complex structural pattern. Most of the longitudinal strike ridges either follow fault lines or form a limb of elongated brachyanticlines, which are half breached, especially those near the coast. The thrown half of these folds now lies below the gulf water or below a thick column of Quaternary deposits. The striking orientation of the ridges, parallel to the gulf, is delineated by nearly two perpendicular

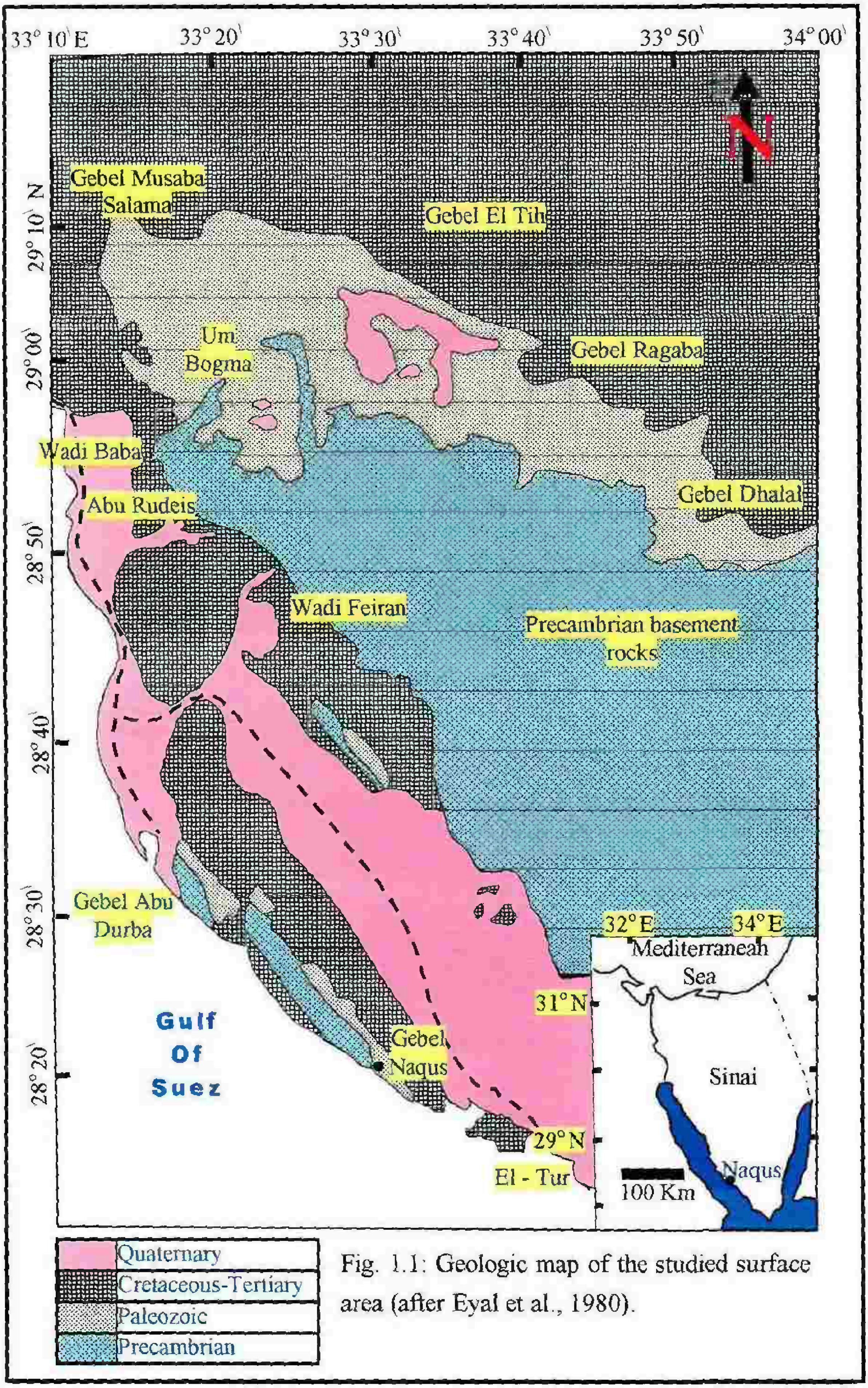

Fig. 1.1: Geologic map of the studied surface area (after Eyal et al., 1980).

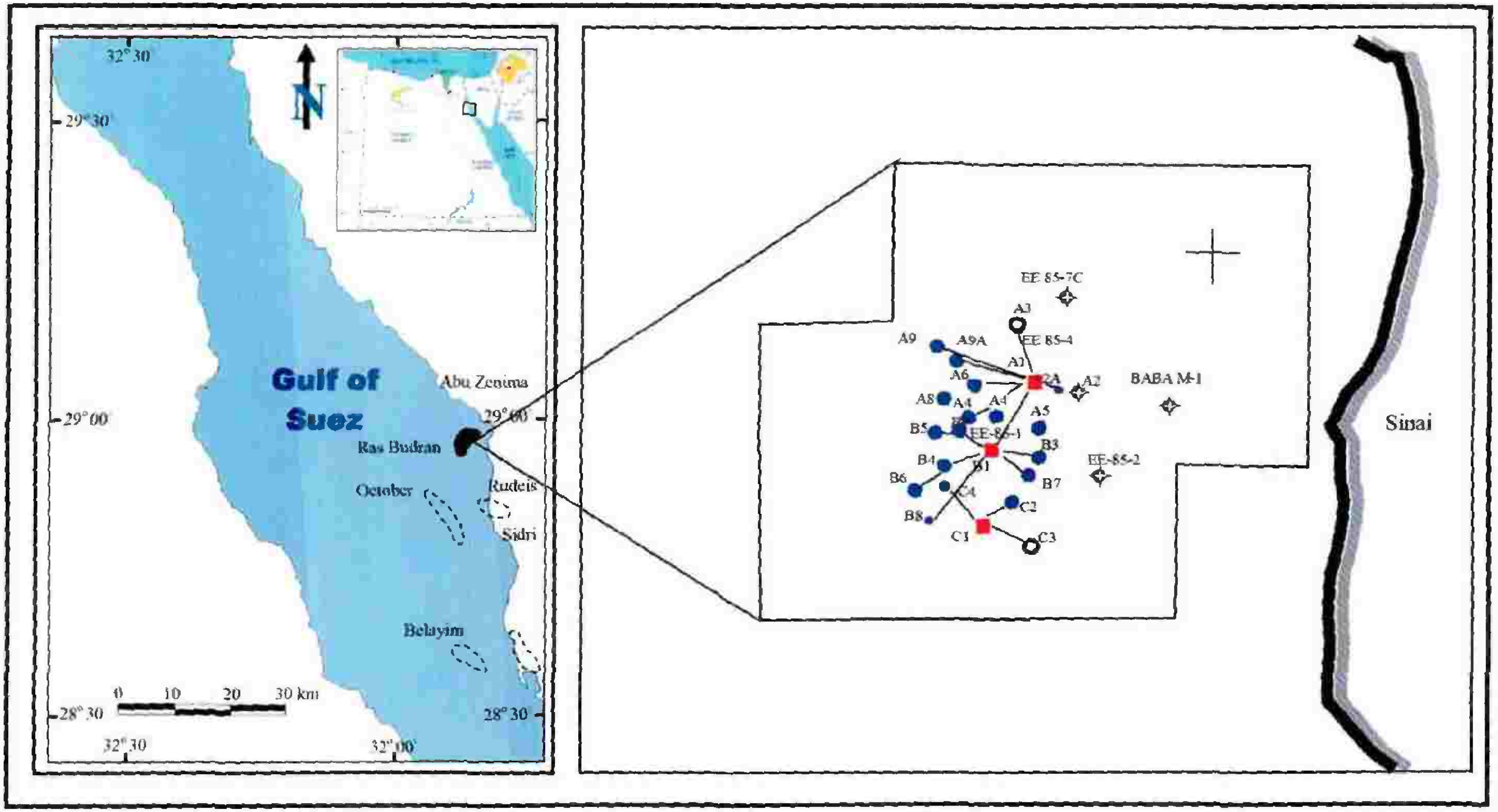

Fig. 1.2: Location map of Ras Budran oil field (after Khairy& Swidan, 1992).

wadies, namely Wadi Feiran in the north and Wadi Araba in the south. These two wadies mask on the other hand, a slight westward shift of the longitudinal ridges all seem to be structurally controlled. The main physiographic units in the area may be subdivided as follows:

1.2.1 Gebel Qabeliat

Gebel Qabeliat ridge makes the western side of the flat El-Qa`a plain. The ridge assumes an elevation of 400 m above sea level and is mostly covered by Miocene strata. The western side of the ridge overlooks Wadi Araba and thus Qabeliate is truly a water shed between El-Qa`a in the east and Araba in the west.

1.2.2 Gebel Abu Durba

This is a longitudinal igneous mass of 10 km length and a width of 2 km near its northern peak, which rises 449 m above sea level. The gulf water nearly hugs its southern foot slopes and the coastal strip attains its minimum width in this locality. The gebel overlooks Belayim bay at its northern tip whereas its southern part stands above the Wadi Araba fan.

1.2.3 The coastal plain

The coastal plain in the studied area is rather narrow, most probably due to the recent tectonics, hence the sea was not active over the area for a long time. This idea is strengthened by the fact that drilling along the coast, reveals a section of several thousand meters of Quaternary deposits. The widest part of the plain is met at the south of Wadi Feiran where a width of 10 km is known. The wadi sediments must have contributed to the building up of the coast, and thus a wide arc was observed opposite the wadi. The curvature decreases rapidly to the south, where Gebel Abu Durba basement rocks are more resistant to water erosion than the northerly sediments. The structural delineation of the eastern cliffs controls the extension of the plain further east. The breached parts of the anticlines must have been buried under recent sediments covering the surface of the plain whereas the other halves stand much higher overhanging the plain to the east-witness to their exhumed flanks to the west (Issawi et al., 1981).

1.2.4 The El-Qa`a plain

The El-Qa`a plain is an extensive gravelly plain stretching in a northwest direction. It occupies the area between the Araba range and the main central hills of Sinai and then, after the termination of the Araba range near El-Tor, continues between the main granitic hills and the coast of the Gulf. South of El-Tor, its surface is covered by a mixture of blown sand and granitic boulders crossed by the drainage lines descending from the main hills. At the southern most end of Sinai Peninsula (near Ras Mohammed), the plain becomes dotted with patches of igneous rocks. The whole plain, measuring about 150 km, is mainly covered by recent deposits and is flanked on the sea-shore by recent coral reefs (Said, 1961).

1.3 Previous work

The sedimentary succession in southwestern Sinai was studied by many authors, of these works, those of Barron (1907), Ball (1916), Beadnell (1927), Kostandi (1959), Mckee (1962), Hassan (1967), Soliman and El-Fetouh (1969a, b; 1970), Omara (1972), Issawi et al. (1981), Issawi and Jux (1982), Brenckle and Marchant (1982), Kora (1984; 1989a), Beleity et al. (1986), Barakat et al. (1986), Abdel-Hameed et al. (1986), Allam and Khalil (1987), El-Mansey et al. (1988), Allam (1989), Klitzsch (1990), Abdel-Wahab (1990), Abdel-Wahab and McBride (1991), Salem (1995), McBride et al. (1996), Abdel-Wahab et al. (1998), Salem et al. (1998) are to be mentioned. Most of these studies were mainly concentrated on the structure, stratigraphy and paleontology. Few studies were performed on the sedimentology, petrology and mineralogy of these rocks.

The sandstone sequence above the basement rocks and below the first regional marine transgression of the Cenomanian in southern Sinai was a matter of dispute. This sequence was first described by Ball (1916) who subdivided the lower 300 m of the sequence into Lower and Upper Carboniferous separated by the fossiliferous Um Bogma Limestone. The overlying sequence was attributed to the so-called Nubia Formation, the contact is coinciding with the Lepidodendron shale. This work was taken as a background to most of the proceeding work.

In the late forties, the whole sequence was described by the oil geologists as "Nubian Sandstone" which comprises four units denoted as A, B, C and D (tetrapartite classification). This classification was modified by Beets (1948) to a bipartite classification, namely, Paleozoic A and Paleozoic B, which are well represented in Abu Durba area.

Oil companies gave the informal name Nubia D to Facies D (underlies facies C and overlies the basement complex). It is characterized by laminated brown, fine grained sandstone and siltstone, cemented by kaolinite, illite and carbonate in parts. Fossils associated within this facies are traces of Crusiana and Skolithos. Nubia C to Facies C (underlies facies B and its equivalent B' and overlies facies D). It is formed of quartz sand and sandstone. Sand is unfossiliferous, white and medium to coarse grained. Nubia B to Facies B and its equivalent facies B'. Both facies represents the crinoidal zone. Facies B underlies facies A and its equivalent facies A' in Ataqa, Wadi Araba and Um Bogma areas and overlies facies C. It is composed of carbonates, greyish at top (Facies B1) and rosy at base (Facies B2). Facies B' underlies the Mesozoic rocks and overlies facies C and is restricted to the northern part of Abu Durba area and is formed of shale with few streaks of both limestone and sandstone. The shale is greyish at top (Facies B'1) and becomes black at base (Facies

B'2). Nubia A to Facies A and its equivalent facies A'. Both facies are absent at Abu Durba area. However, they are recorded in Ataqa, Wadi Araba and Um Bogma areas and are bounded at the top by the Mesozoic and at the base by the crinoidal facies. Facies A is located in Ataqa area and is characterized by fossiliferous marl, shale and sandstone. Facies A' is located in Wadi Araba and Um Bogma areas and is characterized by sandstone at base and shale at top. The shale forms subfacies A'1 and the sandstone forms subfacies A'2. The two subfacies are separated in some places by a volcanic sheet or sill (Beleity et al., 1986).

The term Nubia Formation is now restricted to a suite of lithobio-stratigraphic units, generally of Late Cretaceous–Early Tertiary ages, exposed in southern Egypt (Issawi, 1973). This paved the road to abandon the use of the term Nubia Formation to clastic rocks older or younger than the Upper Cretaceous epoch. Many Egyptian sandstone outcrops previously regarded as Nubia facies are now regarded as separate formations ranging in age from Cambrian to Cretaceous (Omara, 1965; Hassan, 1967; Soliman and El-Fetouh, 1969a; Said, 1971; Issawi and Jux, 1982; Kora, 1984; Beleity et al., 1986; Allam, 1989; Klitzsch, 1990; Abdel-Wahab et al., 1992 and Abdelwahab, 1998).

In this concern, Said (1971) suggested a modified classification to the Paleozoic rocks that takes into consideration the works of Omara (1965), Hassan (1967), Soliman and El-Fetouh (1969a). From this classification, the previous conclusions that attributed the whole Paleozoic sequence to the Carboniferous were dropped since Cambrian indications were identified in the form of their ichnofaunal content. He gave the name "Durba Shale" to facies B', "Naqus Formation" to facies C and "Araba Formation" to facies D. Durba Shale is carboniferous, and both Araba and Naqus formations are questionable Carboniferous after Hassan (1967).

Issawi et al. (1981) gave the name Aheimer Formation (Early Permian) to the grey shale (facies B1), Durba Formation (Early Carboniferous) to the black shale (facies B2), Naqus Formation to facies C and Araba Formation to facies D.

Issawi and Jux (1982) gave the name Wadi Malik Formation (Devonian) to the varicolored shaley section forming top of facies C, Naqus Formation (Late Ordovician-Early Silurian) to the basal white quartizitic sandstone part of facies C, and Araba Formation (Cambrian-Early Ordovician) to facies D.

Kora (1984) gave the Pre-Carboniferous clastic sediments of the Um-Bogma area the following names from base to top; Sarabit El-khadim, Abu-Hamata, Nasib and Adedia formations. He assigned them a Cambro-Ordovician age. He also concluded that the Um-Bogma Formation is the oldest marine Carboniferous rock unit known in the Gulf of Suez region and its carbonate succession should be placed stratigraphically below the sandstone-shale succession of the Abu-Durba Formation, which yielded a fauna of Late Carboniferous affinity (Kora, 1989a).

Naggar and El Hilaly (1985) classified the subsurface Paleozoic section in Ras Budran oil field into the informal rock units Nubia B for facies A'1 and Nubia C and D for facies A2.

The sandstones that directly overlie the Precambrian basement in the area under study were suggested to be Cambrian in age by many authors and were classified into Araba and Naqus formations. The proven Cambrian age of these strata is based on the presence of stromatolites and small archeocyathids in these sandstones in the Wadi Feiran-El Tor area (Omara, 1972) and also according to their trace fossil and trilobite tracks in the Um Bogma area. However, these strata in the Wadi Feiran-El Tor area were found to be penetrated by a regular pattern of vertical tubes of

Skolithos that are typical of Cambro-Ordovician rocks and are most characteristic in Araba Formation (Issawi and Jux, 1982). However, some workers have advocated a Carboniferous age for Araba and Naqus formations. Eames (1984) recovered Early Carboniferous palynomorphs from subsurface samples from the Gulf of Suez that are considered to be Araba and Naqus formations. Ibrahim (1996) supports this age designation, but notes that the correlation between subsurface and surface units is not well documented.

Nassr (1985), in his study on quartz grain shapes of the Cambrian and Carboniferous sandstones in Gebel Abu Durba, concluded that the Cambrian sandstones can be discriminated from the Carboniferous ones by quartz grain shape and surface texture.

Beleity et al. (1986) studied the stratigraphy, paleogeography and paleotectonics of the Paleozoic in the Gulf of Suez region (Ataqa, Wadi Araba, Um Bogma and Abu Durba areas). They concluded that: (1) the Paleozoic in the Gulf of Suez region could be classified from bottom to top into Araba and Naqus formations of Early Paleozoic age, Um Bogma (and its equivalent Abu Durba Formation) and Ataqa formations (and its equivalent Rod El Hamal Formation) of Late Paleozoic age. (2) Early Paleozoic units have minor facies changes. The basal unit, Araba Formation was deposited in a shallow marine tidal environment and the top unit Naqus Formation as non-marine alluvial deposits. Late Paleozoic units, on the other hand, show major facies variations, the basal unit, Um Bogma limestone changes laterally to Abu Durba shale. The top unit Ataqa marls changes laterally to Rod El Hamal clastics. (3) vertical extension and lateral distribution of these units have revealed the existence of an east-west tectonic belt located between latitudes 28° 30` and 28° 38` North. The southern limit of this belt represents an Early

Paleozoic, down to south fault system, and the northern limit on the other hand represents a Late Paleozoic down to north fault system. These faults form two dislocated successive basins: (a) Early Paleozoic basin located south of the horsted belt, and (b) Late Paleozoic basin to its north. The former is associated with the Caledonian orogeny and the later with the Hercynian.

Bhattacharyya and Dunn (1986) studied the sedimentary sequence along the northeast margin of the Nubian Craton, which comprises the Eastern Desert, The Gulf of Suez and Southwest Sinai. They reported that the sequence contains sedimentary units ranging in age from early Paleozoic to Tertiary. In southwest Sinai and subsurface Gulf of Suez, the entire sequence is present, however, with major breaks. Breaks in the sedimentary record in the area are commonly characterized by erosive contacts and associated basal conglomerates between the stratigraphic units.

El-Mansey et al. (1988) studied the primary and secondary sedimentary structures of some Paleozoic Sandstones in southwest Sinai. The studied structures included: erosional surfaces, fine scale cross-lamination overlain by planar lamination, trough cross-stratification, convolute structures, bioturbation, iron concretions and coloration, flaggy (horizontal) bedding and graded bedding.

Allam (1989) subdivided the Paleozoic sandstone succession between Wadi Feiran and El-Tor in southwestern Sinai into five distinct lithostratigraphic units: the Lower Cambrian Araba Formation, the Upper Cambrian Naqus Formation, the Lower Carboniferous Abu Durba Formation, the Upper Carboniferous Aheimer Formation and the Permian Qiseib Formation. Klitzch (1990) suggested a Lower Cambrian age to Araba and Naqus formations in southwestern Sinai, this is in an agreement with Seilacher (1990), who proposed a Lower Cambrian age to Araba and Naqus formations in Sinai and Eastern Desert.

Ghanem and El-Mansey (1991) studied the lithostratigraphy and the petrography of some Paleozoic sequences in west Sinai and Gulf of Suez. They pointed out that the subsurface Paleozoic section could be subdivided into four units based on lithology, age assignment and stratigraphic position. They suggested a fluvio-marine depositional environment for Araba Formation and aeolian environment interrupted by short periods of fluvio-glacial conditions for Naqus Formation.

Abdel-Wahab (1990) studied the fabric and compaction history of Cambrian sandstones in Gebel Araba-Qabeliat, southwest Sinai, and pointed out that (1) these sandstones are mature, and moderately well sorted diagenetic quartzarenites in which the deformation of ductile grains did not play a role in compaction. The average sandstone lost 20.9 % porosity by mechanical compaction (assuming 45 % initial porosity) and intergranular pressure solution. The loss by grain rearrangement is 19.5 %, aided to an unknown extent by pressure solution, and 1.42 % directly by pressure solution. (2) These sandstones have an average composition of $Q_{97}F_1R_2$. Currently, these sandstones are quartzarenites, but a considerable amount of metastable grains had been lost by dissolution.

Salem (1995) conducted a diagenesis and isotopic study on the Paleozoic (Cambrian and Carboniferous) clastic sequence, southwest Sinai, and concluded that these sandstones were not buried more than 1.5 km until Late Cretaceous and younger, when the deepest rocks reached 2.5 km. Accordingly, these rocks have similar paragenetic sequences with respect to major diagenetic events. He also pointed out that, most authigenic phases in these sandstones precipitated before the rocks reached their maximum burial depth of ~ 2 km.

Ibrahim (1996) studied the petrography and diagenesis of the Cretaceous and Pre-Cretaceou sediments in some oil fields in the Gulf of Suez. In agreement with Eames (1984), he believed that Araba and Naqus formations are of Early Carboniferous age, but notes that the correlation between subsurface and surface units is not well documented.

McBride et al. (1996) investigated the influence of diagenesis on the hydrocarbon reservoir quality of Cambrian and Carboniferous sandstones, southwest Sinai. They came to the conclusion that: (1) the fluvial and shallow marine Paleozoic sandstones were not buried more than 1 to 1.5 km until Late Cretaceous and more recent times, when the most deeply buried rocks may have reached 2.5 km. (2) porosity of these sandstones was reduced by compaction from an assumed original 45 % to about 26 %, grain rearrangement was the main mechanism of compaction, intergranular pressure solution and ductile grain deformation are insignificant. (3) following and during compaction, cementation by iron oxide, quartz, calcite and kaolinite further reduced porosity to 12-15 %, except in silcretes and some ferricretes where porosity was reduced to < 5%. Significant secondary porosity was created (5.8 and 5.1 % for Cambrian and Carboniferous sandstones, respectively) chiefly by dissolution of K-feldspar and probably some rock fragments and calcite cement.

Salem et al. (1998) studied the diagenesis of shallowly buried cratonic sandstones, southwest Sinai. Owing to deposition of Sinai sandstones on a stable craton, which resulted in shallow burial depths and episodic exposure or proximity to the surface, they believed that meteoric water dominated the pore system of these sandstones for most of geologic time.

Abdel-Wahab et al. (1998) studied the nature of quartz cement in silcrete and nonsilcrete sandstones, Lower Carboniferous, western Sinai.

Based on petrographic and oxygen isotope data, they believe that this quartz cement is of meteoric origin. In nonsilcrete sandstones, which lack the strong silicification typical of pedogenic or groundwater silcretes, the quartz cement is mainly represented by a trace to 4 % of normal quartz overgrowths. Evidence favoring near-surface cementation indicates that the cementing waters were thermal fluids; thus, the silcretes are groundwater silcretes and not pedogenic silcretes. The silcretes are probably pre-Cretaceous in age. An episode of igneous activity of Late Triassic-Early Jurassic age in the region may have been the heat source of thermal waters for the silcretes.

1.4 Scope of present study

The Early Paleozoic clastics in Egypt in general, and in Sinai Peninsula in particular, has been of great interest to many workers since the beginning of the last century, not for its dramatic scenery but because of its economic potential, such as, the occurrence of manganese ore deposits at Um Bogma area, coal deposits at Al Maghara area, white sands at different localities, and mainly the production of oil from Nubian "C" sandstones from different oil fields, such as, Ras Budran field. These rocks have been studied in general terms by different authors, many of these studies were concentrated on the structure, stratigraphy and paleontology, and to a less extent on the sedimentology, petrology, mineralogy and diagenesis. To date, almost few serious work has been attempted to study the reservoir quality of surface exposures of Paleozoic strata and to relate this quality to the sedimentology and diagenesis of these rocks. Similarly, very limited correlative studies between the surface exposures and their subsurface oil producing equivalents have been carried out. Consequently, this work is proposed to fill an existing gab in our knowledge of these economically important rocks.

The present work is mainly devoted to study the mineral and petrographic characteristics, the diagenetic history, as well as the reservoir quality of some surface and subsurface sections from Belaiym area and the neighboring localities, southwestern Sinai, Egypt. The following topics are considered in the present study for both the surface and subsurface sections:

1. Collection of all possible varieties for the rocks under investigation.
2. Study of the sedimentary structures and the most dominant field features.
3. Study of the facies environmental analysis of the lithologic sequences.
4. Detailed mineralogical study including the main framework minerals, authigenic mineral phases and the paragenetic sequences in the investigated samples.
5. Scanning electron microscopy (SEM), to investigate three dimensional data on mineral morphology, grain dissolution and relationships concerning the petrographic sequences.
6. X-ray diffraction analysis of clay minerals to determine the compositional variations accompanying the changes of clay types.
7. Study of petrophysical parameters as: porosity, permeability and density to shed light on the reservoir quality and potentiality for oil accumulation and production.
8. The diagenetic history and the relative timing of emplacement of different pore fillings and grain replacement minerals.

1.5 Data of present study

1.5.1 Surface section

A sedimentary section at Gebel Naqus (370m thick), southwestern Sinai, was subjected to detailed field studies and, One hundred and fourteen rock samples were collected representing all the possible varieties. Lithological variations and color changes of strata were taken into consideration during sampling. Observations were also focused on sedimentary textures, structures and facies changes. This section is represented by the entire Naqus Formation (Upper Cambrian) and the uppermost part of the underlying Araba Formation (Lower Cambrian).

1.5.2 Subsurface section

The subsurface data were provided by Suco Oil Company from Ras Budran oil field located in the northern offshore area, 4 km west of the eastern coast of the Gulf of Suez. The field has 3 main blocks A, B and C separated by two main faults and has been developed from 17 produced wells and 4 injectors over 3 offshore platforms. Six wells were selected for this study as key wells. Two wells from block A (RB-A1 and RB-A5), three wells from block B (RB-B3, RB-B4 and RB-B7) and one well from block C (RB-C2). The data provided includes: sixty representative Paleozoic core samples, core photographs, both conventional and special core analysis data and electric logs.

1.6 Methodology

The following laboratory methods and techniques have been carried out to achieve the target of the present study:

1.6.1 Thin section preparation and modal analysis

One hundred and fifty standard thin sections were prepared for the petrographical and mineralogical analysis. All sample stubs were impregnated with blue-dyed epoxy prior to sectioning and were stained subsequently for both K-feldspar and calcite. The use of blue dye has a great advantage in the identification of different types of pores and dissolution features and facilitates the estimation of both primary and secondary porosities, while the staining help identification of both K-feldspars and/or calcite (whenever present).

Detailed microscopic investigation of the studied sandstone samples was carried out following the schemes proposed by Pettijhon et al. (1972) and Blatt (1982). Special attention was given to the diagenetic features displayed by theses sandstones. The paragenetic sequence is also discussed.

Using an automatic point counter, modal analysis was performed for most of the thin sections. Hundred and three thin sections were counted at 400 counts per slide for framework composition, types of quartz (monocrystalline, polycrystalline, undulose and nonundulose), and all cement and porosity types. Special attention was paid to the types of porosity (intergranular, intragranular, fracture and oversized pores) due to their significance in reservoir quality evaluation and diagenetic history identification of the studied sandstones.

1.6.2 Staining techniques

1.6.2.1 Feldspars

Uncovered thin sections were etched in fumes of concentrated hydrofluoric acid for 15 to 20 seconds, then soaked in a saturated solution of sodium cobaltinitrite for about 2 minutes and finally rinsed with distilled water; the potassic feldspars are stained yellow (cf. Bailey and Stevens, 1960)

1.6.2.2 Carbonates

Thin sections were stained for carbonate minerals, by soaking in a solution of alizarine red-S, potassium ferricyanide and hydrochloric acid for 1 minute. By this technique, calcite are stained red, iron-poor calcite are got mauve, iron-rich calcite are stained purple (cf. Friedman, 1971).

1.6.3 Textural parameters

Grain size analysis was carried out for hundred and four samples. Disaggregation of samples and removal of carbonates and iron oxides were done using stannous chloride and hydrochloric acid (cf. Folk, 1980). A representative sample weighting 50 gm was taken for each sample by quartering and was subjected to grain size analysis. The size analysis was carried out using a selected set of six standard screens, according to the Wentworth grade scale, having aperture diameters of 2.0, 1.0, 0.5, 0.25, 0.125 and 0.063 mm, respectively. The sieves were arranged in a descending order with a receiver under the lower screen. The set of screens were shaken for 30 minutes, using a vibrating automatic shaker. The retained weights on the different screens and in the receiver were weighted and their frequencies were calculated, and graphically represented by histograms. The obtained frequencies for each sample were cumulated and the cumulative curves were drawn.

The histograms display the modal class of the grain size distribution as well as the fine and coarse admixtures. The different percentiles were obtained in phi units from the cumulative curves using the phi scale. The four different sedimentological statistical parameters namely: the graphic mean (M_Z), the inclusive graphic standard deviation (σ_I), the inclusive graphic skewness (Sk_i), and the graphic kurtosis (K_g) were calculated for each sample, according to the equations quoted by Folk and Ward (1957) as follow:

Graphic Mean:

$$(M_z) = (\Phi_{16}+\Phi_{50}+\Phi_{84})/3$$

Inclusive Graphic Standard Deviation:

$$(\sigma_I) = [(\Phi_{84}-\Phi_{16})/4] + [(\Phi_{95}-\Phi_5)/6.6]$$

Inclusive Graphic Skewness:

$$(Sk_i) = [(\Phi_{16}+\Phi_{84}-2\Phi_{50})/2(\Phi_{84}-\Phi_{16})] + [\Phi_5+\Phi_{95}- 2\Phi_{50})/2(\Phi_{95} -\Phi_5)]$$

Graphic Kurtosis:

$$(K_G) = (\Phi_{95}-\Phi_5)/2.44(\Phi_{75}-\Phi_{25})$$

The calculated grain size statistical parameters for the sand size fraction of the studied sediments are classified according to the limits given by Folk and Ward (1957), these limits are:

The graphical mean (M_z):

The very coarse sand is from –1.0 Φ to 0.0 Φ

The coarse sand is from 0.0 Φ to 1.0 Φ

The medium sand is from 1.0 Φ to 2.0 Φ

The fine sand is from 2.0 Φ to 3.0 Φ

The very fine sand is from 3.0 Φ to 4.0 Φ

The inclusive graphic standard deviation (σ_1):

The very well sorted sand <0.35 Φ

The well sorted sand 0.35 Φ to 0.50 Φ

The moderately well sorted sand 0.50 Φ to 0.71 Φ

The moderately sorted sand 0.71 Φ to 1.00 Φ

The poorly sorted sand 1.00 Φ to 2.00 Φ

The very poorly sorted sand 2.00 Φ to 4.00 Φ

The extremely poorly sorted sand >4.00 Φ

The inclusive graphic skewness (Ski):

The strongly fine skewed sand from 1.0 Φ to 0.3 Φ

The fine skewed sand from 0.3 Φ to 0.1 Φ

The nearly symmetrical sand from 0.1 Φ to –0.1 Φ

The coarse skewed sand from –0.1 Φ to –0.3 Φ

The strongly coarse skewed sand from -0.3 Φ to -1.0 Φ

The inclusive kurtosis (KG)

The very platykurtic sand <0.67 Φ

The platykurtic sand from 0.67 Φ to 0.90 Φ

The mesokurtic sand from 0.90 Φ to 1.11 Φ

The leptokurtic sand from 1.11 Φ to 1.50 Φ

The very leptokurtic sand from 1.50 Φ to 3.00 Φ

The extremely leptokurtic sand from >3.00 Φ

Grain size data are presented in Tables 3.1-3.2 and Figures 3.3-3.6.

1.6.4 Heavy mineral analysis

Heavy mineral analysis was carried out on sixty-one samples. The samples selected for the study were disaggregated and sieved. The size fractions 0.5 - 0.063 mm were first wet sieved to remove unwanted finer particles, then subjected to hydrochloric acid and stannous chloride for the removal of carbonates and iron oxides, respectively. Heavy mineral separation was carried out using the heavy liquid technique (Carver, 1971). Bromoform (specific gravity 2.89 g/cm^3) was the heavy liquid used, heavy minerals were mounted in liquid Canada balsam on glass slides and were studied using transmitted light. The relative frequencies of the identified heavy minerals for a subset of twenty-five samples were calculated using an automatic point counter (400 counts per slide). Opaque and different non-opaque minerals, excluding micas, were calculated on bases of 100% (Tables 4.5-4.7).

1.6.5 X-ray diffraction analysis

The X-ray diffractometry (XRD) was used to determine the mineral composition of the studied sandstones. Twenty-five samples were analyzed using the X-ray diffractometer at the Geology Department, Faculty of Science, Cairo University. A semi-quantitative estimation of the mineral composition of the bulk samples and the oriented clay fraction was performed (Table 4.8 and Figure 4.4).

Normal, glycolated and heated slides, beside the powder (bulk) of each sample were analyzed using Ni-filtered Cu Kα-radiations of a Philips (SCINTAG/USA) diffractometer at 45 kv and 40 ma. The XRD scans were started from 3° 2θ so that the high lattice spacings up to 30 Å were easily recorded. The scans were ended at 75° 2θ in the bulk minerals analysis while scanning up to 35° 2θ was enough for identification of clay minerals in the clay fraction.

The identification of the different minerals from the XRD pattern was determined according to their main d-spacing and the corresponding 2θ. The primary characteristic peaks of each specific mineral were determined and the intensity of each characteristic peak of each mineral was calculated relative to the intensities of all other peaks for all minerals present in the sample to determine semi-quantitatively the percent of each mineral in all analyzed samples.

1.6.6 Scanning Electron Microscopy (SEM)/Energy Dispersive X-ray analysis (EDX)

This technique is a relatively quick and requires a very small amount of sample (only a few mg) for analysis. Samples in a high vacuum that have been previously mounted onto cupper stubs and coated with a thin film of conductive material (gold) were bombarded with electrons, resulting in a secondary electron emission with unique advantages for sample study, these include: (1) high magnification (2) non-destructive tests (3) good depth of field (4) an image suitable for study as obtained.

A scanning electron microscope (JEOL model JSM-5300) at the Central Lab of the Egyptian Petroleum Research Institute (EPRI) was used to confirm the results of microscope examination and to identify the characteristics of the authigenic minerals assemblage especially their textures and diagenetic history.

1.6.7 Petrophysical measurements

The petrophysical measurements were performed on one-inch diameter cylindrical plugs. These plugs were drilled using a diamond core drill with tap water as a bit coolant and lubricant. The obtained plugs were trimmed with a diamond core saw to form a uniform right cylinder, dried in a regular oven at 60°C over a night and finally numbered for identification. A total of one hundred plug were used in this study. Petrophysical measurements yielded fundamental information about storage capacity for reservoir fluids (porosity), flow capacity (permeability) and density properties of the studied sandstones. The measurements were carried out at the Central Lab of the Egyptian Petroleum Research Institute (EPRI).

1.6.7.1 Porosity (Ø)

Numerous methods have been developed for the determination of porosity of the consolidated rocks. In the lab, two of three variables, bulk volume (v_b), pore volume (v_p) and grain volume (v_g) must be measured to determine porosity. All three may be determined to get a cross-check. In the present work, helium porosimeter (Heise Gauge type) was used for porosity measurement, it utilizes the principle of gas expansion as described by Boyle's low (API-RP-40). In this method, the clean dry samples were initially callipered to determine the length and diameter, and then weighted to determine the dry weight. Each sample then was placed in a sealed sample chamber (matrix cup), using steel disks to minimize void space. The reference cell containing a known volume was pressured with helium to 100 psi. The helium in the reference cell was then allowed to expand into the chamber containing the sample, the temperature was assumed to be constant. The resultant pressure was allowed to stabilize, and the matrix or solid (grain) volume was then calculated from the pressure-volume relationship expressed in Boyles's low. In this porosimeter, the pressure dial face has been scaled to cubic centimeters and the needle indicates the unknown volume directly. Bulk volume was measured by mercury displacement using the DEB-200 instrument that obeys Archimedes' principle. Mercury resists wetting a rock's surface, minimizing surface pore intrusion. A mercury pump utilizes an actuated plunger device to measure the volume of mercury displaced by a sample (API-RP-40).

Knowing bulk volume and solid volume (grain volume) of the sample, porosity or percentage of pore volume was then calculated as follows:

Porosity (%) = $[(v_b - v_g) / v_b] \times 100 = (v_p / v_b) \times 100$

where:

v_b = bulk volume

v_g = grain volume

v_p = pore volume (bulk volume – grain volume)

1.6.7.2 Grain density (ρg)

The grain density of a rock is defined as the mass of a unit volume of the solid phase of the rock (grains and/or crystals). In the current work, the grain density (ρg) has been determined utilizing Boyle's law. A clean dry sample was placed in a chamber of known volume (v_c). Helium gas was allowed to expand from a reference cell of known volume (v_r) to the chamber containing the sample (v_s). The pressure change, from initial (p_1) in the reference cell to a final pressure (p_2) after gas expansion, was measured by a gauge. The following equation was used:

$$p_1 v_r = p_2 (v_r + v_c - v_g)$$

By obtaining a dry sample weight (w_d), grain density (ρg) can be determined as follow:

$$\rho g = wd / vg$$

1.6.7.3 Permeability

To determine specific permeability, a fluid of known viscosity (usually air) is caused to flow through a prepared sample of measured dimensions (API-RP-27). The pressure differential and flow rates are measured, and the permeability is then calculated from Darcy equation. In the present work, gas permeability measurements were done using CoreLab gas permeameter (model: 302138, serial A3148). The clean dry samples were initially callipered to determine the length and diameter. The core plugs were loaded individually into a Hassler–type core holder, with the circumference sealed to prevent bypass using an overburden pressure of 200 psi. Dry air was injected through the samples at a constant pressure. The pressure differential across the length of each sample was measured and the flow rate of the air was determined. The steady–state permeability to air was calculated using Darcy's law for compressible fluids (gases), as follow:

$K_g = 2000\ \mu_a\ P_a\ Q_a\ L\ /\ (P_1^2 - P_2^2)\ A$ or simply as

$K_g = C\ Q_a\ L/A$

where:

K_g = gas permeability (millidarcies)

C = 'C' gauge reading and is equal to: $2000\ \mu a\ Pa\ /\ (P_1^2 - P_2^2)$

μ_a: dry air viscosity (0.0186 centipoise)

P_a: atmospheric pressure (absolute)

P_1: inflow (upstream) pressure (atmospheric)

P_2: outflow (outlet) pressure (atmospheric)

Q_a: volume flow rate of air (cc /sec) at atmospheric pressure

L: length of sample (cm)

A: sample cross sectional area (cm^2)

Values of μ_a, atmospheric pressure, pressure differential, mean pressure and conversion constants are often read directly as a single value 'C' by the 'C' gauge which is a gauge in permeameter graduated into values of 'C' equivalent to selected P_1.