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El-Morgan oil field as a major fault-blocks reservoir masked by the thick Miocene salt; a clue for deeper reserves of hydrocarbons in Gulf of Suez Petroleum Province, Egypt

ABSTRACT: El-Morgan oil field embraces an area of about 46 km². The geologic section is represented by post-Miocene and Miocene successions. Pre-Miocene deposits (Eocene and older rocks) are not penetrated fully in the study area (except in El-Morgan well No. 8; M-8) as well as in most of the wells drilled in the Gulf of Suez petroleum province, based on a traditional concept that hydrocarbon accumulations in the Gulf of Suez region are thought to be confined within the Tertiary sediments especially the Miocene. However, detailed studies on the geologic, tectonic setting and the mode of salt movement in this hopeful petroleum province would be of great help in exploring unknown oil reserves underlying the Miocene and even deeper. Also, detailed structural analysis of these areas will modify completely many of the present day concepts in the Gulf of Suez region concerning the type of structures and petroleum traps which are normally masked and sealed by the thick salt section within the Miocene successions.

INTRODUCTION

This paper deals with the subsurface geology of El-Morgan off-shore oil field, Gulf of Suez petroleum province, A.R., Egypt. The field lies in the Gulf water, between Longitudes 33°17′ and 33°30′ E and Latitudes 28°05′ and 28°33′ N and covers an area of about 46 km² (Fig. 1).

El-Morgan oil field lies some 220 kms south of Suez town, about 40 kms south-east of Ras-Gharib and 20 kms from Ras-Shukier where the land installations and marine terminal are set up. The field is some 13 kms to the west of El-Tor village where, in the off-shore area, a rich development of coral reefs known as El-Tor Banks are present, this gave rise to the Arabic name "El-Morgan" to the field. El-Morgan oil field lies within an area that comprises a group of oil fields in the Gulf of

Suez Petroleum province, *e.g.* Belayim off-shore and on-shore (known as Belayim marine and land or Belayim west and east), Feiran and Abu--Rudies oil fields to the north; and Amer, Bakr, Ras-Gharib, Kareem,

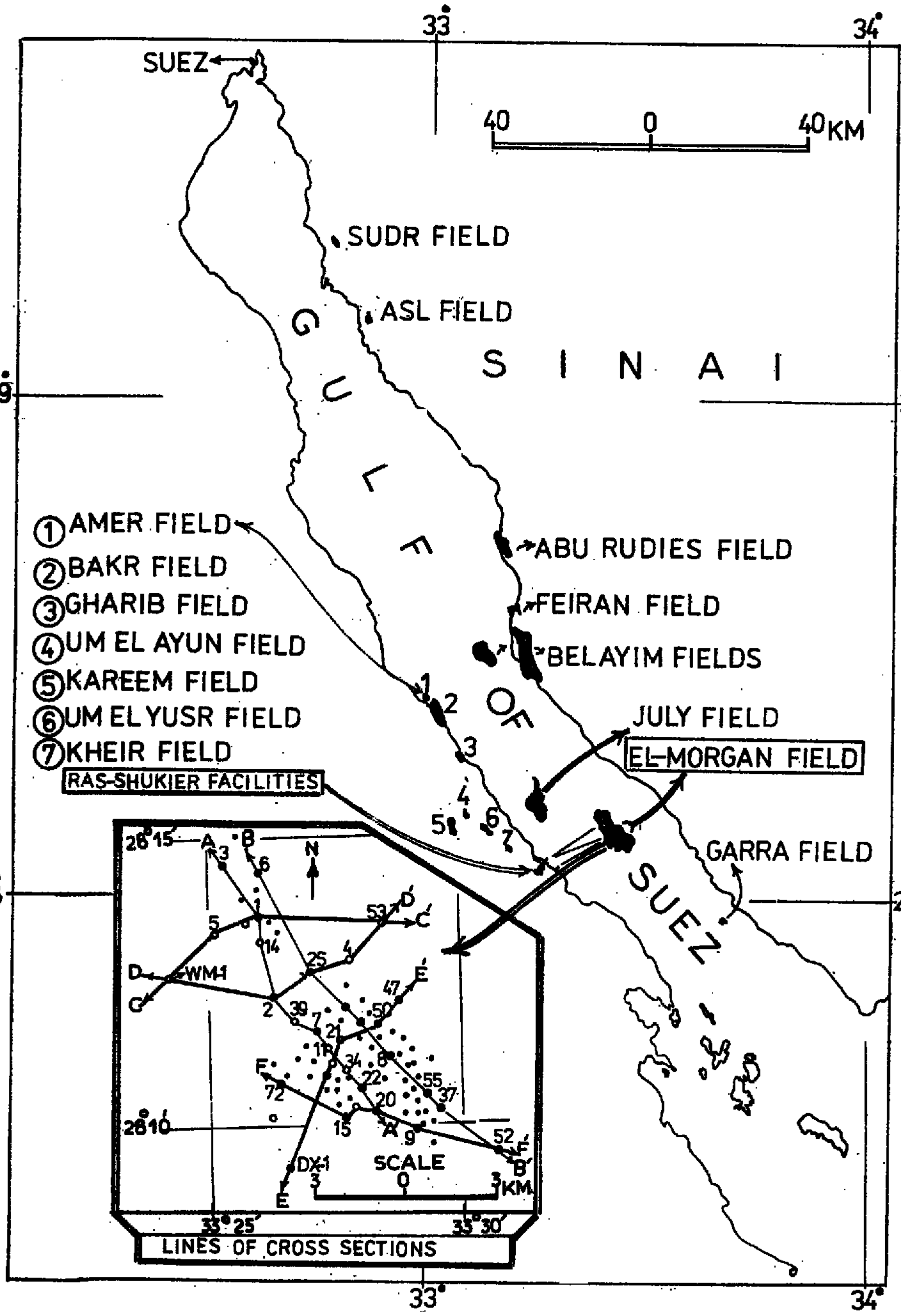

Fig. 1. Location map of the investigated area; inset shows position of cross sections (*A—A'* through *F—F'*) presented in Figs 13—18

Um El-Yusr, Kheir, Shukier, July and Ramadan oil fields to the north--west and west (Fig. 1).

This paper aims to clarify the tectonic setting of the field, with special reference to the structures produced by salt movements in the area, which affect to some extent the hydrocarbon accumulations and the source-reservoir relations (Metwalli & *al.*, 1976). The salt thickness and movements stand as a puzzling problem to the exploration activities in the Gulf of Suez region till the present. However, as deep drilling continues in the Gulf of Suez region a vast amount of data is continually added, this would modify or at least clarify many ideas at present controversial or in doubt.

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HISTORY OF EXPLORATION

Seismic Surveys: Several marine surveys have been carried out in the Gulf of Suez in the study area. The first reconnaissance survey was made in the mid--fifties by the Compagnie Orientale Des Petroles d'Egypte (*COPE*). Two other surveys were run over the Tor Banks area and its surroundings by the General Petroleum Company (*GPC*). In 1964 Pan American U.A.R. Oil Company, resurveyed the area using dynamite as the energy source, with 600% coverage. As a result oil was discovered in El-Morgan field in April 1967 whence the Gulf of Suez Petroleum Company (*GUPCO*) was formed as an operating company from two partners: the Egyptian General Petroleum Corporation (*EGPC*) and the Pan American U.A.R. Oil Company to conduct the rest of exploration obligatories and the commercial development of the field. The field was put on production in April 1967, from the Kareem Formation (Miocene) which is the lower reservoir (pay-zone) and in January 1972, from the upper one (Hammam Faraun Member of the Belayim Formation; Miocene) which is of limited reserves.

Magnetic Survey: In 1964 an aeromagnetic survey was carried out for the Gulf of Suez region in an attempt to draw a regional basement relief map. The depth of the basement was believed to be approximately 15,000 feet.

Gravity Survey: In 1966—1968, a marine gravity survey was conducted which indicated a large Bougeur anomaly underlying the Tor Banks area.

The discovery of El-Morgan oil field has proved the opinion that the Gulf of Suez area was, and still, a highly promising region. El-Morgan oil field is the largest proved structure in Egypt and, till the present, gives the highest production.

GENERAL GEOLOGIC SETTING

The stratigraphic section in the Gulf of Suez region ranges in age from Paleozoic to Recent, but most of the drilled wells ended in Tertiary rocks, *i.e.* the main sequence penetrated is the Miocene evaporites and the underlying Miocene clastics.

The sedimentary section in the Gulf of Suez region includes a thick Miocene succession which was studied by many authors of which Fraas (1867), Mitchell (1887), Deperet and Fourtau (1900), Fourtau (1920), Blankenhorn (1901, 1921), Moon & Sadek (1923), Picard (1943), Stainforth (1949), and Said & Bassiouni (1958) were the pioneers. Said (1962) reviewed the works of the earlier authors and presented a general section for the Miocene in the Gulf of Suez region.

The current subdivisions of the Miocene of that region are summarized below (Fig. 2).

POST-MIOCENE (UNDIFFERENTIATED)

These deposits extend from the sea floor to the anhydrite and shale intercalations making the top of the Zeit Formation. This unit is recorded in all wells drilled in El-Morgan oil field and ranges in thickness from 2500 ft in *M-52* to 620 in *M-5*. The rocks are represented mainly by sands of coarse to very coarse size; gravels of granitic composition, clays, limestones that may be oolitic, coralline or reefal with occasional streaks of gypsum at the lower part. This facies represents shallow marine conditions.

The post-Miocene deposits unconformably overlie the Zeit Formation not only in El-Morgan area but also in Um El-Yusr oil field (Metwalli & Bashat, 1974) and in the exposed section at Ras-Shukier (Mohsen, 1972) to the west of El-Morgan oil field area on the western coast of the Gulf of Suez. Hydrocarbons were not recorded in this unit in El-Morgan oil field area.

MIOCENE

The top of the Miocene deposits in El-Morgan oil field area is marked by the evaporite-shale intercalations directly underlying the clastic deposits of the post-Miocene. The Miocene is represented by the following units from top to base:

(6) Zeit Formation:

Type locality: Gebel El-Zeit well No. 1, Gulf of Suez region. In its type locality this formation is represented by about 3100 ft thick of clastics with thin intercalations of evaporites. The Zeit Formation underlies the "continental sands" of Pliocene age and overlies the South Gharib Formation.

In El-Morgan oil field this formation represents the top of the Miocene evaporites. The top of the Zeit Formation is not marked by paleontologic evidence,

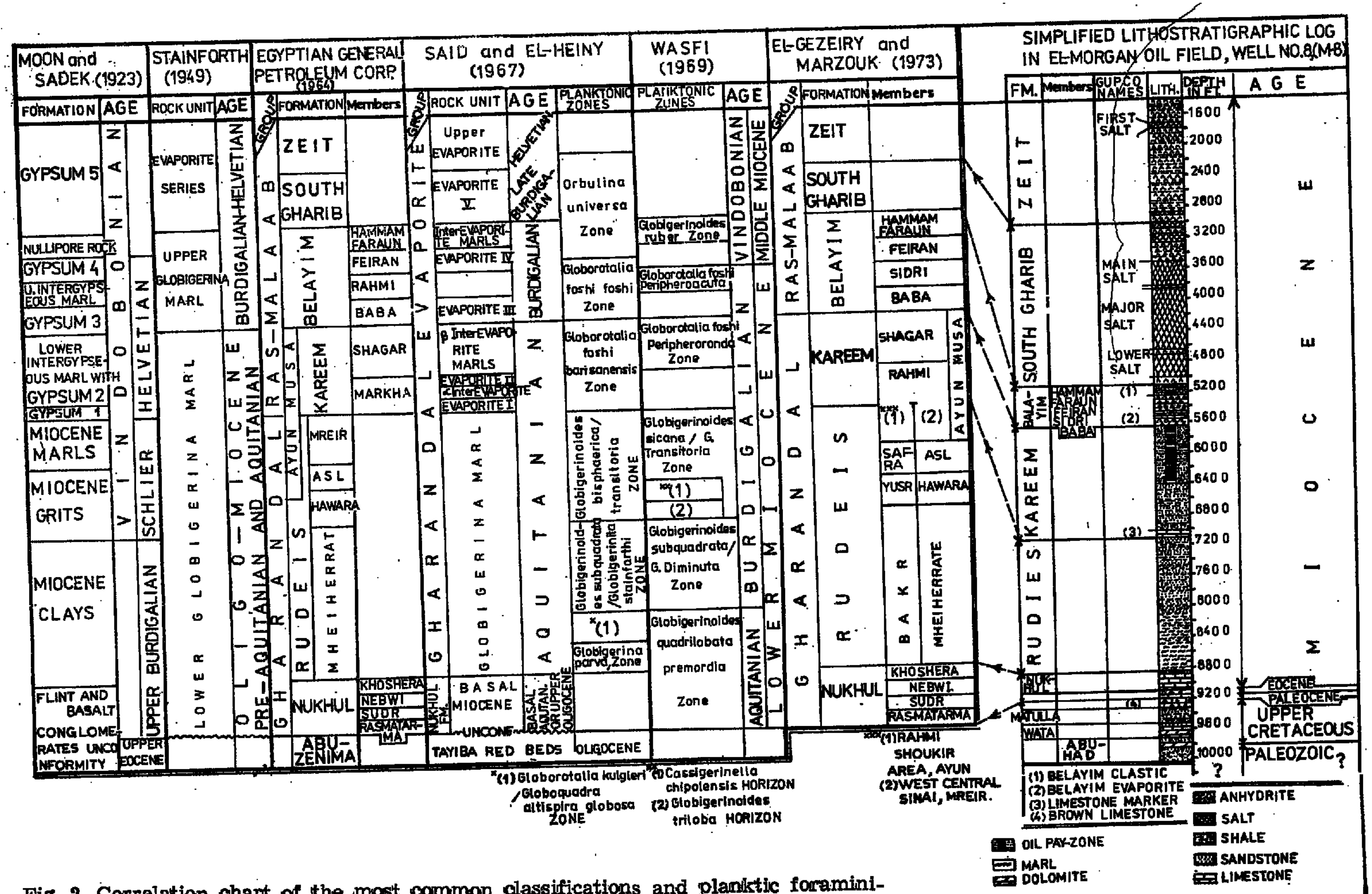

Fig. 2. Correlation chart of the most common classifications and planktic foraminiferal zones of the subsurface Miocene rocks in the Gulf of Suez region and their equivalents in El Morgan Oil field area

but is placed at the first appearance of solid anhydrite beds intercalated with shale (*GUPCO*). The thickness of the unit varies in El-Morgan oil field area from north to south. In the north of the field the thickness ranges from 2900 ft in *WM-1* to 821 ft in *M-3*, while in the south it ranges from 2095 ft in *M-15* to 680 ft in *DX-1* (Fig. 3). The thinning-out of this formation can be related to the flowage that took place in the underlying salt of the South Gharib Formation, while the thickening may be related to faults that affect the underlying formations.

The Zeit Formation consists of interbedded shales and anhydrite of shallow marine to predominant lagoonal facies. A marker bed, known as the "First Salt" by *GUPCO*, of about 60 ft in *M-8* lies near the top of this unit (Fig. 2). This bed reaches a thickness of about 180 ft in WM-1.

The base of the Zeit Formation is fixed by a marker shale bed, about 50—80 ft thick, that has been encountered in almost all the wells drilled in El-Morgan field, except in *M-3* and *DX-1*. This bed is known as "Shale-V" by *GUPCO*.

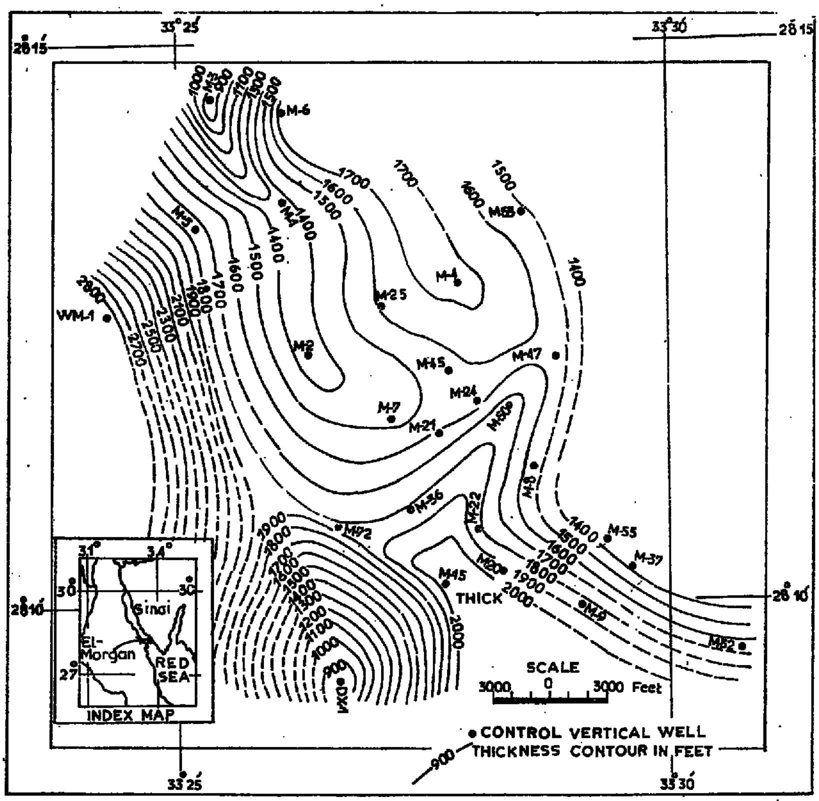

Fig. 3. Isopach map of the Zeit Formation

No sands have been encountered in the Zeit Formation in El-Morgan field contrary to the case in other fields, e.g. Belayim (Philip & Reda, 1967; Said & Zaki, 1967) and July oil field as well as in the type locality.

Hydrocarbons were not recorded in the Zeit Formation in El-Morgan oil field. However, this unit is oil-bearing in Belayim on-shore oil field.

The age of this formation is considered as late Miocene (*EGPC*, 1964) and Helvetian to late Burdigalian by Said & El-Heiny (1967). Abd El-Salam & El-Tablawy (1970) reported the presence of diatoms in the clastics of the Zeit Formation in east Bakr and east Gharib wells directly above and below the first salt, and they identified *Melosira recedens, Hemidiscus ovalis, Rhaphonesis angularis, R. fatula,* and concluded that these are of strictly Pliocene age (after Lohman, 1938), accordingly the Zeit Formation could be considered of late Miocene to Pliocene age.

(5) South — Gharib Formation:

Type locality: South-Gharib well No. 2, Gulf of Suez region. In its type locality this formation is represented by about 2030 ft thick of evaporites with intercalations of shales and sands. It underlies the Zeit Formation and overlies the Belayim Formation.

In El-Morgan oil field area the thickness of this formation varies from 3190 ft in *M-3* to 1500 ft in *WM-1* in the north, while it ranges from 4004 ft in *DX-1* to 1723 ft in *M-52* in the south (Fig. 4). A thinning-out of this formation is recorded in wells *M-8, M-50, M-65* and *M-53* which might be related to the structural high defined by the horst fault block that affected the underlying Belayim and Kareem Formations.

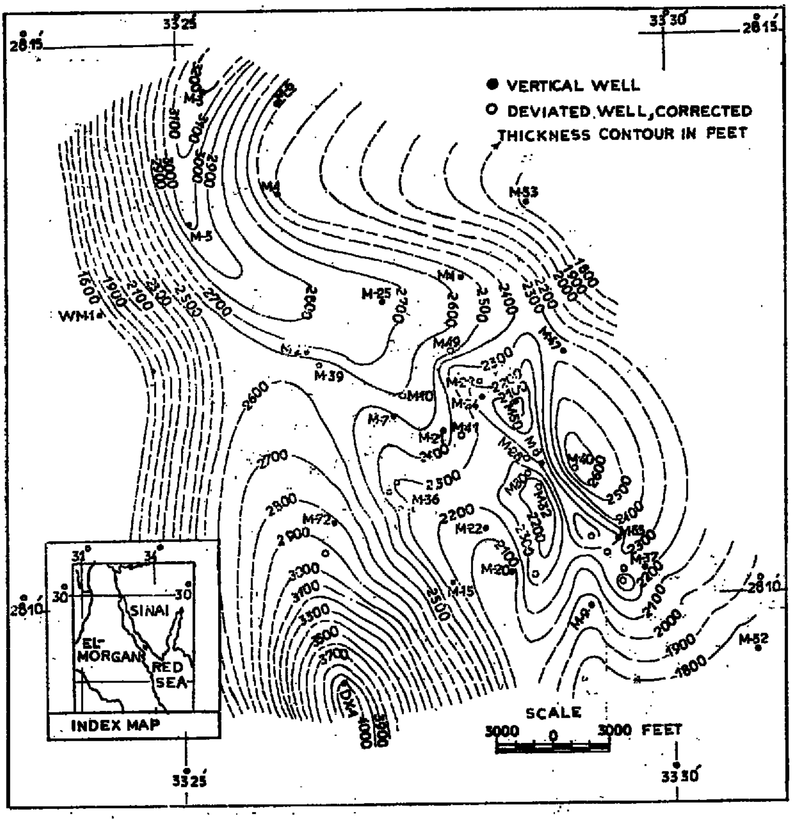

Fig. 4. Isopach map of the South Gharib Formation.

The South Gharib Formation is characterized by a remarkable increase in the thickness and amount of evaporites (mainly rock salt) of proper lagoonal facies. This rock salt forms local and well defined salt bulgs in the location of *M-8* and *DX-1* (Fig. 4). The increase in thickness of the evaporites (salt) resulted in masking the seismic reflections in El-Morgan oil field, as well as in other areas in the Gulf of Suez petroleum province, which caused many problems in interpreting the seismic data.

In the study area, the South-Gharib Formation is subdivided by *GUPCO* into two sub-units:

1) An upper one consisting of several thick salt and anhydrite beds with minor thin shale interbeds.

2) A lower one made up of three massive salt bodies (*a, b, c*) separated by much thinner layers of anhydrite and shale.

(a) The main salt, this shows more or less uniform thickness allover the study area except in the location of *M-3* and *DX-1* most probably due to salt flowage.

(b) The major salt, which is the thickest and more mobile salt body showing remarkable variation in thickness.

(c) The lower salt, which shows small variation in thickness mainly due to the effect of the underlying structural elements.

The base of the South Gharib Formation in most cases is defined by the appearance of the clastics of the Hammam Faraun Member of the underlying Belayim Formation.

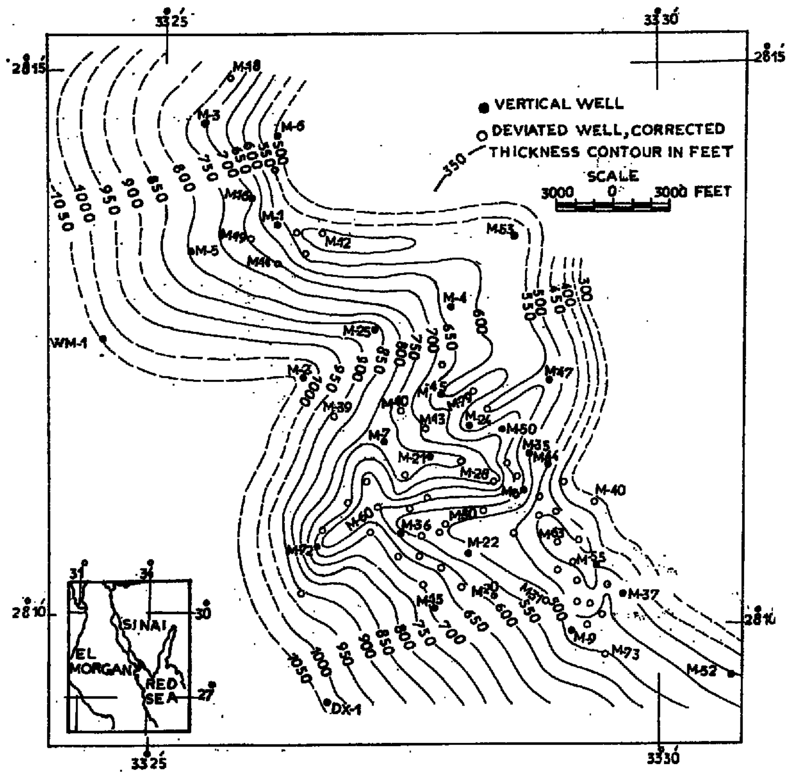

Fig. 5. Isopach map of the Belayim Formation

No traces of hydrocarbons were recorded in the South-Gharib Formation in El-Morgan oil field. However, it is oil-bearing in the Belayim on-shore and Bakr oil fields. The South-Gharib Formation, being a thick salt section, acts as a sealing unit that prevents the migration of oil from the underlying Belayim and Kareem Formations up dip in El-Morgan oil field. It also causes the sealing of probable conduits of oil migration. The mechanism of salt flowage might be a controlling factor in the extension and capacity of oil traps in the study area and other similar areas in the Gulf of Suez petroleum province.

The age of the South-Gharib Formation is difficult to define paleontologically. However according to its stratigraphic position it could be of Helvetian age? (Stainforth, 1949) or Helvetian to late Burdigalian age (Said & El-Heiny, 1967).

(4) Belayim Formation:

Type locality: Belayim oil field, Gulf of Suez. In its type locality the formation is about 1000 ft in thickness, made up of evaporites and interevaporite marls. It underlies the South-Gharib Formation and overlies the Kareem Formation.

In the study area the Belayim Formation varies in thickness from 300 ft in the eastern part of the field to about 1000 ft in the western part (Fig. 5). Lithologically it is formed of four members from top to base:

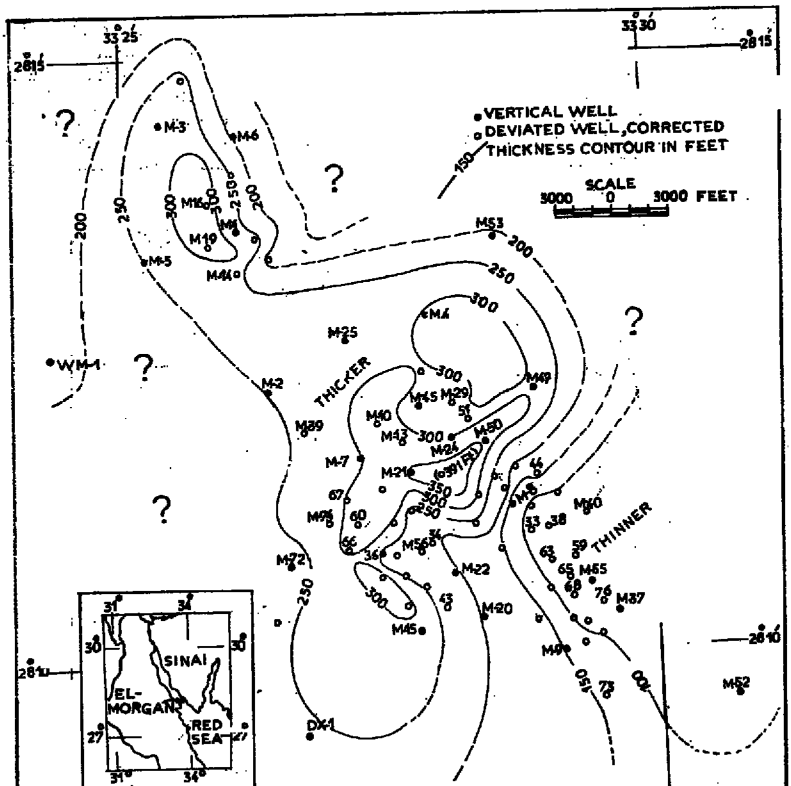

Fig. 6. Isopach map of the Belayim clastics

1) Hammam Faraun Member: this was first described in Wadi Gharandal, north of Gebel Hammam Faraun, as a rock unit which underlies the South-Gharib Formation and overlies the Feiran Member of the Belayim Formation. It is about 400 ft in thickness represented by different facies: a calcareous facies consisting of redalgal and argillaceous limestones with interbedded shales and marls; a shaly facies consisting of shales and marls; a shaly facies consisting of shale and marl and a third facies of sand, sandstone and sometimes conglomerate. In El-Morgan oil field area this member forms the upper pay-zone and produces oil of 24° API. It ranges in thickness from 59 ft to 391 ft (Fig. 6) represented mainly by arkosic sandstones with pyrite and glauconite. Shale intercalations predominant at its lower part in the struc-

turally low areas, also thin limestone streaks are recorded. The sandy facies of this member seems to thin-out east-wards and west-wards, which may be one of the causes of the variation in the capacity of oil production from the Belayim pay-zone.

2) Feiran Member: This member was first described in Feiran well No. 2, Gulf of Suez region, attaining a thickness of about 360 ft of anhydrite with comparatively thin intercalations of shale, marl and sands. It underlies the Hammam Faraun Member and overlies the Sidri Member of the Belayim Formation. In El-Morgan oil field the thickness of the Feiran member is about 200 ft in *M-8* but varies due to faulting. It consists of anhydrite with shale intercalations and occasional salt beds especially in the structurally low areas. Hydrocarbons were not encountered in this member.

3) Sidri Member: The type section for this member is in the Belayim well No. 122—13 where it attains a thickness of about 300 ft of clastic sediments, mainly shales and sands or sandstones. Occasional thin intercalations of limestone, marl and conglomerate may be present. The Sidri Member underlies the Feiran and overlies the Baba Member of the Belayim Formation. In El-Morgan oil field the Sidri Member attains a thickness of about 75 ft in *M-8* consisting mainly of intercalated calcareous shale and limestone with occasional streaks of anhydrite and sometimes sands as in *M-1* and *M-1-16*. Hydrocarbon showings have been recorded in *M-7*. The member is oil producing in Belayim on-shore oil field.

4) Baba Member: It was described in Baba well No. 2, Gulf of Suez region, attaining a thickness of about 190 ft and consisting of anhydrite intercalated with thin streaks of shale, sandy shale or sands. It underlies the Sidri Member of the Belayim Formation and overlies the Shagar Member of the Kareem Formation. In El-Morgan oil field the Baba Member attains a thickness of about 120 ft in *M-8*, but varies due to faulting. It consists of anhydrite with shale, salt and minor intercalations. The salt is best developed to the west and reaches the maximum in *M-2* and *DX-1* while it disappears completely in the

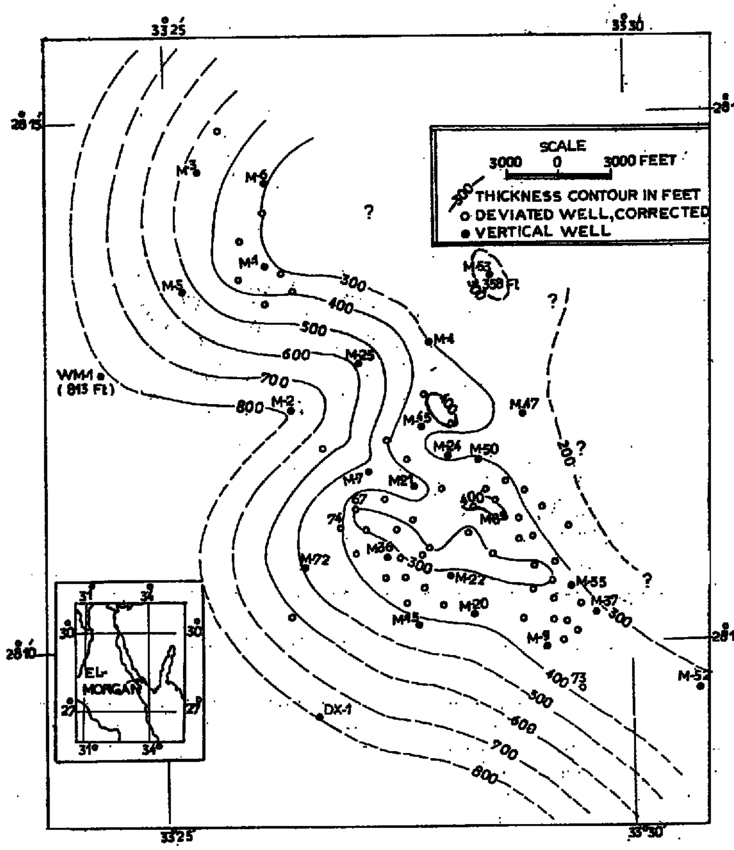

Fig. 7. Isopach map of the Belayim evapor...

eastern part of the field with predominance of anhydrite. The lower part of the Baba Member is formed of sandstone, with oil shows in some wells in El-Morgan oil field, e.g. *M-8-28, M-7, M-8* and *M-41*. This could be correlated with equivalent sand in the Belayim on-shore oil field, where it is oil producing (Hantar, 1967).

The top-most member of the Belayim Formation (Hammam Faraun Member) is known by *GUPCO* as the Belayim clastics, while the three lower members are collectively known as the Belayim evaporites. The Belayim Formation is oil producing in many fields in the Gulf of Suez petroleum province, *e.g.* El-Morgan, Belayim on-shore and off-shore, Bakr, Shukier and Gharib oil fields.

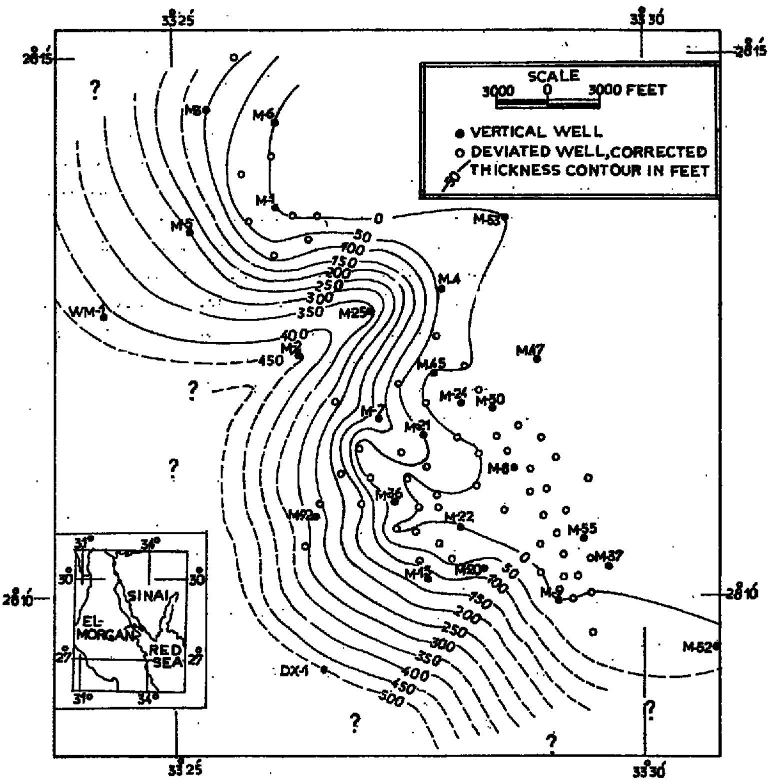

Fig. 8. Salt isolith map of the Belayim evaporites

The present authors agree with Hassan (1975) that the Belayim evaporites show a gradual increase in thickness to the west of the study area (Fig. 7). This observation conforms with the salt isolith map (Fig. 8) of the Belayim evaporites which indicates that the evaporites were deposited on a surface tilted to the west. Visible is a harmony in the thickness contour pattern (Figs 5, 7 and 8) denoting that the Belayim evaporites are more or less uniformly bedded with no indication of any salt flowage; the salt flowage seems to be or took place only in the overlying South-Gharib Formation.

(3) Kareem Formation:

Type locality: The Gharib well No. 2, west Sinai where it attains a thickness of about 800 ft of clastics with interbeds of anhydrite and occasional limestone, divided into two members: the Shagar and Marka. The Kareem Formation underlies the Baba Member of the Belayim Formation and overlies the Gharandal shales and marls of Said & El-Heiny (1967) or the Rudies Formation (*EGPC*, 1964).

In El-Morgan oil field, this formation is composed of calcareous arkosic sandstone with thin shale interbeds and minor evaporite intercalations. It reaches about 1400 ft in thickness in M-8 and was not penetrated fully in most of the drilled wells. The base of this formation is marked by an argillaceous limestone bed about 70 ft in *M-8* known as the "Limestone Marker" by *GUPCO.*

The sand and sandstone of the Kareem Formation in El-Morgan oil field form the main pay-zone, producing oil of about 30° API. The Kareem Formation is also productive in other oil fields in the Gulf of Suez petroleum province, e.g. Kareem and Belayim on-shore oil fields.

(2) Rudies Formation:

Type locality: The Rudies well No. 2, Gulf of Suez region where it attains a thickness of about 2550 ft consisting of sandy clays. The clays may be highly calcareous with abundant planktonic forminifera which resulted in the term „Globigerina marl" by some authors for the Rudies Formation (Fig. 2).

In El-Morgan oil field the Rudies Formation was penetrated fully in two wells only (*M-1* and *M-8*). The thickness of this formation in the study area is 3230 ft in *M-1* and 1646 ft in *M-8*. Lithologically it is made up of calcareous shale, rich in planktonic foraminifera, and approaching the argillaceous limestone in some intervals. The upper interval in *M-8* is of higher sand content than its equivalent in *M-1*.

EGPC (1964) subdivided the Rudies Formation in the north-eastern part of the Gulf of Suez region into four members from top to base: Mrier, Asl, Hawara and Mheiherrat. In El-Morgan oil field area the Rudies Formation is treated collectively as one unit underlying the Kareem Formation and overlying the Nukhul Formation. In *M-8* it is separated from the overlying Kareem Formation by the „Limestone Marker" of *GUPCO* (Fig. 2). The Rudies Formation is oil producing in the Belayim on-shore and off-shore, Sudr, Asl, Feiran, Kareem and Um El-Yusr oil fields from sandstone intercalated with shale. It produces oil of 33° API in July oil field recently discovered by GUPCO to the north-west of El-Morgan oil field. The fact that the Rudies Formation is oil producing in many oil fields in the Gulf of Suez petroleum province should lead to further evaluation of this formation and/or marking the boundary between the Kareem and Rudies Formations in El-Morgan oil field. Oil production from the lower pay-zone in El-Morgan oil field could be related to either the Rudies or Kareem Formations.

(1) Nukhul Formation:

This formation was first discovered by Waite and Pooly (1953) from its type section to the south of Wadi Nukhul where it reaches a total thickness of about 177 ft represented by shale, marl, sandy limestone and conglomerates. Previously this formation was regarded as the lower part of the Miocene clays (Moon & Sadek, 1923) or the Lower Globigerina marl (Stainforth, 1949).

EGPC as well as El-Gezeiry & Marzouk (1973) subdivided this formation into four members from top to base:

a) Khoshera Member which was first described in Asl well No. 26 attaining a thickness of about 36 ft; b) Nebwi Member, 72 ft in thickness in Nebwi well No. 4; c) Sudr Member first described in Sudr well No. 28 reaching about 66 ft in thickness; and d) Ras-Matarma Member which was first described in Ras-Matarma well No. 1 having a thickness of about 117 ft.

In El-Morgan oil field (*M-1* and *M-8*) this formation generally consists of calcareous shale, argillaceous limestone, sandy glauconite limestone with sandstone streaks and anhydrite interbeds. Oil showings were recorded in *M-8* at a depth of 8874 ft in the top part of the Nukhul Formation. Hassan (1975) considered the oil showings as calling for prospection to the south of the studied area, in this formation as well as the underyling clastics of Cretaceous age.

The age of the Belayim, Kareem, Rudies and Nukhul Formations in the Gulf of Suez was fixed using the foraminiferal zonation by many authors, *e.g.* Souaya (1965, 1966 a, b), Said & El-Heiny (1967) and Wasfi (1969, 1972). Wasfi (1969) studied the Miocene section in the wells Shukier No. 1, East Sudr and Rahmi No. 8 and divided it into six planktonic zones. The first is the *Globigerinoides ruber* Zone recorded in the Hamman Faraun Member in the Belayim Formation. This zone could be correlated with the *Heterostegina costata* Zonule (Souaya, 1965, 1966 a, b), and partly with Said and El-Heiny (1967) *Orbulina universa* Zone (Fig. 2).

The second zone, the *Globorotalia foshi peripheroacuta* Zone restricted by Wasfi (1969) to the Sidri Member of the Belayim Formation. This zone could be correlated with Souaya's (1965, 1966a, b) *Rotalia beccarii* Zonule; and Said & El-Heiny (1967) *Globorotalia foshi foshi* Zone; and Banner and Blow (1965) *Globorotalia peripheroacuta* Zone.

The third zone, the *Globorotalia foshi peripheroronda* Zone characterizes the Shagar Member of the Kareem Formation. This zone could be correlated with Souaya's benthonic subzone *Cassidulina cruysi;* and is equivalent to the *Globorotalia foshi barisancnsis* of Said & El-Heiny (1967).

Wasfi (1972) studied the Rudies/Nukhul/Eocene section in El-Morgan well No. 8 and applied his planktonic zonation of 1969. He characterized the upper part of the Rudies Formation by the fourth *Globigerinoides sicana/G. transitoria* Zone given in 1969 as the „Transition zone". This zone could be correlated with the *Globigerina bisphaerica/G. bisphaerica/ /G. transitoria* Zone of Said & El-Heiny (1967) and the *Globigerinoides sicana/G. insueta* Zone of Banner & Blaw (1965). Wasfi characterized the other part of the Mheiherrat Formation (*EGPC*, 1964) or Mheiherrat Member (El-Gezeiry & Marzouk, 1973) by the fifth planktonic zone *Globigerinoides subquadrata/G. diminuta.* This zone is also correlated with *Globigerinoides subquadrata/G. stainforthi* Zone of Said & El-Heiny (1967) and the two benthonic subzones: *Boliva oligocaenica* and *Buliminella cuvillieri* of Souaya (1965, 1966).

The lower part of the Rudies Formation and the Nukhul Formation are characterized by the sixth planktonic zone; *Globigerinoides quadrilobata primordia* Zone which could be correlated with the *Uvigerina semiornata* and *Cibicides ellisi* Zone of Souaya (1966) and the *Globorotalia kugleri/Globoquadrina altispira globosa* and *Globigerina parva* zones of Said & El-Heiny (1967).

Based on the above foraminiferal zonation, the Hamman Faraun Member is given an upper Burdigalian age by Said & El-Heiny (1967) and Vidobonian age by Wasfi (1969). The Sidri Member is related to the lower Burdigalian by Said & El-Heiny (1967) and the upper Burdigalian by Wasfi (1969). Generally speaking, the four members of the Belayim Formation are of Burdigalian age and could be correlated with upper Globigerina marl of Stainforth (1949).

Fahmy & *al.* (1969) studied the fauna of the Miocene section in the Gulf of Suez region and correlated it with adjacent countries of the Mediterranean region, particuliarly with Syria, and considered that the Belayim Formation is of Helvetian age.

The Kareem Formation, which could be correlated with the upper level of the Globigerina marl (Stainforth, 1949) is given an upper Aquitanian age by Said & El-Heiny (1967) and Burdigalian age by Wasfi (1969). Fahmy & *al.* (1969) considered most of the Kareem Formation as of Burdigalian age while the upper part is of Helvetian age.

The Rudies Formation which could be correlated with the major part of the lower Globigerina marl of Stainforth (1949) is given an Aquitanian age by Said & El-Heiny (1967) and an Upper Aquitanian age by Wasfi (1969). Fahmy & *al.* (1969) considered the Rudies Formation as of Burdigalian age.

The Nukhul Formation is equivalent to the lower part of the lower Globigerina marl (Stainforth, 1949) and is considered as of Aquitanian — Upper Oligocene age by Said & El-Heiny (1967) and Aquitanian age by Wasfi (1969) and Fahmy & *al.* (1969).

STRUCTURE OF EL-MORGAN OIL FIELD AREA IN RELATION TO THE GULF OF SUEZ REGION

The regional tectonic setting and structural analysis of the Gulf of Suez region have been discussed by many authors and are still the subject of current research programs. The Gulf of Suez lies within the stable belt of Egypt. It runs in a NW-SE direction, following the Erythrean trend of faulting and forms an elongated depression separating the massives of central Sinai from those of the Eastern Desert.

Shukri (1954) stated that although the major controlling normal faults in the Gulf of Suez region are trending in a NW-SE direction, yet there is a considerable evidence that the Gulf of Suez is profoundly influenced by intersecting systems of faults trending E-W (Tethyan), NE-SW (East African) and WNW-ESE directions. The N-S and WSW-ESE faults are largely responsible for the zigzag shape of the coastal line, the configuration of the Pre-Cambrian shield and the major drianage patterns of the Gulf region.

Shalom (1954) stated that the main period of formation of the Gulf of Suez and Red Sea paar was during the Oligocene which was a time of block faulting and erosion.

Said (1962) stated that bordering of the Gulf of Suez depression on both sides are two marginal faulting zones, usually marked by lines of high vertical escarpments on the upthrown sides. The two lines of fracture determine to a large extent the configuration of the present Gulf with the exception of some irregularities in the north-western side of the depression; he added that a result of the successive Paleozoic-Mesozoic and Tertiary movements that affected the Gulf area, it became one of the most intensively faulted areas in the world. However, the movements which brought the Gulf into its present shape are thought to be of the tentional type of Tertiary (Oligocene) age.

Youssef (1968) and others believed that the Gulf of Suez was also shaped by lateral displacement, for about 60 kms, that is the distance parallel to the Gulf between the Carboniferous outcrops of Wadi Araba on its western side and Um Bogma at the eastern side.

Knetsch (1957) showed diagramatically that the Wadi Araba horst, although a fault block, takes the shape of a fold due to dragging along the fault boundaries. However, Youssef (1958) and Faris (1961) stated that in the Qusier — Safaga area and to the north in Esh El--Mellaha, Gebel El-Zeit and the Nukhul — Baba areas the structures recorded are mainly folds.

Said (1962) noted that folding played a minor role, if any, in determining the structure of the Gulf. All the folds noted were produced either by the bending of the strata before breaking or by movements that caused the less rigid sediments to be in anticlinal or synclinal folds.

El-Tarabili (1964) stated that „the so-called folding" of some of the previous authors is in fact due to dragging of fault blocks along their boundaries. Later on, Youssef (1968) pointed out that supratenuous folds might have been initiated in the Gulf of Suez region during phases of block movements which coincide with the period of deposition. Such folds may not be easily discovered or recognized because their trends coincide with those of the superposed structures. He also added that many of the local unconformities and diastems on the tops of the drilled structures are attributed to the differential block movements during sedimentation.

El-Tarabili (1970) stated that the Graben fault blocks have the form of synclines, whereas the horst fault blocks have the form of anticlines. The direction of the so-called plunge of the fold axis is found to be related to the direction in which the bounding faults intersect and/or the direction of tilting of the fault blocks. The fold aQes are more or less parallel to the bounding faults. The faults have, therefore, no general trends and often show opposite vergings.

The detailed structural analysis of the area of El-Morgan oil field which is the subject matter of this paper is of prime importance to understand the mode and conduits of oil migration and accumulation, as a significant oil geological model in the Gulf of Suez petroleum province.

As far as the present authors are aware, Moustafa (1967), Khaled (1974) and Hassan (1975) were the only authors who dealt with the general geological and tectonic setting of El-Morgan oil field. The elaborate tectonic analysis and set of maps given by Khaled and by Hassan showed that "El-Morgan oil field is an elongated north-west — south-east trending anticline that is divided by a saddle into two lobes". However, they supported Moustafa (1967) who considered that the top of the Kareem Formation in the area between the northern and southern parts is a syncline. Moustafa (1967) supposed that the synclinal area was the result of post-depositional erosion at the close of the deposition of the Kareem Formation, when channel scouring took place. He attributed the fill-in of this presumed channel as a factor that affected the structural pattern of the overlying Belayim Formation.

In the present work, the structural analysis of El-Morgan oil field is based on the drilling data of vertical and deviated wells provided by *GUPCO*. A large number of the wells drilled in El-Morgan oil field area are deviated wells. Data obtained from these wells concerning the depths and thickness of formations were measured along the inclined courses of the holes and accordingly, had to be corrected to the corresponding vertical distance. Corrections were done trigonometrically by *GUPCO*. Coordinates of the tops of the formations were calculated and their locations plotted on the base maps. For the construction of structural cross sections, the courses of the deviated holes were plotted using the angle of inclination and the horizontal displacements from the vertical location of the drilling platform. Only data from vertical wells were used to construct the maps of the Zeit Formation. Maps of the South-Gharib Formation were constructed using data from vertical as well as some deviated wells, because the tops of these two formations were usually encountered at shallow depths whence the horizontal displacement from the platform locations is too small to change the coordinates. On the other hand, the base maps used for both the Belayim and Kareem Formations were constructed using data from all vertical and deviated wells after the latter had been corrected.

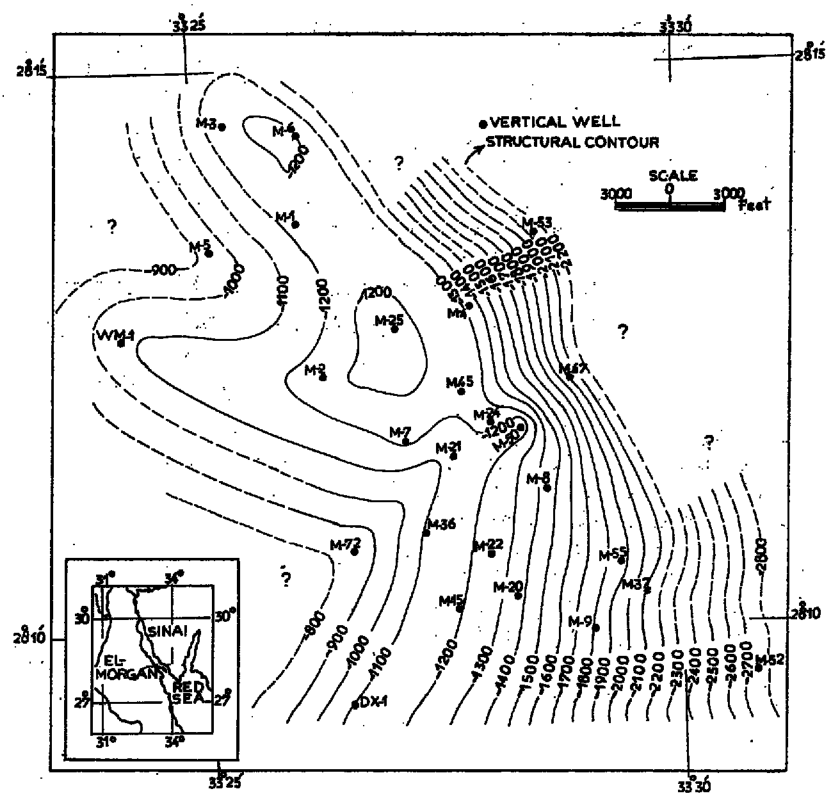

Fig. 9. Structural contour map on top of the Zeit Formation

A set of isopachous maps (Figs 3—8), structural contour maps (Figs 9—12) and structural cross sections (Figs 13—18) are constructed.

The analysis of these maps and sections shows that the study area is dissected by a group of normal faults. However, a major fault trending ENE-WSW aided by the production data and their interpretation and significance given in Metwalli & *al.* (1976), leads to the subdivision of El-

-Morgan oil field into two territorial productive portions of significant crude oil characteristics: northern and southern portions. Metwalli & *al.* (1976) stated that the vertical variability of specific gravities of the crude oils of El-Morgan oil field pay-zones is controlled partially by their structural attitude, *i.e.* the type of fault traps either horst, graben or step fault blocks.

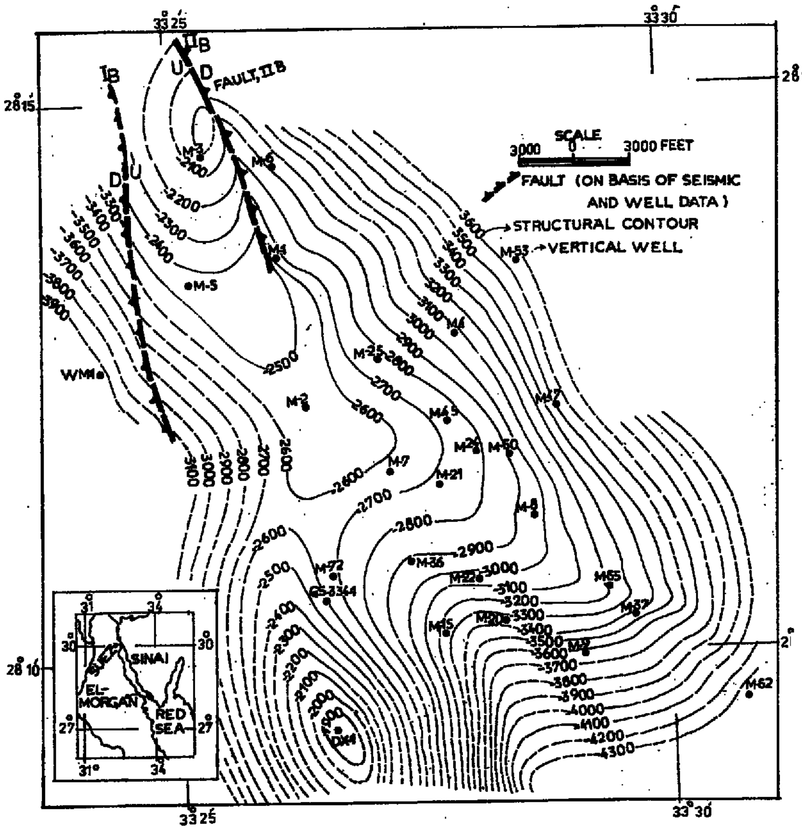

Fig. 10. Structural contour map on top of the South Gharib Formation

The faults that moddeled El-Morgan oil field as traced on the structural contour maps (Figs 10—12) are recorded in two main trends:

1) The major controlling faults trend NW-SE. The faults recorded on tops of the Kareem and Belayim Formations are given the symbol „A", while those recorded on top of the South-Gharib Formation are given the symbol „B". The „A" faults are more important in the structural modelling of the field.

2) A group of faults trending ENE-WSW and are given the symbol „C".

The NW-SE faults can be related to main faulting stages as regarding their extent in the rock and time stratigraphic units in the Miocene section in El-Morgan area, from top to base:

1. Post-South-Gharib Faulting (Figs 10, 15 and 16): This group is represented by two faults which ended by the end of the deposition of the South-Gharib Forma-

tion. The first „IB" is clear at the location of El-Morgan wells *M-3-18, M-6, M-6-25* and *M-1*, while the second „BB" is recorded at the location between *WM-1* and *M-5*. These two faults form a horst structure in the north-western part of El-Morgan oil field. Fault „IB" is confirmed seismically, while fault „IIB" is based on drilling data aided by the seismic data.

2. Post-Belayim Faulting (Figs 11 and 13—18): This group of faults is recorded on top of the Belayim Formation „A" and affects in major cases the lower salt of the South-Gharib Formation. These faults form a group of grabens, step faults and horsts (fault-blocks).

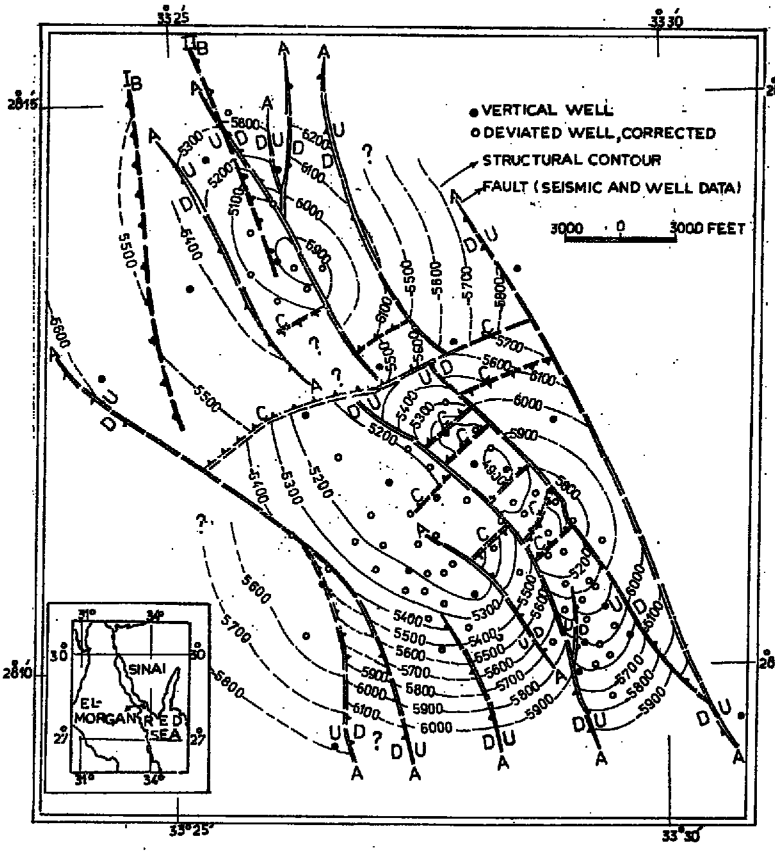

Fig. 11. Structural contour map on top of the Belayim Formation

The ENE-WSW faults seem to have taken place by the end of the Balayim Formation where most of them affect the lower salt of the South-Gharib Formation. These faults „C" form also together step faults, grabens and horsts.

The evaporites overlying the oil pay-zone in Belayim and Kareem Formations acted as a plastic cover and prevented many of the recognized and traced deep faults reaching the overlying South-Gharib and Zeit Formations.

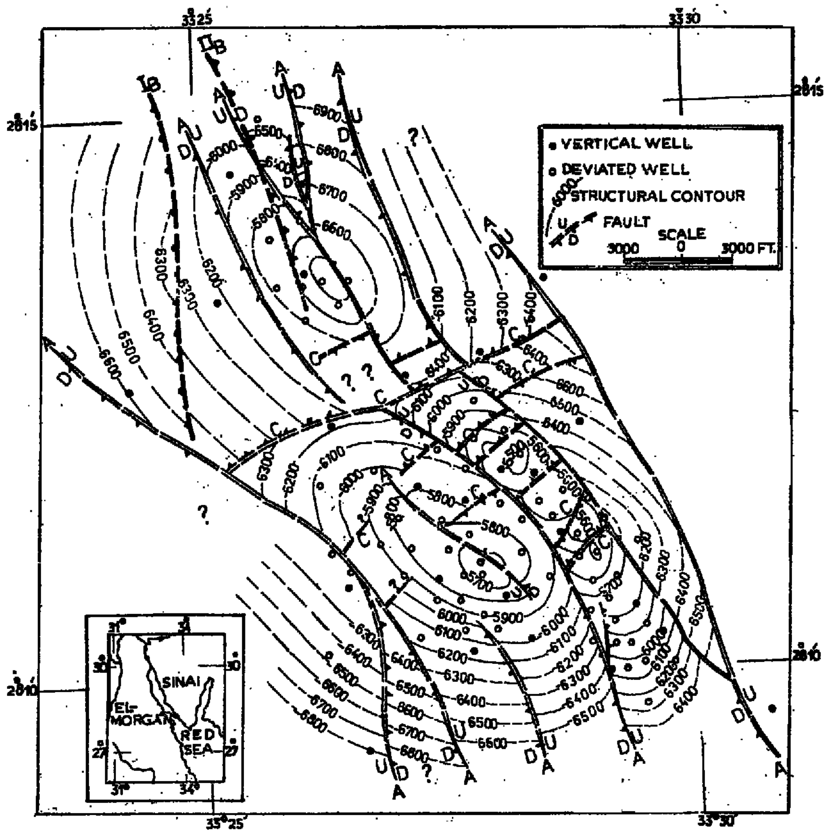

Fig. 12. Structural contour map on top of the Kareem Formation

It is apparent from the structural analysis of the structural contour maps, isopach maps and structural cross sections constructed and the faults traced above, that El-Morgan oil field can be considered as two portions (north and south portions) separated by a major ENE-WSW fault, the area is dissected into a group of horsts, grabens and step faults. The fault blocks which make up the oil reservoir and traps are dragged

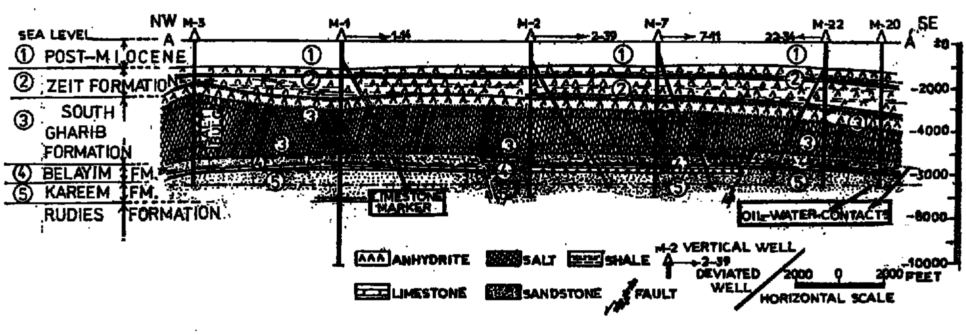

Fig. 13. Structural cross section across the line A—A′ (for location see Fig. 1.

along their boundaries, so that they may be erroneously interpreted as folds. The synclinal area suggested by Moustafa (1967) on top of the Kareem Formation at the location of *M-2* and *M-25* is considered by the present authors as graben, also the presumed anticlinal structure is considered as a series of faults that resulted in horsts, grabens and step faults severely dragged along their boundaries.

The recognition and tracing of the observed fault blocks in two time intervals within the middle Miocene might have produced two minor unconformity surfaces that could be recorded only in some wells in El-Mor-

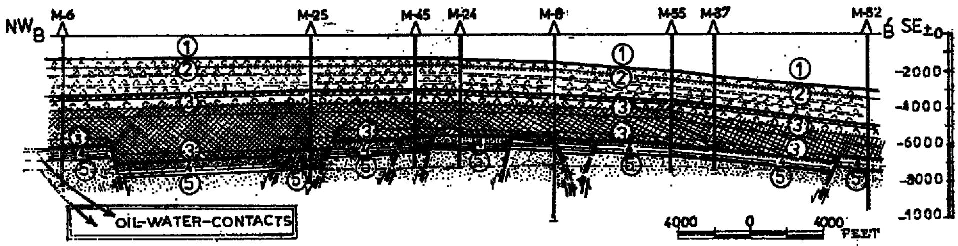

Fig. 14. Structural cross section across the line *B—B'* (for location see Fig. 1)

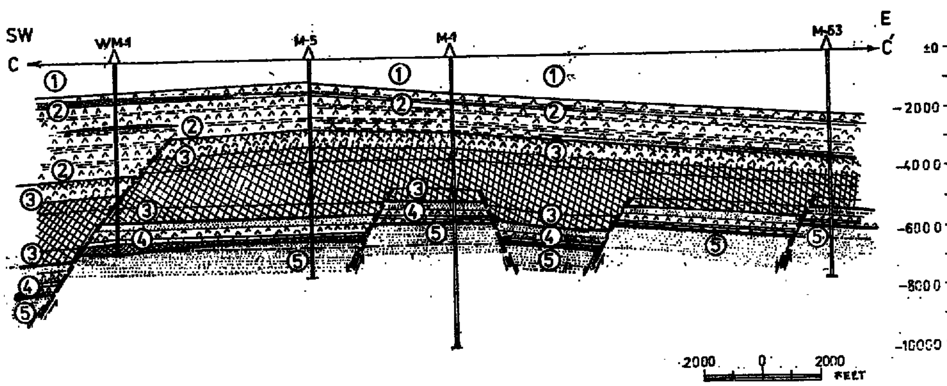

Fig. 15. Structural cross section across the line *C—C'* (for location see Fig. 1)

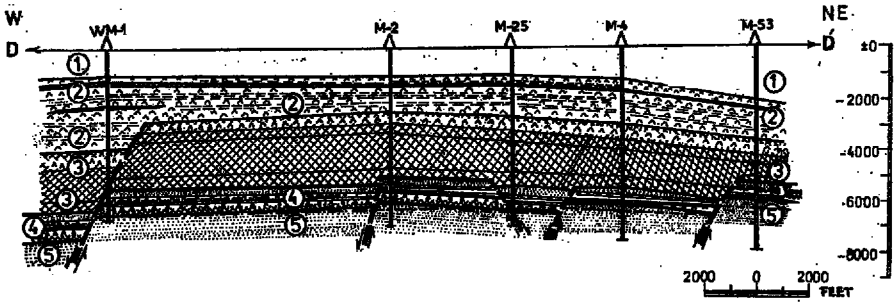

Fig. 16. Structural cross section across the line *D—D'* (for location see Fig. 1)

gan oil field. These are the post South-Gharib unconformity surface well developed in the northern area and the post-Belayim unconformity surface. The present authors are in agreement with Stoffer & Ross (1974) that most of the wells drilled in the Gulf of Suez region show unconformities within the Miocene as well as within the post Miocene sections. This is most probably due to the nature of the Gulf of Suez region which can be looked upon as a series of fault-blocks, each having its own geological history.

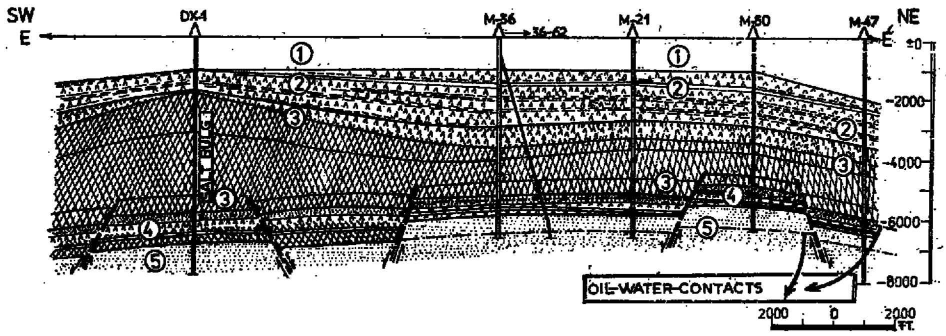

Fig. 17. Structural cross section across the line E—E' (for location see Fig. 1)

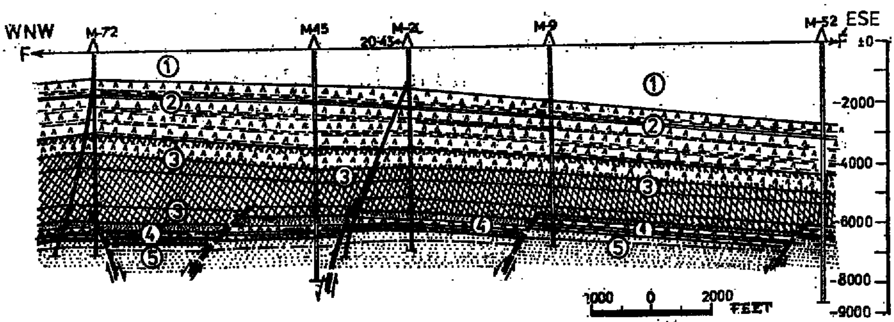

Fig. 18. Structural cross section across the line F—F' (for location see Fig. 1)

Metwalli & Bashat (1974) recognized breaks in the cycles of sedimentation within Um El-Yusr oil field area, Gulf of Suez region, longitude 33°30′ E and latitudes 28°—26°3′ N. Their study revealed three unconformity surfaces from top to base:

3. Post — Ras-Malaab (Post-Zeit Formation)
2. Post — Gharandal (Post-Rudies Formation)
1. Pre-Miocene.

They added that the unconformities which punctuate the stratigraphic column in the outcrops become progressively less distinct in the subsurface Tertiary basins in the Gulf of Suez region.

SALT FLOWAGE AS A CAUSE OF PSEUDO-ANTICLINAL CONTOUR PATTERN IN EL-MORGAN OIL FIELD

The South-Gharib Formation is the lithostratigraphic unit responsible for the salt structures in the study area as well as in other offshore oil fields in the Gulf of Suez region. The thickness of the South-Gharib Formation varies greatly, increasing in the locations where the salt has flowed and moved to form salt pillows. Nevertheless, the thickness of the salt is sometimes affected, not only as a result of salt flowage, but also due to pre-salt faulting (Fig 13, 15 and 16).

From the structural analysis of El-Morgan oil field area the present authors followed Hassan (1975) and Moustafa (1975) who described the structures in the rock salt in El-Morgan area as salt bulgs or salt pillows. According to Trusheim (1960) salt flowage will start when the thickness of the salt is more than 900 ft (300 m) and the overburden is more than 3100 ft (1000 m). However, Moustafa (1975) regarded that salt flowage can result under less ideal conditions due to the high thermal gradient in the Gulf of Suez region. Moustafa based his work on seismic data and showed that the pillow structures recorded in El-Morgan field change into the more advanced diapiric phase in El-Amal area and other localities further south in the Gulf of Suez region. The salt structure in El-Morgan area (*cf.* Figs 3—4) did not result in disturbing the overlying rocks. However, the thickness of the Zeit Formation is affected to some extent, in the location of the salt pillows due to compaction. The marked NW-SE trend of the major salt pillows in the northern and southern areas of El-Morgan field (Figs 4 and 10) and their concordance with the underlying and overlying sequences indicate that the regional dip may have played a signifficant role in their formation.

The NW-SE faulting that affected the Miocene sequence underlying the South-Gharib Formation played also a significant role in the formation of the salt pillows that trend more or less in the same direction. Faulting is known to have occurred during the whole span of the Miocene time in the Gulf of Suez region, however, its effect is not recorded clearly in the evaporites of the South-Gharib and Zeit Formations, most probably due to the absorption of its effect by these plastic rocks.

Isopach maps (Figs 3 and 4) show that the effect of salt flowage is clear in the rock salt of the South-Gharib Formation and not in the evaporites of the Zeit Formation, this may be due to the thickness of the overburden overlying the Zeit Formation being less than that needed to initiate the salt movement. Also the change in lithology from the more plastic rocks salt in the South-Gharib Formation to the anhydrite — shale intercalations in the Zeit Formation may be a good reason.

The isopach and structural contour maps on the top of the South-Gharib Formation (Figs 4 and 10) show pseudoanticlinal contour pattern, separated by pseudo-saddle contour pattern, this disappeared by depth in the Belayim and Kareem Formation (Figs 5, 11 and 12) where the fault blocks are the pronounced structures.

In conclusion: the salt pillows could be considered as a result of the deposition of a thick rock salt unit overlain by a notable thickness of overburden aided by the disharmony of the underlying surfaces due to faulting and the regional dip.

It is of interest to note that the wells drilled in El-Morgan oil field show that the succession underlying the salt pillows is dry or of limited production. This may be due to: (*1*) the effect of salt movement on the porosity of the underlying rocks, an idea which needs in future more data to clarify it; (*2*) or the accumulated or formerly trapped oil underlained the salt pillows is squeezed by the effect of the pressure caused by the formation of salt bulgs or pillows and migrated up-dip to other trap locations which are not overlained by salt pillows.

PETROLEUM POTENTIAL OF MIOCENE AND UNDERLYING FORMATIONS IN GULF OF SUEZ PROVINCE

Most of the reserves of Egypt in the Gulf of Suez petroleum province were thought to be found in the Miocene rocks, *e.g.* sands in El-Morgan and Belayim fields, also other relatively minor accumulations in Miocene sands and sandstones in Sudr, Um El-Yusr, Shukier, Kareem, Feiran and Rudies — Sidri oil fields. However, the Miocene sediments of reefal facies are oil-bearing in Ras-Gharib, Bakr, Kareem and Gemsa oil fields.

Pre-Miocene reservoir rocks ranging from Eocene to Paleozoic?, are also oil-bearing in Hurgada, Ras-Gharib, Bakr, Amer, Kareem, Sudr, Asl, Ras-Matarma and Belayim off-shore oil fields. Accordingly, Miocene sandstones and reefal sediments together with pre-Miocene sands and limestone are the main oil-bearing rocks. The Miocene shales, marls and evaporites form the sealing rocks (cap-rocks) for the majority of traps in the Gulf of Suez petroleum province.

A considerable part of the off-shore areas in the Gulf of Suez region witnessed and conquered the former seismic techniques for mapping below the Miocene salt section represented by the South-Gharib Formation. However, hopeful prospects are thought to be trapped in the pre-Miocene faulted blocks, which are proved as oil-bearing horizons in many localities in the Gulf as a result of the Exploration activities by GPC and other oil companies. Accordingly, the production of oil and gas from the Gulf of Suez province comes from different lithostratigraphic horizons of Miocene, Eocene and/or Mesozoic or older rocks.

Oil production from the Gulf of Suez petroleum province can not be correlated with the complicated tectonic history of this hopeful prospective region in Egypt. The picture is further complicated by lateral and vertical facies changes of the thick Miocene clastics, and the presence of the thick concordant evaporite section. Active drilling operations and activities for the search of hydrocarbons in this complex oil-geological model would lead to an answer to the question formerly mentioned in this study; whether the salt structures were initiated by the underlying faults or not, an interesting problem of research of direct economic importance. If the salt structures represented by the salt bulges or pillows in El-Morgan and northern parts of the Gulf, and the diapiric salt in the Amal area and southern parts of the Gulf are related to faulting they should be continued in the Red Sea. This would be a valuable clue to the presence of hopeful oil-bearing formations underlying the Miocene and/or older rocks in the Gulf of Suez region.

The present drilling program by *GUPCO* for the July field located approximately 18 kms south of Ras-Gharib and 20 kms north-west of El-Morgan field is planned to go deep below the Miocene clastics which will result in valuable information concerning this problem raised by the present authors.

July field seems to be a fault block (Moustafa, 1975) in which oil and gas had been reported in two horizons: the Lower Miocene Rudies Formation and the upper Paleozoic (Carboniferous?) Nubia Sandstones. This discovery by *GUPCO* might nullify the restriction of the hydrocarbon-traps to the Miocene as has been traditionally believed by former authors and supports the presence of oil in the Pre-Miocene virgin section in the Gulf of Suez petroleum province.

The crude oils produced from the different lithostratigraphic horizons in the Gulf of Suez oil fields have variable oil gravities both laterally and vertically (Metwalli & *al.*, 1967). This vertical variations are within the different successive pay-zones of the same or varying reservoir characteristics. Metwalli & al. stated that the successive characters of the gravities of crude oil within the same and in different ages, would reflect more than one cycle of oil generation as well as migration and accumulation in the Gulf of Suez petroleum province.

The future deeper drilling in the Gulf of Suez and adjoining region will clarify many ideas at present controversial or in doubt. The present writers believe that large amounts of oil would be stuck in the thick sedimentary succession underlying the Miocene rocks in the Gulf of Suez petroleum province.

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