

Early – Middle Miocene Suez Syn-rift-Basin, Egypt: A sequence stratigraphy framework

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ABSTRACT

The analyses of thirteen planktonic and benthonic biozones, paleobathymetry and electric log data were used to interpret the sequence stratigraphy of the Early to early Middle Miocene syn-rift section in the Gulf of Suez. The study area is located in the central province of the Gulf and includes six boreholes located in two half grabens and the October Field. The new framework proposes the Suez Supersequence and Suez Depositional Sequence DS 50 instead of the five paleontological sequences commonly cited in the literature (S10 to S50). The Supersequence starts above the regional unconformity that separates the pre- and syn-rift rocks, commonly referred to as Terrace T00. The shallow-marine deposits of the Aquitanian Nukhul Formation form the lowstand systems tract. The Burdigalian Mheiherrat Formation starts with the *Uvigerina costata* flooding event and forms the transgressive systems tract deposited in outer-neritic to upper-bathyal settings. The overlying Langhian Hawara Formation was deposited in upper to middle bathyal settings and represents the maximum flooding interval. The Langhian Asl Formation (early falling stage systems tract, upper bathyal to outer neritic) and overlying Langhian Lagia Member of the Ayun Musa Formation (late falling stage systems tract) closed the Supersequence. Suez Depositional Sequence DS 50 lies unconformably on the Supersequence, and represents a major transgression starting with the *Praeorbulina glomerosa* s.l. flooding event. DS 50 corresponds to the Ras Budran Member of the Ayun Musa Formation (paleontological sequence S50). Its setting is outer neritic and its upper sequence boundary is an unconformable with the Belayim Formation. The Suez Supersequence is interpreted in terms of 35 genetic parasequences and DS 50 by 10 more. The parasequences are interpreted by the coincidence of quantitative paleontological faunal and paleobathymetric breaks with the electric log shifts. The sequences and parasequences are correlated between the six wells to show the evolution of the half-grabens and October Field at different times.

INTRODUCTION

The Gulf of Suez Rift Basin in Egypt is about 300 km long and 80 km wide (Figure 1a). Before the 1990s the principal exploration targets in the Gulf were structural traps. Most of these have been discovered during the last century resulting in more than 10 billion barrels of original oil reserves of which 3.8 billion remain to be produced. These traps coincide with structural highs (i.e. flat-top horsts and the crests of the tilted blocks) and contain excellent clastic reservoirs, principally in the pre-Miocene Nubia, Matulla, Wata and Raha formations. In some cases, stacked Miocene clastic reservoirs were encountered over these highs (Figure 2). However, due to the limited volume of the Miocene clastic reservoirs and their unpredictable lateral distribution and stacking patterns they were considered secondary targets.

The Gulf's undiscovered oil resources are estimated at ca. 4 billion barrels and these are most likely to be found in Miocene stratigraphic traps (Meshref et al., 1988; Khalil and Meshref, 1988; Tewfik et al., 1992; Hassouba et al., 1993, 1994; El Gendi et al., 1994; Fouda et al., 1994; Salama et al., 1994; Ramzy et al., 1998). So since the 1990s the attention of explorationists has been directed to the structural lows (i.e. Miocene half-grabens or sub-basins) between the high blocks. Commercial stratigraphic traps have been discovered in the Gulf, particularly in down-thrown sandstone reservoirs that pinch out against NW-trending faults that bound the major highs. Examples of major structural high trends where this trapping geometries may be present are

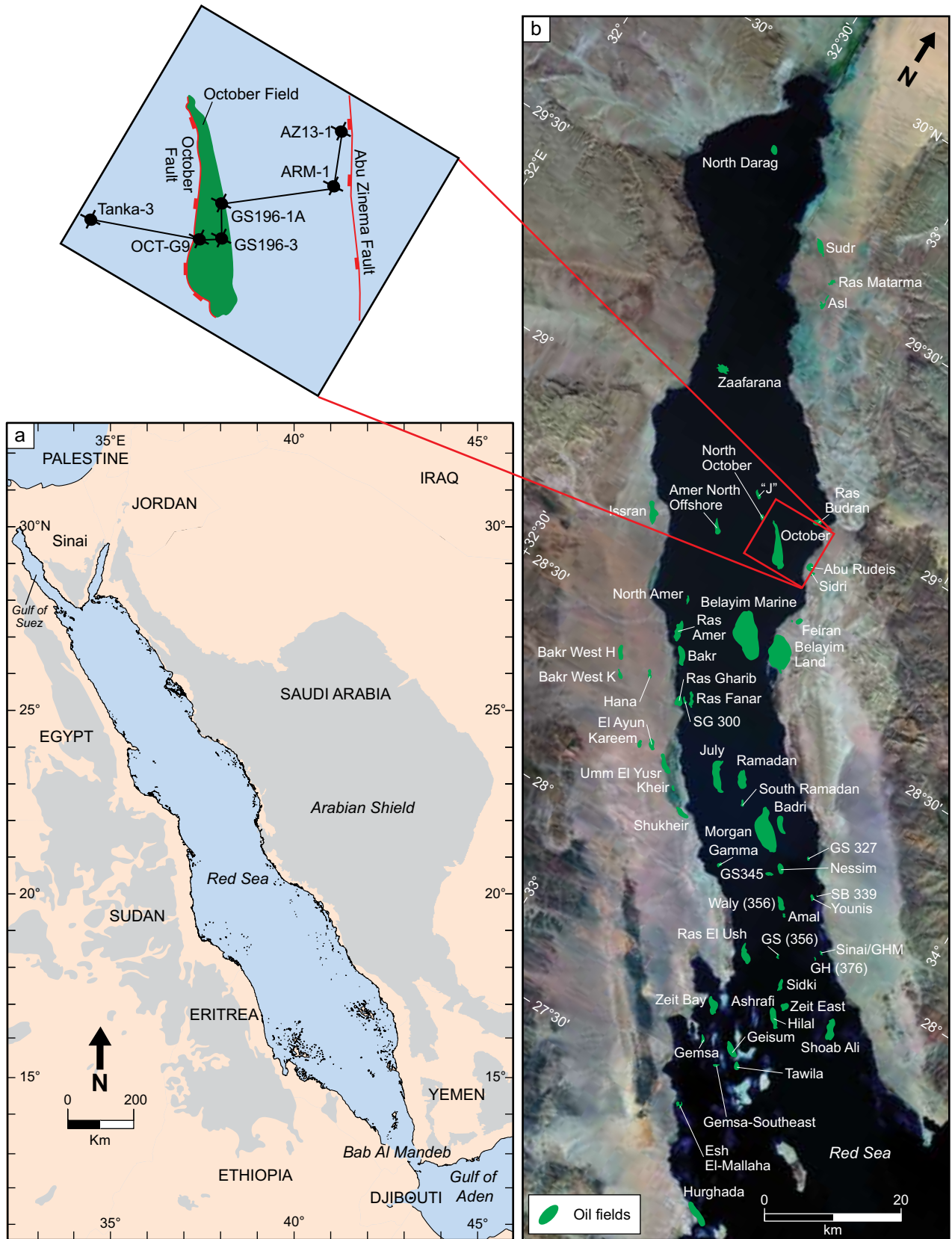


Figure 1: (a) The Gulf of Suez in Egypt forms the northwestern extension of the Red Sea Rift System. (b) The study area is located along the southern part of the October Field and includes six wells shown in the map in the upper left corner of the figure.

(Figure 1): "B", October, Ras Budran and Gebel Zeit trends (Hagras; 1986; Mostafa, 1976; Sultan and Shutz, 1984; Helmy and Zakareya, 1986; Abdel Halim et al., 1986; Zahran, 1986; Barakat et al., 1994; Khalil, 1992; Saad et al., 1996).

In order to conceptualize stratigraphic trap plays it is crucial to understand the sequence stratigraphy of the syn-rift Miocene succession. Many studies of the Gulf's Miocene stratigraphy have been based on graphic correlation methods to define paleontological sequences and terraces (e.g. Beleity, 1982; Dolson et al., 1996; Ramzy et al., 1996; Wescott et al., 1996; Krebs et al., 1997). These sequences are widely used in the industry although they are not chrono-stratigraphic depositional sequences (Vail et al., 1977; Von Wagoner et al., 1990; Gawthorpe et al. 1990, 1994, 1997; Catuneanu et al., 1998) nor genetic sequences (Galloway, 1989). The main objective of this study is to evaluate these paleontological sequences from a sequential depositional perspective rather than a paleontological one.

The paper starts with a review of the geological setting of the Gulf of Suez including the Early to early Mid-Miocene lithostratigraphy, biostratigraphy and the paleontological sequences and terraces (Nukhul to Ayun Musa formations; Figure 2). It then presents a detailed analysis of paleobathymetry using benthic foraminifera to develop a high-resolution sequence stratigraphic model. The model is

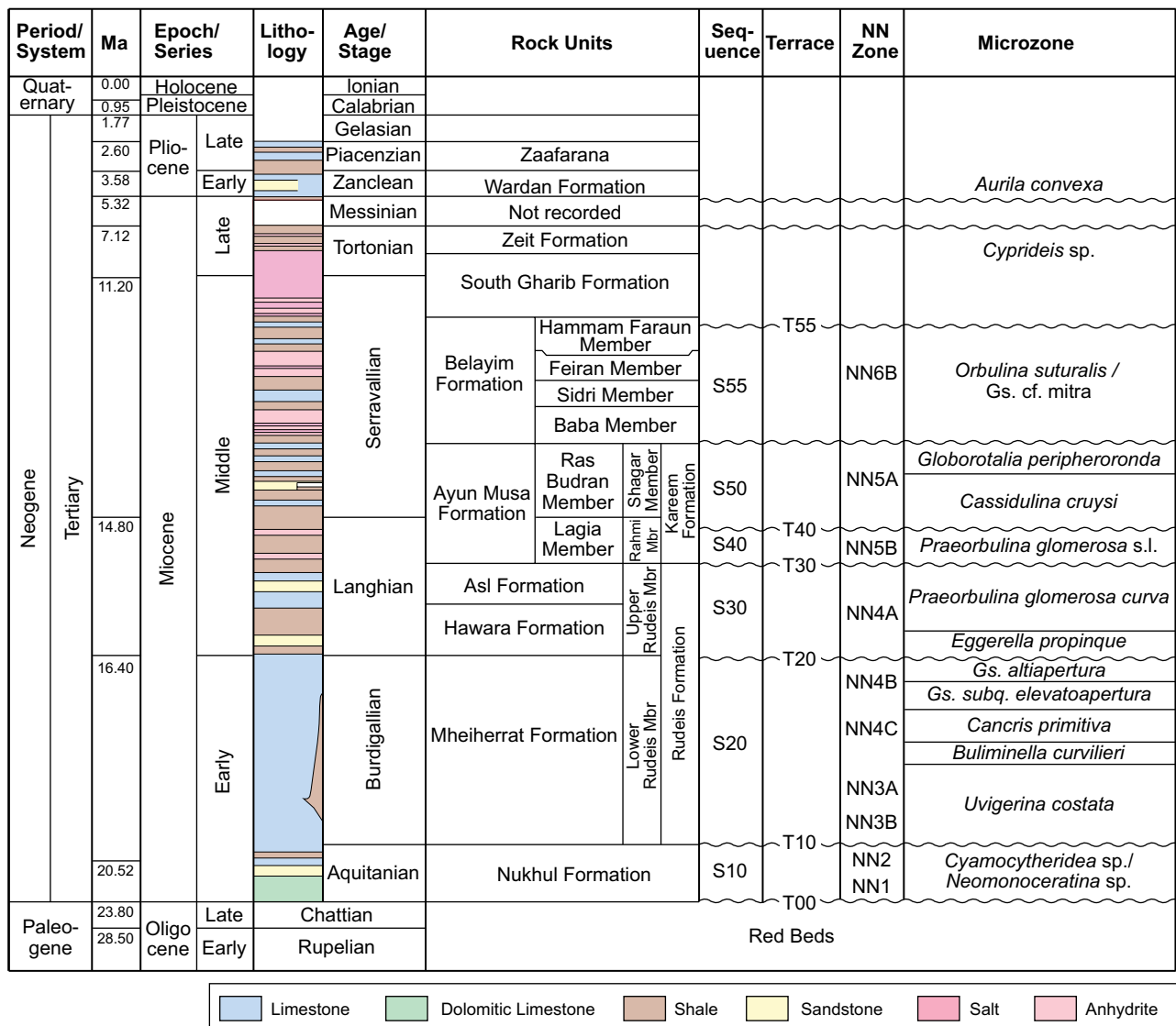


Figure 2: Generalized Miocene stratigraphic scheme of Gulf of Suez (modified after Souaya, 1966; Hosney et al. 1986 and Rateb, 1988). NN Zonation according to W. El-Fiky (2010, written communication).

used to correlate the newly defined sequences and parasequences between six boreholes located in the central Gulf of Suez (Figure 1b). This approach provides a new and comprehensive perspective for understanding the behavior of the rift basin's sequence stratigraphy and hence improves the predictability of oil trapping elements.

MATERIALS AND METHODS

The study area is located between 33°00' and 33°07'E, and 28°53' and 29°00'N in the central province of the Gulf of Suez (Figure 1). It includes the October Field and nearby areas, corresponding to Province I of Hosney et al. (1986). More than 1,400 cutting samples from six representative boreholes (Tanka-3, OCT-G9, GS196-3, GS196-1A, ARM-1 and AZ 13-1, Figure 1b) were used to study the lithology, micropaleontology (Figure 3, see Enclosure) and paleobathymetry (Figure 4) in the area. Time lines were correlated between the boreholes using the first downhole appearances (FDA) of foraminiferal markers.

The Integrated Paleontological System (IPS, after Gary and Gary, 1993) was used to estimate the paleobathymetry by the statistical analysis of benthic foraminifera recovered in the samples. The paleobathymetric curve of the depocenter was studied in the highly fossiliferous Borehole AZ13-1 and used to identify the upward deepening or shallowing trends (Figure 4), i.e. the systems tracts. Each foraminiferal species was cross-referenced to a data file containing species names and their respective upper and lower water-depth range assignments (GUPCO proprietary data). Besides the paleobathymetric curve, other curves were also studied including cosine cetta (dissimilarity), Otsuka (dissimilarity), total count of foraminifera and diversity. The IPS system displays its bathymetric estimate for each sample as a green horizontal bar that indicates the reliability of the estimate (Figure 4; i.e., the longer the bar, the less reliable the estimate). The following Table 1 shows the bathymetric zones determined by the IPS.

Table 1 Bathymetry

Bathymetry	Meter	Feet
Inner neritic	0 to 20	0 to 60
Middle neritic	20 to 100	60 to 300
Outer neritic	100 to 200	300 to 600
Upper bathyal	200 to 500	600 to 1,500
Middle bathyal	500 to 1,000	1,500 to 3,000
Lower bathyal	1,000 to 2,000	3,000 to 6,000

The calculated paleontological and paleobathymetric curves were then correlated to a full suite of electric logs (gamma-ray, density/neutron, sonic and resistivity; Figures 5 to 8 and 9, see Enclosure). The integration of these curves has shown that a good coincidence of the faunal breaks with the electric log shifts (Figures 5-8 and 9, see Enclosure). It helped define maximum and minor flooding surfaces, condensed sections and sequence boundaries (Figure 9, see Enclosure). The framework also facilitated the recognition of the stacking patterns of the parasequence sets (prograditonal, retrograditonal or aggraditonal) through the extraordinary change of relative sea level, not only due to eustasy but also due to the tectonic movements (subsidence).

The sequence-stratigraphic analyses in this study follows the concepts and definitions of Catuneanu et al. (1998), where they stated that the depositional sequence comprises four systems tracts with distinct stratal stacking patterns.

- Lowstand Systems Tract (LST) forms during early rise in relative sea level, when the sedimentation rate exceeds the rate of relative rise in the shoreline area (normal regression).
- Transgressive Systems Tract (TST) forms when the rate of relative sea-level rise in the shoreline area exceeds the sedimentation rate.
- Highstand Systems Tract (HST) forms during late rise in relative sea level, when the sedimentation rate exceeds the rate of relative rise in the shoreline area (normal regression).
- Falling Stage Systems Tract (FSST) forms during relative fall (forced regression).

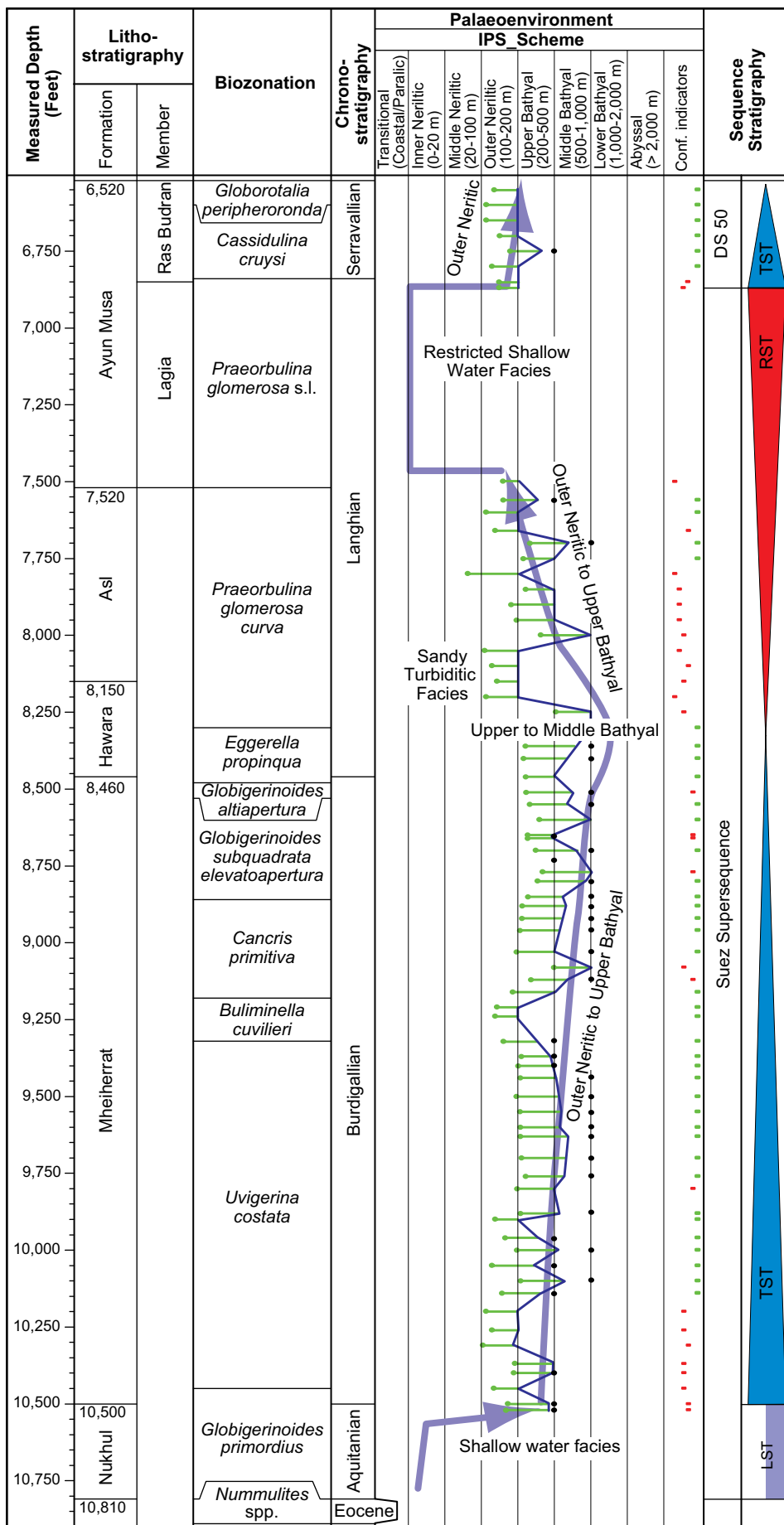


Figure 4: AZ13-1 Well paleobathymetry and depositional sequences.

The three systems tracts (HST, FSST and LST) together form a progradational package known as a Regressive Systems Tract (RST; Embry and Johannessen, 1992).

GEOLOGIC SETTING

Plate Tectonics

Patton et al. (1994) interpreted five major tectonic episodes to have punctuated the stratigraphic record of the Gulf of Suez area: (1) Late Proterozoic to Early Paleozoic Pan-African Orogeny, which involved the accretion of the continental lithosphere of the area; (2) Late Paleozoic Hercynian event; (3) Jurassic Neo-Tethyan Rift; (4) Late Cretaceous – Early Tertiary Syrian Arc event; and finally (5) Oligocene? – Miocene Gulf of Suez Rift. This study is focused on the final episode but recognizes that the structural fabric inherited from the Pan-African Orogeny appears to have played an important role in the subsequent structural development of the area.

The Suez Rift corresponds to the northwestern end of the Red Sea Rift System, resulting from the divergence between the African and Arabian plates, and the Levant Microplate. The Sinai Peninsula forms part of the Levant Microplate, which is rotating anticlockwise with respect to Africa, leading to the opening of the Suez Rift. It is affected by a sinistral strike-slip movement with respect to Arabia leading to the Gulf of Aqaba and Dead Sea opening (Robson, 1971; Colletta et al., 1988; Mostafa, 1992; Patton et al. 1994).

According to Chenet et al. (1984), the Suez Rift began in Late Oligocene (ca. 25–20 Ma) with the intrusion of dyke swarms but without regional uplift or significant normal faulting. Magmatic activity ceased and major faulting started during the Aquitanian with the formation of horsts and grabens, bounded by normal faults (60° to 80°). The tilted blocks typically dip between 10° and 20° but can reach 35°. They interpreted the age of the uplift of the Suez rift shoulders as Late Burdigalian (ca. 17 Ma). The rate of extension was not apparently steady with rapid phases interpreted at ca. 17, 13-14 and probably 5 Ma.

Colletta et al. (1988) estimated that at about 15-12 Ma extension along the Suez Rift ended when the Aqaba-Dead Sea transform fault system started. Steckler and Ten Brink (1986) attributed this transfer to the stronger Mediterranean oceanic lithosphere just north of the Gulf of Suez, which prevented northward propagation.

Abu Zinema and Tanka Half-Grabens

The Gulf of Suez Rift is divided by some authors into three main tectonic provinces, variously referred to as Ataka (Wadi Araba), Gharib (Belayim) and Zeit (Amal) from north to south (Moustafa, 1976; Bosworth, 1985; Rosendahl et al., 1987; Meshref et al., 1988; Rashed, 1990, 1994; Fouda et al., 1994; Farhoud, 2009). They are separated by the structurally complex Zaafarana Accommodation Zone (ZAZ) in the north, and the southern Morgan Accommodation Zone (MAZ) (Younes and McClay, 1998; Khalil and McClay, 1998). The northern and southern provinces are characterized by regional SW dip, whereas the central province by regional NE dip.

On a more detailed scale, the Gulf can be divided into smaller sub-basins or half-grabens (Hagras, 1986; Farhoud, 2009). The present study is focused on two half-grabens located west and east of the giant October Field, named the Tanka and Abu Zinema half-grabens, respectively (Figure 1b). This study area is used to show the application of sequence stratigraphy in a rift basin; some other examples in the Gulf of Suez where this approach is proposed for future studies are: (1) Abu Shaar Half-Graben bounded to the west by the Red Sea Hills and to the east by the Esh El Mellaha Range; (2) The West Zeit Half-Graben bounded to the west by the Esh El Mellaha Range and to the east by Gebel El Zeit; (3) The West Bakr Half-Graben to the north of the West Zeit Half-Graben, extends from Gebel Gharamoul in the south to the foot of the southern Galala Plateau in the north; (4) Offshore East Zeit Half-Graben bounded to the west by Shadwan Island, Gubal and the Gebel El Zeit high trend.

Structural Setting of the Study Area

Patton et al. (1994) documented four fault trends in the Rift. The amount of their strike-slip and dip-slip motions depends on their orientation relative to the principal direction of extension.

- Clysmic trend between 310° and 340°, with its maximum occurring in the range of 320°–330°.
- A significant fault trend that is oblique to the Clysmic trend spanning 350° and 30°.
- Another oblique to the Clysmic trend between 280° and 310° with its maximum between 290° and 300°.
- A distinctive, though relatively infrequent fault population trends between 50° and 75°, which is referred to as the “cross” trend.

The interaction of these four major fault populations defines the shapes of the tilted and horst blocks. The faults frequently bifurcate or splay into two segments involving clysmic and oblique faults, with the oblique faults generally linking clysmic faults. In these situations, the oblique faults act as “transfer faults” (Gibbs, 1984) that relay the lateral or normal displacement between *en echelon* clysmic faults.

According to Fouada et al. (1994) the internal structure of the Suez Rift is characterized by the propagation of listric normal faults that extend from the base of the lithosphere upwards. Garfunkel and Bartov (1977) noted that many faults, which offset pre-Miocene units, terminate or significantly decrease in displacement as they reach the base of the Asl Formation.

The study area starts in the northeast with the major NW-trending Abu Zinema Fault located along the coastal plain (Figure 1b); this master fault offsets the Lower – Middle Miocene succession by as much as 4,400 ft (1,340 m). The downthrown fault block to its west is the Abu Zinema Half-Graben (sometimes East October half-graben or sub-basin) in which the OCT-G9, GS196-3, GS196-1A, ARM-1 and AZ 13-1 boreholes are located. The east-tilting Abu Zinema Half-Graben is bounded to the west by the next major NW-trending October Fault; this listric fault is sometimes referred to as the October Clysmic Master Fault or Tanka Fault. It offsets the Lower – Middle Miocene succession by as much as 4,700 ft (1,430 m). The study area ends in the Tanka Half-Graben (sometimes West October half-graben or sub-basin), which contains the Tanka-3 Borehole. The western boundary of this half-graben is located further west outside the study area.

Early to Middle Miocene Lithostratigraphy

This study follows the lithostratigraphic scheme of Hosney et al. (1986), which is referenced by the EGPC (1964, 1974) in which the Miocene syn- and post-rift section is divided into the Gharandal and Ras Malaab groups. It is mainly focused on the Early to Middle Miocene syn-rift Gharandal Group (Figure 2). Six rock units are recognised in the studied boreholes; from base to top:

Nukhul Formation

This formation is recorded in all the studied boreholes except OCT-G9 and is recognized by this name throughout the Gulf of Suez. The formation generally consists of limestone and shale with dolomite streaks. The limestone is light tannish grey, tan cryptocrystalline to very fine crystalline, soft to moderately hard, slightly argillaceous, dolomitic, and glauconitic in the lower part. The shale is grey to light grey, blocky to sub-blocky, soft, sticky, calcareous to highly calcareous grading to highly argillaceous limestone. The dolomite is colourless, transparent, translucent, very fine crystalline, cryptocrystalline, sucrosic, slightly sandy, slightly glauconitic.

The thickness of the formation varies considerably in subsurface and at outcrop. The most productive reservoir zones consist of sandstone (often conglomeratic) interbedded with red shale that infill channels (J. Dolson, 2010, written communication). In the October Field, the Nukhul Formation produces oil from shallow-marine and fluvial sandstones and conglomerates from the F1 and East Tanka platforms located north of the study area.

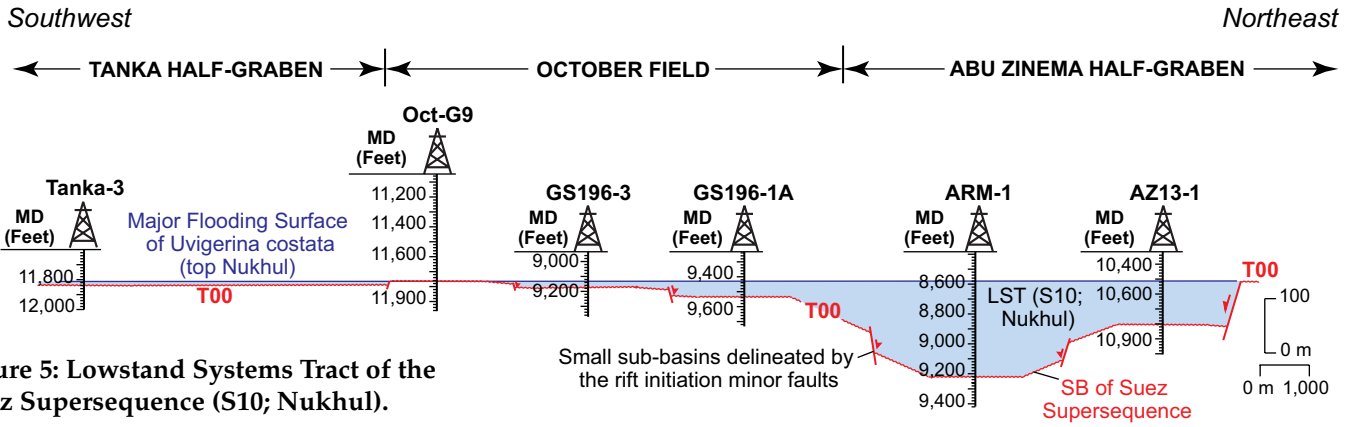


Figure 5: Lowstand Systems Tract of the Suez Supersequence (S10; Nukhul).

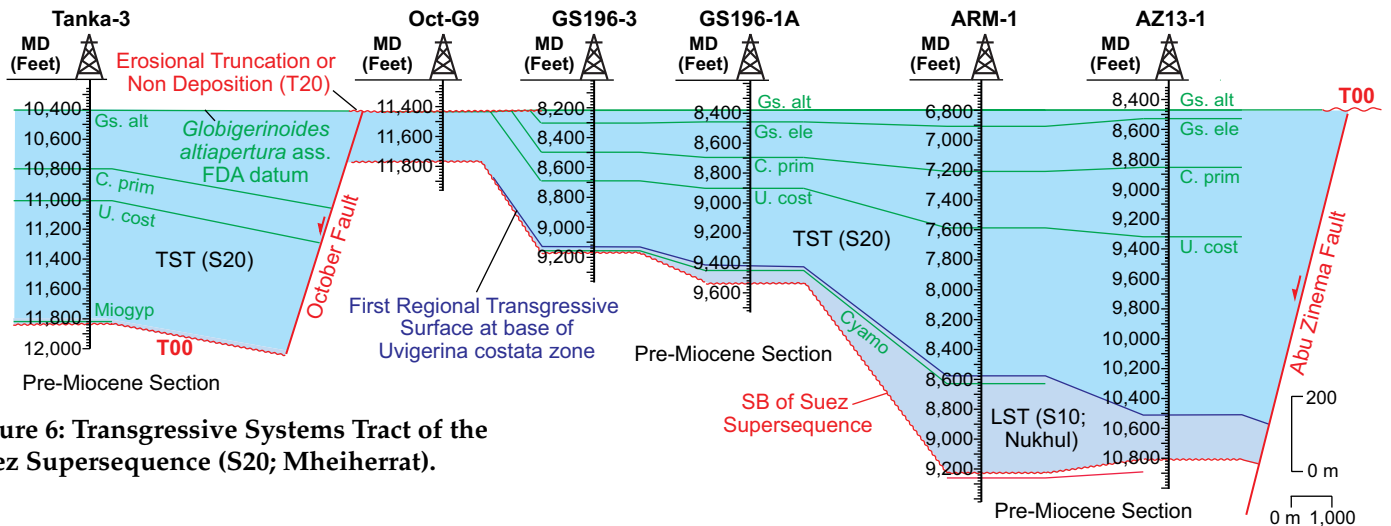


Figure 6: Transgressive Systems Tract of the Suez Supersequence (S20; Mheiherrat).

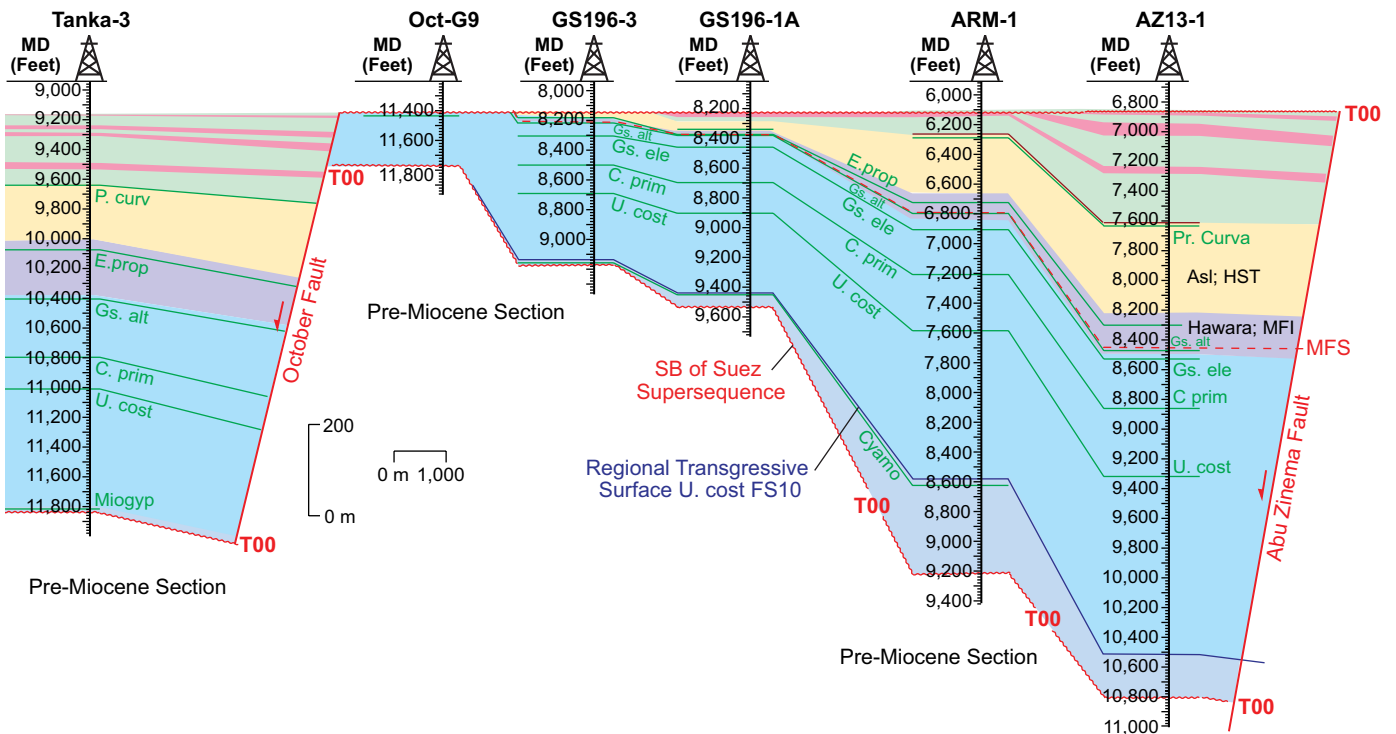
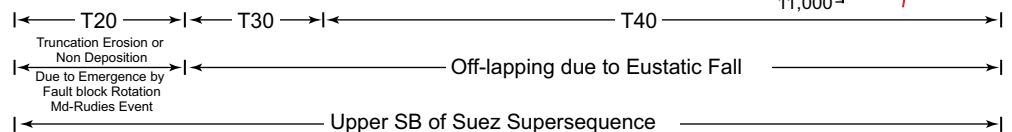


Figure 7: Regressive Systems Tract of the Suez Supersequence (S30 and S40; Hawara, Asl and Lagia).



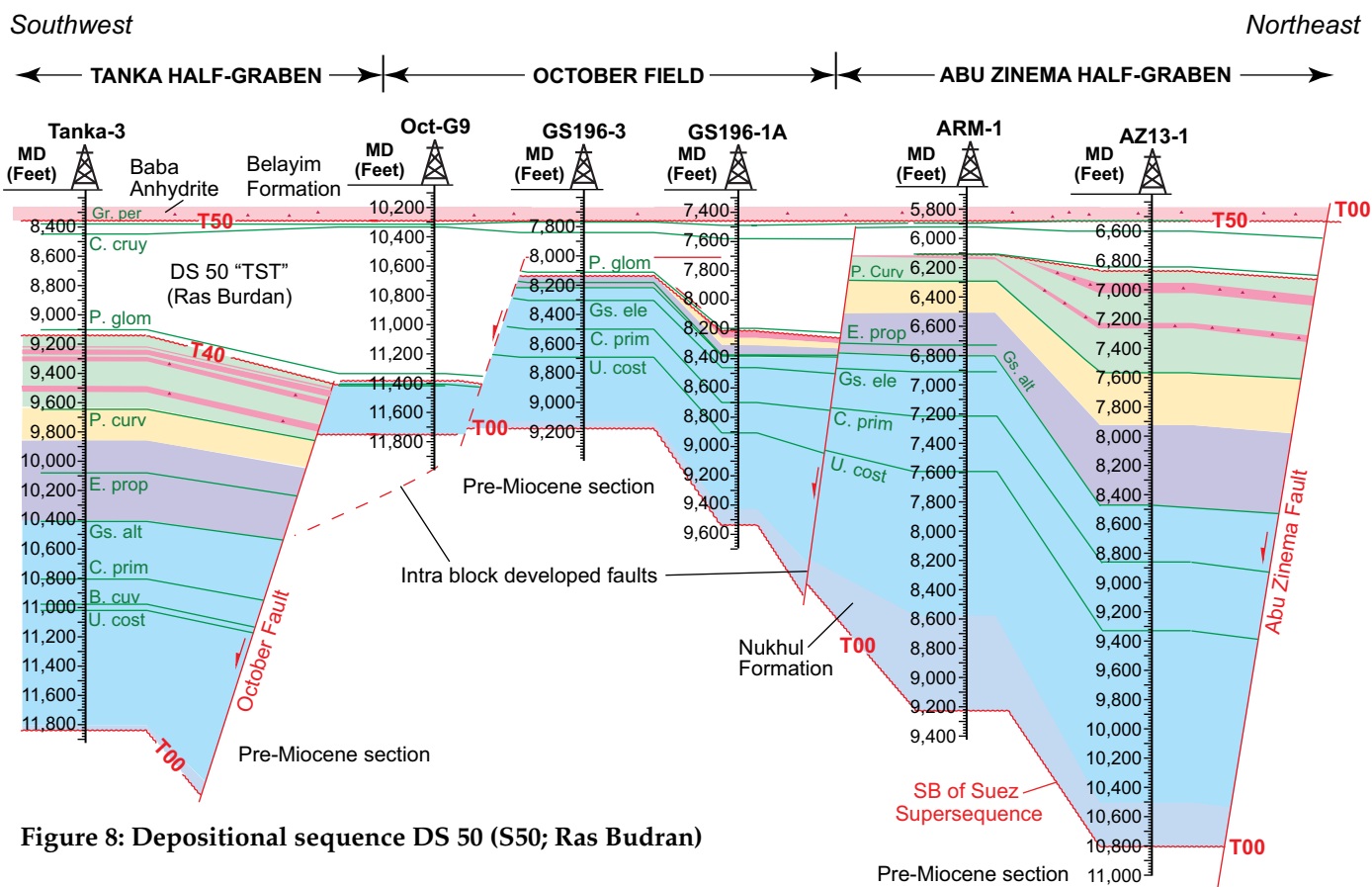


Figure 8: Depositional sequence DS 50 (S50; Ras Budran)

Mheiherrat Formation

This formation is recorded in all the studied boreholes and corresponds to the Lower Rudeis Member in other parts of the Gulf. It consists of light grey, grey, tannish grey, white, cryptocrystalline, soft, argillaceous to highly argillaceous limestone grading to highly calcareous shale. The shale is brownish grey, tanish grey, blocky to sub-blocky, soft, firm, calcareous to highly calcareous shale, grading into argillaceous limestone.

Hawara Formation

This formation is recorded in all the studied boreholes except OCT-G9. It corresponds to the lower part of the Upper Rudeis Member in other parts of the Gulf. It consists of shale with minor streaks of sandstone. The shale is dark grey, dark tanish grey, sub-blocky occasionally blocky, soft, firm, slightly calcareous to non-calcareous. The sandstone is colorless, translucent, white, very fine to fine grained, poorly to fairly sorted, subrounded to subangular, and loose.

Asl Formation

This formation is recorded in all the studied boreholes except OCT-G9 and GS196-3. It corresponds to the middle part of the Upper Rudeis Member in other parts of the Gulf. It consists of shale and limestone with minor streaks of sandstone. The shale is dark grey, dark tanish grey, sub-blocky occasionally blocky, soft, firm, calcareous to highly calcareous. The limestone is light grey, tanish grey, cryptocrystalline, soft to moderately hard, argillaceous, occasionally highly argillaceous, becoming highly sandy in parts. The sandstone is colorless, translucent, white, very fine to fine grained, poor to fair sorted, subrounded to subangular, and loose.

Lagia Member of the Ayun Musa Formation

This member is recorded in all the studied boreholes except OCT-G9 and GS196-3. It corresponds to the uppermost part of the Rudeis Formation (Mreir Member) and the Rahmi (or Markha) Member of the Kareem Formation in other parts of the Gulf. The Rahmi Member corresponds to the upper

part of the Lagia consisting typically of several anhydrite beds and intervening shale intervals. The anhydrite is white to tanish white, cryptocrystalline, soft to hard. The shale is grey to dark grey, sub-blocky to blocky, soft to firm and non calcareous.

Ras Budran Member of the Ayun Musa Formation

This member is recorded in all the studied boreholes. It corresponds to the Shagar Member of the Kareem Formation in other parts of the Gulf. It consists of shale and limestone. The shale is grey to dark grey, sub-blocky to blocky, soft to firm, calcareous grading to highly calcareous, occasionally grading into highly argillaceous limestone. The limestone is light grey, grey to tannish grey, cryptocrystalline, soft, occasionally moderately hard, argillaceous to highly argillaceous. grading to highly calcareous shale.

PREVIOUS STRUCTURAL - PALEONTOLOGICAL SEQUENCE STUDIES OF MIOCENE SUEZ RIFT

Beleity (1982) was the first to use the graphic correlation method to define three regional structural events, which were subsequently referred to as Paleontological Terraces T10, T20 and T50 (Figure 2; Dolson et al., 1996; Ramzy et al., 1996; Wescott et al., 1996; Krebs et al., 1997). The unconformity separating the pre- and syn-rift formations is referred to as Terrace T00. Two more terraces T30 and T40 were defined at the tops of the Asl and Lagia, respectively (Dolson et al., 1996; Ramzy et al., 1996). In between the terraces five paleontological sequences are abbreviated by "S": S10 for Nukhul, S20 for Mheiherrat, S30 for Hawara and Asl, S40 for Lagia and S50 for Ras Budran.

The Post-Nukhul event of Beleity (1982) was adopted by Evans (1988) and Evans and Moxon (1986) and represents a Gulf-wide depositional hiatus corresponding to Terrace T10. It is interpreted as the initiation of accelerated rifting seen by the abrupt change in depositional environment from the relatively shallow-water of the Nukhul Formation (S10) to the deeper-water of the Rudeis (Mheiherrat, S20) Formation.

The Mid-Rudeis event of Beleity (1982) corresponds to Terrace T20 between the Mheiherrat (S20) and Hawara (S30) formations. It is not represented in basinal area where sedimentation was uninterrupted. Over structural highs this event is expressed as an erosional unconformity. Patton et al. (1994) stated that the Mid-Rudeis event always occurs at or immediately prior to the transition from rapid subsidence of the Lower Rudeis Member (Mheiherrat, S20) to the relatively slower post-Middle Miocene subsidence.

The Post-Kareem event of Beleity (1982) corresponds to Terrace T50 between the Ayn Musa (S40 and S50) and Belayim (S55 or S60) formations, and is interpreted as a pronounced unconformity by him and other authors (e.g. Evans and Moxon, 1986; Dolson et al., 1996). The Belayim Formation records the onset of significant evaporitic deposits, which becomes the main lithology of the overlying South Gharib and Zeit formations. These three formations reflect diminishing tectonic subsidence and increasing basin restriction. The event is detected in many places in the Gulf where the Belayim Formation is present on the downthrown side of the fault and missing on its upthrown side. Terrace T50 represents the start of a marked decrease in subsidence rate, a period of structural quiescence and the abandonment of the Gulf as a site of extension (Moretti and Colletta, 1987; Richardson and Arthur, 1988); Evans, 1988; Steckler et al., 1988).

According to Dolson et al. (1996) paleontological sequences S10, S20, S30 and S40 cannot be classified as true unconformity-bounded packages *sensu* the sequence model of Vail et al. (1977). They considered these pre-Belayim sequences to be bounded by basin-wide biostratigraphically defined time breaks, which only approximately represent sequence boundaries. The nature of each terrace varies depending on structural position and paleobathymetry. Terraces T10, T20 and T30 represent amalgamations of shorter time breaks and their utility as high-resolution correlation points is therefore limited.

Krebs et al. (1996) based on fieldwork in the Sinai Peninsula concluded that T00 to T30 and their associated fossil assemblages indicates that they represent widespread regressive or transgressive events. The number of true sequences (those bounded by regressive erosional surfaces) is therefore less than the number of paleontological sequences revealed by graphic correlation.

As explained later, the present study is in agreement with their interpretation of T00 and T20 as sequence boundaries *sensu* Vail. However this study interprets Terrace T20 as an unconformity over the crest of blocks and correlative conformity down-dip in the depocenter, where the deposition was continuous.

BIOSTRATIGRAPHY

The use of the biostratigraphy in the oil industry depends basically on the first downhole appearance FDA of the foraminiferal species. A generalized Miocene stratigraphic scheme (Figure 2) of the Gulf of Suez (modified after Souaya, 1966, Hosney et al. 1986; Rateb, 1988) is applied in this study. It was established based on the extinctions (i.e. the last evolutionary occurrence) of the planktic and benthic foraminifera species. This paper applied only the foraminiferal zonation on all the study wells based on this scheme. Though nannoplanktonic analysis has not been applied here, the nannoplanktonic zonation is implied for the scheme according to W. El Fiky (2010, written communication). The Suez Rift is a semi-restricted basin, so minor changes in the paleoecology should affect the whole of the biotic system. Accordingly the extinctions of the planktic and benthic foraminifera species have been used to subdivide the Early to early Middle Miocene section in the study area. The biozonation scheme recognized in the study's boreholes are from top to bottom:

***Globorotalia peripheroronda* Zone**

This zone is identified in all boreholes in the upper part of Ras Budran Member (Figures 8 and 9, see Enclosure). The upper boundary is defined by the local extinction of *Globorotalia peripheroronda* (globally it extends younger) and the lower one by the extinction of *Cassidulina cruysi* (modified after Souaya, 1966, Rateb, 1988). The absence of gradational forms between *Globorotalia peripheroronda* and *Globorotalia peripheroacuta* from the uppermost part of Ayun Musa Formation suggests a time of differential erosion in probably N10 time (Rateb, 1988).

***Cassidulina cruysi* Zone**

This zone is identified in all boreholes in the middle to lower parts of Ras Budran Member (Figures 8 and 9, see Enclosure). The upper boundary is defined by the extinction of *Cassidulina cruysi* and the lower one by the extinction of *Praeorbulina glomerosa* s.l. (modified after Souaya, 1966; Rateb, 1988).

***Praeorbulina glomerosa* s.l. Zone**

This zone is identified in all boreholes in the lower part of Ras Budran Member (Figures 8 and 9, see Enclosure). The upper boundary is defined by the common occurrences of *Praeorbulina glomerosa glomerosa* or the *Praeorbulina glomerosa circlaris*. Its lower boundary is defined by the first appearance of the *Praeorbulina glomerosa curva*, *Praeorbulina sicanus*, *Praeorbulina transitoria* and *Globigerinoides bisphericus* (after Rateb, 1988).

***Praeorbulina glomerosa curva* Zone**

This zone is identified in all boreholes except OCT-G9 and GS196-3 in the upper part of Asl Formation (Figure 7). The upper boundary is defined by the last occurrences of *Praeorbulina glomerosa curva*, *praeorbulina sicanus*, *praeorbulina transitoria* and *Globigerinoides bisphericus*. The lower boundary is defined by the last occurrence of *Eggerella propinqua* (modified after Souaya, 1966; Rateb, 1988).

***Eggerella propinqua* Zone**

This zone is identified in all the boreholes except OCT-G9 in the Hawara Formation (Figure 7). The upper boundary is defined by the last occurrence of the *Eggerella propinqua* and the local extinction of *Globigerina ciperoensis fariasi*. The lower boundary is defined by the extinction of *Globigerinoides altiapertura* (modified after Souaya, 1966; Rateb, 1988).

***Globigerinoides altiapertura* Zone**

This zone is identified in all boreholes except Tanka-3 and GS196-3; it is highly fossiliferous and marks the uppermost Mheiherrat Formation (Figure 6). The upper boundary is defined on the extinction of the nominate zonal marker and the lower boundary on the extinction of *Globigerinoides subquadratus elevatoapertura*, *Globoquadrina praedehiscens* and *Catapsydrax dissimilis*. It is characterized by the high frequencies of *Globigerina ciperoensis* (Rateb, 1988).

***Globigerinoides subquadratus elevatoapertura* Zone**

This zone is identified in all boreholes except OCT-G9 in the middle Mheiherrat Formation (Figure 6). The upper boundary is defined on the extinction of the nominate zonal marker, which coincides with the extinction of *Globoquadrina praedehiscens* and *Catapsydrax dissimilis*. The lower boundary is marked by the extinction of *Cancris primitiva* (modified after Souaya, 1966; Rateb, 1988). This zonal marker provides a reliable marker value corresponding to the top of N6 Zone (Rateb, 1988).

***Cancris primitiva* Zone**

This zone is identified in all the boreholes except OCT-G9 in the middle Mheiherrat Formation (Figure 6). The upper boundary is defined on the extinction of the nominate zonal marker. The lower boundary is marked by the extinction of *Uvigerina costata* (Souaya, 1966).

***Buliminella cuvillieri* Zone**

This zone is only recorded in the AZ 13-1 Borehole in the lower middle part of Mheiherrat Formation (Figure 6). Its upper boundary is defined on the extinction of the nominate zonal marker. The lower boundary is marked by the extinction of *Uvigerina costata* (Souaya, 1966).

***Uvigerina costata* Zone**

This zone has been identified in all boreholes in the lower part of Mheiherrat Formation (Figure 6). Its upper boundary is defined on the extinction of the nominate zonal marker. The lower boundary is marked by the extinction of *Globigerinoides* aff. *primordius* (modified after Souaya, 1966, Rateb, 1988).

***Globigerinoides* aff. *primordius* Zone**

This zone is only identified in the AZ 13-1 Borehole and is equivalent to the lowermost part of Mheiherrat Formation (Figure 6). The upper boundary is marked by the extinction of *Globigerinoides* aff. *primordius* (modified after Rateb, 1988). The lower boundary is marked by the last occurrences of Nukhul Formation ostracodes *Cyamocytheridea* sp., *Neomonoceratina* sp., and the larger foraminifera *Miogypsina* sp.. It is difficult to recognize this zone in subsurface because of the scarcity of the zonal marker and caving problems.

***Cyamocytheridea* sp. / *Neomonoceratina* sp. Zone and *Miogypsina* sp. Zone**

These combined zones are identified in all boreholes except OCT-G9 and AZ 13-1 boreholes and indicate the Nukhul Formation (Souaya, 1966) (Figure 5). The *Miogypsina* sp. and *Cyamocytheridea* sp./*Neomonoceratina* sp. zones are recorded in some boreholes.

PALEOBATHYMETRY

The IPS program was applied to Borehole AZ 13-1 to obtain paleobathymetric results in the Mheiherrat, Hawara, Asl and Ras Budran formations. Two other paleobathymetric intervals were tentatively defined in the Nukhul Formation and Lagia Member although they are poorly fossiliferous and barren of fauna.

Ras Budran Member (6,850–6,520 ft): outer neritic (Figure 4, Table 1).

Lagia Member (7,520–6840 ft): The Lagia interval in the study's boreholes is barren of fauna (Figure 4, Table 1). It consists mainly of non-calcareous shale with anhydrite beds in other areas in the Gulf of Suez. The anhydrites precipitated in restricted conditions with the non-calcareous shale indicating shallow-marine conditions.

Asl Formation (8,000–7,520 ft): upper bathyal to outer neritic (Figure 4, Table 1). An abrupt change in the paleo-water depth occurs from outer neritic at the top Asl Formation and restricted environment in the Lagia Member.

Hawara Formation (8,460–8,000 ft): upper bathyal to middle bathyal (Figure 4, Table 1). This interval is considered the deepest in the syn-rift section. A turbiditic siliciclastic package is sandwiched within it. The shale streaks within these turbiditic packages contain deep bathymetric benthic indicators such as *Eggerella propinqua*, *Bathysiphon taurinensis*; indicating that the deposition of this siliciclastic packages was in an overall deep-water environment.

Mheiherrat Formation (10,500–8.460 ft): gradual change from outer neritic at the base to upper bathyal at the top (Figure 4, Table 1). The gradual change in water depth implies that the subsidence rate slightly exceeded the rate of deposition. Segments of shallowing upward trends are superimposed on the general deepening paleobathymetric trend. A sharp change in paleobathymetry is recorded from the shallow facies of the Nukhul Formation to the basal Mheiherrat Formation at 10,500 ft.

Nukhul Formation (10,810–10,500 ft): The sandy facies of this formation in AZ 13-1 is barren of fauna (Figure 4, Table 1). The tentative paleobathymetric analysis in other studied boreholes showed it was deposited in very shallow water; i.e. middle to inner neritic; it contains rare *Ostracoda* spp., *Cyamocytheridea* sp., *Neomonotheratina* sp., *Miogypsina* sp. and *Ammonia beccarii*, (G. Azazi, oral communication, 2008). The regional lithofacies of the formation in the Gulf of Suez change from north to south. In the central and southern provinces they are evaporitic, whereas in the northern province they are clastics. In the study area they are sandy, limy and shaley.

SEQUENCE STRATIGRAPHY

In this study only two major depositional sequences are interpreted instead of the five paleontological sequences. The first spans the Nukhul Formation to Lagia Member and is referred to as the *Suez Supersequence*. It combines paleontological sequences S10 to S40 between Terraces T00 and T40. The second is the late syn-rift Depositional Sequence DS 50 between T40 and T50 (Figure 7).

The Suez Supersequence is interpreted in terms of 35 parasequences and DS 50 by 10 more. The parasequences are genetic sequences *sensu* Galloway (1989) because they are bounded by flooding surfaces (FS) rather than sequence boundaries (Vail et al., 1977). They are interpreted by the coincidence of quantitative paleontological and paleobathymetric breaks with the electric log shifts (Figure 9, see Enclosure). The electric log description of each parasequence is based on the following characteristics:

- (1) Gamma-ray curve generally decreases upwards indicating a cleaning and shallowing trend;
- (2) Sonic curve generally decreasing upward indicating a shallowing trend;
- (3) Neutron curve generally decreasing upward;
- (4) Density curve generally increasing upward implying gradual change to denser carbonate and/or marl intervals;
- (5) Resistivity curve; generally increasing upward.

Abrupt changes in all the electric log curves coincide with the flooding surface (FS). A considerable narrow separation of the density and neutron curves, with low gamma-ray and low sonic readings, directly underlies the flooding surface (Table 2). A considerable wide separation of the density and neutron curves, with high gamma-ray and high sonic readings, directly overlie the flooding surface (Table 3). The stacking of a newly formed parasequence gradually decreases the accommodation space ending up with carbonate and marl deposits, which close the parasequence with the next flooding surface.

Table 2 The relative values of the electric log curves directly underneath the flooding surface

Gamma-Ray	Sonic	Neutron	Density	Resistivity
Low	Low	Low	High	High

Table 3 The relative values of the electric log curves directly above the flooding surface

Gamma-Ray	Sonic	Neutron	Density	Resistivity
High	High	High	Moderately Low	Low

The parasequences are named by the abbreviation of the biozone they occur in or when very thin by that of the overlying zone (Figure 9, see Enclosure). The *Uvigerina costata* Zone of the Mheiherrat Formation is interpreted in terms of 12 parasequences named UC 10 to UC 120, each bounded by flooding surfaces (Figure 9, see Enclosure). The five parasequences within the *Buliminella cuvillieri* and *Cancris primitiva* zones are abbreviated CP 10 to CP 50 after the latter zone due to the small thickness of the former zone. Similarly because the *Globigerinoides altiapertura* assemblage Zone is thin, the six parasequences within it and the *Globigerinoides subquadrata elevatoapertura* Zone are abbreviated GSE after the latter (Figure 9, see Enclosure). Four condensed-section parasequences are interpreted in the *Eggerella propinqua* Zone (EP 10 to EP 40). Five parasequences are interpreted in the *Praeorbulina glomerosa curvoa* Zone (PGC 10 to PGC 50).

Three parasequences (Lagia 10 to Lagia 30) are interpreted in the Lagia Member, which closes the Suez Supersequence; each starts at the base with shale and ends with an anhydrite bed (Figures 8 and 9, see Enclosure). The Lagia parasequences have been tentatively interpreted based on: (1) the absence of the faunal content; (2) the non-calcareous shale recorded in the Lagia, which is devoid of marine microfossils; (3) the presence of a variable number of anhydrite streaks, which indicates a distinctive restricted environment; (4) gamma-ray generally decreasing upward; (5) sonic generally decreasing upward; (6) neutron generally decreasing upward; (7) density generally increasing upward; and (8) resistivity generally increasing upward and ends up with the electric log response of anhydrite.

Depositional Sequence DS50 starts with a single parasequence in the *Praeorbulina glomerosa* s.l. above the Lagia Parasequence 30. It is bounded below by the major flooding surface of the *Praeorbulina glomerosa* s.l. PG FS 10 and at the top by the CC FS 10 of the *Cassidulina cruysi* Zone. Nine parasequences are identified in the *Cassidulina cruysi* and *Globorotalia peripheroronda* zones and abbreviated CC because of the small thickness of the latter zone. They are named as in previous examples with the uppermost Parasequence CC 90 bounded at the base by the CC flooding surface 90 and at the top by Terrace T50. These parasequences become thinner up-dip towards the southwest and pinch out over at the crestal location of the October Block; they thicken down-dip towards the northeast towards the Abu Zinema Fault (Figures 8 and 9, see Enclosure).

The AZ 13-1 Borehole is considered as the reference section for the parasequences because it is located in the depocenter. All the Mheiherrat parasequences are represented in the three boreholes between AZ 13-1 and OCT-G9 boreholes but they decrease in thickness or pinch out in OCT-G9 (Figures 6 and 7).

SUEZ SUPERSEQUENCE

The Suez Supersequence spans the Aquitanian, Burdigalian and Langhian and corresponds to paleontological sequences S10 to S40. In the following sections it is described according to its sequence stratigraphic architecture from base to top.

Lower Sequence Boundary

A regional unconformity, Terrace T00, separates the pre-Miocene rocks from the Nukhul Formation. In the study area the underlying rocks are of Mid-Eocene age based on *Acarinina pentacamerata*, *Robulus trompi*, *Bullimina jacksonensis* and *Nummulite* spp. The Late Eocene and Oligocene are a hiatus in this area and base Nukhul represents the lower sequence boundary of the Suez Supersequence. The first syn-rift marine flooding over the T00 unconformity is approximately coeval with the initiation of rifting.

Nukhul Formation: Lowstand Systems Tract

Age: Aquitanian, NN2 Zone according to W. Elfiki (2009, oral communication). In AZ 13-1 the formation is barren. Elsewhere in the Gulf it contains rare to common *Cyamocytheridea* sp., *Neomonotheratina* sp., *Miogypsina* sp., *Ammonia beccarii*, and *Ostracoda* spp. attributed to Lower Miocene. The Nukhul Formation is equivalent to Paleontological Sequence S10.

Description: In Figure 5 the stratigraphic cross section is datumed on the top of the Nukhul Formation to show the paleostructure at the end-Nukhul time. The formation is absent in the OCT-G9 Borehole due to exposure on the October Block (Figure 6). Lateral thickness variations and facies changes reflect minor scale intra-block sub-basins.

Interpretation: Although a paleobathymetric analysis of the Nukhul Formation was not possible in AZ 13-1, its faunal content elsewhere in the Gulf and its sandy facies indicate deposition in brackish, very shallow water setting (i.e. inner to middle neritic). In the study area the Nukhul Formation is interpreted as the LST of the Suez Supersequence. The Nukhul LST was deposited in numerous small sub-basins that formed during the earliest phase of rifting. The sub-basins are characterized by slightly deeper water depocenters surrounded by very shallow coastal areas (Figure 5).

The Nukhul Formation was deposited during the rift-initiation event. It was deposited in weakly established half-grabens and its thickness varies depending on its local position within the graben and sediment supply. According to J. Dolson (2010, written communication) the naming of the Nukhul Formation as a “lowstand systems tract” may not be appropriate.

Nukhul/Mheiherrat Boundary: Flooding Surface *Uvigerina costata* (FS10)

A great faunal bloom (foraminiferal planktic and benthic associations) is documented directly above the Nukhul Formation. It represents the *Uvigerina costata* flooding surface FS 10 and is considered the first major transgressive surface separating the Nukhul LST from the overlying Mheiherrat TST (Figures 5 and 6). Flooding surface FS 10 onlaps Paleontological Terrace T10. In the crestal Borehole OCT-G9, T10 merges with T00 to form a composite unconformity.

Mheiherrat Formation: Transgressive Systems Tract

Age: Burdigalian with five biozones from base to top; *Uvigerina costata*, *Buliminella cuvillieri*, *Cancris primitiva*, *Globigerinoides subquadrata elevatoapertura* and *Globigerinoides altiapertura* assemblage zones.

Description: The Mheiherrat Formation is recorded in all the studied boreholes. In Figure 6 a stratigraphic cross section is datumed on the *Globigerinoides altiapertura* assemblage FDA. The formation is wedge shaped. The transition from the Nukhul and the Mheiherrat formations shows a dramatic shift from a poorly fossiliferous or barren shallow-marine section to a highly fossiliferous one (planktic foraminifera and deeper water benthic association). This open-marine foraminiferal association represents the first major flooding surface overlying the Nukhul Formation, which is consistently recorded over the study area (Figures 5 and 6).

Interpretation: This paleobathymetric interval is interpreted as the TST following the Nukhul LST. This abrupt deep-marine flooding is attributed to a major tectonic stretching event.

Mid Rudeis Event: Local Unconformity

Age: Late Burdigalian.

Description: This surface represents the maximum hiatus in the OCT-G9 Borehole and a minor one in GS196-3 and GS196-3A. The hiatus is not recorded in ARM-1 and AZ 13-1. It is equivalent to the Paleontological Terrace T20.

Interpretation: The Mid Rudeis surface is not a regional unconformity but rather a localized terrace. It can only be traced over the emergent crest of the October Block. The rotation of this fault block over the Abu Zinema Fault increased the relative water depth down-dip in the Abu Zinema Half-Graben and decreased relative water depth up-dip on its crest. This structural geometry occurs in many parts of the Suez Rift region over the crests and around up-dip areas of the fault blocks. In this sense it is considered a localized terrace or stratigraphic disturbance in the depositional continuity of the supersequence over crestal positions (Figures 6 and 7).

The *Uvigerina costata* parasequences UC 90 to UC 120 in addition to those of the *Cancriis primitiva* and *Globigerinoides subquadrata elevatoapertura* zones (CP 10 to CP 50, GSE 10 to GSE 60), are erosionally truncated or not deposited at the crestal position OCT-G9 Borehole (Figure 6). It is believed that the thickness of parasequences increase towards the depocenter (i.e. the Abu Zinema Fault), and *vice versa*: they thin, pinch out or are truncated up-dip at the crestal position. These criteria provide good evidence for the rotation of the fault block eastwards, which could have been syn- or post-depositional. The truncation of these parasequences occupies a narrow area trending NW-SE of the October Block on the crestal position. The remaining area of the fault block contains all the parasequences.

This interpretation is in a good agreement with Ramzy et al. (1996) who stated that continuous deposition of either shale, limestone or sandstone can occur immediately adjacent to major clysmic faults. It is also consistent with passive margin-type stratal patterns responding to relative sea-level fluctuations occurring a short distance away in shallower parts of the basin. Erosion of footwall strata can occur through this time interval across structurally high blocks. As a result regional correlation surfaces such as a single MFS are difficult to substantiate, and may not even exist. The erosional unconformity across a high structural block may be reflected immediately basinwards by a series of water-deepening events (ravinement surfaces and condensed sections) formed as a subsiding hanging wall.

J. Dolson (2010, written communication) considered the top Mheiherrat T20 surface as a major syn-rift event, which would explain erosion on high blocks and deposition in the lows. In essence it is a 'highstand' event only in the lows and a 'lowstand' on the highs.

Hawara Formation: Maximum Flooding Interval

Age: Early Langhian, NN4A Zone according to W. Elfiki (2009, oral communication) and based on the Hawara Formation directly overlying the FDA of the *Globigerinoides altiapertura* assemblage in the depocenter of the Abu Zinema Half-Graben. It is equivalent to the lower part of Paleontological Sequence S30.

Description: The Hawara Formation thickens towards the hanging wall of the Abu Zinema Fault in the Abu Zinema Half-Graben and is absent over the crest of the October Block (OCT-G9 Borehole; Figures 7, 8 and 9, enclosure). Its thickness is comparable in the Tanka-3 and AZ 13-1 boreholes. These structural geometries imply that the October and Abu Zinema faults were active during its deposition.

The paleobathymetry of the hemipelagic shales of the Hawara Formation is upper to middle bathyal and represents a sudden sea-level deepening following the outer neritic setting of the Mheiherrat Formation (Figure 4). The deeper-water fauna are represented by *Bathysiphon taurinensis*, *Eggerella propiqua* and common agglutinated species. Thick siliciclastic packages, however, are sandwiched between the hemipelagic shales.

Interpretation: The Hawara Formation is interpreted as a condensed section and the main flooding interval (MFI) of the Supersequence (Figure 7). A number of condensed parasequences and flooding surfaces have been identified and correlated in both half-grabens (Figures 7, 8 and 9, see Enclosure). The maximum shift in relative water depth is interpreted as the maximum extensional tectonic pulse in the Miocene Suez Rift. This event caused fault blocks to rotate on the Abu Zinema Fault, thus causing the hanging wall to subside rapidly and the footwall to rotate to a position that is relatively higher.

Ramzy et al. (1996) argued that because the Asl and Hawara sandstones appear to be developed far into the basin, they represent a major eustatic lowstand. Their interpretation would explain such a long distance transport for these major clastic packages. This study does not agree with their interpretation because the Hawara contains the MFI of the supersequence as supported by the benthic indicators. Instead the siliciclastic packages are interpreted as turbidites that were carried into the depocenters via the drainage system activated during the Mid Rudeis extensional event. The event created a great

topographic difference between the source areas on the rift margins and the depocenters along the longitudinal axis of the rift. This great difference in the elevation generated strong hydrodynamic and turbidity currents, and the latter invaded this trend and deposited siliciclastics.

Asl Formation: early Falling Stage Systems Tract (Highstand Systems Tract)

Age: Langhian as the *Praeorbulina glomerosa curva* Zone is recorded in this formation.

Description: A clear gradual change occurs from hemipelagic upper to middle bathyal setting of the Hawara Formation to outer neritic setting of the Asl carbonate. This is clear in the cross section (Figure 7), where the parasequences prograde towards the depocenter of the basin. The parasequences occur in the depocenter but some of are missing up-dip. The position of the depocenter at this time did not shift with respect to the Abu Zinema Fault.

Interpretation: The study area experienced a major regressive cycle terminating the maximum flooding interval of the Hawara Formation. This regressive cycle was due to a gradual decrease in the eustatic sea level (Figure 7). The cessation of Asl sedimentation occurred concurrently with the disconnection of the open-marine water of the Mediterranean from the Suez Rift. The high contrast in the faunal content between the upper part of Asl Formation (deep benthic indicators) and the Lagia Member (non-fossiliferous and non-calcareous shale) supports this interpretation. The off-lapping of the parasequences of the Asl Formation is very clear up-dip, which implies the formation represents a regression towards the trough of the half-graben i.e. it shows a deltaic wedge prograding towards the depocenter.

The terrace is associated with a eustatic sea level fall and occurs up-dip at the crestal position of the October Block (Figure 7).

J. Dolson (2010, written communication) regarded the Hawara Shale and Asl Formation to mark a major pulse of temporary rift cessation culminating in widespread shallow-water sedimentation and evaporite deposition. He added that in the producing October Field the Asl Formation is a coarse-grained to conglomeratic sandstone with sharp erosional base into the deep water Hawara. But in the upper portion it actually contains pelloidal limestones of the 'Asl Marl', which were probably deposited in shallow water prior to exposure and deposition of the Lagia evaporites. Hence, it doesn't fit adequately in the Vail-type model. He believes that this represents a regional period of isostatic rebound of the basin floor, which created widespread supratidal packages except in the deepest half-grabens (such as in front of the C Platform) where the Lagia evaporite is absent and replaced with deeper-water shales and carbonates.

Lagia Member: late Falling Stage Systems Tract

Age: Langhian; restricted between the *Praeorbulina glomerosa curva* Zone at the base and the *Praeorbulina glomerosa* s.l. Zone at the top. The Lagia Member corresponds to Paleontological Sequence S40 and is capped by Terrace T40.

Description: The Asl/Lagia boundary represents a drastic basin-ward shift in paleobathymetry from outer neritic to very shallow-water restricted (Figure 7). A stratigraphic cross section datumed on the top of the Lagia Member (Figure 7) shows the shift in facies during this time due to reducing water by evaporation and precipitation of anhydrites.

Interpretation: During the deposition of the Lagia Member, the half-grabens were highly restricted as manifested by the poverty of the foraminifera, anhydrite precipitation and the deposition of non-calcareous shales. The Lagia Member in the AZ13-1 Borehole is interpreted in terms of three regressive parasequences (Lagia 10 to Lagia 30) based on the interpretation of the responses of the electric log data. Each starts at the base by shale and ends with an anhydrite layer (Figure 7). The highest Lagia

30 parasequence starts on top of the third anhydrite bed and ends with the uppermost Lagia shale. In this study the Lagia shale units are mainly non-calcareous and the member does not contain marls, marine limestone or marine microfossils. Accordingly, there is no evidence for significant marine influence (transgression) during the deposition of the Lagia Member. The Lagia shale may have been deposited in a restricted setting flushed by fresh waters from river systems, which was followed by the precipitation of anhydrite in the final stage of each cycle.

The present interpretation contradicts the one by Al-Husseini et al. (2010), which they based on the occurrence of limestone and highly calcareous shale beds between the three Rahmi (Lagia) Anhydrite beds in Wadi Feiran and several boreholes. They took the presence of these lithologies to represent sea level rising starting from the base of each Rahmi Anhydrite followed by marine floodings. They interpreted these as Kareem subsequences 1 to 3 and fourth-order orbital sequences (DS⁴ 1.1.1 to 1.1.3; Stratons 40–38) and the transgressive systems tract of the Kareem Sequence (their Figure 10). The three Rahmi Anhydrite beds were deposited during arid periods, when the Red Sea and global sea level were at lowstands. The arid phases represented by Rahmi Anhydrites 1 to 3, the highstands of subsequences 1 to 3 represent successive, step-wise increases in Red Sea and global sea levels.

Ramzy et al. (1996) interpreted the anhydrite and salts facies as restricted basin-centered lowstand deposits. These widespread evaporite beds form regionally correlative markers defining sequences as evident for the Lagia and lower members of the Belayim Formation. J. Dolson (written communication, 2010,) reported that the Lagia evaporites, in outcrop and in some cores, show a “chicken-wire” texture, indicating full subaerial exposure on tidal flats. This is significant in that biostratigraphic analyses of these horizons is not possible. He also interpreted the sequence boundaries at the base of the anhydrite beds as proposed by Ramzy et al. (1996) and Al-Husseini et al. (2001).

Upper Sequence Boundary of Suez Supersequence

This sequence boundary is complicated because it consists of three hiatuses: T20, T30 and T40. The major transgressive *Praeorbulina glomerosa* s.l. flooding surface onlaps the upper sequence boundary of the Suez Supersequence. It caps the Lagia 30 parasequence and the upper sequence boundary of Suez Supersequence. This interpretation differs with that of Krebs et al. (1996) and Ramzy et al. (1996) who interpreted Terrace T40 as a condensed section: “T40 surface subdivides the Kareem interval into two mappable genetic sequences. The T40 surface, when identified by biostratigraphy, always occurs in hot gamma-ray shale, which shows high abundant and diversity foraminiferal populations. This suggests it is actually a maximum flooding surface MFS consisting of condensed section formed in a marine setting.”

The stratigraphic cross sections (Figures 6 and 7) demonstrate the relation between the local terraces T20 (Mid Rudeis) to T40 (upper boundary of Suez Supersequence) and how they merge to form the upper sequence boundary of the Suez Supersequence. All three are not regional unconformities but rather localized ones that occupy a narrow area on the crestal position (Figure 6).

SUEZ DEPOSITIONAL SEQUENCE DS 50

Age: Late Langhian to Early Serravallian.

Definition: The late syn-rift Suez DS 50 was previously defined as paleontological sequence S50. It encompasses the major transgressive *Praeorbulina glomerosa* s.l. flooding surface (FS 10) and a TST in the Ras Budran Member. Flooding surface (FS10) is recorded in all the study’s boreholes.

Lower Sequence Boundary: Top of Suez Supersequence (see above). Paleontologic analysis documents an abrupt biofacies change from non-fossiliferous shallow restricted evaporitic facies of Lagia Member to a high-diversity and frequency foraminiferal planktic and benthic deep-water indicators in the Ras Budran Member (Figure 4). An abrupt rise in relative sea level is manifested in the IPS paleobathymetric curve: Lagia time restricted conditions to deep-water benthic indicators at the base Ras Budran Member (Figures 8 and 9, see Enclosure). The abrupt change is interpreted as due to a sudden and regional tectonic subsidence event immediately after the Lagia was deposited.

Upper Sequence Boundary: Base Belayim Formation corresponding to Terrace T50 and a sequence boundary. The boundary corresponds to a sudden shift from open-marine deposits of the Ras Budran Member to very shallow restricted evaporitic facies (salt and anhydrite) of the Baba Member (Belayim Formation). Paleontologic analysis documented an abrupt biofacies change from a high-diversity and frequency foraminiferal planktic and benthic deep-water indicators in the Ras Budran Member (DS 50) to non-fossiliferous shallow restricted evaporitic facies of Baba Member. The boundary between the two members is recorded in all the study's boreholes and is regional. It is believed that a drastic drop in the eustatic sea level occurred after DS 50 deposition. A new cycle of restricted conditions succeeded DS 50 with the precipitation of the Baba Member evaporates.

Structural Aspects: The TST (S50) is characterized by the minor scale intra-block sub-basins. The configuration of the thickness trend of DS 50 does not coincide with the wedge shape of the Suez Supersequence. It is believed that a new tectonic event occurred after the Lagia's deposition that modified the previous structural configuration. A new generation of intra-block minor faults were created within the Abu Zinema Half-Graben resulting in the creation of new minor-scale, intra-block sub-basins superimposed on the previously existing wedge (Figures 8 and 9, see Enclosure).

It is noted that the maximum thickness of DS 50 does not occur above the thickest packages of the Suez Supersequence (Figures 8 and 9, see Enclosure). It is shifted to the west suggesting the depocenter was transferred due to a structural element that affected the Abu Zinema Fault (Figures 8 and 9, see Enclosure).

CONCLUSIONS

This study presented a detailed sequence stratigraphic model for the Gulf of Suez Miocene syn-rift section (Figure 2) extending from the Aquitanian Nukhul Formation to the Langhian – Early Serravallian Ras Budran Member. The integration of biostratigraphic, paleobathymetric and electric log data was used to identify the sequence stratigraphic elements in both a general framework and in terms of high-resolution parasequences. The biostratigraphic analysis consistently defined 13 planktic and benthic biozones within the stratigraphic scheme (Figure 2). The IPS program analysis defined four distinctive paleobathymetric intervals starting from outer neritic to upper bathyal in Mheiherrat; upper to middle bathyal in Hawara; upper bathyal to outer neritic in Asl; and outer neritic in Ras Budran (Figure 4). The IPS program did not work for the Nukhul Formation and Lagia Member, which were deposited in very shallow environments but are poorly fossiliferous and barren of fauna, respectively.

The study defined the Suez Supersequence and Suez DS 50 instead of the five paleontological sequences S10, S20, S30, S40 and S50 discussed in the literature. Three sequence boundaries were documented as regional unconformities caused by major eustatic sea-level drops: (1) Late Eocene to Oligocene T00 separating the pre-rift and syn-rift successions at the base of the Supersequence; (2) Miocene (Late Langhian) top of the Supersequence (combined T20, T30 and T40); and (3) Miocene (Early Serravallian) top of the Ayun Musa Formation (top Suez DS 50).

The model offers new insights for exploration opportunities in the context of stratigraphic traps. The high relief between the hinterland catchment areas and the axial depocenter of the Suez Rift basin created powerful hydrodynamic currents that carried siliciclastic packages into the numerous troughs distributed in the axial center of the basin. The stratigraphic position of these siliciclastics can be predicted in the flexible sequence stratigraphic model and applied to all the sub-basins of the Suez Miocene rift. The TSTs of the Suez Supersequence and DS 50 Sequence contain siliciclastics that may be trapped along the coastal areas on the paleomargins of the rift. Siliciclastic packages may also form traps in the Hawara and Asl sections located beneath the sealing evaporites and shales of the Lagia in the depocenters between rotated fault blocks. Siliciclastics (turbidites) sandwiched between the deep-water Hawara hemipelagic shales also offer an exploration target.

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REFERENCES

- Halim, M.A., M.J. Brady and J.C. Harms 1988. Miocene platform carbonates in Hurghada area south western Gulf of Suez, Egypt. Proceedings of the 8th Exploration Seminar, Cairo, 1986. Egyptian General Petroleum Corporation, v. 1, p. 74-95.
- Al-Husseini, M.I., M.D. Mahmoud and R.K. Matthews 2010. Miocene Kareem Sequence, Gulf of Suez, Egypt. *GeoArabia*, v. 15, no. 2, p. 175-204.
- Barakat, M.G., M. Darwish, M.L. Abdel Hamid and M. Taher 1994. Geological model and hydrocarbon habitat of Amer oil field, Gulf of Suez, Egypt. Proceedings of the 12th Petroleum Exploration and Production Conference, Cairo, 1994. Egyptian General Petroleum Corporation, v. 2, p. 132-152.
- Beleity, A.M. 1982. The composite standard and definition of paleoevents in the Gulf of Suez. Egyptian General Petroleum Corporation, 6th Exploration Conference, p. 181-198.
- Bosworth, W. 1985. Geometry of propagating continental rifts. *Nature*, 316, p. 625-627.
- Catuneanu, O., A.J. Willis, and A.D. Miall 1998. Temporal significance of sequence boundaries. *ELSEVIER Sedimentary Geology* 121, P. 157-178.
- Chenet, P.Y., J. Lettouzey and E.S. Zaghoul 1986. Some Observations in the Rift Tectonics in the Eastern Part of the Suez Rift. Egyptian General Petroleum Corporation, Seventh Exploration Seminar, 1984, p. 18-36.
- Colleta, B., P. Le Quellec, J. Letouzy and I. Moretti 1988. Longitudinal evolution of the Suez rift structure (Egypt). *Tectonophysics*, v. 153, p. 221-233.
- Dolson, J., O. El-Gendi, H. Charmy, M. Fathalla and I. Gaafar 1996. Gulf of Suez rift basin sequence models - Part A Miocene sequence stratigraphy and exploration significance in the Greater October field area, northern Gulf of Suez. Proceedings of the 13th Petroleum Conference, Cairo, 1996. Egyptian General Petroleum Corporation, v. 2, p. 227-241.
- Egyptian General Petroleum Corporation (EGPC) 1964. Oligocene and Miocene rock-stratigraphy of the Gulf of Suez region. Report of Stratigraphic Committee, 124 p.
- Embry, A.F., E.P. Johannessen 1992. T-R sequence stratigraphy, facies analysis and reservoir distribution in the uppermost Triassic-Lower Jurassic succession, western Sverdrup Basin, Arctic Canada. In T.O. Vørren, E. Bergsager, O.A. Dahl-Stamnes, E. Holter, B. Johansen, E. Lie, T.B. Lund (Eds.), *Arctic Geology and Petroleum Potential*. Norwegian Petroleum Society Special Publication 2, Elsevier, Amsterdam, pp. 121-146.
- Evans, A.L. and I.W. Moxon 1986. Gebel Zeit chronostratigraphy: Neogene syn-rift sedimentation atop a long-lived paleohigh. Proceedings of the 8th Exploration Conference, Egyptian General Petroleum Corporation, Cairo, November 1986, v. 1, p. 251-265.
- Evans, A.L. 1988. Neogene tectonic and stratigraphic events in the Gulf of Suez rift area, Egypt. *Tectonophysics*, v. 153, p. 235-247.
- Fouda, A., A. Mohamed and S. Guinn 1994. Regional geology and hydrocarbon potential of the offshore west central Gulf of Suez. Proceedings of the 12th Petroleum Exploration and Production Conference, Cairo, 1994. Egyptian General Petroleum Corporation, v. 1, p. 145-155.
- Galloway, W.E. 1989. Genetic stratigraphic sequences in basin analysis I: Architecture and genesis of flooding surface bounded depositional units. *American Association of Petroleum Geologists Bulletin*, v. 73, p. 125-142.
- Garfunkel, Z. and Y. Bartov 1977. The Tectonics of the Suez Rift. *Geological Survey of Israel Bulletin*, no. 71, 45 p.
- Gary, A. C., and Gary, W. S., 1993. The integrated paleontological system: A new tool for the analysis and display of micropaleontological data. *American Association of Petroleum Geologists Bulletin*, v. 77.
- Gawthorpe, R.L., J.M. Hurst and C.P. Sladen 1990. Evolution of Miocene footwall-derived coarse-grained deltas, Gulf of Suez, Egypt: Implications for exploration. *American Association of Petroleum Geologists Bulletin*, 74, p. 1077-1086.
- Gawthorpe, R.L., A.J. Fraser and R.E.L. Collier 1994. Sequence stratigraphy in active extensional basins: implications for the interpretation of ancient basin-fills. *Marine and Petroleum Geology*, v. 11, p. 642-658.

- Gawthorpe, R., I. Sharp, J.R. Underhill and S. Gupta 1997. Linked sequence stratigraphic and structural evolution of propagating normal faults. *Geology*, v. 25, no. 9, p. 795-798.
- Gibbs, A.D., 1984. Structural evolution of extensional basin margins. *Journal of the Geological Society of London*, v. 141, p. 609-620.
- Guindi, O.E., D.R. Smith and B. Leggett 1994. Asl Sandstone (Miocene) downthrown traps and reservoir performance, October field, northern Gulf of Suez. *Proceedings of the 12th Petroleum Exploration and Production Conference, Cairo, 1994. Egyptian General Petroleum Corporation*, v. 1, p. 307-322.
- Hagras, M. 1986. Some geological observations in the Gulf of Suez area, Egypt. *Proceedings of the 8th Exploration Seminar, Cairo, 1986. Egyptian General Petroleum Corporation*, v. 1, p. 53-73.
- Hassouba, M., A. Shafy and S. Sakr 1993. Application of paleobathymetric analysis in oil exploration of the Miocene sequence in the central Gulf of Suez. *Geoscientific Research in Northeast Africa, Thorweihe and Schandelmeier (Eds)*, P. 277-283
- Hassouba, M., M. Sarrawi and S. Sakr 1994. Early synrift sedimentation in October field area, a stratigraphic model for hydrocarbon accumulation. *Proceedings of the 12th Petroleum Exploration and Production Conference, Cairo, 1994. Egyptian General Petroleum Corporation*, v. 1, p. 341-350.
- Helmy, H. and A. Zakareya 1988. El Morgan area - geological framework. *Proceedings of the 8th Exploration Seminar, Cairo, 1986. Egyptian General Petroleum Corporation*, v. 1, p. 1-14.
- Hosny, W., I. Gaafar and A.A. Sabour 1988. Miocene stratigraphic nomenclature in the Gulf of Suez region. *Proceedings of the 8th Exploration Seminar, Cairo, 1986. Egyptian General Petroleum Corporation*, v. 1, p. 131-148.
- Khalil, B. and W. Meshref 1988. Hydrocarbon occurrences and structural style of the southern Suez rift basin. *Proceedings of the 9th Exploration Conference, Egyptian General Petroleum Corporation, Cairo*, 13 p.
- Khalil, M. 1992. The structural evolution of the 'B' trend and its significance for hydrocarbon exploration in offshore Gulf of Suez, Egypt. *Proceedings of the 11th Petroleum Exploration and Production Conference, Cairo, 1992. Egyptian General Petroleum Corporation*, v. 1, p. 64-78.
- Khalil, S. and K. McClay 1998. Structural architecture of the Eastern Margin of the Gulf of Suez: Field studies and analogue modelling results. *Proceedings of the 14th Petroleum Conference, Cairo, 1998. Egyptian General Petroleum Corporation*, v. 1, p. 201-211.
- Krebs, W.N., W.A. Wescott, D. Nummedal, I. Gaafar, G. Azazi and S.A. Karamat 1996. Graphic correlation and sequence stratigraphy of Neogene rocks in the Gulf of Suez. *Proceedings of the 13th Petroleum Conference, Cairo, 1996. Egyptian General Petroleum Corporation*, v. 2, p. 214-226.
- Meshref, W.M., M.S. Abu Karamat and M. Gindi 1988. Exploration concepts for oil in the Gulf of Suez. *Proceedings of the 9th Petroleum Exploration and Production Conference, Egyptian General Petroleum Corporation*, v. 1, p. 1-24.
- Moretti, I. and B. Colletta 1987. Spatial and temporal evolution of the Suez Rift Subsidence. *Journal of Geodynamics*, v. 7, p. 151-168.
- Moustafa, A.M. 1976. Block faulting in the Gulf of Suez. *Proceedings of the 5th Egyptian General Petroleum Corporation Exploration Seminar*, 35 p.
- Moustafa, A.R. 1992. Structural setting of the Sidri-Feiran area eastern side of the Suez Rift. *Cairo, Ain Shams University, Middle Eastern Research Center, Earth Science Series*, v. 6, p. 44-54.
- National Stratigraphic Sub-committee of the Geological Sciences of Egypt (NSSC) 1974. Miocene rock stratigraphy of Egypt. *Egyptian Journal of Geology*, 18, p. 1-69.
- Patton, T.L., A.R. Moustafa, R.A. Nelson and S.A. Abdine 1994. Tectonic evolution and structural setting of the Gulf of Suez rift. In S.M. Landon (Ed.), *Interior Rift Basins. American Association of Petroleum Geologists Memoir no. 59*, p. 9-56.
- Ramzy, M., B. Steer, F. Abu-Shadi, M. Schlorholtz, J. Mika, J. Dolson and M. Zinger 1996. Gulf of Suez rift basin sequence models-Part B. Miocene sequence stratigraphy and exploration significance in the central and southern Gulf of Suez. In M. Youssef (Ed.), *Proceedings of the 13th Petroleum Conference, Cairo, Egypt. Egyptian General Petroleum Corporation*, p. 242-256.
- Ramzy, M., B. Steer, J. Thorseth and J. Garing 1998. Integrated exploration: The SG310-4 case history. In, M. Eloui (Ed.), *Proceedings of the 14th Petroleum Conference, Cairo, Egypt. Egyptian General Petroleum Corporation*, p. 359-373.
- Rashed, A. 1990. The main fault trends in the Gulf of Suez and their role in oil entrapment. *Proceedings of the 10th Petroleum Exploration and Production Conference, Egyptian General Petroleum Corporation*, v. 1, p. 143-178.
- Rashed, A. 1994. The effect of clysmic and cross faults on the reservoir style and hydrocarbon entrapment in west Gharib sub-basin, GOS. *Proceedings of the 12th Petroleum Exploration and Production Conference, Cairo, 1994. Egyptian General Petroleum Corporation*, v. 1, p. 127-144.
- Rateb, R. 1988. Miocene planktonic foraminiferal analysis and its stratigraphic application in the Gulf of Suez region. *Proceedings of the 9th Exploration Seminar, Cairo, 1988. Egyptian General Petroleum Corporation*, v. 1, p. 275-299.
- Richardson, M. and M.A. Arthur 1988. The Gulf of Suez-northern Red Sea Neogene rift, a quantitative basin analysis. *Marine and Petroleum Geology*, v. 5, no. 3, p. 247-270.

- Robson, D.A. 1971. The structure of the Gulf of Suez (Clysmic) rift, with special reference to the eastern side. *Journal of the Geological Society of London*, 127, p. 247-276.
- Rosendahl, B.R. 1987. Architecture of continental rifts with special reference to East Africa. *Annual Review of Earth and Planetary Sciences*, 15, p. 445-503.
- Saad, H., M. Zinger and A. Ghaly 1996. The regional structural trends, their pattern, and association with hydrocarbon accumulations in the offshore south Gulf of Suez area. *Proceedings of the 13th Petroleum Conference, Cairo, 1996. Egyptian General Petroleum Corporation, v. 1, p. 97-120.*
- Salama, A., S. El Moughy, M.A. Moneim and S. Hakim 1994. Exploration in Ras Garra area, a case history, southern Gulf of Suez, Egypt. *Proceedings of the 12th Petroleum Exploration and Production Conference, Cairo, 1994. Egyptian General Petroleum Corporation, v. 1, p. 240-257.*
- Souaya, F.J. 1966. Miocene foraminifera of the Gulf of Suez region, U.A.R., part 3; *Biostratigraphy, Micropaleontology*, v. 12, no. 2, p. 183-202.
- Steckler, M. and U. ten Brink 1986. Lithospheric strength variations as a control on new plate boundaries: Examples from the northern Red Sea. *Earth and Planetary Science Letters*, v. 79, nos. 1 and 2, p. 120-132.
- Steckler, M.S., F. Berthelot, N. Lyberis and X. LePinchon 1988. Subsidence in the Gulf of Suez: Implications for rifting and plate kinematics. *Tectonophysics*, v. 153, p. 249-270.
- Sultan, N. and K. Schutz 1984. Cross faults in the Gulf of Suez area. *Proceedings of the 7th Exploration Seminar, Cairo, 1984. Egyptian General Petroleum Corporation, p. 5-17.*
- Tewfik, N., C. Harwood and I. Deighton 1992. The Miocene, Rudeis and Kareem formations of the Gulf of Suez. Aspects of sedimentology and geohistory. *Proceedings of the 11th Exploration Conference, Egyptian General Petroleum Corporation, Cairo, p. 84-112.*
- Vail, P.R., R.M. Mitchum Jr. and S. Thompson III 1977. Seismic stratigraphy and global changes of sea-level, Part 4: Global cycles of relative changes of sea-level. In C.E. Payton (Ed.), *Seismic Stratigraphy - Applications to Hydrocarbon Exploration. American Association of Petroleum Geologists Memoir 26*, p. 83-98.
- Wagoner, Mitchum, Campion and Rahmanian 1990. Siliciclastic sequence stratigraphy in well logs cores, and outcrops. *American Association of Petroleum Geologists Methods in Exploration Series, no. 7. Society of Sedimentary Geology Special Publication 42 (1988). Sea-Level Changes - An Integrated Approach.*
- Wescott, W.A., W.N. Krebs, J.C. Dolson, S.A. Karamat and D. Nummedal 1996. Rift basin sequence stratigraphy: Some examples from the Gulf of Suez. *GeoArabia v. 1, no. 2, p. 343-358.*
- Younes, A.I. and K. McClay 1998. Role of basement fabric on Miocene rifting in the Gulf of Suez - Red Sea. *Proceedings of the 14th Petroleum Conference, Cairo, 1998. Egyptian General Petroleum Corporation, v. 1, p. 35-50.*
- Zahran, M.E. 1988. Geology of October oil field. *Proceedings of the 8th Exploration Seminar, Cairo, 1986. Egyptian General Petroleum Corporation, v. 1, p. 35-52.*

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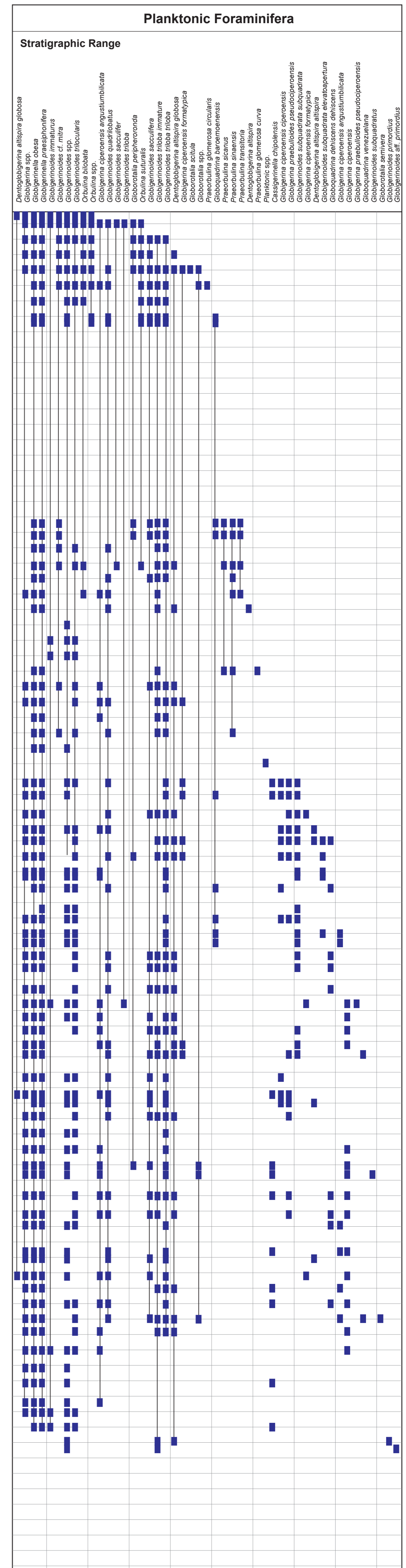
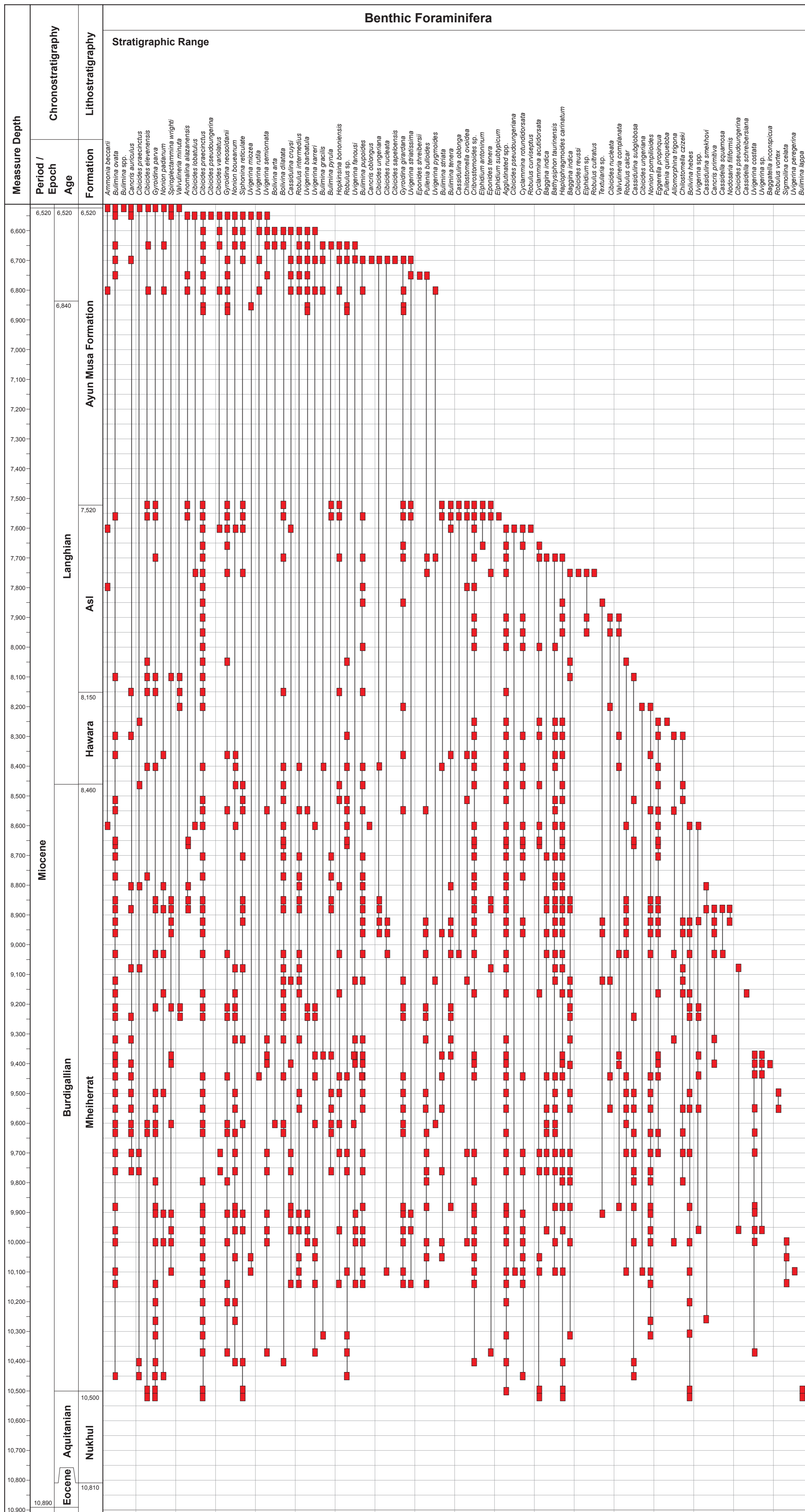


Figure 3: Faunal range chart based on the last occurrences of the recorded foraminifera species in the borehole AZ13-1.

ENCLOSURE
Figure 3

**EARLY – MIDDLE MIOCENE SUEZ
SYN-RIFT-BASIN, EGYPT:
A SEQUENCE STRATIGRAPHY FRAMEWORK**

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