Egyptian Geophysical Society
EGS Journal, Vol. 11, No. 1, 121-135 (2013)

STRUCTURAL EVOLUTION OF THE SOUTHERN GULF OF SUEZ RIFT: IMPLICATIONS FOR HYDROCARBON EXPLORATION IN A MATURE BASIN

A.S. Afifi*, A.R. Moustafa** and H.M. Helmy*

* *BP Egypt / GUPCO, ** Ain Shams University*

التطور التركيبى للجزء الجنوبى من أخدود السويس: ماهيات استكشاف البترول فى منطقة إنتاج قديمة

الخلاصة: يمثل الجزء الجنوبى لخليج السويس نطاقا تركيبيا فريدا، اذ أنه أحد أنصاف الأخاديد الثلاثة التى تكون أخدود السويس الممتد من مدينة السويس شمالا الى شمال مدينة الغردقة جنوبا. وتوجد فى أنصاف الاخاديد الثلاثة عدة وحدات استراتجرافية يتراوح عمرها من حقب الحياة القديمة الى الحقبة الحديثة، ترسبت فى بيئات ترسيب متنوعة. وتحتوى هذه الوحدات الاستراتجرافية على عدد من الصخور الخازنة للبترول التى تنتمى الى مجموعة الصخور التى سبقت والتى تزامنت مع تكوين أخدود السويس والتى تم التعرف عليها فى حقول البترول الموجودة بالخليج وبها احتياطى بترول يقدر بعدة ملايين من البراميل. ويعتبرحوض خليج السويس من الاحوض الناضجة، حيث انه كان ومازال محور التنقيب عن ا لبترول وإنتاجه منذ بداية القرن العشرين، بالاضافة الى افتقاره للاستكشافات البتروليه الغنيه في العقد الأخير. وعلى الرغم من أنه حوض ناضج ، فأن فرصه حفر ابار جافة لاتزال موجودة و خاصه على بعض التراكيب في منطقة الدراسة، وذلك بسبب قله جودة البيانات السيزمية وعدم إعادة بناء القطاعات الجيولوجية التركيبة عند فترات زمنية سابقة. وقد أدى نشاط الاستكشاف مؤخرا الى عدة مفاجآت، بسبب تآكل صخور الخزانات عند قمم الكتل الصدعية المائلة. ومن هنا فان معرفة توقيت امالة هذه الكتل الصدعية ذو أهمية قصوى حيث أن ميل الصخور هو أحد الأسباب فى وجودها من عدمه عند قمم الكتل المائلة. وقد أدى تكامل المعلومات السطحية وتحت السطحية لمنطقة بها ٣٥ بئر وخمسة قطاعات استراتجرافية سطحية بالاضافة الى ٤٠٠ كيلومتر مربع من البيانات السيزمية ثلاثية الابعاد الى التمكن من اعادة بناء الشكل التركيبى للمنطقة مما أتاح تصورا عن توقيت الحركة على الفوالق الموجودة بالمنطقة وكيفية المحافظة على الصخور الخازنة للبترول بقمم الكتل الصدعية المائلة. وتشمل المنهجية التى تم استخدامها للدراسة عمل عدة قطاعات مضاهاة بين القطاعات الاستراتجرافية السطحية والتسجيلات الكهربية للابارالمدروسة و للوحدات الصخرية التى سبقت والتى تزامنت مع تكوين أخدود السويس حيث تم تحديد النطاقات الصخرية المفقودة ونسبها الى وجود فوالق بالابار أو الى عدم توافق بسبب التعرية أو عدم الترسيب. وتلى ذلك رسم خرائط سمك للقطاعات الرسوبية وخريطة مكشف قديم للصخور الأقدم من صخور عصر الميوسين، بالاضافة الى رسم خرائط تركيبية من البيانات السيزمية ثلاثية الابعاد. وقد ساعدت هذه الخرائط مجتمعة على رسم قطاعات جيولوجية تركيبية تم بعد ذلك استعادة بنائها عند فترات زمنية سابقة مما أدى الى فهم تاريخ الحركة على الفوالق ومقدار دوران الكتل الصخرية المصدوعة والمحافظة على صخور ما قبل تكوين الاخدود عند قمم الكتل الصدعية المائلة. وقد أفاد استعادة بناء القطاعات التركيبية فى أعطاء تصور أفضل عن التطور التكتونى للمنطقة وتأثيره على استكشاف البترول للتمكن من معرفة تواجد الصخور الخازنة عند قمم الكتل الصخرية المائلة وتحديد شكل المصيدة البترولية.

ABSTRACT: *The southern part of the Gulf of Suez is a unique structural province, as it represents one of three half grabens, that make up the asymmetric Suez rift, which extends from Suez in the north to Hurghada in the south. Different stratigraphic units ranging in age from Paleozoic to Cenozoic are recorded and preserved in the half-grabens, with a variety of depositional environments, thicknesses and facies. Significant syn-rift and pre-rift reservoirs do exist in the Southern Gulf of Suez fields, with multi million barrels of resources. The Gulf of Suez basin is considered mature, as it has been the focus for hydrocarbon exploration and production since the beginning of the twentieth century, and presently lacks significant discoveries in the last decade, which supports the term mature basin. Even though it is a mature basin, the humbling experience of drilling a dry hole still do exist on some structures, particularly in the study area, due to poor seismic imaging and lock of structural restorations. Recent exploration activity has resulted in surprises, due to erosion of the crests of fault blocks. Knowing the timing of rotation on these blocks is of prime importance, since the main resources in these fields are within the potentially eroded pre-rift section. The integration of the surface and the subsurface data sets represented by 5 surface sections, 35 wells, and 400 km2 of 3D seismic data, enabled the reconstructions of the geologic cross sections to be performed, allowing insight regarding fault timing, evolution and reservoir preservation on the tilted blocks' leading edges. The work methodology was made through a series of well correlation panels, using wire line logs of all the syn-rift and pre-rift stratigraphic units to identify the missing sections and attribute them to either faults or unconformities. Constructing isopachs for the sedimentary section, Miocene subcrop mapping along with the 3D seismic mapping, allowed the construction of structural sections that were restored and balanced at different startigraphic levels to reveal fault history, amount of block rotation and preservation of the pre-rift section at the updip edges of the fault blocks. The restoration process helped in better understanding of the tectonic evolution, which has an impact on the hydrocarbon exploration, as it helps in predicting the reservoir presence at the edges of tilted blocks and defining the trap geometry.*

1. INTRODUCTION

The purpose of this paper is to use the available surface and subsurface datasets, which were provided by the Gulf of Suez Petroleum Company (GUPCO), to model the structural evolution and phases of deformation of the southern part of the Gulf of Suez and its impact on the hydrocarbon exploration. The area of study (Figure 1) extends from the latitude of the northern edge of Gebel Esh El-Mellaha in the north to the north of Shadwan Island in the south and extends from the Sinai massif in the east to the Red Sea hills in the west.

The provided data are 400 km^2 of 3D PSDM seismic data, 35 well logs and published geological data of 5 measured surface sections in Sinai and the Eastern Desert. The methodology and approach used in the study are the conventional subsurface mapping evaluation techniques: where the first step was to establish the stratigraphic framework by subdividing the stratigraphic section into time startigraphic units that are correlatable in the surface and the subsurface data. Two well correlation panels were then constructed to identify the missing startigraphic sections and to demonstrate the comparable changes in facies and thickness.

Isopach, structural and subcrop maps were constructed to illustrate the relationship between the Miocene tectonics and sedimentations of the syn-rift units and the preservation of the pre-rift units. Finally, structural restoration technique was performed on two constructed structural cross sections to validate the structural interpretation and to show the age relationships and the evolution of the major faults and the amount of rotation, that the pre-Miocene block had undergone through the development of rift structures and how it relates to the pre-rift reservoir presence. If this is integrated with other elements, it could enhance drilling optimum structural locations with most likely commercial hydrocarbon discoveries.

2. Regional setting:

The Gulf of Suez is one of the world-class prolific hydrocarbon-bearing basins, and it is considered as one of the best studied examples of a continental rift in the world (Bally and Roberts, 2010). The Gulf of Suez rift extends in the northwest-southeast direction and its width is about 80 km in the south. The length of the rift, from the Strait of Jubal to Suez city is about 320 km.

The Oligo-Miocene Gulf of Suez rift is the northern termination of the Red Sea rift, which developed as a result of the northeastward separation of the Arabian plate from the African plate (Bosworth and McClay, 2001). Several authors (Evans and Moxon, 1986; Moretti and Colletta, 1987; Richardson and Arthur, 1988; Steckleret al., 1988; Patton et al., 1994; Bosworth and McClay, 2001) suggested that by the late middle Miocene, rifting became subdued in the Gulf of Suez, as the opening of the Red Sea became linked to sinistral strike-slip displacement along the Gulf of Aqaba-Dead Sea transform fault system.

The Gulf of Suez is characterized by three distinct half-grabens, that flip in the dip of bedding from north to south. In the northern Darag basin, the dominant faults dip to the NE and bedding dip is predominantly to the SW, whereas the Lagia to Belayim basins have opposite SW-dipping main faults and regional bedding dip to the NE, and in the southern gulf the main faults dip to the NE and regional fault blocks dip to the SW (figure 1).

The areas of major change in the structural dip domain have been termed accommodation zones or transfer zones by previous workers (e.g. Patton et al., 1994; Bosworth and McClay, 2001; and Moustafa, 2002). Younes and McClay (2002) have termed the northern zone, the Zafarana accommodation zone (ZAZ) and the southern zone, the Morgan accommodation zone (MAZ) after Moustafa (1976). On the other hand, Moustafa (2002) used other names like Gharandal and Sufr El Dara accommodation zones.

Hydrocarbon exploration in the Gulf of Suez dates back to the 1880's-90's, when the first drilling for oil occurred at Gebel el Zeit, in the general vicinity of the oil seeps. Shortly later, oil was encountered in mine shafts dug for sulfur within the Middle to Late Miocene evaporite outcrops on Gemsa Peninsula, just to the south of Gebel El Zeit. The first oil field of Egypt was discovered in 1909-1910 (Gemsa field, ~1.45 MMBO reserve). Discovery of the larger Hurghada field (~ 44.5 MMBO reserve) in 1913 by Anglo-Egyptian Oil Fields, Ltd., and the Ras Gharib field in 1938 by Standard Oil of Egypt (~ 290 MMBO reserve) established the Gulf of Suez, as a significant hydrocarbon province (El Ayouty, 1990).

3. Stratigraphy:

As the study integrated both surface and subsurface data, the tie between the surface formations and the subsurface age equivalent startigraphic units is vital to construct the time stratigraphic unit, which represents a certain geological time. The surface sections are well distributed between Sinai and the Eastern Desert. 5 surface sections were included in the study, Ras Kenisa (Moustafa and Helmy, 1985) in South Sinai, Gebel El Zeit (Evans and Moxon, 1986 and Winn et al., 2001) and three measured sections in Gebel Esh El-Mellaha in the Eastern Desert (Aboul Karamat, 1987).

The startigraphy and sedimentology of the Gulf of Suez rift fill are well known in comparison to most continental rift systems. With exception of the basal syn-rift strata, the section is almost entirely of marine and marginal marine origin, and hence can generally be accurately dated with the planktonic foraminifera and calcareous nanno-fossils (Bosworth, 1995). The following summary describes the startigraphy of the southern part of the Gulf of Suez (Figure 2).

3.1 Pre-rift stratigraphy:

Eighteen wells out of the thirty-five wells used in the present study encountered the Precambrian basement rocks. The basement rocks encountered in the subsurface and recorded in the surface outcrops consist mainly of granite, which was dated at 530-620 Ma (Hassan and Hashad, 1990). The granite outcrops at Gebel El Zeit yielded an Rb-Sr age of 592 Ma (Stern and Hedge, 1985).

The pre-rift sedimentary sequence is subdivided into several units that range in age from Paleozoic to Eocene with some debate about the exact age of the oldest unit (Nubia Sandstone). For the sake of consistency, the Nubia Formation term will be used to describe a predominantly sandstone rock stratigraphic unit, that directly overlies the Precambrian basement and range in age from Early Paleozoic to Early Cretaceous (the sandstone unit in Figure 2). Aboul Karamat (1987) considered the unit, which disconformably overlies the Precambrian basement in Gebel Esh El-Mellaha range as Araba Formation.

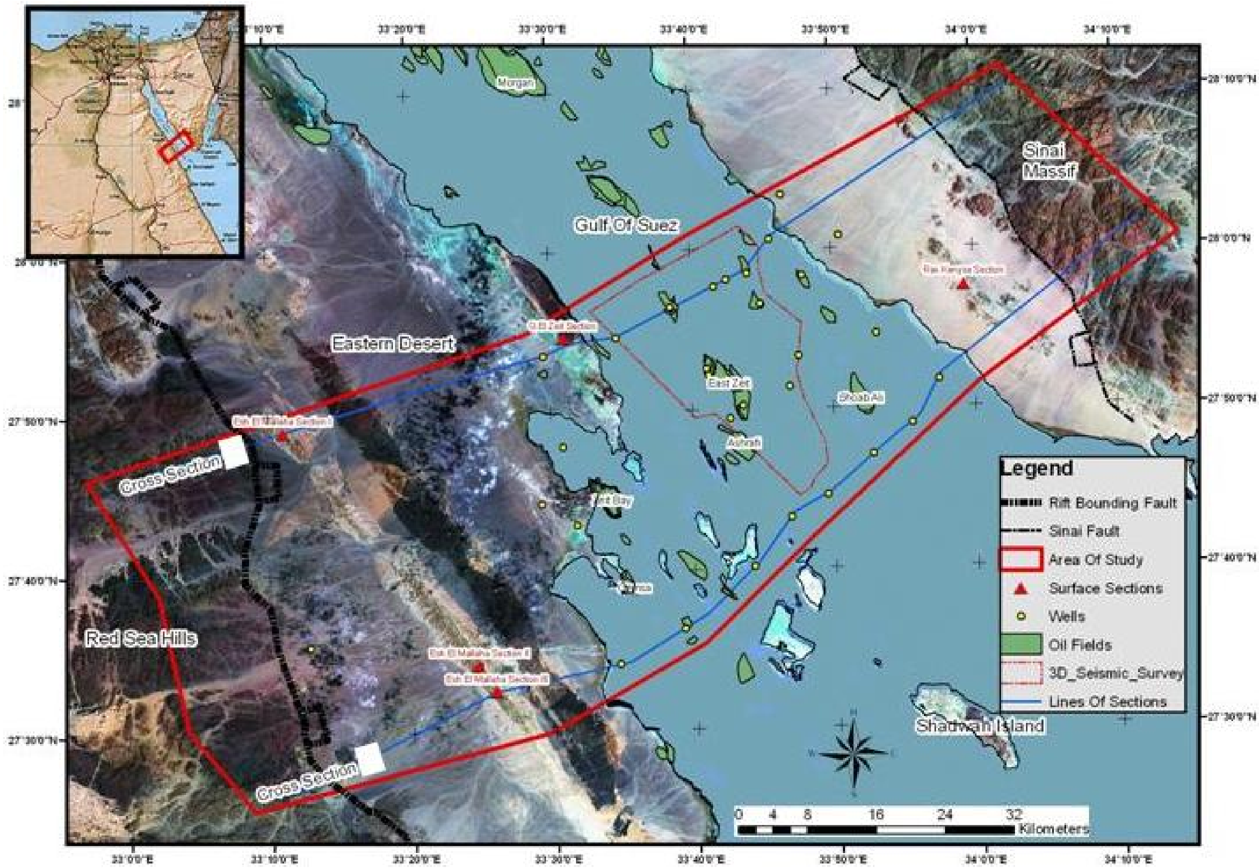

Figure (1): Area of study and utilized data.

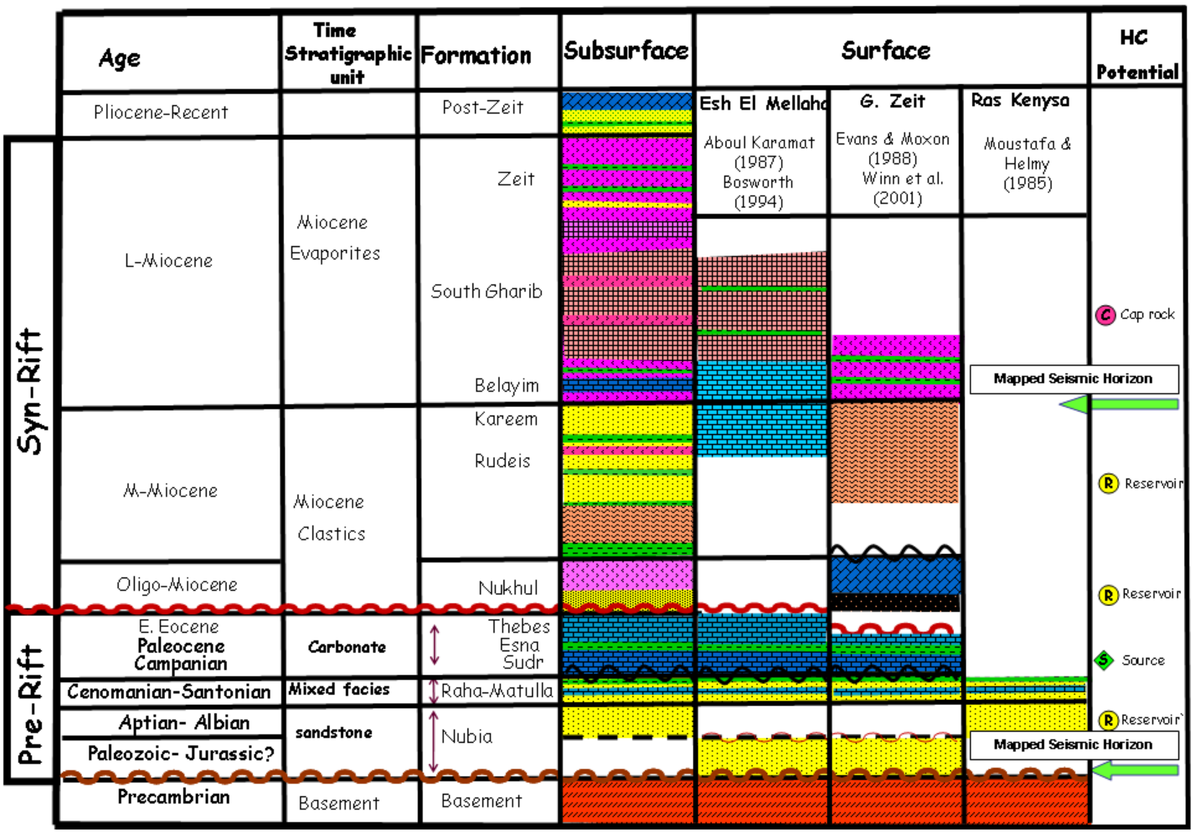

Figure (2): Generalized stratigraphic column of the Southern Gulf of Suez, with the hydrocarbon (HC) source, cap and reservoir rocks.

He attributed both the Araba Formation and the overlying Naqus Formation, which unconformably underlies different marine Upper Cretaceous rock units to have Early Paleozoic age.

At Gebel El Zeit, the Nubia includes a discontinuous red shale and sandstone interval and is possibly of Late Paleozoic-Triassic age and a probable Aptian-Albian, medium-grained to coarse-grained quartzoze, dominantly cross-bedded sandstone unit of several hundred meters thick (Winn et al., 2001) . The Nubia sandstone is 1312 ft thick at Gebel El Zeit and the Cenomanain to Turonian rocks are 820 ft thick. Both sections comprise the conformable Pre-Miocene section. However, erosional remnants of Upper Senonian chalk and Eocene limestone occur locally (Evans and Moxon, 1986). The pre-rift sequences in Gebel Esh El-Mellaha (Aboul Karamat, 1987) and Gebel El Zeit (Evans and Moxon, 1986 and Winn et.al, 2001) are summarized and correlated to the subsurface rock units in table (1).

At Ras Kenisa section in Southwest Sinai, the exposed pre-Miocene sedimentary section consists of 305+ ft basal Nubia Sandstone section, and is overlain by 152 ft of Cretaceous mixed facies (Nezzazat Group) and approximately 5-7 ft of weathered, bedded chert, which is assumed to represent the Upper Cretaceous Sudr Chalk (Moustafa and Helmy, 1985; unpublished GUPCO report). The Upper Cretaceous rocks (the Cenomanian –Santonian mixed facies unit), that unconformably overlie the Paleozoic Nubia, show more open marine facies. These rock units are equivalent in age to the Wata and the Matulla Formations and they consist of sandstone, carbonate and shale beds.

The Sudr, Esna and Thebes Formations, which represent the carbonate dominated units in the pre-rift sequence overlie the Upper Cretaceous rocks in Gebel Esh El-Mellaha. The carbonate unit is mainly chalk at the base, limestone at the top and shale in-between.

In the subsurface, the pre-rift succession includes the Nubia Sandstone at the base. The Nubia Sandstone is characterized by loose sandstone with traces of kaolinite. The thickness varies dramatically from north to south, ranging from 1,600 to 200 ft and the depositional strike, as shown on the Nubia isopach map (Figure 5), is NW –SE. The age dating of the Nubia Sandstone in the subsurface was done by the oil companies, which operate in the Southern Gulf of Suez by using palynological dating. The Nubia Sandstone in the subsurface was assigned to the Early Cretaceous and is considered the oldest unit, which disconformably overlies the Precambrian basement. As it is considered the prolific hydrocarbon reservoir in the Gulf of Suez, the preservation of the Nubia Sandstone is important in the oil exploration and the effect of early rift structural deformation is the main objective of this study.

Overlying the Nubia Sandstone is the Nezzazat Group or the Mixed Facies unit, which consists of sandstone with shale and limestone. The sandstone in the Nezzazat Group is thought to be deposited in a channel system, so predicating the sand distribution in the subsurface is challenging, especially with the poor seismic data quality. Such target needs special data acquisition and processing for the purpose of seismic stratigraphic analysis, not for structural analysis, as available. The thickness of the Nezzazat Group in the northern part of the study area is about 500 ft and it thins gradually to the south.

The Sudr Chalk and its Brown Limestone Member unconformably overly the Nezzazat Group. The unconformity surface between the Nezzazat Group and the Brown Limestone is the Campanian / Santonian unconformity, which is thought to be related to the Syrian arc deformation. Detailed outcrop mapping has delineated shortening structures in the pre-Miocene sedimentary section of the Eastern Desert from the latitude of Gebel El Zeit, to the area south of Quseir on the Red Sea coast that was related to the Syrian arc deformation (Bosworth et al., 1999). Well correlation panels (Figures 3 and 4) show that, some wells have a hiatus between the Nezzazzat and the Campanian Brown Limestone, which is probably equivalent to and supports the deformational features seen on the surface in other parts of Egypt. Overlying the Sudr Chalk is the Esna Shale, which underlies the Thebes Formation. The Sudr, Esna and Thebes Formations are collectively referred to as Carbonate unit, which thins gradually to the south, but at less magnitude than the thinning in the Nubia Sandstone and the Mixed Facies units.

The rift breakup unconformity bounds the pre-rift section at the top. The top of the Thebes Formation is always considered an unconformity surface, as shown in Figures 3and 4. At the footwall of the early rift faults, that were formed early in the rift history, the breakup unconformity cuts deep in the Thebes Formation (wells 4 and 5, in Figure 4). With more erosion of the Thebes Formation, the likelihood of encountering a very thin or sometimes zero thickness of the overlying Nukhul Formation is obvious.

3.2 Syn-rift Stratigraphy

The early syn-rift stratigraphy is represented by clastics deposition in the basin and it consists of Nukhul, Rudies and Kareem formations, which were mainly deposited in a marine environment. The late syn-rift deposits are characterized by the abundance of evaporation and deposition of salt and anhydrite, with minor clastics input.

The evaporites section consists of Belayim, South Gharib and Zeit Formations. The Miocene evaporites are considered the prime top seal in the Gulf of Suez and they represent the lateral seal for most of the Miocene producing fields. The thickness and distribution of the evaporites facies are controlled by young structures, fault movements and the upward salt flow. In surface outcrops, the preserved Miocene evaporites are not extensive and the thickness is comparatively very thin compared to the thick subsurface sections, where the depocenters of the half-grabens exist.

Esh El Mellha Section I (Aboul Karamt -1987)					Study Area	G Zeit (Evans and Moxon, 1986 and Winn et.al 2001)		
Age	Fm	Mbr	Formation Thick. (ft)	Total Thick. (ft)	Subsurface		Total Thickness (ft)	
EARLY EOCENE	Thebes		213	545	Carbonate	Carbonate	Erosional Remnants	
PALEOCENE-E EOCENE	Esna		66					
MAASTRICHTIAN	Sudr		246					
CAMPANIAN	Duwi		20					
SANTONIAN	Nubia	Quseir clastics	249	384	Nezz	Raha / Matulla	393	
CONIACIAN		Taref sandstone						
TURONIAN	Wata		45					
CENOMANIAN	Galala		90					
PALEOZOIC	Naquas & Araba(undiff.)		984	984	Nubia(Ke)	Nubia	1312.4	(Pz ,J and Ke)

Table (1): The thickness of pre-rift units in Gebel Esh El-Mellaha and subsurface rock units (this study). Pz: Paleozoic; J: Jurassic; Ke : Early Cretaceous.

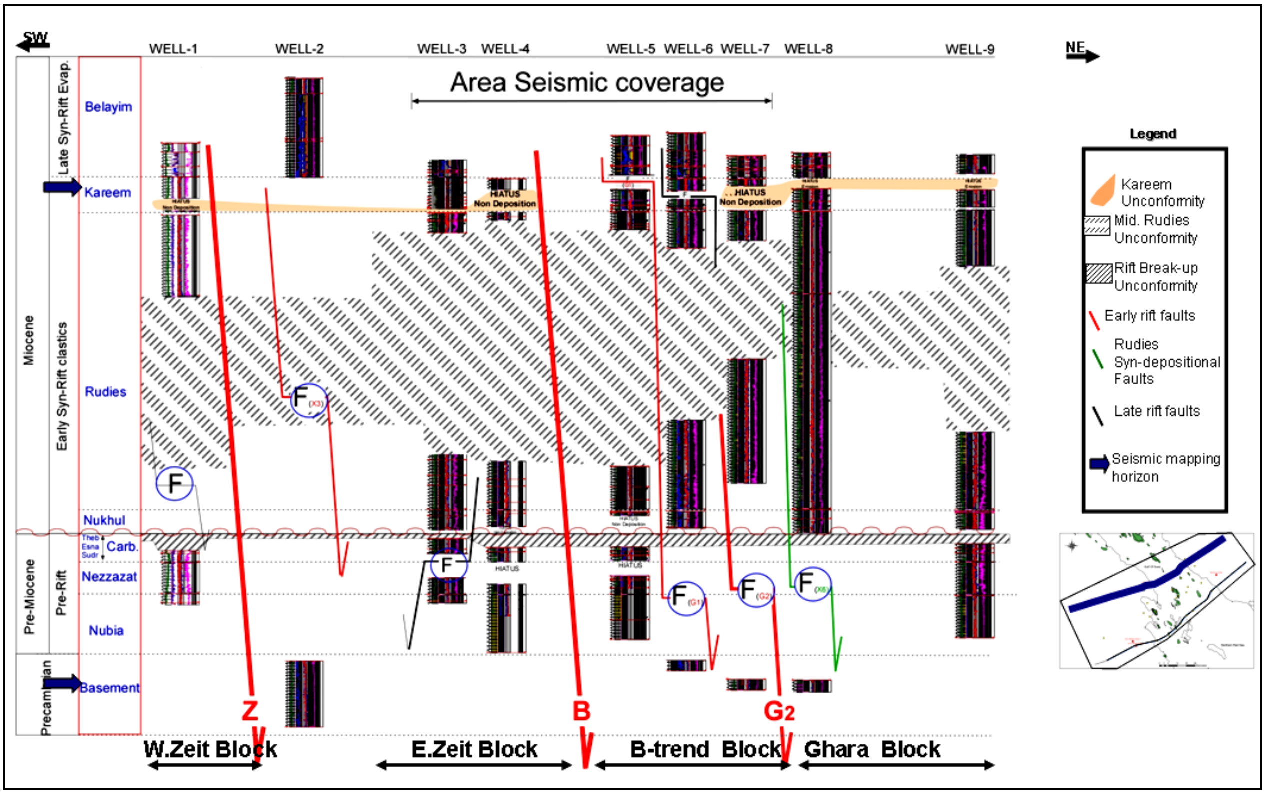

Figure (3): The northern stratigraphic correlation panel showing the major half grabens. (F: fault, TD: well total depth).

At Gebel El Zeit for instance, the Miocene section is highly compressed. Less than 150 m of Nukhul through Kareem (Aquitanian to Seravallian) deposits are present at West Gebel El Zeit, in contrast to over 1500 m of correlative section in the subsurface (Evans and Moxon, 1986). This thickness variation clearly indicates that, the Zeit fault that bounds the Gebel El Zeit structure is as old as the rift initiation and the block continued to act as a high throughout the Miocene and the Pliocene. This relationship is also obvious from the subsurface data, where well-1 in the first correlation panel (Figure 3) encountered a very thin and condensed Miocene section overlying highly eroded carbonate unit at the footwall of the Zeit Fault.

The Nukhul Formation, the oldest syn-rift unit, consists of two members; clastics at the base and evaporites at the top. The thickness of the Nukhul Formation is highly controlled by the early rift faults. Figure 6 shows the thickness of the Nukhul Formation in the early defined half-grabens. The thickness in the hanging wall troughs is more than 4000 ft and thins towards the updip edges of the tilted fault blocks, with less than 500 ft thickness. At the updip edge of the Zeit and B-trend fault blocks, the Nukhul Formation is completely missing, due to non-deposition. The presence of thin Nukhul Formation or its complete absence is a good indication of the absence or erosion of the pre-Miocene section at the leading edge of the tilted fault block. As it will appear later in the restored section, the absence of the Nukhul Formation is a strong evidence for the likelihood of the eroded pre-rift section.

The Rudies Formation overlies the Nukhul Formation and it consists mainly of marl, shale and limestone with occasional occurrence of sand bodies, where the clastics influx is available. The Rudies Formation represents the first deep marine sediments in the basin, and its thickness is controlled by the syn-rift faults. Figure 7 shows the isopach map of the Rudies Formation and it shows a similar thickness trend like the Nukhul isopach map, where it has zero thickness due to the non deposition at the footwall of the Z Fault. The Mid-Rudies unconformity between the Lower Rudies and Upper Rudies is considered the peak of the rift subsidence, as the thickest section in the syn-rift package is the Lower Rudies and the variation in thickness across the rift faults is more pronounced than the younger syn-rift rocks.

Overlying the Rudies Formation is the youngest Miocene clastics, Kareem Formation, which is the primary reservoir in a number of fields in the southern Gulf of Suez (e.g. GH 376 and Ghara Marine).

4. The structural settings of the study area

The Gulf of Suez and Northern Red Sea rift consist of large-scale half-grabens, which alternate in polarity (predominant stratal dip direction) along the basin axis (Moustafa, 1976; Moretti and Colleta, 1987; Coffield and Schamel, 1989; Jarrige et al., 1990; Patton et al., 1994; Bosworth, 1994, 1995; Bosworth and McClay, 2001; Younes and McClay, 2002; Moustafa, 2002). The study area is situated in the southern part of the Gulf of Suez, to the south of the Morgan accommodation zone.

The structural setting of the southern gulf is characterized by the existence of north-northwest oriented structural trends (Helmy, 1990).

Wells correlation, cross sections and seismic mapping have indicated that, the Southern Gulf of Suez can be subdivided into five major tilted fault blocks named from west to east: Esh El-Mellaha Block, West Zeit Block, East Zeit Block, B-trend Block and Gahara Block. They comprise Miocene and pre-Miocene southwest dipping fault blocks bounded by major down-to-the-northeast clysmic normal faults (Helmy, 1990). Each block or half-graben is characterized by steep stratal dip (30^o-40^o) and the main faults dipping at 20^o-30^o. One exception from this is the Esh El-Mellaha fault, which dips at about 50-52^o and the block is dipping at 8^o. The reason behind that, is the timing of the last structural rotation of the Esh El-Mellaha block, which is Middle Miocene as constrained by the Miocene reef talus, and the back-reef lagoons at Abu Shaar El Qibili. As the Esh El-Mellaha basin stopped activity in the Middle Miocene (i.e. stopped rotation), the main bounding fault for the rift shifted from the foot of the Red Sea Hills to the Zeit Fault (Bosworth 1994; and Dart et al., 1995).

The major faults bounding the half-grabens are striking NW-SE (clysmic), while the transfer faults (Moustafa, 2002), that link between the clysmic faults segments strike NNE-SSW, resulting in the zigzag pattern of the major rift faults. The change in throw of the B-trend Fault along the strike, as shown in the basement structure map (Figure 8) suggests that, the fault was initiated first as discrete separate segments, that were linked later by transfer or linking faults. Figure 9 shows the two structural cross sections, that were constructed using the surface sections, wells and seismic data, where available.

The sections show that, the old or early rift faults (i.e. faults initiated at the Nukhul time) are gentler in dip angle than the younger faults and bounded the early formed tilted blocks, that witnessed rotation up to 30^o-$40^{o.}$ These faults define the area of likelihood of eroded pre-Miocene section. The areas of eroded pre-Miocene section define the updip edges of the early formed half-grabens.

The Miocene subcrop map (Figure 10) shows the areas, where it is expected to encounter either a complete, partly eroded or completely eroded pre-Miocene section underneath the Miocene section. This map can be used as a reference for guiding the exploration for the pre-Miocene Nubia Sandstone prolific reservoir and the erosion of the local top seal of Nubia Formation (Sudr, Esna and Thebes Formations).

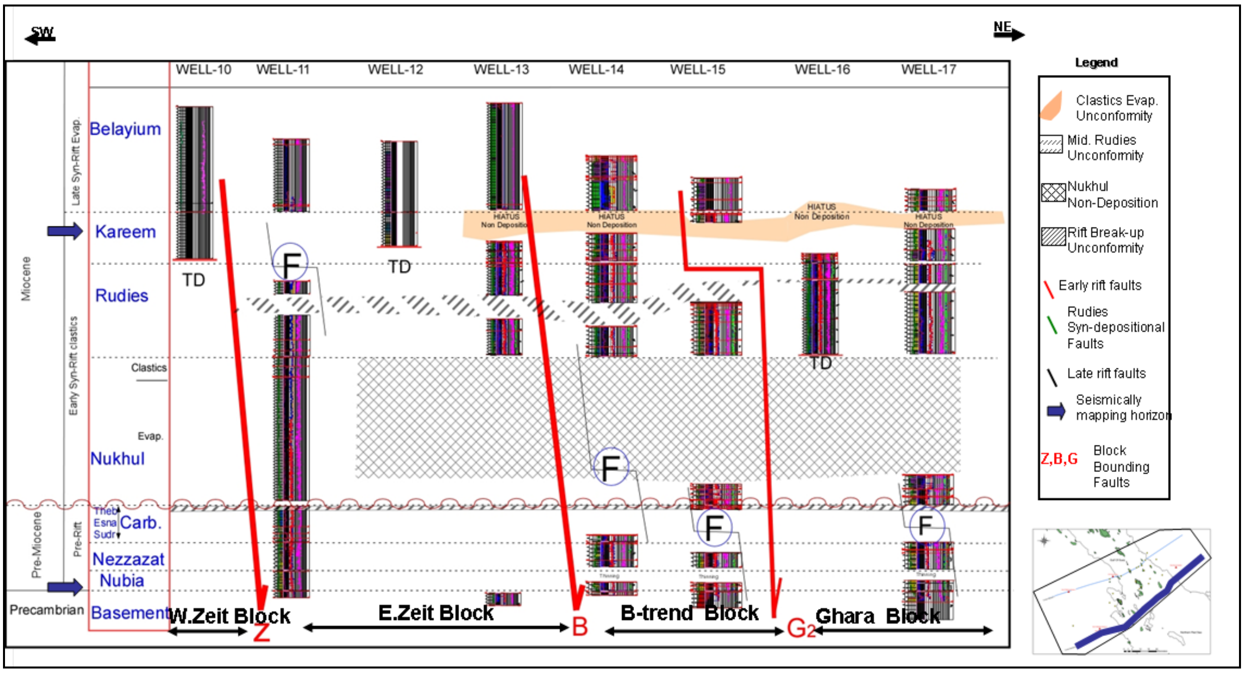

Figure (4): The southern stratigraphic correlation panel showing the major half grabens (F: fault; TD: well total depth).

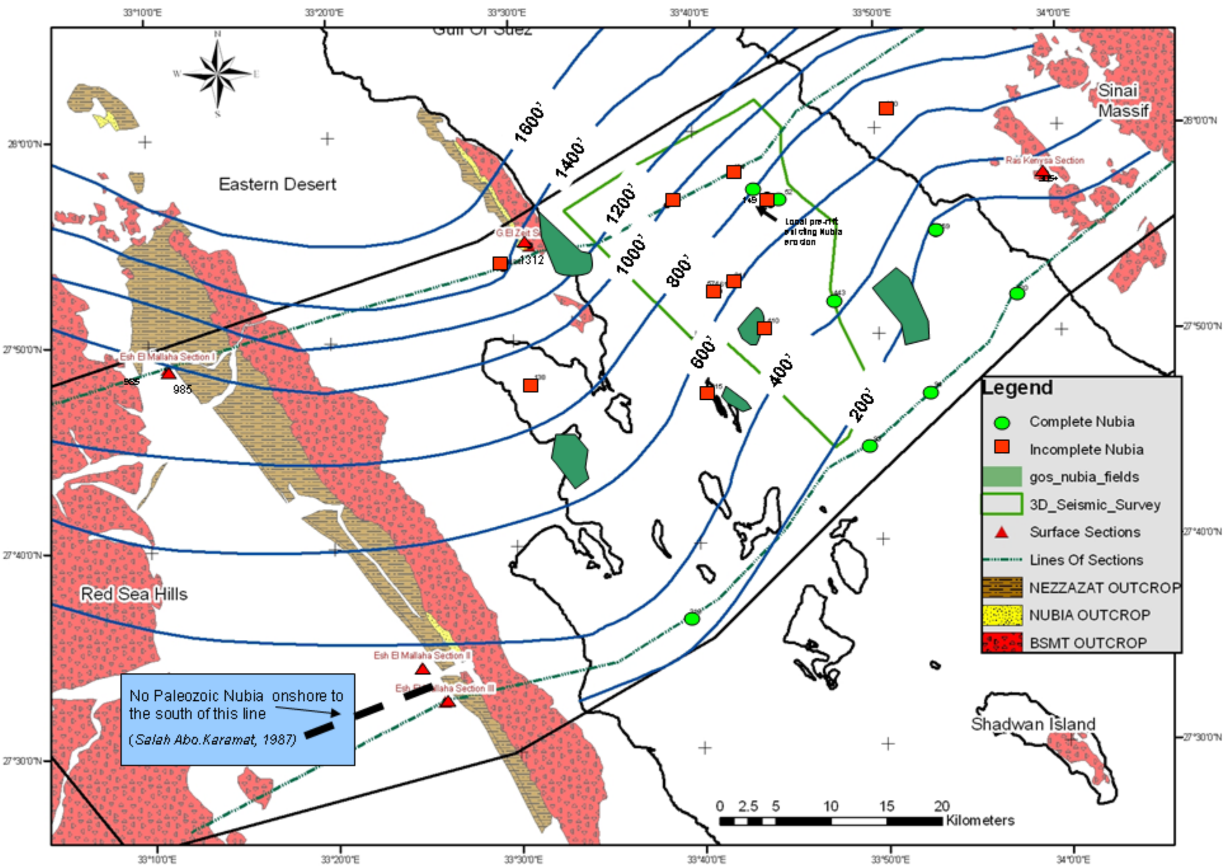

Figure (5): Nubia Sandstone isopach map (values in feet). The thickness of Nubia is restored to the depositional thickness in case of faulting and erosion.

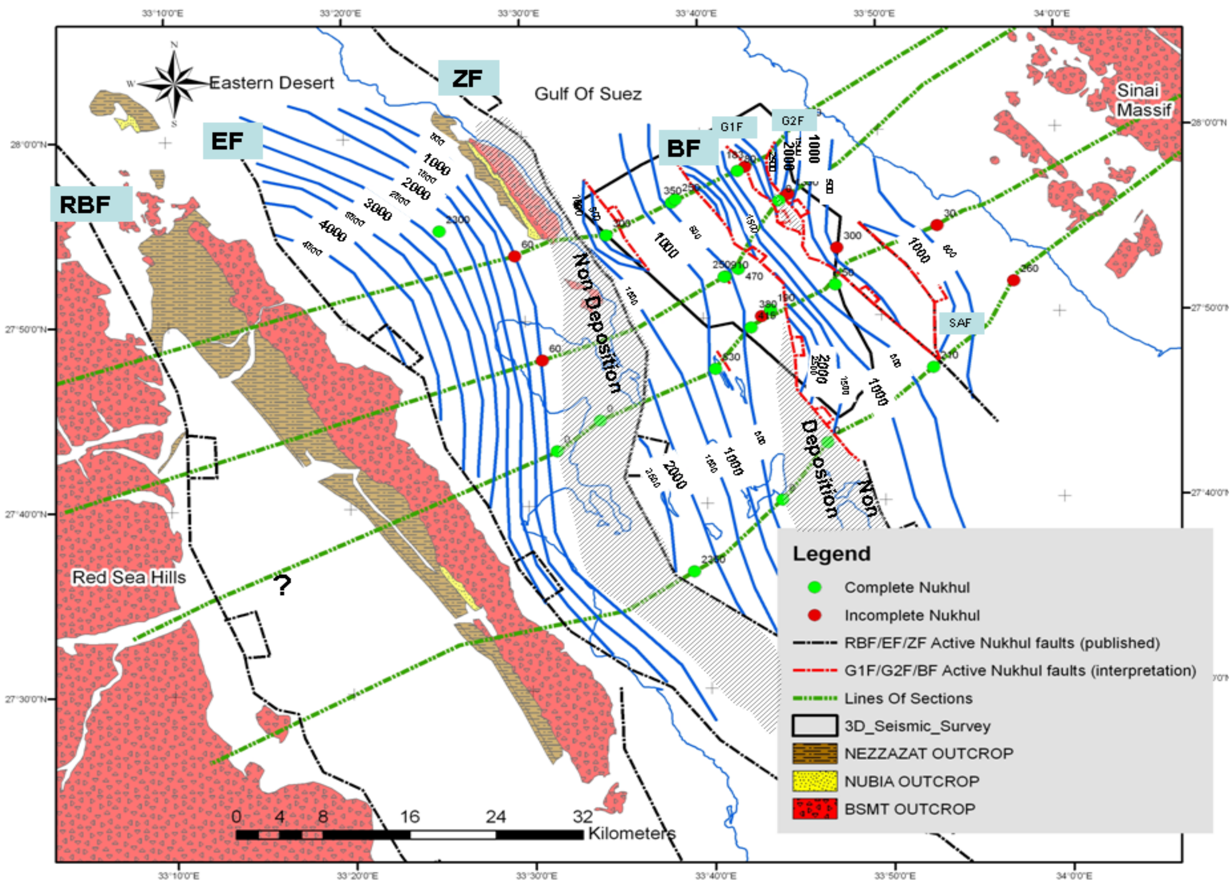

Figure (6): Nukhul Formation isopach map (values in feet) showing the effect of early rift faults. The main faults shown on the map are RBF: rift-bounding fault; EF: Esh El-Mellaha Fault; ZF: Gebel El Zeit fault; BF: B-trend fault; G1F: Ghara Fault 1; and G2F: Ghara Fault 2.

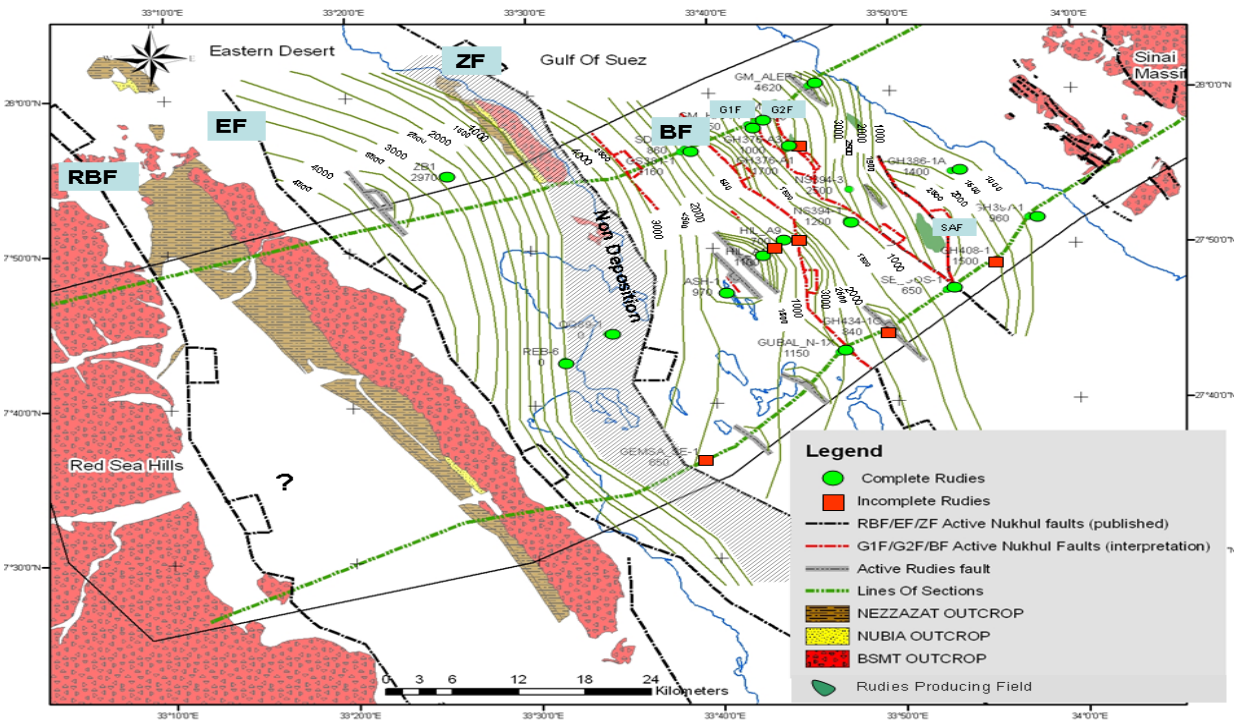

Figure (7): Rudies Formation isopach map (values are in feet) showing the effect of early rift faults. The main faults shown on the map are RBF: Rift-Bounding fault; EF: Esh El-Mellaha Fault; ZF: Gebel El Zeit fault; BF: B-trend fault; G1F: Ghara Fault 1; G2F: Ghara Fault 2.

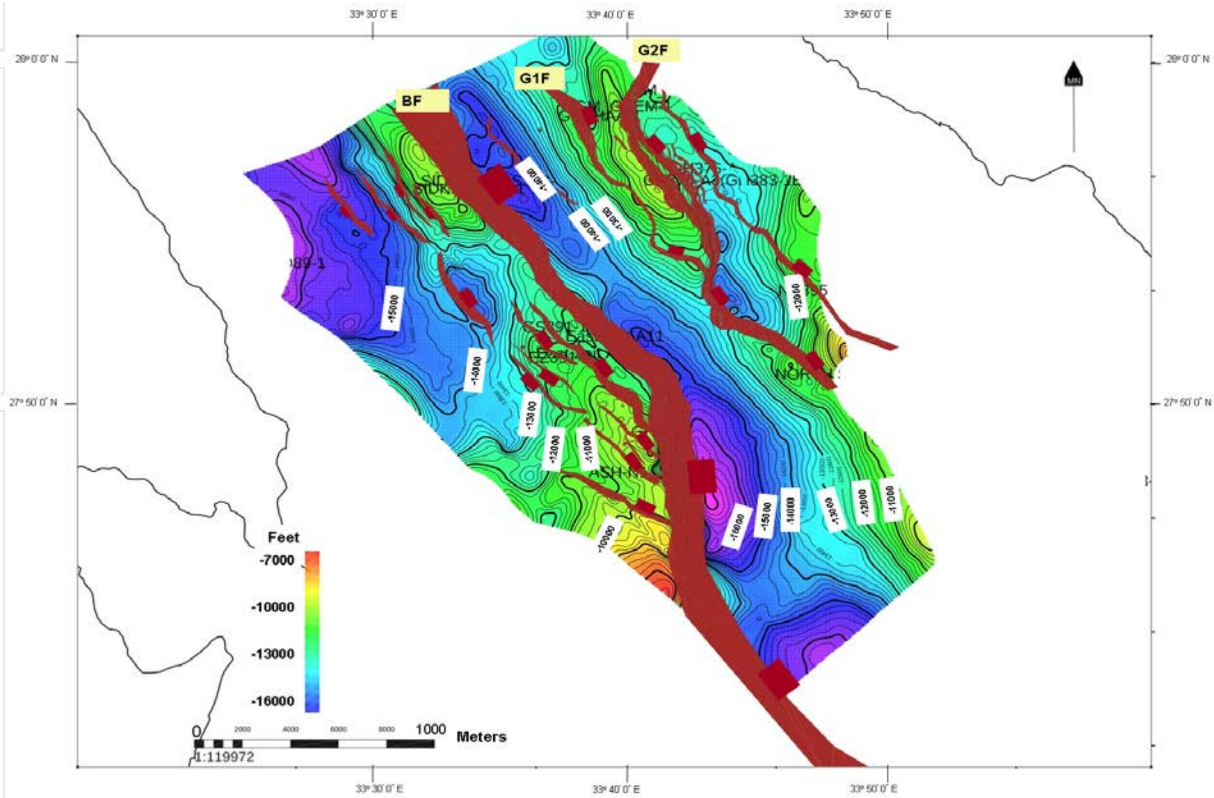

Figure (8): Basement depth structure map, driven from seismic interpretation, CI = 200 ft. Fault names are the same as in Figure 7.

5. Structural Evolution

Restoring or balancing a structural section is important to improve the understanding of the structural evolution of an area. Since the deformation is assumed to neither create nor destroy rock volume; thus, reassembling the undeformed state from the deformed state is possible. Balancing assumes conservation of rock volume during deformation, therefore any changes in volume must be quantitatively assessed. However, a valid model may not balance. Lack of rock volume may be caused by processes such as erosion, sediment compaction, tectonic compaction, pressure solution, and elongations along orogenic strike. Therefore, when assessing the validity of an interpretation, these processes need to be considered (Hossack, 1979).

The two cross sections in Figure 9 have been restored using the inclined shear method in 2D Move software. The workflow allowed the geological horizons to be restored to a pre-deformation datum, which is the sea level. This method allows the preservation of the volume between the deformed and un-deformed states.

The structural sections (Figures 11 and 12) were restored to the top Nukhul Formation and the top of Kareem Formation, to see which faults were active during the early rifting stages and how the dip angles of the pre-Miocene rocks progressed with time. The red colored faults are the faults that were initiated early at the Nukhul time. Theses faults were responsible for rotating the early rift major blocks, which in turn resulted in erosion of the pre-Miocene section at the updip edges of the fault blocks and non deposition of the Nukhul Formation. These faults continued activity till the evaporites section deposition. The pre-Miocene blocks increase in dip angle as the time progresses and the rotation on the old faults increases. The two restored sections (Figures 11 and 12) show that the present-day dip angles of the pre-Miocene blocks are steeper than the block angles at the Nukhul Formation time and the Kareem Formation time.

Regional extension estimates have been calculated for the two sections (see Figures 11 and 12) at Nukhul time, Kareem time and the present-day, by measuring the initial length of the restored section L_o), the final extended length of the present day cross section (L_f) by summing the gaps between the offset layers (i.e. the heaves) in the present-day cross section and adding the result to the initial restored cross section length (L_o) and then calculating the extension factor (β) as: $\beta = 1 + (L_f - L_o) / L_o$ (Gibbs, 1983). The extension factor (β) for the northern cross section is calculated to be 1.1 at the end of the Nukhul Formation time then it increased to reach 1.36 at the end of the Kareem Formation time and it is 1.43 at the present day (Figure 11). The southern cross section shows more extension values than the northern cross section, where the extension factor (β) at the end of the Nukhul Formation time is 1.2, at the end of the Kareem Formation time is 1.5, and reaches 1.7 at the present day (Figure 12).

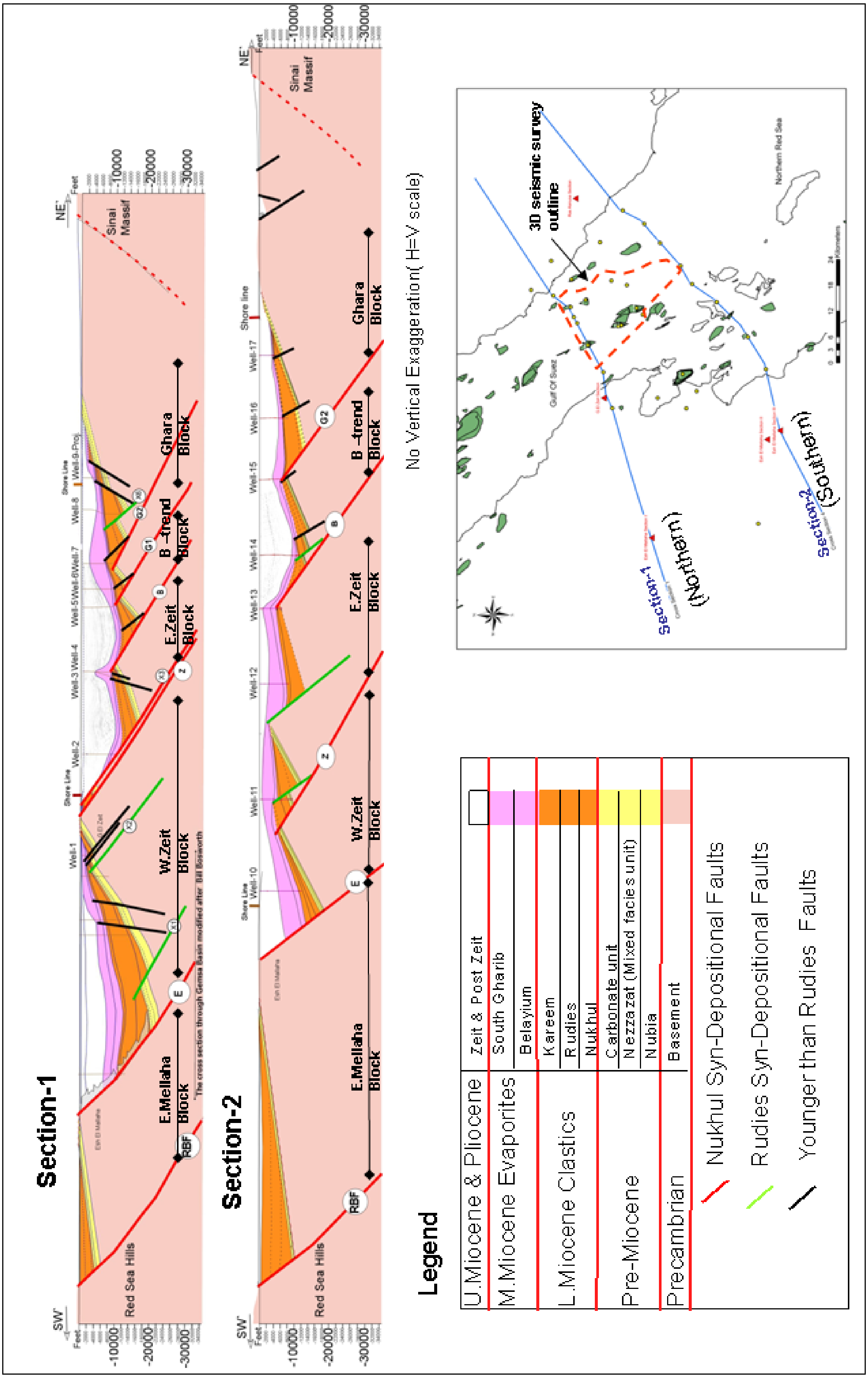

Figure (9): Structural cross sections through the area of study.

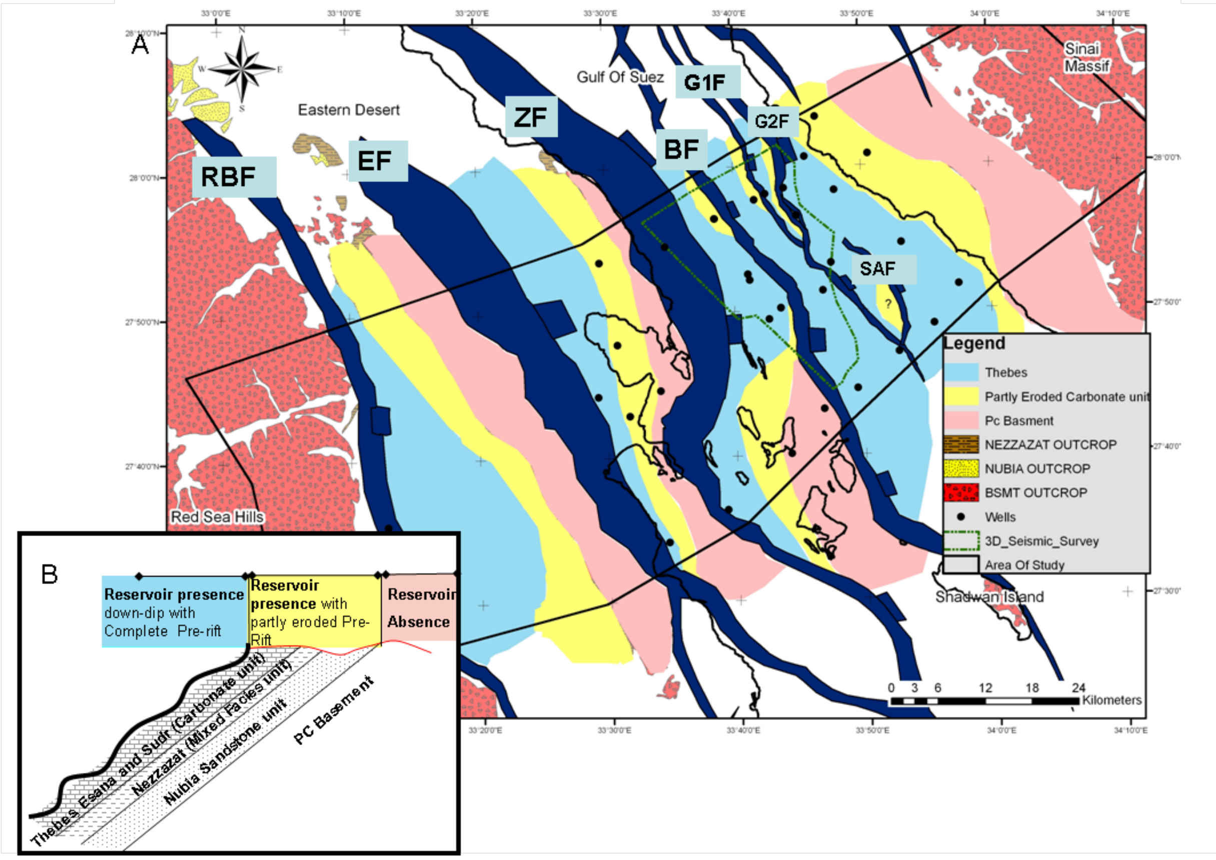

Figure (10): A: Miocene sub-crop map, B: Schematic section illustrating the anticipated formations below the Miocene section.

6. Hydrocarbon Exploration

Understanding the structural evolution is very important in exploring for hydrocarbons, especially in South Gulf of Suez, where the extension is at the maximum and the amount of block rotation is significantly high and can reach up to 40-45 degrees.

Figure 13 shows the major risks associated with the prospects in the Southern Gulf of Suez and their potential failure mode. Whereas on the crests of the tilted blocks close to the bounding faults, which witnessed great amount of rotation, the risks of reservoir preservation or erosion of the local top seal for the Nubia Sandstone (Sudr, Esna and Thebes Formations) are pretty high.

Preserving the Nubia Sandstone reservoir and / or the local Nubia Sandstone top seal at the edges of the tilted fault blocks are primarily constrained by the age of the fault bounding the block this in turn links to the amount of rotation that, this block has undergone through the progressing of rifting. So knowing the age of the block bounding fault and the amount of rotation are very critical and can mitigate the risk of hydrocarbon Exploration in the Southern Gulf of Suez.

7. SUMMARY AND CONCLUSIONS

400 km^2 of post-stack depth migrated 3D seismic data, 35 wells and 5 surface sections have been used in the study to demonstrate the structural setting and the evolution of the southern part of the Gulf of Suez and their impact on the hydrocarbon exploration in this part of the basin.

Structurally and /or stratigraphically missing sections in wells have been identified through well correlation. Isopach maps have been constructed to illustrate the relationship between the tectonics and the sedimentation.

Constructing isopach maps for the sedimentary section and Miocene subcrop mapping along with 3D seismic mapping allowed the construction of structural sections that were restored and balanced at different startigraphic levels to reveal fault history, amount of block rotation and preservation of pre-rift section at the updip edges of the fault blocks. The restoration helped in the better understanding of tectonic evolution that has an impact on hydrocarbon exploration as it helps in predicting the reservoir presence at the edges of tilted blocks and defining trap geometry.

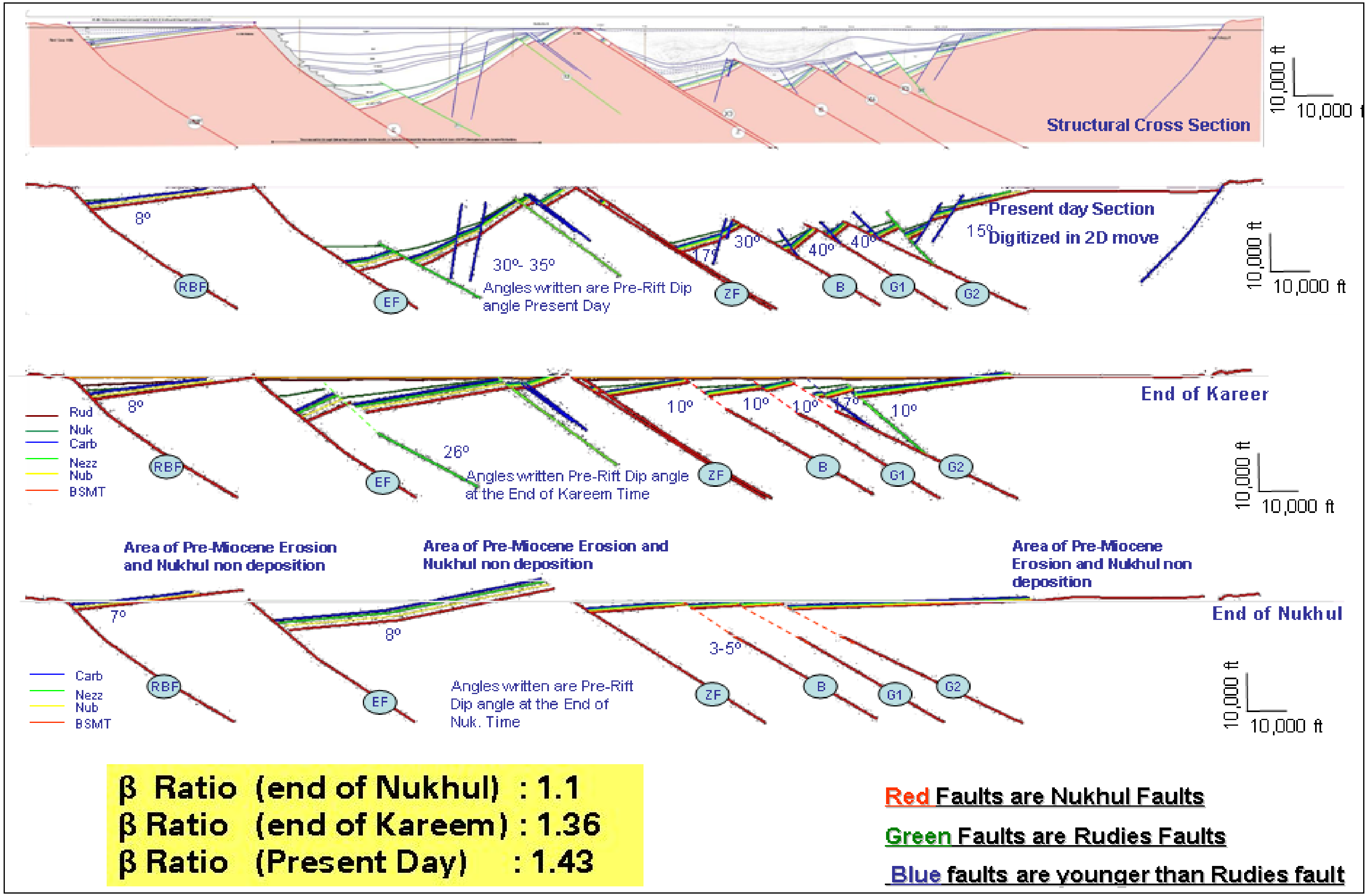

Figure (11): Restoration of the Northern Section (at end of Nukhul time and at end of Kareem time). Colors define the following formations: Red (top Basement), Yellow (top Nubia), Green (top mixed facies unit), Blue (top Carbonate unit

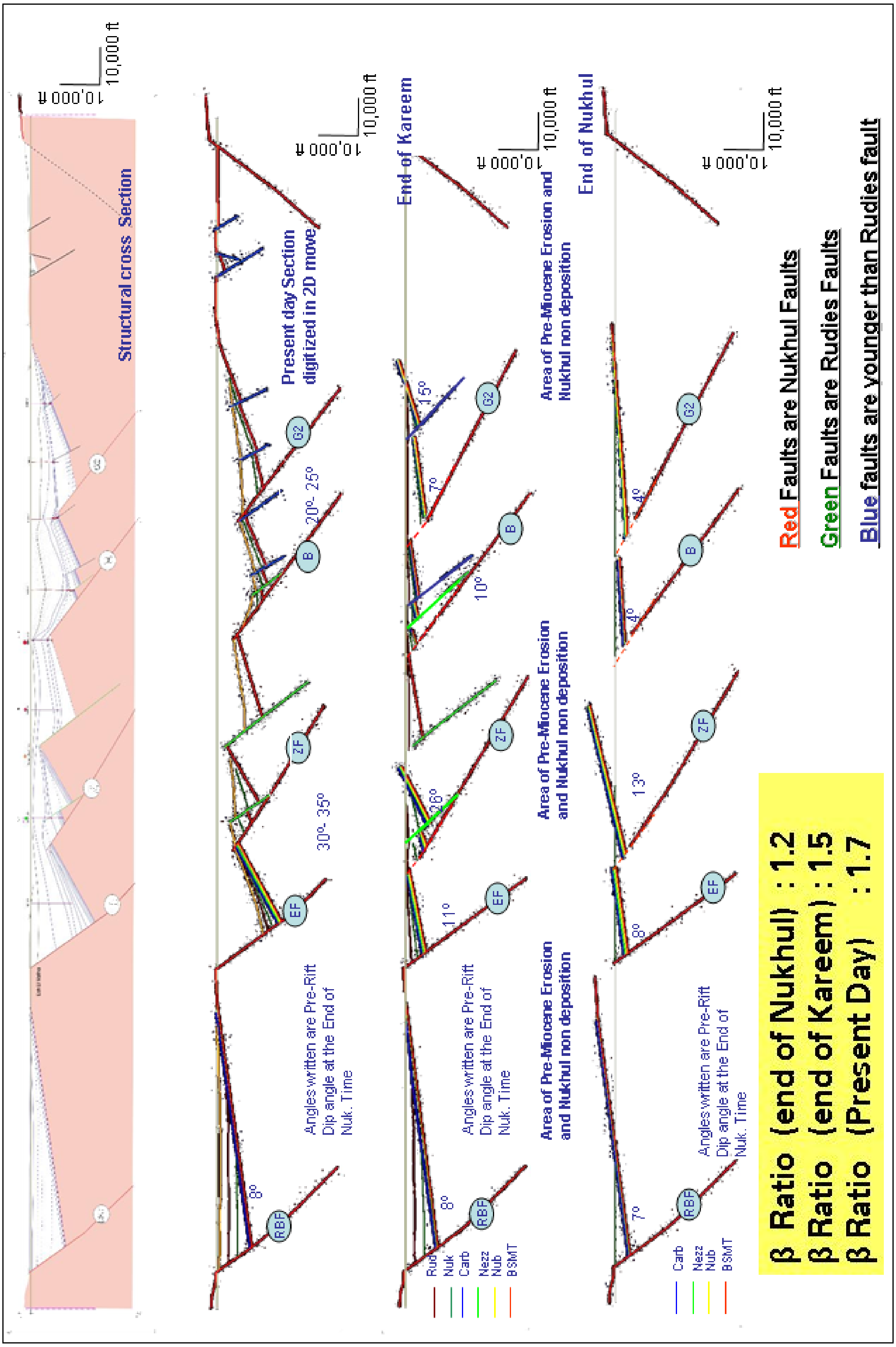

Figure 12. Restoration of the Southern Section (at end of Nukhul time and at end of Kareem time). Colors define the following formations: Red (top Basement), Yellow (top Nubia), Green (top mixed facies unit), Blue (top Carbonate unit).

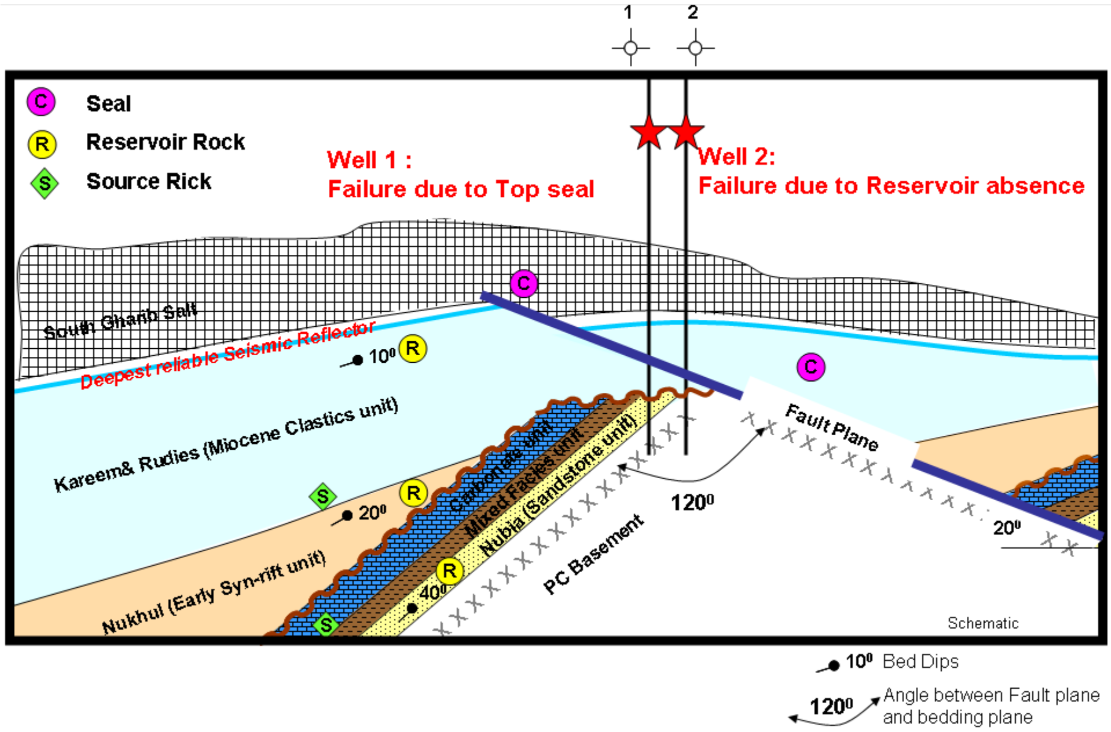

Figure (13): Diagram showing the risk of drilling dry holes at the edge of a tilted fault block and geometry of the pre-rift block in relation to the Miocene.

REFERENCES

ABOUL KARAMAT, 1987. - Geological Studies on the sedimentary succession of Esh El-Mellaha Range. M.Sc thesis, Cairo University.

BALLY, A. and ROBERTS, D.G. 2010.- Phanerozoic Regional Geology of the World. Elsevier Science and Technology.

BOSWORTH, W., 1994.- A model for the three-dimensional evolution of continental rift basins, north-east Africa. In: H. Schandelmeier and R.J. Stern (Eds.), Geology of Northeast Africa (part 2), Geol. Rundsch., 83: 671-88.

BOSWORTH, W., 1995.- A high- strain rift model for the southern Gulf of Suez (Egypt). In: J.J. Lambiase (Ed.), Hydrocarbon Habitat in Rift Basins, Geol.Soc. London Spec. Publication 80: 75-112.

BOSWORTH, W. and MCCLAY, K., 2001.- Structural and stratigraphic evolution of the Gulf of Suez rift, Egypt: A synthesis. In: P.A. Ziegler, W. Cavazza.

BOSWORTH, W., GUIRAUD, R., and KESSLER, L.G., 1999.- Late Cretaceous (+84 Ma) compressive

deformation of the stable shelf of NE Africa (Egypt): far-field stress effects of the “Santonian event” and origin of the Syrian arc. Geology, 27: 633-636.

COFFIELD, D.Q. and SCHAMEL, S., 1989.- Surface expression of an accommodation zone within the Gulf of Suez rift, Egypt. Geology, 17: 76-79.

DART, C., COHEN, H.A., SERDAR AKYUZ, H. and BARKA, A., 1995.- Basin ward migration of rift border faults: Implications for facies distributions and Preservation Potentiality. Geology, 23:69-72

EL AYOUTY, M.K., 1990.- Chapter 27 : Petroleum geology. In: R. Said (ED.), The Geology of Egypt, A.A. Balkema, Rotterdam, 567-599.

EVANS, A.L. and MOXON , I.W., 1986.- Gebel Zeit chronostratigraphy: Neogene syn-rift sedimentation atop a long-lived paleohigh. Proceedings of 8th Exploration Conference, Egyptian General Petroleum Corporation, Cairo, November 1986, 1: 251-65.

GIBBS, A.D., 1983. Balanced cross-section construction from seismic sections in areas of extensional tectonics. In Structural Concepts and Techniques I. American Association of Petroleum Geologists. Treatise of Petroleum Geology Reprint Series, No. 9. p.679-686.

HASSAN, M.A. and HASHAD, A.H., 1990.- Chapter12, Precambrian of Egypt. In: R. Said (Ed.), The Geology of Egypt. A.A. Balkema, Rotterdam, PP. 201-245.

HELMY, H.M, 1990.- Southern Gulf of Suez, Egypt: structural geology of the B-trend oil fields: Classic petroleum province, Geological Society special publication No 50, p. 353-363.

HOSSACK , J., 1979.- The use of balanced cross-sections in the calculation of orogenic contraction:

A review Journal of the Geological Society, London 136: 705-711.

JARRIGE, J. J,. OTT D' ESTEVOU,P., BUROLLET, P.F., MONTENAT, C., PRAT, P., RICHERT, J.-P., and THIRIET, J.P., 1990.- The multistage tectonic evolution of the Gulf of Suez and northern Red Sea continental rift from field observations. Tectonics, 9: 441-465.

MORETTI, I. and COLLETTA, B., 1987.- Spatial and temporal evolution of the Suez Rift Subsidence. J. Geodynamics, 7: 151-168.

MOUSTAFA, A.M., 1976.- Block faulting of the Gulf of Suez. Presented at 5th Exploration Seminar , Egyptian General Petroleum Corporation, Cairo, 19 p.

MOUSTAFA, A.R., 2002.- Controls on the geometry of transfer zones in the Suez rift and northwest Red Sea: Implications for the structural geometry of rift systems. American Association of Petroleum Geologists Bulletin, 86: 979-1002.

MOUSTAFA, A.R., AND HELMY, H.M., 1985.- Structural setting of the Ras Kenisa area, southwest Sinai. Unpublished GUPCO internal report.

PATTON, T.L., MOUSTAFA, A.R., NELSON, R.A., and ABDINE, S.A., 1994.-Tectonic evolution and structural setting of the Suez Rift. In: S.M. Landon (Ed.), Interior rift basins, American Association of Petroleum Geologists Mem. 59: 7-55.

RICHARDSON, M. and ARTHUR, M.A., 1988.- The Gulf of Suez-northern Red Sea Neogene rift: a quantitive basin analysis. Marine and Petrol. Geol., 5: 247-70.

STECKLER, M.S., BERTHELOT, F., LYBERIS, N. and LE PICHON, X., 1988- Subsidence in the Gulf of Suez: implications for rifting and plate Kinematics. Tectonophysics, 153: 249-70

STERN, R.J. and HEDGD, C.E., 1985.- Geochronologic and isotopic constraints on late Precambrian crustal evolution in the Easter Desert of Egypt. American Journal of Science, 285: 97-172.

WINN, R.D., CREVELLO, P.D., and BOSWORTH, W., 2001.- Lower Miocene Nukhul Formation of Gebel el Zeit, Egypt: sedimentation and structural movement during early Gulf of Suez rifting: American Association of Petroleum Geologists Bulletin, 85: 1871-1890.

YOUNES, A.L. and MCCLAY, K.R., 2002.- Development of accommodation zones in the Gulf of Suez- -Red Sea rift, Egypt. American Association of Petroleum Geologists Bulletin, 86: 1003-1026.