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Original Article

Insights on the hydrocarbon possibilities of the offshore Egyptian Red Sea margin

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ABSTRACT

The Egyptian Red Sea basin has been the focus for several oil and gas exploration efforts, that started in the last century's mid-seventies, until the early millennium. However, due to the limited number of wells, relative to its vast untested area, it can be considered an underexplored basin. Evidence of working hydrocarbon systems in the basin have been observed and documented onshore and offshore by some of the wells drilled along the Egyptian and Saudi margins. Information from the drilled wells support the presence of good quality source and reservoir rocks, in addition to having several oil and gas shows, that support charging from thermally mature source rock(s). Furthermore, oil seeps have been documented in other parts of the basin in Ethiopia-Eretria and the offshore Yemen in the southern Red Sea basin, where the rift extension is greater. The syn- and pre-rift petroleum systems have been proven north of the Red Sea, in the Gulf of Suez basin, which represents the northern arm of the Red Sea-Gulf of Aden rift system. The Gulf of Suez basin has been explored and produced hydrocarbon since 1886 and can be used as, an analogue for the petroleum systems elements, such as source and reservoir rocks, and trapping mechanism. In this paper, integrating well information and the available mid-seventies 2D seismic lines, we were able to highlight the hydrocarbon possibilities of the western margin of the Egyptian Red Sea basin. Two potential play fairways and trapping styles have been described along the northern Egyptian Red Sea margin. They are mainly syn-rift Miocene Clastics and probable pre-rift fairways, similar to the Gulf of Suez petroleum system elements. However, due to the uncertainties in the stratigraphic correlation between the different rock units between the Northern Red Sea and Southern Gulf of Suez and the limited offshore well penetrations in the Northern Red Sea these fairways have source and reservoir rocks distribution and quality uncertainties. The presence of thick and mobile evaporites sequence in the syn-rift section, provides the ultimate top seal for the identified fairways.

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1. Introduction

Several unsuccessful exploration activities were made in the Egyptian Red Sea offshore basin in the last few decades. Due to the shared tectonic evolution and rifting history between the Gulf of Suez and the Red Sea, several oil companies thought that, the success made in the Gulf of Suez hydrocarbon exploration since the 19th century, can be continued in the Northern Red Sea. However, seismic data quality, coupled with the increased geologic and structural complexity, as a result of the increased extension rate, have made the exploration efforts more challenging than the proven Gulf of Suez basin. Subsequently, the hydrocarbons exploration efforts can be considered in the early stages of fully evaluating the potential of the offshore Northern Red Sea.

In this paper, we utilized 2D seismic data, well information and outcrop data of the western onshore area (Fig.1), to highlight the hydrocarbon possibilities of the Northern Red Sea, and to identify the potential play fairways and trap types. We also made an overview about the main petroleum system elements in the Gulf of Suez, since it is used as the main analogue for the Red Sea

2. Geologic setting:

The Gulf of Suez-Red Sea rift basin was formed, as a result of the separation of the Arabian plate from the African plate during the Late Oligocene to Early Miocene, through a regional north- eastward normal extension (Patton et al., 1994 and Bosworth et al., 2005). It represents one arm of the Afar Triple junction, where the Gulf of Aden, Red Sea and the East African Rift converge.

The Afar region forms a topographic depression, where a mantle plume started the rifting process at ~ 30 Ma. It is located at the intersection of successful opening of oceanic basins along two rift arms, the Gulf of Aden and the southern Red Sea, where seafloor spreading and oceanic crust formation started at 17 My and 5ma respectively (Roeser, 1975 and LeRoy et al., 2004). While the East African rift system is considered an intra-continental ridge system, comprising an axial rift, where the break-up into oceanic basin has not yet occurred (see references in Chorowicz, 2005). The Southern Red Sea rift basin is characterized by an axial rift valley floored by oceanic basalt and extends north to about 19.5°N (Roeser, 1975 and Cochran, 1983) where a fracture zone displaces the oceanic crust (Bosworth, 2015). The northern part of the Red Sea basin, beyond the Zabargad island and the Gulf of Suez, did not develop oceanic crust and are floored by continental crust, as proved by well penetrations in the present study, which are bottomed in granitic basement. About 30 -40 km of extension occurred in the Southern Gulf of Suez (Patton et al., 1994, Bosworth et al., 2005 and Afifi et al., 2016), and it is basically a failed continental rift that remains floored by continental crust, with a complex extensional system of blocks that have rotated along low-angle or listric fault planes (Bosworth et al., 2005), with three distinct depocenters for sedimentation.

The formation of the Gulf of Aqaba left-lateral transform fault system in the Middle Miocene, isolated the Gulf of Suez from the active Northern Red Sea rift (Steckler et al., 1988, Cochran, 2005, Bosworth et al., 2005) and led to the switch from orthogonal rifting to oblique rifting and hyper extension in the Northern Red Sea (Bosworth et al., 2020). It also marked the transition in the syn-rift sedimentary section from predominately clastics deposition to mainly evaporites deposition. Since the Middle Miocene, the extension of the Northern Red Sea is linked to the Gulf of Aqaba strike-slip fault system and is still experiencing rifting at present-day as indicated by the active seismicity (Bosworth et al., 2020) and the extensional faults displacing the sea floor in the present study. Such extensional faults and active seismicity have been recorded present-day in the Northern Red Sea, Southern Gulf of Suez and Gulf of Aqaba, as evident by the instrumental earthquake records.

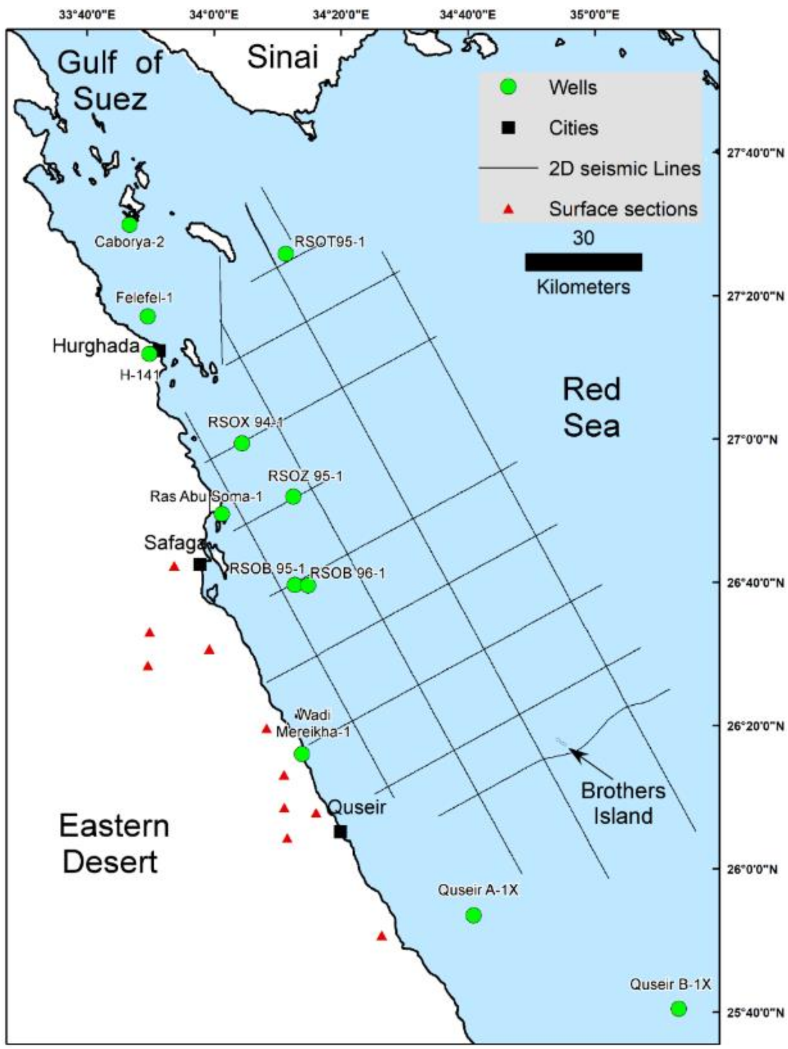

Fig. 1: Map of the study area showing surface sections, wells, and the available seventies 2D seismic ventage used in the study.

3. Stratigraphic framework of the Study area:

The sedimentary section of the Egyptian margin of the Northern Red Sea resembles the Southern Gulf of Suez basin and includes syn- and pre- rift stratigraphic units. The stratigraphic subdivisions used in the present study (Fig. 2) are obtained from the available well information and from publications (Khalil and McClay 2001, Afifi et al., 2016 and Moustafa and Khalil, 2020) and were generated by correlating the time stratigraphic units in the Northern Red Sea and Southern Gulf of Suez.

The pre-rift stratigraphic sections in the Northern Red Sea and Southern Gulf of Suez, are similar and consist of three main units, that are informally referred to as, Nubia Sandstone, mixed facies unit and carbonate unit (Afifi et al., 2016). These units are well exposed on both sides of the Gulf of Suez, as well as in the NW onshore area of the Egyptian Red Sea (see Moustafa and Khalil, 2020, for surface geologic map). The Nubia Sandstone ranges in age from Palaeozoic to Albian in Southern Gulf of Suez (Aboul Karamat, 1987 and Moustafa and Khalil, 2020), while it is Turonian-Coniacian in the Northern Red Sea (Khalil and McClay, 2001). The Mixed facies unit comprises the Upper Cretaceous (Cenomanian to Santonian) Raha, Wata and Matulla formations in the Southern Gulf of Suez and Quseir and the lower part of the Duwi formations in the Northern Red Sea. Those units in the Northern Red Sea are Coniacian to Santonian in age. The Carbonates unit (Campanian to Eocene in age) consists of Sudr, Esna and Thebes formations in the Southern Gulf of Suez and the upper Duwi, Dakhla, Esna and Thebes formations in the Northern Red Sea. Due to the change in facies, similarity in the published informal formation names, the different published assigned ages of both units from the southern Gulf of Suez to the northern Red Sea and the lack of high resolution biostratigraphic data, the Nubia Sandstone and the mixed facies units have been combined and referred to as Clastics unit in this paper.

Moreover, none of the offshore wells drilled in the Egyptian Red Sea margin encountered the pre-rift sedimentary section. However, several onshore wells in the Northern Red Sea area penetrated a pre-rift section, such as Ras Abu Soma-1 well, which penetrated 230 m of the pre-rift Clastics overlying the Precambrian granitic basement. In general, the pre- rift stratigraphic units form a wedge, that thins towards the south in the southern Gulf of Suez and increases in thickness again toward the south beginning just north of Hurghada field, as recorded from the onshore measured exposed stratigraphic sections (Peijs et al., 2012 and Afifi et.al., 2016) (Fig. 3). This sedimentary section is interpreted to have been deposited during a platform phase, that covered most of Northern Egypt, contemporaneous with the Early Mesozoic Neo-Tethys rifting and lasted until the end of Early Cretaceous (Moustafa, 2020).

The Miocene syn-rift section was penetrated by all the wells drilled onshore and offshore in the Northern Red Sea. It can be subdivided into three main units: Miocene Clastics, Miocene Evaporites and post Evaporites. The Miocene syn-rift clastics unit is composed mainly of sandstone, shale and minor limestone. The Miocene evaporites unit is predominantly salt and anhydrite, with intercalation of sand, shale, and carbonate units. This unit exhibits salt-related structures and act as a detachment surface for post evaporite sequence faulting, which is related to the active ongoing extension in the Red Sea and led to salt withdrawal features. It also impacts the seismic data quality since, imaging of the subsalt structures is challenging. The post evaporites unit is predominately composed of clastics, with thin evaporites and carbonates.

4. **Structural setting of the study area:**

The main structural elements and faults at the crystalline basement level in the Northwestern Red Sea and Southern Gulf of Suez are shown in figure 4. These elements are compiled from Afifi et al., 2016 in the Southern Gulf of Suez and mapped from the available 2D seismic lines in the northwestern Red Sea, in addition to compilation of the exposed faults, as published by Patton et al, 1994, Khalil and McClay, 2001, Ligi et al., 2018 and Moustafa and Khali, 2020. Due to the presence of salt and the antiquity of the data, the seismic quality is suboptimal. However, the dip of the major faults and the tilted blocks were interpreted on these data and integrated with well and outcrop information. The three offshore wells (RSOT 95-1, RSOX94-1 and RSOB-96-1), which penetrated the crystalline basement, were tied to the seismic lines to map the top basement. To the east and south of the current well control, a sub-horizontal to gently dipping reflector marking the top of a chaotic package, was interpreted as top basement (Fig. 5). The mapped geometries of salt structures in the Miocene evaporite unit were also used to infer the sub-salt basement structures, that controlled salt evacuation. In the northern part of the study area, the mapped extensional faults trend northwest-southeast and have the same polarity, as the Southern Gulf of Suez, where most of the faults dip to the northeast while the fault blocks dip to the southwest. The faults, that cut all the stratigraphic section down to the crystalline basement, are mostly planner with domino style and well developed thick syn-rift stratigraphy in their hanging walls.

The seismic line in figure 5 shows that, the seafloor is displaced and offset by series of faults, that form the typical negative flower structure which is probably associated with strike-slip movement. This negative flower structure is characterized by a synform structure and normal fault separations, that are bounded by upward branching strands of a wrench fault, with mostly normal separations. These negative flower structures are interpreted to be associated with the left-lateral strike-slip movement of the Gulf of Aqaba transform in the mapped area.

A major down to the east fault is mapped, close to the western limit of the seismic data, that is parallel to the coastline.

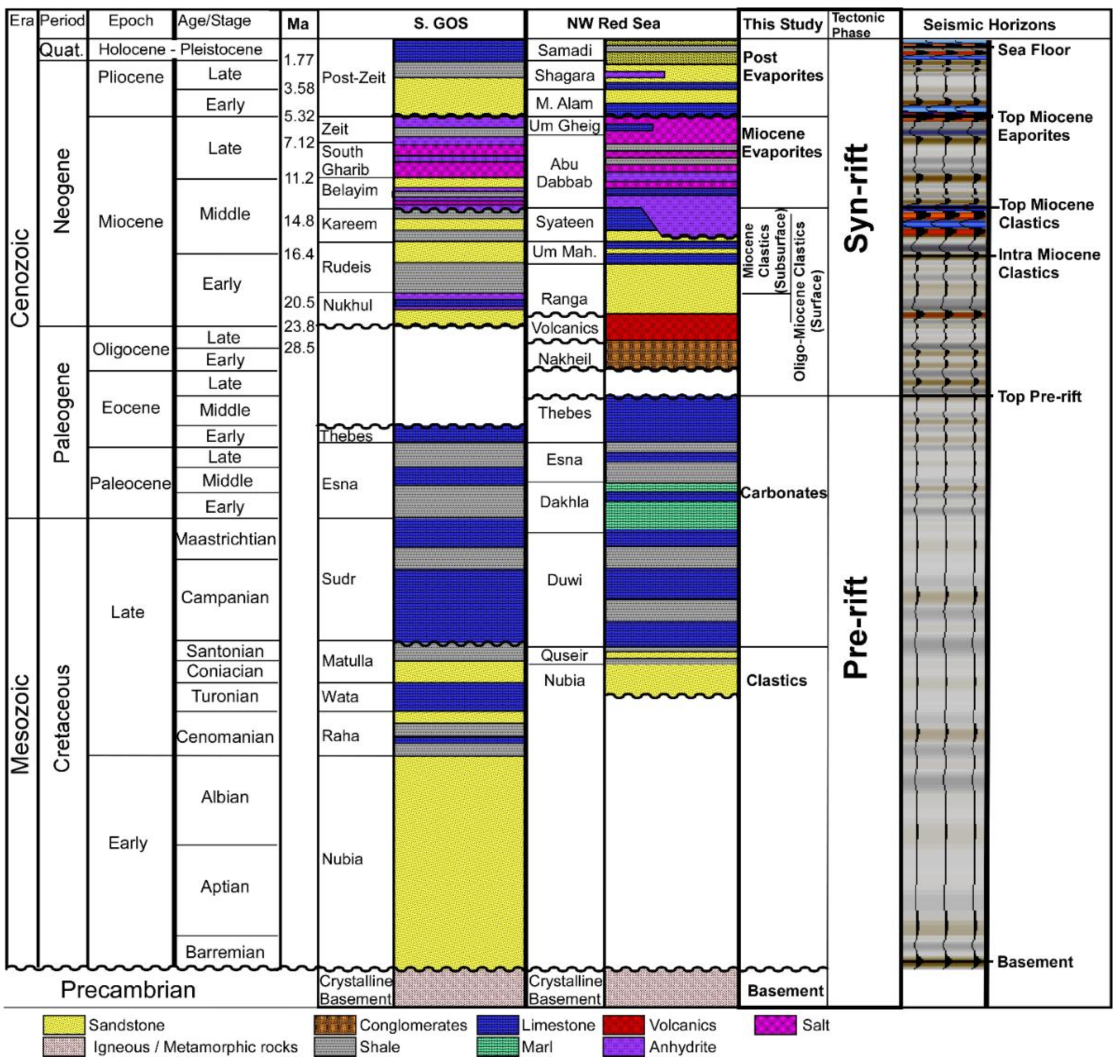

Fig.2: Stratigraphic framework and tectonic phases of the northern Red Sea and southern Gulf of Suez used in this study. Major mapped seismic reflectors. Lithologic and stratigraphic information of the southern Gulf of Suez is from

Afifi et al., (2016), of the NW Red Sea is from wells used in the present study, Khalil and McClay (2001) and Moustafa and Khalil (2020). Absolute dates of the Oligocene – Neogene section is from Youssef (2011).

The footwall of this fault is believed to have been penetrated by Ras Abu Soma well, which was drilled onshore and encountered the top of Miocene Clastics unit at 800 meters' depth (Fig. 6). The hanging wall of the fault was penetrated by RSOZ95-1 well, where the Miocene Clastics section was encountered at 3400 meters' depth, which indicates a vertical separation of around 2600 meters across this fault system. We have termed this fault, the continental shelf fault system, due to its proximity to the coastline and the abrupt change in bathymetry across it. The continental shelf fault system, in our study, extends along the western part of the offshore area of interest. However, due to the lack of wells in the southern area no vertical separation values were estimated.

Pliocene -Recent supra-salt rift related faulting, impacting the Miocene evaporites and post evaporites units, was observed in the seismic lines across the Northern Red Sea (e.g., Figures 5). These faults have listric surfaces and have been decoupled from the pre-salt faulting through salt and evaporites sequence and represent the continuation of regional extension after the end of the Miocene evaporites unit deposition. These extensional fault systems sole-out at the base of the evaporites section, accommodating the post-Miocene clastics loading and leading to the salt mobilization, salt withdrawal and salt-cored antiformal structural style within the Miocene evaporites unit. This evaporites unit acts as a shallow detachment system, that decapitates many of the deeper structures (Stockli and Bosworth, 2019 and Bosworth et al., 2020). This detachment system within the Miocene evaporites unit has also been observed in the Midyan region along the Saudi margin of the Red Sea (Mougenot and Al-Shakhis, 1999). This is significantly different from the Southern Gulf of Suez (Afifi et al., 2016), where such recent extensional faults are not observed, mainly due to the decrease in extensional rates by the Middle Miocene to Pliocene time because of the development of the Gulf of Aqaba Fault.

At the southern part of the study area, the seismic data indicate that, the dip direction of the main faults changes south of the Duwi accommodation zone, to be mainly southwest (Fig. 7). The change of the fault dip direction south of the Duwi Accommodation zone was also mapped in the onshore area (Moustafa, 1997, Khalil and McClay, 2001 and Younes and McClay, 2002).

As observed in the northern part of the study area, the Miocene syn-rift Clastics unit is preserved in the western part of the area, while they disappear to the east, in which the younger Miocene evaporites unit overlies the crystalline basement. The southern seismic lines also show the continuation of the recent (post evaporites unit) faulting, that detach at the base evaporites. Closer to the southern end of the study area, most of the major structures display the same dip regime observed south of the Duwi accommodation zone with more prominent basement highs, that reflect significant footwall uplift, forming the substrate of the Brothers Islands. Seismic mapping of the study area indicates the increase in the Pliocene-Recent faulting activity and the increase in the thickness of the Miocene syn-rift evaporites unit east of the continental shelf fault system. While both the early syn-rift Miocene clastic units and the later syn-rift Miocene evaporites units are present on the western side of the study area, to the east the Miocene evaporites unit, directly overlying the crystalline basement. Quseir B- 1X, well which was drilled in the southeastern part of the area of study, penetrated the Miocene evaporites over the basement. This suggests that, through time, rift faulting has become focused inward and is progressively younger towards the rift axis. This resulted in a depocenter of the Miocene evaporites toward the center of the basin. This is consistent with the observations from other rifted margins such as the Iberia-

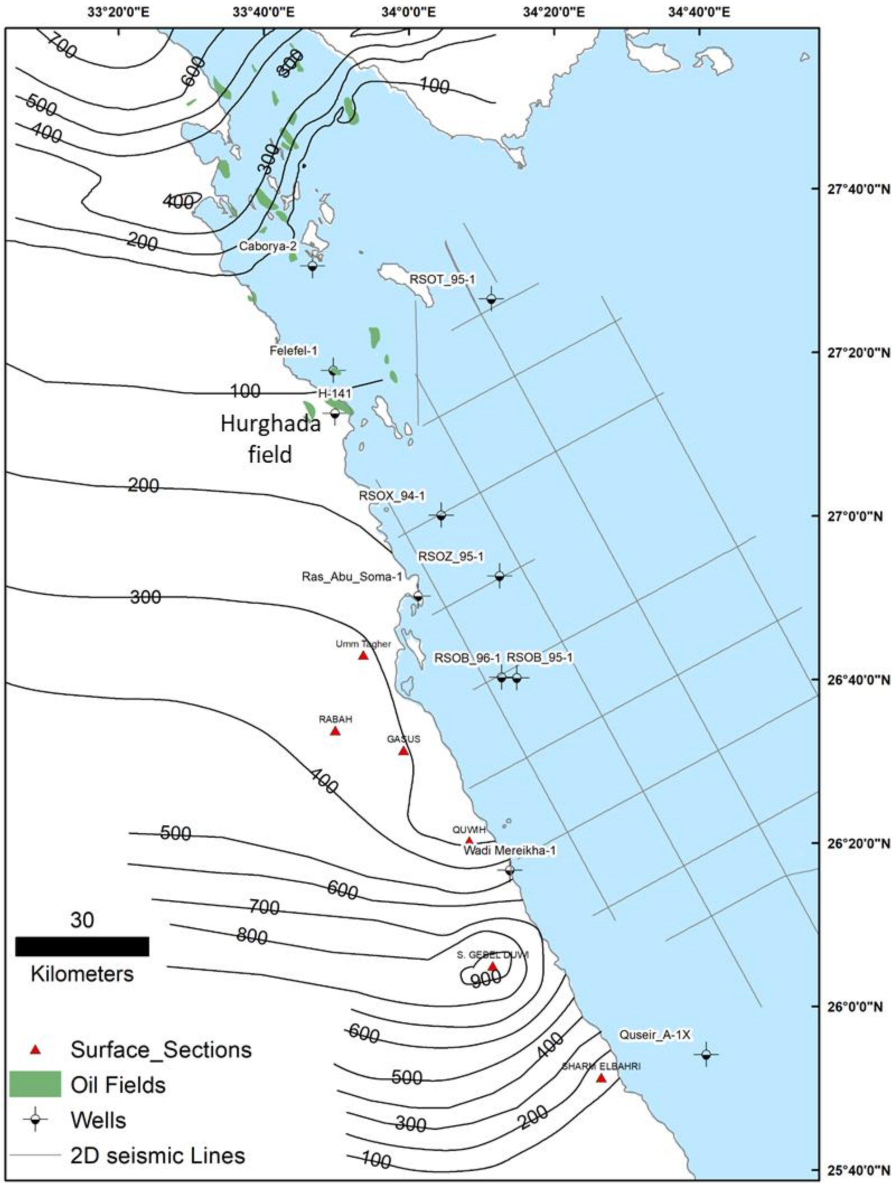

Fig. 3: Isopach map of the pre-rift clastics unit in the study area showing the gradual decrease in thickness south of the Gulf of Suez and the gradual increase in thickness towards the Red Sea. Surface sections' thickness values are after Helmy (2018). Contour values are in meters.

Newfoundland margin (Whitmarsh and Manatschal, 2012), where the rifting is propagated basin ward, eventually resulting in break-up, forming new oceanic crust. It is also consistent with the Red Sea onshore surface mapping, where the coastal fault system appears to have been active later than the border faults system, as documented by Khalil and McClay 2001.

5. Gulf of Suez Petroleum systems elements:

The Gulf of Suez rift is one of the world class hydrocarbons-bearing basins. Significant hydrocarbon discoveries made in the Suez rift, since the beginning of the last century established the Gulf of Suez as a significant hydrocarbon province. Below is a summary of the Source, reservoir and Cap rocks in the Southern Gulf of Suez, along with the trapping styles. The other petroleum system elements, such as the source rock maturation, hydrocarbons generation, migration and the timing of the trap formation, are not included in the summary below and are out of the scope of the paper.

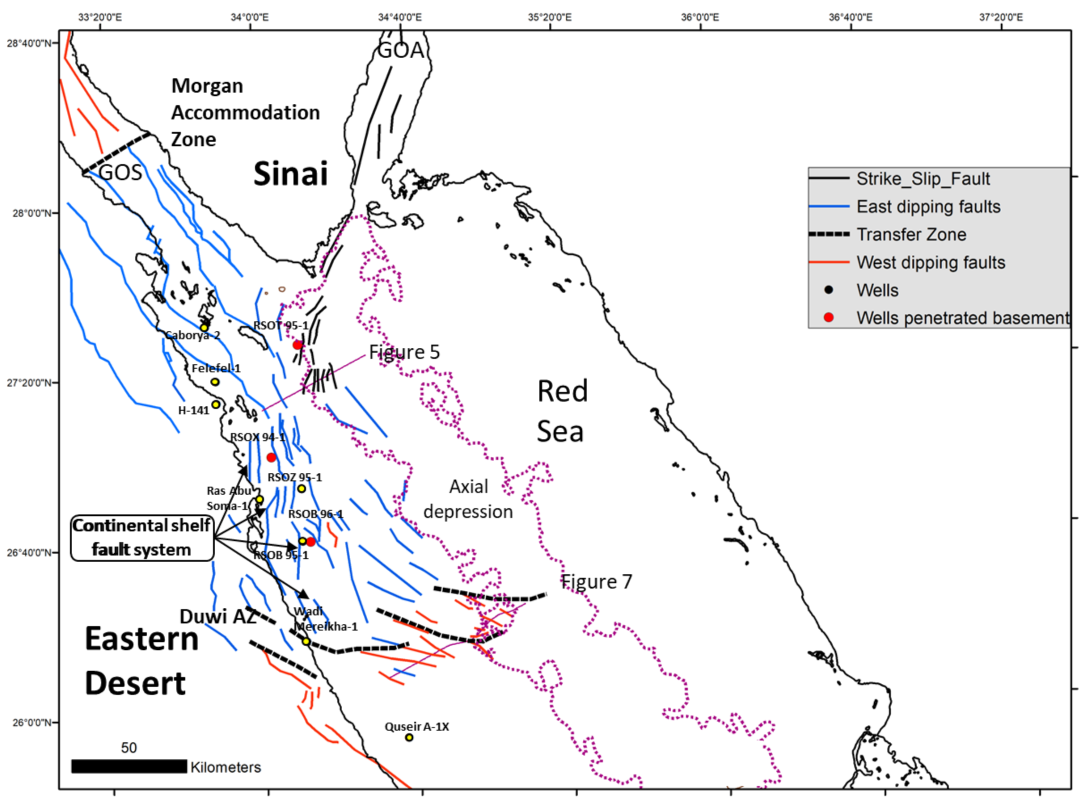

Fig.4: Structure elements map of the Area of Study showing the major faults polarity and the accommodation/transfer zones. Offshore faults in Red Sea are from seismic mapping in the present study. The Gulf of Suez faults are after Patton et al. (1994) and Afifi et.al., (2016). The onshore part of the Duwi accommodation zone is after Moustafa (1997) and Younes and McClay (2002) and the offshore part is based on the WNW oriented fault mapped from 3D seismic data from Ligi et al., (2018).

Source Rocks: The Campanian Brown limestone member at the base of the Sudr Formation in the pre-rift Carbonate unit is the main source rock that generated most of the hydrocarbons produced in the southern Gulf of Suez fields. It has an average of 2.5 % TOC (Total Organic Carbon) and is widely distributed across the entire basin (Alsharhan and Saleh 1994). However, the distribution of the Brown limestone in the northern Gulf of Suez is controlled by the Wadi Araba inversion structure, where the source facies are not present north of this structure in the Darag Basin (Peijs et al., 2012). The Thebes Formation has also been identified as a potential source rock within the pre-rift stratigraphy, with an average of 1.5 TOC (Rohrback, 1982, Barakat, 1982, Shaheen and Shehab, 1984 and Salah, 1992). Within the Syn-rift sequence, the Miocene shale of Rudeis Formation is considered a potential source rock with 2.5 % TOC (Alsharhan and Saleh, 1994).

Reservior Rocks: One of the major reservoirs in the Southern Gulf of Suez basin in the pre-rift clastics section is the Nubia Sandstone. Significant discoveries were made in this good quality reservoir (e.g., Hilal, GH376 and Shoab Ali fields). Its proximal stratigraphic position to the Brown Limestone source rock, which reduces the hydrocarbon migration losses, in addition to its good reservoir quality (average porosity is 13-25% and average permeability is 70-400 mD) and good vertical and lateral continuity, made it the most prolific reservoir interval. Additional reservoir intervals exist in the pre-rift section and include fractured basement, Clastics and Carbonates units, such as the sandstone rich intervals within the Nezzazat Group and the fractured Thebes Formation.

In the syn-rift section, the reservoir intervals are the Nukhul sandstone and the sandstone-rich members in Kareem and Rudeis formations. These sandstone-rich members within Kareem and Rudeis formations were derived by erosion of the pre-rift Nubia Sandstone and Precambrian basement in the structural highs within the rift, as well as in the rift shoulders (McClay et al., 1998). Another reservoir interval in the syn-rift section of the Southern Gulf of Suez is the Belyaim Formation carbonates, that encountered in Gemsa field. The Belyaim carbonates are reefal build-ups on the fault-controlled Precambrian basement highs, that have porosity ranging between 10 and 19%.

Cap Rock: The Late Miocene evaporites unit (South Gharib and Zeit formations) is the ultimate top seal for the syn-rift Gulf of Suez traps. While the pre-rift Cretaceous carbonates and shales, Esna shale and Thebes Limestone formations are the cap rocks for the pre-rift Nezzazat and Nubia sandstones.

Trapping Style: As the structural style of the Gulf of Suez rift basin is characterized by tilted fault blocks, most of the traps in the Gulf of Suez are structural traps. Although other stratigraphic and combination traps exist, the most common trap is the 3-way tilted fault block. This trap geometry has always been the primary exploration target; however, the presence of the lateral seal is a key factor to exploration success. The Rudeis and Kareem formations can act as lateral seals for the pre-rift traps in areas where shaly facies exist

5.2. Red Sea Petroleum potential play fairways:

Successful petroleum play fairway requires the presence of essential elements, which are a mature source rock, migration pathway, reservoir rock, trap and cap rock. Appropriate relative timing of formation of these elements and the processes of generation, migration and accumulation are necessary for hydrocarbons to accumulate and be preserved. Working hydrocarbon systems have been discovered along the greater Red Sea basin, such as in the Midyan and Barqan fields along the Saudi margin and the Tokar–Suakin delta of the Sudan (Bosworth, 2015). In addition, several surface seepages of oil have been reported along the Red Sea basin (Beydoun, 1989 and Mitchell et al., 1992). These seeps are documented north of Massawa and at the Dahlak Islands in Eretria, near Zeidiye in Yemen and in Saudi Arabia at the Farasan Island.

Several wells were drilled onshore and offshore in the Northern Egyptian Red Sea basin. All the offshore wells are considered commercial failures and they failed to encounter any pre-rift sedimentary section. Five wells in the area of study penetrated the basement and two are bottomed in the Miocene Rudeis Formation. While few onshore wells, such as the Hurghada oil field wells, Ras Abu Soma and Wadi Mereikha wells penetrated the pre-rift sedimentary section. Although no significant hydrocarbon discovery was made offshore, the hydrocarbon shows indicate a working petroleum system in the offshore area, as described below.

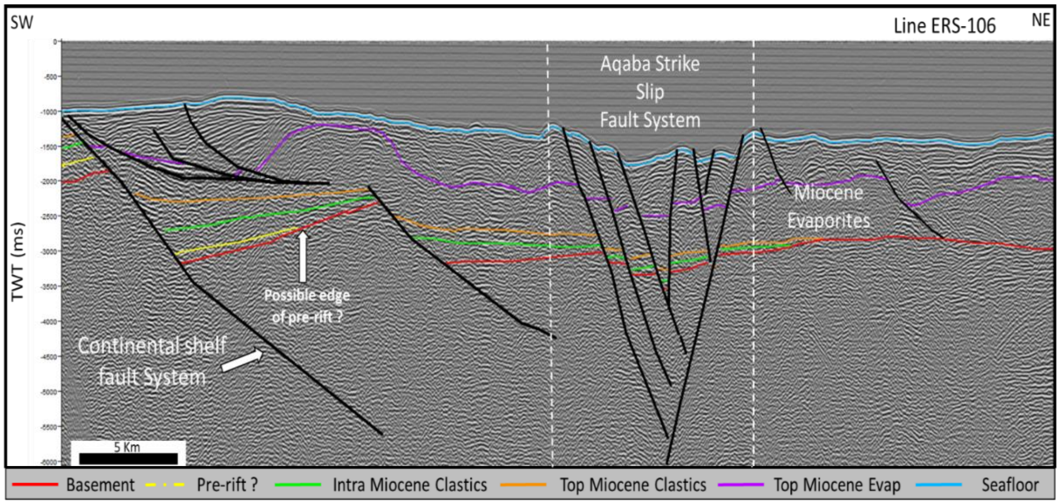

Fig. 1: shows the locations of the wells and their information below, that based on the mud and wireline logs, and the final well reports.

RSOT 95-1: The well was drilled in 1977 by Exxon, as a part of an exploration drilling campaign, that lasted until 1981. It was bottomed in the Basement rocks at 1950 meters. The well encountered the syn -rift Kareem and Rudeis formations, with around 166 meters of good quality reservoir rock, averaging 15-18 % porosity and with minor gas and trace oil shows (Fig.8 a).

RSOX94-1: The RSOX94-1 well was drilled in1981 by Exxon and was the last well in Exxon's drilling campaign. It found a 150 m gas and condensate column with 50^0 API in the non-reservoir siltstones of the thin bedded Kareem Formation, based on the calculated pressure gas gradient and recovered sample from the RFT pressure tool, as documented in the final well report (Figure 8b). The well also penetrated several sections within the Lower Rudeis Formation, with >1% TOC (Total Organic Carbon) content indicating, potential source rock facies. The well was bottomed in granite at 2880-meter depth.

RSOZ 95-1: The RSOZ 95-1 well was drilled in 1977 by Exxon and was bottomed in the Lower Miocene Rudeis shale at 3645 meters. Several oil shows were recorded in the thin-bedded calcareous Upper Rudeis sands, through side-wall cores and fair to good oil and gas shows in the penetrated thick Belyaim evaporite section (Figure 8c).

RSOB 95-1: The RSOB 95-1 well was drilled in 1976 and bottomed in the Rudeis Formation shales at 4022 meters. The well encountered a total of 243 porous Miocene arksoic Rudeis sandstone. Fair source rock potential was described in the Belyaim Formation, with 2-4 % TOC. The post well report failure analysis indicates that, the well was drilled off structure and the subsequent RSOB96-1 well was closer to the structural accumulation originally targeted by RSOB95-1 well.

Figure 5 Southwest seventies ventage 2D TWT seismic sections across the northern part of the study area showing the easterly dip polarity of the major rift-related faults and westerly dipping beds. Note the negative flower structures that is related to the Aqaba transform fault system. Rollover anticlines are also observed on the hanging wall of the Pliocene-Recent faulting. See figure 4 for location.

RSOB 96-1: The RSOB 96-1 well was drilled in 1981 and is located 600m northeast of and updip from RSOB-95-1 well. It encountered syn-rift Miocene rocks overlaying the basement and was bottomed in the granite at 4258 meters. Good oil and gas shows were reported in a 186 m oil stained Rudeis Formation sands. The oil stains were correlated and typed to a mature Brown Limestone/Duwi shale oil source. This well proved the existence of potential reservoirs in the Miocene and proves a working hydrocarbon system, with a mature Brown Limestone/Duwi oil source.

Quseir A-1X: The Quseir A-1X well was drilled in 1977 by Philips and it penetrated the syn-rift Miocene Clastics section overlying the basement. It was bottomed in the Precambrian metasediments facies of quartzitic sandstones, siltstones, and shales at 5038 meters. Minor oil and gas shows were reported in the Miocene evaporites section, however the drilled well failed to find any reservoir facies intervals.

Ras Abou Soma -1: Ras Abou Soma-1 onshore well was drilled in 1978 and it is one of the few onshore wells, that penetrated the pre-rift sedimentary section. It is bottomed in the granitic basement at 1230 m MD depth. It penetrated 230 m of wet good quality Nubia reservoir section and recorded oil shows in the syn-rift Rudeis section.

Based on the well information and the available 2D seismic data, two main play fairways potentially exist in the Northern Red Sea; pre-rift and syn-rift Miocene Clastics fairways, like what had been proven in the Gulf of Suez basin. The primary source rock for the pre-rift play is considered the high TOC Duwi and Dakhla formations, which are equivalent to the Sudr and Esna formations in the Southern Gulf of Suez (Barakat and Miller, 1984, Mitchell et al., 1992and Helmy, 2018). The organic-rich sediments in the Duwi and Dakhla formations, of Campanian age, are usually assigned as “oil shale” and are considered marine origin oil prone source rocks (El-Kammar, 2014). Geochemical analysis of samples obtained from the outcrops of Duwi and Dakhala formations indicate a TOC average value of 3-5 %, with the highest recorded value in the Quseir-Safaga area, as 14 % TOC (Ganz, 1984, Ganz et al., 1990 and El-Kammar, 2014). The Upper Cretaceous Nubia sandstone, of the pre-rift Clastics unit, is the primary reservoir, with recorded thickness of more than 300 m in Gebel Duwi and with good rock quality (Helmy, 2018). The intercalated shale within the Clastics section in addition, to the shale and Carbonate rich interval in the pre-rift Carbonate sections, provide the cap rock for the pre-rift play. Analogues to the pre-rift play abound in the SGOS, one of the southernmost plays is the onshore Hurghada field (41 MMBO). The play was further penetrated south onshore the Red Sea by Ras Abou Soma-1 well, as demonstrated before. Although the pre-rift sedimentary sequence has not been found in any of the wells drilled offshore in the Northern Red Sea, the pre-rift may be locally preserved, but obscured on the seismic sections by the thick Miocene evaporites sequence. It may be preserved only in the implied structural lows, as a result of the rift onset erosion at the up-dip edges of the tilted fault blocks, similar to what have been documented and discussed in the Southern

Gulf of Suez by Afifi et al., (2016). A possible pre- rift sequence was interpreted on the seismic data by Barakat and Miller, 1984.

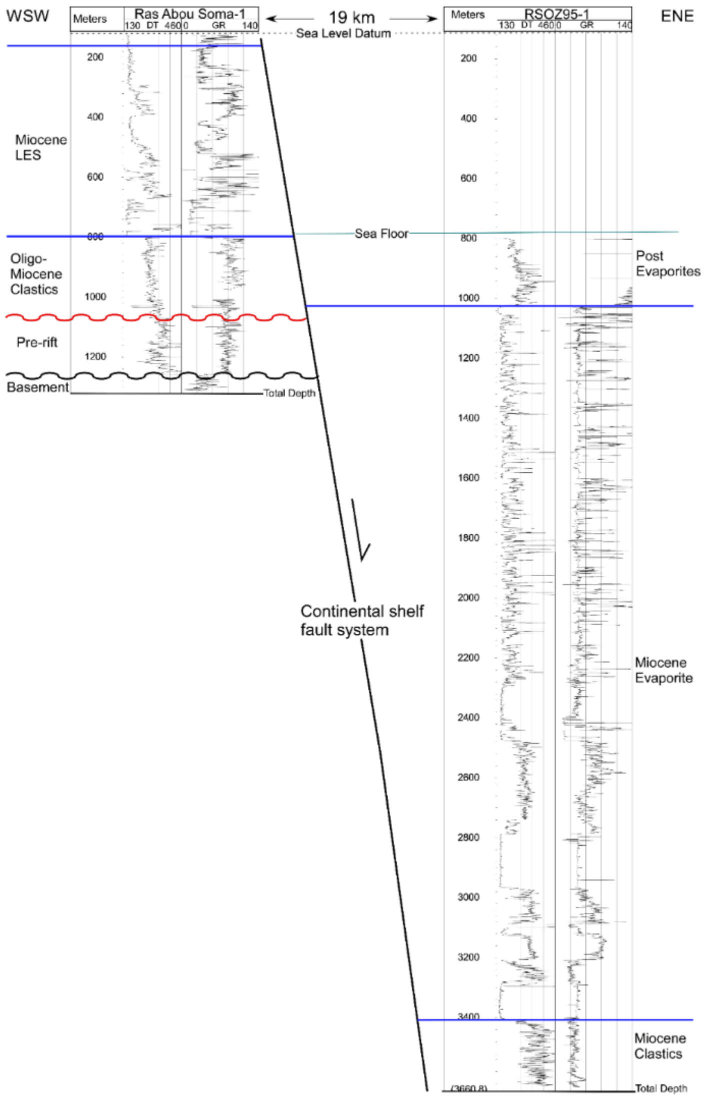

Figure 6 structural Cross -section between Ras Abu Soma and RSOZ95-1 wells showing the significant vertical separation (~ 2600 m) of the continental fault system and the increase in thickness of the Miocene sediments in the RSOZ95-1 well on the hanging wall of the continental shelf fault system. GR is gamma ray log and values are in API units. DT is sonic log, and the slowness values are in microsecond/meter. See figure 1 for well locations.

An alternative model is that, the pre-rift depositional setting might have constrained the limited distribution of the pre-rift section in the Red Sea offshore parts, leading to a narrow offshore area, close to the coastline, that might contain pre-rift section, as guided by the onshore distribution of the pre-rift section. However, a complete evaluation of the presence or absence of the pre-rift stratigraphic section offshore the Red sea is beyond the scope of this paper, due to the lack of enough well control and the limitation of the 2D seismic data quality.

Unlike the pre-rift play, all the wells drilled offshore penetrated the syn-rift Miocene Clastics play. The play comprises good source rock potential within the Miocene Belyaim, Kareem and Rudeis formations, as shown by RSO-X 94-1 and RSOB 95-1 wells. In addition, several reported oil and gas shows in all the wells drilled offshore. The Duwi /Dakhla pre-rift source rock can also charge the syn-rift play, as indicated by RSOB 96-1 well. Syn-rift reservoir rocks have been proven by RSOT 95-1, RSOZ 95-1, RSOB 95-1 and RSOB 96-1 wells which drilled good quality reservoir intervals in the Kareem and Rudeis formations. The Miocene evaporites unit, with its South Gharib and Zeit formations, provides excellent seal capacity. In addition to the mudstones of Belyaim and Kareem formations, and the shales of Rudeis formation offer a good seal potential. Mapping the limited available seismic lines suggests that, the Miocene evaporites unit overlies the basement complex in the eastern part of the area of study, as discussed formerly in the structural setting of the paper. This indicates that, the Miocene syn-rift play may be limited to the western and central parts of the study area (Figure 9).

The tectonic and structural setting of the Red Sea basin has shaped the potential petroleum trapping mechanism, leading to the structural traps, being the potential dominant trap types. Figure 10 shows the potential plays and trap types in the area of study of the Northern Red Sea basin for the pre-evaporites sequence. In the westernmost part of the basin, the classical 3-way tilted fault block traps, that are similar to the proven trap style in the Southern Gulf of Suez, sourced from the pre-rift and syn-rift source rocks, are the dominant style. This trapping style forms attractive plays in the Northern Red Sea, where the Pre-rift Clastics or Miocene Clastics units are the potential reservoirs, that sealed by the overlying impermeable shales and limestones of the Pre-rift carbonate unit, or the salt and anhydrite of the Miocene evaporites, respectively. In the central part of the study area, the potential trap types are the rotated fault blocks and onlap edges of the Miocene Clastics unit, in addition to the Miocene reefal build-ups generated on the basement highs. These trap types are sealed by the overlying evaporites.

Structuring the Miocene evaporites and the post-evaporites Pliocene sequences resulted in an additional structural trapping system, that does not exist in the Southern Gulf of Suez. Salt withdrawal features, as the diapir and salt-cored anticlines, offer a variety of trapping mechanisms in the Northern Red Sea. Several rift basins and passive margins, such as the Gulf of Mexico, West African South Atlantic margin and Brazil Campos basin have proven hydrocarbon discoveries developed in similar structural settings of the post-evaporites section. Although

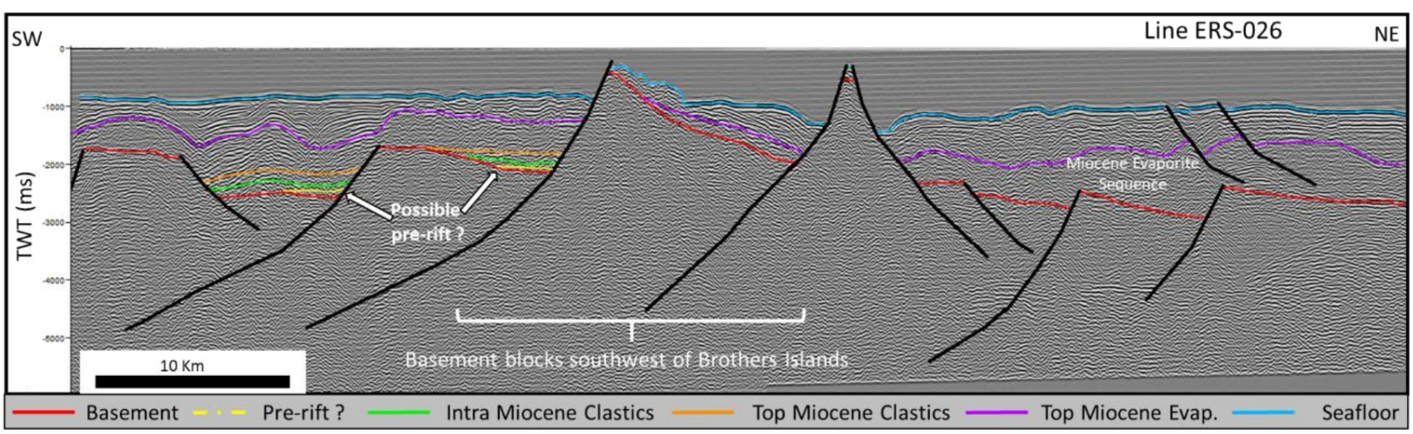

Fig. 7: TWT seismic sections showing the westerly dipping polarity of the major rift-related faults and the eastly dipping blocks south of the Duwi accommodation zone. See figure 7 for the location.

the Miocene evaporites and Pliocene post-evaporites sections contain intervals of potential source rocks (Mitchell et al., 1992), this play may have limited hydrocarbons potential along the Northern Egyptian Red Sea margin, due to the shallow burial depth.

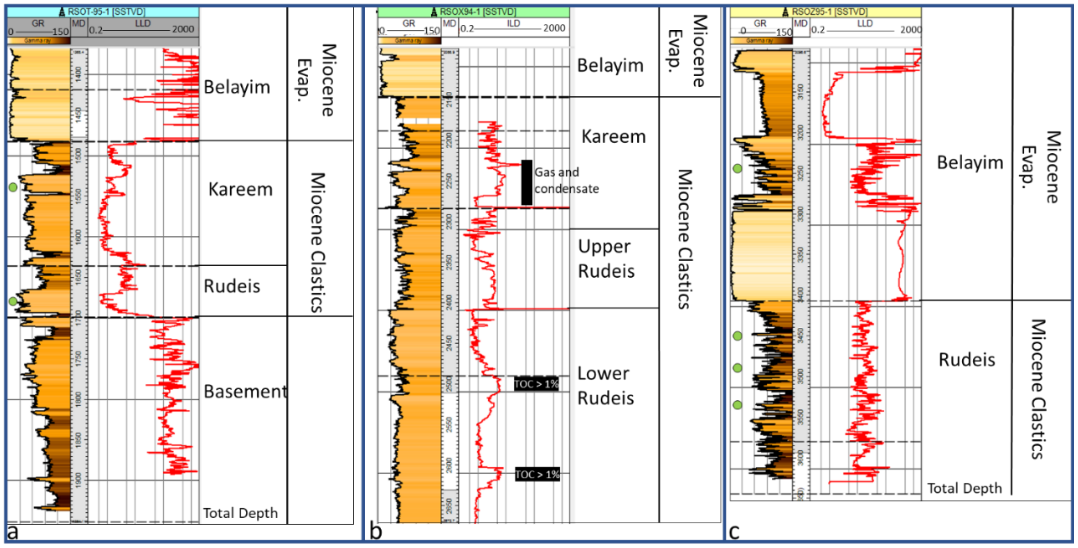

Fig. 8: simplified well logs of a) RSOT 95-1 b) RSOX 94-1 and c) RSOZ 95-1 wells. Green dots are oil and gas shows and/or oil stain. Black boxes are intervals of high TOC. Well depths are in meters. See figure 1 for well locations.

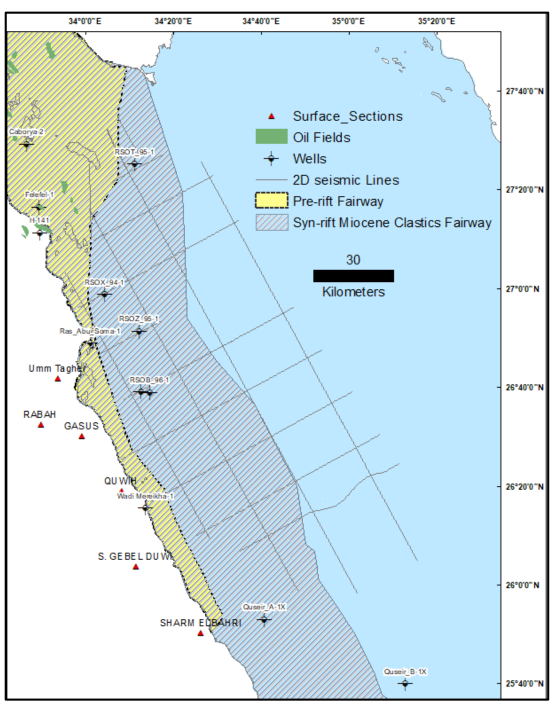

Fig. 9: The outlines of the proposed pre-rift and Syn-rift Miocene Clastics plays

Increasing the geothermal gradients and depth of burial may result in the maturation of this play source rocks to the south, towards the Central and Southern Red Sea along the Sudanese Red Sea (Mitchell et al., 1992). Detailed description of the hydrocarbon possibilities within the Miocene evaporites unit and Pliocene post evaporites unit is beyond the scope of this paper.

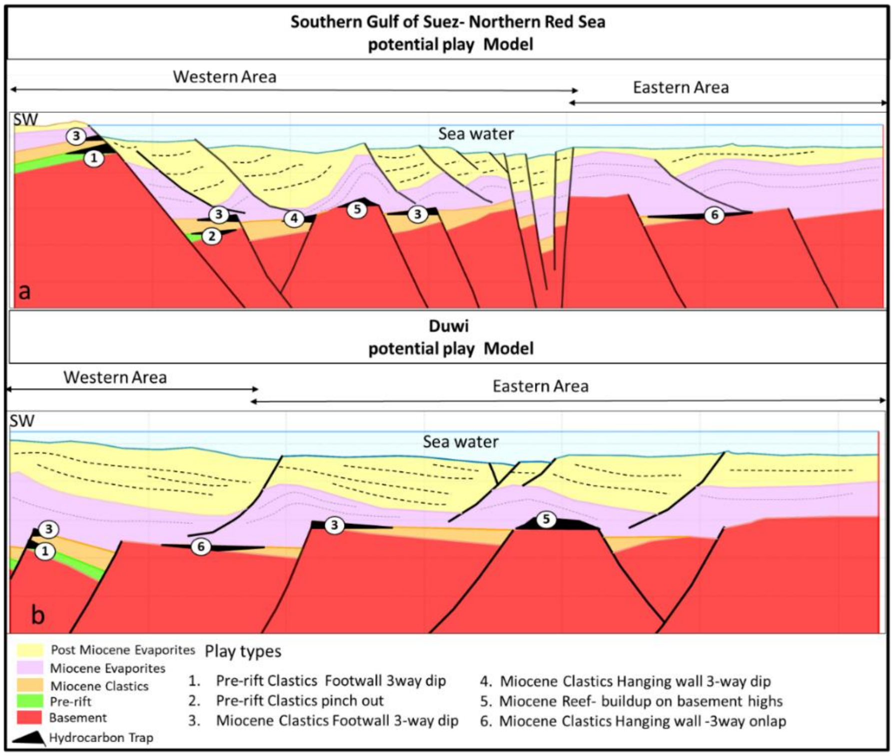

Fig. 10: Schematic play cartoons a) Northern part of the study area. b) Southern part of the study area (Duwi).

6. Conclusions:

Although there was no single commercial hydrocarbon discovery made to date in the Egyptian northwestern part of the Red Sea basin, multiple evidence of working hydrocarbon systems has been observed. Wells drilled offshore and onshore penetrated potential source, reservoir and cap rocks within the two identified pre-rift and Miocene syn-rift clastics fairways. The pre- rift play comprises the Late Cretaceous clastics unit, Nubia sandstone reservoir and the Duwi/Dakhla shale, as the main source rock. The precise definition of the offshore pre-rift fairway is poorly constrained, due to the limited well data and challenging quality of the seismic data. The syn-rift

Miocene Clastics play comprises syn-rift source and reservoir rocks, within the Belyaim, Kareem and Rudeis formations. The clastics dominated Nakheil Formation, which is equivalent to the Nukhul Formation reservoirs in the Southern Gulf of Suez and exposed onshore the Red Sea, is another potential syn-rift reservoir. However, the Nakheil Formation was not penetrated by any of the offshore wells. It may be missing from the edge of the tilted fault blocks and preserved only in the downdip parts. All the reservoirs are sealed by the Miocene evaporites, as ultimate top and lateral seal, as indicated from the subsurface data set. The continuation of the Gulf of Suez proven pre-rift and syn-rift hydrocarbon plays and trap styles are expected to be predominately present in the area of study. However, improvement in the seismic imaging is critical to reducing the play and trap definition risks in the northwestern part of the Egyptian Red Sea.

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Declaration of Competing Interest

The authors declare that they have no conflict of interest

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