Preferential deposition and preservation of structurally-controlled synrift reservoirs: Northeast Red Sea and Gulf of Suez

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ABSTRACT

An integrated GIS-based play evaluation, which incorporates restorations of the North Red Sea and Gulf of Suez, has helped to identify potentially prospective areas in the Northeast Red Sea associated with point-sourced synrift sandstone reservoirs. The three largest synrift Gulf of Suez fields (Belayim Land, Belayim Marine, and Morgan) are located along major fault-transfer zones that optimized the conditions for the deposition and preservation of thick point-sourced sands adjacent to extensive hydrocarbon source kitchens. Belayim Land and Morgan fields contain stacked submarine fan, delta, and alluvial fan systems that developed during the deposition of the Miocene Rudeis, Kareem, and Belayim-South Gharib formations, respectively. This continuous, point-sourced sedimentation is indicative of stable drainage and by inference, a stable eastern border fault system. We attribute this stable border fault system to a stress heterogeneity related to the pre-existing Najd Shear Zone, and polarity reversals in upper-plate transport direction.

Tectonic restorations indicate that the North Red Sea, like the Gulf of Suez, should have reservoir facies deposited in similar structural positions, but preservation is a significant risk due to additional crustal extension. Although crestal block erosion remains a great concern for reservoir preservation, seismic mapping indicates that block size along the coastal region and inboard areas are similar to the Gulf of Suez. This suggests that most of the strain may have been accommodated along the warmer axial portion of the rift where weaker crustal rheology exists.

Landsat mapping of the Northeast Red Sea border fault system has found a high degree of variability in structural styles. The southern Yanbu-Jeddah and Umm Luj-Al Wajh sub-basins are bound by listric, down-to-the-west-southwest border faults, separated by suture-controlled accommodation zones. To the north, the Midyan-Ifal sub-basin is located along the Miocene flexural margin, and is structurally more complex. Northwesterly-trending (Najd Shear Zone) planar faults are overprinted by a strong northeasterly (Aqaba) trend, such that transpressional and transtensional features exist. Although structurally complex, the offshore northern flexural margin has been determined to have the best potential for localized, second-generation, thick, synrift sediments similar to that of the Gulf of Suez.

INTRODUCTION

Exploration issues, approaches, and interpretations of the Northeast Red Sea are addressed in this paper. The area of interest is between the Gulf of Aqaba and Jeddah, and is bounded to the west by the Saudi Arabian-Egyptian median line, and to the east by the first outcrop of basement rock (Figure 1). Due to the large size of the Northeast Red Sea exploration area, severe data limitations, and play-element (i.e. trap, reservoir, seal, and source) uncertainties, a process-oriented, play-element analysis of the North Red Sea and the Gulf of Suez provides an exploration model for the Northeast Red Sea. The study compares and contrasts the structural controls related to synrift deposition and preservation of point-sourced sandstone reservoirs in the North Red Sea and Gulf of Suez in order to evaluate the hydrocarbon potential of the Northeast Red Sea.
RED SEA GEOLOGIC UNCERTAINTY AND EXPLORATION ISSUES

As early as 1929, Alfred Wegener identified the Red Sea as the type example for continental plate separation (Bayer et al., 1989). Subsequent scientific studies have generated a plethora of controversial models and interpretations that affect a hydrocarbon system. Rift models include:

1. lithospheric simple shear (Wernicke, 1985; Voggenreiter et al., 1988);
2. pull-apart basins (e.g. Makris and Rhim, 1991);
3. active rifting (e.g. White and McKenzie, 1989);
4. passive rifting (e.g. McGuire and Bohannon, 1989);
5. active/passive hybrid (e.g. Davison et al., 1994; Drury et al., 1994).

Even the nature of the crust throughout the Red Sea is disputed, largely due to inadequate data coverage and quality. In general, there is agreement that oceanic crust exists along the axial deep of the Red Sea, between 15° and 20°N, where magnetic anomalies as old as five million years (Ma) are well-documented (Girdler and Styles, 1974; Roeser, 1975; LaBrecque and Zitellini, 1985). However, outside the axial trough, crustal interpretations vary from completely oceanic (e.g. LaBrecque and Zitellini, 1985) to transitional in nature (Cochran, 1983). These are but a few fundamental controversies that highlight the geologic uncertainty that impact the hydrocarbon system.

Hydrocarbon exploration in the Red Sea dates back to the early 20th century with the first well drilled in 1915. Subsequently, over 50 wells were drilled along the Egyptian and Saudi Arabian margins. These resulted in the discovery of the Saudi Arabian offshore Barqan field in 1969, and onshore Midyan field in 1992 (Lindquist, 1998). The low number of discovered fields may be due to inherent play element inadequacies, although this is uncertain due to poor geologic understanding compounded by inadequate geophysical data.

EXPLORATION INSIGHTS:
RIFT BASIN TECTONICS AND FACIES DISTRIBUTION

Extensional Processes

Extensional processes engender changes in topography, both creating and destroying accommodation space. The lithosphere responds both kinematically and isostatically to regional extension in a predictable way. In addition to creating space adjacent to large normal faults (which is filled by sediment, water and/or air), space is destroyed through uplift associated with the flexural behavior of the crust (e.g. Weissel and Karner, 1989). In the simplest configuration, subsidence and uplift are greatest on the hanging-wall and footwall, respectively, adjacent to the region of greatest displacement (Figure 2). Depending on a number of factors, including crustal strength, fault geometry and displacement, and density of infilling material, the subsidence is many times greater than the associated uplift. However, this uplift still produces a significant topographic feature, often hundreds of meters to more than a kilometer, above the regional surface and rift flanks.

Rift basins usually consist of a series of aligned half-grabens. Since discrete, large normal faults and associated half-grabens comprise rift basins, the topography varies as a function of how these large fault systems are linked (Figure 3). Elevated regions (e.g. accommodation or transfer zones) segment rifts between half-grabens where border fault displacements are diminished. It has been recognized that the border fault systems of these half-grabens can be of similar or opposed polarity, and that they may be overlapping and 'hard-linked' or non-overlapping and 'soft-linked' (Figure 3) (e.g. Rosendahl et al., 1986; Rosendahl, 1987; Morley, 1988; Morley et al., 1990). Regional topography and drainage patterns reflect these half-graben geometries and their recognition provides a powerful predictive aid for understanding facies distribution within rift basins.
Figure 1: Landsat image of the North Red Sea and Gulf of Suez showing locations discussed in the paper. The Landsat Thematic Mapper image is a mosaic with a 28.5 meter resolution of bands 7 (red), 4 (green) and 2 (blue) (Earthsat). The area of interest, the Northeast Red Sea, lies between the Gulf of Aqaba and Jeddah, and is bounded to the west by the Saudi Arabian-Egyptian median line (approximately bisects the Red Sea), and to the east by the first outcrop of basement rock (dark colors along the coastal region). The study compares and contrasts the hydrocarbon potential of the North Red Sea and Gulf of Suez, to that of the Northeast Red Sea.
Structure, Drainage and Facies Development

The fault geometries discussed above exert a fundamental control on topography and on drainage patterns, both within and around their associated basins; and ultimately on how facies vary within the basin (Gawthorpe and Hurst, 1993; Reynolds, 1998) (Figures 3 and 4). Structural features within the rift are also predictable based on the linkage geometry of adjacent half-grabens (Figure 3). The regions that segment the rift are areas of higher relief within the rift basin: since the most space is created adjacent to the center of the fault and the least near the tips.

Drainage can enter the basin from the border fault (high-relief) margin, the flexural (low-relief margin), or the axial margin (Figures 3 and 4). On the high-relief margin, transverse drainage is generally controlled by breaks in the border fault system (segmentation structures). Significant backshed drainage can occur behind the border faults, thereby increasing the drainage area and focusing sediments towards breaks in the border fault system. Uplift of the footwall, due to unloading along the fault plane, is greatest where displacement is at a maximum, i.e. the middle of the fault segment. Therefore zones of relatively little or no footwall uplift, are located near fault tips, where displacement is least. Fault tips define rift segments, and thus topographic breaks in the rift shoulder are found adjacent to segmentation zones. It is through these breaks that drainage on the high-relief margin enters the rift basin. The important point is that the topography along both the hanging-wall and footwall margins is controlled, to a first-order, by the basin’s main border faults. Other clastic input, from the high-relief margin, also occurs as alluvial fans that are deposited against the border fault. Occasionally, antecedent drainage systems may be maintained by eroding through the footwall, but these are rare and dependent on rates of uplift, erosion, and bedrock lithology.

Recognizing the interplay of facies and structure within the context of extensional processes and half-graben geometries (which are often times discernable on Landsat, sparse seismic data, and potential field data) is an enormous aid when exploring in frontier areas such as the Northeast Red Sea. These extensional processes have influenced many fields globally (Figure 3), including Gulf of Suez fields that carry unique lessons for the Northeast Red Sea due to their shared early geologic history.

DATA

Data used in this study include 2-D seismic, well bore data, potential field data, Landsat, Digital Elevation Models (DEM), and surface geologic maps (United States Geological Survey). All data and interpretations were compiled and integrated into a GIS-based repository.
Figure 3: (a) Examples of border fault systems with generalized structure. Brown areas represent highlands with erosion; green areas are lowlands with their basinal strike indicated by green arrows. Blue arrows show structurally-controlled drainage patterns that transport clastics to point-sourced fans. (b) Examples of border fault systems with generalized structure. Examples of petroleum fields found in opposed listric fault system are El Morgan (Gulf of Suez), Agua Grande (Reconcavo, Brazil), North Rankin (Dampir, Australia) and Cinta (Sunda, Indonesia). Examples of fields found in similar (synthetic) fault system are (green text) Belayim Land and Marine, July fields (Gulf of Suez), Brae (North Sea, United Kingdom), Groningen (Saxony, Netherlands), Beryl (North Sea, United Kingdom), Hibernia (Jeanne d’Arc, Canada) and AVS (Sunda, Indonesia).

Figure 4: Schematic diagram showing the relationship between drainage, deposition and fault segmentation in a marine half-graben (modified after Gawthorpe et al., 1994).
2-D Seismic Data

The available seismic coverage in the northeastern Saudi Arabian Red Sea was limited to approximately 600 km of reconnaissance 2-D data acquired by Esso (now ExxonMobil) in 1977 (Figure 5a). In addition, Esso acquired significant seismic coverage in the northwestern Egyptian Red Sea during exploration operations in the late 1970s and early 1980s. Seismic surveys totaling 8,700 km of data were gathered and interpreted resulting in the drilling of five unsuccessful wildcat wells in the Safaga Concession (Figure 5a).

The Saudi Arabian portion of these data, were acquired with a 3,250-foot streamer and a relatively low-energy propane sleeve exploder source. Record length was 6.0 seconds, with a 4 millisecond sample rate. Common Mid Point (CMP) fold is 66, with a CMP spacing of 22.5 m. Although the data were acquired and processed with the technology available at the time of acquisition, it was generally of poor quality. Recent reprocessing efforts improved the sub-salt

![Figure 5: The data used for this study include (a) seismic lines and wells; (b) reduced-to-pole magnetics; and (3) isostatic gravity (courtesy of GTECH).](http://pubs.geoscienceworld.org/geoarabia/article-pdf/10/1/97/5441808/polis.pdf)
signal and imaging. The primary processing tools were multiple removal and structural migration routines. Multiple removal required a three-step process:

(1) Wave equation-surface multiple attenuation to remove primary water-bottom multiples.

(2) Predictive deconvolution techniques involving common-shot wavelet estimation. This routine enabled the retention of near traces required for post-stack depth migration.

(3) Radon demultiple program to attenuate interbed multiples. This involves the modeling of the water bottom and prediction of 1\textsuperscript{st}, 2\textsuperscript{nd}, and 3\textsuperscript{rd}-order multiples.

Figure 6: Example of processing and interpretation of a Red Sea seismic line. The graphic at the top shows the image in time without demultiple processing. The graphic in the middle shows the pre-stack depth migration of the same data. The lower graphic shows the interpretation of the depth-migrated image.
Structural enhancement and sub-salt imaging was greatly improved by the pre-stack time and pre-stack depth migration (Figure 6). Reprocessing reduced noise and improved pre-salt reflection continuity and positioning of reflectors. However, interpretation for the presence and distribution of sub-salt reservoir is still hindered due to the inherent nature of the acquisition parameters of the time.

**Well Bore Data**

Well control within the Northeast Red Sea is geographically restricted to the onshore and nearshore areas. The wells are unevenly distributed with most concentrated in the Midyan, Al Wajh, and Yanbu areas (Figure 5a). This distribution provides limited coverage for these...
provinces, and precludes a stratigraphic understanding for much of the offshore region. However, the Gulf of Suez has a well-distributed dense coverage of wells, and only a subset of our database was used.

**Potential Field Data**

Regional marine magnetic data and satellite-derived gravity data, calibrated with 1970s-vintage, ship-borne gravity, allow for the qualitative identification of crustal and structural offshore trends. For example, the highly-attenuated axial deep and rhombochasms correlate with gravity and magnetic highs (Figures 5b and 5c). These data were processed using bandpass filters, derivatives, and isostatic residual filters, and the resultant grids were integrated into a GIS-based visualization platform to assist in their interpretation.

**Surface Data**

GTOPO 30, and 200-meter Russian digital elevation models (DEM) aided the structural interpretations and drainage analyses (Figure 7). Interactive processing for the DEM improved subtle responses and utilized the full range of the data (e.g. bandpass and directional filtering, edge and contrast enhancements). As an example, contrast enhancement for the separate onshore, offshore, and combined DEM grids are striking due to better utilization of the dynamic range.

Landsat has proven to provide meaningful exploration insights related to both mineral and petroleum systems in highly-extended terranes (e.g. Wilkins and Heidrick, 1995; Frost and Heidrick, 1996; Polis, 1999). Interactive processing, visualization and integration of full-resolution (28.5 m) seven-band digital Landsat data played an important role in onshore structural interpretation and the Miocene provenance analyses (Figure 1). In the Landsat-DEM image, the onshore structural and drainage trends can be tied to recent offshore fan deposition (Figure 8).

**GULF OF SUEZ: CONTROLS ON SYNRIFT RESERVOIRS AND SOURCE KITCHENS**

The Gulf of Suez is a world-class hydrocarbon province with over 100 years of exploration activity, and contains 80 oil and gas fields with total original oil reserves exceeding 11 BBOE (Lindquist, 1998; Winn et al., 2001). Basement, pre-rift strata (Paleozoic and Mesozoic), and synrift Miocene carbonate and clastic reservoirs are all productive; with the Miocene synrift reservoirs providing approximately...
50% of the reserves (Lindquist, 1998; Figure 9). The Gulf of Suez has an apparently similar early rift history to the North Red Sea, and therefore provides a unique opportunity to apply its documented structural, stratigraphic and petroleum system relationships to the Northeast Red Sea.

Although the synrift section is a large reserves contributor, reservoir prediction can be difficult due to the extreme facies variability related to structural relief. The present-day Tarbul Embayment illustrates this variability with the juxtaposition of fluvial sandstones, a carbonate platform, deeper-marine clastic-carbonate system, and exposed basement all within a few kilometers of each other (Figure 10). However, an important element of reservoir predictability exists within synrift sedimentation related to fault segmentation. This is also observed in the Tarbul Embayment with the present-day deposition of an alluvial fan down dip of a relay ramp (Figure 10).

| Series         | Gulf of Suez   | Age (Ma) | Northeast Red Sea |
|----------------|----------------|----------|-------------------|
|                | Rock Unit      | Onshore  | Offshore          | Rock Unit       |
| Pleistocene    | Shuheir Formation |          | Lisan Formation   |
| Upper Pliocene | Zeit Formation |          | Ghawwas Formation |
| Lower Pliocene | South Gharab Formation | 5 | Mansiyah Formation |
| Upper Miocene  | Belayim Fm     |          | Kial Fm           |
|                | Kareem Fm      |          | Jabal Kibrit Fm   |
| Middle Miocene | Rudeis Formation |      | Burqan Formation |
| Lower Miocene  | Nukhul Formation |        | Musayr Fm         |
| Oligocene      | Abu Zenima Fm  |          | Yanbu Fm          |

**Figure 9:** Generalized stratigraphy of the Gulf of Suez and Northeast Red Sea, and oil and gas bearing reservoirs.
On a sub-regional scale, fault segmentation has had a first-order control on the basin and on specific fields (e.g. Morgan, Belayim Land, and Belayim Marine; Figure 12a). The Gulf of Suez basin is comprised of three major sub-basins with alternating border fault polarities that produced stratal dip-domains to the southwest, northeast, and southwest (Moustafa, 1976). From south to north respectively, the Morgan and Zaafarana Accommodation Zones separate these sub-basins. Synrift point-sourced sands developed within the accommodation zones, and down-dip from major synthetic relay ramps, due to topographic lows related to border fault segmentation (Figure 11).

When evaluated in more detail, the majority of the faults are planar, as suggested by the linear two-dimensional geometries (Figure 12a). Four major trends have been recognized (Figure 12b): (1) north-northwestern ‘clysmic’, (310° and 340°); (2) northern (350° and 30°); (3) northwestern (280°); and (4) ‘clysmic’ cross-trends (50° and 75°) (Patton et al., 1994). Along the eastern Sinai coast, and the central and northern sub-basins the northwestern trend is prevalent. This is evident from the fault geometries, the sedimentary erosional retreat along the Sinai Peninsula, and the Zaafarana Accommodation Zone. Locally, along the western Sinai Peninsula, this trend is recognized in the Precambrian Rihba Shear Zone, which has been identified as a primary factor in controlling the eastern rift system and the Zaafarana Accommodation Zone (Younes and McClay, 2002).
Figure 11: Structural framework of the Gulf of Suez showing four cross-sections (modified after El-Ashry, 1972; Gawthorpe and Hurst, 1993; Patton et al., 1994). The Gulf of Suez is comprised of three sub-basins with alternating border fault polarities, and the sub-basins are separated by the Morgan and Zaafarana Accommodation Zones (Moustafa, 1976).
Many of the Early to Middle Miocene sandstone depocenters (> 600 ft net sand) are associated with fault segmentation, intra-basin highs, and synrift fields (Figures 12a and 13). The four largest synrift fields (i.e. July, Belayim Land, Belayim Marine, and Morgan) all have point-sourced reservoir sands (Evans, 1990; Pivnik et al., 2003). The Morgan and Belayim fields are intra-basin highs formed by minimal fault displacement during synrift deposition. Point-sourced sands developed as a function of structurally-controlled, up-dip drainage as opposed to preferential accommodation space (Figures 12 and 13). The Morgan and Belayim fields are juxtaposed with half-graben deeps (> 2,000 m) that have developed from increased fault displacement and hanging-wall subsidence away from the structural highs. These sub-basins are positioned ideally for hydrocarbon migration from extensive kitchens adjacent to up-dip reservoir sands (Figure 13).

The Morgan and Belayim Land fields demonstrate temporal continuity with sand deposition that transitions in time from submarine fans to deltas and eventually alluvial fans during deposition of the Rudeis, Kareem, and Belayim-South Gharib formations (Evans, 1990). This temporal and spatial depositional continuity is indicative of drainage stability, and by inference, a relatively stable eastern border fault system. A possible explanation for this structural setting is that the Precambrian Najd Shear Zone, referred to locally as the Rihba Shear Zone, influenced the development of the eastern border fault system (Younes and McClay, 2002), and constrained the drainage throughout much of the rift history.

**GULF OF SUEZ-NORTH RED SEA RIFT EVOLUTION**

**Purpose and Controls**

The Gulf of Suez and Northeast Red Sea were evaluated through a series of restorations to clarify the major tectono-stratigraphic similarities and differences that influenced their hydrocarbon habitats. Parameters that controlled the original pre-rift configuration for the North Red Sea and the Gulf of Suez include 106 km left-lateral motion restored along the Dead Sea Fault, and 30 km of orthogonal extension restored in the southern Gulf of Suez (Patton et al., 1994). Precambrian sutures and Najd Shear Zone-related features (e.g. Wadi Azlam of Saudi Arabia and Gebel Duwi in Egypt) served as cross-rift piercing points. The depth converted SRS-2 seismic line served as a control for the present-day cross-section, which does not account for compaction. West of the SRS-2 seismic line, the section is constrained by bathymetry, magnetic, gravity, and seismic observations made throughout the surrounding area. The purpose of the restorations is to highlight important aspects of the hydrocarbon habitat of the North Red Sea and Gulf of Suez, and is not intended to be a rigorous account of the timing, geometries, and kinematic development of the rift system.

**Prerift: Influences on Hydrocarbon Habitat**

**Basement**

Two fundamental basement grains (visible in digital elevation maps, DEM, Landsat, and potential field data; Figures 5 and 8) have been identified as major controls for the sub-basin development of the North Red Sea-Gulf of Suez rift system: (1) east-northeast trending Precambrian Pan-African sutures; and (2) the younger northwestern trending Precambrian Najd Shear Zone (Figure 14).

The Pan-African sutures formed between 620-580 Ma, during the amalgamation and final cratonization of the Arabian-Nubian shield. Several tectono-stratigraphic terranes were incorporated through the NS- to NW-oriented subduction, accretion, and suturing of the Arabian Plate onto the African continent (Gass, 1979; Engel et al., 1980; Fleck et al., 1980; Stoeser and Camp, 1985; Krüner, 1993; Krüner et al., 1994). The present-day Saudi Arabian Yanbu and Bir Umq sutures exhibit cross-rift continuity with the Onib-Sol Hamed and Nakasib Sutures of the western Red Sea respectively, and provide pre-rift piercing points (Figure 14).

The Najd Shear Zone (Figure 14) is believed to have formed as a late Precambrian rift-related transform fault (Stern, 1985), marking the final stages of Pan-African deformation (Shackelton et al., 1980;
Figure 12: (a) Thickness of Early and Middle Miocene net sand is shown together with the seismic time map of the base South Gharib Formation (salt). Also shown are the main sub-basins and tectonic trends based on the Landsat image. (b) The main trends of the Gulf of Suez are characterized as clysmic (310° and 340°), cross-clysmic (50° and 75°), NW (280°), and North (30° and 350°).
The shear zone is a regional left-lateral strike-slip system that is approximately 250-km wide and 300 km long, with a cumulative lateral offset between 240 and 300 km (Brown and Coleman, 1972; Davies, 1984). The Najd Shear Zone is best developed between the Midyan Peninsula and the Al Wajh sub-basin, where 250 km the Saudi Arabian coastline is characterized by a north-northwest linear shoreline. Along this margin, Wadi Azlam and Gebel Duwi of Saudi Arabia and Egypt, respectively, are Najd Shear Zone-related grabens that restore as prerift piercing points.

**Stratigraphy**

The Mesozoic and Cenozoic pre-rift section of the Gulf of Suez is generally thicker, and exhibits more of a marine influence, than the North Red Sea. This is due to the more proximal position of the Gulf of Suez to the Tethyan Sea during this time (Figures 9 and 14). In the Late Cretaceous and Early Tertiary, a southern embayment, or ‘proto-Red Sea’, formed at least as far south as Jeddah (Hughes et al., 1999). The Late Cretaceous transgression deposited the uniform organic-rich marine phosphatic shales of the Brown/Duwi Member of the Sudr Formation, which is the primary source interval for the Gulf of Suez (Lindquist, 1998). In the Northeast Red Sea, the age-equivalent Adaffa Formation is largely terrigenous, and has poor source quality (Hughes and Filatoff, 1995). However, the Late Cretaceous phosphatic facies is present in northern Egypt south to the Quseir area and may be present offshore (Lindquist, 1998).

Prerift Paleozoic to Mesozoic reservoirs of the Gulf of Suez are estimated to have between 33% (Salah and Alsharhan, 1997) and 49% (Petroconsultants, 1996) of total reserves within a pre-rift section that...
Figure 14: Prerift restoration illustrating key structural controls. (a) The two fundamental basement grains are the E-NE-trending Precambrian Pan-African sutures, and the younger northwestern trending Precambrian Najd Shear Zone. (b) Cross-section AA’ shows the complete closure of the basement across the Red Sea.

Figure 15: (a) At approximately 20 Ma in the Early Miocene, the Red Sea regional fault systems linked and subsidence accelerated. (b) Extension moved inboard, the initial border fault system became inactive and onshore grabens were abandoned. Cross-section BB’ is situated along the same profile as AA’ in Figure 14.
Figure 16: (a) At the end of the Middle Miocene, the left-lateral Gulf of Aqaba Transform System was initiated and the Gulf of Suez was separated from the North Red Sea. The Red Sea’s stress direction changed from orthogonal (N55°E) to oblique (N15°E) with the initiation of the Gulf of Aqaba Transform System. Motion along the Gulf of Aqaba-Dead Sea Fault is estimated at 106 km of left-lateral displacement. (b) Cross-section CC’ is situated along the same profile as AA’ and BB’ in Figures 14 and 15.

Figure 17: (a) Present-day tectonic elements of the Gulf of Suez and North Red Sea. (b) Cross-section DD’ (same as Figures 14–16) shows the axial rift as a magmatic zone (in red).
is up to 1,065 m (3,493 ft) thick (Alsharhan, 2003). The prerift has not been identified in the offshore Northeast Red Sea, although Cambrian-Ordovician sandstones with thickness up to 950 m (3,116 ft) have been reported in Saudi Arabia along the erosional scarp (Brown et al., 1989), and in scattered isolated coastal outcrops near Jeddah (Hughes et al., 1999).

Synrift: Early Basin Continuity

Rift Initiation
The North Red Sea and Gulf of Suez were initiated in latest Oligocene-earliest Miocene as one contiguous rift system under an orthogonal stress (N55ºE) regime as indicated by rift-parallel dikes. Minimal fault throws and low subsidence rates took place in the Gulf of Suez throughout the deposition of the Nukhul Formation (Patton et al., 1994), and a similar structural situation is expected throughout the North Red Sea area for the time-equivalent Tayran Group (Figure 9). Early rift sedimentation is characterized by assemblages of volcanics and continental to shallow-marine facies in the Abu Zenima and Nukhul formations of the Gulf of Suez, and the Al Wajh, Yanbu and Musayr formations of the Tayran Group of the Northeast Red Sea (Figure 9).

The structural style was strongly influenced by pre-existing crustal anisotropies. The Najd Shear Zone controlled the placement and style of faults, drainage and accommodation zones in the Gulf of Suez (Figures 11 and 12). To the south in the North Red Sea, planar faults and the Azlam-Duwi Accommodation Zone formed along the pre-existing Najd Shear Zone. North of the Azlam-Duwi Accommodation Zone, a flexural margin was established along the eastern rift to the Morgan Accommodation Zone with planar east-northeast-dipping planar faults dominating the structural style. The corresponding border fault margin formed along the western side of the rift, from the Morgan Accommodation Zone to Gebel Duwi.

South of the Azlam-Duwi Accommodation Zone, along the Saudi Arabian margin, the border fault system has had little influence from the Najd Shear Zone. Instead, the margin is composed of a series of en-échelon, down to the west-southwest, concave listric faults that appear to tip out into the Yanbu and Bir Umq Pan-African sutures that have localized accommodation zones. The formation of accommodation zones along the sutures may be due to previous strain hardening related to Precambrian suture development.

Development of Prolific Synrift Point-Sourced Reservoirs and Source Intervals
At approximately 20 Ma, the rift system organized as the fault system linked, and subsidence accelerated (Figure 15). Extension moved inboard and the initial border fault system became inactive along much of the rift, as supported by seismic and well control and through analogy with the Gulf of Suez rift (Steckler et al., 1988; Bosworth et al., 1998). The precise timing of this event is difficult to establish due to the lack of marine facies and age control within the abandoned onshore grabens.

In the Gulf of Suez, Rudeis (submarine fan) and Kareem (submarine fan and delta) reservoirs were deposited from river systems that entered the basin along major synthetic relay ramps and accommodation zones. Away from the fan depocenters, sediment starvation occurred as deep-marine Globigerina shales and marls with source potential developed. In the Northeast Red Sea, the same deep-marine Globigerina shales and marls are present in the time-equivalent Burqan Formation and Maqna Group (Hughes et al., 1999), though significant submarine fan and delta facies have not been recognized to date.

Postrift: Suez Quiescence and Oblique Red Sea Extension

Red Sea Play Element degradation?
Regional plate reorganization associated with the final closing of the Tethyan Ocean began at the end of the Middle Miocene, as crustal extension reached approximately 50% for the southern Gulf of Suez and North Red Sea. The left-lateral Gulf of Aqaba Transform System was initiated and separated the two basins. Crustal extension decreased significantly for the Gulf of Suez, and became oblique (N15ºE) for the North Red Sea (Figure 16).
The continued strain in the North Red Sea most likely affected the hydrocarbon system negatively as existing normal faults (and new normal and strike-slip faults) segmented traps, reservoirs and hydrocarbon source kitchens. Both transpression and transtension occurred throughout the North Red Sea as the Midyan Peninsula experienced contraction due to a constraining geometry while many offshore rhombochasms started to develop. Seal facies started to develop as basin restriction resulted from episodic hypersaline conditions observed in the Belayim Formation of the Gulf of Suez and Kial Formation of the Northeast Red Sea. By the Late Miocene, both basins were extremely hypersaline, as thick halite and anhydrite precipitated in the Gulf of Suez and North Red Sea, forming the respective South Gharib and Mansiyah formations.

Connection with the Indian Ocean occurred by the Early Pliocene as seafloor spreading initiated in an axial bathymetric trough, underlain by highly-extended and magmatized continental crust, in the southern Red Sea between 15° and 20°N (Girdler and Styles, 1974; Roeser, 1975; LaBrecque and Zitellini, 1985). North of this area, incipient fracture zones that parallel the Gulf of Aqaba segmented the axial trough. Individual segments were rotated counter-clockwise from the original Miocene rift trend in response to the oblique regional extension direction. Salt began to mobilize, allowing for the deposition of the Zeit-Shukheir and Ghawwas-Lisan formations, in rim-synclinal basins within the Gulf of Suez and Northeast Red Sea, respectively. This resulted in sediment ponding and a starved axial region where the salt maintained an attenuated sub-horizontal upper surface despite extensive faulting at depth.

**PRESENT-DAY NORTHEAST RED SEA: IMPLICATIONS FOR EXPLORATION POTENTIAL**

**Onshore Northeast Red Sea**

**Structural Development**

The onshore ‘Rifted Margin’ of the Northeast Red Sea is characterized by structural variability (Figures 17 and 18). The northern margin between the Midyan Peninsula and the Al Wajh sub-basin demonstrates a high level of structural complexity where both the Najd Shear Zone and cross-cutting Aqaba grains are prevalent. Strike-slip related structures occur within this area (e.g. transpressional folds along the Midyan Peninsula). To the south, the onshore border fault system displays limited relationships to the active offshore axial trough and fracture zones. The Umm Luj-Al Wajh and Yanbu-Jeddah sub-basins are bounded by Early Miocene listric, down to the west-southwest border faults that tip-out into Precambrian sutures that have localized accommodation zones.

**Clastics Provenance**

Individual catch basin sizes range from 1,100–73,800 sq km. The largest basin is associated with the Najd Shear Zone grain that apparently allowed for preferential erosion due to the inherent weakness of the shear zone (Figures 18 and 19). The same Najd Shear Zone erosion also influenced the second largest catch basin (12,500 sq km) located within the Azlam-Duwi Accommodation Zone. The two next-largest catch basins (9,600 and 10,700 sq km) reside within suture-controlled Yanbu and Bir Umq Accommodation Zones, respectively.

It is reasonable to postulate that the Precambrian basement controls that have influenced the present-day drainage would also have had similar controls in the Early and Middle Miocene. The largest and most significant drainage catchments are related to the preferential head-wall erosion associated with the Najd Shear Zone. Interestingly, the suture-related accommodation zones are not related to preferential erosion. Instead, both areas are basement promontories that have retained some of their original broad, ramp-type geometries related to the lack of through-going border faults.

Relative reservoir quality for the Middle Miocene sand bodies was determined through inspection of USGS digital maps and postulations based on prerift restorations (Figures 14 and 20). The provenance lithologies are widely varied along the Northeast Red Sea (Brown et al., 1989) with better relative reservoir potential in the northern portion due to thicker Cambrian-Ordovician sandstone and less synrift volcanics.
Offshore Northeast Red Sea

Structural Development
The offshore Northeast Red Sea is more difficult to characterize due to data limitations (Figures 5a to 5c):

The Shelf Margin is located along the nearshore areas due to footwall crest support or recent delta deposition, and is often rimmed by reef walls with deep-water areas immediately offshore (Figures 8 and 9). The Mansiyah salt section has been mobilized throughout much of this trend and is present only locally.

The Basin and Ridge trend is characterized by continuous to semi-continuous salt ridges associated with rotated basement-involved horst blocks. The horst blocks, along the reprocessed SRS-2 dip line, are kilometers in size (Figure 6), similar to many of the Gulf of Suez horst blocks (Figure 12a). The horst blocks and associated salt ridges, are separated by Pliocene to Recent rim-synclinal basins with the potential for large salt withdrawal anticlines. Gravity models in this trend suggest that the salt can reach 3 km in thickness.

The Axial Deep trend is defined by a bathymetric trough with an associated isostatic gravity high and reduced-to-the-pole magnetic maxima (notably in the southern sector). The trend is postulated to be a zone of highly attenuated crust, though poor imaging precludes confirmation of this model. There is very little evidence of significant post-salt depocenters in the trend, and consequently the region experienced only minor loading and mobilization of salt. This results in attenuated tabular salt bodies covering much of the area (Figure 17).

Synrift sand-bodies
Early to Middle Miocene point-sourced sands are structurally controlled in the Gulf of Suez. Sands of similar reservoir scale and variable quality are postulated in the Northeast Red Sea (Figures 17 and 20). Reservoir quality decreases to the south due to increased uncertainty in the presence and thickness of pre-rift sands and an increase in synrift volcanics. Relative depositional positions and size are postulated based on onshore pre-existing structure and border fault segmentation that appears to have been largely inactive since their origination or reactivation in the Early to Middle Miocene. The offshore areas, juxtaposed to the Najd Shear Zone and accommodation zones, have been high-graded due to better potential for long-lived drainage systems. Although Early to Middle Miocene sands were almost certainly deposited in what is now the axial deep region, this area is interpreted to be highly attenuated crust that has serious preservation issues.

DISCUSSION
This integrated, process-oriented, play-element analysis of the North Red Sea and the Gulf of Suez provides a model for exploration of point-sourced synrift sandstone reservoirs in the Northeast
Red Sea. The tectono-stratigraphic interpretation of the Northeast Red Sea predicts a strongly variable synrift depositional architecture because of temporal changes in sediment supply, and accommodation creation and destruction throughout rifting. Sediment supply is the critical factor in the Burqan Formation and Maqna Group for the development of point-sourced deltas and submarine fans. Accommodation space and eustatic changes are believed to be less important for the synrift facies due to the under-filled nature of the Red Sea basin during this time. Therefore, identification of the Miocene border fault system and the associated sediment entry points is of paramount importance to postulate the existence of offshore depocenters. However, structurally controlled sediment supply may change through time as a fault system develops.

As large synthetic fault systems link, topographic (or bathymetric) expression of these segmentation structures is diminished (Figure 21a). A good example of this process is the East Tanka fault zone in the Gulf of Suez (Jackson et al., 2002). This can change drainage patterns in the area as the fault evolves as a single system (Dawers and Underhill, 1999; Young et al., 2001). As the fault tip propagates along strike, the drainage system at the tip may migrate laterally with it, so potential reservoir units migrate laterally and vertically in a systematic way in the stratigraphic record. Additionally, low-side structural highs may migrate as well. If the two faults link and become one, sediment load from rivers can be redirected away from the basin and low-side structural culmination may diminish or become synclinal (Figure 21a).

Conversely, as rifts evolve, the individual half-grabens and their associated segmentation structures may become well established where large fault zones may consist of seismogenically distinct segments and the regions between them are ‘fixed’ spatially (e.g. Wasatch Front, Utah; as described
by Cowie and Scholz, 1992b). In particular, rifts with opposing half-graben geometries appear to maintain their segmentation structures for much of their history. This is because it is mechanically difficult for a border fault to propagate further along strike within the stress shadow of the adjacent basin. Therefore, structural accommodation zones that separate sub-basins with opposing dip-domains (e.g. Zaafarana, Morgan, and Azlam-Duwi Accommodation Zones) have the best potential for long-lived sedimentation along intra-basin highs (Figure 21b).

Frequently, accommodation zones in rift basins are coincident with pre-existing lineaments or shear zones. This is particularly true where these antecedent structures intersect the rift axis obliquely. This has been observed in the North Sea (Cartwright, 1992), the western branch of the East African rift system (Versfelt and Rosendahl, 1989; Lezzar et al, 2002 ), and the Gulf of Suez (Younes and McClay, 2002). Depending on the geometry of the intersecting trends, border faults may become pinned due to inhibiting stresses and displacement may be transferred to another border fault system. For all of the reasons outlined above, the recognition of long-lived sediment input points, coincident with accommodation zones and pre-existing shear zones, provide a framework for predicting reservoir distribution along the margins of the Northeast Red Sea.

Post-depositional (Middle Miocene) preservation of reservoir, trap and hydrocarbon source kitchens is a concern for the North Red Sea. Present-day extension for the North Red Sea is estimated to be approximately 200%, compared to an estimated 50% for the Gulf of Suez. Most of the strain appears to be localized in the highly attenuated Axial Deep, with the Rifted Margin, Shelf Margin and Basin and Ridge provinces less affected. In addition to the increased extension rate, the Red Sea’s extension direction has also changed relative to that of the Gulf of Suez. This occurred when the Red Sea’s stress

![Diagram](http://pubs.geoscienceworld.org/geoarabia/article-pdf/10/1/97/5441808/polis.pdf)  
**Figure 21:** Diagram illustrating structural and stratigraphic changes through time. In (a) as the two faults link, sediment load from rivers can be redirected away from the basin (AA') and low-side structural culmination may diminish (BB'). In (b), a structural accommodation zone separates the two sub-basins with opposing dips (e.g. Zaafarana, Morgan, and Azlam-Duwi Accommodation Zones) resulting in long-lived sedimentation along intra-basin highs.
direction changed from N55°E to N15°E with the initiation of the Gulf of Aqaba Transform System. This caused the North Red Sea to become segmented while the Gulf of Suez experienced only minor extension. In particular, cross-cutting N15°E-oriented, left-lateral strike-slip faults segmented the northernmost Red Sea as structural complexity increased significantly.

SUMMARY

This study provided new insights on major controls for the development of the largest Gulf of Suez synrift fields (i.e. July, Belayim Land, Belayim Marine and Morgan). The most significant of these are:

1. The fields have synrift Miocene point-sourced sandstone reservoirs that are positioned down-dip from major fault tips or fault-minima zones. Along the high-side of the fault system, these zones have relatively less footwall uplift and formed topographic lows that localized the sediment entry-points.

2. The fields are located within the basin along broad highs, up-dip from sub-basins. This geometry provides a trap that allows for sediment accommodation and preservation juxtaposed to sub-basins (hydrocarbon source kitchens) down-dip.

3. The Belayim Land and Morgan fields, positioned along the eastern-border fault system, have received long-lived point-sourced sands during the deposition of the Rudeis, Kareem, Belayim and South Gharib formations. This steady sedimentation is attributed to a ‘pinned’, or stable, eastern-border fault system controlled by the Najd Shear Zone, and a polarity change in the upper plate transfer direction.

Restorations indicate that the North Red Sea and the Gulf of Suez shared similar early rift histories and should have had comparable structurally controlled Early to Middle Miocene point-sourced sandstone reservoir facies. The postulated location, size, and relative quality of Northeast Red Sea sand-bodies are interpreted based on the border fault segmentation and provenance lithologies. In general, provenance quality decreases to the south, and major sediment entry-points are positioned along Precambrian sutures (accommodation zones), and the Najd Shear Zone. Taken as a whole, the northern flexural margin has the best potential for localized, second-generation, thick, synrift sediments similar to that of the Gulf of Suez due to the Azlam-Duwi Accommodation Zone, the onshore provenance, and the Najd Shear Zone. However, continued extension and higher heat flow do not bode well for the hydrocarbon system as a whole, because of increased potential for degraded reservoir quality and preservation, reduced trap size, and additional fluid and migration complexities.

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