Accommodation zones and tectono-stratigraphy of the Gulf of Suez, Egypt: A contribution from aeromagnetic analysis

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ABSTRACT

This paper starts with an up-to-date literature review of the pre-rift, syn-rift and post-rift stratigraphy of the Gulf of Suez. The geometry and depth of the Proterozoic basement is not generally known due to poor seismic images below the Upper Miocene evaporites (including massive rock salt) and clastics. The pre-rift Paleozoic to Early Oligocene succession shows that several local basins (c. 10s of km in extent) occur in the Gulf, with thick sedimentary sections (e.g. c. 3,000 m for Paleozoic and 1,000 m for Jurassic and Lower Cretaceous). The origin and distribution of these basins is not well understood and the presence of similar pre-rift basins in the southern Gulf is not known to occur. The syn-rift Late Oligocene to Middle Miocene and post-rift Late Miocene – Pliocene successions are widely distributed within the rift basin and reach a thickness in excess of 5,000 m.

In order to visualize the grain and relative relief of the Proterozoic basement, a series of aeromagnetic images are shown in this paper. The images include Total Magnetic Intensity (TMI), Reduced-to-Pole (RTP), filtered regional and structural RTP, and Second Vertical Derivative (SVD). The paper also shows a three-dimensional visualization image of the magnetic basement that highlights the distribution of the basins in the Gulf. The magnetic lows do not generally trend along the Suez (NNW-trending Clysmic) Fault, but instead show highly variable orientations attributed to a complex pattern of criss-crossing faults. In particular, two areas were selected to interpret the geometry and depth of the basement. The first area covered the northern Zaafarana Accommodation Zone and involved modeling five aeromagnetic profiles. The Zone was interpreted as an EW-trending basement plateau bounded by basins that are c. 8,000 m deep. The second modeled area (four profiles) covered the southern Morgan Accommodation Zone. This zone was interpreted as an ENE-trending plateau of similar relief to the Zaafarana Zone. The Morgan Zone is terminated in the eastern Gulf by the 8,000-m-deep Morgan Basin. The very deep basins surrounding the two plateaus may contain both pre-rift and syn-rift source rocks, from which the numerous surrounding petroleum fields were sourced.

INTRODUCTION

The Gulf of Suez is located in Egypt, between the Sinai Peninsula and the African continent (Figure 1). It originally formed during the Paleozoic as a narrow embayment of the Tethys Ocean, and was rejuvenated as an inter-continental, rift basin in the Late Oligocene (e.g. Robson, 1971; Jarrige et al., 1990; Bosworth et al., 1998; Montenat et al., 1998a, b). The basin contains nearly 100 petroleum fields and has been producing since the early 20th Century (Figure 1; EGPC, 1996). One of the greatest challenges faced by exploration in the Gulf is the poor seismic images obtained from the target reservoir zones below the thick evaporites of the Miocene South Gharib and Zeit formations (Figure 2).

In many frontier basins, geophysical exploration activities generally start with magnetic and/or gravity prospecting. These cost-effective techniques (known as potential methods) estimate the thickness of the sedimentary section above the basement. Once potential methods identify anticlinal basement structures, geophysical exploration continues with seismic prospecting leading to exploratory drilling. In contrast to frontier basins, the Gulf of Suez has been extensively explored with seismic and many 100s of exploration wells. Nevertheless, due to the poor sub-salt seismic images, it continues to hide petroleum fields. The shortcoming of seismic prospecting is precisely why magnetic imaging should
Figure 1: (a) Landsat Thematic Mapper image showing the basement outcrops and oil fields around the Gulf of Suez region. Satellite image courtesy of GeoTech, Bahrain. Original Copyright Earth Satellite Corporation.

(b) Basins and major faults in the Gulf (modified after EGPC, 1996; Amgad and McClay, 2002; updated structural map reproduced by permission of W.M. Meshref).
be considered as an important tool for exploring this otherwise mature basin. Moreover, in parts of the Gulf, wells do not reach the basement and the deeper stratigraphy is not known.

The present study starts with an up-to-date review of the tectono-stratigraphic setting of the Gulf of Suez. It then shows regional aeromagnetic images of 1981 survey from the Gulf including Total Magnetic Intensity (TMI), Reduced-to-Pole RTP, high-pass and low-pass spatial filters of the RTP image, and Second Vertical Derivative (SVD) of the TMI image. These images provide different ways to see the magnetic basement and a valuable database for explorationists. The final part of the study focuses on using aeromagnetic data to map the basement depth, and in particular the geometry and extent of two major accommodation zones that cross the Gulf.

STRATIGRAPHY OF THE GULF OF SUEZ

The stratigraphy and petroleum geology of numerous oil and gas fields in the Gulf of Suez was published by the Egyptian General Petroleum Corporation (EGPC) in 1964 and 1996. The stratigraphic column in Figure 2 follows with some modifications from these publications as well as numerous papers and books (e.g. Said, 1962, 1990; Saoudi and Khalil, 1986; Richardson and Arthur, 1988; Evans, 1988; Patton et al., 1994; Alsharhan and Salah, 1997; Purser and Bosence, 1998; Bosworth and McClay, 2001; Jackson et al., 2006). The stratigraphy of the Gulf is divided into (Figure 2):

- Proterozoic Basement,
- Paleozoic, Mesozoic, and Lower Tertiary pre-rift succession,
- Late Oligocene, Early and Middle Miocene syn-rift succession,
- Late Miocene, Pliocene, and Pleistocene post-rift succession.

Proterozoic Basement

The Proterozoic Basement of the Arabian-Nubian Shield runs along the margins of the Gulf of Suez. It is represented by a great variety of crystalline and metamorphic rocks, frequently cut by dykes and sills of basic and acidic intrusives (Schurman, 1966). Different types of granites, schists, gneiss and porphyrites are recognized. The youngest intrusive igneous rocks are intermediate and acidic plutons, which yield radiometric ages averaging ca. 570 million years (Ma). Basement rocks crop out along the Gulf Rift shoulders, for example Esh El-Mallaha, Gebel El Zeit, Gebel Araba and Abu Durba, and also throughout the northwestern flank of the Sinai massif (Figure 1). They were uplifted along the coastal ranges most probably in Late Oligocene and Early Miocene time. They are the provenance for clastics deposited in the Gulf throughout the Paleozoic to Quaternary times.

Figure 3a shows an interpretation by Meshref et al. (1976) for the basement from aeromagnetic and geological data. Three major NE-trending shear zones were interpreted to cross the basin. Figure 3b (unpublished map reproduced by permission of W.M. Meshref), shows the basement depth map, which attains a maximum depth of c. 17,000–18,000 ft (c. 5,300 m). Since these pioneering studies, the fault system of the Gulf was interpreted to be more complex (Figure 1b) and as discussed below the basement’s depth to be substantially greater (c. 8,000 m).

Pre-rift Succession

Paleozoic sediments crop out at several localities on both sides of the Gulf and are encountered in numerous boreholes in the offshore Gulf (Abdallah and Adindani, 1963; Al Far, 1966; Issawi and Jux, 1982; see review by Alsharhan and Salah, 1997). On the eastern side (Figure 1), Paleozoic outcrops are found near several gebels (jabals) including Gebel Qibliat, Gebel Durba, Gebel Araba, Gebel Nezzazat, Gebel Umm Bogma, Gebel Nukhul, and Wadi Feiran; along the western-side, outcrops occur at Esh El-Mallaha Range, Gebel El-Zeit, southern and northern Galala plateaus and Wadi Araba.

In the Gulf, the terms *Nubia Sandstone, Nubia Group* or *Nubia Complex* are used to describe undifferentiated Paleozoic and Mesozoic sandstones. Alsharhan and Salah (1997) reviewed the
**Figure 2a:** Generalized stratigraphic column of the Gulf of Suez for the pre-rift succession (after EGPC, 1996, Alsharhan and Salah, 1997, and Hafez, 2000).

| Lithostratigraphy | Lithology | Type Section (meter) |
|-------------------|-----------|----------------------|
| **LOWER OLIGOCENE** |          |                      |
| Upper             |           |                      |
| Tayiba Formation  |           |                      |
| Tanka Formation   |           |                      |
| Kharaba Formation |           |                      |
| Darat Formation   |           |                      |
| Thebes Formation  |           |                      |
| **MESOZOIC**      |          |                      |
| Upper             |           |                      |
| Eocene            |           |                      |
| Esna Formation    |           |                      |
| Sudr Formation    |           |                      |
| Duwi Formation    |           |                      |
| Matulla Formation |           |                      |
| Wadi Matulla      |           |                      |
| Wata Formation    |           |                      |
| Abu Qada Formation|           |                      |
| Raha Formation    |           |                      |
| Malha Formation   |           |                      |
| Qiseib Formation  |           |                      |
| **PERMIAN**       |          |                      |
| Lower             |           |                      |
| Cretaceous        |           |                      |
| El Tih Gp         |           |                      |
| Rod El Hamal      |           |                      |
| Wadi Rod El Hamal |           |                      |
| Abu Durba Formation|        |                      |
| Gebel Durba       |           |                      |
| **PALEOZOIC**     |          |                      |
| Lower             |           |                      |
| Carboniferous     |           |                      |
| Ataqa Gp          |           |                      |
| Umm Bogma Formation|        |                      |
| Gebel Nukhul      |           |                      |
| **CAMBRIAN-ORDOVICIAN** |    |                      |
| Qibliat Gp        |           |                      |
| Naqus Formation   |           |                      |
| Arba Formation    |           |                      |
| Gebel Qibliat     |           |                      |

**Legend**
- Mature source rock
- Reservoir
- Seal
- Conglomerate
- Sandstone
- Shale
- Marl
- Limestone
- Evaporite
- Dolomite
- Volcanics

The lithostratigraphy, sedimentology and hydrocarbon habitat (reservoirs and source rocks) of the Nubian Sandstone in the Gulf and proposed the following scheme (Figure 2a):

1. **Qibliat Group** consisting of the Cambrian – Ordovician Arba Formation (Nubia D member) and Ordovician Naqus Formation (Nubia C member).

2. Early Carboniferous Umm Bogma Formation (lower part of Nubia B member), which is not assigned to a group.

3. Late Carboniferous and Permian Ataqa Group consisting of the Abu Durba and overlying Rod El Hamal Formation (upper part of Nubia B member).

The isopach of the Paleozoic succession is shown in Figure 4 (modified after Zahran, 1987, and Hafez, 2000). It shows the NW-trending October Basin contains a Paleozoic section c. 3,000 m
Figure 2b: Generalized stratigraphic column of the Gulf of Suez for the syn-rift and post-rift succession (after EGPC, 1996, Bosworth et al., 1998, Hafez, 2000, Alishanam, 2003, and Jackson et al., 2006).

Lithostratigraphy

| Fault Style | Tectonic Subsidence | Events |
|-------------|---------------------|--------|
| Gulf of Aqaba Rift System | • Subsidence • Halokinesis • Margin uplift | End of Suez Rift • Start of Aqaba Transform System |
| • Transfer to high-angle normal faults | • Marine transgression | • Early rifting and igneous activity |
| • Low-angle normal faults and rotated fault blocks | | |

Type Section

| Syn-Rift Succession | Post-Rift Succession |
|---------------------|----------------------|
| Gebel Zek-2 | Gebel Zeit-2 |
| South Gharib-2 | South Gharib-2 |
| Belayim 12.12 | Belayim (300 m) |
| Gharib N-2 | Gharib N-2 |
| Abu Zenima-1 | Abu Zenima-1 |
| Rudeis-2 | Rudeis-2 |
| Zeit Bay-1 | Zeit Bay-1 |

Lithostratigraphy

| Ras Mafdet Group | Gharian Group |
|------------------|--------------|
| Zaitaara Formation | Zaitaara Formation |
| Wardan Formation | Wardan Formation |
| Zeit Formation (940 m) | Zeit Formation (940 m) |
| South Sharm Formation (700 m) | South Sharm Formation (700 m) |
| Hamman Farman Member | Hamman Farman Member |
| Firan Member | Firan Member |
| Shari Member | Shari Member |
| Baba Member | Baba Member |
| Abu Zenima Formation | Abu Zenima Formation |
| Shagar Member | Shagar Member |
| Markha Mbr | Markha Mbr |
| Rahim Mbr | Rahim Mbr |
| Gharandal Group (300 m) | Gharandal Group (300 m) |
| Gharandal Group | Gharandal Group |
| Zaafarana Formation | Zaafarana Formation |
| Wardan Formation | Wardan Formation |
| South Gharib Formation (700 m) | South Gharib Formation (700 m) |
| Gharandal Group | Gharandal Group |
| Gebel Zeit-2 | Gebel Zeit-2 |
| Gharib N-2 | Gharib N-2 |
| Abu Zenima-1 | Abu Zenima-1 |
| Rudeis-2 | Rudeis-2 |
| Zeit Bay-1 | Zeit Bay-1 |
| Gharandal Group | Gharandal Group |
| Gebel Zeit-2 | Gebel Zeit-2 |
| Gharib N-2 | Gharib N-2 |
| Abu Zenima-1 | Abu Zenima-1 |
| Rudeis-2 | Rudeis-2 |
| Zeit Bay-1 | Zeit Bay-1 |
| Gharandal Group | Gharandal Group |

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Figure 3: (a) Basement fracture/fault map for the Gulf of Suez (after Meshrif et al., 1976). (b) Depth to basement using geological data (unpublished map reproduced by permission of W.M. Meshref).
Figure 4: Paleozoic isopach map of Gulf of Suez (modified after Zahran, 1987, and Hafez, 2000).

Figure 5: Isopach of the Late Jurassic and Early Cretaceous Malha Formation of the Gulf of Suez (modified after Zahran, 1987, Khalil, 1993, and Hafez, 2000).
thick, with the North October and giant October fields lying to its northeast. These fields produce oil from the Nubia Sandstone (EGPC, 1996).

(4) El Tin Group (Nubia C member, or Mesozoic Nubian) consisting of the Triassic – Early Jurassic Qiseib Formation and Late Jurassic – Early Cretaceous Malha Formation. Triassic rocks are only developed in Arif El Naga in the northern Sinai Peninsula. Jurassic sediments are restricted to the northern part of the Gulf, and exposed in the Maghara Uplift in northern Sinai and Khashm El Galala.

The isopach of the Malha Formation shows several basins in the northern and central Gulf (Figure 5, modified after Zahran, 1987; Khalil, 1993; Hafez, 2000). These basins formed during the Late Jurassic along E-W trending faults (Kerdany and Cherif, 1990), and are associated with Early Cretaceous basaltic igneous activity. The clastics of the Malha Formation are producing reservoirs in several oil fields (Figure 2a; EGPC, 1996).

The Late Cretaceous formations are from base to top, Raha, Abu Qada, Wata and Matulla of the Nezzazat Group, and the Duwi and Sudr formations assigned to the lower part of the El Egma Group (Figure 2a). The lower part of the Sudr contains the Brown Limestone unit, which is an important source rock in the Gulf. Paleogene deposits are widespread in Egypt and represented by the Esna Formation of the El Egma Group (Said, 1962), which was probably deposited in most parts of the Gulf (Figure 6).

In the Hammam Faraun fault block (Figure 1), Jackson et al. (2006) studied the Eocene and Oligocene succession in order to pinpoint the onset of rifting in the Gulf. They reviewed the lithology, biostratigraphy and depositional setting of this succession based on earlier works (see references therein). The Eocene part of El Egma Group consists of four formations (Figure 2a): (1) Lower Eocene Thebes Formation, (2) Middle Eocene Darat Formation, (3) Middle Eocene Khaboba Formation, and (4) Upper Eocene Tanka Formation. In this area, Jackson et al. (2006) identified the Lower Oligocene Tayiba Formation (0–56 m thick) as the youngest preserved pre-rift unit. They also suggested that a regional mid-Oligocene sea-level drop accompanied the onset of rifting.

**Syn-Rift Succession**

The oldest syn-rift rock unit in the Gulf is represented by the latest Oligocene to earliest Miocene Abu Zenima Formation (0–112 m thick, Figure 2b; Patton et al., 1994; Jackson et al., 2006). This Formation corresponds to the “Red Bed Series of Group A” (Montenat et al., 1988) and in part to the Shaab Ali Member of the Nukhul Formation (Saoudi and Khalil, 1986). The Abu Zenima Formation contains basaltic flows, which have been dated at ca. 24.0–22.0 Ma (Montenat et al., 1988; Evans, 1988).

The Nukhul Formation represents the oldest unit of the Gharandal Group (Figure 2b). Above the Shaab Ali Member, the upper part of this Formation consists of three laterally equivalent Early Miocene members (Saoudi and Khalil, 1986). From the northern to the southern Gulf: (1) continental clastics of the October Member, (2) alternating marls and evaporites of the Ghara Member, and (3) carbonates of the Gharamul Member. The thickness of the Nukhul Formation varies considerably due to syn-depositional faulting and ranges from zero to 800 m.

Above the Nukhul Formation, two stratigraphic schemes are used in different parts of the Gulf for the upper part of the Gharandal Group (Figure 2b). The first is characterized by the Lower Miocene Rudeis Formation (100s–2,000 m thick) and Middle Miocene Kareem Formation (250–350 m thick). The Rudies Formation is further divided into Upper and Lower Rudies members separated by the Mid-Clysmic Unconformity. The Kareem Formation is divided into the lower evaporitic Markha or clastic Rahmi members, and upper clastic Shagar Member. The Kareem Formation contains some of the most prolific petroleum reservoirs in the Gulf (EGPC, 1996; Alsharhan, 2003).

In the second scheme (e.g. Wescott et al., 1996; Krebs et al., 1996), the upper part of the Gharandal Group is represented by the Mheiherrat Formation (Lower Rudeis Member), Hawar and Asl formations (in part correlative to Upper Rudies Member). The overlying Ayun Musa Formation consists of the...
Figure 6: Isopach of the Paleogene in the Gulf of Suez (Farhoud, 2006).

Figure 7: Northern limits of Miocene salt and anhydrite, Gulf of Suez (modified after Zahran, 1987, Hafez, 2000, and Schütz, 1994).
evaporitic Lagia Member (in part correlative to the Markha Member of the Kareem Formation) and the clastics of the Ras Budran Member.

**Post-Rift Succession**

The post-rift Ras Mala’ab Group is mainly composed of evaporites and clastics. It is divided into Middle Miocene Belayim Formation, and Upper Miocene South Gharib and Zeit formations (Figures 2 and 7). The Belayim Formation (c. 300 m thick) consists of the evaporites of the Baba Member (10 to c. 100 m thick), fine clastics of the Sidri Member (several 10 m thick), evaporites of the Feiran Member (c. 100 m thick) and fine clastics and carbonates of the Hammam Faraun Member (c. 50–100 m thick). The overlying Late Miocene South Gharib consists mainly of anhydrite and salt, more than 1.0 km thick in salt domes (Fawzy and Abdel Aal, 1984). The Zeit Formation consists mainly of interbedded anhydrite and shale layers and can attain a thickness of c. 1.0 km in salt withdrawal basins. The post-Miocene succession consists of the Warden Formation and overlying Zaafarana Formation, which together can attain a thickness in excess of 1.0 km in salt withdrawal basins.

**TECTONIC SETTING OF THE GULF OF SUEZ**

The Gulf basin is characterized as a failed rift system related to the relative movements of the African, Arabian, and Levant plates. The rift was initiated in Late Oligocene (ca. 24.0 Ma) as evident from the volcanic rocks of the Abu Zenima Formation. Several basin-wide unconformities interrupted the Phanerozoic sedimentary record, and according to Dolson et al. (2001) they were primarily in response to regional tectonic adjustments associated with different rift phases. Figure 2b summarizes the tectonic factors that affected the Gulf since the Late Oligocene (Bosworth et al., 1998; Alsharhan, 2003).

Crustal extension and tectonic subsidence of the Gulf’s axial trough reached a maximum during the Early Miocene (ca. 19.0–17.0 Ma; Schütz, 1994), when the syn-rift Rudeis Formation was deposited. The shoulders of the basin may have risen in the Oligocene and Early Miocene due to thermal effects (Steckler, 1985). Moretti et al. (1986) concluded that the rift shoulders were formed as a result of advection in the asthenosphere away from the center of the rift combined with regional stretching of the lithosphere. By Middle Miocene (ca. 15 Ma) strike-slip movements began along the Aqaba-Dead Sea Fault System and the Gulf became less active if not inactive as a spreading center (Abdel Gawad, 1970a, b; Bartov et al., 1980).

Meshref et al. (1976); Moustafa (1976) Moustafa (1996, 1998); Amgad and McClay (2002) concluded that the structural configuration of the Gulf is largely controlled by a complex pattern of faulting with two main trends: (1) NW Suez fault trend (Clysmic), which played the most important role, and (2) NE Aqaba trend. The interaction of the two fault trends resulted in a pattern of en-echelon faulted blocks. The Gulf of Suez basin is generally divided into three structural provinces separated by two accommodation zones (Figure 1b):

1. Northern Wadi Araba Province with strata dipping regionally to the southwest,
2. Zaafarana Hinge Zone (also Galala–Zenima),
3. Central Belayim Province with strata dipping regionally to the northeast,
4. El Morgan Hinge Zone (also Sufr El Dara),
5. Southern Amal Province with strata dipping regionally to the southwest.

The initial rift fault system was highly segmented with numerous isolated and smaller rift basins developing throughout the three provinces (Amgad and McClay, 2002). Abdel Gawad (1970a, b) noted that three fault systems (trending N, NW, and WNW) appear to have influenced the structure of the Gulf and Red Sea areas. In the western part of the Sinai Peninsula, at Gebels Araba and Abu Durba, he interpreted left-lateral displacements along the N-S faults, and right lateral movements with the WNW faults. Issawi et al. (1981) in their structural study of the Wadi Feiran and Sinai Peninsula concluded that folds are related to faulting in an overall extensional setting rather than to regional compression.
The first aeromagnetic survey over the Gulf of Suez was acquired in 1964; it consisted of flights spaced 5 km apart NE-SW and two tie lines over the coasts. In 1981 an aeromagnetic survey was conducted for 10 petroleum companies by Aero-Service; the flight lines were spaced one kilometer apart NE-SW with tie line spaced at 5 km. In 1997 a high-resolution aeromagnetic survey was flown over the southern half of the Gulf with flight-line spacing of 250 m and 400 m tie-line spacing. In 2002 the northern half of the Gulf was covered by another high-resolution aeromagnetic survey with the same specifications as the 1997 survey. The sensitivity and spatial resolution of the cesium vapor magnetometer used in 1997 and 2002, was greater than of that of the proton magnetometer used in the 1981 survey. As a result the later two surveys measured the magnetic field with a spacing of 7–9 m compared with 70–90 m in the 1981 survey.

The present study uses the data acquired by Aero-Service in 1981. It has been interpreted by other authors in different localities in the Gulf (Meshref, 1990; Hammouda, 1986; Zahran, 1987; Said, 1990; Sharafeldin, 1991; Hafez, 2000). The 1997 and 2002 surveys, however, are not available in the public domain. The maps presented here were digitized and compiled by the present author, starting from Total Magnetic Intensity (TMI) readings that were subjected to leveling and joined into one regional map.

**ANALYSIS AND INTERPRETATION OF AEROMAGNETIC DATA**

The Earth’s magnetic field at its surface arises from four basic sources:

1. Magnetic basement rocks and basement topography (granitic and basaltic basement rocks either by their varying distances to the surface or by changes in their magnetic properties),
2. Near-surface and surface cultural iron contamination,
3. Local intrusive and volcanic rocks or debris that may lie at semi-shallow depths,
4. Authigenic magnetic alterations in shallow sedimentary formation (sedimentary residual magnetization “SRM”).

Total Magnetic Intensity (TMI) data records the vector sum of all these magnetic bodies. Each body contributes to the total measurement based on the strength of its magnetic susceptibility and its depth of burial. The TMI of the Gulf is shown in Figure 8; it is displayed as an image rather than a contoured map in order to enhance regional geological structural features.

Two major types of anomalies are present in magnetic data. The first is mainly produced by changes in the magnetic susceptibility of the basement’s composition. It results in anomalies (referred to intra-basement anomaly or regional anomaly) that are regionally broad (low frequency or high wave number) and of considerable amplitude (100s of Nanotesla – nT). The second type of anomaly is more sharp (high frequency) and with relatively smaller amplitudes (several 10s nT). It mainly reflects the basement relief, and is referred to as supra-basement anomaly or residual anomaly. Many techniques in the space (wave number) and frequency domains can be applied to aeromagnetic data to enhance regional and residual anomalies or to sharpen subtle anomalies by derivatives and frequency filters.

**Reduction to the North Magnetic Pole (RTP)**

The inclination of the Earth’s magnetic field varies between 90° to 0° from the Pole to Equator. Magnetic anomalies located at middle latitudes show a dipole nature, which causes difficulties in differentiating and locating their magnetic sources. In order to position the magnetic anomaly directly over its source body, the TMI data (Figure 8) was Reduced-to-Pole (RTP) as shown in Figure 9, assuming a total magnetic field strength of 42,000 nT, inclination of 40.2°, and declination of 02.8°. In the RTP image the magnetic field appears as if the body was situated at the Earth’s magnetic poles, thus simplifying the interpretation procedures. The RTP transformation assumes that all magnetization is induced (i.e. the magnetization direction is parallel to the Earth’s magnetic field), which produces a northward shift of the positive part of each anomaly to a location over the causative body.
Figure 8: Digitized Total Magnetic Intensity (TMI) field in Nanotesla (nT) of the Gulf of Suez (compiled after W.M. Meshref, 1990; Hammouda, 1986; Zahran, 1987; Sharafeldin, 1991; Hafez, 2000).

Figure 9: Total Magnetic Intensity (TMI) field reduced to the north magnetic pole (RTP).
Regional - Residual Separation of RTP Data

A magnetic anomaly is composed of a broad spectrum of frequencies, each characterized by an amplitude. If the susceptibility at a certain depth increases, the amplitude of the anomaly will increase and so will its contribution to the corresponding part of the power spectrum. The relationship between wave number and amplitude, for any given depth, may be expressed as a plot of the logarithm of the amplitude power spectrum versus wave number (Spector and Grant, 1970).

Figure 10 shows the power spectra for the Zaafarana and Morgan accommodation zones. The decreasing gradient with increasing wave number reflects shallower sources. The plot can be used to design filters that separate the regional and residual anomalies (Nettleton, 1976). This technique, known as the pseudo depth slice, sets the cut-off for the filter at the intersection of the slopes of the deep and shallow components. It is not however useful for the accurate determination of depth (Spector and Grant, 1970). Figures 11 and 12 compare the residual and regional anomalies after they were separated by a spatial filter.

Second Vertical Derivative (SVD) of RTP data

The second vertical derivative technique is one of the most useful technique for defining the edges of magnetic bodies and amplifying subtle anomalies. The zero contour line is particularly important in identifying the locations of faults (Figure 13) as discussed below.

AEROMAGNETIC INTERPRETATION

The pioneering study by Meshref et al. (1976) interpreted three NE-trending shear zones from the 1964 aeromagnetic data (Figure 3). Figure 14 shows the distribution of magnetic basins derived from the present study as a 3-D visualization image of the low-pass magnetic map of the Gulf. Many of the magnetic lows can be correlated with well-defined basins.

2-D Magnetic Modeling of Accommodation Zones

Depth interpretations were carried out along nine profiles that cross the magnetic anomalies over the Zaafarana and Morgan accommodation zones (Figures 15 and 16). These zones represent the border areas where changes occur in the depth of the basement and for the dips of faults and strata. The objective of the depth modeling is to map these changes along the nine profiles.

Figure 10: Radially averaged power spectrum of the reduced to the north magnetic pole (RTP) for the Zaafarana and Morgan accommodation zones. See Figure 1b for location of accommodation zones.
Figure 11: High-pass component of the Total Magnetic Intensity (TMI) field after it was reduced to the north magnetic pole (RTP, shown in Figure 9).

Figure 12: Low-pass component of the Total Magnetic Intensity (TMI) field after it was reduced to the north magnetic pole (RTP, shown in Figure 9).
The RTP magnetic values were digitized along the profiles and are shown as the observed points in Figures 15 and 16. The geological models are two-dimensional (2-D) and shown as Basement and Sedimentary Section in the profiles. The models included drilled depths to basement, and accounted for measured susceptibility contrasts, altitude of outcropping basement, magnetic inclination (40.2°), declination (2.8°), and variable flight altitude, especially in rugged topographic areas.

For each profile three main parameters were considered in building the initial geological model: (1) depth to top of magnetic basement, (2) depth to base of magnetic basement, and (3) magnetic susceptibility of the basement (constant in case of regional work like the present study or can be varied laterally in more detailed work). The GM-SYS™ modeling software (Northwestern Geophysical, Canada) was used because it allows intuitive and interactive manipulation of the model and real-time calculation of the magnetic response. Once the parameters were selected, an iterative technique was used to minimize the root mean square (RMS) error between the calculated and observed magnetic data. The differences are shown in Figures 15 and 16.

The inversion procedure applied in this study is non-linear and does not produce a unique solution in most cases. However, the initial models for Profile-1 (Zaafarana area, Figure 15) and Profile-6 (Morgan area, Figure 16) were constructed with sufficient depth control to the basement to allow constraining the magnetic susceptibility of the basement rocks.

**Zaafarana Accommodation Zone**

In Profiles 1 to 3 (Figure 15), the magnetic basement depth dips gently from northeast (c. 2,500–3,500 m) to the southwest where it reaches 4,500–5,500 m. Profile-4 ties the first three profiles and confirms the depth calculations at their intersections (Figure 15). The first four profiles suggest that the Zaafarana Zone forms a broad plateau in the eastern side of the Gulf. In contrast, Profile-5 provides evidence for the hinge zone along the western flank of the Gulf (Figure 15). It shows that the plateau is about 5,000 m deep in the western side, the model suggests that Zaafarana zone extends c. 25 km EW in the offshore Gulf, attains a width of c. 20 km NS and is bounded to the north and south by basins that exceed 8,000 m in depth.

Figure 13: Second Vertical Derivative (SVD) of the Total Magnetic Intensity (TMI) field after it was reduced to the north magnetic pole (RTP, shown in Figure 9).
**Morgan Accommodation Zone and Morgan Basin**

Profiles 6, 7 and 9 reveal the deep Morgan Basin, which may have a sedimentary section that exceeds 8,000 m in thickness (Figure 16). The Basin trends along the Suez Rift and is c. 10 km wide near the eastern side of the Morgan Accommodation Zone. Surrounding the Basin, the basement is much shallower and ranges in depth between 3,000–4,000 m. Profile 8 (Figure 16) shows the northern termination of the Morgan Accommodation Zone and the limit of the Morgan Basin. The model suggests that the Morgan Zone extends 18 km into the Gulf and ends within it where it attains a width of c. 11 km.

**IMPLICATIONS FOR PETROLEUM SYSTEM**

In the northern Gulf, the Darag and Nebwi basins occur to the north of the Zaafarana Zone (Figure 14). The models in Profiles 1–5 suggest that the Zone extends across the Gulf and separates these two basins from the Zenima Basin in the central Gulf. The RTP and regional magnetic images (Figures 8 and 12) show that the Darag and Nebwi basins trend WNW (290°–310°) as suggested by Patton et al. (1994) rather than parallel to the Suez Clysmic trend (310°–350°) seen in the residual magnetic image (Figure 11) and SVD image (Figure 13). These interpretations imply that the Zaafarana Zone is a structural high, which separates two deep (8,000 m) broad basins: Darag and Nebwi basins to its north and Zenima Basin to its south. Each basin may contain a substantial pre-rift and/or Miocene reservoir and source rocks.

In the central Gulf, the Zenima, October, Issran and South Belayim basins correlate to magnetic lows (Figure 14). The Zenima, October and Issran basins trend approximately to the north (350°–030°), whereas the Belayim Basin trends EW. The Belayim Basin is located north of the Morgan Zone, which was modeled with Profiles

Figure 14: Three-dimensional view of regional magnetic component showing the magnetic basins (blue color) correlated with known geological basins. The two rectangles are centered over the Zaafarana and El Morgan offshore accommodation zones and modeled in depth (Figures 15 to 16). Faults north of Zaafarana Zone and south of the Morgan Zone (yellow shade) are downthrown to the NE with strata dipping SW. Between the two accommodation zones (gray shade), the faults are downthrown to the SW with strata dipping NE. See Figure 1b.
CONCLUSIONS

The Gulf of Suez contains a sedimentary succession that spans the Phanerozoic Era reaching as much as 8,000 m in thickness (Figures 2 to 7). It is segmented into a complex pattern of basins bounded by faults with numerous orientations (Figures 1 and 14). The precise faulting configuration and depth to the basement is difficult to map because of poor seismic data and sparse deep well control. This paper shows that the interpretation of 1980s aeromagnetic data can assist in resolving regional aspects of the basement’s configuration and its relief. Regional aeromagnetic images of the Gulf are shown including Total Magnetic Intensity (TMI, Figure 8), Reduced-to-Pole (RTP, Figure 9), residual structure (high frequency, Figure 11), regional (low frequency, Figure 12) and Second Vertical Derivative (SVD, Figure 13). They show that the Gulf is segmented into numerous magnetic lows that better define the shapes and depths of geological basins (Figure 14).

Two areas were selected to illustrate the contribution of aeromagnetic data to constrain the basement's configuration in the Gulf. The two areas contain deep geological features that do not run parallel to the Suez Clysmic direction (NNW) and are known as the Zaafarana and Morgan accommodation zones (Figures 15 and 16). Nine aeromagnetic profiles were sampled from the RTP maps and used to estimate the basement depth and thickness of the sedimentary section. The Zaafarana Zone cuts across the northern Gulf as a broad EW-trending plateau. The plateau dips westwards, and its depth is interpreted to increase from c. 2,500–3,500 to 4,500–5,500 m. It extends c. 25 km EW and attains a width of c. 20 km NS. Its western part is bounded to the north and south by deep basins with a sedimentary section exceeding 8,000 m in thickness. The NE-trending Morgan Zone also forms a plateau, c. 11 km wide, which extends c. 18 km across the Gulf. It terminates eastwards at the Morgan Basin, which has c. 8,000 m of sediments. The two zones separate deep basins, which are interpreted to contain the source rocks for many of petroleum fields.

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Zaafarana Area, North Gulf of Suez

(a) Reduced-to-Pole magnetic image of the Zaafarana Accommodation Zone (see Figure 14 for Location). (b to f) Geomagnetic profiles 1 to 5 showing depth model of the basement.
Figure 15: (a) Reduced-to-Pole magnetic image of the Zaafarana Accommodation Zone (see Figure 14 for Location). (b to f) Geomagnetic profiles 1 to 5 showing depth model of the basement.
Figure 16: (a) Reduced-to-Pole magnetic image of the Morgan Accommodation Zone (see Figure 14 for Location). (b to e) Geomagnetic profiles 6 to 9 showing depth model of the basement.
Figure 16: (a) Reduced-to-Pole magnetic image of the Morgan Accommodation Zone (see Figure 14 for Location). (b to e) Geomagnetic profiles 6 to 9 showing depth model of the basement.
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