The major tectonic boundaries for the Northern Red Sea rift, Egypt derived from geophysical data analysis

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ABSTRACT

In the present study, we try to map the plate boundary between Arabia and Africa at the Northern Red Sea rift region, including the Suez rift, Gulf of Aqaba-Dead Sea transform and southeastern Mediterranean region, using horizontal gradient gravity data analysis. The boundary analysis method was applied low-pass filtered on the gravity anomalies of the Northern Red Sea rift region, which has different crustal type and thicknesses, sediment thicknesses and different heat flow anomalies. According to the results, there are six subzones (crustal blocks) separated from each other by tectonic plate boundaries and/or lineaments. It seems that, these tectonic boundaries reveal complex structural lineaments, which mostly influenced by a predominantly set of NNW-SSE to NW-SE directed lineaments bordering the Red Sea and Suez rift regions. In the other side, the E-W and N-S to NNE-SSW trended lineaments bordering the Southeastern Mediterranean, Northern Sinai and Aqaba-Dead Sea transform regions, respectively. The analysis of the low pass filtered Bouguer anomaly maps reveals that positive regional anomaly over both the Red Sea rift and Southeastern Mediterranean basin subzones are considered to be caused by the high density of the oceanic crust and/or the anomalous upper mantle structures beneath these regions. Whereas, the broad medium anomalies along the western half of Central Sinai with the Suez rift and the Eastern Desert subzones are attributed to low-density sediments of the Suez rift and/or the thick upper continental crustal thickness below these zones. Observable negative anomalies over Northern Arabia subzone, in areas covered by Cenozoic volcanics. These negative anomalies may be attributed to both the low densities of the surface volcanic and/or to a very thick upper continental crust. Whereas, the negative anomaly belongs to the Gulf of Aqaba-Dead Sea transform zone is due to crustal thickening (with limited heat flow values) below this region. Additionally in this study, the crustal thinning was investigated with heat flow, magnetic and free air gravity anomalies in the Northern Red Sea rift region. Indeed, the crustal thinning of the study area was also proportional with the regions of observable high heat flow values. Finally, our results are well correlated with the topography, free air, aeromagnetic and heat flow dataset profiles crossing most of the study area.

Keywords: Red Sea rift, Potential field, low pass filtering, Boundary analysis, crustal structure

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1- Introduction

The Red Sea has formed by the rupturing of the Precambrian lithosphere beginning in the Late Oligocene. Sea floor spreading began at about 5 Ma in the southern Red Sea (Roeser, 1975) and the transition from continental to oceanic rifting is presently occurring in the Central and Northern Red Sea (Martinez & Cochran, 1988; Guennoc et al., 1990; Cochran et al., 1991). Based on the geophysical data in the Northern Red Sea, Cochran (2005) suggested that rift development occurs via the rotation of large crustal fault blocks that sole into a zone of plastic creep in the lower crust, resulting in a flat Moho and high upper crustal relief. Initial broadly distributed extension is eventually replaced by focused extension at the rift axis leading to rapid lithospheric thinning and melt generation. Melt formed within individual rift segments is focused to form small axial volcanoes (Cochran 2005).

This study will focus on the northern Red Sea rift from 25° to 28°N (Figure 1), where small cells of magmatic extension are just beginning to nucleate at the axis of what has been nearly magmatic rift. The purpose of this paper is to utilize a new compilation and synthesis of geophysical data from the northern Red Sea to map the plate boundary around and in this continental Rift.

We used Boundary Analysis method (Cordell and Grauch, 1982, 1985; Blakely and Simpson, 1986) to identify boundaries of gravity contacts by calculating the horizontal gradient magnitudes of the gridded gravity anomaly data. The method is used by many studies (Ekinci & Yiğitbaş 2012), 2015).

In this study, first of all, the different types of filters were applied to Bouguer gravity values for the study area, and then the boundary analysis method was applied. The horizontal gradient amplitudes were calculated from the Bouguer gravity anomaly on space domain and then the location of the horizontal gradients were computed, and lastly a new plate boundary map was constrained. According to these results, six subzones (crustal blocks) are estimated and separated from each other by tectonic plate boundaries.
Finally, crustal thinning for the northern Red Sea rift region was also discussed. Thin crustal zones values were remarked in a region where magnetization decreased while the amplitude of the free air anomalies increased (Von Frese et al., 1982; Pamukçu et al., 2007). Comparing the same previous approach with heat flow anomaly values, we can conclude that, the crustal thinning of the study area was also nearly noteworthy beneath regions of very high heat flow values (Saleh et al., 2013).

2- Tectonic and geological settings

Egypt is located in the northeastern corner of the African continent. It is bounded by three active tectonic margins: the African Eurasian plate margin; the Red Sea plate margin; and the Aqaba-Dead Sea fault (Figure. 1). This in its turn creates critical continental conditions that are responsible for the major seismic activities in Egypt since prehistoric time. The recent geodetic data and GPS measurements imply that the African plate is moving NW with respect to Eurasia with a velocity of 6 mm/year (McClusky et al., 2000) and the spreading rates along the Red Sea decrease from 14 mm/year at 15° N to 5.6 mm/year at 27° N. Along the southernmost segment of Aqaba-Dead Sea fault, motion is a left-lateral strike-slip of 5.6 mm/year (McClusky et al., 2003). This left-lateral motion shows a rate of about 2.8 mm/year at the northern segment of the Dead Sea with slight spreading of the Suez rift (Wdowinski et al., 2004).

This yields some secondary deformation manifested by moderate earthquake activity along the northern Egyptian coast. Based on geophysical studies in the territory of Egypt, three major tectonic trends are recognized, namely the Red Sea trend oriented NW–SE, the Gulf of Aqaba trend oriented NE–SW and the Mediterranean trend oriented E–W (Yousef, 1968). Owing to these complex tectonics, the distribution of seismic activity in Egypt is observed in four narrow belts: Levant-Aqaba; Northern Red Sea-Gulf of Suez–Cairo–Alexandria; Eastern Mediterranean- Cairo-Fayum; and the Mediterranean.
Coastal Dislocation (Sieberg, 1932; Ismail, 1960; Maamoun et al., 1984; Kebeasy, 1990; Abou Elenean, 1997).

Northeastern part of Egypt is dominated by the relative movements of major plates (Africa, Arabia and Eurasia) and relatively aseismic small plates. The Red Sea, which forms the boundary between the African plate and the Arabian plate, bifurcates into two branches: the Gulf of Suez and the Gulf of Aqaba. The Gulf of Suez follows the main trend of the Red Sea and constitutes the boundary between the African plate and the Sinai sub-plate (Said, 1963; Youssef, 1968). The Suez Rift is considered to be the plate boundary between the African and Sinai Subplates (McKenzie et al., 1970; Le Pichon & Francheteau, 1978). In general, it is accepted that the Gulf of Suez and Red Sea depressions were formed by the anti-clockwise rotation of Arabian Plate away from African Plate (Cochran, 1983).

Several geological and seismological investigations assert that the area surrounding the Gulf of Suez displayed, in the past, extensional tectonics with large deformation rate (e.g., Ben-Menahem et al., 1976; Le Pichon & Gaulier, 1988; Steckler et al., 1988, 1998; Piersanti et al., 2001). The tectonics of the Sinai Peninsula and the Gulf of Aqaba is strongly dominated by the active boundaries between the African and the Arabian plates (Figure 1) that are separated from each other. According to the current literature, from Neogene to Late Miocene, this area was subjected to different phases of motion.

Geologically, the oldest known formation in the study area is of Late Precambrian age, igneous and metamorphic rocks forming the northern edge of the African Shield (Figure 2). Saleh et al. (2006) evaluated outcropping of basement complex in southern Sinai and in the Eastern Desert (Red Sea mountain range) using 3D Geophysical modeling. Said (1962), El-Gezeery & Marzouk (1974) and Saleh et al. (2013) showed that the depth of the basement increases north-wards towards the Mediterranean Sea.

Generally the Egyptian platform may be subdivided into four major structural domains (e.g., Said 1962, Meshref 1990) with one minor one, as seen in Fig. 3. The study area covers all of them, namely:
1- **The Nerubian-Arabian Shield (Craton)**, the shield is well exposed at Sinai Peninsula, the Eastern desert and in extreme southern part of the West desert. It consists essentially of Precambrian rocks. El Shazly (1977) distinguishes several stages within these metamorphic sequences of geosynclinals Archean formations with frequent intrusion of plutonic and volcanic rocks.

2- **The Stable Shelf**, the shelf embraces the area north and west of the Nerubian-Arabian shield. It exhibits a gentle tectonic deformation and its sedimentary cover is mainly represented by continental and epicontinental deposits such as the Mesozoic Nubian Sandstone. The sedimentary sequence on the stable shelf is relatively thin with some 400 meter sediment near the Nerubian-Arabian area and increasing to as much as 2500 meter near the transition into the unstable shelf on the north. It is composed of sand and shale in its lower section and of shallow water of carbonates in its upper part.

3- **The Unstable Shelf**, is situated north of the stable shelf with the transition between two structural-deposition-all units following a line approximately set from the Siwa Oasis through Fara-Fara Oasis and Suez into Central Sinai. The sedimentary sequence of the unstable shelf is relatively thick with the lower part of the section composed mainly of clastic sediment, followed up section by middle calcareous series and topped by blanket of biogenic carbonates. The formation is gently folded and show sign of lateral stress. Overthrust is reported by the northern structure. This structural deformation is related to Laramide phase of the Alpine Orogeny. The trends of this fold bundle are lightly trended to the northeast and referred to as The Syrian Arc system.

*The Gulf Suez-Red Sea Graben* is a subsidence area within the stable shelf and the northern part of Nerubian-Arabian shield. It is formed originally during Paleozoic times as a narrow embayment of Tethys and intensively rejuvenated during the rifting phase of the great East Africa Rift system in Lower to Middle Tertiary times. Great accumulation of sediments form this fast subsiding depression, interrupted at times by general and regional uplift with subsequent erosion. It connection to Mediterranean Sea to the North and Red Sea to the south is established during early Miocene and witnessed by the distribution of Mediterranean fauna from the north as far south as southern Red Sea.
The Red Sea originated during the Oligocene time after the arching and crustal thinning in the general area of the Nerubian-Arabian Shield and the subsequent collapse, in the context of East African rifting. Spreading of the Red Sea floor, was and still is relates to the relative motion of various plates present in northeastern Africa and the Near East.

4- **Hinge Zone**, located between the mobile shelf and the miogeosynclinal basinal area; it is characterized by a rapid thickening of Oligocene to Pliocene sediments, and partially coincides with the present Mediterranean coastal area;

5- **Miogeosyncline**, presently partially buried under thick Plio-Pleistocene deposits of the Nile Delta; the structural grain of the basement is dominated by two orthogonal trends induced by successive diastrophic phases; the sedimentary formations are gently folded and over thrusting is also locally reported; the described deformation is related to the Laramide phase of the Alpine orogeny; the trend of these folds is lightly arcuate to the northeast and referred to as the Syrian Arc.

3- **Applications**

3.1. **Bouguer datasets of Northern Red Sea Rift**

3.1.1. **Bouguer data source:**

Considerable amounts of gravity data are now available to unravel the gross crustal structure of Egypt. The Bouguer anomaly map of our study area (Northern Red Sea and southeastern Mediterranean), at a constant contour interval of 5 mGal (Fig.), has been regridded by the World Gravity Map project team (WGM), from various published maps (Allan and Morelli, 1970; Riad, 1977; Woodside 1976, 1977; Egyptian General Petroleum Corporation (EGPC) 1980; Folkman and Assael, 1980; Ben-Avraham, 1985; Tealeb and Riad, 1986; Minich, 1987; Martinez and Cochran, 1988; Kamel, 1990; Ginzburg et al. 1993; Makris and Wang 1994; Rybakov et al., 1997; Segev et al. 2006).

Gravity surveys for the study region were conducted by the Sahara Petroleum Company (SAPETCO) and PHILIPS Company between 1954 and 1958. These surveys covered a large area of the Gulf of Suez,
Sinai and the Eastern Desert. All data of these surveys were compiled, classified and ranked according to instrument sensitivity and measurement density. The gravity measurements were conducted using two Worden gravimeters. The instruments are temperature compensated and have a sensitivity of $\pm 0.1$ mGal (Kamel, 1990).

Marine gravity data in the northern Red Sea were taken from publications (Minich, 1987; Martinez and Cochran, 1988), whereas in Southeastern Mediterranean were taken from publications (Woodside 1976, 1977; Ginzburg et al. 1993; Makris and Wang 1994).

In the northern Red Sea, the underwater gravity survey was conducted using a Bell Aerospace BGM-3 marine gravity meter system that was installed on the R/V ‘‘Robert D. Conrad’’, north of 26° N, in 1984. The system consisted of a vertical component forced feedback accelerometer which is not subject to cross coupling errors, mounted on a gyro-stabilized platform. The performance of this system is described in detailed by Bell and Watts (1986).

In the Red Sea, gravity data values were obtained at 1 min intervals, with discrepancies at ship track intersections of less than about 1 mGal for the northern sections, and not more than about 3 mGal in the worst cases. Data from previous cruises in the area were included in our contour map if discrepancies at intersections of individual ship tracks and scatter of their discrepancies at intersections with the new data were less than 7 mGal. Those cruises satisfying the above criteria and their data, adjusted by adding a constant to remove the average gravity discrepancy at intersections with those cruises, as well as, Sinai Peninsula data, were collected, from Tealeb and Riad (1986).

A complete file of the datasets is available now on a web site at: http://bgi.omp.obs-mip.fr/index.php/eng/Activities/Projects/World-Gravity-Map-WGM.

The WGM project is a gravity mapping project undertaken under the aegis of the Commission for the Geological Map of the World (CGMW) to complement a set of global geological and geophysical digital maps published and updated by CGMW, such as the World Digital Magnetic Anomaly Map (WDMAM), released in 2007. This new global digital map aims to provide a high-resolution picture of
the gravity anomalies of the world based on the available information on the Earth gravity field. The WGM project is conducted by the Bureau Gravimetricque International (BGI), a center of the International Gravity Field Service (IGFS) of the International Association of Geodesy (IAG) with the support of the United Nations Educational Scientific and Cultural Organization (UNESCO). The gravity data compilation includes the available measurements issued from land, marine and airborne surveys and achieved in the global database, as well as new available gravity datasets collected from recent surveys or available in other global or regional databases. Major contributions to WGM include the official EGM08 global model, recently released by the National Geospatial-Intelligence Agency (NGA, USA), as well as the new global ocean gravity field derived from satellite altimetry (DNSC08 computed at the Danish National Space Centre and Sandwell and Smith models computed at Scripps Institution of Oceanography).

3.1.2 Correction of Gravity data

The distance between the consecutive observation stations ranges from approximately 2–5 km. The calculated Bouguer gravity anomaly is: (1) based on the international gravity formula of 1967, referenced to the IGSN-1971, reduced to sea level and corrected with the standard density of reduction, 2670 kg/m³. For onshore stations, terrain corrections up to 50 m were made in the field using topographic charts and Hammer tables (Hammer, 1939). The horizontal positions of the stations were obtained from 1:500,000 topographic sheets. The station locations were converted to the Universal Transverse grid coordinates with the central Meridian at 30º E. Elevations at each station were measured by a barometric altimeter and all measurements are referenced to absolute elevation. The corrections were applied to all land stations. These corrections generally are ≤1 mGal, however, along the mountains of the Red sea hills they reach more than 4 mGal.
The combined errors in the Bouguer gravity values depend upon the sum of errors in observation, elevation and terrain corrections. i.e. Where $\varepsilon_B^2 = \sqrt{\varepsilon_g^2 + \varepsilon_h^2 + \varepsilon_p^2 + \varepsilon_T^2}$

$\varepsilon_B$ the combined errors in Bouguer gravity measurements,

$\varepsilon_g$ error in observation,

$\varepsilon_h$ error in elevation,

$\varepsilon_p$ error in position,

$\varepsilon_T$ error in terrain correction.

The errors in measurement during the regional gravity survey in the study area were found to be within ±0.1 mGal. The errors in elevation depend upon the number of benchmarks, the number of quality GPS observations, topographic relief, and variability of weather. The errors in elevation $\varepsilon_h$ were calculated by multiplying the errors in elevation measurement with the combined Bouguer slab and free air correction (0.1967 mGal/m) values. The total sum of errors in the Bouguer gravity value, taking into consideration the different errors mentioned above is ±0.4 mGal in the basin and ±1 mGal on the plateaus.

3.1.3. Bouguer anomalies interpretation

The general trend of the Bouguer gravity anomalies is NW-SE. At the southern tip of the Sinai Peninsula the gravity field switches from positive to negative values in the Gulfs of Suez and Aqaba. Both the Gulfs of Suez and Aqaba are characterized by gravity minima with the values in the Gulf of Suez approximately one-half those found in the Gulf of Aqaba. Along the Dead Sea Rift itself the Bouguer anomaly field is characterized by very steep gradients towards the Rift Zone and a series of strong negative gravity closures from north to south. The anomaly increases in magnitude with a decrease in the relief of the topography and attains its maximum of +95 mGal along the axis of the Red Sea rift floor. A systematic slight decrease of the amplitude occurs to the north; where the maximum
amplitude is of the order 80 mGal south the iterance of Gulf of Aqaba. The highest mountains in the Red Sea margins for example have values of over 1000 m, and their negative Bouguer anomalies are only about -10 to -30 mGal, aligned parallel to the Red Sea along a NNW trend. Alternative negative and positive anomalies along the Gulf of Suez may be due to the faulted blocks or presence of different basins with different thickness of sedimentary sequence in the area. This leads to the conclusion that the shallow parts are extending along the two Gulfs and southern part of Sinai where the basement rocks are outcropping (Figure 3). It was observed an elongated anomaly with gravity value between -35 and -50 mGals extended from 26° to 28.5° N and 31.5° to 33° E. The elevation of this area is fairly smooth and only 200 to 400 m above sea level. The Red Sea Mountains with altitudes over 800 m show Bouguer anomalies between -10 mGals and -35 mGals, the values increasing to zero gravity level at the Red Sea coast. These anomalies suggest that the crust attains its maximum thickness below the Red Sea Mountains and thins considerably towards the Red Sea Rift (Saleh et al., 2006). In the Red Sea, the anomalies are positive; the anomaly increases in magnitude with a decrease in the relief of the topography and attains its maximum of +80 mGal along the axis of the Red Sea Rift floor. In eastern Egypt and the Gulf of Suez, the anomalies have a NNW-SSE trend which is associated with the Miocene and Post Miocene opening of the Red Sea and Gulf of Suez.

3.1.4. Bouguer data analysis

At the first stage of the study, the low passed filtered technique with different frequency domains have been applied to analysis the Bouguer anomaly dataset. To find the impact of the deepest structure, the low passed filtered parameters were estimated as the cutting frequency; \( f_c = 0.01 \text{ km}^{-1} \) and filter dimension; 11*11 (Figure 5). The filtered Bouguer gravity anomaly map (Figure 5) was used to enhance the anomaly wave length associated with deep sources. This map reveals the influence of the regional gravity field demonstrates a general smooth trend pattern. The most attractive feature of this map is that,
it readily shows alternating high and low linear and isometric anomalies of NW-SE trend occupying Saudi Arabia, the Red Sea and Suez rift regions. In the other side, the E-W and N-S to NNE-SSW trended anomalies at the southeastern Mediterranean, northern Sinai and Aqaba-Dead Sea transform regions respectively.

And then, we have used filtered Bouguer gravity values in Figure 5 and the boundary locations were obtained in Figure 6. Applying the approach of Von Frese et al. (1982), which have been used as an investigation basis of inversely proportional correlation between long wavelength, free air gravity and low magnetic data. Application of filtering and horizontal gradient techniques to Bouguer gravity data, the results can be associated with differences in crustal thickness, heat flow, seismic activity, basement surface (sedimentary thickness) and fault structures. However, as any potential field model is ambiguous we seek to constrain the tectonic boundary by integrated interpretation of available free air, magnetic and topographic data analysis..

3.2. Magnetic datasets of Northern Red Sea rift

The study region includes land, marine and magnetic surveys for the northern Red Sea rift region and its surroundings including the Gulf of Suez, Gulf of Aqaba, Sinai Peninsula, and northern parts of the Eastern Desert. The magnetic map (includes the Sinai Peninsula and some regions of the eastern desert) was prepared by the EGPC (1990), with a flight elevation of 1 km. The land magnetic survey was performed using two magnetic protons of geometric type. One instrument is used as a base station for diurnal corrections for each profile, and the second is used to measure the observed magnetic data. The distance between the stations ranges from 200 to 300 m according to the changes in the recorded geomagnetic data. The marine magnetic map was compiled for both the Gulf of Suez and the northern Red Sea based on Cochran et al. (1986) and Meshref (1990). The total magnetic intensity data resulting from different magnetic surveys was compiled and reduced to one set of data.
Recently, the magnetic data sets became available after compilation through the World Digital Magnetic Anomaly Map project; WDMAM: (http://models.geomag.us/wdmam.html; and GETECH, http://www.getech.com/).

There are principles of map compilation according to the following definitions:

**Definition of anomaly:** Total field anomaly component of the Earth’s magnetic field at an altitude of 5 km above the Earth’s surface, caused by quasi-static upper lithospheric sources.

**Definition of wavelength band:** Low cut limit corresponds to degree and order 15 of global spherical harmonics (approx. 2600 km wavelength at equator). Short-wavelength limit corresponds to 10 km, due to 5 km resolution of grid.

**Definition of grid:** 5 km resolution, geographic and planar grids as defined at World Geological Map 1:50 million scale by CGMW. (Three projected grid windows, the main one in Mercator but with two (north and south) polar stereographic projections). Closer definition will be given at the call of data sets and candidate global grids.

**Definition of path:** complete processing paths starting from WDMAM list data sets to global sub-grids and further to each candidate global grid.

**Source data:** Initial data and their specifications (metadata) will be available from WDMAM, by permission of the data owners, and will be same for all contributors. The official list of available, authorized data sets will include continental and oceanic data (national and regional grids, and profiles), and whole-earth satellite models for lithospheric sources (e.g. MF3-4) plus models of the Earth’s magnetic field for reduction of the data (e.g. CM4). WDMAM will accept data sets with proper authorization only.

**Methods:** The contributors may freely choose the methods, provided that they are transparent, scientific, and reproducible for desired parts at the review. An adequate description of the methods and merging procedures of specific large segments of maps must be attached to the candidate models.
The magnetic fields due to geological bodies are distorted by the local inclination and declination of the magnetic earth’s field, making difficult to estimate their shapes and locations correctly. In order to eliminate that effect in the appearance of an anomaly, which depends on the magnetic latitude of the survey area as well as on the dip angle of the magnetization vector in the body, a mathematical procedure known by reduction to the pole (RTP) is applied to the grid of total magnetic intensity values using geosoft program (Oasis Montaj, 2008). The resultant map is then reduced to the north magnetic pole map (Figure 7), which is more utilizable, because its anomalies are independent on the magnetic inclination of the source bodies. The reduction to the pole procedure was first described by Baranov, 1957, Baranov and Naudy, 1964, Bhattacharyya, 1965 and Bhattacharyya, 1967 and Baranov (1975).

The RTP map shows the distribution and relief of the exposed basement rocks. High magnetic anomalies can be observed at the southern part of the Sinai Peninsula which well matches with the exposed geologic units that are mainly composed of igneous rocks (back to geologic map in Figure 2). The map indicates also, that most of the observed anomalies show NE-SW, NW–SE and N–S trend patterns with some sharp gradients at varying locations. Since the magnetic maps are related directly to the basement rock features, this indicates the presence of a basement relief change. It can also be observed that the Sinai Peninsula is divided into two geologic provinces based on the magnetic features. The southern province is characterized by high magnetic anomalies and the Northern Province with low magnetic anomalies.

In addition, the RTP map clarifies a pattern of magnetic anomalies within the marine portion of the northern Red Sea which exhibits a relatively flat magnetic field on which a number of large-amplitude dipolar anomalies are superimposed. Magnetic anomalies in the northern Red Sea are all dipolar anomalies (Figure 7) implying a compact localized source. These anomalies have been interpreted as arising from discrete localized volcanoes (Cochran et al., 1986; Martinez & Cochran, 1988; Guennoc et al., 1988).
3.3. **Topographic and Free Air gravity anomaly of the northern Red Sea region**

In the north, the Red Sea bifurcates into the Gulfs of Suez and Aqaba. The floor of the Gulf of Suez is quite smooth and the depth of water is shallow, averaging about 55 m. In contrast, the Gulf of Aqaba has varied bottom topography with much greater depths of water reaching 1460 m. North of latitude 24° to 25° N, the Red Sea consists of one main trough approximately 150 km in width with shallow shelves on either side some 30 to 40 km in width (Figures 1 and 8). The water depth in the trough is about 1000 m and the shorelines are straight.

The bathymetry of the active, main trough of the northern Red Sea rift consists of a series of terraces stepping down to an axial depression at a depth of 1100–1200 m (Martinez & Cochran, 1988; Cochran, 2005). Sediment deformation within the axial depression is much more intense than in the remainder of the Red Sea (Knott et al., 1966; Guennoc et al., 1988; Martinez & Cochran, 1988), implying that tectonic activity and extension is presently concentrated predominantly in the axial depression.

Also, although earthquakes with $M_L=3$ are concentrated in the axial depression, smaller earthquakes are distributed throughout the northern Red Sea (Badawy, 2005). These two observations imply that some extension still occurs within the main trough away from the axial depression.

Satellite altimeter free air gravity anomaly of the northern Red Sea region is given in Figure 7 as computed by Sandwell et al. (1997). Free air gravity anomaly map of the northern Red Sea is generally characterized by negative free air gravity anomalies with average values of about 0 to -20 mGal in the margin areas and a consistent gravity low from -30 to -40 mGal of the axial depression. A “Y” shaped region of very low values of a minimum -70 mGal is found near the junction of the Red Sea with the Suez and Aqaba Gulfs. A series of elongated gravity highs parallel to the overall Red Sea trend are located outside the axial rift. High gravity anomalies range from 0 to 20 occurs of some seaward terraces. Moreover, a series of smaller structure features appears on both side of the axial rift of the Red Sea. These may be attributed to irregular bathymetry of the Red Sea (Figure 8) related to the spreading
along the axial Rift (Martinez & Cochran, 1988). Most of these small terraces are coincide with
bathymetric features especially the negative anomaly of the axial rift or the varying anomaly terraces
along the axial rift as shown in Figure 8.

4. Crustal Structures, heat flow and seismicity
Previously, several studies have been carried out to evaluate the crustal structure in northern Red Sea,
Egypt and Arabian Shield by using data observed from seismic explosion, deep seismic sounding,
shallow refractions, and gravity (e.g., Drake & Girdler, 1964; Tramontini & Davies, 1969; Tealeb, 1979;
Makris et al., 1979, 1983, 1988, 1991; Rihm, 1984; Marzouk, 1988; Gaulier et al., 1988; Rihm et al.,
1991; Dorre et al., 1997; Al-Damegh et al., 2005; Saleh, 2006).

Dorre et al. (1997), Saleh et al. (2006) and Saleh et al. (2013) constructed a crustal thickness map of
Egypt, Red Sea and southeastern Mediterranean regions respectively using gravity modeling studies.
Their results using gravity modeling allowed the construction of a map showing the depth variation of
the interface between the upper mantle and the lower crust (Moho depth map). Their estimated Moho
depth map was revealed in Figures 9a and 9b. Nevertheless, Al-Damegh et al. (2005) estimated the
average crustal thickness of the late Proterozoic Arabian Shield, using seismological data analysis which
was 39 km. The crust was observed thin to approximately 23 km along the Red Sea coast. Their study
area was extended to the northern part of Red Sea rift region, occupying our study area, as shown in
Figure 9c. Their estimated crustal depths along the Red Sea and Gulf of Aqaba coastal regions are
consistent and well correlated with the previous Moho depth that was inferred from the gravity data
analysis (e.g. Dorre et al. (1997) and Saleh et al. (2006); see the correlations in Figures 9(a), (b), and (c).
Along the northern part of the Red Sea Egyptian coastline, the crust is oceanic (Makris and Rihm,
1991). Near the Red Sea, the crust is continental consisting of a sedimentary layer of 3 km with velocity
of 3.5 km/s, overlying a 30 km thickness of crust having a moderate velocity changes from 6.0 to 6.35
km/s (Meshref, 1990). Near the Nile Valley, the crustal structure is rather heterogeneous and changes abruptly from area to another. Within the Nile Valley graben, loose water-saturated sediments are present having a rapid decrease in sediment thickness and water saturation in both directions away from the graben (El-Sayed and Wahlstrom, 1996). For instance, the type of the crust beneath the eastern Mediterranean Sea varies from oceanic to continental types (Saleh, 2013).

The northwestern regions of Saudi Arabia are distinct from the Arabian Shield, as this region is characterized by high seismicity in the Gulf of Aqaba and Dead Sea Rift. Active tectonics in this region is associated with the opening of the northern Red Sea and Gulf of Aqaba as well as a major continental strike-slip plate boundary. For comparison purposes we also presented a crustal thickness map for the study area, which clearly reveals northward and eastward trends of the crustal thinning toward the Mediterranean Sea and Red Sea, respectively. This was also observed by Makris et al. (1988), Marzouk (1988), Dorre et al. (1997), and Seber et al. (2000) who describe the Egyptian territory as a continental crust with a thickness of 30–34 km, bounded by thin new oceanic crust (<20 km) that is formed by the Red Sea rifting.

In Sinai Peninsula, the crust is more or less flat, 32–33 km in thickness, and tending to thin toward the Gulfs of Suez and Aqaba and towards its southern border where a sudden crustal thinning occurs beneath the northern Red Sea. An additional crustal thickening northwestward is observed in the northwestern part of Sinai at the border of the study area.

Generally, we do find thicker crust below the Red Sea Mountains than the southeastern Mediterranean Basin and Sinai Plateau, but we also find comparably thin oceanic crustal layer below the northern Red Sea Rift Basin. Gulf of Suez and Gulf of Aqaba zones are also underlain by comparable crustal thickness according to their seismic velocities. These findings along with observations that variations in crustal thickness within each tectonic province do well correlated with topography, heat flow, aeromagnetic data and seismological activity indicated that geophysical tools play an important role for discriminating the
various tectonic zones. Thus, our study indicates a broad-scale of correlation between Bouguer gravity results with other accessible geophysical tools, consequently the estimated tectonic zones in northeastern part of Egypt and Red Sea region.

In addition, Saleh (2009) has been constructed the sedimentary thickness (depth to the basement) for the Northern Red Sea region as shown in Figure 10(a), by applying and reviewing the available relevant information on the Red Sea rift (well logs data, seismic profiles, magnetic and gravity data). Interpretations derived from power spectrum and 3D geophysical modeling methods confirm the depths to the basement-sedimentary contacts derived from the analytical signal and 3D Euler deconvolution techniques. This new compilation enabled significant upgrading of the database for the Northern Red Sea rift region. The basement map of Saleh, (2009), was a good comparable with the compiled one of Laske & Masters, (1997) as shown in Figures 11(a) and (b). Both resulted sedimentary thickness maps are existing and were correlated for comparison the different profiles.

Previous studies of heat flow and geothermal regime in Egypt (Issar et al., 1971; Morgan & Swanberg, 1979; Morgan et. al., 1980, 1985; Swanberg et al., 1983; Boulus, 1990; Zaghloul et al., 1995; Hosney & Dahroug, 1999; Hosney, 2000) related the geothermal features with the tectonic evolution of the area. The plate margin to the north of Egypt (Figure 1) appears to be too distant to result in any geothermal anomalies in northern Egypt. The Mediterranean Sea is characterized by heat flow 30-45 mWm$^{-2}$. The low heat flow of the Eastern Mediterranean Sea extends at least as far south as 29° N (Morgan et al., 1977; Čermak et al., 1977; Riad et al., 1989). Boulos, (1990), Morgan et al. (1980, 1983 and 1985), Feinstein et al., (1996), Hosney & Morgan, (2000), Hosney (2000) and Saleh et al. (2013) studied the heat flow values along the Gulf of Suez and Red Sea. The highest value of heat flow in the eastern part of Egypt was in the Precambrian basement (92 mWm$^{-2}$). Heat flow density in the Red Sea is generally high, reflecting the shallow depth to the asthenosphere and its recent age of intrusions. The early surveys, e.g. Girdler & Evans (1977), Haenel (1972), Girdler & Evans (1977), reported high heat flow density (HFD) values of approximately 600 m Wm$^{-2}$ for the axial trough, whereas the flanks have
values of twice the world mean (59 m Wm$^{-2}$). The heat flow in the Gulf of Suez could be as high as 80 or even 100 mWm$^{-2}$ (Morgan et al., 1977; Hosney & Morgan, 2000). The last value 80-100 mWm$^{-2}$ could be true where it is consistent with the observed low velocity below the Moho in the Gulf of Suez (Gaulier et al., 1988) and the mean heat flow of the Red Sea of 116 mWm$^{-2}$ (Boulus, 1990). Saleh et al. (2013) have evaluated the HFD for the northern Red Sea rift region using magnetic data analysis (Figure 11). They found that the mean values of HFD reach to ~160-190 mWm$^{-2}$ along axial part and active tectonic regions of Red Sea.

The fact that part of the mantle at depths below 15 to 17 km is much softened and partially melted leads to this assumption. Melts are concentrated at the base of the crust below the deeps. They transport the heat by convection, are responsible for the intrusions in the shallower parts of the crust and the volcanic activity and deliver the thermal energy which, together with the lateral variation of lithostatic pressure, drives the water circulation in the sediments, where the observed HFD distribution is depressed (Makris et al., 1991a, b).

High level of seismicity along the Gulf of Suez and the Red Sea indicates active tectonics in eastern Egypt (Maamoun et al., 1980; Maamoun, 1985; Dogget et al., 1986; Mousa, 1989; Kebeesy, 1990; Riad et al., 2000). Geodynamic phenomenons are ultimately governed by thermal process in the Earth’s interior. The knowledge of petrophysical properties, like thermal conductivity, P wave velocity and heat generation is very important in the interpretation of terrestrial heat flow pattern and the geothermal processes in the lithosphere. Based on the Cenozoic volcanism along the Red Sea, previous research has argued that the Red Sea is underlain by hot mantle (e.g., Coleman & McGuire 1988; Dixon et al., 1989). Ebinger & Sleep (1998) proposed rifts may present natural channels for hot material from mantle plumes to flow horizontally beneath thin lithosphere. The Red Sea has been proposed as such a channel for hot material from the Afar plume to cause the Cenozoic volcanism in western Arabia (e.g., Hansen et al., 2006; Park et al., 2007, 2008; Ritsema et al., 1999).
Based on geophysical studies in the territory of Egypt, three major tectonic trends are recognized, namely the Red Sea trend oriented NW–SE, the Gulf of Aqaba trend oriented NE–SW and the Mediterranean trend oriented E–W (Yousef, 1968). Owing to these complex tectonics, the distribution of seismic activity in Egypt is observed in four narrow belts: **Levant-Aqaba; Northern Red Sea-Gulf of Suez–Cairo–Alexandria; Eastern Mediterranean-Cairo-Fayum; and the Mediterranean Coastal Dislocation** (Sieberg et al., 1932; Ismail, 1960; Maamoun et al., 1984; Kebeasy, 1990; Abou Elenean, 1997). The interaction of the aforementioned tectonics creates continental conditions that are responsible for the major earthquake activity in Egypt.

Significant seismic activity is also found along the entire Gulf of Suez and its extension on the northern part of the Eastern desert towards the Nile Delta along the E–W and WNW faults. This activity trend does not continue further towards the Mediterranean Sea and ceased closer to the west of Nile Valley at Dahshour area where the 12 October 1992 earthquake (ML5.9) took place.

### 5. Discussion and conclusions

Cochran (2005) based his model on data from the northern Red Sea and assumes that the structural framework deduced in the north continues to the south where sea-floor spreading exists. However, it is entirely conceivable that the two areas, separated by a major tectonic boundary (the ‘Zabargad fracture zone’ Crane & Bonatti, 1987), have developed differently and observations in the northern Red Sea cannot be extrapolated to the south where few data are available for comparison. Thus, the difference between the two regions may be owing to a fundamental difference in lithosphere rheology, explaining why sea-floor spreading developed in the southern, but not the northern, Red Sea. The counter-argument is that the entire Red Sea is developing similarly, but rifting in the northern and central Red Sea simply has experienced insufficient extension to develop into sea-floor spreading at this time.
In this study, we will try to compare and map the plate boundary between Arabia and Africa at the northern Red Sea rift region including the Suez rift, Gulf of Aqaba-Dead Sea transform and southeastern Mediterranean region using horizontal gradient gravity data analysis. According to boundary analysis results (as shown in Figure 6), six distinct provinces (blocks) within the main northern Red Sea rift in the area lies between 24° to 32° N (Figure 12) have been identified. The estimated boundary tectonic zones in the present work were classified according to their potential field and heat flow anomalies values, distinctive tectonic trends and thus regarding to characteristics of their own crustal and sedimentary thicknesses. The evaluated main boundary zones of the present work could be classified as the following zones;

a) The southeastern Mediterranean tectonic zone (Zone1)

The southeastern Mediterranean zone is marked by east-west trending linear anomaly with gravity high. It is characterized by moderate continental crustal thickness (~27-29 km) with very thick sedimentary cover (~ 9 km), as shown in Figures 10 and 11. This zone is actually traversed by sub-parallel NE Pelusium megashear system, which extends from Turkey to the south Atlantic. It runs subparallel to the eastern margin of Mediterranean Sea (Neev et al., 1982). Indeed, according to the microtectonic analysis (Eyal & Reches, 1983; Letouzey & Tremolieres, 1980), the resulted from E-W to WNW-ESE horizontal compression where this was generally NNW-SSE directed in the Western Desert, shifting progressively to NW in Sinai and nearly E-W in neighboring regions to the east (Sehim, 1993). This eastward increase in the shortening along the Tethyan margins (Guiraud & Bosworth, 1997) is synchronous with counterclockwise rotational northward drift of the African-Arabian plate and its increased collisional coupling with the Eurasian plate (Le Pichon et al., 1988; Ziegler, 1990). However, distinctive parallel NNW structural trends (Red Sea tectonic trend) were noticed crossing northern Sinai. According to Ramşay (1986) and Camp (1986) these structural trends caused by transtentional forces initiated during the time of the Red Sea evolution and were commonly erupted by Cenozoic basalt flows. Stern (1985),
declared that, during the Late Precambrian and Early Cambrian (about 600-540 Ma) extensive left-lateral faulting along the complex NW-SE-trending Najd fault system cut across the Arabian shield. This tectonic episode was accompanied by NW-SE-directed extension in northern Egypt and the Sinai Peninsula.

**b) The Gulf of Suez tectonic zone (Zone2)**

The Gulf of Suez zone is marked by NNW trending linear anomaly with gravity high. Gulf of Suez zone is marked by (NNW-SSE) trending linear anomaly with gravity low correlates with the proto-Clysmic or Erithrean fractures of Keely (1994). The NNW-SSW trending lineaments chiefly extracted from gravity and the topographic data (Figures 4 and 8) are notably situated in the Early Cretaceous deposits. This corresponds with the fact that the Red Sea–Gulf of Suez rifting likely commenced in the Cretaceous period (Makris & Rihm, 1991) and reached its climax in the Oligocene period, predominantly controlling the linkage of rift-parallel faults in the Gulf of Suez (Guiraud & Bosworth, 1999). This zone is distinguished by moderate continental crustal thickness (~32 km) with thin sedimentary cover (~ 2-3 km), as shown in Figures 9 and 10. In fact, subsurface studies conducted onshore just north of the Gulf of Suez (Moustafa & Khalil, 1995) argue that the rift was terminated by pre-existing nearly orthogonal structures that were rejuvenated. These structures include the Cairo-Suez fault zone to the west and the Sinai-Negev shear zone to the east (Moustafa & Khalil, 1995; Figure 1).

Saleh et al. (2013) have estimated the heat flow for northern Red Sea rift region (Figure 12). They found that, in the upper northern part of the Gulf of Suez (near Suez city), represents medium heat flow value of 89 mW m$^{-2}$. Whereas, along Hammam Faroun area (the highest temperature hot spot in Egypt, 70° C), characterized by high heat flow value of ~104 mW m$^{-2}$. They have recognized that the heat flow values increase intensively toward the south (toward the marine part of the northern Red Sea along the tip of the Sinai Peninsula).
c) **Eastern Desert tectonic zone (Zone3):**

The rocks of Eastern Desert zone of Egypt form part of the Nubian Shield, a component of the Neoproterozoic Pan-African Orogeny. This zone extends in the south from northern part of Nasser Lake along the Nile River at 24° N to Esh El Mallaha boundary line which is located in the northeastern side close to the Gulf of Suez (Figure 14). Moreover, it is bordered by Red Sea from the eastern side. The gravity anomalies of this zone are slightly negative due to its continental crustal thickness which is ranging about 32-38 km thick. Seismically, this estimated tectonic zone contains two seismic zones according to the classification of Haggag et al, (2008), which are: a) Seismic zone at Abu-Dabbab area, which consider the most active zone in the Eastern Desert; many famous earthquakes were occurred in it. This seismic zone lies on the Red Sea coast and its activity is distributed parallel to the Red Sea coastal line NNW-SSE. b). This seismic zone contains the activity located in the northern part of the Eastern Desert of the Upper Egypt, it can be considered as an active area where many earthquakes were recorded with magnitude ranging up to 4.2. The general trend of the seismicity runs almost N-S.

Indeed, according to the geothermal study of Saleh et al. (2013), at Safaga city (along the western shoreline of Red Sea, Figure 13), represents high heat flow region with a value of nearly 195 mW m\(^{-2}\). It was also observed along the southwest border of study area along the River Nile (e.g. along Luxor and Esna cities), high heat flow of 200–220 mW m\(^{-2}\).

d) **Marine northern Red Sea tectonic zone (Zone4)**

Structurally, the Red Sea is a graben along the crest of an anticline that formed in the Arabian-African Shield. The inner margins of the shield apparently undergo considerable uplift that formed prominent scarps at the edge of the Red Sea rift. A zone of 1-2 km. wide that is composed of high and tensional faults concealed by coastal sediments lies at the foot of the escarpments. On the seaward side of this zone, the basement has been step faulted downward in blocks and lies beneath the shelf area at depth of 2-3 km below sea level (Chapman, 1978). Three sets of faults seem to have controlled the development
of the Red Sea. These were the NW-SE trending main line of faults which are associated with step faulting and the WNW-ENE major fault trend in the Precambrian basement which caused many irregularities in the coastline (Chapman, 1978). Indeed, based on seismicity data, the northernmost part of the Red Sea defines three zones at the entrance of the Gulf of Suez and southern tip of the Sinai Peninsula. The thermal activity and the triple junction nature control the activity in this area. The activity defines also an active trend extending from the southern tip of the Sinai Peninsula to the median zone of the Red Sea. The seismicity of this trend is probably related to the active spreading zone associated with the opening of the Red Sea (Korrat et al., 2006).

Previous crustal structural results (Dorre et al., 1997 and Saleh et al., 2006) evaluated the extreme oceanic crustal structures which are flooring the axial trough of the northern Red Sea rift and 30–38 km thick continental crust underneath the Dead Sea rift.

e) Gulf of Aqaba-Dead Sea tectonic zone (Zone 5)

It considers the most active main earthquake zone in Egypt (Kebeasy, 1990). This tectonic zone is bounded from the west by the western half of Sinai Peninsula and is bounded by Arabian Plate from the east. It is crossing, through its central part, by a long transform fault zone, extending from Turkey and passing through the Ghab depression in Lebanon, the Dead Sea, the Gulf of Aqaba, and at last arriving to the floor spreading zone of the Red Sea (McKenzie, 1970; Dewey et al., 1973). The later was thought to be the separation between Africa and Arabia (Cochran, 1981, 1982, 1983; Girdler & Styles, 1982) and it is between the opening of the Gulf of Suez and the predominantly sinistral shear along the Gulf of Aqaba-Dead Sea.

Regarding the heat flow values (Figure 12) in the Gulf of Aqaba, it appears to increase from north to south. This increase may be related to the more advanced rifting stage of the Red Sea immediately to the south, which presently includes creation of an oceanic crust. This trend also corresponds to the general trend of the deep crustal structure in the gulf (Ben Avraham & Vonherzen, 1987, Saleh et al., 2013).
f) Northwestern region of Saudi Arabia (Tabouk) tectonic zone (Zone 6):
The northwestern regions of Saudi Arabia are distinct from the Arabian Shield, as this region is characterized by high seismicity in the Gulf of Aqabah and Dead Sea Rift. Active tectonics in this region is associated with the opening of the northern Red Sea and Gulf of Aqabah as well as a major continental strike-slip plate boundary. The Arabian Plate boundary extends east-northeast from the Afar region through the Gulf of Aden and into the Arabian Sea and Zagros fold belt. The boundary is clearly delineated by teleseismic epicenters, although there are fewer epicenters bounding the eastern third of the Arabian Plate south of Oman. Most seismicity occurs in the crustal part of the Arabian Plate beneath the Zagros folded belt (Jackson & Fitch, 1981). Al-Damegh et al. (2005) estimated the average crustal thickness of the late Proterozoic Arabian Shield, which was 39 km. The crust thins to approximately 23 km along the Red Sea coast. They observed shallower Moho for the stations along the Red Sea than in the shield. Moreover, they noticed that the change in the Moho depth becomes more pronounced when they compare stations LTHS and TAIF or FRSS and DJNS in particular (Figure 10c), where a change of approximately 25 km in Moho depth occurs in a distance of less than 200 km. Toward the east, we observed a slight thickening of the crust near the platform, where the Moho depth reaches approximately 44 km.

The Zagros is a prolific source of large magnitude earthquakes (events with magnitude ≥7) occurring in the last few decades. The overall lack of seismicity in the interior of the Arabian Peninsula suggests that little internal deformation of the Arabian plate is presently occurring. There is widespread Quaternary volcanism along the Red Sea coast, with at least one documented historical eruption in 1256 A.D. (Barazangi, 1981). Some seismicity was associated with that eruption. Seismicity may also be related to transform faults in the Red Sea continuing onto land as well as other causes. To date, few onland epicenters are accurately located and there are few focal mechanisms available.
Although all earthquakes associated with active volcanoes are ultimately related to volcanic processes, volcanic earthquakes are directly associated with magma movement, whereas tectonic earthquakes occur in zones that are separated from the principal areas of the magma movement (Heliker et al., 1986).

Generally the crustal thickness in the Arabian Shield area varies from 35 to 40 km in the west adjacent to the Red Sea to 45 km in central Arabia (Sandvol et al., 1998; Rodgers et al., 1999).

Next step, it was correlated the Bouguer anomaly field quantities the magnetic with the variation of the heat flow, crustal and sedimentary thicknesses. In the case of uniform extension, Mckenzie (1978) has shown that there are two main contributors to vertical motions: subsidence due to crustal thinning and uplift caused by lithospheric heating. The magnitude of these motions is determined from the amount of extension, as well as from the initial crustal and lithospheric thickness assumed. The process of rifting involves changes in crustal thickness as well as changes in density due to replacement of cold lithosphere by hot asthenosphere. Extended crust that may have been relatively high shortly after rifting subsides as the underlying mantle cools and increases its overall density. In Mckenzie's (1978) model, an isostatic system is assumed in which a column of extended lithosphere is in balance with unstretched lithosphere. This assumption is supported by the nearly zero average free-air gravity anomalies observed over many starved rift-type basins (e.g., Bay of Biscay margin).

To perform a qualitative interpretation of all available geophysical data sets covering the study area, four profiles were chosen from the Bouguer gravity and magnetic anomaly maps (Figures 14a - 14e); all of them were correlated with the variation in the crustal and sedimentary thicknesses in addition to the heat flow values along the area of the study. The location of the profiles were chosen in a way that they pass where major estimated boundary were located.

Examining the crustal thickness distribution produced by this study, one clearly sees large scale structures which reflect important lineaments corresponding to the main tectonic trends of the region.
For instance, the discontinuities form patterns of shallow-deep structures that shallow towards the northern and eastern coast, and deepen towards the west and northeastern Sinai.

Their studies clearly reveal northward and eastward trends of the crustal thinning toward the Mediterranean Sea and Red Sea, respectively. This was also observed by Makris et al. (1988), Marzouk (1988), and Seber et al. (2000) who describe the Egyptian territory as a continental crust with a thickness of 30–34 km, bounded by thin new oceanic crust (<20 km) that is formed by the Red Sea rifting.

A northwest–southeast trend of crustal thickening covering the northern part of the Western Desert (exhibiting the most thick crust) and coinciding with the Desert Oases, Kharga, Dakhla, and Fayoum depression (Figure 1). Between the thick crust of the Western desert and the Red Sea, crust tends to thin gently eastward in north–south lineament trend. This lineament probably extends northward to the Nile Delta and offshore, where it rapidly loses thickness following the northern coast crustal thinning (Figure 10a).

The study clearly reveals northward and eastward trends of the crustal thinning toward the Mediterranean Sea and Red Sea, respectively. This was also observed by Makris et al. (1988), Marzouk (1988), Dorre et al. (1997), Seber et al. (2000), Saleh et al. (2006) and Abdel-Wahed et al. (2013) who explained the Egyptian territory as a continental crust with a thickness of 30–34 km, bounded by thin new oceanic crust (<20 km) that is formed by the Red Sea rifting.

A northwest–southeast trend of crustal thickening covering the northern part of the Western Desert (exhibiting the most thick crust) and coinciding with the Desert Oases, Kharga, Dakhla, and Fayoum depression (Figure 1). Between the thick crust of the Western desert and the Red Sea, crust tends to thin gently eastward in north–south lineament trend (Figures 10(a) and 10(b)). This lineament probably extends northward to the Nile Delta and offshore, where it rapidly loses thickness following the northern coast crustal thinning.
On the Sinai Peninsula, the crust is about 31 km in thickness, and tending to thin toward the Gulfs of Suez and Aqaba and towards its southern border where a sudden crustal thinning occurs down the northern Red Sea. An additional crustal thickening northwestward is observed in the northwestern part of Sinai at the border of the study area. In southern of Egypt, the crust tends to be thicker near the south eastern border of the area. It is tempting to speculate that the Red Sea opening may be one of the consequences of the presence of a mega plume that extends from the core-mantle boundary into the upper mantle beneath East Africa, the Red Sea, and the western portion of the Arabian Plate (Romanowicz & Gung, 2002; Nyblade et al., 2000). It is possible that this mega plume may have rivaled those that drove the breakup of Gondwanaland and Pangea. Based on the surface geological observations and the widespread volcanic activity (Camp & Roobol, 1992a), it appears that this plume has affected the lithospheric structure over a large distance (>4,000 km) in east Africa and western Arabia, and it may have resulted in a considerable thinning of the mantle part of the lithosphere. This thinning is partially documented in western Arabia based on the recent tomographic results of the high-attenuation and low-velocity uppermost mantle (Camp & Roobol, 1992b; Al-Lazki et al., 2004; Garson & Krs, 1976).

It is noted that, the eastern part of the intensely thinned crust corresponds to areas affected by the Egyptian Tertiary basaltic volcanism (Meneisy, 1990). The quartzo-tholiitic magmatic character of the basalts suggests an oceanic spreading volcanism (Abdel Monem & Heikal, 1981) and therefore a distinctive geodynamic mechanisms studies made on these volcanic rocks indicated that they are closely comparable to the Eithiopean Plateau basalts and the other East African basalts attributed to zones of crustal thinning (Abdou, 1983). These zones of intracrustal thinning may therefore be the determining cause of the above cited Oligocene transgression. Moreover, these regions corresponding with high heat flow anomalies (as shown in Figures 14a - 14e).

Generally, the thinned crustal regions are observed where magnetization value is decreased while the amplitude of the free air anomalies increased (Von Frese et al., 1982; Pamukçu et al., 2007). Using the
same approach, crustal thinning, which is represented as thick curves in Figure 10, is well interpreted using our investigated profiles as shown in (Figures 13 and 14). On the Sinai Peninsula, the crust is about 31 km thick almost everywhere. It rapidly losses thickness toward the Gulfs of Suez and Aqaba and toward their southern borders, where a prominent crustal thinning occurs beneath the northern Red Sea (down to 14 km) in northwestern Saudi Arabia, southern Palestine and Jordan. It runs parallel to the Aqaba-Levant transform fault system (Freund, 1965; Girdler & Styles, 1974). This transform zone has undergone about 100 km of strike-slip and transtensional movement (Stickler et al., 1988) and represents the main active seismic zone of the whole area. Positive gravity, negative magnetic anomalies and high heat flow values on the thinned crustal regions (Figure from 14a to 14e) suggests that the asthenosphere is uplifted in this region.

Furthermore, it was observed an inverse correlation between sediment and crustal thickness, observed in extensional tectonic regimes (Ritzmann et al., 2007), where thinned crust acquires correspondingly thicker sedimentary column especially in continental rift regions. This statement is well correlated for all cross sections in our region case study (northern Red Sea rift), where thinned crustal regions for selected profiles are always accompanied with thick sedimentary grabens formed under the effect of extensional tectonic regime.

6. Conclusions

We can conclude that, the plate boundary between Arabia and Africa at the northern Red Sea rift region including the Suez rift, Gulf of Aqaba-Dead Sea transform and southeastern Mediterranean region was estimated using horizontal gradient gravity data analysis. The boundary analysis method was applied using low pass filtered of gravity data analysis for the northern Red Sea rift region.

Generally, in the delineation and identification of the tectonic zones related to the estimated tectonic boundaries in the northern Res Sea rift, some criteria were followed and utilized as guidelines. These are
the geological parameter map of regional tectonics in the area which indicates the location of joints, faults, lineaments, and rift systems that are associated with seismic activities. The boundaries of the tectonic source zones are the results in the inter-agreement of these criteria with the higher priority given to the heat flow and crustal and sedimentary thicknesses with seismic activity. The tectonic zones are selected that are composed of systems of faults or lineaments or rift systems whose boundaries do not traverse generally other tectonic units. From these considerations and gravity analysis, there are six tectonic zones (crustal blocks) that were identified and delineated.

Furthermore, it is noted that, the regions of intensely thinned crust (especially beneath Sinai and Arabian plate boundary) corresponds to areas affected by the Tertiary basaltic volcanism, due to extensional tectonics.

The six heat flow provinces were distinguished: 1- the west of Nile-north of Egypt normal province with low heat flow about 46 mWm\(^{-2}\) and reduced heat flow of 20 mWm\(^{-2}\) typical of Precambrian platform tectonic setting and 2- the eastern Egypt tectonically active province with heat flow up to 80-130 mWm\(^{-2}\) including the Gulf of Suez and the northern Red Sea Rift System with reduced heat flow of > 30-40 mWm\(^{-2}\), at the transition between the two provinces. The high heat flow of the Gulf of Suez-Red Sea Rift, which is due to anomalous heated upper mantle, falls down laterally to reach the characteristic value of 46 mWm\(^{-2}\) at about 90 km away from the Gulf of Suez axes; and about 150-200 km away from the northern Red Sea coast. This marks the limit or the transition zone between the rift tectonic zone and the normal province (zone) of north Egypt (as shown in profiles 2 and 4 in Figures 14(b) and 14(d)). This result supports that the opening of the Red Sea Rift increases southeastward.

The thinned crustal regions are characterized by decreasing amplitude of magnetic anomalies, which being inversely proportional with Bouguer gravity anomaly (high gravity values) is seen together with high heat flows and iso-statistically unbalanced. Thus, there is very well inverse relationship between surface heat flow and crustal thickness observed in some of the Earth’s continental crust regions.
Furthermore, this inverse relation between surface heat flow and crustal thickness is also well observed along most oceanic crustal structures of northern Red Sea rift as correlated in Fig. 14e in profile 5.

7. Acknowledgments

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References


Figure Captions:

Figure 1: Tectonic boundaries of the Eastern Mediterranean Region. Red lines delineate the recent surface faults, Red Sea Axial rift, and tectonic boundaries (Compiled after Abou Elenean; 2007). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Figure 2: Geologic map of Northern Egypt and its surroundings (modified after U.S. Geological Survey; 1963; Neev, 1975 and EGSMA, 1993).

Figure 3: The main geographical features and major tectonic trends of Egypt (after Meshref, 1990). The study area is also shown (green framed area).

Figure 4: Bouguer gravity anomaly of the Northern Red Sea Rift region

Figure 5: Filtered Bouguer anomaly map (map grid interval 0.1 data set 49x81).

Figure 6: Filtered Bouguer anomaly map (map grid interval 0.1 data set 49x81) with boundary analysis (black point)

Figure 7: Total magnetic anomaly map reduced to the pole of the Northern Red Sea Rift region. Contour interval is 50 nT. The locations of the sections of Figure 14a, b, c, d and e are shown with black dashed lines.

Figure 8: Topographic anomaly map of the Northern Red Sea Rift region (derived from Sandwell and Smith, 1997). Locations of the sections of Figure 14a, b, c, d and e are shown with black dashed lines.

Figure 9: Free air anomaly map of the Northern Red Sea Rift region (derived from Sandwell and Smith, 1997).

Figure 10a: Crustal thickness map of Egypt and the adjoining areas as compiled after Dorre et al. (1997), Saleh (2006) and Saleh (2013). Contour interval: 2 km. The
thick curves show the areas of thinned crust. Locations of the sections of Figure 13a, b, c and d are also shown with dashed red lines.

Figure 10b: Crustal thickness map of Northern Red Sea Rift region derived from Figure 9a, compiled after Dorre et al. (1997), Saleh (2006) and Saleh (2013). Contour interval: 2 km. The thick curves show the areas of thinned crust. Locations of the sections of Figure 13a, b, c, d and e are also shown with dashed red lines.

Figure 10c: Map showing the crustal thickness contour map (Moho depth) of the Arabian Shield region (after Al-Damegh et al., 2005). The seismic stations are shown as open triangles. The contour lines based on the kriging approach are shown in different colors, and the hand-drawn contour lines are shown in solid black. The figure shows also the outline of the Arabian Shield (open small circles), the escarpment (long dashes), and the Red Sea ridge (small dashes).

Figure 11a: Top of the basement map (sedimentary thickness) estimated using well logs data, seismic profiles, magnetic and gravity data analysis and 3D geophysical modeling for the northern Red Sea region (after Saleh 2009).

Figure 11b: Sedimentary thickness map of the Northern Red Sea Rift region compiled after Laske and Masters, (1997). Thick curves show the areas of thinned sedimentary. Locations of the sections of Figure 13a, b, c, d and e are also shown with black lines.

Figure 12: Heat flow anomaly map the Northern Red Sea Rift region (from Saleh et al., 2012). Thick curves show the areas of thinned sedimentary. Locations of the sections of Figure 13a, b, c, d and e are also shown with dashed black lines.

Figure 13: Tectonic boundary map estimated from Bouguer anomaly map. The area was divided into six tectonic zones (crustal blocks). Seismicity was also located on the map; (seismicity derived from ENSN, 2008).
Figure 14a: Cross-section (P1), Correlation of free air anomaly filed quantities the aeromagnetic with the variation of the heat flow, crustal and sedimentary thicknesses,

Figure 14b: Cross-section (P2), Correlation of free air anomaly filed quantities the aeromagnetic with the variation of the heat flow, crustal and sedimentary thicknesses,

Figure 14c: Cross-section (P3), Correlation of free air anomaly filed quantities the aeromagnetic with the variation of the heat flow, crustal and sedimentary thicknesses,

Figure 14d: Cross-section (P4), Correlation of free air anomaly filed quantities the aeromagnetic with the variation of the heat flow, crustal and sedimentary thicknesses,

Figure 15: Location of grid intersections used to test for a maximum near (HGM i,j). Curved lines represent contours of horizontal gradient values of magnetic or gravity anomalies.
Figure (1)
Figure (3)
Figure (4)
Figure (5)
Figure (6)
Figure (9)
Figure (10a)
Figure (10b)
Figure (11a):
Figure (13)
Figure (14- a)
Profile P1 (Fig. 14a), 550 km long, started from the end of Gulf of Suez, crossing central Sinai and ended at the northern part of Gulf of Aqaba at Israel. This Moho depth (crustal thickness) profile is derived from Dorre et al. (1997), shows an abrupt decrease (thinning) in the crustal thickness beneath northern continental part of Gulf of Aqaba region (zone 5), with a rapid increase of high heat flow density (HFD) values of approximately 137 mWm$^{-2}$ beneath this crustal thinning region (zone 4).
Figure (14- b)

Profile P2 (Fig. 14b) is 550 km long, started from the Eastern Desert passing throughout Safaga city, crossing northern Red Sea rift region and ended at the Arabian plate. The Moho depth (crustal thickness) profile is derived from Dorre et al. (1997) and Saleh et al., (2006), shows an abrupt decrease (thinning) in the crustal thickness beneath northern marine oceanic part of Red Sea (zone 4), with a rapid increase of heat flow density (HFD) value ($\geq 175$ mWm$^{-2}$) beneath this crustal thinning region (zone 4). Moreover, further rapid high heat flow density (HFD) value ($\geq 200$ mWm$^{-2}$, of noticeable crustal dropping value) was observed beneath the tectonic boundary region (Red Sea coastal area) between zone 3 and zone 4.
Figure (14- c)
Profile P3 (Fig. 14c) is 850 km long, passes parallel to the Red Sea coast from Arabian side, NW to SE. All the Moho depth (crustal thickness) is derived from Dorre et al. (1997), which shows a decreasing (thinning) in the crustal thickness beneath the Red Sea rift (see P3, Fig. 14c). The Heat flow profile shows a rapid increase to reach maximum value beneath the Red Sea rift region (zone 4). Continuing to the NW direction of crustal profile (Northern Egypt), the crustal thickness increases rapidly, this reaches its maximum value (34 km) beneath north Sinai (zone 5). In contracts, the heat flow profile show minimum value beneath north Sinai (zone 5). At the end of this profile, the sedimentary cover sequence shows a rapid increase, reaching to its maximum value beneath southeastern Mediterranean coastal region (zone 2).
Profile P4 (Fig. 14d) is about 800 km long, crosses northern Red Sea from SW to NE, passing through Qena city and crossing the northern Red Sea. All the Moho depth (crustal thickness) is derived from Dorre et al. (1997), which shows a decreasing (crustal dropping) in the crustal thickness reached to its minimum value beneath the iteration of Gulf of Suez and/or Gulf of Aqaba (between zones 3 and 5; see P4, Fig. 13c). However, the heat flow profile shows a rapid increase to reach maximum value beneath the Red Sea rift region (zone 4). Continuing to the NW direction of crustal profile (Northern Egypt), the crustal thickness increases rapidly, this reaches its maximum value (34 km) beneath north Sinai (zone 5). In contracts, the heat flow profile show minimum value beneath north Sinai (zone 5). At the end of this profile, the sedimentary cover sequence shows a rapid increase, reaching to its maximum value beneath southeastern Mediterranean coastal region (zone 2).
Profile P5 (Fig. 14e) is nearly 650 km long, and extended from SSW corner through many famous localities ongoing through Qena city at River Nile, Red Sea Hills, Eastern Desert and Esh EL Melha near Gulf of Suez, which ends at the Mediterranean coastal region north Sinai.

The crustal thickness profile shows increasing the thickness (crustal thickening) toward the SSW direction with maximum value beneath the Eastern Desert (Red Sea Hills). On contrary, the sedimentary cover sequence profile shows very thin sedimentary cover and/or cropping out the basement complex along Eastern Desert and South Sinai. Continuing to the NNW direction of crustal profile (toward the Mediterranean coastal region), the crustal thickness decrease rapidly, reaches its minimum value (28 km) beneath north Sinai and Mediterranean coastal region (crustal dropping), with a rapid increase of high heat flow density (HFD) values over 125 mWm$^{-2}$ beneath this crustal thinning region (zone 2). The sedimentary sequences attain its maximum value beneath Southeastern Mediterranean coastal area (zone 2).