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A TECTONIC MODEL AND BOUNDARIES FOR THE SOUTHEASTERN MEDITERRANEAN REGION, INCLUDING NORTHEASTERN PART OF EGYPT, FROM BOUGUER AND SATELLITE ALTIMETRY DATA ANALYSIS

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النموذج التكتونى والحدود التكتونية لمنطقة البحر الأبيض المتوسط الجنوبية الشرقية، بما فى ذلك الجزء الشمالى الشرقى من مصر، من Bouguer والأقمار الصناعية وتحليل البيانات قياس الارتفاعات

الخلاصـة: منطقة شرق البحر الأبيض المتوسط هى واحدة من المناطق المعنية من الناحية التكتونية والزلزالية. هذا يبين حدود التكتونية النشطة نسبت الى اصطدام الالواح الأفريقية والآسيوية من أحد الجوانب وتقارب اللوح العربى والمنطقة الأوروآسيوية من الجانب الآخر. ويعزى هذا الوضع التكتونى إلى النشاط الزلزلى المستمر، الأمر الذى يؤثر تقريبا فى جميع بلدان شرق البحر الأبيض المتوسط بما فى ذلك شمال مصر.

وفقا لنتائج خرائط التدرج الأفقى (HG) ومشتقة الميل (TDR)، تم تقسيم منطقة الدراسة بشكل رئيسى إلى أربعة مناطق تكتونية فرعية هامة اعتمادا على خرائط عمق كلا من صخور القاعدة و سطح الموهو. وتتوزع هذه المناطق الفرعية من الجنوب الى الشمال على النحو التالي: ١- منطقة دلتا النيل، شمال سيناء،٢-المنطقة الساحلية المصرية، ٣-منطقة الحوض الشامى Levantine، وأخيرا منطقة القص الشمالية (قبرص وضواحيها). يتم فصل هذه المناطق عن بعضها البعض بواسطة الحدود التكتونية الأفقية أو الصدوع العمودية التى تعرض أسلوب التصدع للكتل التكتونية لهذا الحزام.

نتائج خرائط التدرج الأفقى (HG) ومشتقة الميل (TDR)، تبين خطورة عدد من الملامح التكتونية سواء كانت قوية مؤثرة أو ضعيفة. يبدو أن هذه الملامح التكتونية تأخذ الاتجاهات: شرق-غرب، شمال-شرق وشمال-غرب، وهى تتوافق مع المناطق التكتونية الرئيسية الفاصلة بين القشرة القارية و المحيطية. وعلاوة على ذلك، فقد تم تحديد بعض الملامح التكتونية الشهيرة فى هذه الدراسة، مثل منطقة القص الكبرى Pelusium mega shear وذلك بأستخدام البيانات التثاقلية ثلاثية الأبعاد. ومناطق القص هذه يزداد اتساعها فى اتجاه شمال شرق وقد تطابقت كذلك مع كلا من منطقة الحدود القارية المحيطية من الحوض الشامى Levantine Basin ، ومع المنطقة الغربية للساحل الإسرائيلى (Neev وآخرون، ١٩٧٥). أخيرا، تم الحصول على خريطة تكتونية لمنطقة الدراسة أعتماداً على كلا من خرائط النماذج التثاقلية الثلاثية الأبعاد والحدود التكتونية. وأخيرا الدراسة الحالية تشير إلى أن بيانات الجاذبية بواسطة الأقمار الصناعية تعتبر مصدرا قيما للبيانات وفى فهم سلوك الحدود التكتونية فى المنطقة المدروسة وأن بيانات جاذبية القمر الصناعى يشكل مصدرا هاما للبيانات الحديثة فى دراسات ديناميكية الأرض.

ABSTRACT: *The Eastern Mediterranean region is one of the interested regions from tectonic and seismic point of views. It shows an active tectonic boundaries attributed to the collision of the African and Eurasian plates from one side and the Arabian-Eurasian convergence from the other side. This tectonic setting is attributed with continuous seismological activity, which affects almost all the countries of the eastern Mediterranean including northern Egypt.*

According to the results of horizontal gradient (HG) and tilt derivative (TDR) maps, the study area was mainly divided into important four tectonic subzones depending on the estimated basement relief and Moho depth maps. These subzones are distributed from south to the north as: Nile delta-northern Sinai zone, north Egyptian coastal zone, Levantine basin zone and northern thrusting (Cyprus and its surroundings) zone. These zones are separated from each other by horizontal tectonic boundaries and/or near-vertical faults that display the block-faulting tectonic style of this belt.

The horizontal gradient (HG) and tilt derivative (TDR) gravity maps show a number of steep and gentle lineaments. It seems that these lineaments E-W, NE and NW-trending correspond to major structural zones of continental or oceanic crust. Moreover, the prominent Pelusium tectonic mega shear zone was well defined in this study using both HG and 3D density models. This zone is extended in NE direction and well coincided with the continental-oceanic boundary zone of Levantine basin for the western Israeli offshore region. The crustal relief beneath this zone, as indicated from the 3D Bouguer interpretation, shows a poor flattening, which almost resulted from left-lateral movements (Neev et al., 1975). Finally, a plate tectonic map for study area was obtained using the evaluated 3D crustal modeling and tectonic boundary map.

The current study indicates that satellite gravity data is a valuable source of data in understanding the tectonic boundary behavior of the studied region and that satellite gravity data is an important modern source of data in the geodynamical studies.

***Keyword**: 3-D density modeling. South eastern Mediterranean region. horizontal gradient (HG). Tilt derivative (TDR).*

INTRODUCTION

The eastern Mediterranean including Egypt is a complex tectonic region evolving in the long term located in the midst of the progressive Afro-Eurasian collision. Its geological-geophysical structure has been studied for years, but is still not completely known. The present tectonics are driven by the collision of the African and Eurasian plates, the Arabian Eurasian convergence and the displacement of the Anatolian Aegean microplate. The boundary between the African and the Anatolian Aegean microplates is delineated by the Hellenic arc, the Pliny Strabo trench, the Florence Rise and Cyprus in the west, while in the east the boundary has been identified in the Herodotus basin or east of Cyprus (Aksu et al., 2005 and references therein).

Since the beginning of the plate tectonic theory, many geophysical and tectonic studies of the Eastern Mediterranean have been conducted in recent years (e.g. Ben-Avraham et al., 1987, 2002 and 2006; Smith et al., 1994; Garfunkel, 1998, Di Luccio and Pasyanos, 2007, Segev and Rybakov 2010; Eppelbaum and Katz, 2011; Saleh, 2012).

Cordell and Grauch (1982, 1985) have developed a three-step method to identify boundaries of magnetic or gravity contacts by calculating the horizontal gradient magnitudes of the gridded magnetic or gravity anomaly data. The final step of this technique is the construction of the maximum horizontal gradient map. To determine the maxima of the horizontal gradient a simple inspection can be put down by comparing its eight nearest neighbors in four directions along the row, column and both diagonals. The steepest gradient will be located directly over the edge of the body if the edge is vertical. The lineaments of maximum gradient magnitudes of the gravity anomalies delineate the positions of lithologic or structural boundary of upper crustal rocks. The method is normally applied to the gridded data rather than to profiles. This technique is also applied to the magnetic data after transforming to the pseudo-gravity field by using Poisson’s equation (Blakely and Simpson, 1986; Blakely, 1995).

In the current study we estimate quantitatively the African plate boundaries for Egyptian coastal region relative to the Eurasian plate beneath Cyprus and Florence Rise using Bouguer horizontal gradient (HG) in addition to the tilt derivative (TDR) anomaly maps for evaluating the structural elements.

The estimated tectonic boundaries using surface gravity Bouguer and satellite altimetry data analysis are well coincided with the previous tectonic results. Furthermore, the estimated crustal structural map (derived from Saleh, 2012) and plate boundaries system was outlined together in order to evaluate the tectonic model relative to crustal structures of the study area. Finally, we try also to investigate a very prominent tectonic line (e.g. Pelusium megashear system) from the results of the current study.

GEOLOGIC AND TECTONIC SETTINGS

The formation of the Eastern Mediterranean is largely dominated by the relative movement of the Arabo-African plates and the Eurasian plate (McKenzie 1972 and Dewey et al. 1973). These two large blocks have converged since the end of the Cretaceous to close the northern arm of the Tethys Ocean and form the Alpine chain between them (Biju-Duval et al., 1978).

Cyprus is located on the southern margin of the Anatolian microplate (Fig. 1), adjacent to the African plate boundary (Dewey et al., 1973). Because of the northward-directed movement of Africa, the Levant oceanic segment is subducted beneath the Tauric arc south of Cyprus. The Cyprian and Hellenic arcs are dominated by compression, whereas to the east of Cyprus a left lateral motion with an eastward increasing of the tensional component near the Dead Sea Transform Fault (DTF) is predominant. Plate motion slip rates have been accurately determined by recent GPS data (McClusky et al., 2000 and 2003); a slip rate of ~6 mm/yr is associated to the northeastward motion of the African plate whereas the northward motion of the Arabian plate has rate of ~18 mm/yr. The differential motion of Africa and Arabia relative to Eurasia is accommodated by the sinistral transpressional DSF. Northward motion of the Arabian plate relative to Eurasia causes crustal shortening and thickening in Eastern Turkey.

Indeed, the Pelusium megashear system (Fig. 2) was first identified by Neev (1975, 1977) as a tectonic line extends from the border zone of Anatolia, along the eastern Mediterranean and across Africa from the Nile Delta to the delta of the Niger in the Gulf of Guinea. Moreover, the tectonic interpretation given in the earlier papers (Neev et al., 1982) suggests that the Pelusium megashear system exhibit northward convergence patterns, which propose counterclockwise rotation of the crust. These probably result from left-lateral movements within the asthenosphere which have continued since the Precambrian. Mart, (1982) defined it as a prominent fault line runs ca. 35–50 km offshore subparallel to the Israeli coastline. It represents the western edge of the Syrian Arc fold belt. The evolution of this regional compressional tectonic feature began in the Late Cretaceous and continued until the Early–Middle Miocene (Walley, 1998; Gardosh and Druckmann, 2006). Its evolution was related to the closure of the Neo-Tethys (see Garfunkel, 1998, 2004 for comprehensive summaries).

GRAVITY DATA ANALYSIS

The techniques developed in our study were applied to detecting tectonically significant boundaries and characterizing the geologic structures for south Eastern Mediterranean region including north Egypt (Fig. 1). The region is geologically and structurally complex, composed of lithologies of different types and ages and showing varying tectonic styles and trends. Better understanding of the kinematics and the spatial extent of the dominant tectonic trends may have implications for identifying the potential for natural resources in the area. The region has been shaped through extension-dominated tectonism alternated with intermittent less-influential but intense compressive phases (Guiraud and Bosworth, 1999). Extensional tectonics leads to the Neotethys opening along the Mediterranean Basins in the Permian (Guiraud and Bosworth, 1999).

In this study, tectonic boundary with structural elements played a significant role in understanding the region's geodynamic evolution. However, these were commonly generalized sketches reviewed from interpretations of geologic observations and scarce geophysical surveys which lack spatial inter-relationships. Integrating lineaments extrapolated from various spatial data describing surface and subsurface features seems a more promising way to draw a detailed, reliable tectonic map of the region.

We used two grid data sets: 1) the Bouguer anomaly gravity anomaly grid at a constant contour interval of 5 mGal (Fig. 3) has been re-gridded and prepared from published maps (Gass and Masson-Smith, 1963; Woodside, 1976 and 1977; Egyptian General Petroleum Corporation (EGPC), 1984; Kovach and Ben-Avraham, 1980; Ginzburg et al., 1993; Makris and Wang, 1994; Rybakov et al., 1997).

A complete file of the Bouguer datasets is available now on the World Gravity Map site (WGM). 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 Gravimetrique International (BGI), a centre 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). 2) The 1- arc minute gravity (satellite altimetry) anomalies grid data set (mGal, Fig. 4) by Sandwell and Smith (1997).

Bouguer and free air anomalies interpretation

Figure (3) represents the Bouguer anomaly map of the region of the Eastern Mediterranean including the northeastern Egyptian off-shore area in the south, extending to southern Cyprus region in the north. Bouguer anomalies in the Eastern Mediterranean are predominately positive, as might be expected for an oceanic area, however, they are substantially less positive than Bouguer anomalies in the western Mediterranean or in deep ocean areas in general (Woodside and Bowin, 1970). This map (Fig. 4) shows that there exists a considerable difference between the features of the gravity field over the central and southern Levantine Basin, Eratosthenes Seamount, and south Florence Rise zone structure in the eastern, central and western north regions respectively, and the Nile Delta and north Sinai in the south.

In the southern part, gravity values range from –30 mGal to +50 mGal beneath the Nile Delta (Nile Cone) and south Levantine Basin which may attribute to the thick sedimentary cover existing below these regions. Whereas, the negative anomaly value below northern Sinai of the study area explains clearly increase of continental crustal thickness. The Levantine basin is characterized by a NNE-SSW trending high positive reaching Bouguer values of +135 mGal between eastern offshore of Mediterranean and Eratosthenes Seamount indicates a higher mass that was probably caused by uplifting of the Moho boundary by dynamic tectonic forces. The maximum value is +160 mGal below the south Florence Rise reflect thinning of continental crust which was gradually changed to oceanic type. The gravity anomalies of free air satellite altimetry map (Fig. 4) are very similar to that of Bouguer (Fig. 3) in size, trend and amplitudes. The dissimilarity between the two maps was observed only in northern Nile cone region, which may due to the lack of Bouguer gravity surveys along this region.

Estimation the boundaries and structural elements using Bouguer analysis

The horizontal gradient method has been used to locate the abrupt lateral changes in the density of near surface rocks. The horizontal gradient anomalies of the gravity data, if the edge is vertical, give the maxima over the edge of the body (Cordell and Grauch, 1982, 1985; Blakely and Simpson, 1986). Cordell and Grauch (1982, 1985) proposed a three-step procedure to locate the edge of magnetic boundaries. Firstly, the observed magnetic anomaly is converted into the pseudo-gravity anomaly (Baranov, 1957) in the Fourier domain. Secondly, the horizontal gradient of the pseudo-gravity or gravity anomaly is calculated. Thereafter the contour map of the horizontal gradient magnitude is drawn (Fig. 5). Only the final two steps are used when the method is applied to gravity data. The magnitude of the horizontal gradient of the Bouguer gravity or pseudogravity anomaly is given by

$$h(x,y)=\sqrt{\left(\frac{\partial g(x,y)}{\partial x}\right)^2+\left(\frac{\partial g(x,y)}{\partial y}\right)^2} \qquad (1)$$

formulae (where $\partial g(x,y)/\partial x$ and $\partial g(x,y)/\partial y$ are the two first-order horizontal derivatives of the gravity field, respectively) and is easily calculated by using the finite difference method (Blakely, 1995). Above, the expressions in parenthesis are the partial derivatives of the gravity anomaly data with respect to x and y axis, respectively. Locating maxima in the horizontal gradient can be done by simple inspection. Blakely and Simpson (1986) have automated an algorithm procedure that scans the row and columns of gridded data. In this procedure, at each value of horizontal gradient of the gravity grid intersection (gi,j) (except margins), is compared with its nearest neighbors in four to ascertain if a maximum is present.

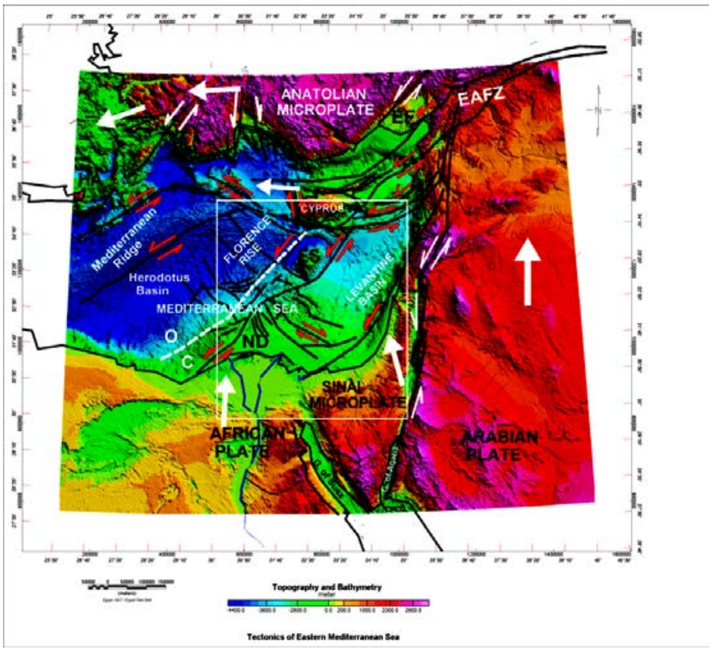


Figure (1): Present-day tectonic map of the Eastern Mediterranean region (after Harrison and Panayides (2004) and Harrison et al., (2004). ES- Eratosthenes Seamount, FR- Florence Rise, which occurs along left-lateral strike-slip structure (Ten Veen et al., 2004); EF- Ecemis fault, EAFZ – Eastern Anatolian fault zone (paleo-location to the south during Mesozoic & Paleogene shown by ghost lettering) DST- Dead Sea transform, ND- Nile delta, HA- Hellenic arc; bold dashed line is approximate boundary between oceanic (O) and continental (C) crust (Dolson et al., 2004 a and Dolson et al., 2004 b); large arrows represent relative plate motions (after Jackson and McKenzie, (1988) and McClusky et al., (2000)). The fault system between Cyprus and ES is the Cypriot transform, which marks the northern African plate boundary (Dewey et al., (1973) and Şengör et al., (1985).

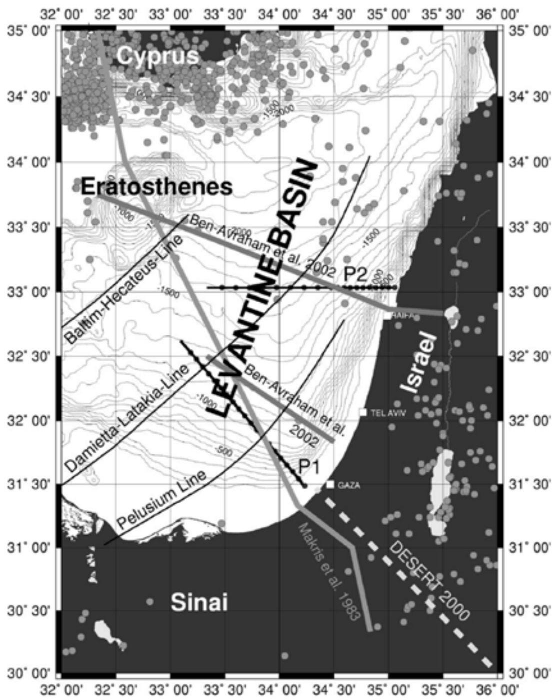


Figure (2): Map of the Levantine Basin (after Netzeband et al., 2006). Thick solid lines mark the locations of profiles P1 and P2, with solid black circles indicating the positions of the OBH. The shear zones Pelusium Line, Damietta–Latakia Line, and Baltim–Hecateus Line are shown after Neev et al. (1976). Gray circles mark hypocenters of earthquakes since 1973 according to the US Geological Survey. Previous refraction seismic lines in the Levantine Basin are marked as light gray lines.

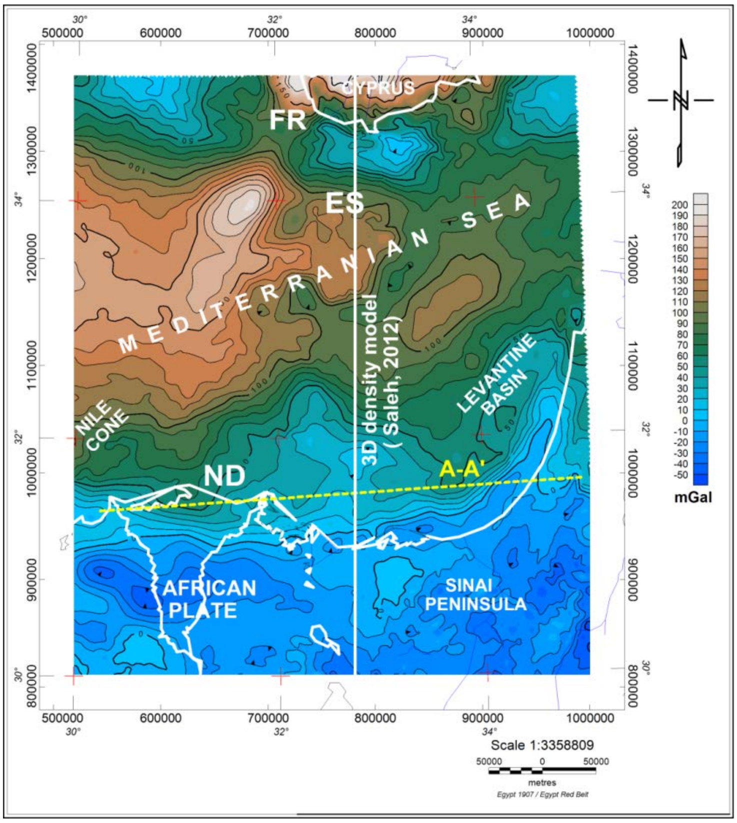


Figure (3): Bouguer grid data derived from the official Earth Gravitational Model (EGM2008) released by the National Geospatial Intelligence Agency (NGA). 3D gravity modeling profiles are also shown. AA' and plane 14 (Saleh, 2012) are shown shown in figure (7).

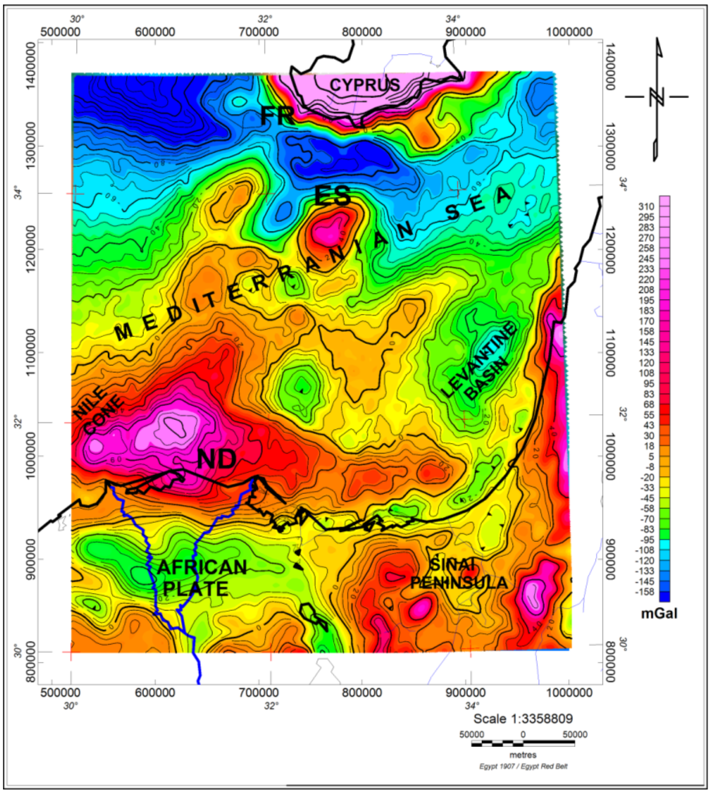


Figure (4): Free air anomaly map of the study area (derived from Sandwell and Smith, 1997).

Indeed, the free air altimetry data sets give also good picture about the general subsurface structure of the study. Tilt derivative filter (TDR) is applied to free air anomaly data, which is useful for mapping shallow basement structures and/or contacts. This filter is estimated by dividing the vertical derivative by the total horizontal derivative (Verduzco et al., 2004) as below.

$$\mathrm{TDR} = \tan^{-1}\left(\frac{\mathrm{VDR}}{\mathrm{THDR}}\right), \qquad (2)$$

Where VDR and THDR are first vertical and total horizontal derivatives, respectively, of the gravity and/or total magnetic intensity T.

$$\mathrm{VDR} = dT/dz \qquad (3)$$

$$\mathrm{THDR} = \sqrt{\left(\frac{dT}{\partial x}\right)^2 + \left(\frac{dT}{\partial y}\right)^2} \qquad (4)$$

Tilt derivative processing also combines the dx, dy and dz derivatives. One of the major positive features of the TDR is that it is very effective in allowing anomalies to be traced out along strike. This is because the filter performs an automatic gain control which tends to equalize the response from both weak and strong magnetic or gravity anomalies. In addition, this enhancement is also designed to look at fault and contact features. It usually produces a more exact location for faults than the first vertical derivative. Also, TDR map (Fig. 6) clarifies the orientations of deep seated structural or faulted orientation which are very well comparable with the regional tectonics. Integrating lineaments extrapolated from geophysical data describing the subsurface features seems a more promising way to draw a detailed, reliable subsurface structural map of the region.

Delineation of boundaries and structural domains of Eastern Mediterranean

Recognition of crustal blocks and domain boundaries is the key application of potential fields to geological interpretation. Major basement domains should have pronounced expressions in gravity data. Domain boundaries cannot, however, be distinguished from other linear structural contrasts (*e.g.*, created by stacking accreted terranes) on the basis of potential-field interpretation alone. Thus, we prefer a conservative term "structural contrasts" for the extended linear features observed in the map, although many of these features could still be associated with significant basement blocks. In our interpretation, major basement blocks and structural contrasts are identified mainly from applying the horizontal gradient (HG) and tilt derivative (TDR) maps (Figs 5 and 6 respectively). Domain boundaries are then roughly delineated by the areas of parallel or subparallel trends that have comparable amplitudes of the anomalies. This method was applied to gravity data. From gravity results, we present the interpreted structural boundary and domain definition based on the additional and improved potential-field.

a) Nile Delta and north Sinai boundary zone-BZ1 (NDS):

The north Nile delta and north Sinai boundary zone is marked by east-west trending linear anomaly with gravity low. It is characterized by thin sedimentary cover with very thick continental crustal thickness (~30-35 km total thickness, as shown in Figs. 7 and 8). 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 and Reches, 1983; Letouzey and Tremolieres, 1980), the shortening during the development of Cretaceous/Paleocene structures 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 and 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. Whereas, minor observable NW trended structures (Najd fault system) were observed crossing northern Nile Delta. Stern (1985) interpreted the Najd fault system as a set of transform faults emanating from a rift basin in NE Egypt. extensional model, in northern Egypt, may be expanded regionally to include the eastern part of the Arabian plate and the Indian subcontinent. The Najd Fault System thus represents a set of continental transforms developed in response to a major episode of Late Precambrian extensional continental crust formation in northernmost Afro-Arabia.

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) Northeastern Egyptian coastal offshore (Hinge) boundary zone-BZ2 (NECO):

This zone as shown in Figs 5 and 6 is prominent by east-west trending linear anomaly with medium gravity value. As illustrated in the 3-D gravity profiles and Moho depth map (Figs 7b and 8b), this zone is characterized by very steep transitional crustal layer with thick sedimentary cover (nearly with Moho depth ~22-27 km).

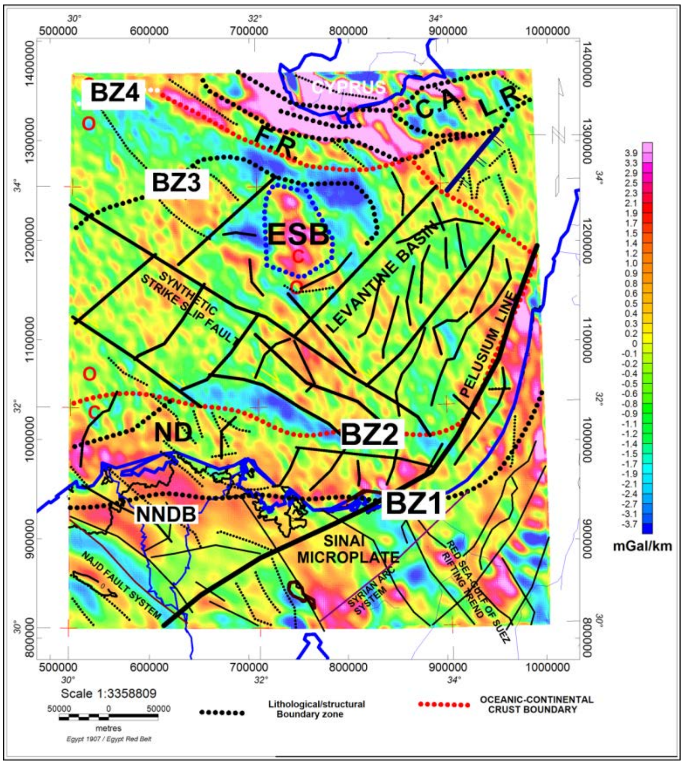


Figure (5): Full horizontal-gradient amplitude map calculated from Bouguer gravity data of the Eastern Mediterranean Sea. Black lines represent lithologic and structural elements of North Eastern part of African continental plate. Black thick lines show the boundaries of the sub-tectonic zones of the Eastern Mediterranean. Blue dotes line is approximate boundaries between oceanic (O) and continental (C) crust derived from this study. NNDB = north Nile Delta Basin.

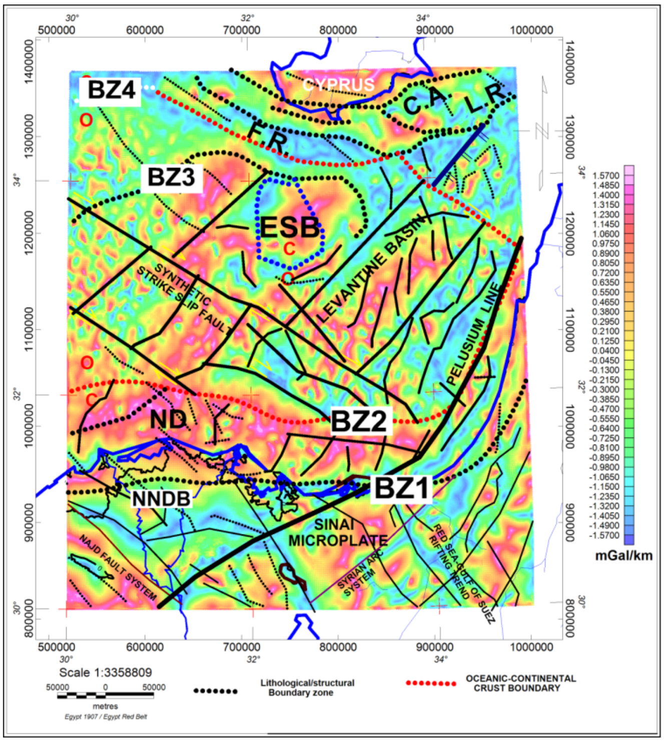


Figure (6): Tilt Derivative (TDR) of the Bouguer Gravity Anomaly. Narrow black discontinuous lines represent lithologic and structural boundaries. Black thick discontinuous lines show the boundaries of the sub-tectonic zones of the Eastern Mediterranean. Blue dotes line is approximate boundary between oceanic (O) and continental (C) crust derived from this study.

The sedimentary cover alone is nearly with thickness of ~7-12 km (Figure 8a) beneath this narrow zone, which is abruptly increasing from the Egyptian coastal line in the south to latitude 32°N in the north.

It is actually traversed by NE Pelusium megashear line at eastern margin of Mediterranean Sea (Neev et al., 1982). The density cross section AA' was projected running from west to east parallel to the coastal boundary zone (Fig. 7b). It is cutting the northern Nile delta and Levantine basin. The upper continental crust got very thin through this transition zone (~6 km thick). The sedimentary cover is relatively thicker than the previous zone (~10-12 km). As a result of 3D density profile (Fig. 7a).

The present results are well coincided with Neev et al., (1982), that the Pelusium megashear exhibit northward convergence patterns which suggest counter clockwise rotation of the crust. These probably result from left-lateral shear movements within the asthenosphere which have continued since the Precambrian.

c) Eastern Mediterranean and Levantine Basin boundary zones-BZ3 (EMLB):

This zone is the widest one in the study area (as shown in Fig. 5 and 6), which is extending from 32° to 34°N. The results of our 3D density model indicated that, it is mostly characterized by oceanic crust. The sedimentary cover is very thick beneath the Levantine basin (~14 km thick).

The basin has undergone significant subsidence for more than 100Ma (Mart, 1982; Tibor et al., 1992; Almagor, 1993; Vidal et al., 2000), over 2 km since Pliocene (Mart, 1982) and is still subsiding (Tibor et al., 1992). The basement is buried under up to 14 km of sediments (Ben-Avraham et al., 2002). The slope on the shelf steepens from 4° off Sinai to over 10° off northern Israel (Mart, 1984). Faults trending NE–SW have been observed onshore (Mart, 1982) and offshore (Neev et al., 1976; Abdel Aal et al., 2000; Farris et al., 2004).

The present estimated tectonic map (Fig. 9) depicts two types of structural systems were evaluated according to the horizontal gradient (HG) and tilt derivative (TDR) maps. Distinctive parallel NE structural trends were observed bounding the Levantine Basin and Eratosthenes Seamount. These structural systems were crossed by NW synthetic strike slip faults. According to convergent wrench model of Smith (1971), these structural elements may be synthesized due to the transcurrent motion between Africa and Laurasia (Eurasia)

The basin and its surroundings went through intense normal faulting during this period. The most common trend recognized in many places is NE–SW (Cohen et al. 1990; Garfunkel 1998; Vidal et al. 2000; Gardosh & Druckman 2006) but others like NW–SE structures exist as well (Garfunkel & Derin 1985). Kinematic models (Dercourt et al. 1986; Stampfli & Borel 2002) predict a north–south opening of the basin and some difficulties arise in adaptation of these models with the local extensional fabrics of the basin and surroundings. Another characteristic of the area is the long-lived rift activity, which likely included several rifting pulses, and various ages for the opening of the basin have been proposed, from Triassic or Late Permian to Cretaceous (Dercourt et al. 1986; Garfunkel 1998; Ben-Avraham et al. 2002; Stampfli & Borel 2002).

The Moho relief (upper mantle depth) as indicated from 3D density results shows poor flattening especially beneath the Pelusium megashear system (well represented in AA' cross section, in Fig. 7b). Moreover, the boundary location, which separates the continental crust beneath the Israeli coastal region from the oceanic one in the south Levantine Basin is well coincided with the Pelusium megashear system defined by Neev et al. (1982) and Netzeband (2006) as shown in the Moho depth map (Fig. 8b).

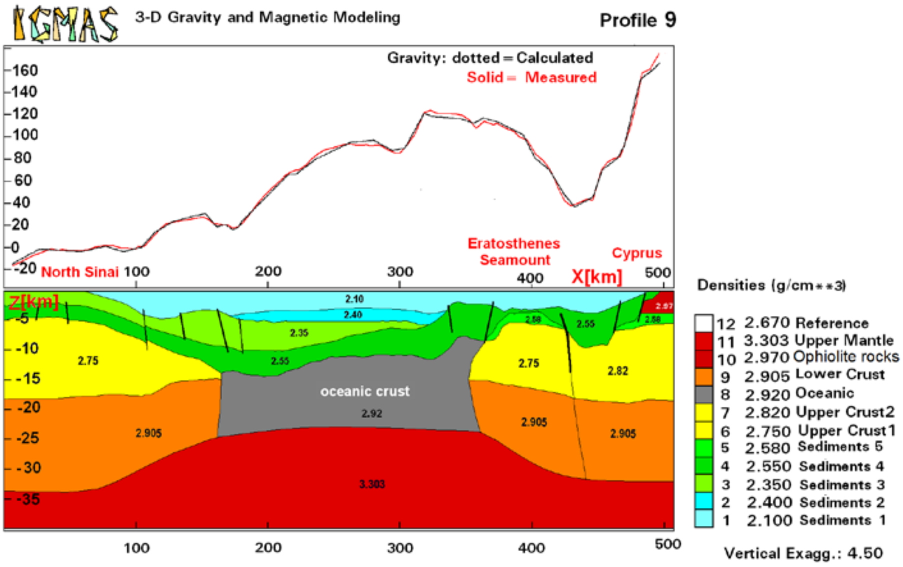
d) Cyprus and its surroundings boundary zones-BZ4 (CBZ):

Generally, the 3D density profiles interpretations (as shown in Fig. 7a) explain the crustal type variation (continental and/or oceanic) along the region of the northeastern Egyptian coastal region including north Sinai and Nile delta in the southern part extending northward to Levantine basin, the Eratosthenes seamount and south Cyprus. The sedimentary cover was modeled for both Levantine Basin and Eratosthenes Seamount with almost ~14 km and ~6 km beneath the two areas respectively (Fig. 8a). The obtained continental crust got thicker (with Moho depth of 30-34 km) beneath Sinai, Nile delta and south Cyprus (Figs. 7a and 8b).

Gravity data show a higher Bouguer anomaly in Cyprus with respect to the Eratosthenes seamount (Khair & Tsokas, 1999), These anomalies may be caused by combination of various tectonic sources that are located at different depths.(e.g., may be caused by varying combinations of ophiolites and thinning sediments as estimated from the 3-D gravity modeling).

The issue about the continental or oceanic nature of the crust beneath the Eratosthenes seamount and the Levantine basin is still a matter of discussion. From results in Figure (8) we conclude that the crust beneath the Eratosthenes Seamount is almost continental crust, as many authors suggest (BenAvraham *et al.*, 2002, Di Luccio et al., 2007 and many reference therein) and whose thickness varies in the range 22-26 km.

The existence of continental type crustal blocks in the eastern Mediterranean basin is due, as suggested by many authors, to the rifting from the African continental crust (BenAvraham *et al.*, 2002 and reference therein).



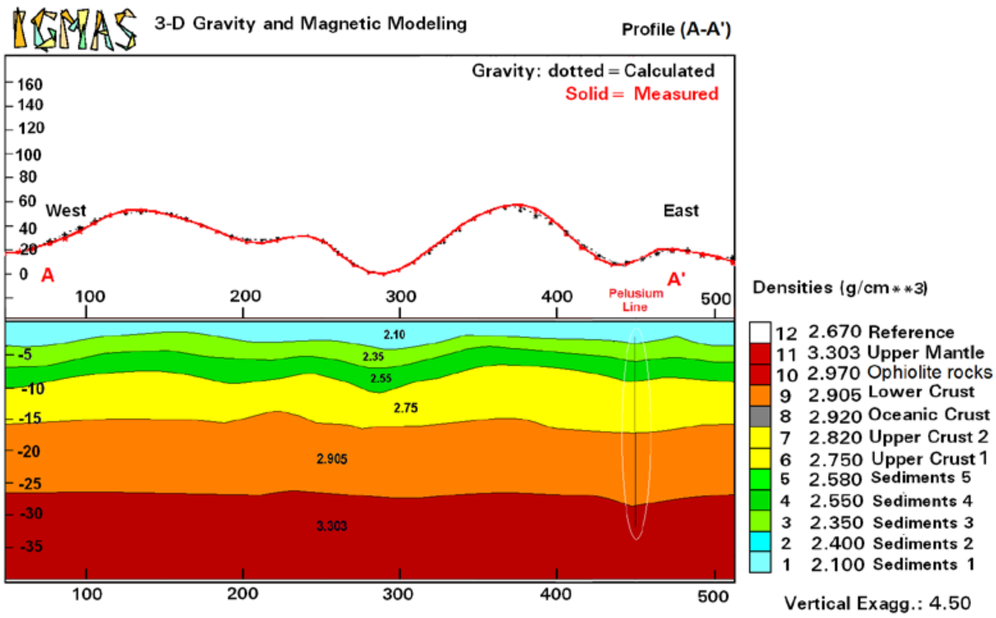


Figure (7): a) The vertical cross section of the 3D gravity model from the middle sector of the Eastern Mediterranean, along profile (P9). The lithological and/or structural boundaries are represented by bold black lines derived from *(Saleh, 2012)*. b) The vertical cross section of the 3D gravity model (AA') (from *Saleh, 2012)*. Location of modeling profile is shown in figure (3). The white zone represents the location of Pelusium mega shear system, which exhibit northward convergence patterns and propose counterclockwise rotation of the crust. These probably result from left-lateral movements within the asthenosphere which have continued since the Precambrian.

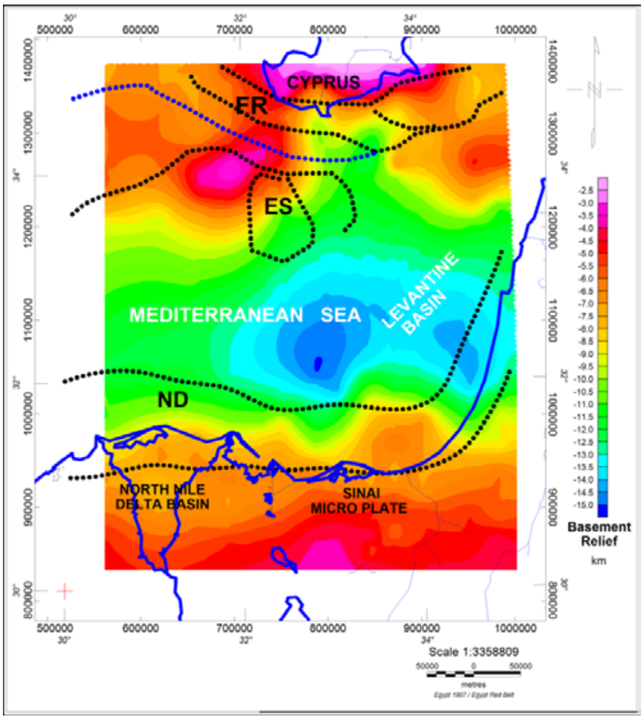


Figure (8a): Basement Relief (sedimentary thickness) map (from *Saleh, 2012)*. FS- Florence Rise, ES-Eratosthenes Seamount and ND-Nile delta. Note that the basement relief was found to increase towards the Cypriot Arc thrust zone in agreement with gravity interpretation; the results were also consistent with the regional crustal values.

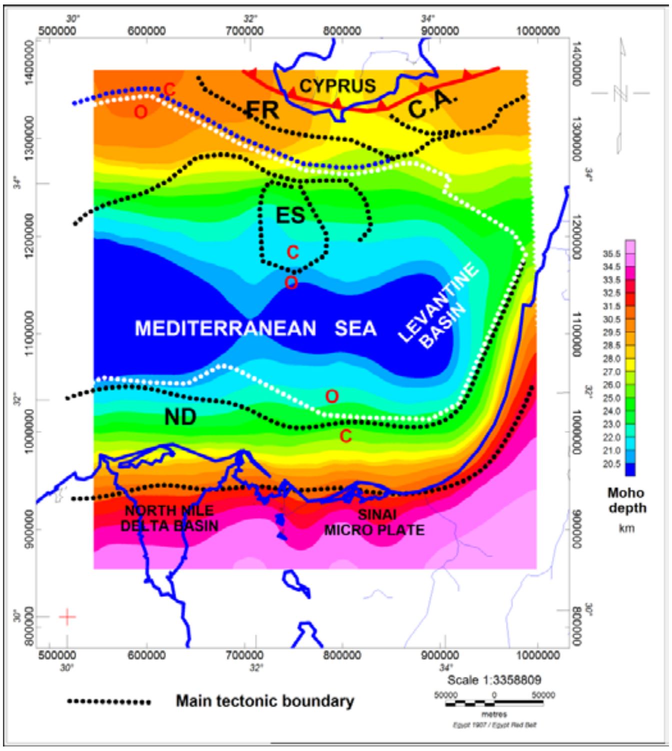


Figure (8b): Moho depth Map of the study area (from *Saleh, 2012)*. FS- Florence Rise, ES- Eratosthenes Seamount and ND-Nile delta White bold dots line is approximate boundary between oceanic (O) and continental (C) crust derived from this study. It is noted that the crustal thickness was found to increase towards the Cypriot Arc thrust zone in agreement with gravity interpretation; the results were also consistent with the regional crustal values.

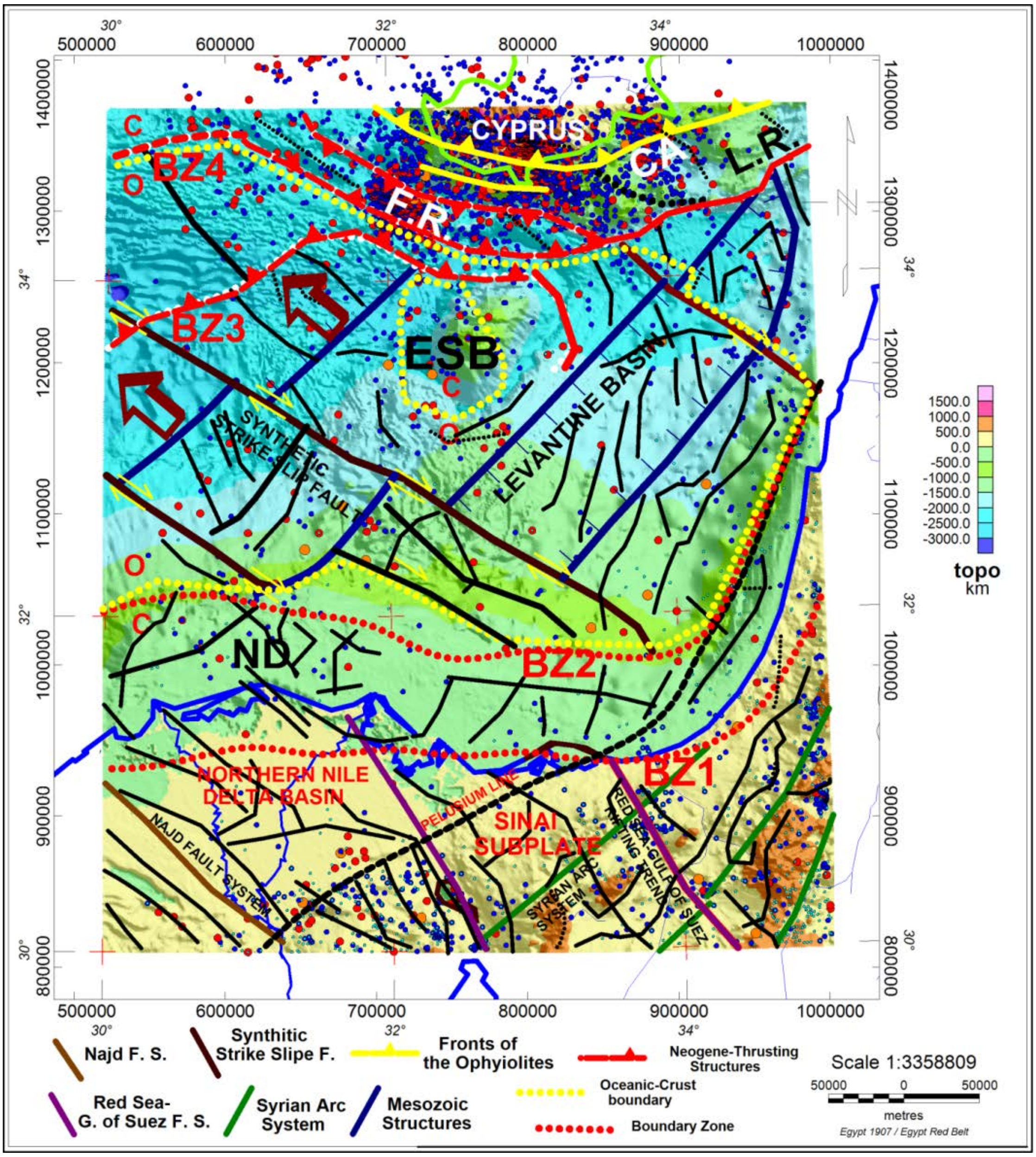


Figure (9): A plate tectonic model and tectonic boundaries of the South Eastern Mediterranean with Levantine Basin. Plate boundaries were derived from Bouguer data analysis of this study. The estimated tectonic plate boundaries were correlated with Garfunkel (1988), Bosworth et al. (2005), Robertson (1998a and 1998b), and Hall et al. (2005). CA, Cypriot Arc; LR, Larnaka Ridge FR, Florence Rise; ND, Nile Delta; ESB, Eratosthenes Seamount block; BZ1, BZ2, BZ3, BZ4 are boundary zones. Heavy black dashed line represents the Pelusium megashear line. Narrow black lines represent lithologic and structural elements. Red thick discontinuous lines show the main boundaries of the sub-tectonic zones of the Eastern Mediterranean region. Other colored lines are represented below the map with their legends. The two big arrows represent the extension direction along the Late Triassic-Early Jurassic age (Meshref, 1990).

DISCUSSIONS

This study is an attempt to achieve a better understanding of tectonics, and geodynamical processes along a complex tectonization region such as crustal structure, thickness of sediments, transition between oceanic and continental crust and regional integrated model of the gravity field observed in the area investigated. In addition, a delineation of boundaries and structural anomalies of Eastern Mediterranean were discussed. The geographic setting and geology of the study area show that the Eastern Mediterranean region includes a short segment of the convergence boundary between Africa and Eurasia. Subduction in this segment is along very small Arc, called Cyprean Arc as shown in Figure (9).

On the basis of the present detailed 3D gravity modeling, boundary analysis domain and previous geological, geophysical and tectonic results, a new tectonic with boundary map was evaluated (Figure 9). The estimated boundary tectonic map coincides well with both the resulted basement relief (sedimentary thickness) and Moho depth maps of the study area.

The estimated boundary tectonic map (Fig. 9) identifies four tectonic zones and associated trends that characterize critical plate boundary and intra-plate features including basin boundaries and intra-basin fractures. Four major fault trends (tectonic lineaments) extrapolated from the concentrated co-linear long lineaments and the fault types are compared to referenced structural features. This comparison is summarized below in order of the reactivation period, starting from the oldest:

Najd Fault System (NFS) trend (WNW-ESE to NW-SE), positional corresponds with the gravity lineaments, represents principally Late Precambrian sinistral strike-slip transpressive shear zones (Stern, 1985). Another characteristic representative of the NFS trending system is its unusual continuity from the southern Sinai to South Cairo (Fig. 9). Longacre et al. (2007) demarcated this fault zone in the offshore as a sinistral ocean-continent transform boundary that separates the ocean crust of the southern Tethys from the mildly-extended continental crust of northern Egypt.

The Trans-African Lineament (TAL) trend (NE-SW) correlates with the Tethyan shear zones (Keely, 1994) and the Pelusium Line (Neev et al., 1982). The variable senses of strike-slip movement induced transtention and transpression stress fields, by which the TAL-parallel lineaments became active during the Tethyan rifting (Keely, 1994). This TAL trend demarcates also the Red Sea extensional faults that have continued to be active from Tertiary to Recent times (e.g. Cochran and Martinez, 1988).

Red Sea–Gulf of Suez trend (NNW-SSE) correlates with the Clysmic or Eritrean fractures of Keely (1994). The NNW-SSW trending lineaments chiefly extracted from the topographic and gravity data are notably situated in the Early Cretaceous deposits (Fig. 9). This corresponds with the fact that the Red Sea–Gulf of Suez rifting likely commenced in the Cretaceous period (Makris and Rihm, 1991) and reached its climax in the Oligocene period, predominantly controlling the linkage of rift-parallel faults in the Gulf of Suez (Guiraud and Bosworth, 1999).

Eastern Mediterranean Basin (EMB) related-trends are represented generally by a perpendicular conjugate set of zones oriented nearly E-W resulting from compressional stress fields and N-S resulting from extensional ones associated with the northward movement of Africa and still active till today. Lineaments of these trends were derived jointly from the gravity anomalies in the Eastern Mediterranean offshore area dominated by reverse and strike-slip types (Fig. 9). E-W striking lineaments are commonly concentrated near the southern boundary of the EMB, while the less common N-S oriented lineaments represent intra-basin features. The EMB trend's agreement with the well-known Hellenic and the Cyprian Arc (See Fig. 9) is striking.

Whereas, the Eastern Mediterranean basin include the Levantine basin and Eratosthenes Seamount continental block could be divided into sub-basinal crustal blocks. Eratosthenes Seamount is only the continental crustal block which is in the process of actively subsiding, breaking-up and being thrust, beneath both Cyprus to the north and the Levantine Basin to the south (Robertson, 1995). In addition, the tectonic shear zones (Pelusium line, as discussed in Neev et al. 1976) were well recognized in the present work.

However, the existence of a component of NW-SE movement of the southeastern Mediterranean with respect to the Aegean plate is considered to be responsible for some deformation occurring in the Levantine Basin, namely the apparent reactivation of "Syrian arc" folding and faulting (Said, 1962) as suggested by the interpreted thrusting west of Eratosthenes Seamount.

Depending on the detailed 3D density modeling of Bouguer anomaly map with the boundary analysis results, and previous geological and geodetic data analysis, as well as onshore fault trends, and regional arguments for plate tectonic reconstructions, we agree with the results of Meshref (1990) and Garfunkel (1998; 2004) in proposing an opening direction that was strongly in ENE-WSW direction oblique to the present-day continental margin of northern Egypt (Figure 9). In our suggested tectonic picture for initial development and rifting of the Eastern Mediterranean Basin (EMB), the southern margin of the basin (BZ2) develops as a left-lateral ocean-continent transform boundary separating oceanic crust of the southern Tethys (BZ3) from the extended continental crust of the northern Egypt (BZ1). Whereas the northern margin of the basin (BZ4) developed as an oceanic-continental thrusting boundary separating the continental crust of

Eratosthenes Seamount and Cyprus from the oceanic crust of the southern Tethys region.

Our structural elements and tectonic boundaries results as show in Fig. (9) are well coincided with structural observations along the Levant margin and offshore north Sinai (Garfunkel, 2004; Farris et al, 2004; Longacre et al., 2007).

CONCLUSIONS

The compiled Bouguer anomaly map of Eastern Mediterranean enabled us to establish a possible density model along the South Eastern Mediterranean region including the African boundary of Egyptian coast of Nile Delta and Sinai, South Levantine Basin, Eratosthenes Seamount, Florence Rise and southern region of Cyprus. The gravity data have proved to be useful for delineating shallow and deep structures and helping the definition of models which agree with the basic information supplied by the previous geophysical investigations, as well as, from geological knowledge. The Bouguer anomaly map of the study area is characterized by the presence of different anomalies that differ in their amplitudes, sizes and trends. These anomalies are caused by combination of various tectonic sources that are located at different depths. The main important contributions of this work are defining and estimate the tectonic boundary map of the study area using gravity data analysis.

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