SATELLITE GRAVIMETRY AS A POWERFUL TOOL FOR DELINEATION OF REGIONAL TECTONO-GEOPHYSICAL DOMAINS: IMPLEMENTATION FOR THE ARABIAN-AFRICAN REGION

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Satellite gravimetry is recognized now as powerful and reliable tool for regional tectono-geodynamic zonation. Regular observation grid and comparatively high accuracy (1-1.5 mGal) of satellite gravity data retracked to the Earth's (together with other kinds of gravity observations) surface makes these data indispensable instrument for examination of deep geological features (mainly, Earth crust and upper mantle). The area under study – Arabian-African region – is very attractive geological-geophysical polygon from geodynamical (high seismic activity, active rift zones and collision processes), structural (presence of mosaic block system of continental and oceanic Earth's crust of different age), geophysical (presence of several greatest gravity anomalies and intricate magnetic pattern) and economical (occurrence of main hydrocarbon resources of the world) points of view. Examination of satellite derived gravity data by use of advanced qualitative methodologies enabled to develop a series of principal new maps indicating the tectono-geophysical zonation of the region, presence of different types of the Earth's crust terranes and slabs. Semi-quantitative analysis was applied for determination of the depths of contrast density masses surface in lithosphere. These data were used, together with other isolated geophysical-geological features, for elaboration and generalization of earlier constructed tectonic maps and schemes. On this basis, a new tectonic map of the Arabian-African region has been developed – geological data were supported by satellite gravity (mainly), magnetic, GPS, seismic, seismological and some other geophysical data analysis.

INTRODUCTION

Satellite derived geophysical (first of all, gravity) data is the powerful tool of regional tectono-geophysical examination of the Earth's crust and upper mantle. It is well known that regional long-term seismological prognosis, strategy of searching economic deposits and many other important geological-geophysical problems are based mainly on results of combined tectono-geophysical zonation.

Some authors' experience of the tectono-geophysical zonation in the Eastern Mediterranean (both sea and land) with satellite derived gravity field examination (Eppelbaum and Katz, 2015a,b) indicates a high effectiveness of the data employment for delineation of different tectono-structural units. Therefore, on the basis of the previous successive application, satellite derived gravity field analysis was applied for the disproportionally large and complex Arabian-African region (Figure 1). The gravity field retracked from the Geosat and ERS-1 altimetry (e.g., Sandwell and Smith, 2009) was utilized by the use of different mathematical apparatus employment enabling to underline these or those tectonic features of the region under study.

The main goals of present investigation are following: (1) employment of a modern powerful regional geophysical tool – satellite derived gravity data and its transformations for unmasking some buried tectonic and geodynamic peculiarities of the study area, (2) development of a novel tectonic map of this area (on the basis of careful examination and generalization of available geological and geophysical data), (3) finding definite relationships between the novel tectonic map and the gravity field transformations.

Application of advanced statistical, informational and transformation methods to satellite derived gravity data led to the development of several maps clearly reflecting the tectono-geophysical features of the region and location of different types of the Earth's crust. Semi-quantitative analysis was applied for determination of the depths of contrast density masses surface in lithosphere.

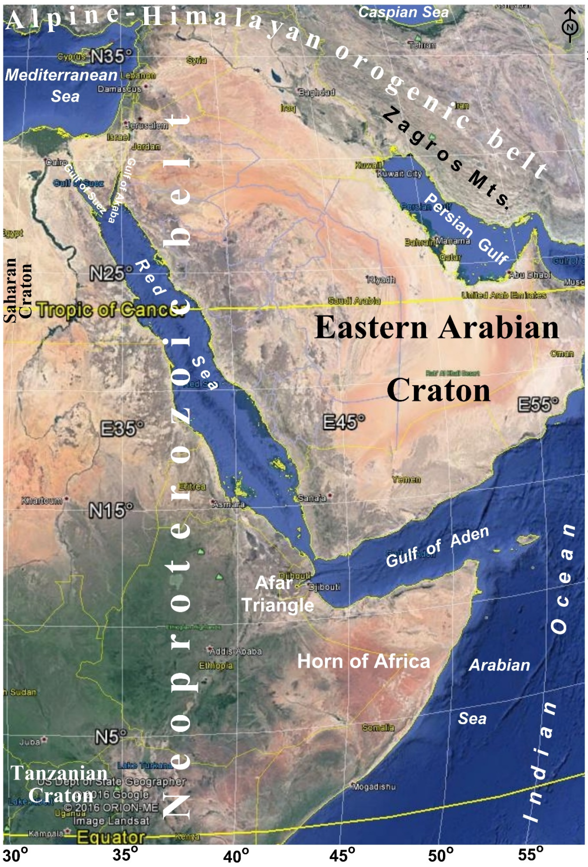

Figure 1. Areal map of the region under study (on the basis of Google Earth image) supplemented by main tectonic elements

Commonly, this investigation indicates the possibility of application of gravity field retracked from satellites for the small-scale tectono-geophysical zonation in both marine and land areas. At the same time, for the areas with the predominant development of mountainous systems some additional reduction may be necessary.

Obviously, further geophysical studies will include combined examination of gravity data with multilevel observed magnetic data and thermal data as well as seismic, GPS and some other methods.

SATELLITE GRAVITY DATA RETRACKED TO THE EARTH'S SURFACE AND THEIR IMPORTANCE

It is known that in the 'pre-satellite gravimetric epoch', regional gravity observations (shipborne and airborne) were as a rule non-regular ones, with large 'white spots' and different accuracies and methodologies of gravity field observations. Besides this, the most part of available shipborne and airborne gravity data is characterized by the error of gravity field computation > 2-3 mGals.

Some evaluation of the satellite derived gravity field accuracy (averaged data from different satellite missions were examined) is shown in Table 1. Apparently reaching the gravity field accuracy of 0.7-0.8 mGal until 2020 will allow to include to the satellite gravimetry a new circle of applied geological-geophysical problems.

Table 1

Accuracy of satellite derived gravity data for different epochs

Epoch	Error of gravity data computation, mGal	Gridding, km	Available data
1965-1970	20	20 x 20	Separate regions of the Earth
1995-2000	8	10 x 10	70% of the Earth
2014-2016	1.5-1	2 x 2	95% of the Earth
2018-2020	0.7-0.8 (?)	1 x 1(?)	All the Earth

The satellite gravity data (joined with other kinds of gravity observations), employed in this analysis, were obtained from the World Gravity DB as retracked from Geosat and ERS-1 altimetry (Sandwell and Smith, 2009; Andersen et al., 2009). A highly positive factor is that these observations were done with regular global 1-minute grids (Sandwell and Smith, 2009) and the error of gravity data computation was estimated at 1-1.5 mGals (Sandwell et al., 2013). The satellite-derived data have the advantage of global coverage that makes the measurements independent to the ruggedness and remoteness. Furthermore, by using the satellite data, is avoided a long-wavelength problem in the gravity field that can be introduced by combination of different surface measurement surveys (Braitenberg and Ebbing, 2009).

It is necessary to note that the maps of vertical gradient of gravity anomalies (T_{zz}) obtained by use the GOCE missions (e.g., Hirt et al., 2011; Rummel et al., 2011) were also tested for revealing essential deep tectono-structural peculiarities of the region under study. However, these maps and their transformations usually reflect only subsurface geological section (first km, and in the best case – first 10-15 of km of the Earth's crust).

The satellite derived gravity retracked from Geosat and ERS-1 (e.g., Sandwell and Smith, 2009) data cannot be related to the conventional type of gravity reduction but can be assumed as close to 'free air' anomalies (Sandwell et al., 2013; Eppelbaum and Katz, 2015a). At the same time, this difference usually is not significant for marine areas

(Sandwell and Smith, 2009; Sandwell et al., 2013) and land areas with relief amplitudes near the mean sea level, but may reach considerable values in the land areas with middle and high-amplitude topography.

Theoretically, free air gravity anomalies are mainly produced by non-uniform density distribution in the Earth's crust and upper mantle and reflect the differences of shape and mass distribution between the real Earth and geodetic ellipsoid (Grushinsky, 1976). Jin-Yu et al. (2014) have formulated two important items: (1) for the areas with gentle terrains (assuming that width of terrain relief in general more than in ten times exceeds the compensation depth), free air gravity anomalies can be applied for crustal isostatic research and for analysis of significant tectonic movements; (2) recent tectonic events and lithospheric structure have more visible signatures just in the free air field. Concerning item (1) we should note that the region under study (see Figure 1) does not basically characterize by high relief amplitudes. In general, we agree with item (2), but propose that not only 'recent events'. Our experience indicates that earlier constructed satellite derived gravity map of the Eastern Mediterranean (retracked to the sea and land surfaces) reflects practically all main structural-tectonic elements of this region (after Eppelbaum and Katz, 2012b). Preliminary computations indicate that the satellite derived gravity field may also be effectively applied for solving different rheological and eustatic problems (e.g., Morner, 1980).

The area under study is limited by coordinates (0^o – 37.0^o north, and 30^o – 57^o east) and presents a giant region of the Near and Middle East and Eastern (and partially – Northern) Africa (see Figure 1). Totally this area covers more than 10 mln. km^2 and its regional geological-geophysical peculiarities are presented in numerous publications (e.g., Stacy et al., 1980; Ben-Avraham and Ginzburg, 1990; Glennie et al., 1990; Said, 1990; Johnson, 1998; Khain, 2001; Ben-Avraham et al., 2002; Davis and Slack, 2002; Pollastro, 2003; Alsharhan, and Nairn, 2004; Robertson, 2004; Stern et al., 2004; Jimenez-Munt et al., 2006; Reilinger et al., 2006; Hansen et al., 2007; Bordenave, 2008; Johnson and Kattan, 2008; Johnson et al., 2008; Milesi et al., 2010; Stern and Johnson, 2010; Motavalli-Anbaran et al., 2011; Nyblade, 2011; Stampfli et al., 2013; Korostelev et al., 2014; Muluneh et al., 2014; Eppelbaum and Katz, 2015a,b; Tunini et al., 2015; Alizadeh et al., 2016; Globig et al., 2016).

Figure 3 shows satellite gravity anomalies distribution (nealy 4 mln. observations were utilized) which obviously has quasi-normal character. The compiled gravity map accompanied by main tectonic features (Figure 4) shows the intricate gravity pattern of the investigated area. Analysis of the gravity field behavior shown in Figure4 enabled to separate two main types of tectonic structures: (1) stable zones of continental and oceanic crust, and (2) mobile belts. First type displays the homogeneous character of the gravity field pattern (for instance, see the Eastern Arabian Craton in Figure 4), whereas second type is characterized by the mosaic and variable behavior of gravity field (especially, active rift zones).

It should be noted that 'youngest' mobile structures (Alpine-Himalayan orogenic belt and active rift systems of the Red Sea – East Africa) significantly differ in the gravity field pattern from the Mesozoic terrane belt and Neoproterozoic belt (Figure 4).

TRANSFORMATIONS OF SATELLITE DERIVED GRAVITY MAP

Some examples of satellite derived gravity field transformations were shown in (Eppelbaum and Katz, 2012b; Gaina et al., 2013; Li et al., 2013; Eppelbaum, 2014; Klokočník et al., 2014; Eppelbaum and Katz, 2015b). For example, computation of first directional derivatives (south-north) of satellite derived gravity field (Eppelbaum and Katz, 2012b) enabled to clearly trace the main tectonic and geophysical peculiarities of the Eastern most Mediterranean, especially a boundary between continental and oceanic crust. Downward continuation of satellite derived gravity field to a depth of 4 km enabled to display a very intricate tectono-gravity pattern for the African Plate and adjacent regions (Gaina et al., 2013). Li et al. (2013) successfully applied continuous wavelet transform to satellite gravity data for delineation of anomalous sources at different depth within the Chad lineament (North-Central Africa). The use of Marussi tensor and some gravity field invariants were successfully applied for computation of transformations derived from satellite observed gravity anomaly in different regions of the world (Klokočník et al., 2014). An informational approach employed to satellite gravity examination in the South Caspian Basin (Eppelbaum, 2014) enabled to obtain new important characteristics about the buried geological targets. Entropy map derived from the satellite gravity anomalies (Eppelbaum and Katz, 2015b) unmasked some buried tectonic peculiarities of the eastern Mediterranean.

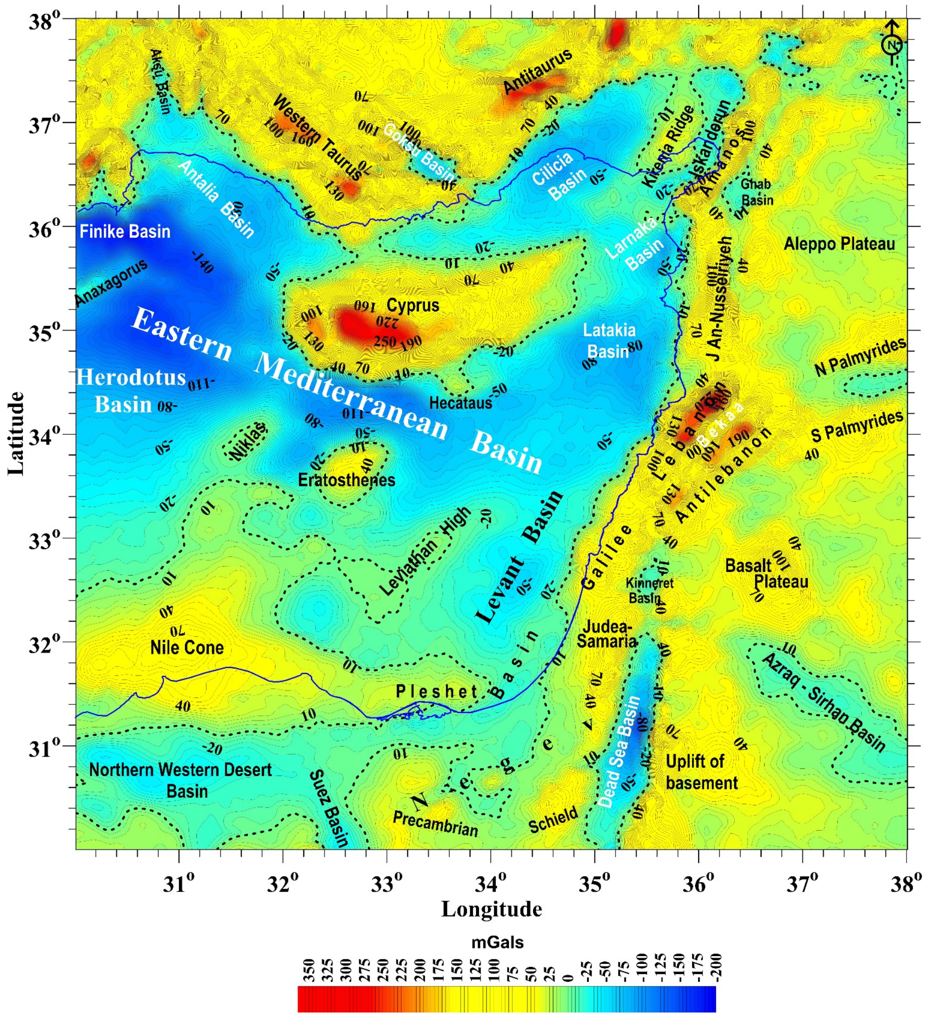

Figure 2. Satellite derived gravity map of the Easternmost Mediterranean with main tectonic units (after Eppelbaum and Katz, 2012b, with modifications). Blue lines outline the Easternmost Mediterranean coast

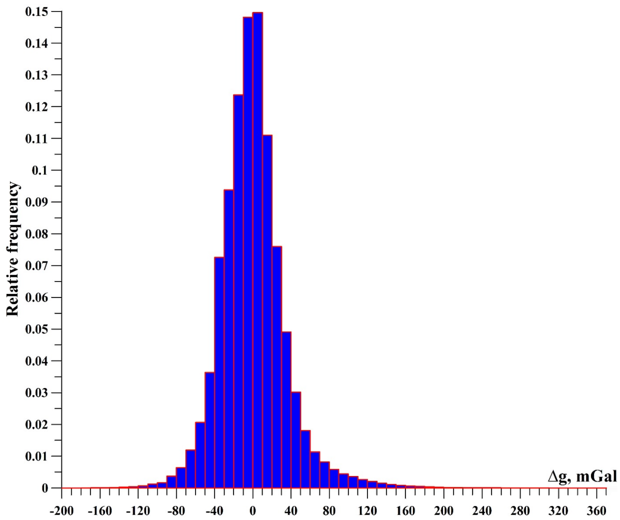

Figure 3. Histogram of satellite derived gravity anomalies distribution for the region under study

In this investigation six most effective computations (totally 12 different transformations were compiled) are presented: multidimensional statistical analysis by the use of sliding window (Figure 5), low-pass filtering (Figure 6), informational approach (Figure 7), gradient operator (Figure 8), entropy processing by sliding window of adaptive form (Figure 9), and 3D inverse methods (Figure10).

Application of the multidimensional statistical analysis (MSA) (Petrov et al., 2011) is carried out on the basis of computation a smoothed gravity field and its dispersion in the sliding window of adaptive (changing) rectangular (or inclined) form. Such a parametrization enabled to compute the effects from the geological targets with different locations along the strike; standard field pattern was automatically detected. Application of the MSA enabled not only to delineate geodynamical parameters of the studied region (collision zone at the boundary between the Arabian and Eurasian Plates, and active rift zones between the Arabian, Nubian and Somalian Plates, etc.), but also to estimate some tectonic characteristics of the Earth's crust (Figure 5). This map clearly shows zone of development of the oceanic crust of the Easternmost Mediterranean and zone of oceanic crust of the Gulf of Aden and eastern (oceanic) part of the Somalian Plate. Besides this, in this map the Arabian and East African active rift zones and collision zone between the Arabian and Eurasian plates are visibly traced.

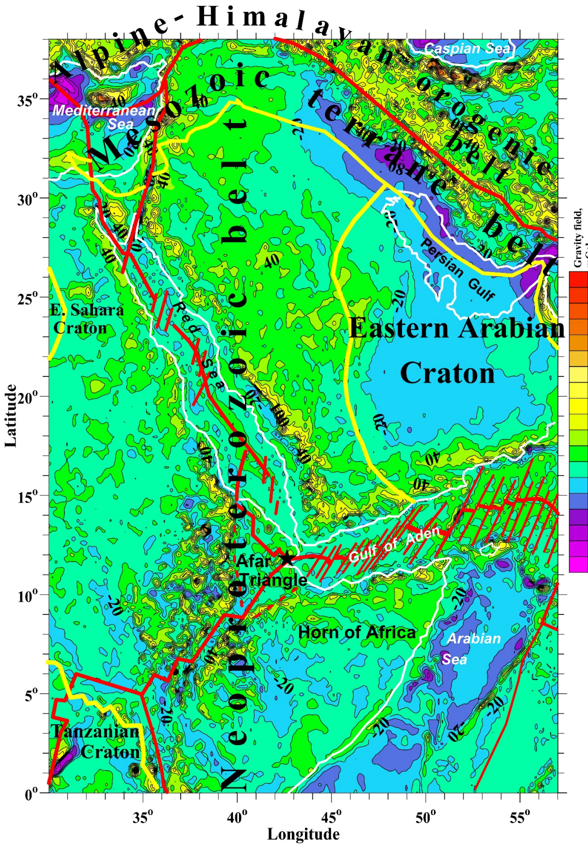

Figure 4. Satellite derived gravity map retracked to the Earth's surface with general tectonic features (cratons, belts and fault systems). Isoline interval is 30 mGal. Red lines indicate fault systems, yellow lines show boundaries of cratons and tectonic belts, and white lines show boundaries between the land and marine areas

Figure 6 presents results of the low-pass gravity field filtering. Here the most contrast crust-mantle structures could be recognized. For example, the Afar triangle is clearly detected. Zones of the Neotethys closing can be identified: Easternmost Mediterranean, Persian Gulf, Zagros Fault Zone, and South Caspian Basin. Subduction zones associated with plate boundaries are reflected by elongated gradient pattern. These nonstable zones are conjugated with large mobile belts: the Alpine-Himalayan belt and the Mesozoic terrane belt. We can suggest that the regional pattern shown in Figure 6 displays relict structures of interaction between the ancient mobile belts, continental lumps and oceans. The zone of active rifting of the Red Sea rift, Gulf of Aden rift and complex structure of the Afar triangle and East African rift system are noticeably fixed. The boundary between the continental and crust in the SE part of the region (where occurs a transfer zone between the Gulf of Aden and Arabian Sea) is visibly detected.

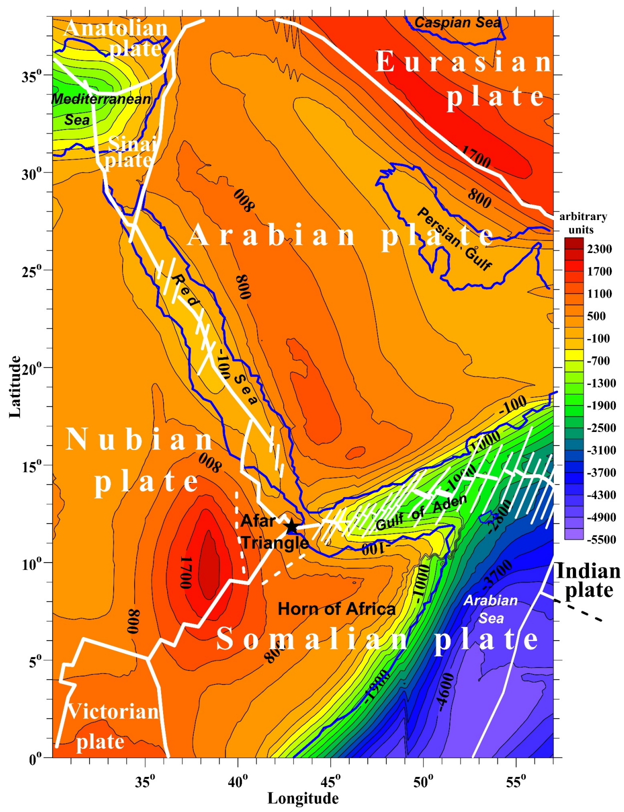

Figure 5. Comparison of the satellite derived gravity field transformed by the use of multidimensional statistical analysis and main plate tectonics units. White lines indicate fault systems, and blue lines show boundaries between the land and marine areas

Informational approach has been earlier tested (Khesin et al., 1996; Eppelbaum and Khesin, 2012) for solving a wide range of geological-geophysical problems. Application of informational approach enabled to reliably fix both continental and oceanic cratons and all belts (Figure 7). To south-east of the Horn of Africa the Arabian Sea Basin with oceanic crust is clearly distinguished. The Eastern Arabian Craton (platform) as well as its framing are noticeably detected.

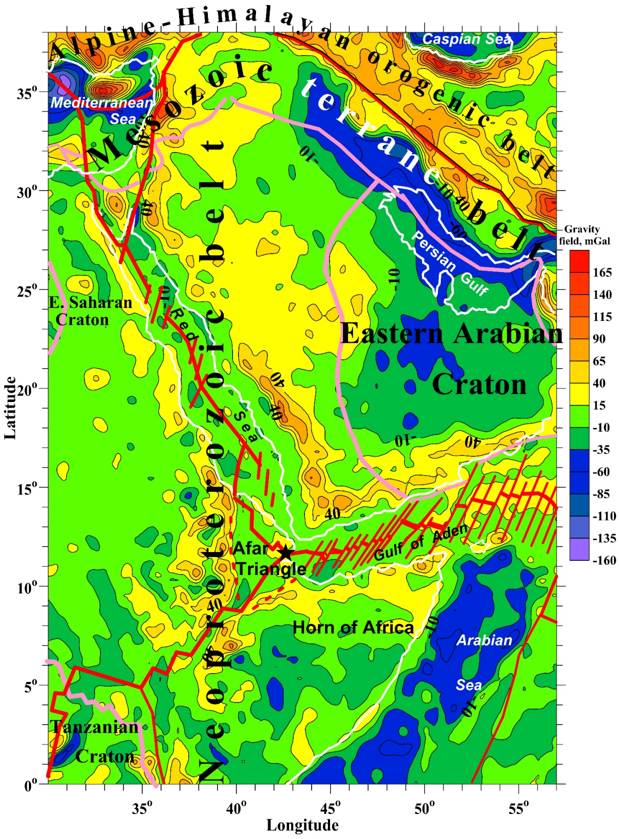

Figure 6. Low-pass filtered gravity map with general tectonic features (cratons, belts and fault systems). Isoline interval is 25 mGal. Symbol ★ designates the triangle junction. Red lines indicate fault systems, pink lines show boundaries of cratons and tectonic belts, and white lines show boundaries between the land and marine areas

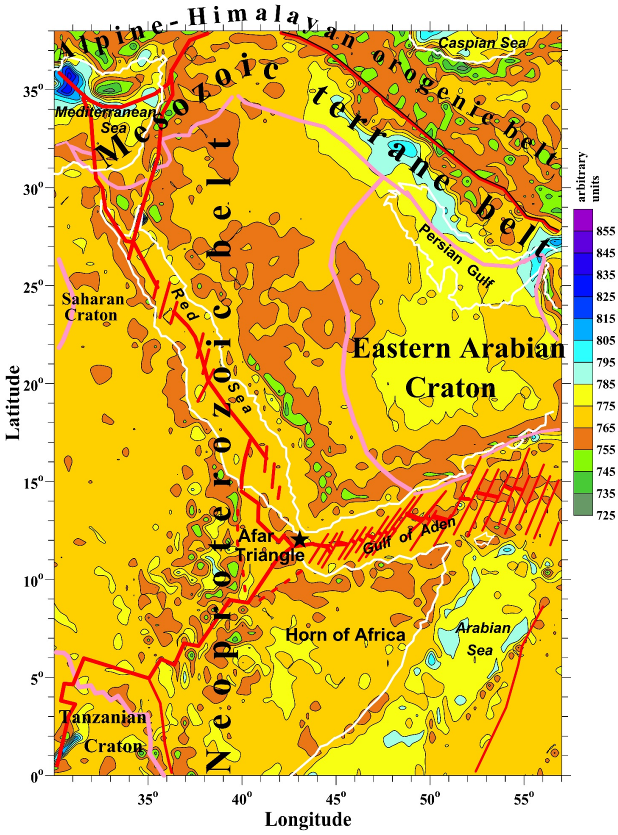

Figure 7. Gravity map transformed by the use of informational approach with general tectonic features (cratons, belts and fault systems). Red lines indicate fault systems, pink lines show boundaries of cratons and tectonic belts, and white lines show boundaries between the land and marine areas

Figure 8 displays the results of gradient operator employment. Here the relatively stable and mobile zones of the Earth's crust are visibly delineated (see also explanation of previous figures).

Computation of entropy map from the satellite derived gravity field was earlier successfully tested by the authors in the Easternmost Mediterranean (Eppelbaum and Katz, 2015a) and other regions. Application of the adaptive form sliding window (Petrov et al., 2011) enables to receive the most reliable entropy estimations in conditions of complex field caused by superimposed influence of targets of different order. Obviously, computation of an entropial map by the same method for the region under study (Figure 9) reproduces mainly deep tectonic units (elements) of the region. Complex pattern of the entropial field in the SE part of the region reflects transfer from Somalian Plate to Indian Plate (this area is characterized by the most mosaic pattern). This map nicely indicates position of the Mesozoic terrane belt and transition zone between the Victorian and Tanzanian plates.

The advanced inverse method developed by Priezzhev (2010) is based on the downward analytical continuation realized in the spectral domain. Applying this methodology, the most density contrast surface (discontinuity) in the upper mantle (lithosphere) was constructed (Figure 10). This map presents an intricate density-tectonic depth pattern of the region. In this map are noticeably recognized such important tectonic features as the Afar Triple Junction and collision zone between the Arabian and Eurasian lithospheric plates. Besides this, we can note increasing of lithospheric thickness in central parts of the Arabian and Somalian Plates. Both these plates are countered by low-thickness lithospheric zones corresponding to active rift zones. As indicated in the map, the thick lithospheric zones are associated with collisional zones at the boundaries between cratons and mobile belts. We suggest that the lowered values in the northern boundaries of the Arabian Plate correspond to subduction zones. The zones of lowered values in the middle of western part of the region correspond to the Neoproterozoic belt where ophiolitic and back-arc complexes with a thinned crust (e.g., Stern et al., 2004) are developed. Some very preliminary analysis of heat flow (collected from different sources) indicates that there is a direct correlation between the compiled map (Figure 10) and thermal data.

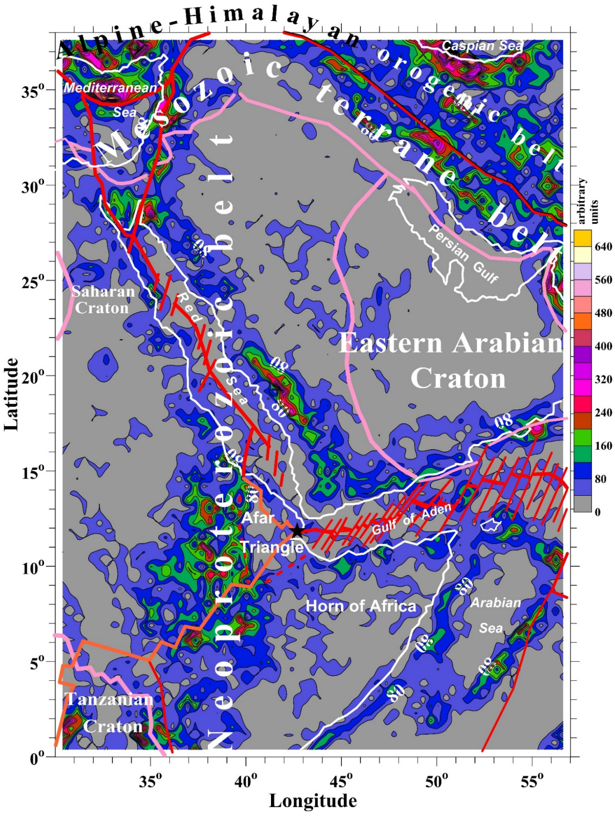

Figure 8. Gravity map transformed by the use of gradient operator with general tectonic features (cratons, belts and fault systems). Red lines indicate fault systems, pink lines show boundaries of cratons and tectonic belts, and white lines show boundaries between the land and marine areas

The depths of contrast density surface (discontinuity) presented in Figure 10 were compared with the results of various geophysical investigations, where some disturbing objects (slabs) were determined at corresponding depths in separate areas of the region (e.g., Yakobson, 1997; Jimenez-Munt et al., 2006; Pasyanos and Nyblade, 2007; Park et al., 2008; Agard et al., 2011; Bastow et al., 2011; Nyblade, 2011; Korostelev et al., 2014; Tunini et al., 2015). The comparison shows reasonably good agreement between the values derived from the satellite gravity data on the one hand, and from the seismic, seismological, temperature and some other data – on the other hand (Table 2).

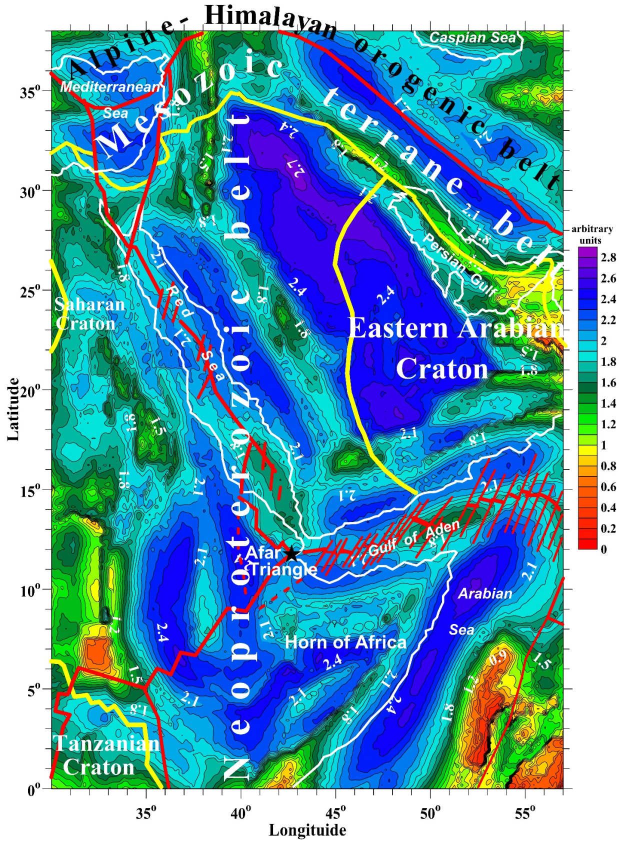

Figure 9. Entropy map transformed from the satellite gravity map accompanied by general tectonic features (cratons, belts and fault systems). Red lines indicate fault systems, yellow lines show boundaries of cratons and tectonic belts, and white lines show boundaries between the land and marine areas

Further geophysical data analysis in the region will include computation and inspection of airborne magnetics (in the areas where these data are available) (for analysis of magnetic anomalies under conditions of oblique magnetization, rugged terrain relief and unknown level of the normal magnetic field a special interpreting system has been developed (e.g., Khesin et al., 1996; Eppelbaum et al., 2004; Eppelbaum and Mishne, 2011; Eppelbaum, 2015)), and satellite derived magnetic data. Thermal flow measurements, which are necessary component of the deep tectono-geophysical analysis (Eppelbaum et al., 2014) will also be examined.

All the data can be used for elaboration of new schemes of long-term seismological prognosis, development of 3D regional physical-geological models and searching different types of economic minerals.

Table 2

Comparison of depth of disturbing bodies occurring in lithosphere (derived from publications of various authors) and map of contrast density masses distribution in lithosphere obtained by the use of satellite derived gravity field transformation

Authors	Applied geophysical method	Latitude	Longitude	Depth of disturbing slab occurrence, km	Depth of slab occurrence, km from map presented in Figure 10
Jimenes-Munt et al., 2003	Seismology	32 – 34°	32 – 34°	120-125	120-130
Jimenes-Munt et al., 2003	Seismology	33 – 36°	38 – 39°	83	85
Tunini et al., 2015	Temperature	30.5°	44°	145	140-145
Tunini et al., 2015	Seismics	30.5°	53 – 53.5°	85	95
Bastow et al., 2011	Seismics	9 – 9.5°	38.5 – 39°	90	90-95
Davis and Slack, 2002	Seismology	3°	37°	120	110
Park et al., 2008	Seismics	24	47	150	135
Hansen et al., 2007	Seismics	31.4°	37.3°	61	70
Yakobson, 1997	Seismics	37.5 – 37.7°	53.8 – 54°	65	63
Mulugeta and Ghebreab, 2001	Analogue modeling	16°	33.5°	100	110

DEVELOPMENT OF A NOVEL TECTONIC MAP FOR THE REGIONS UNDER STUDY

Compiled satellite derived gravity field (Figure 4) and its different transformations (Figures 5-10), described in the previous sections, were utilized for development of a novel tectono-geophysical zonation map of the Arabian-African region. Structurally-geodynamically this region is one of the key Earth's megastructures where are closely disposed remain elements of the Tethys Ocean crust (Ben-Avraham et al., 2002; Robertson, 2004), most ancient Early Permian reversly magnetized Kiama zone (Eppelbaum and Katz, 2012b; Eppelbaum et al., 2014), and the youngest modern oceanic crust of the Afar triangle developed among the continental lumps (Yirgu et al., 2006; Bastow et al., 2011).

Tectonic zonation of this region is based both on the classical geotectonic analysis (e.g., Yanshin, 1965), methods of geotectonic regioning of complex structures and materials of economic deposits prognosis (mostly for the hydrocarbon deposits prospecting).

The tectonic zonation was carried out with application of three main principles of tectonic analysis:

(1) classic basis of space-temporary reflection of structural complexes,

(2) modern structural-geodynamic approach derived from the plate tectonic reconstructions where essential role plays analysis of rift, transform and collision forms of the Earth's development,

(3) revealing of intricate correlation of the mapped tectono-structural elements with lithospheric-mantle complexes delineated by use of both conventional geophysical methods (seismic, seismological, thermal data, etc.) and comprehensive analysis of satellite derived gravity data.

Compiled tectonic map (Figure 11) indicates that the Precambrian basement and Mesozoic-Cenozoic structures play predominant structural-geodynamic role in this region. Precambrian generations include two main structural elements: (1) the Archean platforms (Eastern Arabian, Tanzanian and Eastern Saharan cratons), and (2) the Neoproterozoic belt. In the Neoproterozoic belt, we distinguish: (a) final Proterozoic back-arc belts with ophiolites, and (b) more ancient Early/Middle Proterozoic massifs (detected both in some previous works of various authors and recognized by the authors of this article using a set of geological-geophysical indicators).

In the areas of development of sedimentary Phanerozoic cover in the northern part of the Arabian and African (Nubian) plates, boundaries of the Early/Middle Proterozoic massifs (Tabuk, Haif-Rutfah, Widyan and Nile Cone) and the Neoproterozoic belts (Azraq-Sirhan, Ga'ara and Northern Western Desert) were delineated by the use of: (1) land and airborne geophysical data, and (2) satellite derived gravity data.

Meso-Cenozoic structures of the region contain two tectonic complexes of its forming. 1st complex (from Permian to present) is associated with the Neotethys Ocean evolution. 2nd complex (from Oligocene to present) is associated with the initial phases of spreading in the Arabian-African segment of the Earth's crust.

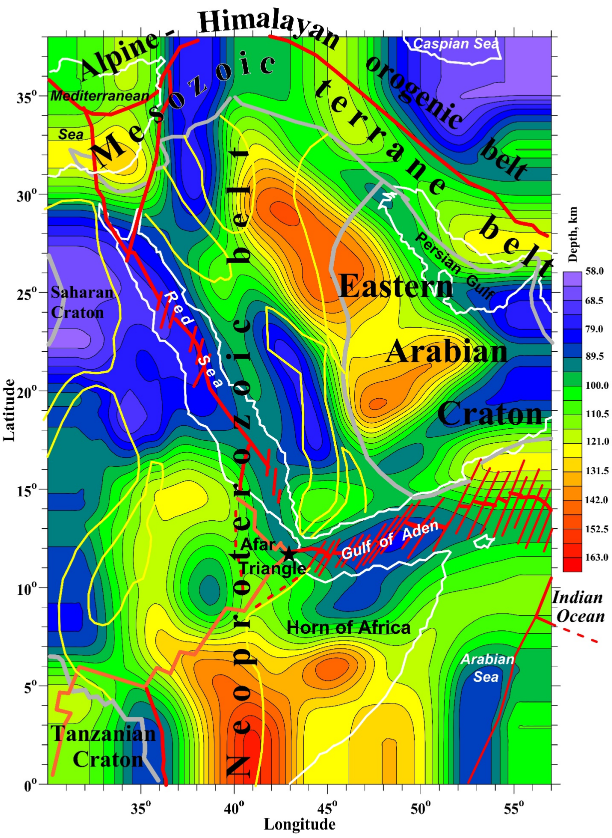

Figure 10. Comparison of map of contrast density masses distribution in the upper mantle obtained by satellite derived gravity map transformation with major tectonic elements (after Eppelbaum and Katz, 2016, with modifications. Red lines indicate fault systems, grey lines show boundaries between cratons and tectonic belts, yellow lines show boundaries between the zones of Early and Late Proterozoic consolidation and Neoproterozoic Belt, and white lines show boundaries between the land marine areas

1st complex structurally and geodynamically is a multiple generation since the Neotethys Ocean evolution was accompanied by processes of spreading, movements of some giant blocks (domains) along transforms, and collisions. These processes have formed structures of three types: (1) the Mesozoic terrane belt, (2) the Cenozoic orogenic belt, and (3) remain depressions of the Neotethys with oceanic crust. In series of our previous publications (Katz and Eppelbaum, 1999; Eppelbaum and Katz, 2012; Eppelbaum et al., 2014; Eppelbaum and Katz, 2015a,b,c, 2016) several novel aspects of structural genesis of the southern side of the Neotethys Ocean were presented. The most important novel aspects are the earlier unknown 'Mesozoic terrane belt' and 'Eastern Mediterranean–Nubian Belt' (EMNB). The last structure is marked by the Cretaceous volcanogenic complexes and diamondiferous kimberlite pipes (Sharkov and Khanna, 1986; Eppelbaum and Katz, 2012a).

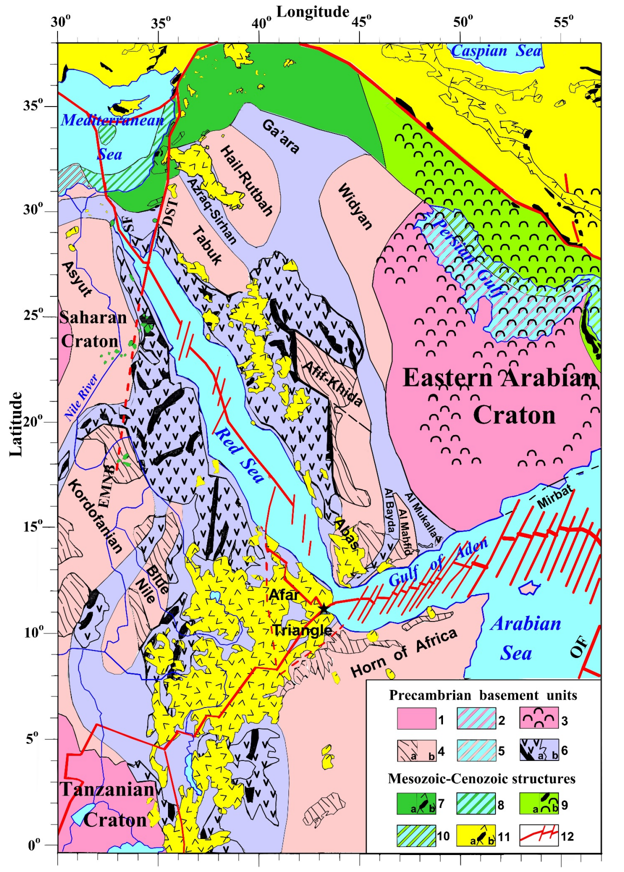

Figure 11. A novel tectonic map of the region under study (1) Archean cratons, (2) submarine continuation of Archean cratons, (3) Upper Precambrian salt basins, (4) Paleo-Mesoproterozoic basement: (a) exposed, (b) buried at the depth, (5) submarine continuation of Paleo-Mesoproterozoic basement, (6) Neoproterozoic belt: (a) exposed with ophiolites, (b) buried at the depth, (7) Early Cretaceous accretional complex: (a) traps and ophiolitic associations, (b) sedimentary rocks, (8) submarine continuation of the Early Cretaceous accretional complex, (9) Late Cretaceous accretional complex: (a) Neoproterozoic salts and Mesozoic ophiolites, (b) sedimentary rocks, (10) submarine continuation of the Late Cretaceous accretional complex, (11) Cenozoic accretional and fault systems: (a) traps and ophiolites, (b) sedimentary rocks, (12) collisional and active rift systems.
EMNB, Eastern Mediterranean-Nubian Belt; SF, Sinai Fault; DST, Dead Sea Transform, OF, Owen Fault, NWD, Northern Western Desert, symbol ★designates the triangle junction

Western (Levantine) part of the Mesozoic terrane belt is characterized by more ancient (Hauterive) age of consolidation comparing with the eastern part of the belt (Persian-Oman).Its terranes (from Zagros to Makran) and ophiolites were joined to

Arabian platform in the Middle Cretaceous (Cenomanian-Turonian) (Eppelbaum and Katz, 2017).

The Mesozoic terrane belt was delineated in the Eastern Mediterranean by the use of variety of geological and geophysical methods (multilevel gravity and magnetic data examination, thermal data analysis, seismic and seismological data) application (Ben-Avraham et al., 2002; Eppelbaum et al., 2012; Eppelbaum and Katz, 2015a, 2015b, 2016). At the same time, eastern Zagros-Makran part of the Mesozoic terrane belt was never analyzed as a separately developing structural part (unit) of the Arabian craton. In all known paleogeographical reconstructions the Zagros-Makran structure is shown as a part of the Arabian craton northern periphery. However, analysis of facial, sedimentary and structural data (presented in Bordenave, 2008) indicates that there is a sharp discordant joining of the Arabian craton and Zagros belt (Eppelbaum and Katz, 2017). Axes of anticline structures of the Arabian craton have a meridional strike, while axes of the Zagros anticline structures are disposed discordantly to them at SW 35-50^{o}. Besides this, paleogeological maps of Paleozoic (Bordenave, 2008) indicate that Devonian and Carboniferous deposits widely developed within the Arabian craton, do not presented in the Zagros belt. It testifies an uplift of the Zagros suture and its isolated evaluation in the post-Carboniferous time when the Tethys Ocean began to form. Geological factors of the Zagros suture zone isolation indicate that it was possibly a part of terrane belt in the southern part of the Neothetys Ocean forming. It is necessary to take into account that the Zagros structure most likely occupied different tectonic position at the different periods of the geological time: (1) up to Carboniferous period the Zagros zone was a part of the Eastern Arabian Craton, (2) in the interval between Permian and Middle Cretaceous it was a part of the terrane belt within the Neotethys, (3) at present it is a marginal part of the Arabian lithospheric plate (see Figure 1). All three aforementioned items find a direct reflection in the compiled gravity map (Figure 4) and its different transformations (Figures 5 – 10):

(1) Common structural-geophysical properties of the Zagros suture zone and Arabian craton can be recognized in informational (Figure 7) and gradient (Figure 8) gravity field transformations.

(2) Examination of initial gravity map (Figure 4), entropial transformation map (Figure 9) and deep structure map (Figure 10) testify that Zagros is an independent structural unit within the Mesozoic terrane belt. Presence of thick Cenozoic sediments in the eastern part of Arabian Plate makes the delineation of boundaries between the Mesozoic terrane belt and Precambrian platform practically possible only by regional geophysical data analysis. In all three above-mentioned maps (Figures 4, 9 and 10) sharp changing of gravity pattern enables to utilize this property as criterion for delineation of southern boundary of the Mesozoic terrane belt.

(3) Map of satellite gravity field transformed by the use of multistatistical analysis (Figure 5) unambiguously indicates that Zagros is a marginal part of the Arabian lithospheric plate.

2nd complex – Late Cenozoic tectonic element– corresponds to post-Tethyan stage of young rift structures of the Eastern Africa, Arabia and Indian Ocean. Uplift of the deep mantle matter caused development of Cenozoic traps and generation of ore fields and kimberlite pipes. Rift zones and volcanic-tectonic structures shown in the deep structure map (see Figure 11) – elements of the triple junction, transform faults and trap complexes – clearly fixed in the zones of uplift of deep asthenosphere masses. Structure of Arabian sintaxis is associated with the same processes. Beginning of its formation relates (taking into account presence of Cretaceous traps of the EMNB) to Middle Cretaceous (probably, Alb-Cenomanian). In the beginning of Paleogene separation of Arabia from the Eastern Africa is marked by Paleocene (53-60 Ma) diamond-bearing kimberlites (Davis, 1977; Tainton et al., 1999), and active riftogenesis is marked by Oligocene traps (approximately 30 Ma). In the northern part of this sintaxis an eastern part of the Mesozoic terrane belt is disposed. According to Eppelbaum and Katz (2015a, 2015c) this belt has been moved anticlockwise from the east to west. Similar effect was clearly detected at the modern stage of geological history in the Easternmost Mediterranean from the regional GPS data analysis (e.g., McClusky et al., 2000; Reilinger et al., 2006). Interestingly to note that the total pattern of the GPS vectors displays here so-called geodynamical vortex structure (mathematical model of this effect was given in Aleinikov et al., 2001). In the center of this vortex the well-known Cyprus gravity anomaly (CGA) (about +180 mGal in the Bouguer reduction) is located. Gass and Masson-Smith (1963) proposed that this anomaly is caused by a mantle plum; later Gass (1968) modified this hypothesis by the use of plate tectonics model and suggested a model of an overthrusted ocean floor over the African Plate. Eppelbaum and Pilchin (2006) proposed that the Earth's crust of the western Cyprus is composed of a doubled ocean crust formed in ancient times by an obduction of the oceanic crust onto itself with its subsequent immersion and partial destruction.

The CGA borders to the south-east with a block of the most ancient oceanic crust is associated with the detected Kiama zone of inverse polarity (Eppelbaum et al., 2014). Obviously, this zone is categorized by a complex superposition of different geodynamic events (Ben-Avraham et al., 2006; Reilinger et al., 2006; Eppelbaum and Katz, 2015b). Noticeably, the vortex effect in the Easternmost Mediterranean (appearing in the GPS data pattern) is one of key elements for understanding the western part arch of the Mesozoic terrane belt (see Figure 7B in (Eppelbaum and Katz, 2015b).

Comprehensive analysis of published sources indicates absence of a common tectonic map for the region under study. Various authors published mainly isolated and uncoordinated maps and schemes of the area, often contradictory each other. At the same time, such a generalized map is of great necessity for solving different geological-geophysical problems: tectono-geophysical mapping, development of 3D physical-geological models, searching different types of economic deposits and long-term seismological prognosis, etc. Therefore, on the basis of detailed analysis of the following main publications: Glennie et al., 1990; Lenoir et al., 1994; Camelbeeck and Iranga, 1996; Johnson, 1998; Pollastro, 2003; Alsharhan, and Nairn, 2004; Bosworth et al., 2005; Hall et al., 2005; Krasheninnikov et al., 2005; Reilinger et al., 2006; Al-Juboury and Al-Hadidy, 2008; Bordenave, 2008; Johnson and Kattan, 2008; Johnson et al., 2008; Scotese, 2009; Milesi et al., 2010; Stern and Johnson, 2010; Motavalli-Anbaran et al., 2011; Verges et al. 2011; Eppelbaum and Katz, 2012a; Moghadam et al., 2013; Muluneh et al., 2014; Stamps et al., 2014; Eppelbaum and Katz, 2015a,b; Tunini et al., 2015; Alizadeh et al., 2016; Globig et al., 2016, and combined geophysical data examination, a novel tectonic map of the Near and Middle East and Northern-Eastern Africa has been developed (Figure11).

For the tectonic map compiling a classic method of such maps development (e.g., Khain, 2001) – historical principle of structural evolution – was applied. Such an approach enabled us to show for the first time an interaction of tectonic structures of three types: (1) the structure of basement of the African-Arabian platform, (2) structures of this platform northern boundaries (including originally delineated Mesozoic-Cenozoic mobile belts), and (3) active rift systems. Some results obtained for the tectonic zonation of oceanic crust (e.g., Bosworth et al., 2005; Eppelbaum and Katz, 2015a) are omitted due to the comparatively small scale of the tectonic map.

For development of this map, results of various geophysical method application (first of all, satellite gravity),GPS, seismic, seismological, magnetic and thermal data) were widely used. For instance, GPS data presented in (Gripp and Gordon, 2002; Muluneh et al., 2014) were employed for tracing rift zone boundaries between the Somalian and Nubian Plates.

MAIN TECTONO-GEOPHYSICAL CONCLUSIONS

First of all, this investigation indicates the possibility of application of gravity field retracked from satellites for the delineation of regional tectono-structural peculiarities both in marine and land areas. Comparison of the novel tectonic map of the area under study (Figure 11) with compiled satellite derived gravity map (Figure 4) and six computed gravity map transformations (Figures 5-10) enabled to recognize the following regional tectono-geophysical peculiarities: (1) observed gravity map (Figure 4) and its transformations (Figures 5-10) reflect essential structural and geodynamic features of the region under study, (2) gravity field and its transformations contain complex patterns reflecting different types of mobile structures (first of all, active rift zones), (3) the gravity field transformations clearly trace both (a) main tectonic boundaries, and (b) boundaries of other ranks; (4) in all the maps (but in the gravity transformations – to a greater extent) different types of the Earth's crust can be distinguished.

Gravity field transformations presented in Figures 5-9 mostly indicate the tectono-geophysical zonation (qualitative analysis) of the region under study, presence of different types of the Earth's crust and possibly position of some slabs (structures) in the upper mantle. Figure 10 demonstrates depths of distribution of contrast density masses surface in lithosphere (semi-quantitative analysis).

All these maps (Figures 4-11) may be effectively employed for the long-term seismological prognosis. These maps may also be useful sources for development of any kind of physical-geological models (delineating physical-geological domains of various origin) and searching various types of economic minerals in the region under study.

Satellite derived gravity field analysis has demonstrated its unique feasibilities for regional (no additional correction for land retracked satellite gravity was introduced) tectono-geophysical zonation (both qualitative and semi-quantitative). At the same time, in the land areas with highly rugged relief some additional corrections to the satellite gravity anomalies may be necessary.

Further geophysical data analysis in the region under study will include map computation and examination of airborne magnetics and satellite derived magnetic data and thermal data employment, with attraction of other kinds of geophysical materials.

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