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REVIEW ARTICLE

Gravity observations at Sinai Peninsula and its geophysical and geodetic applications

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Abstract South Sinai is an interesting region from both tectonic and seismological settings. Tectonically, Sinai Peninsula is strongly dominated by its active boundaries due to its location at the triple junction among the Gulf of Suez rift, the Aqaba–Levant transform fault and the Red Sea Rift. Moreover, reported seismological activities along the three tectonic boundaries indicate its continuous activities.

It is thus of great interest to delineate the subsurface geological structure responsible of its tectonic settings and its relation to the seismological activity. Therefore, terrestrial gravity observation has been carried out to figure out the sub-surface structure representing its tectonic settings.

On the other hand, the location of Sinai Peninsula between Gulf of Suez, Gulf of Aqaba and Red Sea has made the satellite altimetry data an optimum tool to determine the Gravity sources on the marine regions bounding the Sinai region. Finally, temporal gravity variation of the GRACE satellite mission, launched in 2003 gives the opportunity to monitor its temporal gravity variation on regional scale. Temporal gravity variation from GRACE demonstrates any possible mass redistribution along the pounding tectonic settings and its relation to seismicity.

Observed gravity map shows significant gravity anomalies attributed to tectonic and seismicity. Satellite altimetry and gravity data are considered to be a valuable source of data to determine the off-shore subsurface structure. Temporal gravity variations from GRACE shows important zones of mass redistribution attributed to its new tectonics and its relation to the seismological activities. Integrating all available data sheds more light on the geodynamic behavior of the selected region and its relation to the seismic activities.

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1. Introduction

The study area lies at the southern and middle part of Sinai Peninsula between latitude $27^{\circ} 30'$ and $30^{\circ} 00'$ north and longitude $32^{\circ} 30'$ and $34^{\circ} 55'$ east (Fig. 1). Sinai Peninsula, covering an area of some 61,000 km², is triangular in shape and separated geographically from the Eastern Desert by the Gulf of Suez. Sinai Peninsula is one of the main geographic units and represents the Asiatic part of Egypt.

Sinai Peninsula is wedged between the African and Arabian plates, the boundaries of which are defined by the Gulf of Suez and Gulf of Aqaba known as the Dead Sea rift system (Fig. 1). It is considered as an unstable shelf due to the frequent earthquake activities and its relation with the geologic setting of the area, which is controlled by the tectonic activity of the Red sea, Gulf of Suez and Gulf of Aqaba.

Gravity tool is an optimum method to figure out sub-surface structure. Therefore, the current paper is aimed to figure out the subsurface structure of Sinai and its relation to its tectonic settings as deduced from the terrestrial gravity observations. Available altimeter data from satellite observations have been used as a complementary source of data for mapping sea floor structures, including tectonics on the off-shore and to derive its gravity variations. Finally, regional temporal gravity variation from (GRACE) satellite mission has been used to demonstrate any possible mass redistribution along the pounding tectonic settings and its relation to seismicity.

On the other hand, recent progress in satellite altimetry opens a new era in determining the gravity field in the marine region. It can be used as complementary source of data to fill the gap of missing gravity data in the marine region. Unprecedented accuracy obtained from GRACE has made it possible to monitor temporal gravity variation on regional and global scale.

Interested tectonic and seismology of Sinai Peninsula suggest the importance of carrying out terrestrial gravity observation on it from one side. On the other side, it is an optimum test for new satellite observations.

2. Geology and tectonics of SINAI

Sinai is situated at the junction of the African, Arabian and Anatolian plates (McKenzie et al., 1970; Joffe and Garfunkel, 1987). It includes a portion of the Eastern Mediterranean and the Levant Basin (Salamon et al., 2003). Many researchers studied the geology, tectonics and kinematics of its borders (e.g. Shata, 1956; Said, 1962; Woodside, 1977; Garfunkel et al., 1981; Abdel-Fattah, 1999; Bosworth and McClay, 2001). It is highly dissected by igneous and metamorphic mountains, which rise to a height of 2675 m (Gebel Musa) forming the southern tip of the peninsula. In the south, ex-

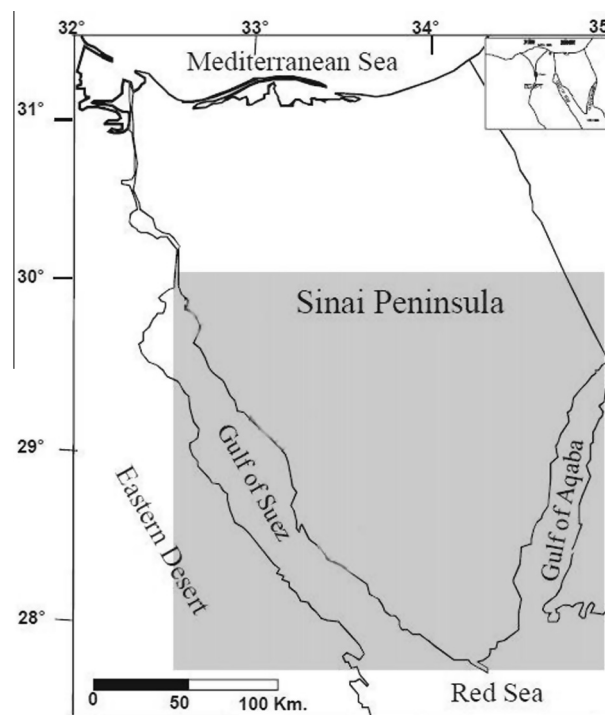


Figure 1 Location map of the study area.

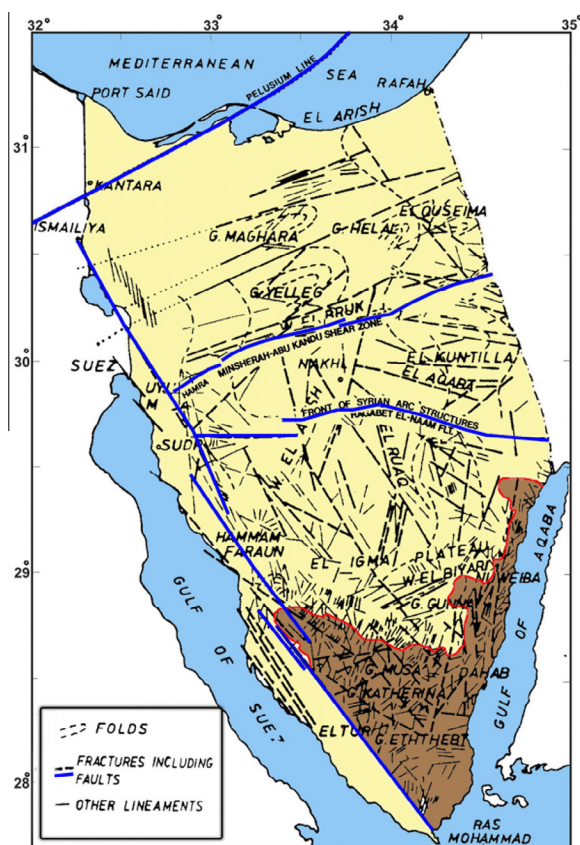


Figure 2 Structural lineation map of Sinai Peninsula (modified after El Shazly and El Ghawaby, 1974 and Neev, 1975).

posed Pre-cambrian igneous and metamorphic rocks form the so-called Arabian-Nubian Shield. In central Sinai lie Gebel El Tih and Egma plateau with 914 m above the sea level, are affected mainly by faulting. This region has been described in detail by Shata (1956) and Said (1962). The surface of the shield dips gently northward with overlying sediments, ranging in age from Cambrian to Recent, which are thickening northward (Said, 1990).

The central part of the peninsula consists of sub horizontal Mesozoic and Tertiary sediments, creating the plateau of Gebel El Tih and Gebel Egma. This part represents a thin sedimentary cover which is affected mainly by normal faulting. An east-west trending shear zone of dextral strike slip with 2.5 Km of displacement has been recognized by Steinitz et al. (1978), named Raqabet El-Naam.

The tectonics of the Suez-Sinai area is dominated by active boundary between the African and Arabian plates, which separate one from the other. The geological and seismological studies reveal that the Sinai Peninsula behaves like a sub-plate of the African plate which accommodates the main motion of the Gulf of Aqaba left-lateral transform fault (about 8-9 mm/yr) (Le Pichon and Gaulier, 1988) with the low extensional motion of the Gulf of Suez (< 1 mm/yr) (Steckler et al., 1988; Jackson et al., 1988). The triple junction among the Gulf of Suez rift, Gulf of Aqaba rift and the Red Sea rift is located south of Sinai. Recent GPS results show spreading rates along the Red Sea varying from 14 ± 1 to 5.6 ± 1 mm/yr at NNE direction (McCluskey et al., 2003).

Faults in central Sinai are of the normal type. These faults are distinguished into N-S to NNE-SSW, NW-SE and E-W trends which are dominating the northern portion of the area. The center of Sinai is characterized by a shear zone of dextral E-W strike slip faults with about 2.5 km of displacement (Steinitz et al., 1978) and Raqabet El-Naam dextral fault. Northward of this zone, the style of deformation gets increasingly complex and consists predominantly of 65°N to 85°E oriented anticlinal folds and monoclinical flexures expressed mainly in the Cretaceous strata. This belt of folds extends offshore into the southeast Mediterranean Sea.

Sinai Peninsula is crossed in the area north of lat. 30°N (Hinge Belt) by a strong fractured zone running in NE-SW direction (Fig. 2) (Shata, 1959). Said (1962) showed that the E-W faults forming the boundaries of the Hinge Belt are older than the Gulf of Suez faults. The Themed Fault (Hinge Belt of Shata, 1959) has an E-W orientation and was considered by Moustafa and Khalil (1994) as the early Mesozoic passive continental margin of the north Sinai.

It was formed in early Mesozoic time and rejuvenated in the Eocene/Miocene age (Youssef, 1968; Moustafa and Khalil, 1994). The Themed Fault separates a tectonically unstable part

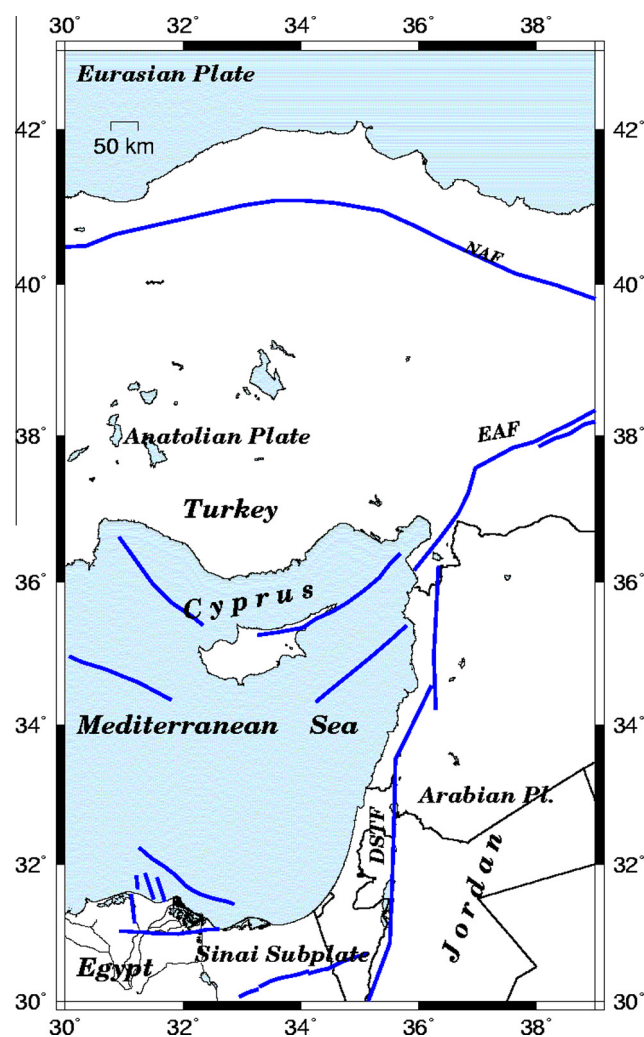


Figure 3 Tectonic elements in the eastern and northeastern part of Sinai subplate.

occupied by the Syrian Arc structures in northern Sinai from a tectonically stable part with flat-lying beds in central and southern Sinai. The northern Galala fault in the Egyptian Eastern Desert, that separates the Galala plateau province on the south from the Cairo-Suez province, is considered to be the westward extension of the Themis Fault in the center of Sinai Peninsula (Hussein and Abd-Allah, 2001). This opinion is approved as both of them: (1) have east-west orientation and northward inclined planes; (2) have dextral strike-slip movement; (3) are initially formed and reactivated at the same time; and (4) have right-stepped on an echelon folds affecting the Cretaceous rocks and obliquely oriented to the fault plane.

The west Sinai rift area is a narrow elongate plain extending from the bitter lakes southwards to Ras Mohammed. This part of Sinai is characterized by the presence of a series of normal faults of varying lengths and displacements. Almost all of these faults are oriented in NW-SE (Fig. 2) direction (El Shazly and El Ghawaby, 1974).

Bauer et al. (2001) conclude that the geodynamic evolution of the region is characterized by: (1) Late Triassic–Early Jurassic rifting and opening of the Neotethyan Ocean; (2) compression since the Turonian, owing to the initial collision of the Afro-Arabian and Eurasian plates. Neotethyan rifting during the Triassic led to the formation of half grabens and basins on the ‘unstable shelf’ (Said, 1962) in northern Sinai (Moustafa and Khalil, 1990).

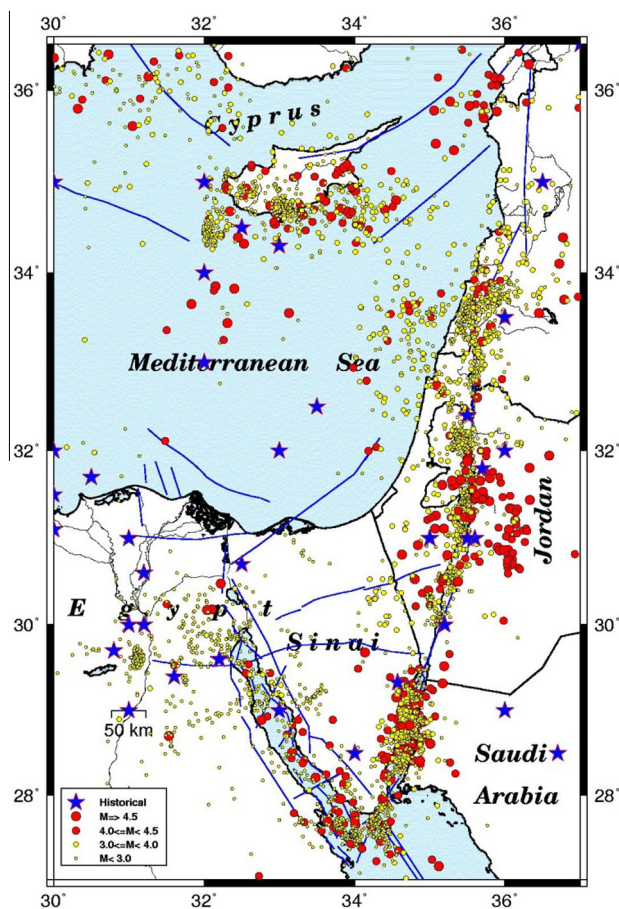


Figure 4 The compiled seismicity map of Sinai sub plate (After ISC, 2003).

The domal anticlines in northern Sinai are part of this intra-plate fold belt (Bauer et al., 2001) which extends from Syria over Lebanon to northern Egypt (Moustafa and Khalil, 1995; Guiraud and Bosworth, 1997; Walley, 1998; Bosworth et al., 1999). From the Coniacian (Late Cretaceous) onwards, a complex morphology of basins highly developed in Sinai (Kuss and Bachmann, 1996) and in the Galala area in Egypt (Kuss et al., 2000), mirrored the Syrian Arc movements (Bauer et al., 2001). The Eastern Mediterranean portion of Sinai sub-plate where Dead Sea Fault; the East Anatolian Fault (EAF) and Cyprian Arc meet (Fig. 3) plays an important role in the local plate tectonics (Salamon et al., 2003).

3. Seismology of Sinai

The observed and recorded earthquakes indicate that there is a noticeable high activity associated with the major trend of fault elements where most of the major and moderate events, $M \geq 4$, occurred in the zone associated with NE-SW faults trending and reveals high gravity frequency (Fig. 4). On the other side, the northern extension of the Gulf of Suez shows low seismicity with low gravity frequency that may be due to the petroleum exploration in this area.

These injections make natural release for seismic energy and display the causes of seismic activity on the other Gulf (Gulf of Aqaba–Dead Sea Transform System and Cyprian Arc) while the intra-plate zones are less active. These distributions of earthquake epicenters associated with structure elements are consistent with the results of some authors (e.g. Salamon et al., 1996).

Concentration of earthquakes' activity around the Cyprian Arc (Fig. 4) is quite sufficient to confirm the connection between the Cyprus Arc and the East Anatolian Fault. The continuation of activity along the upper and lower boundaries of

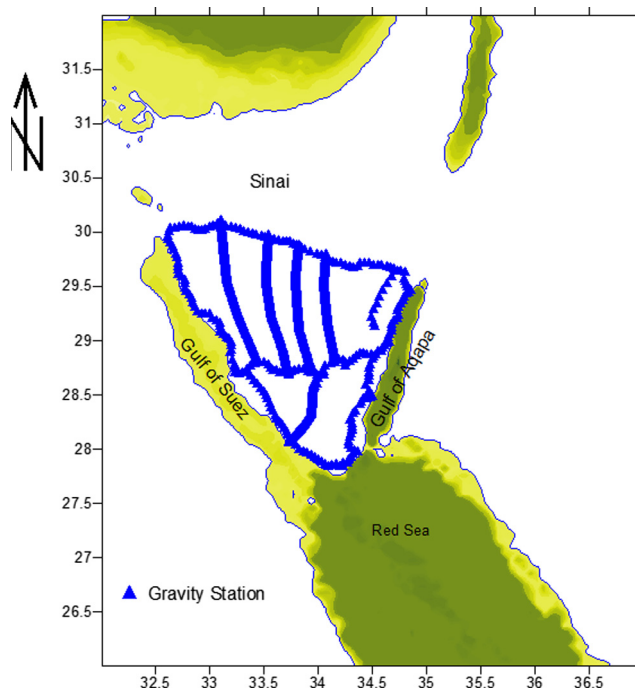


Figure 5 The distribution of gravity stations around the study area.

Cyprus suggests the connection between the eastern and western fault segments. On the other hand, the activity at the triple junction of the northern part of the Levant Fault System, the East Anatolian Fault, and the Cyprian Arc reflects the present active movement between the plates in this region and in turn the strong relations between these motions and the ongoing tectonic setting in this zone.

Blue lines represent the major tectonic setting of the area. Instrumental earthquakes data were compiled from the international seismological centers (e.g. USGS and ISC) and historical earthquakes from [Ambraseys et al., 1994](#).

4. Methodology

The main objective of the current research is to delineate local and regional geologic subsurface structure and its relation to the tectonic and geodynamic behaviors of the selected region. Three data sets have been used for the current objective. Terrestrial gravity observation has been dedicated to detect local gravity anomaly. Meanwhile, satellite altimetry data have been used to detect the marine regional gravity anomaly. Mass redistribution attributed to the tectonic setting of Sinai has been monitored utilizing temporal gravity variation from grace satellite mission.

4.1. Terrestrial gravity observation

Ground-based gravity data precision requires accurate gravity sensor and precise determination of geographical position. On the current research, the Scintrex CG-5 gravimeter was used to collect the gravity measurements. The meter has a range of 200 mGal and a resolution of 1 μ Gal. Positioning has been carried out using dual frequency GPS.

Gravity observations are made on a grid with 3- to 4 km-spacing between the gravity stations. The grid has been selected to be possible to well cover the selected region. The grid comprises of 950 points and is illustrated in [Fig. 5](#).

4.2. Satellite altimetry

In Egypt land and marine geophysical data are inadequate because of rough topography on land and economic reasons of marine observations. The use of satellite altimetry data is of special importance.

The availability of altimeter data from satellite observations, such as data collected by the European Space Agency ERS-1 and data from the US Navy Geosat, has opened new perspectives in the Earth sciences. One of the most important applications of these data is that they provide scientists with an unprecedented view of the Earth's interior and its gravity field over the marine regions ([Sandwell and McAdoo 1990](#)).

The surface of the marine region can be, with some limitations, considered as an equipotential surface of the gravity field, or the so-called geoid surface. The actual geoid surface deviates up to 100 m from the ideal ellipsoid. Deviations of geoid surface obey to a great extent the topography of the marine floor and reflect the tectonic settings and the subsurface structures. Small deviations in the geoid height, which take the form of tiny bumps and dips, can be measured using precise radar mounted on a satellite such as ERS-1 and Geosat.

One of the main applications of collecting gravity data on land is the determination of the geoid height. However, in marine regions the observed geoid can be converted into gravity anomaly or the so-called satellite altimeter gravity. The advantages of this conversion are that it makes it possible to figure out the gravity field over marine regions. In addition, converted gravity anomalies from the precise geoid can enhance the determination of small-scale geological features. The role of satellite altimetry data in geophysics is illustrated in the current study for the Sinai region. These data are evaluated by comparing them with the known tectonic and geologic settings as well as observed land gravity data for the studied region.

On the current study, free air gravity map of Sinai will be used to figure out the gravity anomaly and its relation to its regional tectonic settings.

4.3. Temporal gravity variation (Grace)

Temporal gravity variation was computed from the Gravity Recovery and Climate Experiment (GRACE) of Sinai to determine important mass redistribution zones and shed more light on its geodynamics pattern in relation to its seismological activities.

Gravity field variations as derived from the monthly GRACE solutions result from the integral effect of mass variations in the atmosphere, hydrosphere and geosphere. These effects include oceanic, atmospheric and hydrological mass movements and those caused by dynamics in Earth's interior. In addition, residual signals from insufficient pre-processing may be present.

Geodynamic processes such as changes in Earth's topography or mass distribution as a result of lithospheric plate interactions (collision, subduction, rifting), postglacial rebound, mantle convection, earthquakes, sedimentation and erosion, should also contribute to temporal variations of the Earth gravity field.

Several studies have been devoted to quantitative estimates of the contribution of regional geodynamic processes to temporal variations of Earth's gravity field. [Velicogna and Wahr, 2002](#) addressed the effect of postglacial rebound and the possibility of recovering mantle viscosity profiles using satellite data, and concluded that GRACE data could significantly contribute to solve this problem. In a very recent paper, [Sun and Okubo, 2004](#) compared the GRACE target accuracy to degree amplitude spectra for co-seismic deformations resulting from the 1964 and 2002 Alaska, and 2003 Hokkaido earthquakes. They concluded that co-seismic deformations for an earthquake with a seismic magnitude above 7.5 could be detected by GRACE.

The main objective of this study is to estimate any mass variations attributed to the active tectonics in and around Sinai Peninsula from the GRACE data.

5. Results

5.1. Terrestrial gravity data

Adjustment of gravity observations has been carried out using Geosoft ([Oasis montaj, 1998](#)). The resulted Bouguer anomaly map of the studied region is given in [Fig. 6](#). The

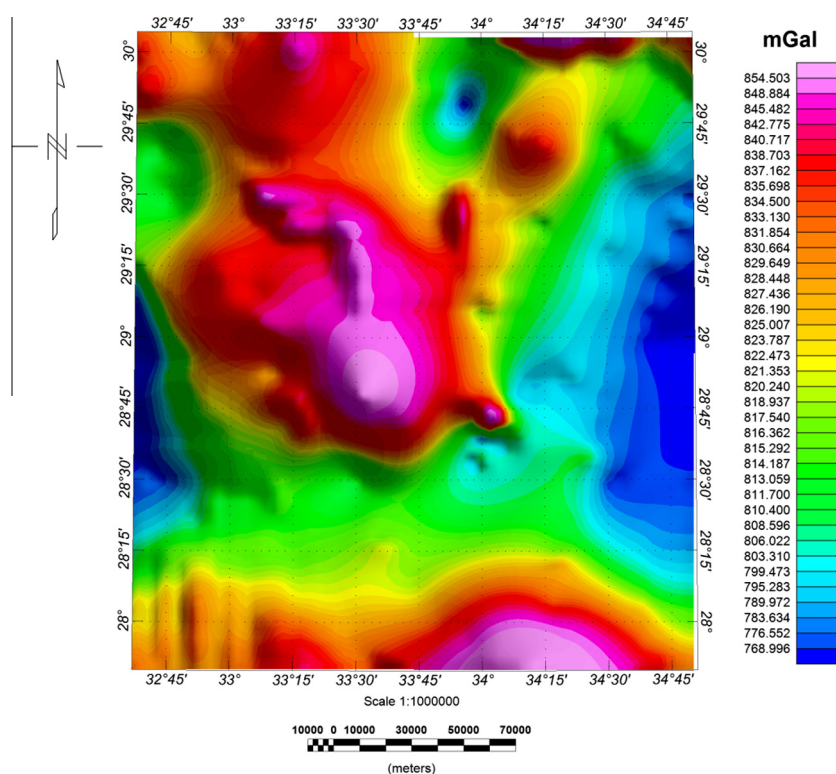


Figure 6 Bouguer gravity anomaly map of the study area.

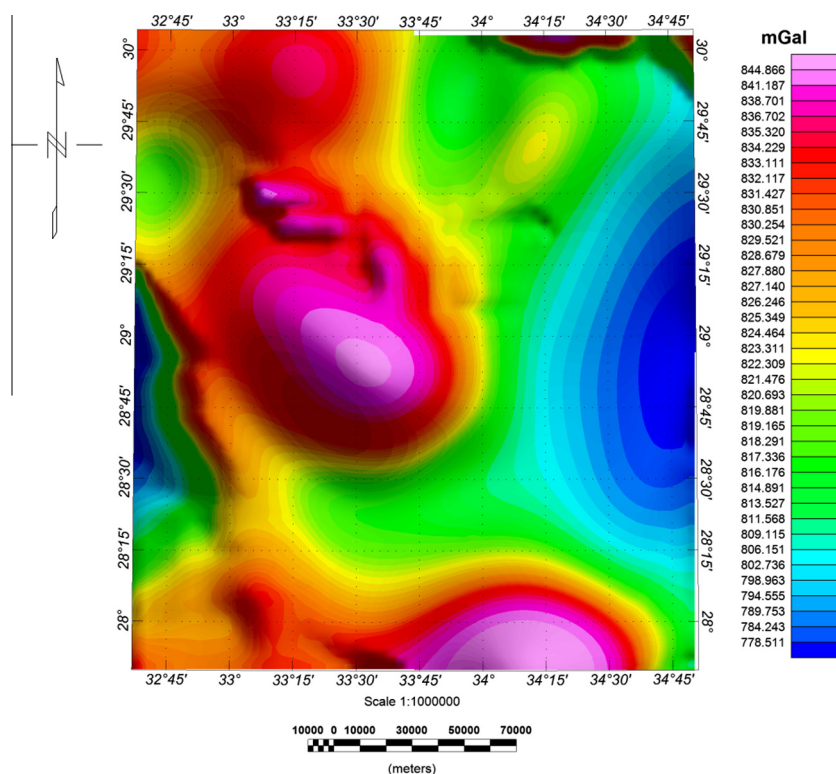


Figure 7 Regional bouguer anomaly map of the study area.

most remarkable gravity anomaly of the region is seen as a high gravity anomaly of the order of about 854 mGal in the southern and central parts, and has a minimum of

about 768 mGal in the Western and Eastern parts of the study area. Central high gravity anomaly can be due to the dense basement section attributed to the El-Tih Plateau.

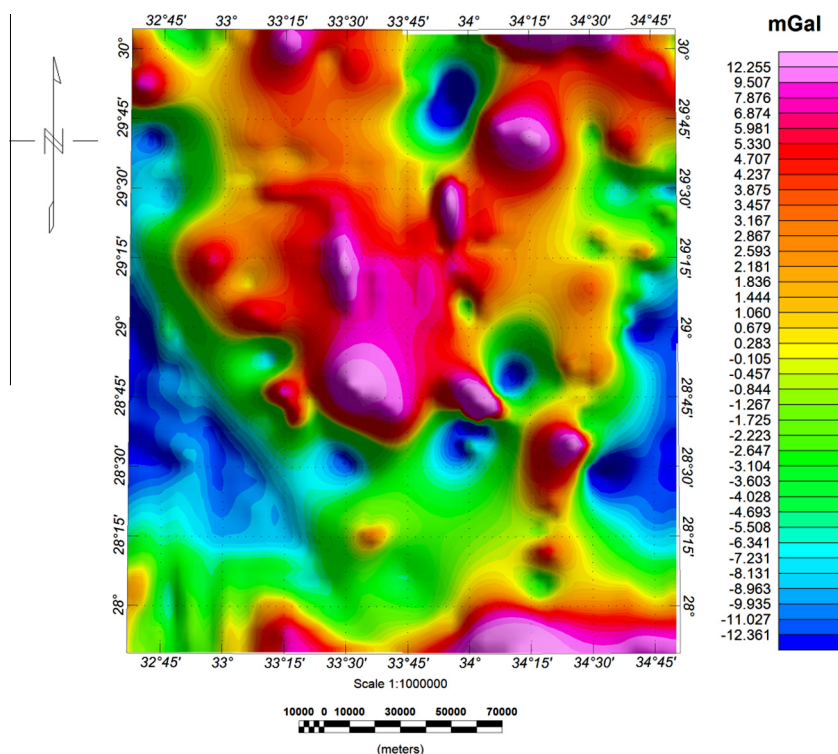


Figure 8 Residual bouguer anomaly map of the study area.

The boundary tectonic elements, Gulf of Aqaba on the east and Gulf of Suez on the west can be seen as significant low gravity anomaly. These negative anomalies estimate the extension of Sinai along these tectonic zones.

The triple junction of the Red sea is represent by high gravity anomaly explains the elongation of the Red sea.

The general trends of the field are NW-SE and NE-SW and in addition E-W trend. Also, most of the steep gradients have alternating negative and positive anomalies at the north eastern and south western parts of the map, respectively. This indicates that the area is structurally controlled by tectonics having major axis in the NW-SE and NE-SW directions and the Syrian Arc structure influence on the gravitational field trend in E-W direction. The south western part has anomalies with definite polarities and is characterized by irregular contouring pattern, with negative value, different sizes and shapes and from moderate to high gradients, while the central part has high positive value with different sizes and shapes and high gradients. On the other hand, the north eastern part of map reveals steep gradients has alternating negative and positive anomalies. The source of the anomaly may be due to an uplifted block of the denser crystalline rocks.

5.1.1. Gravity separation

The strong regional gravity trends mask local gravity sources, such as lineaments and local faults. Therefore, revealing that local structures required removing the regional gravity anomalies. Digital filters have been used to delineate the regional gravity trend and to obtain the residual gravity map. The regional map can be seen in Fig. 7. It shows E-W gradient occupying the central part of the study area and the high gravity

anomalies occupying the central part of about 854 mGal. The northeastern and the central of southern part reflect low gravity anomalies of about 808 mGal.

Fig. 8 shows the residual anomaly map. Although the main gravity sources of them still appear on the map, the map shows more small scale features related to the local structures. By inspection in the residual map may be dissected by different faults trending E-W, NW-SE and NE-SW (Fig. 8) which associated with high frequency for gravity anomaly in area of study.

The E-W trending fault structures with the gravity gradient shed more lights on an area of faults extends to the north of latitude 30° for a distance of 200 Km from east to west.

In addition, there is a narrow elongated plain extending along the western border of Sinai in NW-SE direction and is characterized by the presence of a series of normal faults of varying lengths and displacements which is revealed in the residual map (Fig. 8). Almost all of these faults are oriented in the NW-SE direction parallel to the Gulf of Suez composing west Sinai rift area (El Shazly and El Ghawaby, 1974).

5.2. Satellite altimetry data

The free air gravity anomaly map of Sinai (Fig. 9) is generally characterized by negative free air gravity anomalies, with average values of about 0 to -26 mGal in the land margin areas and a consistent gravity low from -28 to -35 mGal of the axial depression. A Y-shaped region of

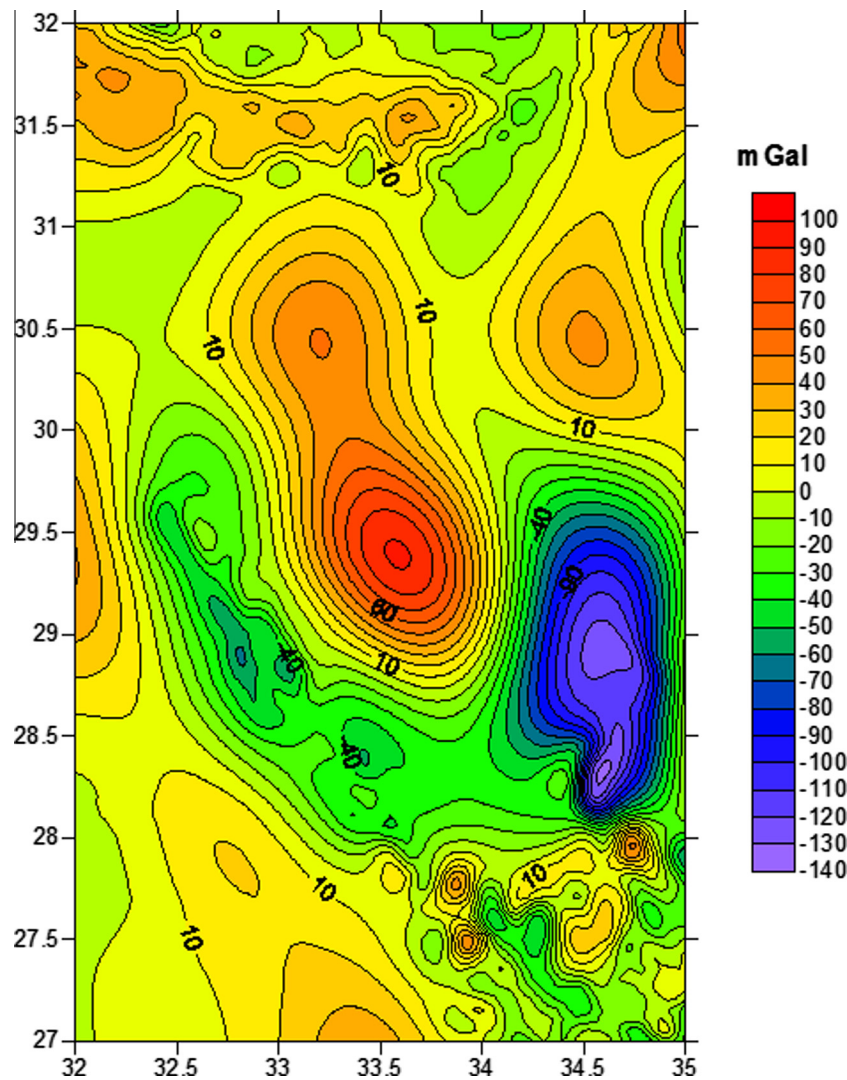


Figure 9 Free-air gravity map of Sinai Area.

very low values of a minimum -183 mGal is found near the junction of the Red Sea with the Suez and Aqaba Gulfs.

- The main obtained gravity features at the satellite free air gravity map correlate well with regional feature of ground-based gravity observed map. This means that, the dominant gravity source is a regional feature rather than local structure on the area.
- Ground-based gravity observed map evaluates well satellite-based map.
- The general tectonic pattern of the Gulf of Suez can be seen as two different gravity anomalies. This indicates that, the Gulf of Suez was separated into two zones of different geodynamic behaviors.
- Triple junction consists of complicated gravity sources; represent the multiple tectonic features' effect on the area.
- The transform dead sea fault can be seen as negative anomaly with a rotation altitude explains the relative movement between African and Arabian plates.
- Gulf of Suez shows less gravity anomaly than Gulf of Aqaba, reflecting its less activities. However, Gulf of Suez shows more complicated tectonics.

- Regional gravity patterns of Sinai appears as positive gravity anomaly in the eastern part represented in the Arabian plate, African plate to the west and Eurasian plate to the north.

5.3. Temporal Gravity Variation (Satellite Mission GRACE)

We used 71 monthly gravity field solutions (RL04 unconstrained solutions) for the Period 2003 to 2011 from the GRACE database (GRACE, 2006) provided by the Center of Space Research of the University of Texas. The gravity field solutions were processed as follows: (1) The temporal mean was removed; (2) Correlated errors were reduced by applying destriping methods developed by Swenson and Wahr, 2006 (3) Spherical harmonic coefficients were converted to grids ($0.5^\circ \times 0.5^\circ$) of equivalent temporal gravity using a Gaussian smoothing function with a radius of 400 km. Fig. 10 displays GRACE temporal gravity variation of Sinai region from 2003 to 2011. Generally, the figures show significant mass redistribution zones attributed to its tectonic and seismological settings.

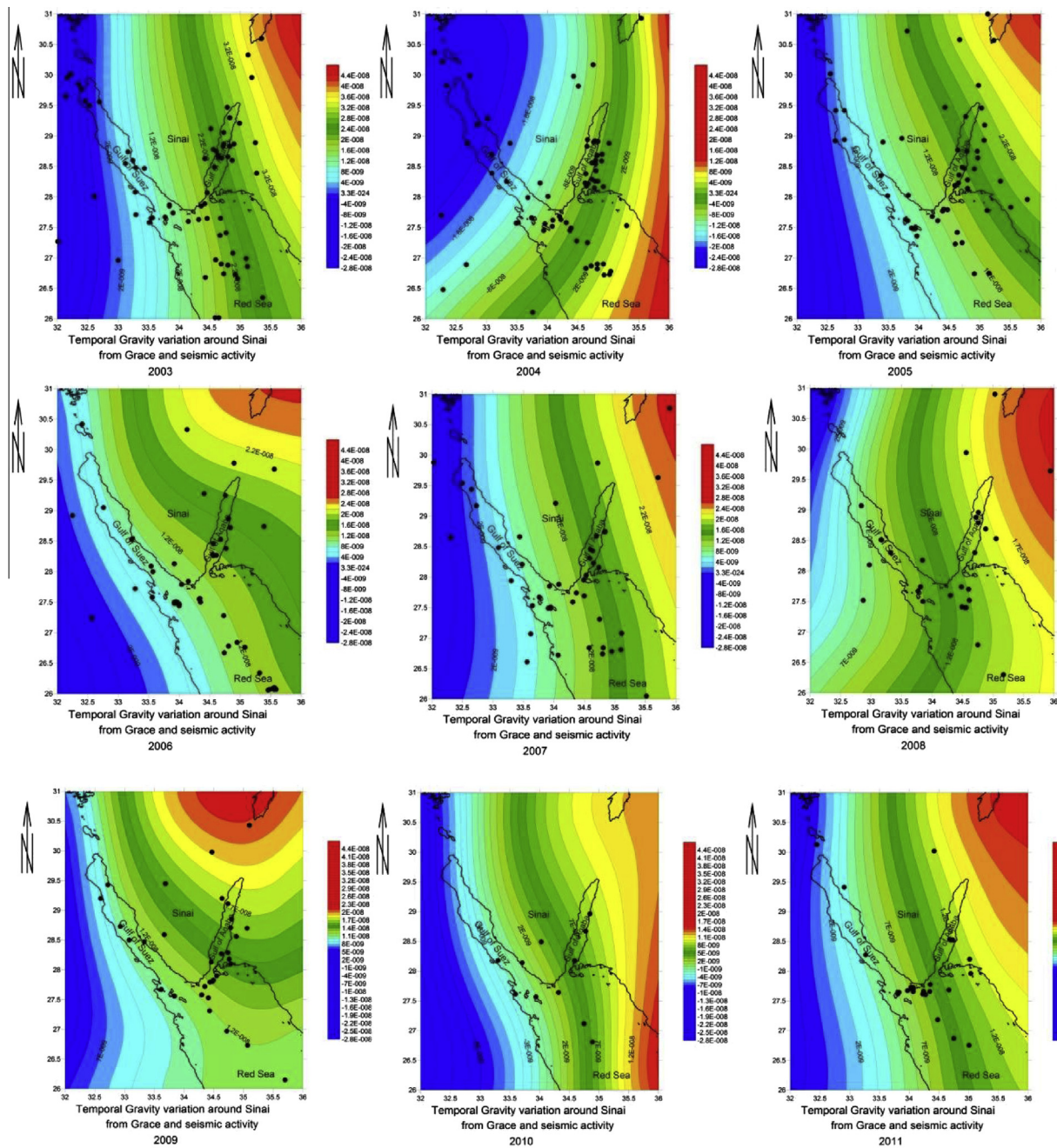


Figure 10 Temporal variation in Sinai determined from GRACE monthly solutions as provided by GFZ, units: $\text{m/s}^2/\text{year}$. Here a Gaussian filter with radius 400 km has been applied.

According to the figures, the following remarks can be drawn:

- Temporal gravity pattern of the whole computed years reflects the regional tectonic settings and indicate that its tectonic settings are controlled by the surrounding regional tectonic pattern.
- High gravity anomaly on the north eastern part suggests that the movement of the Arabian Shield toward the clock-wise movement of the Eastern Mediterranean plate is the main source of activity on Sinai.
- High seismological activity located at the neutral zones between the high gravity anomaly at the north east and the low gravity anomaly at the west. This indicates that, tectonic activity of Sinai is a combination between regional and tectonic settings.
- Mostly, seismological activities increased at the high gradient of the neutral zone.
- Triple junction of the Red Sea, Gulf of Aqaba and Gulf of Suez located on the high gradient zone between the positive anomaly at the north east and the negative anomaly at the west.

- Temporal gravity variation of the Gulf of Aqaba and Dead Sea, indicates complicated thrusting pattern reflecting the high seismic occurrence on this region.

6. Discussion

Sinai Peninsula is an interesting region from the tectonic point of view. It is strongly dominated by its active boundaries due to its location at the triple junction among the Gulf of Suez rift, the Aqaba-Levant transform fault and the Red Sea Rift. Moreover, reported seismological activities along the three tectonic boundaries indicate its continuous activities.

This research studies the potentiality of the terrestrial gravity data and satellite data as an integrated source of information for geophysical and geodetic applications. These data sets have been dedicated as a contribution of the tectonic and geodynamic studies at Sinai Peninsula.

The remarkable resulted feature of the Bouguer anomaly map is a high gravity anomaly at centurial part, which can be due to the dense basement section attributed to the Tih Plateau. The boundary tectonic elements, Gulf of Aqaba on the east and Gulf of Suez on the west can be seen as significant low gravity anomaly. These negative anomalies estimate the extension of Sinai along these tectonic zones.

The satellite altimeter free air gravity anomaly is also compared to the well-known anomalies of Sinai. Free air gravity anomaly map is also evaluated by comparing it with the observed Bouguer gravity anomaly. This means that, the dominant gravity source is regional feature rather than local structure on the area. Temporal gravity pattern of the whole computed years reflects the regional tectonic settings and indicates that its tectonic settings are controlled by the surrounding regional tectonic pattern.

Based on the results of the current study, the following conclusions can be drawn:

- Generally, ground-based observation evaluates well satellite altimetry data.
- The main ground observation is high gravity anomaly at the area which evaluates with satellite altimetry, it indicates its regional effect.
- Although, ground-based observation mainly represents local geological features also some regional tectonics can be obtained along the tectonic boundary of the study area.
- However, satellite altimetry provides more detailed information on the marine regions around Sinai.
- Temporal gravity variation of GRACE estimates the activity of the tectonic zone determined from satellite altimeter data. It represents the mass variation corresponding to the seismic activity. Mostly, seismological activities increased at the high gradient of the neutral zone over the Gulf of Aqaba and the Red sea region.

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