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FULL LENGTH ARTICLE

Geodynamics implication of GPS and satellite altimeter and gravity observations to the Eastern Mediterranean

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Abstract The Eastern Mediterranean region is one of the interested regions from both tectonic and seismic point of views. It shows an active geologic structure attributed to the tectonic movement of the African and Eurasian plates from one side and the Arabian plate from other side. This tectonic setting is attributed with continuous seismological activity, which affects almost all the countries of the Eastern Mediterranean including Egypt.

Crustal deformation as deduced from both European and Egyptian permanent GPS networks provides significant horizontal deformation velocities along this region. GPS crustal deformation parameters were able to reveal the complication of the deformation of the studied region.

Spatial gravity map of the selected region indicates important mass discontinuities zones correlated well with the seismological and deformation activities.

Temporal gravity variation as computed from the Gravity Recovery and Climate Experiment (GRACE) of the considered region were able to determine important mass redistribution zones and shed more light on its geodynamics pattern.

Results show important zones of mass discontinuity in this region correlated with the seismological activities and temporal gravity variations agree with the crustal deformation obtained from GPS observations. The current study indicates that satellite gravity data is a valuable source of data in understanding the geodynamical behavior of the studied region and that satellite gravity data is an important contemporary source of data in the geodynamical studies.

Introduction

The Eastern Mediterranean is one of the key regions for the understanding of fundamental tectonic processes, including continental rifting, passive margins, ophiolites, subduction, accretion, collision and post-collisional exhumation. It is also ideal for understanding the interaction of tectonic, sedimentary, igneous and metamorphic processes through time that eventually lead to the development of an orogenic belt. Below, we will outline some milestones in the development of tectonic-related

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research in the Eastern Mediterranean region (Robertson and Mountrakis, 2006). In addition, the continuous seismicity attributed to its tectonic settings, which affect almost all countries surrounding this region indicates the activities of these tectonics. Thus, tectonics and geodynamics of this region have been always the attention of many interested in earth sciences.

Modern interpretations of this region in terms of plate tectonics effectively began with the pioneering work of Smith (1971) and of Dewey et al. (1973). During the 1970s a scientific project (French-led Tethys) proposed the existence of a Mesozoic-Early Tertiary Tethyan ocean dating from Triassic time, bordered by the African and Eurasian continents. They interpreted the Mesozoic ophiolites as forming at mid-ocean ridges. The Tethyan ocean was subducted northwards beneath Eurasia (Dercourt et al., 1986).

A major advance in recent years has been the testing and confirmation of the early plate tectonics using a combination of field evidence and geophysical modeling (Jackson and McKenzie 1984).

Recently, it was possible to determine the crustal deformation of the neo-tectonics of this region directly by the Global Positioning System method (GPS) (Reilinger et al., 1997).

In addition to the palaeo-tectonics, which refers to stress regimes that are no longer active, there has also been an increasing focus on the neo-tectonic development, which refers to the strain resulting from a stress regime that essentially remains active at the present time of the region (Taymaz et al., 2004). Neo-tectonics is broadly from Miocene to Recent in the Eastern Mediterranean region.

Other advances include the results of ocean drilling in the Eastern Mediterranean Sea that allowed a closer integration of tectonic processes operating on land and under the sea (Robertson et al., 1998).

The main outcome of these studies is that the Eastern Mediterranean region is an ideal test-bed for the development of hypotheses for fundamental tectonic processes. Thus, linking modern observations to the neo-tectonics of this region with its previous tectonic evolution would provide a more complete picture of the evolution of the orogen.

Tectonic settings and seismicity of the Eastern Mediterranean

The tectonic settings of the Eastern Mediterranean region is controlled by the relative motions of three major plates, Eurasia, Africa, and Arabia and most of the resulting deformation occurs at these plate boundaries (Dilek, 2010). Fig. 1 presents the tectonic setting in the Central-Eastern Mediterranean region (Mantovani et al., 2006). The Anatolian continental block, which was originally part of Eurasia, has operated as a microplate between these three major plates since the middle Miocene, when Arabia collided with Eurasia (Dewey et al., 1986). The modern Anatolian–African plate boundary is represented by a north-dipping subduction zone that has been part of a broad domain of regional convergence between Eurasia and Afro-Arabia since the latest Mesozoic (Jolivet and Brun, 2008). The convergence rate between Africa and Eurasia is greater than 40 mm/yr across the Hellenic Arc but decreases to 10 mm/yr across the Cyprus Arc. The Arabia–Eurasia convergence across the Bitlis–Zagros suture zone has been estimated to be 16 mm/yr based on GPS measurements of present-day central movements in this collision zone (Reilinger et al., 1997). The Anatolian micro-plate north of these convergent plate boundaries is moving with respect to Eurasia at 30 mm/yr along the North and East Anatolian fault zones (Reilinger et al., 1997). These collisional events, which started with ophiolite emplacement and were followed by continental collisions, produced nearly EW-trending, sub-parallel mountain belts with high elevation and thick orogenic crust in the Eastern Mediterranean region. The moving Anatolian micro-plate is currently undergoing complex internal

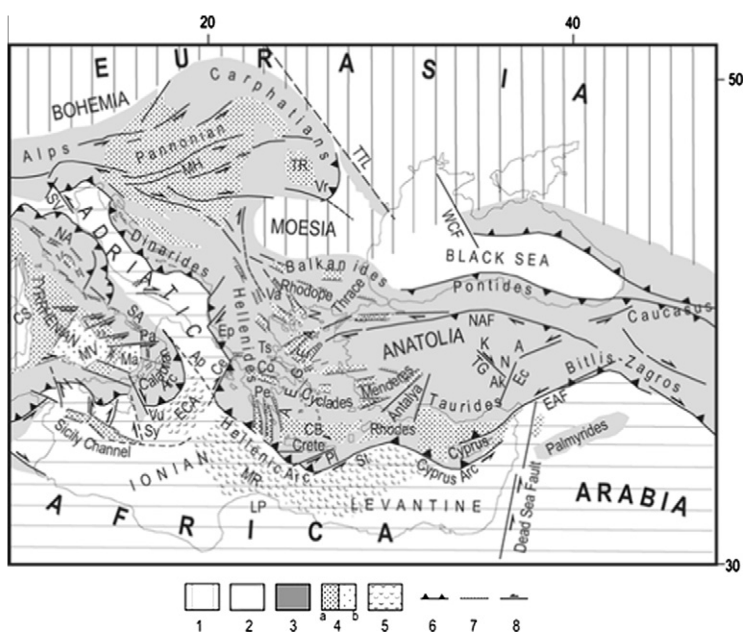

Fig. 1 Tectonic setting of the Eastern Mediterranean (Mantovani et al., 2006). (1) Eurasian domain, (2) African domain, (3) orogenic belts, (4) zones affected by moderate or intense crustal thinning, (5) Mediterranean Ridge, (6–8) compressional, tensional, and strike-slip features, respectively.

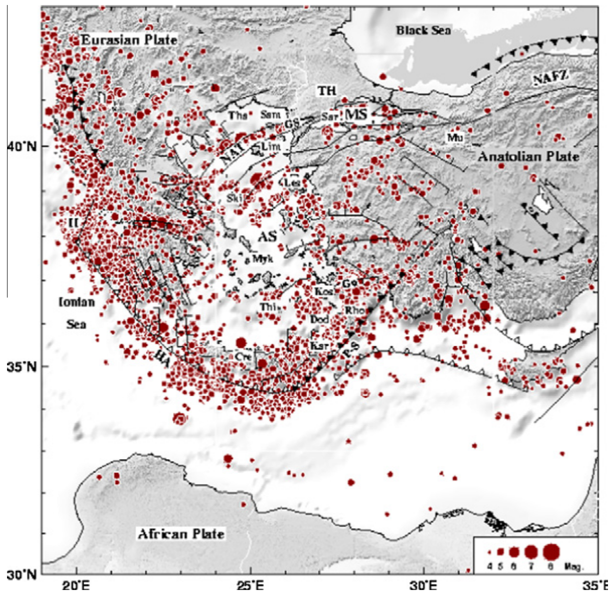

Fig. 2 Seismicity of the Eastern Mediterranean (Peter et al., 1997).

deformation via mainly strike-slip and normal faulting (Fig. 1). This deformation has resulted in extensional collapse of the young orogenic crust, giving way to the formation of metamorphic core complexes and intracontinental basins (Okay and Satir, 2000; Doglioni et al., 2002; Bozkurt, 2003).

The complicated tectonics of the Eastern Mediterranean, as mentioned above, accompanied with a continuous seismic activity. Earthquake occurrence on this region figures out precisely its tectonic settings. Therefore, the Eastern Mediterranean area is an extraordinary natural laboratory for the study of seismo-tectonic processes. This region is one of the world's most seismically active regions. Intensive earthquakes with variable magnitudes occur within this region and affect almost all countries surround it (Fig. 2). Many deadly earthquakes have been reported in this region during the last 20 yr.

Crustal deformation of Eastern Mediterranean region deduced from GPS

The interested tectonic settings of the Eastern Mediterranean have met the successful development of GPS as a recent crustal deformation monitoring tool. The main objective is to study neo-tectonic features by combining previous tectonic studies and GPS crustal deformation. This also enables the determination of the evaluation of active tectonics of the selected region.

Global kinematic models (NUVEL-1A; DeMets et al., 1990) indicate that the Arabian plate is moving in a north–northwest direction relative to Eurasia at a rate of about 25 mm/yr. While the African plate is moving in a north direction relative to Eurasia at a rate of about 10 mm/yr GPS velocities for two sites located south of Bitlis Suture show the same direction of movements from NUVEL-1A with a somewhat slower rate (Reilinger et al., 1997). A combined analysis of 1988–1994 GPS measurements suggests that NE Anatolia moves east–northeastward and the North Anatolian fault has a slip rate of 26 mm/yr (Baraka and Reilinger, 1997). The study shows a few inconsistencies between velocity vectors obtained from GPS and rates obtained from fault studies. Analysis of the regional strain and rotation rate by inverting GPS velocities has been used to determine the full two-dimensional velocity gradient tensor at Tibet, Anatolia, and the Altiplano (Allmendinger et al., 2007).

Results from the previous work were based only on velocities from the EUREF Permanent Network as none of the GPS data from the African Plate were available for the processing at that time. Despite the fact that this effect was based only on the movement of one station TUC2 (Chania, Crete, Greece), characterized by a very different size of relative motion in comparison with surrounding permanent stations, there were no other evident reasons for neglecting its contribution. However, the availability of any other permanent station in this region would strengthen or falsify this statement. Last but not least, the inclusion of the GPS data from the Northern regions of Africa into processing was required to determine the geodynamical interaction between the Eurasian and the African Plate more correctly. Therefore, data from the Egyptian GPS permanent network, which still have never been at disposal for any similar processing, could now be used to enable the possibility of a new precise deformation solution for the region of the Eastern Mediterranean.

GPS data observation

Four permanent GPS stations have been selected for the current research; Nakhel (NKHL), Helwan (PHLW), Safaga (SAFG), and Salum (SLUM). The distribution of these GPS permanent stations is regular around the Northern part of Egypt comprising the locations at the Mediterranean Sea, the Red Sea, the River Nile and also on the Sinai peninsula. Also, we used six European GPS Permanent stations; Ankara (ANKR), Turkey, Matera (MATE), Italy, Noto (NOT1), Italy, Nicosia (NICO), Cyprus, Sofia (SOFI), Bulgaria, and Mitzpe Ramon (RAMO), Palestine (colonial lands) as depicted in (Fig. 3). Such geographical locations are suitable to estimate the deformation between the African and the Eurasian Plates in the Eastern Mediterranean.

The estimation of the deformation between the African and the Eurasian Plates in the Eastern Mediterranean on the basis

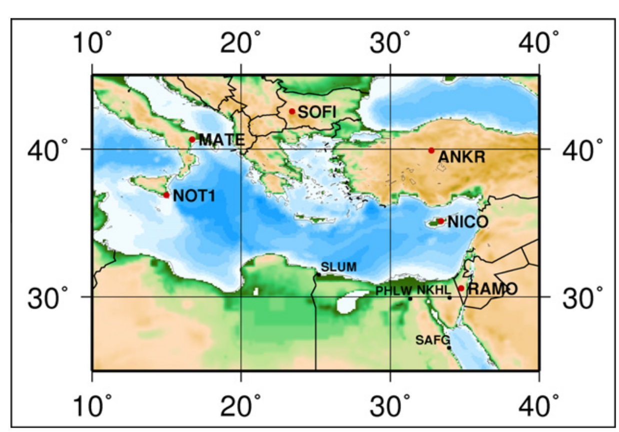

Fig. 3 Locations of the used Egyptian and European GPS permanent stations.

of GPS has been made utilizing two sources of velocities. The first was the freely available site velocity from the European Permanent Network (EPN). The second was the Egyptian GPS permanent network velocity. Their values were determined by the following technique. Firstly, the Egyptian site coordinates were computed from GPS daily observations, using the fiducial EPN stations. The daily site coordinates at a given time interval result in coordinate time series, which were analyzed and used on velocity estimation of the Egyptian stations. Then the formulas of continuum mechanics were applied to all resultant velocities. The regions of possible mutual interactions between the Eurasian and the African Plates in the Eastern Mediterranean were detected. The main reason of this contribution is the update of the results published before by Zeman et al., 2010 to get the common processing of GPS daily measurements from the Egyptian permanent network together with the EPN data. The available Egyptian GPS data cover a period of 5 yr (2006–2011), which represents a sufficient time interval for velocity estimation.

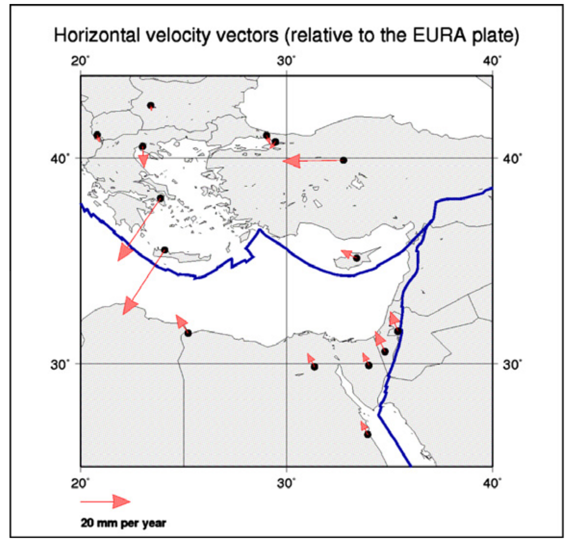

Fig. 5 Annual Horizontal Shifts in ETRF (relative to Eurasian plate).

Results

The deformation rates in the Eastern Mediterranean are characterized by means of graphical outputs. Deformations are based on annual horizontal shifts of the GPS permanent stations situated in the region of interest. (Fig. 4) denotes the annual horizontal shifts expressed in ITRF 2005, Fig. 5 the annual horizontal shifts in ETRF, i.e. relative to the Eurasian Plate, and Fig. 6 refers to interpolated annual horizontal shifts in ETRF.

In Table 1, the horizontal velocities in ETRF are compared with the long-term values published in the papers by Reilinger et al. (2006) and McClusky et al. (2003). The data processed by Reilinger cover an 8-year interval (1994.7–2002.7). The GPS measurements used by McClusky come from the years between 1992 and 2000. The comparison of horizontal velocities is possible only for the station Helwan (PHLW) because this station has a continuous data from long time while the other Egyptian stations (NKHL, SAFG and SLUM) are still suffering from

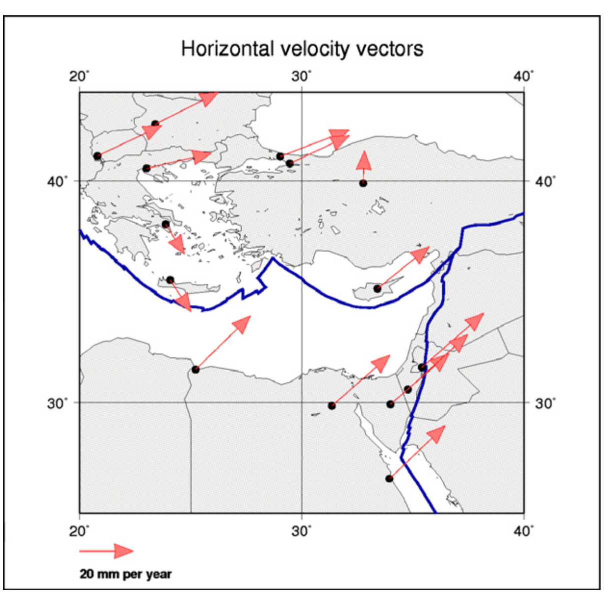

Fig. 4 Annual Horizontal Shifts in ITRF (2005).

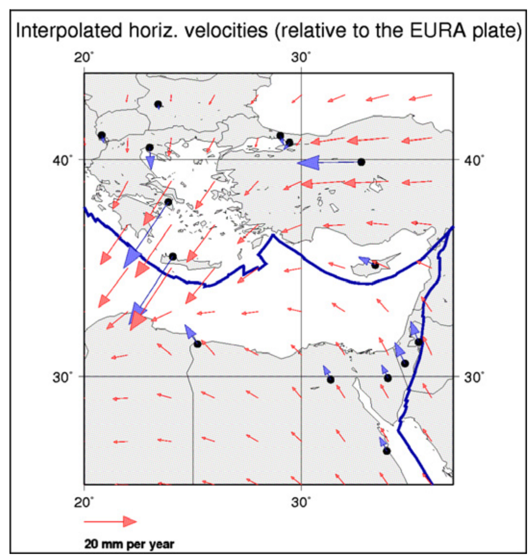

Fig. 6 Interpolated annual horizontal shifts in ETRF (relative to Eurasian plate).

some troubles since the previous work carried on it (Zeman et al., 2010) and also there are not any observable differences.

To describe the deformations, firstly the interpolated annual horizontal shifts (Fig. 6) and finally the interpolated strain tensors (Fig. 7) are presented as the main part of the results. Strain tensors are invariant with respect to the used reference frame.

The ellipses of errors of the interpolated strain tensors are plotted for every node inside the region of interest. Due to the performed solution (horizontal shifts for Egyptian sites estimated from half year measurements) the ellipses of errors in Fig. 7 are still huge in the region of Egypt, whereas in the Northern part of the Eastern Mediterranean, the ellipses of errors are smaller by some orders because of the relatively low standard deviations of the input horizontal velocities of the EPN stations. Therefore the results must be still seen as preli-

Table 1 Comparison of horizontal velocities v_N, v_E and their standard deviations in ETRF for the station PHLW by different authors (see text).

Source	V_N [mm/yr]	σ_{VN} [mm/yr]	V_E [mm/yr]	σ_{VE} [mm/yr]
McClusky et al. (2003)	5.03	0.86	−1.65	0.90
Reilinger et al. (2006)	5.54	0.51	−2.24	0.54
This work	5.40	1.19	−2.84	0.94

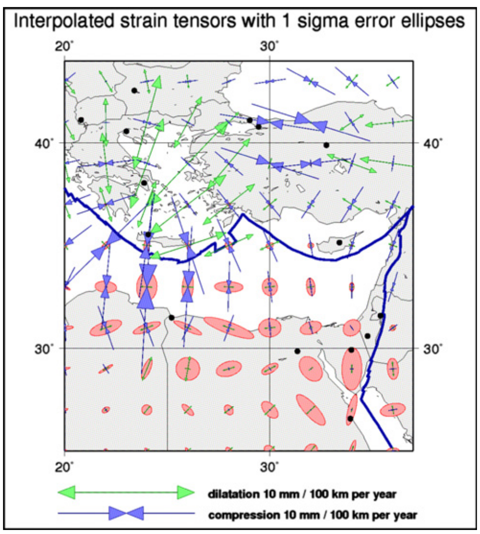

Fig. 7 Interpolated strain tensor.

minary as the processing of the coordinate time series of the Egyptian sites is not completed. The future final solution, based on estimation of Egyptian site velocities from all available observation days, should lead to reduction of the depicted ellipses of errors. On the other hand, it should not be expected that the estimated basic movement tendency of the Egyptian GPS permanent stations would subsequently change too much.

The main contribution of this article consists of gaining new information in the region of North Egypt, completing the known deformation rates derived only from movements of the EPN stations. Horizontal shifts of the stations in Egypt and Israel are similar both in direction and size, which refers to the movement of the African Plate in direction to the Eurasian Plate.

Next, the horizontal shifts of the sites with a tendency of counterclockwise rotation in the Eastern Mediterranean and also significant dilatation in the NE–SW direction in the region of Southern Aegean Sea are verified.

The availability of altimeter data from satellite observations, such as data collected by the European Space Agency ERS-1, 2 and data from the US Navy Geosat, have 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 a 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.

In satellite altimetry, two precise distance measurements are needed to derive the geoid. First, the ellipsoid height is measured by tracking the satellite over globally distributed control stations. Second, the height of the satellite above the ocean surface is measured with a microwave radar altimeter. The difference between these two heights is simply the geoid undulation.

The geoid can be transformed into gravity anomaly by using inverse Stoke's formula or by taking the derivatives of the geoid using Laplace's equation (Sandwell and Smith, 1997).

Li and Goetze (2001) give a simple relation between the gravity anomaly and the geoid undulation. Gravity anomaly Δg associated with geoid height N with a wavelength λ is given by

$$\Delta g = 2\pi\gamma N/\lambda, \tag{1}$$

where γ = 980,000 mGal is the average gravity of the Earth. This equation indicates that the gravity anomaly of 10 mGal and a wavelength of 10 km is associated with geoid undulation of 16 mm. This shows the precision needed for the geoid determination in order to compute gravity anomalies useful for geophysical applications. Green et al. (1998) show that satellite altimeter gravity has an accuracy of about 5 mGal and a resolution of about 20 km. Zahran and Saleh (2006) evaluated gravity satellite altimeter to the tectonic of the Red Sea.

Satellite altimeter gravity of Eastern Mediterranean

The location of the selected area on a marine region has made it possible to determine the spatial gravity field on a basis of satellite altimeter data. The interest of such computations is to evaluate the tectonic setting of this region regarding to the mass discontinuities. In addition, it is of great interest to determine the plate margins form of the gravity anomaly. Finally, neo-tectonics of this region can be evaluated considering the amplitude of the gravity anomaly.

The satellite altimeter free air gravity anomaly of the northern Red Sea region is given in Fig. 8 as computed by Sandwell and Smith (2009).

The gravity map figures out the tectonic settings of the Eastern Mediterranean region clearly. Interpretation of the spatial gravity field variation can be done utilizing the tectonic map of the region, Fig. 1, as follow:

African–Eurasian interaction can be seen as a high negative anomaly of the order of −200 mGal. It extends from the Adriatic on the east passing through the western Anatolian and ends at the central Anatolian.

The central Anatolian shows a high positive gravity anomaly on the order of 150 mGal indicated as a right lateral thrust fault.

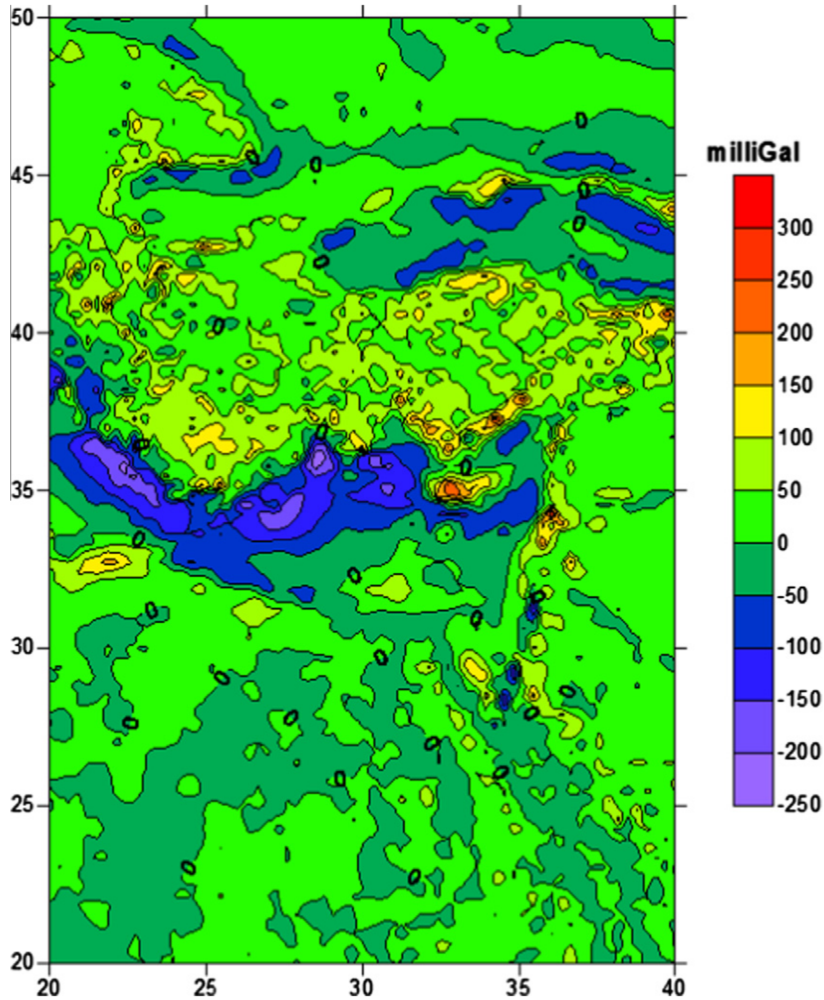

Fig. 8 Satellite altimeter free air gravity map of the Eastern Mediterranean region (after Sandwell and Smith, 2009).

The Eastern Anatolian and Caucasus areas show a complicated fault pattern seen on a high gradient gravity anomaly. The area is surrounded by EW trending thrust, NE–SW and NW–SE trending normal faults. The fault pattern follows to great extent the pattern suggested by Baraka and Reilinger (1997).

Helenic and Cyprus arc are marked by the southern border of the negative anomaly.

Less negative gravity anomaly is observed at the African–Arabian border with the existence of high positive gravity anomaly representing the Dead Sea rift.

North Anatolian–Black sea border represented by a set of separated negative anomalies.

The counterclockwise rotation, as shown from GPS, seen to be attributed with mass discontinuities and the amplitude of the gravity anomaly correlated well with the plate velocities obtained from GPS data analysis.

Temporal gravity variation from grace

The presented spatial gravity anomalies and its tectonic evidences, together with the GPS deduced crustal deformation at the Eastern Mediterranean suggests significant mass redistributions during the neo-tectonic activities. Moreover, distributions of intense seismic activities around the plates and sub-plates boundaries indicate the continuous activities of these zones. Temporal gravity variation could deliver important information about the mass redistribution attributed to the seismological activities and can be considered as important integration of the geodynamic studies of this region.

Until recent, it was not possible to monitor on a regional scale. The Gravity Recovery and Climate Experiment (GRACE) satellite mission was launched in March 2002 to map the temporal variations in the Earth's global gravity field on a monthly basis (Tapley et al., 2004). The variability in these gravity field solutions represents geophysical responses associated with redistribution of mass at or near the Earth's surface, where mass variations are likely to occur on the time scales examined by GRACE measurements. Generally, the largest time-variable gravity signals observable in GRACE data are expected to come from changes in the distribution of water and snow stored on land (Wahr et al., 1998). However, Geodynamic processes such as changes in the Earth's topography or mass distribution as a result of lithospheric plate interactions (collision, subduction, rifting), postglacial rebound, mantle convection, earthquakes, sedimentation and

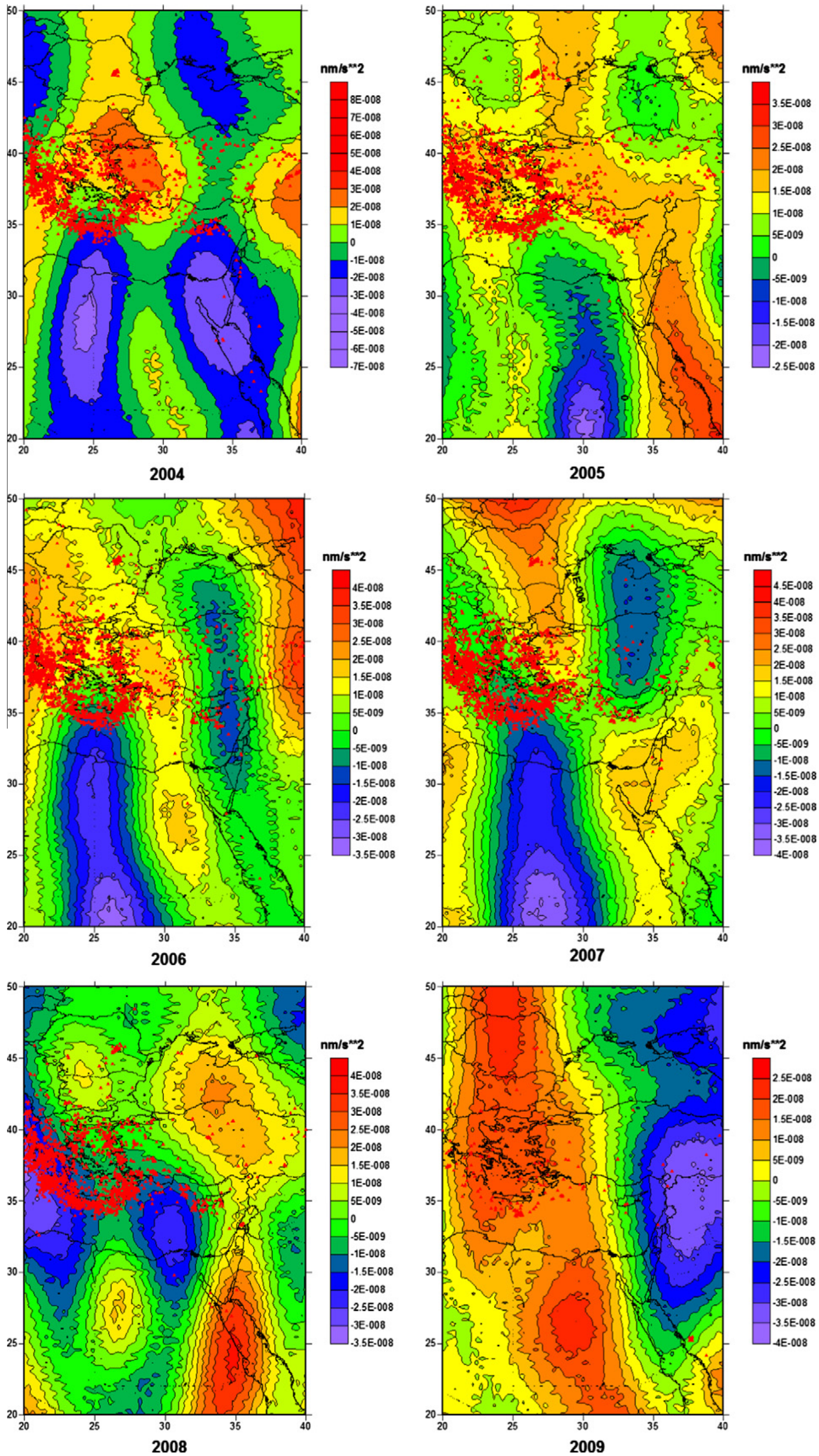

Fig. 9 GRACE temporal gravity variation of the Eastern Mediterranean region from 2004 to 2009 (red points marks earthquakes with $m \geqslant 3$.

erosion, should also contribute to temporal variations of the Earth gravity field. Valentin et al. (2004) investigated whether temporal variations of the gravity field caused by tectonic processes can be recognized in GRACE satellites. They demonstrated that new satellite gravity data can be used to detect and discriminate geodynamic signals generated by subduction zone dynamics.

Temporal gravity variation of Eastern Mediterranean from grace

We used 71 monthly gravity field solutions (RL04 unconstrained solutions) for the Period 2003–2009 from the GRACE database 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 ($0.5° \times 0.5°$) of equivalent temporal gravity using a Gaussian smoothing function with a radius of 300 km.

Fig. 9 displays GRACE temporal gravity variation of the Eastern Mediterranean region from 2004 to 2009. The figure includes earthquakes with magnitude more than 3. The significant temporal gravity variation indicates that the seismic activities attributed to a significant mass redistribution around the seismo-active zones. The wide range of the gravity anomalies which appear on the figure suggests deep mass discontinuities at the lower crust and the upper mantle. The conjunction between Africa and Eurasia is seen as negative gravity anomaly at the African side met by a positive gravity anomaly at the Eurasian side with a temporal gravity variation on the order of 50 μGal. This can be interpreted as subsidence of the African plate and uplift to the Eurasian plate. It is clearly seen that the difference increased with increasing seismic activity, 2004 and 2005, and vice versa, 2009. A similar behavior can be seen at the Arab plate, as it shows a higher gravity anomaly compared to the African plate and a negative gravity anomaly compared to the Eurasian plate. Temporal gravity variation of the Eastern Mediterranean shows a very complex recent tectonics and that the whole area behaves as a complicated right lateral thrust pattern. In order to evaluate the neo-tectonics of the Eastern Mediterranean in terms of the temporal gravity field variation, the mean annual values have been computed using GRACE data from 2004 to 2009 and are given in Fig. 10. Vectors have been added to the temporal gravity var-

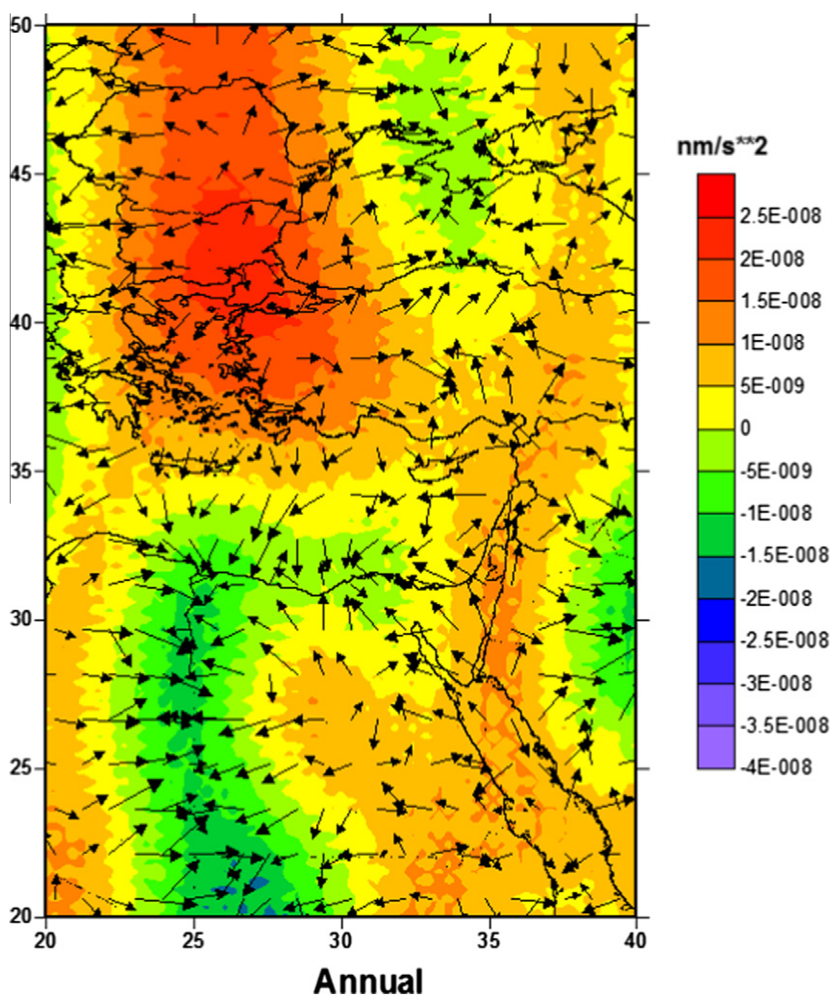

Fig. 10 Annual temporal gravity variation of the Eastern Mediterranean region from GRACE (2004–2009).

iation to delineate the direction of mass redistribution and to figure out plates and sub-plates margins in term of mass discontinuities. The figure shows significant annual temporal gravity variations, and the gravity anomaly patterns figured out precisely the neo-tectonic deformation of the studied region. The main gravity anomaly can be seen on the conjunction of the African–Eurasian plates is on the order of about 40 μGal/yr. A smaller gravity anomaly is present at the African–Arabian plate is on the order of about 15 μGal/yr. The Anatolian plate seems to be a major sub-plate from the Eurasian plate with a different tectonic movement as the Eurasian plate. Random vectors within the Eurasian plate indicate that it comprises of a numbers of small plates moving with respect to each other and that the tectonic setting of the Eurasian plate is very complicated. In contrast, both African and Arabian plates are more uniform. The Dead Sea rift extended uniformly to strikes of the Eurasian plate at north. Due to the spatial distribution limitations of GRACE, it is not possible to reveal minor tectonics within the sub-plates.

Discussion

The Eastern Mediterranean region is considered to be one of the most interested regions on the globe from the tectonic point of view. Its continuous neo-tectonic activities made it a perfect test region for modern Earth observing tools for the geodynamic studies. Therefore, it has been studied intensively during the last 30 yr.

The deformation results were obtained from linking selected Egyptian and European permanent GPS stations. The interpretation of GPS data shows significant rate of deformation along the subduction zones with high velocity rates of the moving plates. The observations indicate significant deformations of the Anatolian plate. Horizontal shifts show a tendency of counterclockwise rotation in the Eastern Mediterranean, and also significant dilatation in the NE–SW direction in the region of Southern Aegean Sea are verified. Evaluation the tectonic setting of this region regarding to the mass discontinuities has been made using gravity-based satellite altimeter data. The gravity map show important zones of mass discontinuities along plates and sub-plates margins. Gravity data enable the revealing the complicated fault pattern of this region on term of gravity anomalies. The counterclockwise rotation, as shown from GPS, seen to be attributed with mass discontinuities and the amplitude of the gravity anomaly correlate well with the plate velocities obtained from GPS data analysis.

The temporal gravity variation from GRACE has been used to detect a possible mass distribution along plates boundaries attributed to the neo-tectonics. Temporal gravity variation indicates that the seismic activities on this region are attributed to a significant mass redistribution around the seismo-active zones. In addition, it gives important information about mass sources responsible for neo-tectonics. The rates of temporal gravity variation correlated well with tectonics of the region and rates of the GPS recent crustal deformations. Due to spatial limitations of GRACE, it is not possible to reveal minor tectonics within the sub-plates.

The study indicates the importance of considering spatial and temporal gravity to the deformation and tectonic studies for completeness of the geodynamic studies. Generally, it can be stated that the satellite data offer additional and complementary data sets to help the geoscientists to determine the Earth's internal structure and tectonics. Determination of spatial and temporal earth's gravity field from satellite opened new perspectives on earth sciences and provides valuable information of the geodynamic studies.

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