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Indications of correlation between gravity measurements and isoseismal maps. A case study of Athens basin (Greece)

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ABSTRACT

In this paper, we discuss the correlation between isoseismal contour maps and gravity residual anomaly maps and how it might contribute to the characterization of vulnerable areas to earthquake damage, especially in urban areas, where the geophysical data collection is difficult. More specifically, we compare a couple of isoseismal maps that have been produced and published after the catastrophic earthquake of 7th September 1999 (5.9R) in Athens, the metropolis of Greece, with the residual map produced from the processing and data reduction of a gravity survey that has been carried out in the Athens basin recently. The geologic and tectonic regime of the Athens basin is quite complicated and it is still being updated with new elements. Basically it is comprised of four different geotectonic units, one of them considered as the autochthon. During the gravity investigation, 807 gravity stations were collected, based on a grid plan with spacing almost 1 km, covering the entire basin and supported by a newly established gravity base network comprised by thirteen bases. Differential DGPS technique was used for the accurate measurement of all the gravity stations and bases coordinates. After the appropriate data reduction and the construction of the Complete Bouguer Anomaly map, we applied FFT filtering in order to remove the regional component and produce the Residual Anomaly Map. The comparison of the Residual Anomaly Map with the isoseismal contours revealed that the areas with the most damage because of the earthquake were located in the areas with the minimum values of the Residual Anomaly Map.

1. Introduction

On 7th September 1999, a 5.9R earthquake occurred in Greece metropolis, Athens city (Fig. 1), causing enormous damages in almost 70,000 buildings with almost 100 of them collapsing. More than 2,000 injuries were recorded along with 143 dead people and at least 100,000 homeless people (Bouckovalas and Kouretzis, 2001). Although a lot of major earthquakes had occurred during the last 100 years in the greater area of Athens basin, this one caused the most damage.

Especially in urban and fully residentially developed areas, knowledge on the existence of concealed active faults is absolutely useful because the damage distribution of an earthquake is usually related to the tectonic structures of the area. Unfortunately, since the areas are covered with buildings, the geological research is quite complicated, with the obtained information being restricted to quite older observations, geological maps, boreholes and data. Also, the geophysical research in urban areas is quite difficult to develop, especially for deep investigations (Xu et al., 2015). For example, it is almost prohibitive to apply the electromagnetic and magnetic methodologies due to the effects from the current cables and buildings. Geoelectrical methods are also difficult to carry out, since most of them require space and straight long lines to measure on. The seismic methods are widely applied in urban areas (Hutchinson et al., 2009; Krawczyk et al., 2012; Symeonidis et al., 2005) but it is quite expensive most of the times and usually they focus on the shallow. The gravity methodology can be applied in urban areas for deeper investigation but the field measurements should be planned with caution, taking into consideration the traffic and the building effects.

A gravity research was organized, focused on the Athens basin structural investigation, in order to reveal possible concealed (blind) faults which could affect the city in the future by generating disastrous earthquakes. The 7th September 1999 earthquake had its epicenter at a fault that hadn't generated severe earthquakes until then. Since Athens basin is covered with human constructions (building, roads, playgrounds, public services station etc.) in a very large percentage, the appliance of great scale geophysics is restricted and expensive. The only cost-effective method for structural investigation seems to be the land gravity measurements.

Gravity measurements are widely used in many cases and on different scales of investigation depending on the target. Some of their applications are in oil-gas and mineral exploration (Chen et al., 2015; Martinez et al., 2013; Wang et al., 2012), structural and basin

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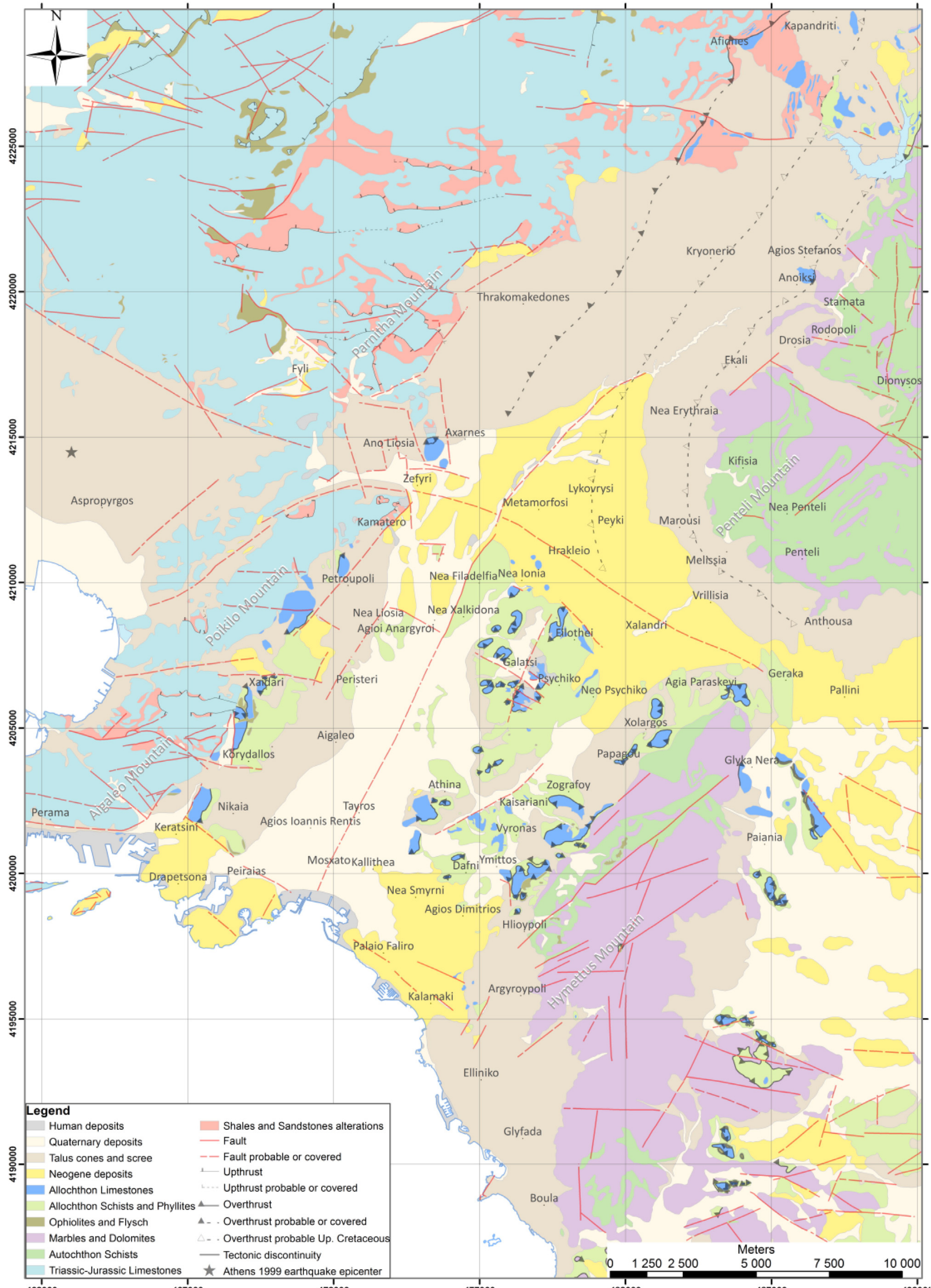

Fig. 1. Geologic and tectonic regime of Athens basin, along with the Athens earthquake of 7th September 1999.

investigations (Braitenberg et al., 2006; de Castro et al., 2014; Karner et al., 2005; Madon and Watts, 1998; Onal et al., 2008; Zheng et al., 2006) and cavity determination (Fais et al., 2015; Leucci and De Giorgi, 2010; Martínez-Moreno et al., 2015). Some other times, gravity measurements are applied for engineering applications (Lamontagne et al., 2011; Narayanpethkar et al., 2007).

Gravity measurements are affected by a lot of things (topography, sea level, elevation etc.) which need to be corrected with the appliance of the proper corrections. After the data reduction and the production of the Residual Bouguer map, similarities have been observed with the isoseismal contours that had been produced by Lekkas (2001) and Tzitziras et al. (2000), after the earthquake damage register and processing.

2. The geotectonic regime of Athens basin and the earthquake of 7th September 1999

2.1. Geologic and tectonic setting

Athens basin hosts the metropolis of Greece, with population up to 4 million people in an area of almost 360 km^2, surrounded by the mountains Aigaleo and Poikilo (West), Parnitha (North), Penteli (Northeastern) and Hymettus (East). Even though many authors had studied and published many papers about the geological structure of Athens (Freyberg, 1951; Lekkas and Lozios, 2000; Lepsius, 1893; Lozios, 1993; Mariolakos and Fountoulis, 2000; Marinos et al., 1971, 1974; Niedermayer, 1971; Sabatakakis, 1991), there are still some open issues left. After the earthquake, a new updated and more detailed geologic and neotectonic mapping was assigned by the Greek Antiseismic Planning and Protection Organization (O.A.S.P.) to Papanikolaou and collaborators (2002).

In this paper, we decided to illustrate a simplified geology regime of the area (Fig. 1) mostly based on this up-to-date geotectonic study by Papanikolaou and collaborators (2002), completed and combined with some of the existent studies where there was no coverage. The geological status is quite complicated, with the appearance of one autochthonous metamorphic geotectonic unit covering the eastern margin (*Hymettus and Penteli mountains*), one allochthonous unit, named "*Ypopelagoniki*", constructing the western margin (*Aigaleo and Poikilo mountains*) and two other local allochthonous units, "*Athens Unit*" and "*Alepovouniou Unit*".

The autochthonous metamorphic unit is compiled mainly of dolomites, marbles and shales, where the last two exist as continuous overlaying layers. On the other hand, the "*Ypopelagoniki*" unit consists of Triassic-Jurassic limestones and some base clastic formations from Paleozoic. The "*Athens*" unit is comprised of two main parts, the upper which is basically limestones and the lower part, called "*Athens shales*" which is basically a geological mix/mélange that consists of sandstones, shales, phyllites, limestones and marls. The "*Alepovouniou*" unit is similar, with limestones in the upper part but schists and phyllites in the base, because of its low metamorphism.

The post-alpine geological formations cover the bigger part of the basin, with the exception of some remaining hills in the center (*Filopapou*, *Acropolis*, *Lycabettus*, *Ardittou*, *Tourkovounia*, *Kokkou*), constituted mainly by the "*Athens*" unit. More than ten different post-alpine, Quaternary and Neogene, geological formations appear in the area based on Papanikolaou and collaborators (2002). Their thickness varies from a few meters to a few hundreds of meters. Because of their existence it is difficult to understand with no doubt the geotectonic regime of the basin. For example the area where the *Kifisos* River flows that is covered with alluvium deposits, is considered to be a critical area, because somewhere under that area the tectonic contact between the metamorphic unit and non-metamorphic (*Ypopelagoniki*) unit, is expected to be located. This major and important tectonic contact has been mapped only in the area northern of our research area (*Kapandriti* and *Oropos*) but is expected to continue southern through the Athens basin, covered by the post-alpine deposits and possible the two local allochthonous units ("*Athens*" and "*Alepovouniou*"). Most of the researchers believe that generally it might have the same directions with the *Kifisos* river flow (NNE-SSW).

From all the geotectonic studies, many faults have been mapped and many more have been implied to exist concealed by the post-alpine deposits. Many of these implications have been originated, based on data from earthquake damages along with surface evidences (Fig. 1).

2.2. Isoseismal contours of the 7th September 1999 earthquake

On 7th of September 1999, one of the biggest and most disastrous earthquakes of the Athens city history took place, with magnitude 5.9R (Fig. 1). Until that time, the only severe earthquakes that affected the Athens metropolis were located to the outer areas, such as the one of Alkyonides in 1981 (Papazachos et al., 1984). The epicenter had been located in the area of Aspropyrgos (Lekkas, 2001), on a fault surface that had been unknown until then and its surface trace was adumbrated afterwards, with geophysical investigations (Papadopoulos et al., 2007).

Although the epicenter was practically out of the Athens basin limits, the damage was mainly located in the basin, at the western and northern part. After the recording of all the damage and their processing, a couple of publications by Lekkas (2001) and Tzitziras et al. (2000) came out, illustrating the produced isoseismal contours from that earthquake. Observing the two isoseismal contour maps, it is obvious that they have great similarities and slight differences. The isoseismal contours from Lekkas (2001) (Fig. 4), based on the enhanced version of EMS-1998 (Grünthal, 1998) are located mainly in the western basin, in the areas of Acharnes, Ano Liossia, Kifisia, Tatoi, Kamatero, Ilion, Peristeri, Aigaleo and the maximum observed intensity here is equal to ten (10). Tzitziras et al. (2000) (Fig. 3) present some more contours in the north-eastern (Marousi and Chalandri) and in the southern-central area (Tayros, Moschato, Agios Ioannis Rentis), but with maximum observed intensity equal to nine (9). As it is expected most of these damaged areas are located in post-alpine deposits.

3. Gravity method

3.1. Data acquisition

In every gravity campaign a network of gravity bases is necessary, where we know the absolute gravity value. Every 2–3 h of measurements we must re-measure the value of the base in order to be able to remove afterwards the drift effect of the instrument. Taking into account the traffic jam of this over-populated metropolis and the increasing time that we would spend in the transfers between the stations and the base re-measurements, we decided to establish a very carefully planned gravity base network, distributing spatially thirteen (13) bases in a way that would minimize the transfer time of the base rounds (Fig. 2). Most of them were located on squares that were close to main roads (quick access) but "quite" in the same time, in order to have stable measurements without noise. The entire gravity base network is referred to the IGSN'71 datum (Morelli et al., 1974) as it was tied with repeated measurements with an already established base in the University of Athens (Hipkin et al., 1988).

Due to the complicated geology of the area, the purpose of the research and the urban environment, the gravity measurements were decided to be organized on a grid and not on a few profiles. The gravity measurements are affected when they are executed very close to walls and buildings, so we had to take great care that the gravity stations would be placed in "open" areas (squares, parks, fields, parking areas, homesites, wide pavements etc.), far from high buildings as much as possible (at least 60 m). In the metropolis of Athens this is quite difficult, as anyone can imagine, especially down town. Fortunately, in the suburbs the circumstances were better. Because of all the pre-mentioned

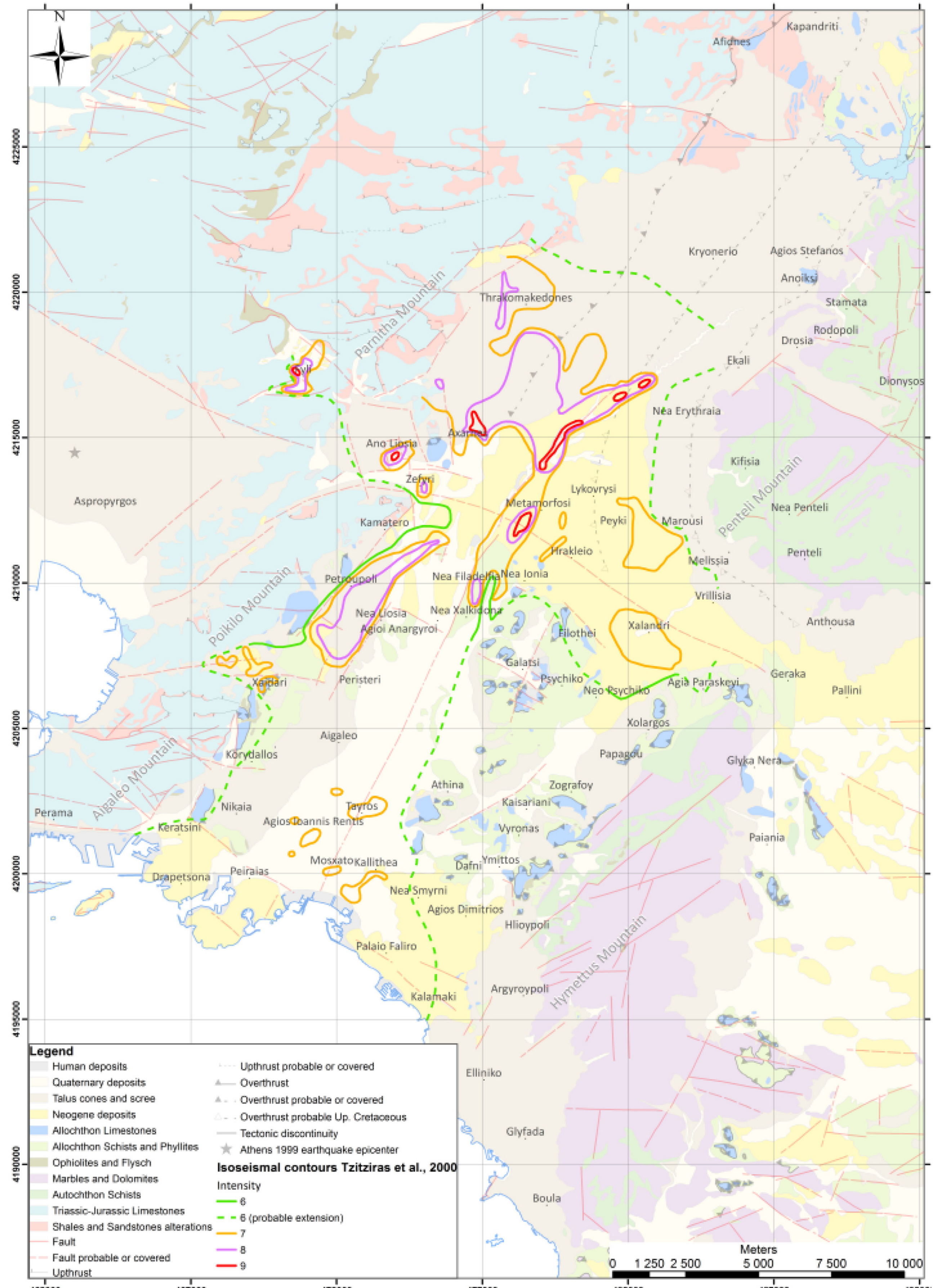

Fig. 2. Isoseismal contours by Tzitziras et al. (2000).

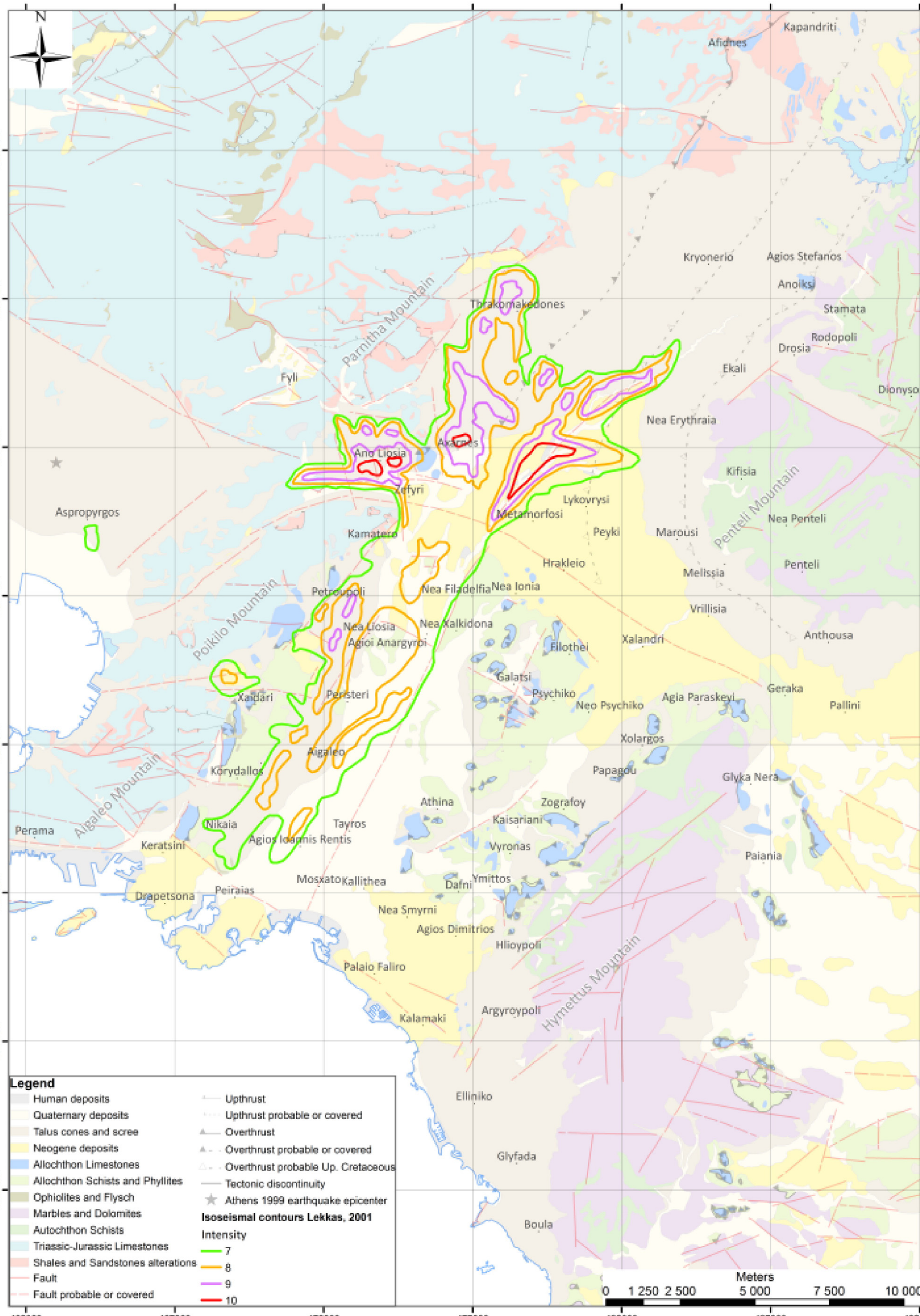

Fig. 3. Isoseismal contours by Lekkas (2001).

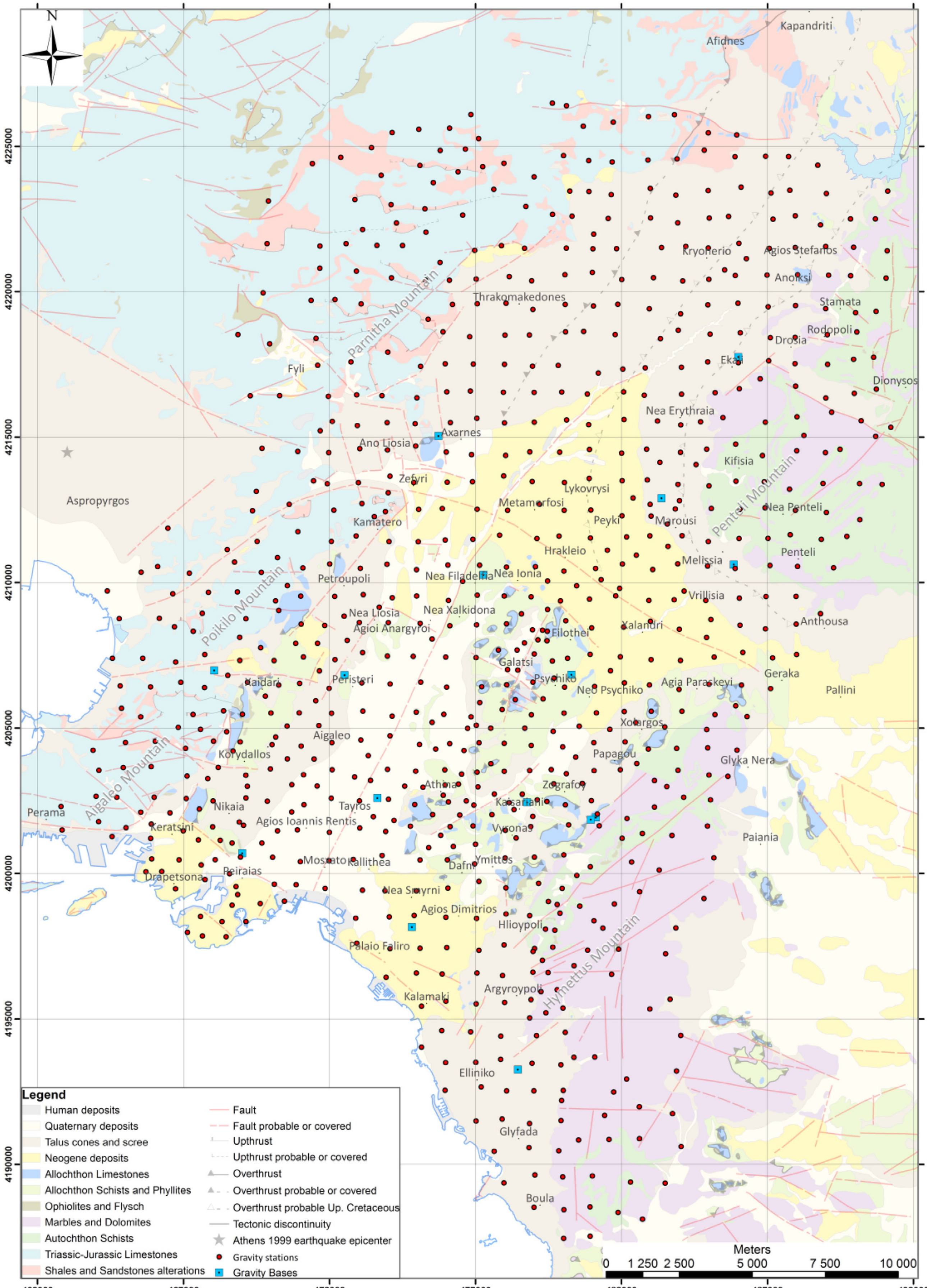

Fig. 4. The locations of the gravity stations and gravity bases.

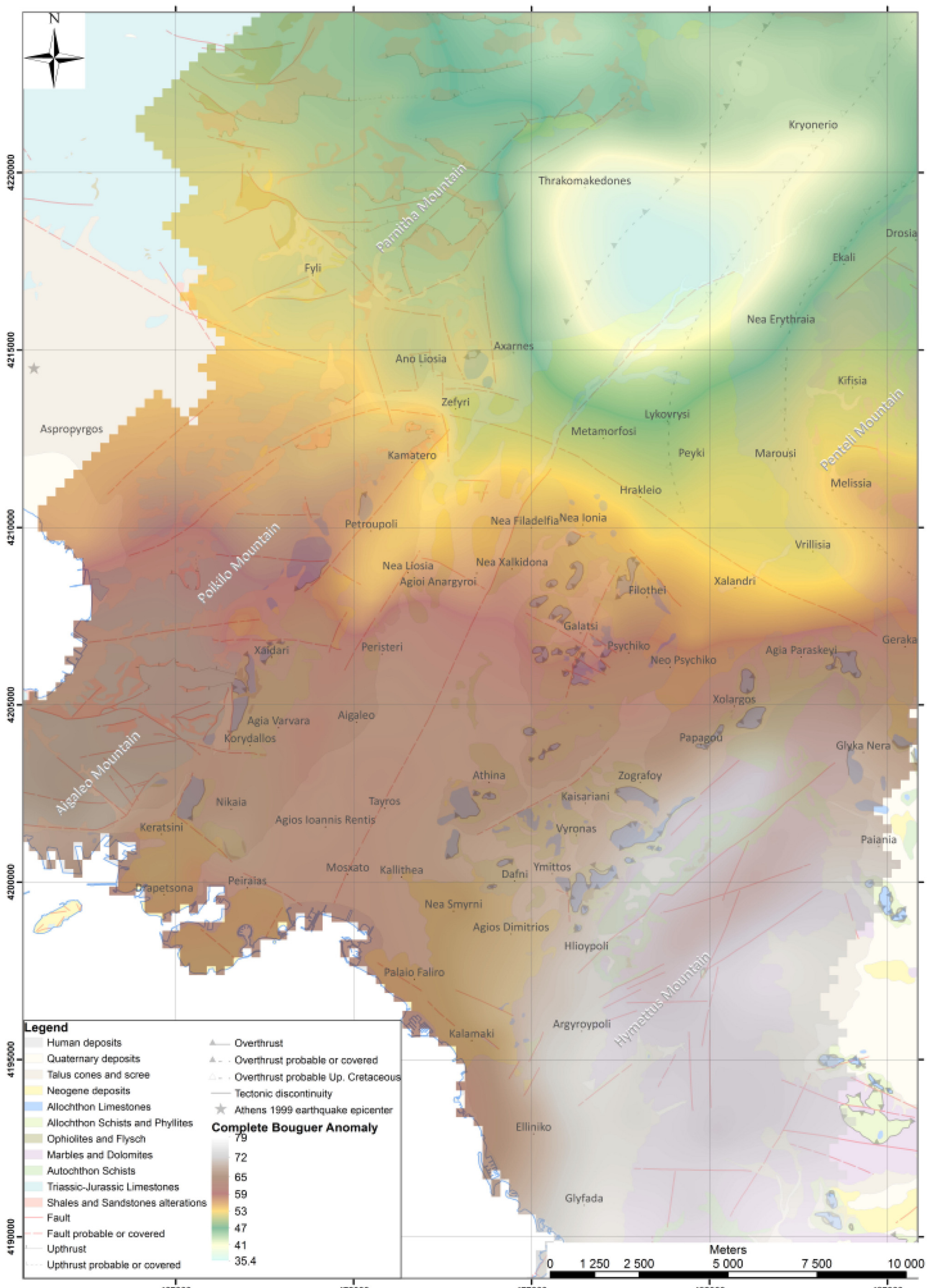

Fig. 5. Complete Bouguer Anomaly map.

data, the gravity stations grid had to be organized very carefully, taking advantage of high-accuracy space images. Due to the human constructions and all the obstacles, a lot of stations had to be relocated to the nearest executable point (usually within the first 100-200 m) in order to avoid the building effects. The grid station spacing had been set primarily to 1 km, but this was slightly changed in some areas due to the numerous re-locations. After the processing of the first dataset, the grid became a little denser, with some stations added in between the first ones, in order to clarify the status in some areas. All the campaigns were carried out during summer when most of the city residents leave for vacations, which means that the traffic jam is reduced, as well as the time consumed between the stations and the bases. The gravity database comprised of 807 gravity stations (Fig. 2). The first field campaign was carried out during the summer of 2013, collecting 500 gravity stations and the second during the summer of 2014, collecting 307 more gravity stations. The gravity meter LaCoste & Romberg G-496 was used for the data acquisition.

In order to calculate the necessary coordinates of each gravity station and base with high precision, we used Differential Global Positioning System (dGPS). This was compiled by two different, dual-frequency *TopCon HiperPro* GPS antennas. The one antenna was used as *base*, positioned at one of the three (3) established topographic bases used (with known coordinates as there were tied with geodetic control points of the Hellenic Military Geographical Service) and the other was used as *rover*, measuring the coordinates of each gravity station, using the *static* technique (because of the long distances and the buildings), at the same time with the gravity observation. In this way, the accuracy of the calculated coordinates was of the centimeter scale, which is very important in order to have precise data corrections and results. The coordinated were in the Hellenic Geodetic Reference System (EGSA'87).

3.2. Data reduction and Bouguer anomaly maps

All the appropriate corrections were applied on the collected gravity data, in order to produce the final Bouguer anomaly map. First of all, based on the re-measurements of the base each 2–3 h, we removed the drift effect of the instrument. The tidal effects were removed during the processing with the *Oasis Montaj* software, based on the measurement time of each station.

In order to continue with the data reduction, we had to process the collected dGPS data, using the *TopCon Tools* software, specialized for the static technique solutions. So, the calculated high-precision coordinates of each gravity station, were taken into account for the latitude (*WGS84 formula*) and for the free-air correction. The assumed constant density for the Bouguer correction was set up to 2.67 g/cm^3.

Athens basin is an urban area, which means that the greater part is covered with artificial constructions (buildings, roads etc.). Sometimes due to large scale manufacturing, great changes in geomorphology occur, modifying the existing topography. For that reason, recently updated DEM maps were chosen to be used for the terrain corrections, which were calculated for a radius up to 21 km for each station. For the inner zones, up to a radius of 1.500 m, the corrections were calculated based on a more detailed DEM with 5 m cell spacing. The corrections for the zones between 1.5 and 21 km were calculated from another DEM, with 25 m cell spacing. The terrain corrections were applied through the *Gravity and Terrain Correction* extension of *Oasis Montaj*.

In the end, after applying all these data corrections, the Complete Bouguer Anomaly map was calculated (Fig. 5). The corresponding map was constructed using the minimum curvature gridding between the gravity stations that were acquired. In that way we produce the smoothest possible contouring for our data.

As we can see, the values of the Bouguer anomaly range from 35.4 up to 79 mGal. A minimum area, with circular shape, is located in the northern suburbs, among the areas of Thrakomakedones, Kryoneri, Ekali, Kifisia, Lykovrysi and Acharnes. The Bouguer values seem to be increasing to the southern areas and especially over the mountain Hymettus and Aigaleo, where the maximum values exist.

3.3. Regional and residual gravity field

One the classic problems for the researchers dealing with gravity measurements and processing is how to calculate and separate the regional gravity field from the residual field(Martínez-Moreno et al., 2015; Nettleton, 1954; Roach et al., 1993). The produced Bouguer anomaly map consists of both the regional and the residual (due to local structures) gravity field components. There are quite a few filtering processes for the regional-residual separation, each one with its pros and cons. The most popular ways are the graphical method, the derivatives (Gönenç, 2014), the upward continuation process (Jacobsen, 1987; Zeng et al., 2007), the polynomial fitting (Beltrao et al., 1991), the finite element approach (Mallick and Sharma, 1999; Mallick et al., 2012) and the application of FFT filters (Götze et al., 1994; Syberg, 1972; Xu et al., 2009), which tend to be applied more nowadays.

In this research, the regional-residual separation was carried out with FFT filters through the algorithms of *Oasis Montaj*, since the measurements were executed on a grid plan. Having a great spatial cover of the inner Athens basin but also from the surrounding mountains, would help calculating correctly the regional component. The *Gaussian* filter had been chosen as the most appropriate for this case. The grid was prepared for the transformation by removing the first order trend (based on all points). Afterwards, there were the grid expansion and filling, so that it would be acceptable for Fourier transformation, in order to convert the space domain data to the Fourier domain. Depending on the value of the standard deviation parameter that we will choose, we can produce in a way residual anomaly maps of different depths.

After the FFT filtering, the Residual Anomaly Map of Fig. 6 came up. Two areas of minimum values (down to −14 mGal) are illustrated. The main one is located among the areas of Thrakomakedones, Kryoneri, Ekali, Kifisia, Lykovrysi and Acharnes, with circular morphology, along with two linear extensions, one to the zone between Petroupoli and Agioi Anargyroi and one other to the zone between Vrillisia and Chalandri. A second area of minimum values is located northern, almost parallel to the urban coastline, at the areas of Piraeus, Moschato and Palaio Faliro, reaching a minimum anomaly value of −5 mGal.

On the other hand, the maximum anomaly values are observed at the areas of the surrounding mountains Hymettus (up to 8.5 mGal), Aigaleo-Poikilo (up to 2.5–3 mGal) and Parnitha (up to 2–4 mGal). Moreover, an area of the inner basin appears with a maximum positive anomaly value of almost 2.5 mGal, located among the down town of Athens city, the Aigaleo and Peristeri municipalities. The area's general direction (WNW-ESE) is almost perpendicular to the general direction of the mountains Hymettus and Aigaleo (NNE-SSW), to which it seems to be connected. This maximum anomaly values area might reveal a zone where we have a shallow subsurface expansion of the allochthonous units under the alluvium deposits.

4. Comparing residual gravity map with isoseismal contours

A Residual anomaly map practically is determined by the local scale geotectonic structures. Likewise, the damage distribution of an earthquake, which will be presented by the isoseismal contours, is usually related to the tectonic structures (fault directions etc.). Consequently, the qualitative interpretation of both maps seems to be related. We decided to compare the residual anomaly map that had been produced with the isoseismal maps, by Lekkas (2001) and by Tzitziras et al. (2000), by overlaying them (Figs. 7 & 8). It is obvious that there are great similarities.

At a first view of them (Figs. 7 & 8) someone could say that the isoseismal contours, are located mainly in the areas that we have minimum values (white/purple/blue colors). The most impressive part of

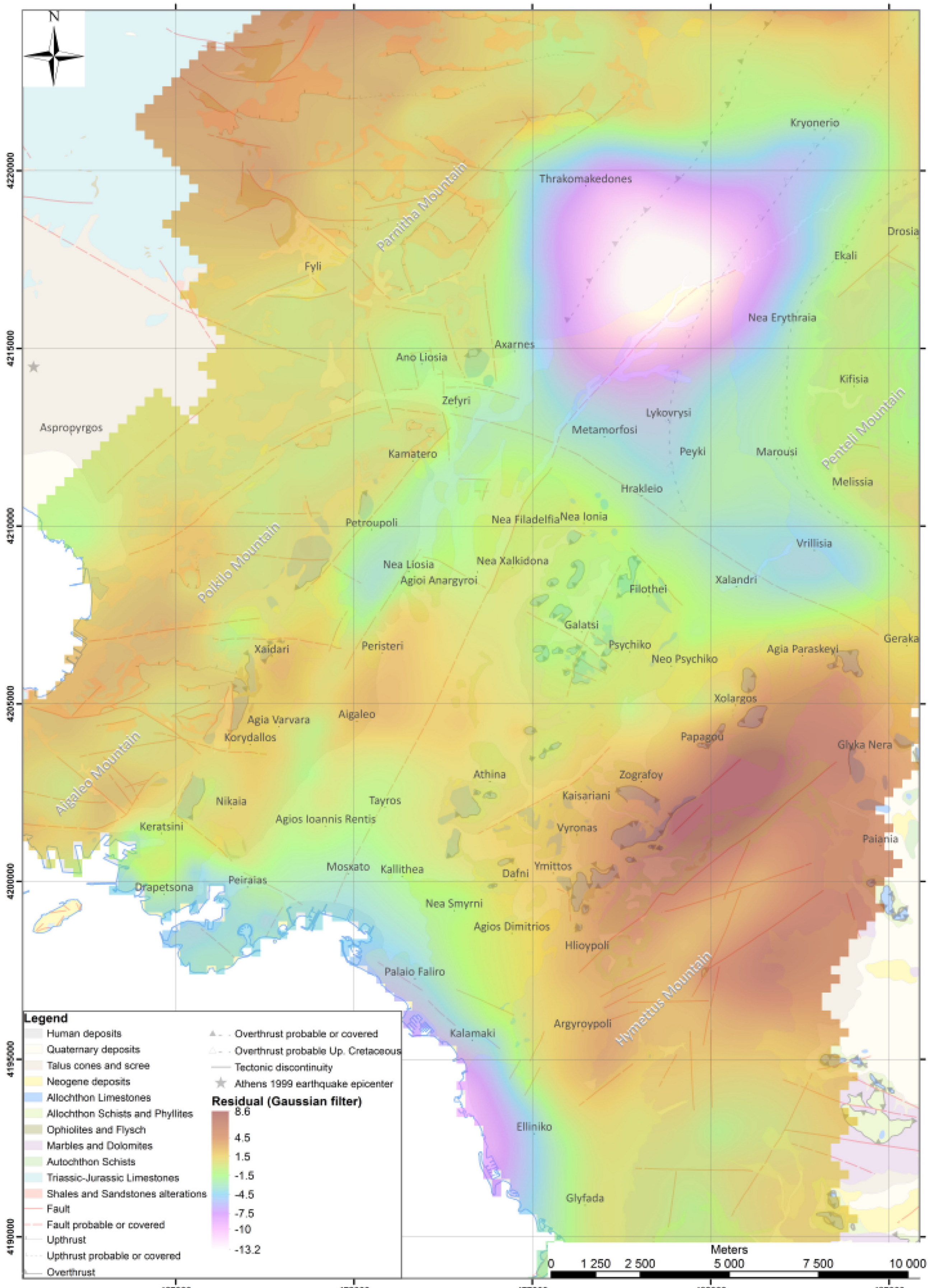

Fig. 6. Residual Anomaly map.

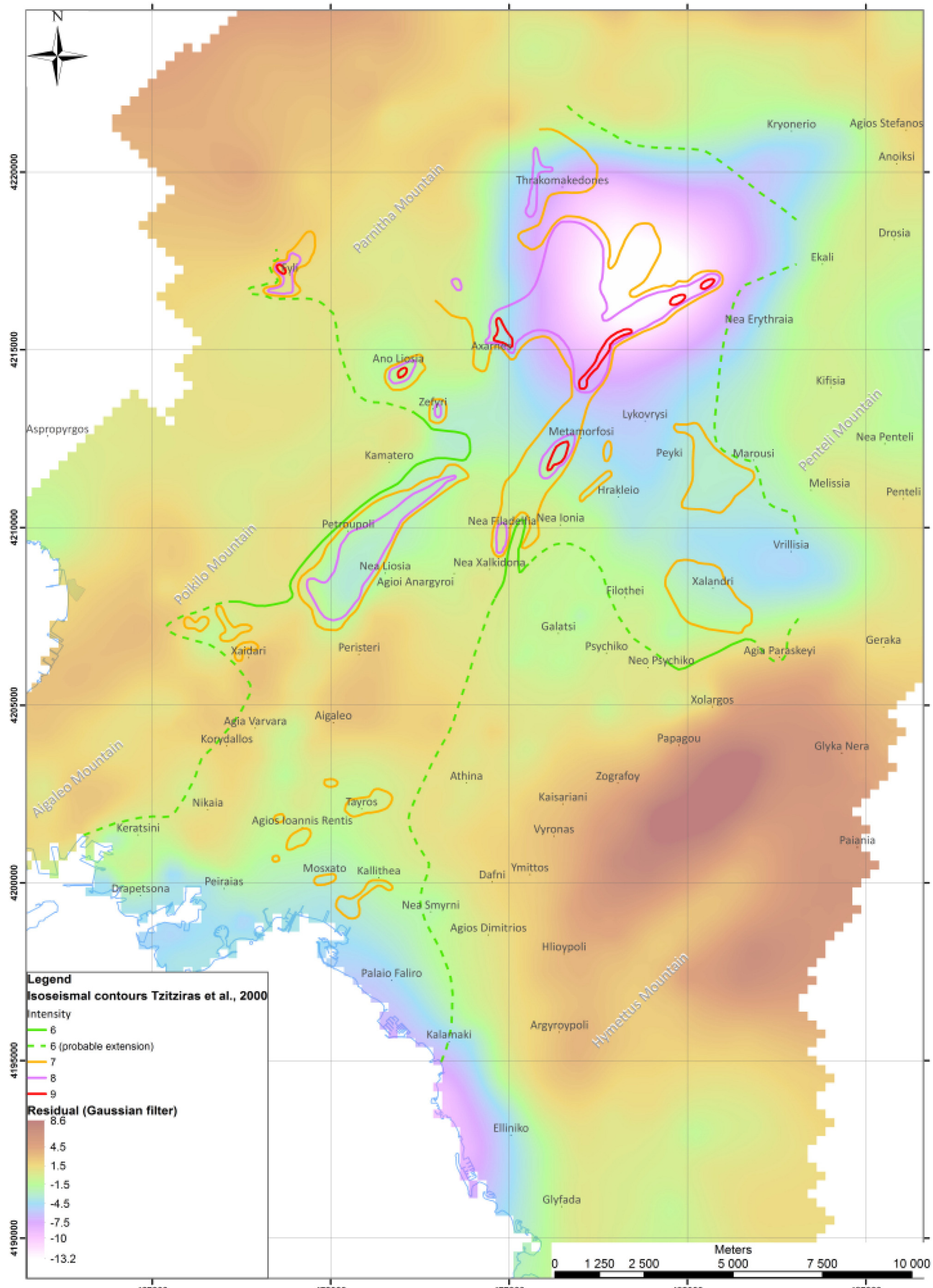

Fig. 7. Residual Anomaly map and isoseismal contours by Tzitziras et al. (2000).

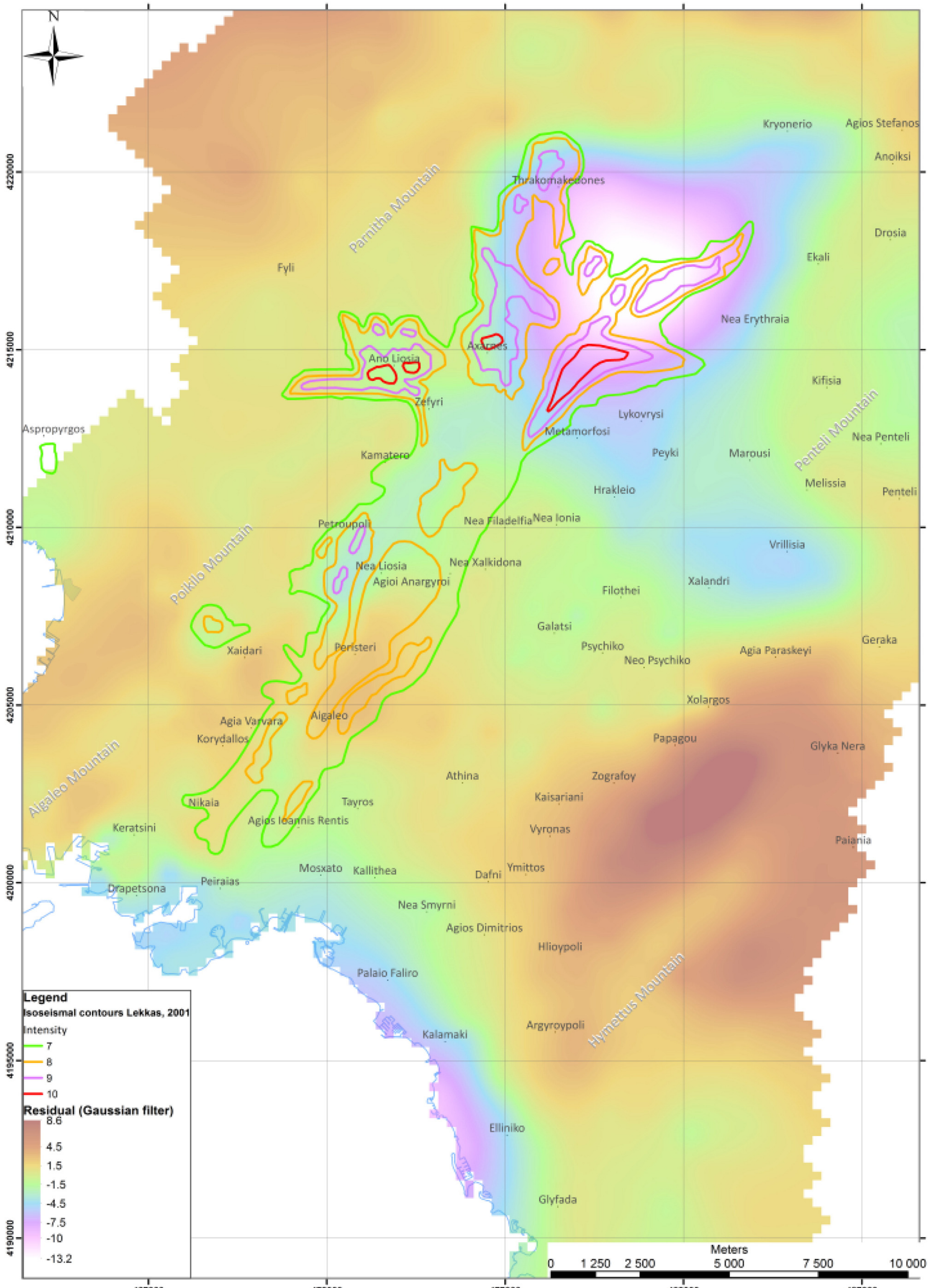

Fig. 8. Residual Anomaly map and isoseismal contours by Lekkas (2001).

identicalness is the zone between Petroupoli and Nea Liossia (Fig. 7), where Tzitziras et al. (2000) appear a separate lobe of isoseismal contours with maximum intensity equal to 8. This lobe seems to be identical with a similar lobe of minimum anomaly values observed in the Residual anomaly map. The isoseismal contours at this location seem to be hedged by the greater residual gravity values. Additionally, the main circular shaped area, with minimum residual anomaly values, seems to "include" the majority of high intensity isoseismal contours. Basically, almost all the isoseismal contours with intensity more than 7, are located in the areas with minimum residual anomaly values. Almost no isoseismal contours are observed at the areas of maximum residual gravity field values.

As far as the isoseismal map of Lekkas (2001) is concerned (Fig. 8), the contours seem to be more dense and continuous, with a general direction NE-SW. Here also, the isoseismal contours with intensity more than 8 appear in the areas of the main circle of low residual anomaly values, among Thrakomakedones, Kryoneri, Ekali, Kifisia, Lykovrysi and Acharnes. The zone among Petroupoli, Kamatero and Nea Liossia has good identicalness, but not as good as the contours by Tzitziras et al. (2000). On the other hand, here we have good fit of low residual anomaly values (no minimum, just low) in the area of Ano Liossia and Zefyri, where new high intensity isoseismal contours appear by Lekkas (2001).

5. Conclusions

After almost fifteen years from the catastrophic 7/9/1999 earthquake in Athens, a large gravity research was organized, with the aim of adumbrating possible concealed faults and providing new information concerning the tectonic and geologic regime of the Athens basin, the metropolis city of Greece. The good knowledge of the tectonic setting is important when we have to deal with earthquake damage since it is the determinant factor that controls it.

After the comparison of the isoseismal maps, produced by Tzitziras et al. (2000) and by Lekkas (2001), with the residual anomaly map that had been produced in this paper, great similarities came up. Specifically, we observed that the areas with the most damages, mapped out by the isoseismal contours, seem to be clearly adumbrated by the areas that have the lowest values in the Residual anomaly map (Figs. 7 & 8), produced after a gravity survey in the Athens basin.

This could mean that we might have one more scientific way to locate and define the most dangerous and susceptible to potential earthquake damage areas, especially in urban zones, where the collection of the necessary data is difficult. Subsequently, gravity studies could be taken into consideration in order to minimize future damage and deaths in urban environments. They could adumbrate zones of increased risk after an earthquake.

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