Case Study

The contribution of an urban gravity survey to the determinable perspective of Athens city (Greece) underground structure

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Abstract

An urban gravity survey with more than 1120 measurements was carried out in order to adumbrate the deeper subsurface of Athens city basin. The aim was to gather quantitative information of the subsurface structure derived from the acquisition of gravity measurements. At first, a gravity base network has been established for the data collection. The standard data reduction has been carried out along with an additional Building Correction that has been calculated due to the urban characteristics. Subsequently, the residual anomaly was isolated with the contribution of the Fourier filters. The Euler deconvolution has been applied, with two different techniques, providing depth solutions for the residual maps. Based on these maps, we managed to retrieve quantitative information for the depths of anomalous sources, ranging between 500 and 3760 m. Moreover, unconstrained three-dimensional density models of the area have been constructed in order to obtain a good image of the subsurface, up to depths of 4500 m. For each three-dimensional density model, we provide a couple of images; one illustrating only the structures of lower densities and one other only with the structures of higher densities, in an effort to delineate better the tectonic structures. Finally, two geophysical-geological profiles (2.75D) have been constructed, along which the geotectonic regime of the subsurface seems to be adumbrated in a better way. Major known tectonic structures of Athens basin have been identified beneath the surface.

Keywords 2.75D Interpretative sections · Three-dimensional density models · Euler deconvolution depths · Gravity bases · Urban gravity measurements

1 Introduction

The metropolis city of Greece is located in Athens basin, where 4 million people live and work. Taking into consideration the major damage caused by the devastating earthquake of 7th September 1999 ($M_w = 5.9R$), the need for further and deeper investigation of the geological structure of the subsurface came up. Especially in such urban and fully residentially developed areas, the knowledge on the existence of concealed active faults is absolutely valuable. The damage distribution of an earthquake is known to depend on the tectonic pattern of the area. A small problem arises due to the fact that the artificial

surfaces (buildings, roads, bridges etc.) dominate along Athens, making the geological research more difficult.

The geophysical methods can overcome this difficult situation by retrieving information for the deep subsurface. Taking into account the land cover data presented in Fig. 1, provided by CORINE 2012 project [28], the areas of artificial surfaces cover a 54.5% of our study area [21]. The land gravity survey seems the most suitable method for the deep geotectonic investigation. Gravity measurements have been applied widely the last few years contributing to the investigation of basin structure [20, 25, 26, 35, 41, 43, 63].

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Fig. 1 Simplified land cover map of the study area, based on CORINE 2012 data. An index map is also provided

One of the methods used in this paper is the Euler deconvolution, successfully applied in the past by other authors [18, 24, 31, 40, 59, 62, 63]. Practically, Euler methods are considered as derivatives method of first, second or even third order. The method uses three orthogonal gradients of the gravity field along with the field itself, in order to determine the location and the depth of the target. The obtained results provide us with the necessary information which will lead to the production of a set of maps, illustrating the locations and depths of the geologic sources of gravity anomalies that have been identified in grid-based gravity data. This information can help us understand better the seismotectonic structure of Athens basin.

In the context of outlining the basin subsurface structure, we will take advantage of the quantitative gravity interpretation and its three-dimensional density models that will be produced. Through their analysis, we can try to define some specific parameters, such as the location, depth, shape and density contrast of the geological bodies. Thus, gravity interpretation cannot be characterized by its uniqueness and absolute solution, due to its ambiguity problem, but any additional, data can constrain the quantification errors and limits. The real aim of the gravity inversion is to define model bodies that could realistically correspond to geological and tectonic structures.

This paper is structured in the following 4 sections. In Sect. 2 we provide detailed geological and tectonic information of the study area, which is essential for the final interpretation of the gravity results. In Sect. 3 all the steps of the gravity method are presented, beginning from the establishment of the gravity base network and the acquisition of the gravity data, then the data reduction procedures and finally the application of the Euler method, the production of the three-dimensional density models along with the 2.75D geological-gravity sections. In Sect. 4, a detailed presentation and discussion of the 2.75D geological-gravity sections is provided, in order to fully understand them. Finally, in Sect. 5 the results of the gravity survey and the geological interpretation are presented, along with the new insights for the area.

2 Geological and tectonic setting

The Athens basin covers an area of almost 360 km², bounded by the mountains *Hymettus* (East), *Parnitha* (North), *Penteli* (Northeastern) and *Aigaleo-Poikilo* (West). Its geology has been studied by many authors due to its complication [32, 44, 49, 51, 53, 55–57, 64, 67, 68, 75].

In Fig. 2, we provide a simplified geology regime of the area [21, 25] mostly based on this up-to-date geotectonic study by Papanikolaou et al. [67] but completed and combined with some of the existent studies where there was

no coverage. The geological regime is quite complicated. An autochthonous metamorphic geotectonic unit covers the eastern margin (*Penteli* and *Hymettus* Mountains), while an allochthonous unit ("*Ypopelagoniki*") structures the western margin (*Aigaleo* and *Poikilo* mountains). Finally, there are two more local allochthonous units, "*Alepovouni Unit*" and "*Athens Unit*".

The autochthonous metamorphic unit includes dolomites but also marbles and shales, as continuous overlaying layers. The "*Ypopelagoniki*" unit is comprised of the Triassic-Jurassic limestones and clastic formations from Paleozoic at its base. The "*Athens Unit*" has practically two main parts, the upper one with limestones and the lower one (known as "*Athens Schists*"), which is a geological mélange including shales, sandstones, phyllites, limestones and marls. The "*Alepovouni Unit*" consists of limestones in its upper part, while schists and phyllites appear in the base, because of its low metamorphism. It is located tectonically between the autochthonous metamorphic unit and the "*Athens*" one.

The biggest part of the basin is covered by the post-alpine geological formations, apart from the remaining hills in the center (*Tourkovounia*, *Filopappou*, *Lycabettus*, *Ardittou*, *Acropolis*, *Kokkou*), where the "*Athens Unit*" dominates. The research of Papanikolaou et al. [67] mentions more than ten different Quaternary and Neogene geological formations, which were unified in groups [21, 25] for a better handling. Because of their existence, it is difficult to understand with no doubt the geotectonic regime of the basin.

The alpine tectonic regime is controlled mainly by low-angle fault zones, known as part of the West Cycladic Detachment System [15, 33, 36, 50, 76, 77]. The *Alepovouni Unit* is delimited by two low-angle fault zones, one with the relative autochthonous underlying Metamorphic Unit dipping to Northwest. The tectonic contact between the *Alepovouni* and *Athens* Units is considered to be a major tensile detachment zone, where metamorphic formations adjust to unmetamorphic ones, leading to the rise of the metamorphic up to the surface [37, 38, 66, 86].

3 Gravity survey

3.1 Establishment of gravity bases and data acquisition

In the past, several authors (e.g., [8, 17, 23, 45, 46, 74, 80, 83], have discussed the establishment of absolute gravity bases networks, in several areas of the world, mostly for quite larger areas.

Taking into account the traffic jam of this over-populated metropolis and the increased time that we would

Fig. 2 Geological and tectonic map along with the locations of the gravity stations and gravity bases. The locations of the two interpretative geological-gravity profiles (sect. 3.5) are also illustrated

spend moving among the stations and the base re-measurements, we planned and established very cautiously a gravity base network [23], distributing spatially fourteen (14) gravity bases (Fig. 2-blue squares) in a way that would be less time-consuming for the base loops. Each established base (Table 1) was characterized by 3 engraved permanent marks on the ground for more enduring results. In that way, the re-measurements would always be at the exact same point. Detailed sketches and photographs of each gravity base and its surrounding stable structural characteristics (columns, balusters, stairs, walls, yards etc.) were kept. The established gravity base network is referred to the IGSN'71 datum [61] as it was tied to an existing base in the University of Athens [34].

Taking into consideration the complex geology of the area and the urban characteristics, we planned the gravity survey on a grid. Because of the urban character of the study area, the gravity grid had to be organized very carefully, taking advantage of high-accuracy space images. The station grid spacing had been set primarily to 1 km and then some stations had been added in between the first ones, in order to clarify the status of some ambiguous areas. All the campaigns were carried out during summer (2013–2015) in order to minimize the time consumed between the stations and the bases (reduced traffic jam). The gravity meter LaCoste & Romberg G-496 was used for the data acquisition, with an accuracy of ± 0.01 mGal. The gravity database is comprised of 1.122 gravity stations (Fig. 2).

In order to calculate the necessary coordinates of each gravity station and base with high precision, we used Differential Global Positioning System (dGPS), compiled by two different, dual-frequency *TopCon HiperPro* GPS

antennas. The *static* technique had been chosen, because of the long distances and the blur of the buildings. In this way, the achieved accuracy of the calculated coordinates was of the centimeter scale. The coordinates were calculated in the Hellenic Geodetic Reference System (EGSA'87).

3.2 Data processing and reduction

The data processing and reduction of the gravity measurements have already been presented and analyzed by the authors in the past [21, 25, 27] and for that reason we will present them briefly. The assumed constant density for the Bouguer correction was set up to 2.67 g/cm^3 , generally used by several other researchers in the broader area [13, 54, 65]. Therefore, the Simple Bouguer Anomaly has been calculated and has been presented by [25]. In order to calculate the necessary terrain correction up to a radius distance of 21 km, we took advantage of the *Gravity and Terrain Correction* extension of *Oasis Montaj* software. Due to the urban characteristics of the survey, we have calculated and added the Building Corrections [21, 27] caused by the gravitational attraction of the buildings and infrastructures of the city. The final construction of the Complete Bouguer Anomaly map has been presented and discussed thoroughly by [25].

Among the existing filtering processes, we chose to proceed to the regional-residual separation with the application of the Gaussian filter with a cutoff wavelength of 500 m that has been applied successfully in several other cases [4, 20, 22, 25, 30]). The separation of the regional and residual gravity fields was based on the information provided by the corresponding Power Spectrum Analysis [25]. Based on its results, two different depths of the

Table 1 Established gravity bases in Athens (Fig. 2) along with their determined absolute values

Gravity base name	Absolute gravity (mGal)	Maximum Deviation (mGal)	Easting (Egsa'87,m)	Northing (Egsa'87, m)	Elevation (m)
UoA_Office	980,010.75	± 0.00	480,948.310	4,201,848.100	252.000
UoA_Oulof	980,029.86	± 0.03	478,772.001	4,202,445.816	134.792
Rouf	980,049.35	± 0.04	473,639.680	4,202,590.600	20.239
Psychiko	980,017.27	± 0.03	480,288.710	4,206,831.900	179.091
Nea Smyrni	980,043.88	± 0.04	474,819.600	4,198,156.400	42.662
Peristeri	980,044.15	± 0.07	472,514.450	4,206,815.757	51.888
Dilaveri	980,052.98	± 0.08	469,013.766	4,200,694.898	7.536
Kifisia	979,991.51	± 0.04	483,373.599	4,212,901.998	287.379
Filadelfia	980,029.07	± 0.04	477,276.990	4,210,270.695	116.118
Elliniko	980,039.12	± 0.07	478,453.689	4,193,259.660	80.884
Acharnes	980,017.08	± 0.07	475,726.609	4,215,036.626	168.425
Ekali	979,981.33	± 0.07	485,997.896	4,217,756.564	344.891
Vrilissia	979,997.11	± 0.07	485,846.098	4,210,619.196	269.935
Dafni	980,031.44	± 0.05	468,050.208	4,206,980.671	109.281

anomaly sources seem to have been identified, at 2.06 km and 0.48 km depth. Subsequently, a residual map has been produced (cutoff wavelength 500 m) with standard deviation of 0.25 cycles/km (Figs. 4, 6) and a second residual map of the basement, with standard deviation of 0.02 cycles/km. The first one is mainly for the shallow structures, (Figs. 3, 5) while the second one ("basement residual") includes the anomaly sources and information from deeper structures of the bedrock.

3.3 Euler deconvolution

Although Euler deconvolution is mostly applied for the magnetics, it can sometimes be applied successfully for gravity data [39] as an approximation. The only difference is that the calculated depth solutions for the gravity method are located at a deeper level, closer to the center of the mass, in regard with the ones of magnetics.

The outcome of the Euler deconvolution here is a map, illustrating the locations and depths of the geologic sources of gravity anomalies that have been identified in grid-based gravity data, like in several other cases [18, 24, 31, 40, 59, 62, 63]. For the best results from Euler deconvolution, Reid et al. [72, 73] discuss the avoidable errors during its application to gravity data and how to determine suitably the required parameters (SI, window size, grid interval etc.). The grid cell of the processed data is important, since the minimum depths defined are about the same as the cell size.

One fundamental parameter for Euler deconvolution is the Structural Index (SI) value, which depends on the type of the source body, causing the gravity anomaly. In the context of this paper, we have calculated Euler depth solutions by using values equal to 0 (Figs. 3, 5) and 1 (Figs. 4, 6), since both are considered to be close to the fault/contact type that we want to delineate. Of course, the $SI = 0$ is estimated to appear almost the twice the uncertainty of the one for $SI = 1$, which appears depth uncertainty equal to 10% and horizontal one equal to 20%. Although several researchers have used non-integer values such as 0.5 for Structural Index [78, 81], we decided not to, based on the comments of Reid et al. [71, 73]. Additionally, Reid et al. [72, 73] propose that the SI equal to -1 is the appropriate value for finite contacts and faults in gravity surveys, but it has not been embedded as a possible value in most software and therefore we cannot test its results. The window size was set to 15×15 grid points, trying to compromise with all the conflicting requirements [72]. This means that it should be as small as possible but also greater than twice the acquired data grid spacing. Simultaneously, it should be greater than half the desired depth of investigation, which here is at least 2–3 km. Moreover, some eliminations of spurious

solutions were executed, by setting some acceptable parameters, such as the maximum acceptable distance (7500 m), the maximum depth tolerance (14%) and the maximum horizontal tolerance (35%).

The Euler deconvolution has been carried out with the *Euler3D* extension of *Oasis Montaj* software and more specifically with two different methods, the *Standard Euler* (Figs. 3, 4) and the *Located* one (Figs. 5, 6). The second one produces far fewer spurious solutions (Figs. 5, 6) since it is based only at the areas with existing anomalies (picks) in the analytic signal. The input grid data were the residual and the basement residual ones. The generated Euler depth solutions from both input data were merged and presented together in order to have a common image that would lead to an easier evaluation.

The produced solutions for the Structural Index zero (0) are located mainly around the main low-gravity spherical area (*Thrakomakedones, Kryoneri, Ekali, Nea Erythraia, Lykovrysi, Acharnes*) observed in the basement residual map, with depths mostly between 500 and 1500 m and some deeper (1500–2300 m) at the southwest corner. Moreover, we observe solutions of depths ranging from 500 to 1000 m along two linear areas. The first area is located at the western foothills of *Hymettus* Mountain, from *Anthousa* to *Kaisariani* and the second one is at the southern foothills of *Parnitha* Mountain, along *Agios Stefanos* and *Drosopigi*. Additionally, solutions for depths from 500 up to 1500 m are observed at the southern suburbs of Athens basin, along smaller areas, such as *Agios Ioannis Rentis-Moschatokallithea, Nea Smyrni-Agios Dimitrios, Kalamaki-Elliniko* and *Elliniko-Glyfada*. The solutions clusters are more extended and systematic in the Standard Euler technique, while the solutions in the Located Euler are constrained a lot. On the other hand, there are not large differentiates of depths and locations between the two methods.

For Structural Index equal to one (1), the number of the produced Euler solutions is quite higher (Figs. 4, 6), especially for the ones produced through the Standard Euler procedure. It seems that we have enough correlations between the locations of the solutions and possible or existing fault zones. For $SI = 1$, we can also observe great clusters of solutions around the margins of the main low-gravity area, similar to the $SI = 0$ ones. The calculated depths are bigger, reaching up the 3760 m, when the $SI = 0$ gave maximum depths up to 2300 m and quite restricted in swarm. Furthermore, the two linear areas of solutions, presented for $SI = 0$ (Figs. 3, 5), along the foothills of *Parnitha* and *Hymettus* Mountains, also appear with greater calculated depths (up to 3760 m for *Parnitha Mt* and up to 2000 m at *Hymettus Mt.*) and expanded in length. This means that the one is running along *Anthousa-Agia Paraskevi-Holargos-Kaisariani-Argyroupoli-Kalamaki* and the other along *Agios Stefanos-Drosopigi*. For the linear areas

Fig. 3 Standard Euler solutions (graduated symbols with depth) for SI=0 along with the Residual Map of Athens basin, illustrating the deeper bedrock anomaly sources

Fig. 5 Located Euler solutions (graduated symbols with depth) for SI=0 along with the Residual Map of Athens basin, illustrating the deeper bedrock anomaly sources

Fig. 6 Located Euler solutions (graduated symbols with depth) for SI=1 along with the Residual Map of basement, illustrating the shallow anomaly sources

located in the southern suburbs, we can also observe larger depths.

Beyond the clusters of solutions detected for both Structural Indexes 0 and 1, by setting $SI=1$ we observe new clusters of solutions, in other areas, located in the central and western part of the basin. More specifically, clusters of solutions for depths 500–1,000 m are spotted along the zone *Zefyri-Kamatero-Petroupoli-Haidari*, *Keratsini-Drapetsona-Piraeus*, *Agioi Anargyroi-Peristeri*, *Aigaleo-Votanikos-Downtown-Psychiko*, *Penteli* and *Hymettus Mt.* For bigger depths (1,000–2,000 m) along *Nea Penteli-Melissia-Marousi-Nea Erythraia*, *Agia Paraskevi-Halandri-Herakleion-Metamorfosi-Acharnes*, *Kryoneri-Agios Stefanos* and *Piraeus-Faliro-Moschato*. At the areas of *Fyli* and *Poikilo-Aigaleo* mountains, the depths of solutions range from 500 to 2,000 m.

3.4 Three-dimensional density models

The three-dimensional gravity modelling has been evolved rapidly during the last years [7, 9, 12, 14, 16, 19, 29, 58, 70, 82, 84]. Three-dimensional modelling of the gravity data provides us with information concerning the volume and geometry of the anomalous sources that cause gravity anomalies and can be a powerful tool for geological interpretation. The density model is constructed based on a mesh of blocks/cells of equal dimensions, specified from the beginning, each one characterized by a certain value of density or density contrast.

All the density inversions within the context of this paper have been carried out using the “VOXI” Earth modelling module [7, 29, 59, 85] of Oasis Montaj by Geosoft. They have been integrated with the defined densities of the geological formations, derived from the application of three different methods [21, 25]. Therefore, we managed to determine the density of all the formations, even of the ones compiled of different lithologies, such as the Neogene formations and the Athens Schists.

We applied the unconstrained three-dimensional gravity modelling on both Complete Bouguer Anomaly data and the Residual anomaly data in order to compare the results, based on the fact that for the Complete Bouguer Anomaly, a trend removal procedure has to be first applied. Insignificant differences derived, proving that the trend removal procedure is reliable. The inversion results were almost identical with those of the Residual data, where the regional field has already been removed with the FFT. The desired absolute error was 5%.

We discretized the subsurface in a three-dimensional block mesh, with blocks that have a cell size equal to 1000 m for X–Y and 500 m for Z direction (Fig. 7). Therefore, the subsurface area was divided in a total of 12,760 blocks of individual density contrast. The density contrast ranges from -0.32 g/cm^3 (bluish colors) to 0.669 g/cm^3 (reddish colors) for depths up to 6800 m (or else absolute elevation -5300 m). In Fig. 8, we provide an alternative pseudo-three-dimensional view based on the

Fig. 7. Three-dimensional gravity inversion of Athens basin, with cell size of 1000 m (mesh $40 \times 29 \times 11$ blocks). The area's DEM is presented as the upper plane and is the Residual Anomaly (0.02 cycles/km) as the lower one

Fig. 8 Depth slices of the three-dimensional gravity inversion model of Athens basin. The upper left plane illustrates the DEM of the area

depth slices [2, 3, 9, 60, 82] of the inversion model we have calculated for a better understanding of the subsurface density structure.

In Fig. 9, we have isolated the bodies with negative density contrast (ranging from -0.32 to -0.02 g/cm^3) at the areas of *Thrakomakedones*, *Kryoneri*, *Drosia*, *Kifisia*, *Melissia*, *Vrilissia*, *Halandri*, *Herakleion*, *Metamorfosi*, *Acharnes*, *Petroupoli*, *Agioi Anargyroi*, *Piraeus*, *Palaio Faliro* and *Kalamaki* producing the low gravity anomalies in the Residual maps (Figs. 3, 4, 5, 6). In Fig. 10, below the areas of Mountains *Hymettus*, *Aigaleo-Poikilo*, *Parnitha* and the downtown of Athens city, the bodies with positive density contrast (0.02 – 0.67 g/cm^3), producing the high gravity anomalies have been adumbrated. These bodies define the geometric boundaries of the anomalies, producing both low and high gravity values respectively. The DEM and the Residual maps have been positioned above the three-dimensional

model of the area for a better understanding and evaluation of the results.

Taking into consideration the anomalies already observed in the general model (Figs. 9, 10), additional inversions were carried out for smaller areas, in order to reduce the cell size down to 500 m (Figs. 11, 12, 13, 14) or even 250 m for the horizontal directions. This would provide greater detail of the final three-dimensional density model and consequently better adumbration of the geometry of the source bodies.

The results of the three-dimensional models (Figs. 7, 8, 9, 10, 11, 12, 13, 14) are quite impressive and revealed important subsurface structures that might play important role for the seismotectonic structure of Athens basin. Several fault zones already mapped are verified by these models and more information about their characteristics might be gained (e.g., throw, depth and

Fig. 9. Three-dimensional gravity inversion results (cell size 1000 m), illustrating the structures of low densities (density contrast from -0.32 to -0.02 g/cm³)

Fig. 10. Three-dimensional gravity inversion results (cell size 1000 m), illustrating the structures of high densities (density contrasts from 0.02 to 0.67 g/cm³)

dip). But the most significant contribution of the three-dimensional density models is that they also validate the existence of several fault zones mapped as possible (blind faults), based on other criteria.

3.5 2.75D geological-gravity modelling

Interpretative geological-gravity profiles have been constructed, with the contribution of GM-SYS [1, 6, 10,

Fig. 11. Three-dimensional gravity model (cell size 500 m, mesh $42 \times 45 \times 17$ blocks), showing structures of low densities (density contrast from -0.24 to -0.02 g/cm³) in the area of *Thrakomakedones*, *Acharnes*, *Metamorfofi*, *Acharnes* and *Petroupoli*

Fig. 12. Three-dimensional gravity model (cell size 500 m, mesh $42 \times 45 \times 17$ blocks), showing structures of high densities (density contrast from 0.02 to 0.41 g/cm³) in the area of *Thrakomakedones*, *Acharnes*, *Metamorfofi*, *Acharnes* and *Petroupoli*

11, 25, 26, 42, 48, 69, 79, 85]. It is a program by *Geosoft* for calculating the gravity response from a geological cross-section, compared to the observed field anomaly response. The models in GM-SYS are built with polygons

that represent different geological formations and a density value is assigned at each one. The 2.75D models can have two-dimensional prisms asymmetrically positioned

Fig. 13. Three-dimensional gravity model (cell size 500 m, mesh $44 \times 46 \times 13$ blocks), showing structures of low densities (density contrast from -0.26 to -0.02 g/cm^3) in the area of Haidari, Peristeri, Athens and Hymettus Mt

Fig. 14. Three-dimensional gravity model (cell size 500 m, mesh $44 \times 46 \times 13$ blocks), showing structures of high densities (density contrast from 0.02 to 0.49 g/cm^3) in the area of Haidari, Peristeri, Athens and Hymettus Mt

and extended at some distance from the line of the profile, in the strike direction.

In Fig. 2, the location of the profiles along the Athens basin, selected to create the interpretative geological-density 2.75-D models, is presented. Two (2) sections have been constructed (Fig. 15) in order to contribute to the adumbration of the tectonic framework of the Athens basin subsurface. The density values assigned to each block/prism are based on the values proposed by Dilalos

[21] and Dilalos et al. [25]. In each of these figures, the upper part illustrates the observed residual gravity data (squares) along with the calculated one (line) based on the geological model, which is illustrated on the lower part of the figures. Each block colored differently, simulates a geological body, with a certain density quoted in the brackets. The sections are presented with a scale 1:2, therefore, there is a vertical exaggeration for better presentation and understanding.

Fig. 15 Interpretative geological 2.75-D profiles (scale 1:2). The observed (squares) and calculated (line) residual anomaly are illustrated. The geological formations are: T-J: Triassic-Jurassic Limestones (*Ypopelagoniki Unit*), C-P: Shales and Sandstones alterations (*Ypopelagoniki Unit*), M: Marbles (*Metamorphic Unit*), Sch: Schists (*Metamorphic Unit*), D: Dolomites (*Metamorphic Unit*), Sch-Vari: Varis

Schists (*Metamorphic Unit*), SchA: Athens Schists (*Athens Unit*); CA: Limestones (*Athens Unit*), Sch-Al: Schists (*Alepovouni Unit*), CAL: Limestones (*Alepovouni Unit*), Msl: Upper Miocene Terrestrial and Lacustrine deposits (*Neogene Formations*), Pt.sc: Pleistocene Talus and Scree, Al: Alluvium deposits (*Loose Quaternary deposits*)

4 Discussion

In Section CC' (Fig. 15), the Neogene deposits (*Msl*) are observed with thickness, up to 150 m and lateral coverage below the areas of *Agios Ioannis Rentis* and *Tavros*, producing the low residual values (down to -1 mGal). There is also a layer of 40–50 m of Alluvium deposits (*Al*) and Pleistocene Talus and Scree (*Pt.sc*), overlying. Between the areas of *Korydallos* and *Tavros*, a few neotectonic fault zones have been discovered beneath the Neogene deposits and their underlying formation of Athens Schists.

A great part of the subsurface, beneath the Neogene deposits, is covered by the Athens Schists (*SchA*) and the Schists of Alepovouni Unit (*Sch-Al*), with a maximum thickness of 300 and 155 m correspondingly. Furthermore, the Dolomites (*D*) of the *Metamorphic Unit* seem to dominate at the lower area below the basin (from depths of 350 m) and the *Hymettus Mountain*, with thickness that reaches 950 m. The Marbles (*M*) are also detected below *Hymettus Mountain*, while the Schists (*Sch*) have been restrained to a thin layer of a few meters. A structure similar to the one of extension-parallel folds [5, 47, 52] seems to appear

among the formation of the *Metamorphic Unit*. The formation of Varis Schists (*Sch Vari*) is also illustrated underlying the Dolomites (*D*) at the end of the section.

In Section EE' (Fig. 15), the Neogene deposits are observed below the areas of *Piraeus (Plm)* and *Marousi (Pl)*, with thickness, up to 250 and 200 m correspondingly, producing the low values in the residual gravity field (down to -4.8 mGal). At the area of *Piraeus* and *Neo Faliro* a couple of neotectonic fault zones have been revealed at the basement of the post-alpine deposits. There is also a layer of 40–50 m of Alluvium deposits (*Al*) partially overlying the *Plm* sediments at *Piraeus* area. The first part of the section is dominated by the existence of the Triassic–Jurassic Limestones (*T–J*). The Athens Schists (*SchA*), with great surface exposure (outcrops), also cover a great part of the subsurface, with maximum thickness up to 600 m, mostly below the central area of the basin. The Schists of *Alepovouni Unit (Sch–Al)* have been determined with a thin layer of maximum thickness of 200 m, below the Athens Schists. At the central area of the profile (from depths of 300 m) and below the *Penteli Mountain*, the Dolomites (*D*) of the *Metamorphic Unit* seem to dominate, with thickness that reaches 750 m. The Schists (*Sch*) seem to dominate against the Marbles (*M*) below *Penteli Mountain*, since they appear with thicknesses up to 1,750 and 100 m correspondingly.

There are some common major fault zones that have been delineated along both sections. The West Cycladic Detachment System [15, 33, 36, 50, 76, 77] seems to have been identified, along which the underlying metamorphosed *Metamorphic Unit* is moving upward relatively to the overlying tectonic units of *Ypopelagoniki*, *Athens* and *Alepovouni*. The schists of *Alepovouni Unit (Sch–Al)* or the Athens Schists (*SchA*) are mostly located overlying. The dolomites (*D*), schists (*Sch*) or even the marbles (*M*) of the *Metamorphic Unit* are located underlying. Furthermore, three to four upthrusts between the Triassic–Jurassic limestones (*T–J*) and the Shales and Sandstones alterations (*C–P*) seem to have been recognized. Beyond that, a thrust fault with the Athens Schists (*SchA*) of the *Athens Unit* overlying tectonically on the *Ypopelagoniki Unit* can also be observed along both sections.

5 Conclusions

In this paper, the quantitative results of an urban gravity survey of Athens city basin have been presented. More specifically, a total of 1120 gravity measurements were acquired, based on a grid plan and supported by a newly established gravity base network. Due to the difficulties raised from the urban characteristics of the area, the acquisition planning was organized very carefully. Beyond that, during the standard reduction processing,

an additional Building Correction has been added in order to remove the gravitational effect of the buildings on the measurements.

The next step involves the application of the Euler deconvolution in order to calculate depth solutions for the residual maps of the area. Two different techniques have been applied, the *Standard Euler* and the *Located* one but also two different Structural Indexes (0 and 1). At first, it seems that the *Standard Euler* method (Figs. 3, 4) provides better results and far more solutions than the *Located* one (Figs. 5, 6). On the other hand, the Structural Index 0 (Figs. 3, 5) produces less solutions than the Structural Index 1 (Figs. 4, 6). Additionally, the Euler deconvolution depth solutions (Figs. 3, 4, 5, 6), for both selected Structural Indexes (0 and 1) and for both applied Euler deconvolution methods (*Standard* and *Located*), seem to have great similarities to the structural maps presented by Dilalos [21] and Dilalos et al. [25]. The calculated depths are ranging close to the source depths that have been estimated by the Energy Spectrum Analysis, except for some solutions of $SI = 1$ that reach greater depths. Based on these maps, we managed to retrieve quantitative information for the depths of anomalous sources, ranging between 500 and 3760 m.

Furthermore, the unconstrained three-dimensional density model of the area has been constructed (Figs. 7, 8) in order to obtain a good image of the density distribution of the subsurface. The model information reaches the depth of 4500 m, which is considered quite important for the area. For a better understanding of the three-dimensional density distribution and in an effort to delineate better the tectonic structures, we selected to present it in two separate images; one illustrating only the structures of lower densities and one other only with the structures of higher densities (Figs. 9, 10, 11, 12, 13, 14). Figures 9, 10 present the whole study area, while Figs. 11, 12, 13, 14 present two focused areas in detail.

Finally, two geophysical-geological profiles (Fig. 15) have been constructed and presented. Practically, along with these two sections we present the geological interpretation of the gravity survey, providing valuable new information for the geotectonic regime of the subsurface. Along with these sections several geotectonic structures have been adumbrated, such as neotectonics fault zones, upthrusts, thrust fault, extension-parallel folds and a structure evaluated as the West Cycladic Detachment System. Beyond these, the thickness of several geological formations has also been estimated. For example, the Neogene deposits appear with 250 m maximum thickness, the Athens Schists (*SchA*) with 600 m and the schists of *Alepovouni Unit (Sch–Al)* with 200 m. Additionally, the Dolomites (*D*) and the Schists (*Sch*) appear with thickness 950 and 1750 m correspondingly.

The 2.75D interpretative profiles and the three-dimensional density models revealed important subsurface structures for the geotectonic structure of Athens basin subsurface, for depths up to 2500 m. Several fault zones already mapped are verified by these models [21, 25] and more information about their characteristics might be gained (e.g., throw, depth and dip). But the most significant contribution is that, along with the Euler deconvolution depths, they also validate the existence of several fault zones mapped as possible (blind faults), based on other criteria. The three-dimensional density models (Figs. 7, 8, 9, 10, 11, 12, 13, 14) define in a good way the geometry of the identified anomaly bodies and therefore the geometry of the subsurface geology.

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Data availability Data will be made available on request.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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