We_INFRA_P23

Quantitative Subsurface Information of Athens Basin (Greece) Derived from Urban Gravity Measurements

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Summary

A disastrous earthquake of the past (7th September 1999) was the reason for acquiring 1.122 urban gravity measurements in order to investigate and model the deeper subsurface of Athens city basin. The aim was to gather any additional quantitative subsurface information based on the gravity survey, such as the density distribution provided by the 3D density models and depths of potential anomaly sources. The standard corrections have been applied (drift, tide, latitude, free-air, Bouguer, terrain ones) along with an additional Building Correction that was calculated based on the urban characteristics. The isolation of the residual anomaly has been accomplished with the contribution of the Fourier filters and power spectrum analysis. The Euler deconvolution has been used in order to calculate the depth solutions of anomalous sources, based on the residual maps. These solutions seem to identify with several fault zones. Some of these zones have already been mapped or proposed (covered ones) but additionally some new zones have been revealed. The 3D density model of the area provides information about the geometry of the subsurface geological bodies that can also be related to the tectonic structures of Athens basin beneath the surface.

Introduction

Athens is the capital of Greece, with almost 4 million residents. A disastrous earthquake on 7th September 1999 (5.9R) caused enormous damage and great casualties. Therefore, the need for further and deeper investigation of the geological structure of the subsurface came up. Unfortunately, since the areas are covered with artificial surfaces, such as buildings, industrial infrastructures, roads, bridges and generally artificial surfaces, the geological research is quite complicated. New information for the subsurface setting can be retrieved by geophysical methods but given the fact that the 54.5% of Athens basin is covered with artificial surfaces (Dilalos, 2018), not all the geophysical methods can be applied. In the context of a quantitative gravity interpretation, we shall try to determine some specific parameters for the subsurface geological bodies, such as their location, depth, shape and density contrast through the Euler deconvolution and 3D density modeling.

Geological and tectonic setting

The autochthonous metamorphic unit is compiled mainly of dolomites, marbles and shales. 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 one which is basically limestones and the lower one, called "*Athens Schists*" which is basically a geological mélange that consists of sandstones, shales, phyllites, limestones and marls. The "*Alepovouni"*, located tectonically between the autochthonous metamorphic unit and the "*Athens"* unit, consists of limestones (upper part) and additionally schists and phyllites in the base, because of its low metamorphism.

Data acquisition and processing

The gravity measurements were planned on a grid with a station grid spacing set primarily to 1km. Some denser stations had been added among the first ones, in order to clarify the status of some ambiguous areas. The gravity database is comprised of 1.122 gravity stations, which were collected during summers (2013-2015) in order to minimize the loops time (reduced traffic jam). The gravity meter LaCoste & Romberg G-496 was used for the gravity data acquisition along with a Differential Global Positioning System (dGPS) for the accurate determination of their coordinates. The coordinates were calculated in the Hellenic Geodetic Reference System (EGSA'87).

The data reduction (drift, tide, latitude, free-air and Bouguer corrections) was carried out with the *Oasis Montaj* software. The assumed constant density for the Bouguer correction was set up to 2.67gr/cm^3., We took advantage of a Digital Elevation Model (DEM) and the *Gravity and Terrain Correction* extension of *Oasis Montaj* in order to calculate the necessary terrain correction. An inner radius equal to 1.500 meters had been set, along with an outer radius distance equal to 21 kilometers. Normally, with the aim of calculating the Complete Bouguer Anomaly only the Terrain corrections need to be added to the Simple Bouguer Anomaly. However, in this urban geophysical survey, we have calculated and added the necessary Building Corrections (Dilalos, 2018; Dilalos *et al.,* 2018), caused by the gravitational attraction of the buildings and infrastructures of the city.

The regional-residual separation was accomplished through Fourier analysis and Filtering, carried out with the contribution of Oasis Montaj software and the *MAGMAP* extension, since the measurements were executed on a grid plan. The separation of the regional and residual gravity fields was based on the information provided by the corresponding Power Spectrum Analysis (Dilalos, 2018) of the Complete Bouguer data, a common procedure executed before the Fourier filtering (Fernandez-Cordoba *et al*., 2017; Gabtni & Jallouli, 2017). The application of the Gaussian filter (Damaceno *et al*., 2017; Dilalos & Alexopoulos, 2017; Fernandez-Cordoba *et al*., 2017) has been chosen. Based on the results of the power spectrum, we produced a residual map with a cutoff wavelength of 500m and standard deviation equal to 0.25 cycles/km mainly for the shallow structures. Beyond that, a second residual map of the basement, with standard deviation equal to 0.02 cycles/km, was produced, including the anomaly sources and information from deeper structures.

Euler Deconvolution

The determination of the appropriate parameters (SI, window size, grid interval etc.) was based on Reid *et al.* (2014). In the context of this paper, we have calculated Euler depth solutions by using Structural Index (SI) values equal to 0 (Fig. 1) and 1 (Fig. 2), since both are considered to be close to the fault/contact type that we want to delineate. The window size was set to 15x15 grid points. The Standard Euler deconvolution has been carried out with the *Euler3D* extension of *Oasis Montaj* software based on data from the two residual maps (shallow and deeper structures). The generated Euler depth solutions were merged and presented together (Figs. 1-2).

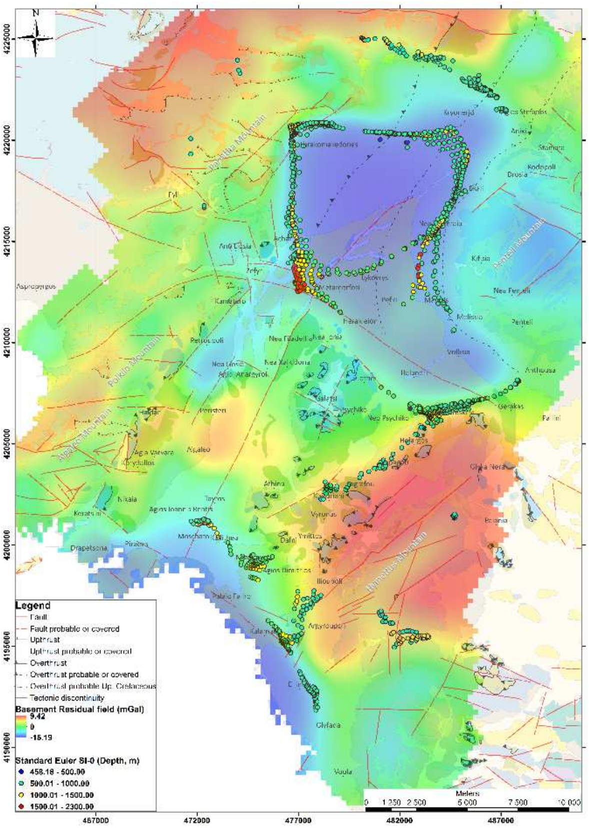

Figure 1. *Standard Euler solutions (graduated symbols with depth) for SI=0 on the basement residual map.*

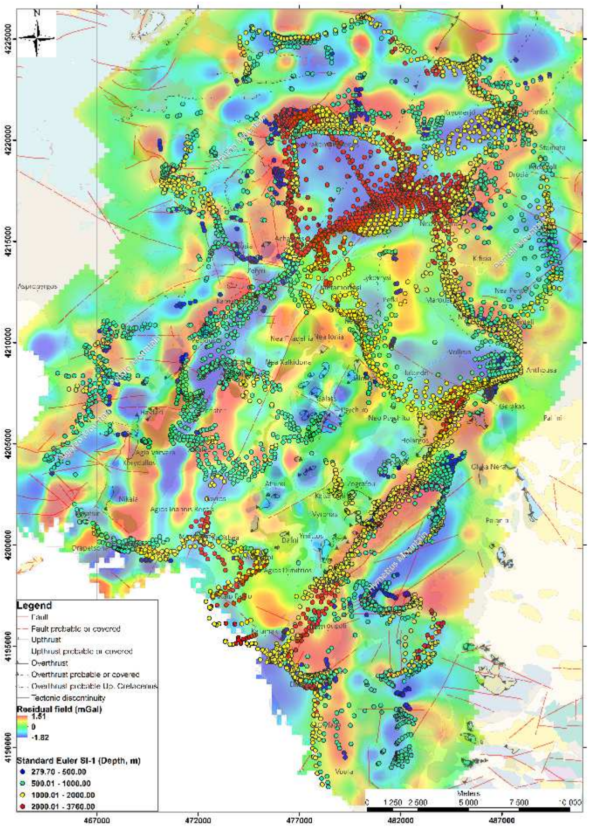

Figure 2*. Standard Euler solutions (graduated symbols with depth) for SI=1 on the residual map.*

The produced solutions for the Structural Index zero (0) are located mainly around the main low-gravity spherical area observed in the basement residual map (Fig. 1), with depths mostly between 500 and 1,500 meters and some deeper (1,500-2,300m) at the southwest corner. Moreover, we observe solutions of depths ranging from 500 to 1,000 meters along two linear areas, the one located at the western foothills of *Hymettus* Mountain and the second one at the southern foothills of *Parnitha* Mountain. Additionally, solutions for depths from 500 up to 1,500 meters are observed at the southern suburbs of Athens basin, along smaller areas. On the other hand, for Structural Index equal to one (1), the number of the produced Euler solutions is quite higher (Fig. 2). It seems that we have enough correlations among the locations of the solutions and possible or existing fault zones. 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 3,760 meters, when the SI=0 gave maximum depths up to 2,300 meters and quite restricted in swarm. Furthermore, the two linear areas of solutions, presented for SI=0, along the foothills of *Hymettus* and *Parnitha* Mountains, also appear with bigger calculated depths (up to 2,000m and 3,760m correspondingly). For the linear areas located in the southern suburbs, we can also observe larger depths. By setting SI=1 we observe new clusters of solutions, in other areas, located in the central and western part of the basin, with determined depths of 500-2,000 meters.

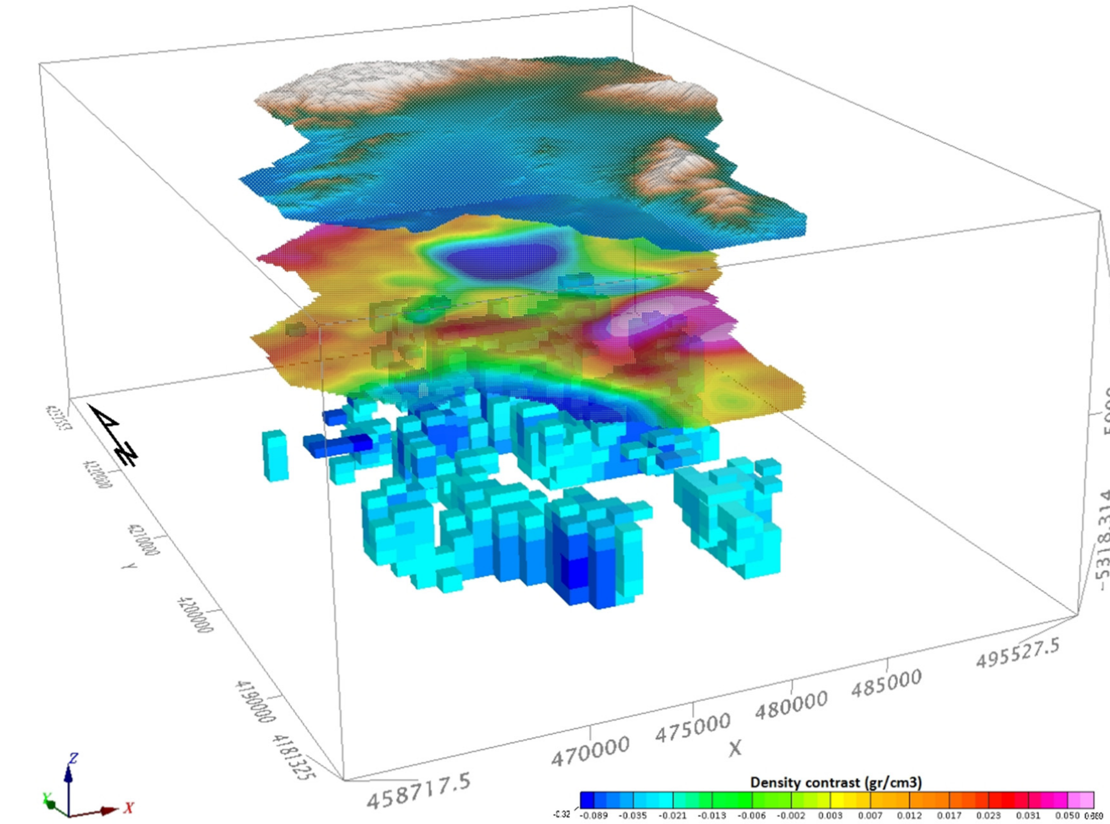

Figure 3. *3D gravity inversion (cell size 1000m, mesh 29x40x11 blocks), showing structures of low densities (density contrast from -0.32 to -0.02 gr/cm3).*

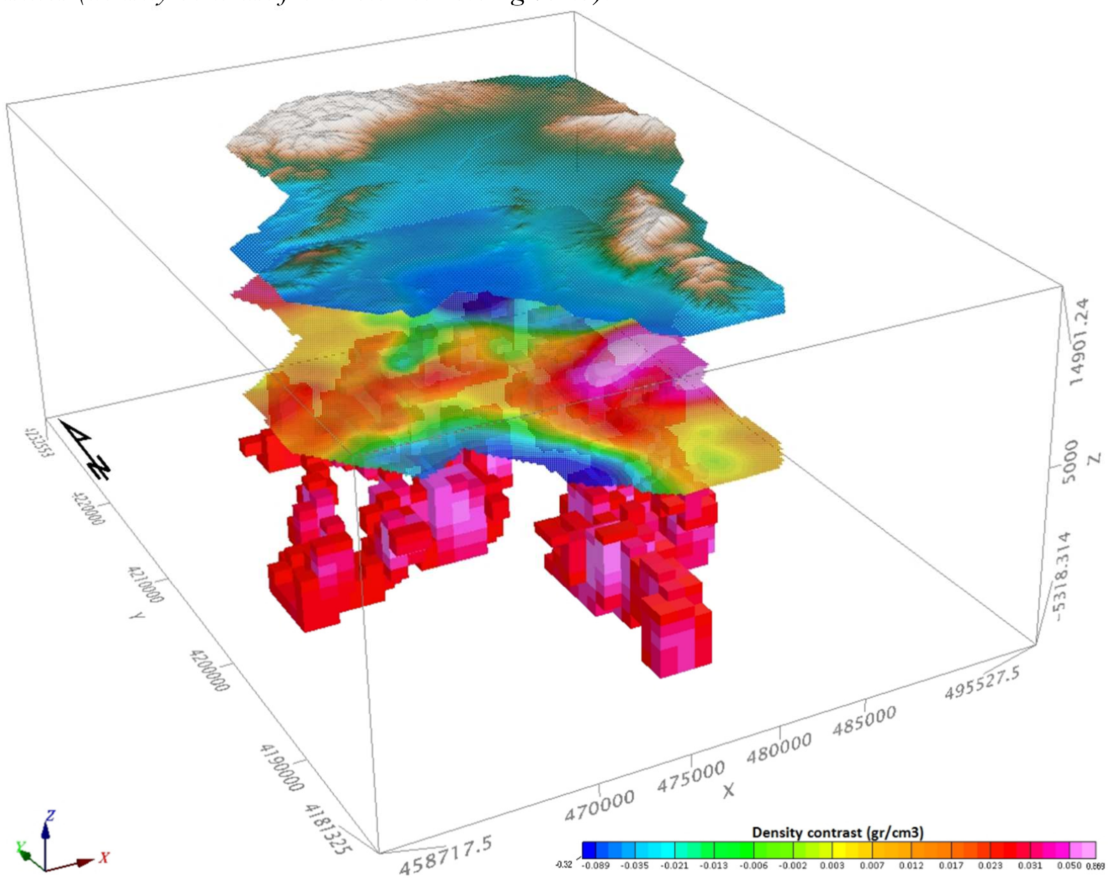

Figure 4. *3D gravity inversion (cell size 1000m, mesh 29x40x11 blocks), showing structures of low densities (density contrasts from 0.02 to 0.67 gr/cm3).*

3D density models

We applied a geologically unconstrained 3D gravity modelling on Complete Bouguer Anomaly data. The subsurface was first discretized in a 3D block mesh, where all blocks have a cell size equal to 1000 meters for X-Y and 500 meters for Z direction (Figs. 2-3). Practically, the produced block mesh is constituted by a total of 12,760 blocks of individual density contrast. The density contrast ranges from -0.32 gr/cm^3 (bluish colors) to 0.669 gr/cm^3 (reddish colors), with a maximum depth of almost 6,800 meters (absolute elevation -5,300m).
In Figure 2, we have isolated the bodies with negative density contrast (ranging from -0.32 to -0.02 gr/cm^3) at the central area, producing the low gravity anomalies in the Residual maps. On the other hand, in Figure 3, the bodies with positive density contrast (0.02-0.67 gr/cm^3), producing the high gravity anomalies, have been adumbrated below the areas of Mountains *Hymettus*, *Aigaleo-Poikilo*, *Parnitha* and the *downtown* of Athens city. These bodies define the geometric boundaries of the anomalies sources, producing both low and high gravity values respectively. The DEM and the Residual maps have been positioned above the 3D model of the area for a better understanding and evaluation of the results.

Results

The results of the 3D models revealed the subsurface density structure that combined with the depth information determined from the Euler deconvolution provide valuable information that could help understand better the seismotectonic structure of Athens basin. Several fault zones already mapped can be verified by these models but also new ones can be proposed. Beyond that, based on this gravity information it seems that we can validate the existence of several fault zones mapped by other scientists as possible (blind faults). The 3D density models (Figs. 3-4) define in a good way the geometry of the identified anomaly bodies and therefore the geometry of the subsurface geology.

Acknowledgments

The fieldwork was partially supported by the SARG-NKUA (contract no. 70/4/9254). The authors would also like to thank Ms. Achtypi S., Ms. Kaplanidi H., Mr. Papaelias S., Mr. Mavroulis S., Mr. Michelioudakis D.and Ms. Drosopoulou E. for their valuable contribution to the field measurements.

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