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3D Gravity Inversion by Growing Bodies and Shaping Layers at Mt. Vesuvius (Southern Italy)

GIOVANNA BERRINO,[1] and ANTONIO G. CAMACHO[2]

Abstract—To improve our knowledge of the structural pattern of Mt. Vesuvius and its magmatic system, which represents one of the three volcanoes located in the Neapolitan area (together with Campi Flegrei and Ischia; southern Italy), we analyze here the Bouguer gravity map that is already available through its interpretation by means of 2.5-dimensional modelling. We have carried out a three-dimensional interpretation using a new and original algorithm, known as 'Layers', that has been especially processed for this purpose. Layers works in an automatic and non-subjective way, and allows the definition of the structural settings in terms of several layers, each representing a specific geological formation. The same data are also interpreted in terms of isolated and shallow anomalous density bodies using a well tested algorithm known as 'Growth'. We focus our inversions on the Mt. Vesuvius volcano, while globally analyzing the entire Neapolitan area, in order to investigate the deep structures, and in particular the deep extended 'sill' that has been revealed by seismic tomography.

The final models generally confirm the global setting of the area as outlined by previous investigations, mainly for the shape and depth of the carbonate basement below Mt. Vesuvius. The presence of lateral density contrasts inside the volcano edifice is also shown, which was only hypothesized in the 2.5-dimensional inversion. Moreover, the models allow us to note a high density body that rises from the top of the carbonate basement and further elongates above sea level. This probably represents an uprising of the same basement, which is just below the volcano and which coincides with the V_P and V_P/V_S anomalies detected under the crater. The three-dimensional results also reveal that the two inversion methods provide very similar models, where the high density isolated body in the Growth model can be associated with the rising high density anomaly in the Layers model. Taking into account the density of these modelled bodies, we would also suggest that they represent solidified magma bodies, as suggested by other studies. Finally, we did not clearly detect any deep anomalous body that can be associated with the sill that was suggested by seismic tomography.

Key words: Gravity, Bouguer anomaly, Mt. Vesuvius, three-dimensional inversion, model exploration, algorithms.

1. Introduction

As already well known, the gravity method is a powerful tool for the exploration of the subsoil. It is largely applied to understand volcanic activity too, and it can also be

[1] Istituto Nazionale di Geofisica e Vulcanologia, sezione di Napoli 'Osservatorio Vesuviano', Via Diocleziano 328, 80124 Napoli, Italy. E-mail: berrino@ov.ingv.it

[2] Instituto de Astronomía y Geodesia (CSIC-UCM), Plaza Ciencias 3, 28040 Madrid, Spain.

applied to volcanic areas where knowledge of the structural setting is helpful for the outlining of routes of probable magma uprisings. This is the case for Mt. Vesuvius.

Together with Campi Flegrei and Ischia, Mt. Vesuvius is one of the three active volcanoes that are located in the Neapolitan area (southern Italy; Fig. 1). These Neapolitan volcanoes lie within the Campanian Plain, a graben that is bordered by a Mesozoic carbonate platform that stretches from Mt. Massico, deepens to more than 3 km in its central part, and then re-emerges in the Sorrento Peninsula. The Campanian Plain is bordered on the NE by NW-SE-trending faults, and on the S and the N by a horst that is limited by NE-SW trending faults. This important graben is filled with volcanic deposits and continental and marine clastic deposits (Balducci *et al.*, 1985). The buried geometry of the carbonatic basement has been outlined through gravity data on land (Oliveri Del Castillo, 1966; Carrara *et al.*, 1973; Cameli *et al.*, 1975; Luongo *et al.*,

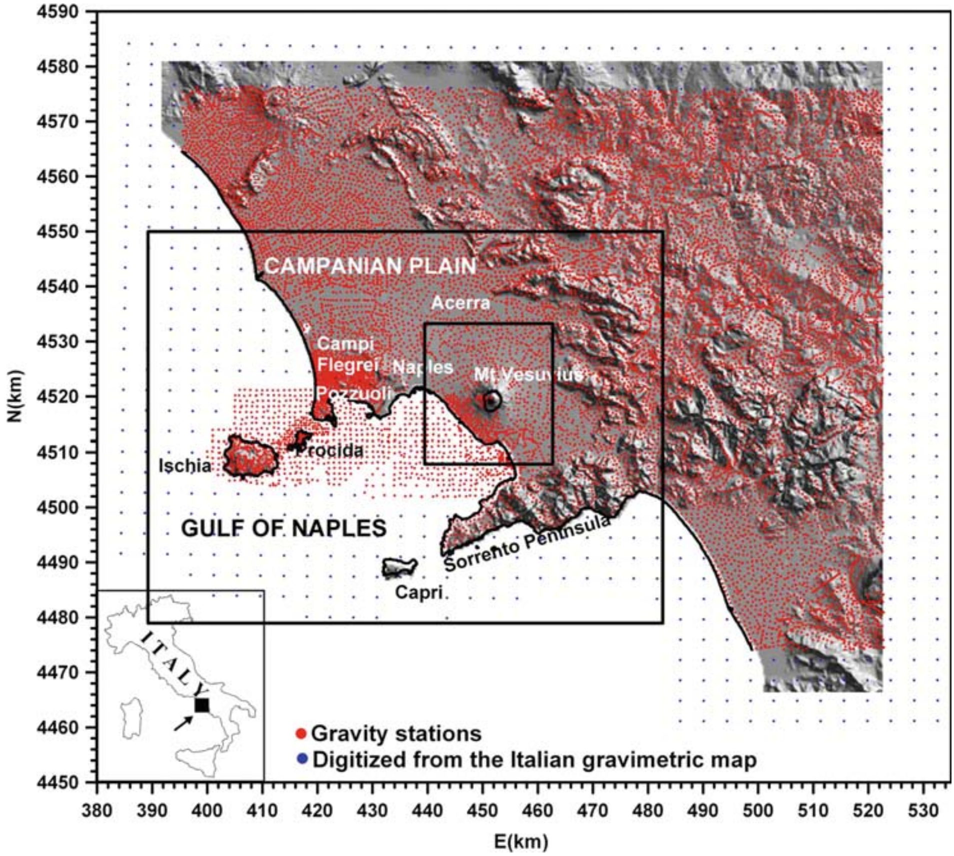

Figure 1
Distribution of the gravity stations (red points). The blue points indicate the values digitized on the Italian Gravity Map (Carrozzo *et al.*, 1986; see text for details). The two black rectangles show the two 3D inversion areas (see text for details).

1988; FERRI *et al.*, 1990; CUBELLIS *et al.*, 1995). Many studies have suggested that the main feature of the central part of the Campanian Plain is a structural depression, known as the 'Acerra depression' (BARBERI *et al.*, 1978; SANTACROCE, 1987). Another important depression, known as the 'Pompei graben', was detected by CASSANO and LA TORRE (1987).

Mt. Vesuvius is a strato-volcano that lies about 15 km southeast of Naples, and it consists of an older structure (Mt. Somma) with a nested younger structure (Mt. Vesuvius). It is located on a NE-SW trending fault that borders the southeastern edge of the Acerra depression (MARZOCCHI *et al.*, 1993), and it lies on a sedimentary basement. Gravimetry on land (CASSANO and LA TORRE, 1987) and seismic profiles at sea (FINETTI and MORELLI, 1974; FINETTI and DEL BEN, 1986) have shown that this fault displaced the more recent formations. Information about the sedimentary basement below Mt. Vesuvius has been provided by the deep geothermal Trecase well that intercepts the limestone layer at about 1,700 m below sea level (b.s.l.) (BALDUCCI *et al.*, 1985). Moreover, the inversion of both on-land and off-shore gravity data has suggested that the sedimentary basement is 11 km thick, with the top at a depth of 2 km (BERRINO *et al.*, 1998). This was confirmed by a joint seismic tomographic inversion of first P-wave arrivals along several profiles intersecting the crater, and from gravity data that provided a clear image of the continuous structure of the Mesozoic carbonate basement top as well as of a conduit structure 5 km wide that extends from the surface to the maximum depth of the model (6 km) (TONDI and DE FRANCO, 2003, 2006). No significant evidence has been seen for the existence of a shallow magma chamber embedded in the basement (ROSI *et al.*, 1987; CORTINI and SCANDONE, 1982).

A recent seismic tomography study was carried out to define the evidence within the Vesuvius magmatic system of an extended (at least 400 km^2) low-velocity layer at about 8 km in depth, which would represent an extended sill with magma interspersed in a solid matrix (AUGER *et al.*, 2001). This body was also modelled by new isotopic data (CIVETTA *et al.*, 2004) and by a new inversion of P-wave and S-wave arrival times for local earthquakes, highlighting a lower V_s velocity below the Mt. Vesuvius cone in a 0.35-km-thick layer (NUNZIATA *et al.*, 2006). Moreover, a joint inversion of P-wave and S-wave arrival times (from local earthquakes) and shot data collected during the TOMOVES 1994 and 1996 experiments showed the presence of a high V_p and V_p/V_s anomaly that is located around the crater axis, between 0 km and 5 km in depth, which involves the volcano edifice and the carbonate basement. This anomaly has been interpreted in terms of magma quenching along the main conduit, because of the exsolution of magmatic volatiles (DE NATALE *et al.*, 2004).

To improve our knowledge of the structural pattern of Mt. Vesuvius and its magmatic system, we analyze here the Bouguer gravity map that is already available through its interpretion by means of 2.5-dimensional (2.5-D) modelling (BERRINO *et al.*, 1998). We have carried out a 3D interpretation using a new and original algorithm that was specifically realized for this study and that starts from a known algorithm (CAMACHO *et al.*, 2000, 2002). We have focused our inversions on the Mt.Vesuvius volcano, although we also globally analyze the entire Neapolitan area to investigate the deep structures, and particularly that known as the 'sill' that was revealed by a seismic tomography study carried out by AUGER *et al.* (2001).

A description of this first version of the new algorithm is given, together with the results obtained.

2. *Gravity Data and Previous Interpretations*

Here we use a Bouguer anomaly map that consists of both on-land and off-shore gravity data. To complete the existing gravity map that was limited to on-land data, a sea-gravity survey was carried out in the Gulf of Naples during five cruises that lasted from 1988 to 1994 (BERRINO *et al.*, 1991, 1998), whereby 850 off-shore points where measured. In this way the Bouguer map was created, and it provides a global set of 2,876 gravity values (BERRINO *et al.*, 1998, 2008). All of the data have been made uniform and globally re-analyzed through the referencing of the gravity values to a new absolute gravity station set up in Naples in 1986 (BERRINO, 1995), which also belongs to the new Italian 'Zero Order' Gravity Net (BERRINO et al., 1995). Later, in the framework of a cooperation in the TOMOVES Project (ACHAUER *et al.*, 1999, 2000), additional gravity data became available for the whole Campanian Plain (provided by P. Capuano). These data were collected and combined with the previous dataset, such that after an additional revision and data cleaning (SCALA, 2002), a new gravity dataset of 17,225 gravity values was obtained, as shown as red points in Figure 1. In this case too the updated dataset was recomputed and linked to the absolute gravity station in Naples. The detailed references relating to the available on-land gravity data and the information as to how the offshore gravity data were collected, integrated with the on-land data and globally analyzed, as well as the information about the interpretation of some of the previous geophysical investigations, are all given in BERRINO *et al.* (1998, 2008).

Two Bouguer gravity maps were obtained with reference to the 1980 Ellipsoid (MORITZ, 1984), using the density values of 2,200 kg/m^3 and 2,400 kg/m^3, to calculate the Bouguer and terrain effects. The first of these values is more suitable for volcanic areas (BERRINO *et al.*, 1998), while 2,400 kg/m^3 is more appropriate for the global interpretation of the whole Campanian Plain (SCALA, 2002). Moreover, this second case allowed the area investigated to be enlarged through the addition of a border about 10 km larger, which was obtained by digitizing 517 anomaly values (Fig. 1, blue points) from the Italian Bouguer gravity map (CARROZZO et al., 1986).

Detailed descriptions of the Bouguer gravity maps are given in BERRINO *et al.* (1998, 2008) and SCALA (2002). However, their main features can be summarized as follows: A strip of maximum gradient runs almost parallel to the Sorrento peninsula, turns towards the southwest at the southern sector of Somma-Vesuvius, and ends in the southern part of the Gulf of Pozzuoli, in a broad gravity minimum. The Somma-Vesuvius and Campi Flegrei volcanoes are settled at the southern edge of the large gravity minimum, to the north of Naples. A well defined gravity minimum that spans Campi Flegrei is evident. Strong gradients border the Island of Ischia. The Vesuvian area is characterized by a Bouguer anomaly of small extension and amplitude, which follows a tortuous pattern due to the presence of local minima and maxima. A vast gravity low southeast of Somma-Vesuvius is the main feature in this area; it corresponds to the so called 'Pompei graben' (CASSANO and LA TORRE, 1987).

The Bouguer anomaly gravity map has already been interpreted by means of 2.5D modelling (WON and BEVIS, 1987; FEDI, 1988) along a series of profiles that have provided information about the main volcanic structures, and particularly about the shape and depth of the limestone and crystalline basements (BERRINO *et al.*, 1998, 2008; SCALA, 2002). This kind of inversion has also allowed the building up of a pseudo-3D pattern of the limestone basement and the delineation of the main tectonic structures under the Neapolitan volcanoes (BERRINO *et al.*, 1998, 2008).

In this way, no important information has been obtained about very shallow and isolated bodies, and therefore a 3D interpretation using a new and original algorithm has been used here, with the aim of better defining the shallow density distribution. We have used the Bouguer anomaly map that has been reduced with the density value of 2,200 kg/m^3 because we have limited our first investigation to the volcanic area. Therefore, we have selected an area of about 20 km $\times$ 20 km (see Figure 1, small black rectangle) centered on Mt. Vesuvius, where 616 gravity stations lie. First, we focused our inversions on a local and shallow body below the volcano, then we attempted to globally analyze the entire Neapolitan area in order to investigate deep structures, and mainly the sill that was revealed by the seismic tomography study. This second aspect was carried out by analyzing the 6,203 gravity values inside the area (90 km $\times$ 70 km) that is illustrated with the larger black rectangle in Figure 1.

Although we aimed to design objective models without any subjective preliminary information or input model, the information provided by the previous 2.5D interpretation has been taken into account as a reference, if necessary and when possible.

The Bouguer anomaly map that has been reduced with a 2,200 kg/m^3 reference density and that spans the larger area of analysis is shown in Figure 2.

3. The 3D Gravity Inversion Method

3.1. Introduction to the Gravity Method

Very extensive results have been obtained for gravity modelling by methods of 'trial and error'. For instance, the IGMAS method is an interactive, graphical computer system for the interpretation of potential fields (gravity and magnetic) by means of numerical simulations (GÖTZE and LAHMEYER, 1988). These direct methods are based on strong personal experience and *a priori* knowledge of the structure at depth, and they have a more or less subjective character.

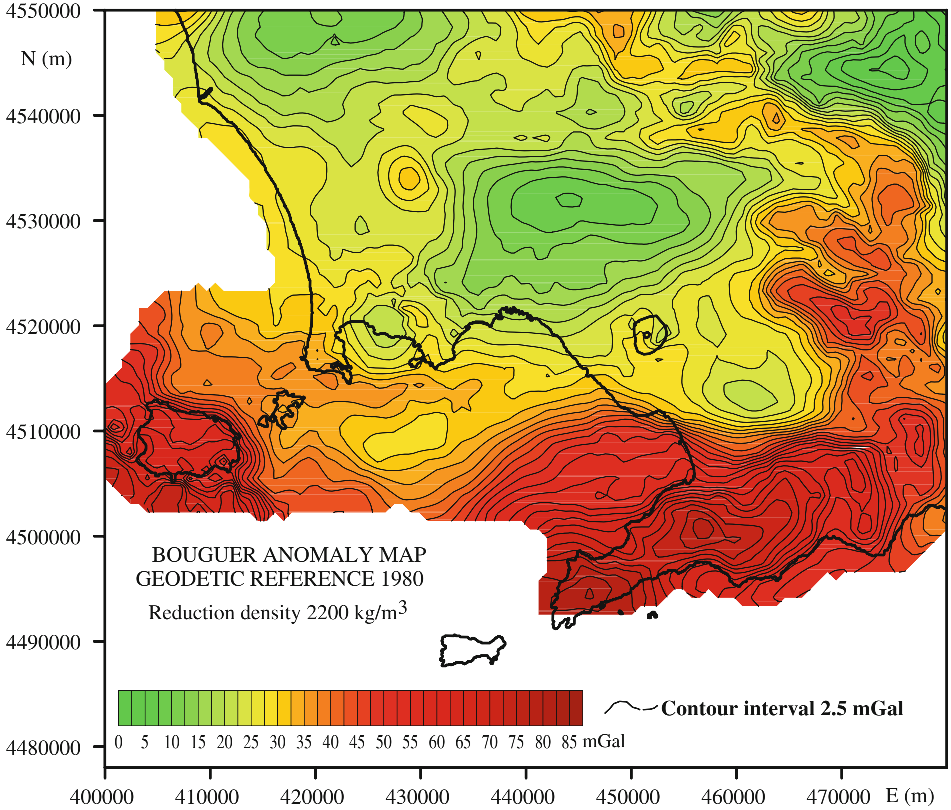

Figure 2
Bouguer anomaly map, reduced with a 2,200 kg/m^3 reference density, for the large selected area (see Fig. 1 and text for details).

We look for the determination, in a non-subjective way, of a model of the subsoil density distribution that can reproduce the observed gravity anomaly. Taking into account the information coming from other geophysical investigations (mostly seismic information), we wanted to describe the 3D anomalous density structures mainly by means of several sub-horizontal discontinuity layers (density discontinuities) with irregular boundaries. This is a traditional use of gravity inversion (e.g., studies of sedimentary basins). Considering only one irregular discontinuity surface, the inversion process is not hard to detect, and many studies that have been providing suitable procedures to obtain inversions for just one discontinuity surface are available (e.g., RADHAKRISHNA MURTHY and JAGANNADHA RAO, 1989; RAMA RAO *et al.*, 1999; GALLARDO-DELGADO *et al.*, 2003). A more problematic question is to obtain a non-subjective inversion model when several discontinuity layers are simultaneously considered. In this case, the assignment of the anomalous density structures among the several layers is not so easy to determine. In general terms, short wavelength features of the gravity anomaly should be assigned to shallow surfaces, and long wavelength features should be mostly assigned to deep discontinuity surfaces. In this sense, several studies have addressed the inversion process in a frequency domain (e.g., CHAKRABORTY and ARGAWAL, 1992), similar to studies in magnetic prospecting.

Clearly, short wavelength features will correspond to shallow structures; long wavelength features can instead be associated to deep structures, although they can be also associated to extensive enough and not very deep structures. The classical non-uniqueness problem in potential fields requires some additional constraints, which will possibly come from good geological and/or geophysical data, or from general mathematical hypotheses.

On the other hand, gravity inversion by means of the adjustment of sub-horizontal surfaces falls into the nonlinear inversion problems. This requires using some iterative or exploratory approaches to obtain a solution.

To face these problems, we adapted the basic ideas of a previous method for 3D inversion (CAMACHO *et al.*, 2002), which we modified for use in our new context. In the previous method (the Growth method), the anomalous model is described as being composed of isolated anomalous bodies, which are constructed in a very free growth process as 3D aggregations of cells (see Fig. 3, left). This method is very interesting for gravity anomalies due to isolated bodies. In a versatile and non-subjective form, and with few constraints, the process can produce 3D models of the anomalous structure (position, depth, size, shape), which are more valuable if suitable values for the density contrast are previously defined. Conversely, some application problems can arise when the causative structure cannot be clearly associated with isolated bodies. In this case, the inversion model will provide a simplified, rather indicative, solution to the inversion problem, that needs further analysis to reach any realistic conclusions. This is the case, for instance, of anomalies due to small distortions of sub-horizontal layers in the subsoil.

Now we want to describe the subsoil model as sub-horizontal layers, where the irregular discontinuity surfaces are constructed by displacing, step by step (according to a system of connected cells, in a growth process), the original flat mean surface (Fig. 3, right). Then, working with similar minimization conditions and similar constructive processes, such as the aggregation of small filled cells in an explorative process of growth, the methodology is modified to allow the aggregation of filled cells that are only connected (up and down) to previous discontinuity surfaces. For a continuous structure (a stratified structure), this looks more realistic than has been described by isolated bodies.

3.2. Inversion Method

The inverse gravimetric problem, namely the determination of a subsurface mass density distribution corresponding to an observed gravity anomaly, has an intrinsic non-uniqueness in its solution (e.g., AL-CHALABI, 1971). Moreover, the data must be considered as insufficient and inaccurate. Nevertheless, particular solutions can be obtained by including additional information about the model parameters (e.g.,

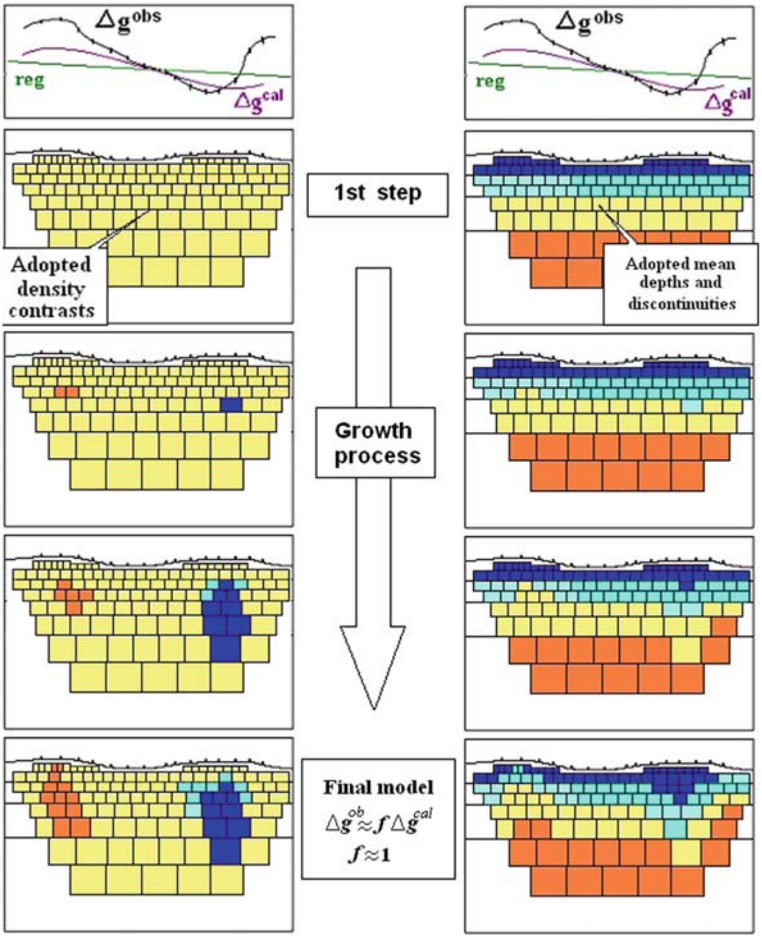

Figure 3
The step by step process in the design of the inversion models: As cells for the Growth model (left) and stratified for the Layers model (right), for the distribution of density according to isolated bodies and sub-horizontal layers, respectively. The geometry of the closed and isolated bodies, together with the discontinuity layers, generates anomalous high and low density areas that are responsible for the anomaly seen.

subsurface structure) and about the data parameters (the statistical properties of inexact data; e.g., a Gaussian distribution). The inversion methods looking for the geometrical properties of anomalous bodies with prescribed density contrast (e.g., PEDERSEN, 1979; BARBOSA *et al.*, 1997) correspond to a nonlinear context and offer interesting results that are limited by the validity of the hypothesis used. Unfortunately, linearized techniques depend strongly on the accuracy of the initial estimates of the model parameters (ROTHMAN, 1985). For a fully nonlinear treatment, the methods of random space model exploration often provide the best option (TARANTOLA, 1988; SILVA and HOHMANN, 1983).

Here, we develop a nonlinear inversion method for the geometrical description of the anomalous density structure as sub-horizontal layers. We have named it '*Layers*'.

This method starts from several horizontal layers (up to four in the initial version), which can be introduced *ad hoc*, or conversely, they can be automatically selected in an optimizing approach. Also, several corresponding density contrasts are previously selected (or automatically chosen in a relatively optimizing process). Then, the algorithm works according to a nonlinear explorative approach, to 'deform', or better, to 'shape', the layers step by step, to finally obtain some irregular shapes that can fit the observed anomaly satisfactorily (see Fig. 3, right).

A general tool to describe the geometry of the anomalous mass structure corresponding to irregularities in the sub-horizontal layers is obtained through an aggregation of small parallelepiped cells filled with anomalous mass close to the adopted layers. This procedure can be used to describe general 3D models, as with CAMACHO *et al.* (2000, 2002), although generates a very large number of degrees of freedom for the model. Therefore, a general exploratory inversion approach would be ineffective. An interesting idea was proposed by RENÉ (1986): He applied an exploratory method (in a more restrictive context) not to the global model, but just to every step of its growth process. Under these conditions, the number of degrees of freedom is drastically reduced for each step of the model growth, consequently so the exploratory process becomes very effective.

Let us consider n gravity stations P_i (x_i,y_i,z_i), $i = 1,\ldots, n$ that are not necessarily gridded, which are located on a rugged topography and which have observed anomalous gravity values Δg_i^{obs} (Bouguer anomaly). We assume a mostly Gaussian distribution for the observation uncertainties given by a covariance matrix $\boldsymbol{Q_D}$ (as deduced from analysis of the data). Let us also consider nh horizontal surfaces with depths d_k and density discontinuities $\Delta\rho_k$ (positive differences between the upper and lower media limiting with this surface), for $k = 1,\ldots, nh$.

Our goal is to construct a 3D model that is described as sub-horizontal layers for prescribed mean depths and density discontinuities, and which is 'responsible' for the anomaly observed. As previously indicated, the subsurface volume close to the survey area is dismantled into a global discrete 3D partition of m prismatic elements. The desired solution will be described as an aggregation of some of the prismatic cells filled with prescribed density contrast close to the discontinuity surfaces, thus giving rise to 'shaped' layers. When the filled cell is just below the discontinuity surface, this means that there is an intrusion of low density from the upper medium into the lower one. Conversely, when the filled cell is close and above the discontinuity surface, this means there is an intrusion of high density from the lower medium into the upper one (see Fig. 3, right).

The gravity attraction A_{ij} at the i-th station $P_i(x_i,y_i,z_i)$ due to the j-th prism, per unit density, can be found in PICK *et al.* (1973). Matrix A, with components A_{ij} is the design matrix of the physical configuration problem and includes the effects of rugged terrain, station distribution, subsoil partition, etc. Now the calculated anomaly values for the resulting model are:

$$\Delta g_i^{cal} = \sum_{j \in J_+} A_{ij} \Delta\rho_j - \sum_{j \in J_-} A_{ij} \Delta\rho_j + \Delta g_{reg}, \quad i = 1, ..., N, \tag{1}$$

where J_+ , J_- are the sets of indices that correspond to the cells that are filled and are located up and down, respectively, with respect to the corresponding discontinuity surfaces; Δg_{reg} is a regional smooth trend to be simultaneously adjusted; and J_+ , J_- , Δg_{reg} are the main unknowns to be determined in this inversion process. For the sake of simplicity, we are going to adopt a linear expression for the trend:

$$\Delta g_{reg} = p_0 + p_x(x_i - x_M) + p_y(y_i - y_M), \quad i = 1, ..., N \tag{2}$$

where x_M, y_M are the coordinates of an arbitrary central point for the survey; p_0, p_x, p_y are three unknown values which fit a trend (a 1-degree polynomial surface, simplifying the subsequent formulation).

To solve the inherent non-uniqueness problem, an additional condition of minimization of the model variation can be adopted. Thus, the solution is obtained through a mixed condition between the gravity l_2-fitness and the whole anomalous mass quantity, using a λ parameter for the suitable balance:

$$v^T \boldsymbol{Q_D}^{-1} \boldsymbol{v} + \lambda\, m^T\, \boldsymbol{Q_M}^{-1}\, \boldsymbol{m} = E = \min, \tag{3}$$

where $\boldsymbol{m} = \left(\Delta\rho_{1_1}, ..., \Delta\rho_m\right)^T$ is the anomalous density vector for the m cells of the subsoil partition ($-\Delta\rho_j$ or $\Delta\rho_j$ for the filled cells and zero for those not filled); λ is a positive factor that is empirically fixed and provides the balance between model fitness and anomalous model magnitude (and complexity); $\boldsymbol{Q_D}$ is the covariance matrix (usually a diagonal matrix) that corresponds to the estimated (Gaussian) inaccuracies of the gravity data; and $\boldsymbol{Q_M}$ is a diagonal normalizing matrix whose non-null elements that are the same as the diagonal elements of $\boldsymbol{A^T Q_D^{-1} A}$. The first addend of the minimization functional (3) corresponds to the fit residues weighted with the data quality matrix. The second addend is a weighted addition of the model densities. Nevertheless, taking into account that the covariance matrix $\boldsymbol{Q_M}$ contains the prism volumes as a factor, this second addend is connected with the anomalous mass or magnitude of the model. $v = (v_1, ..., v_N)^T$ (T for transpose) is the vector for the gravity residuals for N stations. These are defined as:

$$v_i = \Delta g_i^{ob} - f \Delta g_i^{cal}, \tag{4}$$

where f is a scale factor that allows the fitting of the calculated anomaly for a developing model with respect to the observed values.

The λ parameter governs the application of the minimization conditions with respect to the balance between the total anomalous mass and the residual values. For low λ values, a good fit is obtained, although the anomalous mass may increase excessively and includes some fictitious structures. Conversely, for high λ values, the adjusted model can be too slight, and a poor gravity fit is obtained.

Thus, the inversion process seeks to determine a geometrically anomalous model that is described as an aggregation of filled cells that is connected to discontinuity surfaces and that verifies the minimization condition (3). As previously indicated, we have addressed this nonlinear problem with a process that explores the model possibilities. The exploration of the possibilities for the entire model is substituted by the exploration of several possibilities of growth (cell by cell) for each step of the surface deformation. Thus, the prismatic cells that are connected (up or down) to discontinuity surfaces are systematically tested, step by step.

For one step, some cells have been previously filled to modify the geometry of the initial discontinuity surfaces, although not enough to reproduce the anomaly observed. Now every cell (up and down) that is connected to every actual discontinuity surface is tested. For each cell considered, the linear least-squares problem connected to (3) is solved for unknown parameters f, p_0, p_x, p_y; then the value E of expression (3) is obtained. Once a certain number of cells are randomly selected and verified, we chose to use the smallest value E as the best option for incorporation into the growth approach for the discontinuity geometry.

This process is repeated successively, including a detection of outliers (Rousseeuw and Leroy, 1987). In the subsequent steps, the scale value f decreases, and the trend parameters p_0, p_x, p_y reach nearly stable values. The process will stop when f approaches 1, which is reached for a final geometry of the discontinuity surfaces and a final regional trend.

Finally, the solution appears as a 3D distribution of prismatic cells filled with some of the prescribed contrast densities. These prismatic cells are ordered to produce a model of stratified density according to some distribution of the layers limited by sub-horizontal discontinuity surfaces, as illustrated in Figure 3 (right). Moreover, a regional trend supplementing this anomalous mass distribution is also obtained.

This inversion approach has been attempted for the gravity anomaly of the Mt. Vesuvius area, to investigate the structural results that can be obtained in a non-subjective 3D inversion process. As standard for this kind of automatic modelling without a prior hypothesis, the results are valuable as non-subjective information. Of course, some further interpretative subjective work based on some of the initial geological/ geophysical constraints is necessary to 'translate' the model into a more realistic structure.

4. Analyses, Results and Discussion

First of all, from the total of 616 points, for homogeneity purposes we selected 400 points with mutual distances greater than 350 m.

To investigate the shallow structures and possibly the magma system of Mt. Vesuvius, at first the well tested Growth process was adopted. In this case, we did not use any initial constraints and the models obtained are totally non-subjective. Later, taking into account the information from previous geological and geophysical studies about several sub-soil layers with different lithologies, the Layers process was chosen. We selected the following values for the initial depths and density discontinuities: From a topographical level and $\Delta\rho = 0$ kg/m^3 (very shallow deposits with a density range from 2,000 kg/m^3 to 2,200 kg/m^3); 1,100 m b.s.l. and $\Delta\rho = +200$ kg/m^3 (initial depth for the top of the deeper volcano-sedimentary filling of the Campanian Plain—$\rho = 2{,}400$ kg/m^3); 2,700 m b.s.l. and $\Delta\rho = +200$ kg/m^3 (initial depth for the top of the carbonate formation - $\rho = 2{,}600$ kg/m^3); 9,900 m b.s.l. and $\Delta\rho = +200$ kg/m^3 (initial depth for the top of the crystalline formation - $\rho = 2{,}800$ kg/m^3). Starting with these values, a 3D model was obtained in a nearly automatic process. The resulting residual values show a standard deviation of 363 μGal for the Growth inversion, and 385 μGal for that of the Layers; both show a pattern of non-autocorrelated noise (Figs. 4a, b, respectively). The regional trend (Fig. 5a) obtained simultaneously in the inversion process is characterized by a gravity increase of 1.312 mGal/km towards N170°E. In Figure 5b, the consequent local anomaly is shown: It is generally positive, with very small values of the order of 3–5 mGal around Mt. Vesuvius, and with a very short wavelength, which is indicative of shallow and small isolated bodies. A negative anomaly is seen at the W, S and E sides of the base of the volcanic structure. The positions of the 400 points selected are also shown in Figure 5.

Finally, the resulting 3D models of the isolated bodies and sub-horizontal layers are shown in Figures 6 and 7, respectively, by means of vertical *versus* depth profiles and horizontal deep cross sections.

Figure 6 shows several horizontal cross sections from depths of 0 m to 5,000 m, as six W-E, one N-S, one SE-NW and one SW-NE vertical sections. The vertical section *c*, together with the N-S, SE-NW and SW-NE vertical sections, crosses the Vesuvius crater. All of the profiles reach a depth of 6 km. They all indicate the presence of closed positive and negative density bodies limited to a depth of about 3 km, which are more easily detectable in the horizontal sections. The most significant anomalous density bodies are:

— A positive density body located beneath the crater, that extends towards the NE, where it reaches its maximum depth. It is clearly visible in the *a*, *b* and *c* profiles, in the N-S and mainly in the SW-NE vertical sections;
— a very shallow (from above sea level to some hundreds of meters b.s.l.) negative density body inside the volcano edifice that is clearly visible in the *c* profile;
— several negative density bodies around Mt. Vesuvius, which are mainly W and SE and which were also seen by Tondi and de Franco (2006).

The first two density bodies have already been indicated in these same positions, by Berrino *et al.* (1998), along a 2.5D interpretive profile that coincides with our *c* vertical section; they associated the denser body to lavas and hypothesized a shallow structure that is characterized by density contrast just beneath the volcano edifice. However, they also stressed that the density and the geometry of the bodies inside the volcano were chosen only to obtain an acceptable fitting of the anomaly seen. Here, we highlight that the algorithm produces this model in a very free, automatic and non-subjective way.

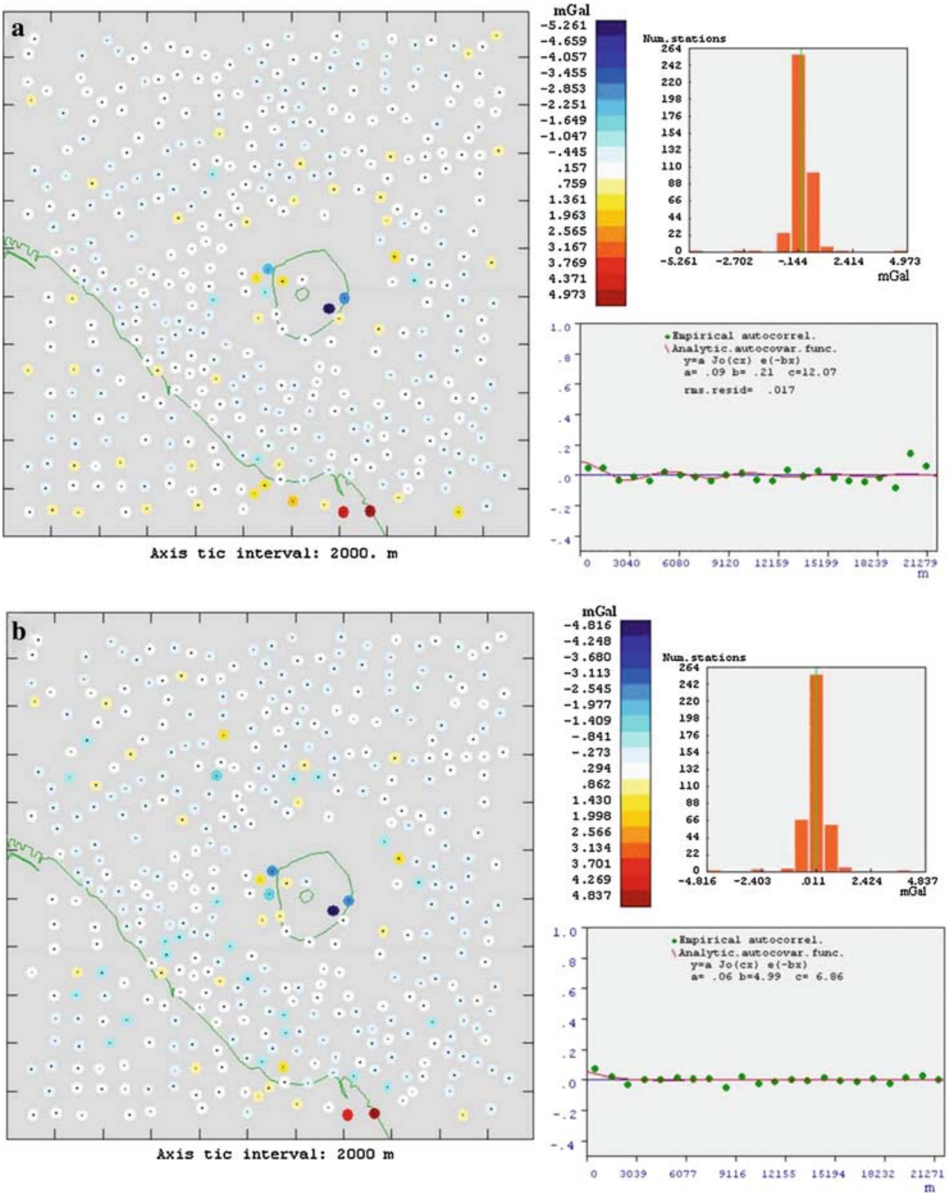

Figure 4
Inversion residuals for (a) the Growth and (b) the Layers models, each including planar distributions, histograms and autocorrelation analyses.

Moreover, high velocity lateral contrast has already been indicated by 2D seismic tomography (ZOLLO *et al.*, 1996), as well as by a more recent study by DE NATALE *et al.* (2004) on the inversion of several seismic signals.

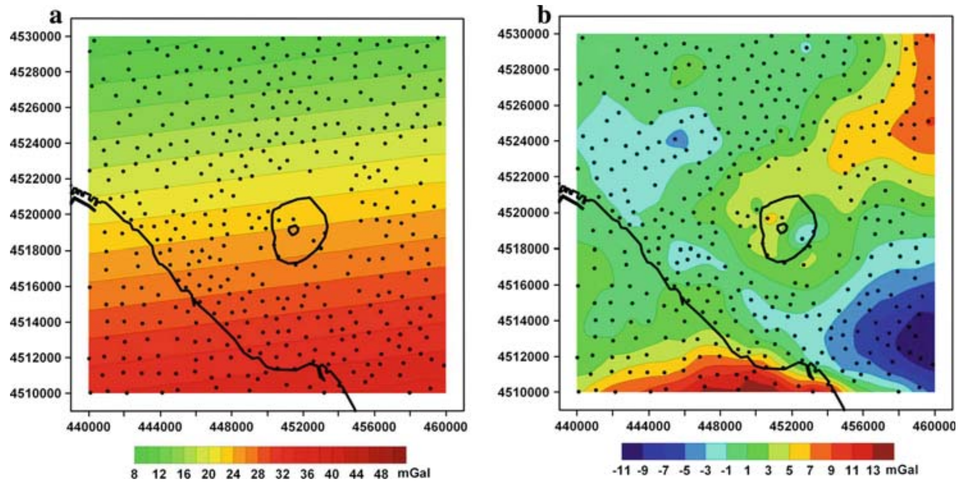

Figure 5
(a) Regional and (b) local gravity anomalies in the small selected area (see Fig. 1 and text for details), as computed by the new algorithm. The black points represent the 400 inversion stations selected.

The model obtained with the Layers procedure is shown in Figure 7, where the same horizontal E-W and N-S vertical cross sections displayed in Figure 6 are shown. There are many similarities to the Growth model regarding the density bodies distributed in the horizontal sections. This interpretation confirms, as shown by BERRINO *et al*. (1998), that the carbonate basement under the volcano (red body in the sections) appears very flat at a depth of about 2.5 km. An uprising of the superimposed layer from about 2 km b.s.l. up to sea level, with a density of 2,400 kg/m^3 to 2,450 kg/m^3 (likely a volcano-sedimentary filling of the Campanian Plain) (BERRINO *et al*., 1998), is clearly detectable in the *b*, *c* and N-S vertical sections, along with a negative density body inside the volcano. Both of these bodies coincide in position with the high and low density bodies already detected through the Growth process, suggesting that they might represent the same structures. Moreover, in the N-S section, there is also an uprising of the carbonate basement. It is surprising that this basement uprising shows the same shape as the high V_P and V_P/V_S anomaly detected under the crater by DE NATALE *et al*. (2004). Also, we should note here that the model was created in an automatic and non-subjective way, and the only initial constraint was the choice of density contrasts.

Finally, to argue about deep sill indicated by AUGER *et al*. (2001), let us analyze a wider area, consisting of 6,203 gravity values (the larger black rectangle in Fig. 1), through both the Growth and Layers processes. The first results here are shown in Figure 8.

Using the Growth process (Fig. 8, left), a large low density body is detectable at a depth of 8 km, which extends to about 12 km, NW of the Vesuvius area. This density body also appears using the Layers approach (Fig. 8, right), although here it appears as a

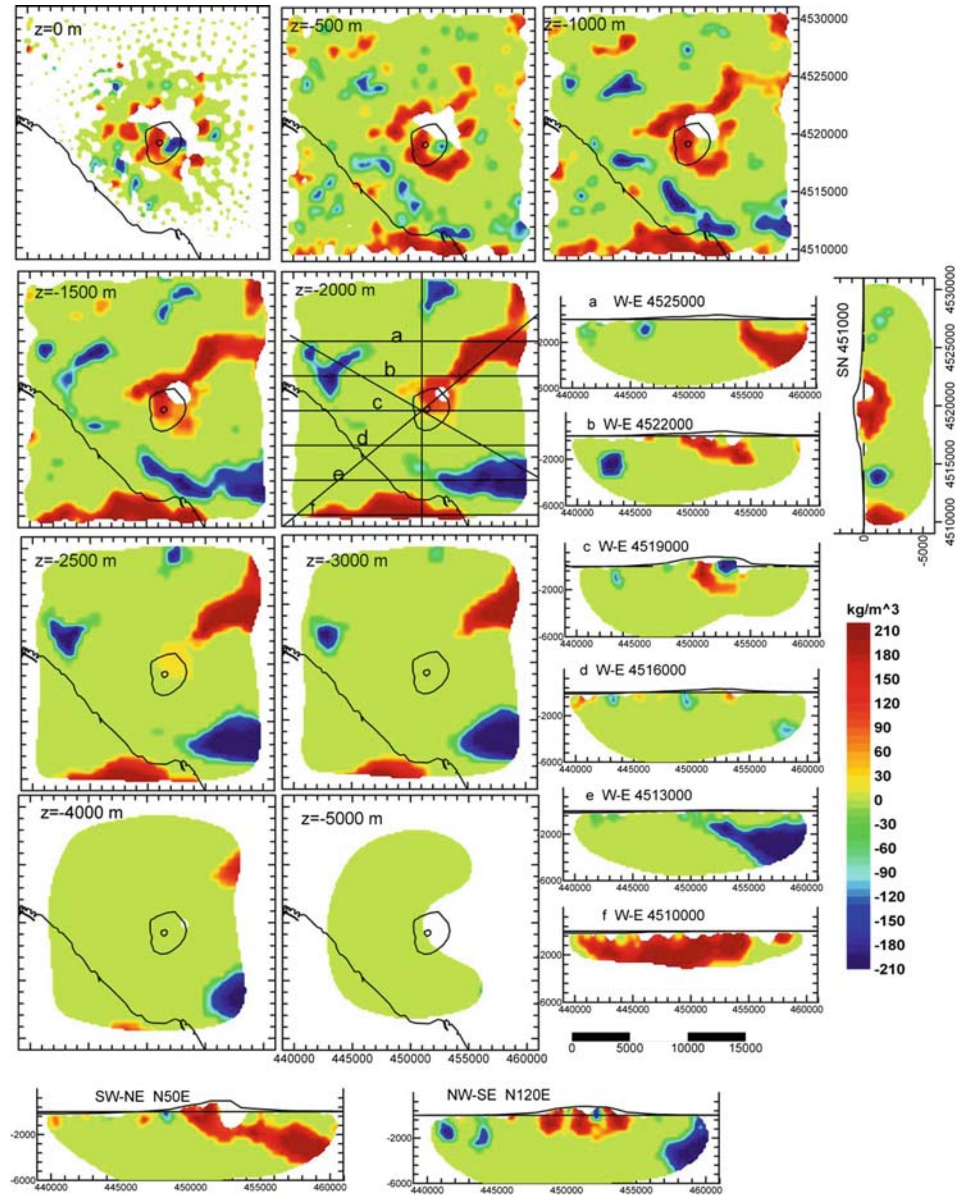

Figure 6
Deep horizontal and vertical *versus* depth cross sections of the inversion model obtained with the cell-Growth process.

body that extends from 8 km down to 10 km, which is elongated mainly in the NW-SE direction and which is in the form of a depression of the top of the crystalline basement (Fig. 8, right, red layers). This depression is evident in the NW-SE vertical profile, but

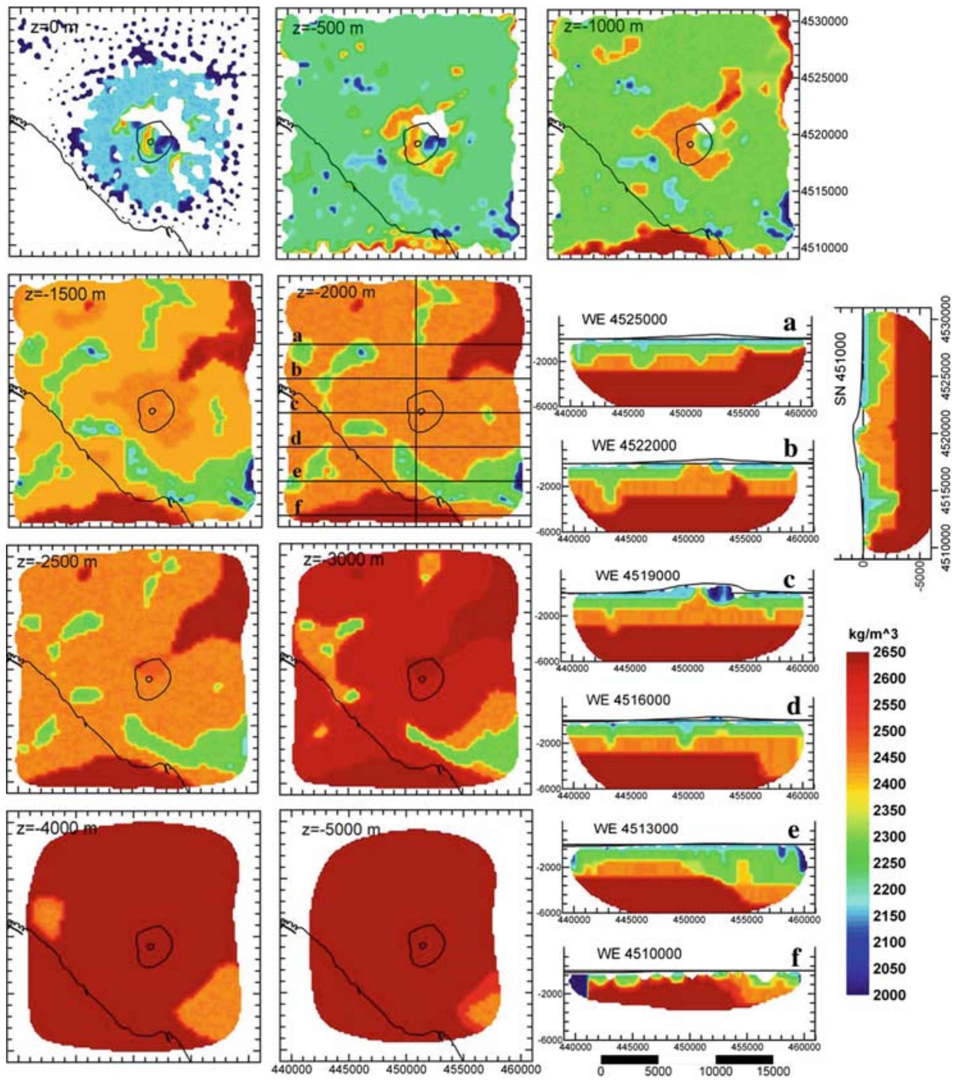

Figure 7

Deep horizontal and vertical *versus* depth cross sections of the inversion model obtained with the shaped-Layers process.

does not appear in the coinciding NE-SW profile analyzed by Auger *et al*. (2001). The depression detected also corresponds to displacements of the superimposed carbonatic basement (see Fig. 8, right, NW-SE profile, orange layers) that occur in coincidence with the Acerra depression (NW) and the Pompei graben (SE). Based on our current results, the low density body is unlikely to represent the sill-like structure suggested by Auger *et al*. (2001) and Nunziata *et al*. (2006). Our results are more in support of the C shaped negative velocity/density anomaly detected by Tondi and de Franco (2006).

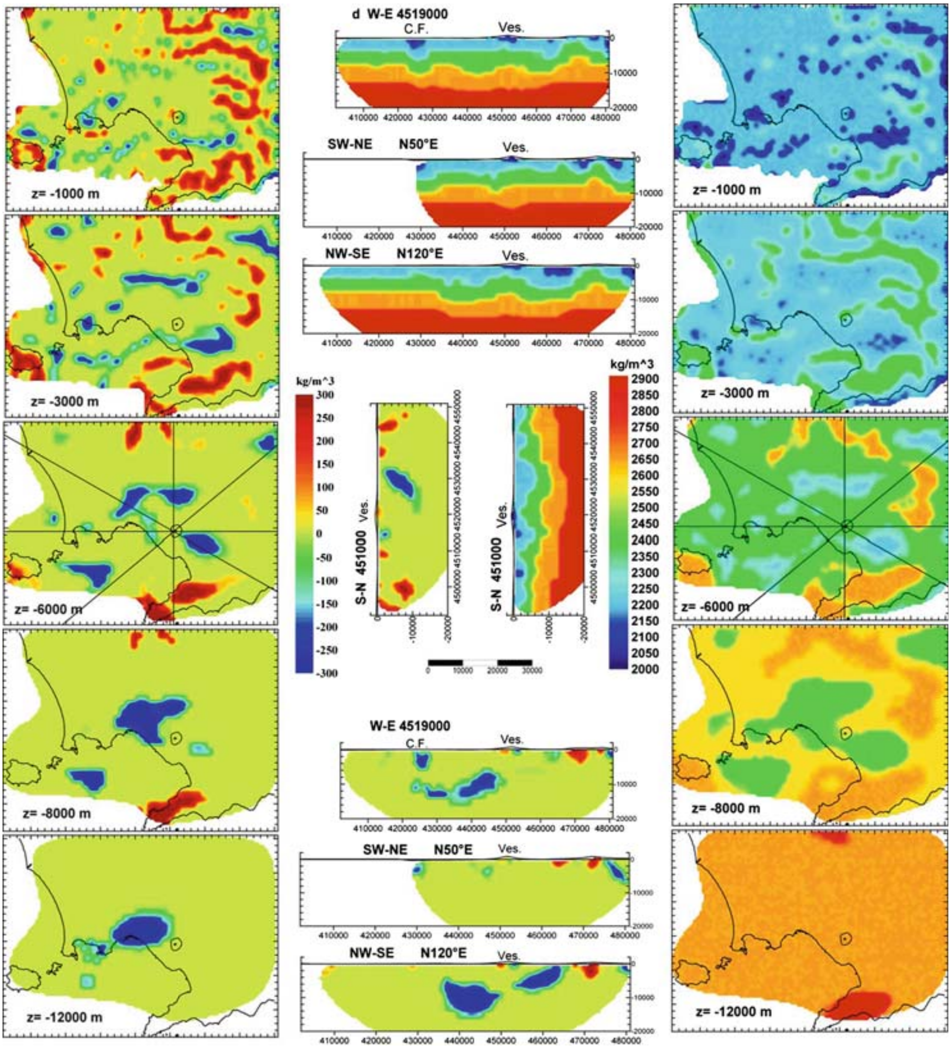

Figure 8
Comparisons along the selected deep horizontal layers (depth from 1 km to 12 km) and the selected vertical *versus* depth profiles crossing the Vesuvius crater, modelled for the whole Neapolitan area with both the Growth and the Layers processes (see text for details).

5. Conclusions

We have carried out a 3D interpretation of the available Bouguer gravity anomalies in the Neapolitan area through a new and original algorithm, known as Layers, which was realized to satisfy the aim of our study. This algorithm works in an automatic and non-subjective way, and it has allowed us to define the structural setting below Mt. Vesuvius in a very objective manner, in terms of several layers, each of which represents a specific geological formation. The same data have also been interpreted in terms of isolated and shallow anomaly density bodies using a well tested algorithm, known as Growth, which also furnished the basic idea for the Layers procedure.

The final models generally confirm the global setting of the area as outlined in previous studies, mainly regarding the shape and the depth of the carbonate basement below Mt.Vesuvius; they also show lateral density contrasts inside the volcano edifice that were only hypothesized in the 2.5D inversion. Moreover, these models have allowed us to indicate a high density body that rises from the top of the carbonate basement and elongates further at sea level, which is probably a rising of the same basement, just below the volcano. As already indicated, the space coincidence of this rising density anomaly with the V_P and V_P/V_S anomaly detected under the crater is surprising. However, since the conversion of seismic velocities to densities and seismic depths is subject to errors, we have to assume some ambiguity in this comparison between the gravity and seismic models.

The results obtained also reveal that the two inversion methods result in very similar models, as the high density isolated body in the Growth model can be associated with the rising high density anomaly in the Layers model. This is supported by comparing the two models through the most significant, in our opinion, selected horizontal (2-km depth) and vertical (SN and WE 4519000 [c] — crossing the Vesuvius crater) profiles (see Figs. 6 and 7).

Taking into account that the density of these modelled bodies, at about 2,400 kg/m^3 to 2,450 kg/m^3, is similar to that assigned to the Vesuvian lavas (2,480 kg/m^3) (Cassano and La Torre, 1987), we suggest that these modelled bodies represent solidified magma bodies, as already indicated by Berrino *et al.* (1998) and De Natale *et al.* (2004).

Finally, with regard to the analysis extended to the entire Neapolitan area to survey the deeper structures, we did not detect any deep bodies that are clearly associable with the sill suggested by Auger *et al.* (2001).

The different ways in which these two algorithms operate (noting that one is aimed at the detection of isolated and shallow masses, the other at the detection of deep subsoil layered structures) is one of the limits of a unique and unambiguous interpretation, in terms of the structural setting provided by the resulting models. This suggests that the fusion of the two algorithms into one will allow the simultaneous modelling of isolated, shallow, deep and layered structures, and this will provide both more information about deep density stratification and a more global vision of the geological and structural setting of the area investigated. We therefore hope to obtain a quasi-univocal model that will be supported by the non-subjective interpretation, and this will be our next tool for further analysis.

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