3GRAINS: 3D Gravity Interpretation Software and its application to density modeling of the hellenic subduction zone

K. Snopek*, U. Casten

Ruhr University of Bochum, Germany

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Abstract

3GRAINS is a program, which allows interactive modeling of a density structure with respect to given gravity anomalies. It is written in standard C++ with the use of Qt Library. It has been compiled on the Linux platform, but it can be also compiled under the Windows environment. The program uses rectangular prisms to calculate the gravity effect of a model. Blocks used in interpretation can have different size; it is useful to model shallow layers with higher resolution than the deep ones. Gravity stations used in modeling can have arbitrary distribution. The software uses the altitude of the station to compute its anomaly. The gravity effect of each block for each station is calculated once and saved together with the modeled structure. A major objective was to reduce the amount of memory used by the program. Thanks to the applied compression algorithm, high-resolution density structures can be accommodated by an average modern computer. The absolute accuracy of modeled anomalies depends on scaling of the problem. The relative error does not exceed 0.001. A very important characteristic of the software is a simplicity in creating and changing of the models by means of the graphical user interface. The three-dimensional density structure can be browsed in 2D cross-sections on one horizontal and two perpendicular vertical planes. The program offers a number of export options. Numerical models as well as different cross-sections and layer boundaries can be saved to a file for further visualization of the results.

As an example a density model of the Hellenic Subduction Zone is presented. The model reflects a very complicated tectonic situation of the region and includes main tectonic units: seawater, sediments, crust and upper mantle. Horizontal density distributions within each unit allow recognition of different types of the lithosphere.

1. Introduction

A goal of gravimetric methods is to deduce the distribution of masses within the Earth’s interior from anomalies that are measured on the Earth’s surface. The interpretation of geophysical data can be divided into three steps: parameterization of the model, selection of a forward modeling algorithm...
and finally application of an inverse modeling technique. All these steps depend on one another. Starting the interpretation one must consider what parameterization fits best into a given problem. The choice of parameters of the model determines of course the solution of the forward problem. The effectiveness of the inversion method depends strongly on the two first steps. The geophysical methods suffer from non-uniqueness and under-determination of the problem. Moreover, the observations are always contaminated with errors. Therefore, it is not possible to produce the single, non-unique solution to a given geophysical problem. Gravimetry, like other potential methods, is subject to non-uniqueness. From Gauss’ theorem we know that an infinite number of density distributions inside a sphere (or any closed body) can produce an identical gravity field on its surface. Every inversion technique must deal with this problem, and it is hardly possible to produce a tool that will generate the right solution without assistance from a human arbiter. Therefore, it is crucial to have a software which enables, by means of graphical user interface (GUI), an interactive control over the interpretation process.

Many methods of forward gravity modeling have been proposed to calculate a density structure from gravity data. The most popular gravity interpretation technique is an interpretation in two dimensions (2D). Assuming that geological bodies extend infinitely along one of the horizontal axes simplifies calculations and allows reduction of model parameters. Talwani et al. (1959) and Won and Bevis (1987) gave the well-known solution for 2D bodies of polygonal shape. Several authors proposed other methods suitable for particular geological problems (see e.g., Murthy and Rao, 1979; Ruotoistenmäki, 1992; Zhang et al., 2001). However, the 2D approach can be used only in cases when the length of the geologic structure is greater than five times its maximum width. In other cases, particularly when dealing with an isometric 2D gravity field, a three dimensional (3D) approach must be used. In a layered subspace a common application has a Parker (1973) formula for the gravity effect caused by a layer with constant density. Most other methods use simple bodies for which gravimetric attraction can be calculated analytically to compute the gravity anomaly of the modeled density distribution. The bodies used in the calculation can be for instance thin laminae of polygonal horizontal shape (see e.g., Talwani and Ewing, 1960), rectangular prisms (see e.g., Nagy, 1966) or polyhedrons (see e.g., Götze and Lahmeyer, 1988; Holstein et al., 1999). The first two methods approximate the shape of geological structures by a stack of bodies. The polyhedrons approach allows computation of the gravity effect of any 3D body without approximation. With a relatively small number of bodies, very complicated geological structures can be constructed and tested against given gravity anomalies. The disadvantage of this method is that the geometry of the modeled structure depends strongly on the initial model. Moreover, the polyhedron approach does not allow application of most of the automatic inversion methods. On the other hand, the approach based on the rectangular prisms allows construction of arbitrary density structures and is also more suitable for an automatic inversion of gravity data. The main restrictions of this method are the number and size of blocks used in the interpretation. Limitations of computer speed and memory have suppressed for a long time application of that way of modeling. Another drawback that suppressed a practical use of this method of forward modeling was the lack of a convenient software which would enable interactive modeling. Nowadays, however, computers are powerful enough to perform the robust calculation of high-resolution density models. The use of modern object-oriented programming techniques provides at the same time a comfortable and easy GUI to build and process complex density models.

The main motivations for the development of a new 3D interactive modeling software was the need for a tool which would allow fast and easy creation of initial models for an automatic inversion as well as for a visualization of the inverted structures. The presented program can be used as a standalone modeling application as well.

3GRAINS stands for 3D Gravity Interpretation Software. It is written in standard C++ with the use of STL (Standard Template Library) and Qt library by Trolltech. Qt environment allows effective programming of the graphical user interface. The program uses the method developed by Nagy (1966) to calculate the gravity attraction of the right rectangular prism. A special compressing algorithm is used to minimize the amount of memory used by the program. The software was tested on a computer with CPU of 700 MHz and 256 MB RAM, running under Linux 2.4. Thanks to the

use of the Qt graphical interface, it can be also compiled on a Windows system. 3GRAINS is fully interactive and easy to use; almost all modeling operations as well as creation of an initial model can be carried out with the use of a computer mouse. The user can browse the 3D structure on one horizontal and two vertical 2D cross-sections. The interpreter can instantly compare the calculated (modeled) anomalies with the measured ones.

In this paper we describe first the forward analysis of the program and describe main functions of the software. Finally, as an example, we present a density model of the Hellenic subduction zone with a brief discussion of the results.

2. The method

The vertical component of the gravitational attraction of a rectangular prism can be expressed after Nagy (1966):

\[
F_z = \gamma \rho \left( x \ln(y + r) + y \ln(x + r) - z \arcsin \frac{x^2 + y^2 + yr}{(y + r) \sqrt{y^2 + z^2}} \right),
\]

where \( \gamma \) is the gravitational constant, \( \rho \) is the density of the prism, limits \( x_1, x_2; y_1, y_2; z_1, z_2 \) are distances from the block edges to the observation point, and \( r = \sqrt{x^2 + y^2 + z^2} \) (see Fig. 1 for details).

The gravitational attraction is a linear function of density and non-linear function of geometry of the body. Calculating and saving the geometrical part of Eq. (1) allows a very fast calculation of the gravimetric attraction of the prism, just by multiplying it by its density. The gravity anomaly of a model built of \( M \) prisms and computed for a station \( i \) is expressed as follows:

\[
d_i = \gamma \sum_{j=1}^{M} \rho_j G_{ij},
\]

where \( G_{ij} \) is geometrical effect of block \( j \) of station \( i \) and \( \rho_j \) is density of \( j \) prism. For \( N \) stations it can be rewritten in matrix form

\[
d = G \rho,
\]

where \( d = (d_1, d_2, d_3, \ldots, d_N) \) is a vector of \( N \) station gravity anomalies, \( \rho = (\rho_1, \rho_2, \rho_3, \ldots, \rho_M) \) is a vector of densities of \( M \) blocks and \( G \) is the \( M \times N \) kernel matrix which translates densities to gravity anomalies.

Calculation of \( G \) could take a long time since it requires summing over three spatial coordinates. To allow an interactive modeling or inversion, it should be computed only once, held in RAM and (or) saved to a hard disc. For high resolution 3D models, e.g. 100 000 blocks and 2000 stations, the kernel matrix may become very large. Each component should be a real number; standard C \,+\, codes high precision double numbers in 8 bytes. Therefore, the size of matrix \( G \) is 1 000 000 \( \times \) 2000 \( \times \) 8 = 1.6 \( \times \) \( 10^9 \) bytes, that is almost 1.6 GB. It does not fit into RAM of a standard PC. Additional operations have to be undertaken to overcome this problem. The analysis of \( G \) shows that it includes only a small number, in comparison to its total size, of different component values. Moreover, some elements of \( G \) are so small that without losing the accuracy they can be set to zero.

Utilizing these two characteristics of \( G \) allows us to minimize the usage of computer memory. This is done in the following way. For each of the \( N \) stations, a real number column vector \( G_i(1, \ldots, M) \) is calculated. \( G_i \) is analyzed and \( L \) different components are saved into the array \( V \). Two numbers are assumed to be the same if the difference between them is smaller than some given significance threshold; elements less than the calculated or assumed threshold value are set to zero. \( G_i \) becomes now an integer number vector \( K_i \) with elements being positions of values \( G_i \) in the array \( V \).
For example, assume:

\[ G_i = (3.2, 2.2, 1.0001, 1.0002, 0.000014, \]
\[ 0.0000026, 0.0000043, 0.99999, 0.01, 0.01001, \]
\[ 0.009996, 2.3, \ldots, G_{iM}) \]

and

\[ G_i < 0.0001 \Rightarrow G_i = 0 \]
\[ \text{abs}(G_i - G_j) < 0.0001 \Rightarrow G_i = G_j \]

then

\[ K_i = (1, 2, 3, 0, 0, 3, 4, 4, 4, 5, \ldots, K_{iM}) \]

and

\[ V = (0, 3.2, 2.2, 1.0, 0.01, 2.3, \ldots, V_N). \]

Please notice that the array \( V \) is indexed from zero.

Every component of \( K_i \) is an integer number, which means, it needs 2 bytes of memory. \( L \) normally does not exceed 20 000. To win additional memory space, \( K_i \) is then compressed with the Run-Length Encoding (RLE) compression algorithm. RLE works by reducing the physical size of repeating numbers called “run”. It finds sequences of the same elements and saves them as a pair: \{run, run count\}. In our example, the compressed array \( K_i \) has the form

\[ C_i = (\{1, 1\}, \{2, 1\}, \{3, 2\}, \{0, 3\}, \{3, 1\}, \{4, 3\}, \{5, 1\} \ldots). \] (5)

The run count is encoded as a one byte number so every pair has a size of three bytes. Our numerical experiments show that, for example, the initial matrix \( G \) of 1.6 GB can be compressed to about 200 MB which is a reasonable quantity. The compression method presented here contains a risk that the compressed array is greater than the initial one. The nature of the kernel matrix \( G \) allows us to expect that it is not a problem in this situation. In the worst case the compressed kernel has the same size as the uncompressed one and the compression ratio increases with the size of \( G \). The use of this compression method allows also reducing time of computation of the anomalies: zero components are skipped and no needless multiplications by zero are carried out.

The compression ratio can be increased by means of the following method. In some cases, the complicated Nagy formula for a prism can be replaced with the formula for the gravity attraction of a linear, vertical mass:

\[ F_z = \gamma \rho w l \frac{1}{\sqrt{r^2 + z^2}} z^2, \] (6)

where \( w, l \) are width and length of the prism and \( r \) is the horizontal distance to the center of the prism.

Because of the simplicity of formula (6) one can let the algorithm to calculate its value in real time except saving it into \( G \). The algorithm looks for blocks and stations for which the values of formulae (2) and (6) are the same (with a reference to the predefined threshold). The corresponding components of \( G \), i.e. \( K \) are indicated by some special number e.g. 65 000. When the function that computes the anomalies finds this number in \( K \) it does not look for the value in \( V \) but calculates the value using formula (6). This method increases the time required for calculation but dramatically reduces the size of the kernel. Our experiments show that 50–80% components of \( K \) can be replaced with the linear mass formula. All these components are coded with the same number, which makes the RLE algorithm very effective.

3. Accuracy of the method

There are two reasons that explain why the employed method does not provide exact gravity anomalies of the modeled structures. The first one is the nature of the formula used in the calculations. It assumes that the station is outside the body. If we assume that in Fig. 1 the station is in the center of the coordinate system, then no dimension of the prism can cross any axis, and every coordinate of the prism must be greater than zero. If this requirement is not fulfilled, the prism must be either divided or the zero coordinate must be replaced with a slightly greater value e.g. \( 1 \times 10^{-6} \). The second effect influencing the accuracy of the computations is the first part of the applied compression algorithm. Replacing the real values of the kernel \( G \) with the smaller number of values \( V \) (see Eq. (4)) causes very small changes in the resulting gravity field. The same effect is produced if we allow the algorithm to calculate the gravity using formula (6). The RLE algorithm is a non-losing method so it does not produce any effects on anomalies.

We tested our program in two steps. First, we constructed an “infinite” horizontal layer (Bouguer slab) and compared the calculated gravity field with
the theoretical value for such a body:

\[ F_z = 2\pi\gamma\rho h, \]  

where \( h \) is the thickness of the slab.

The second test was a comparison between the anomalies of simple bodies (see Fig. 2) computed by our program with those computed by an application called IGMAS. It is a 3D gravity modeling software based on the polyhedrons method (see Götte and Lahmeyer, 1988), therefore it produces exact gravity effects of the modeled bodies. We performed our investigation two times: first time we used meters as dimension for the model (micro-structure) and the second time—kilometers (macro-structure). It should give information about the accuracy in two field cases: microgravimetry and regional gravity measurements.

In both tests a model built of 64,000 blocks of size: 2.5× dimensional unit and 1681 stations was used. The size of the model was 54 MB and about 80% components of \( G \) were replaced with linear mass gravity. In the Bouguer slab test all blocks were included in calculations, so the maximal error from such a test indicates the maximal error of the model. In order to get an “infinite” slab, the edge blocks were extended into “infinity” (see the next section for details).

The results of the tests are shown in Table 1. To investigate what part of errors is produced by the compression algorithm, the slab anomalies were calculated with use of the non-compressed kernel \( G \). The theoretical value of formula (7) for the micro and macro-structure are 4.1928 and 4192.8 mGal, respectively. For the slab tests the relative errors were calculated.

Both tests proved that the errors are mainly produced by the applied compressing technique. The errors resulting from the Nagy formula are neglectable. The absolute values of the errors depend on scaling of the problem but the relative errors remained constant and were of order \( 1 \times 10^{-4} \). Such an accuracy should be sufficient for most gravity modelings.

4. Structure of the program

3GRAINS is written in C++ and employs all benefits of the object oriented programming. This means that the program is built of several more or less independent modules which can be used as standalone applications or replaced by other modules. The program consists of two main parts: the gravity model module and the graphical module. The model part is independent from its graphical interface and can be used as a core for other programs. All modeling operations as well as input–output functions (IO) are realized within the model module. The graphical module calls functions of the gravity model module and provides tools (by means of GUI) for a fast and interactive modification of its parameters.

The model in 3GRAINS is defined as the object containing information about:

- **Station layout**: Information about the spatial distribution of stations and observed gravity anomalies. Each station is defined by five values: its \( x, y, z \) coordinates and a value of the observed and calculated gravity field at this point. 3GRAINS takes into account the elevation of the station. This means that the \( z \) coordinate in Eq. (1) is calculated with the formula: \( z = \text{prism depth} + \text{station elevation} \). This is important because one misunderstands often the nature of the Bouguer correction. It reduces observed gravity anomalies to datum level, but it takes into account the Earth’s
gravity field. When calculating the gravity field of some geological body, the real distance between the stations and the body must be used.

Stations in 3GRAINS can have arbitrary distribution i.e. they do not need to form a regular grid or profile.

Subsurface layout: Information about the blocks used in modeling. Each block is defined by nine parameters: six spatial coordinates \( x_1, x_2, y_1, y_2, z_1, z_2 \) (as in Fig. 1), its density, layer number and block ID. Layer number is a reference number to a table of defined layers. ID is a unique number assigned to each block.

Layers layout: Information about the defined layers. Blocks belonging to the same layer are distinguishable from blocks belonging to the other layers. Each layer is defined by:

- name;
- minimum and maximum density which can be assigned to blocks belonging to it;
- interval of the density scale;
- colors assigned to minimum and maximum density, interpolated colors will be assigned to densities between the extreme values; these colors define a color scale which is used to display the modeled structure.

The layers in 3GRAINS do not need to have a geological sense and they do not need referring to horizontal structures.

Kernel: The compressed kernel array that translates information about density distribution from Subsurface layout to gravity anomaly in Station layout.

Reference density: This value is subtracted from the density of blocks during the calculation of the gravity anomaly of the model. It can be interpreted as an additional layer. Initially all blocks of a new model are assigned to the reference density layer.

Shift value: In order to enable a comparison between these two fields a constant shift value is added to the calculated anomalies. The user can set assumed shift value or it can be calculated automatically. The level of the measured and calculated gravity fields are usually different because:

- the observed field refers to some defined datum while the calculated field refers only to the relative anomalies of the model;
- the observed field is often a residual (e.g. filtered) field;
- the calculated anomalies depend on the difference between applied densities and the arbitrary chosen reference density.

To set up a new model two ASCII files are needed: a Station layout file and a Subsurface layout file. Both should use the same spatial dimension: meters or kilometers. The Station layout file has four columns with \( x, y, z \) coordinates of each station, and a measured gravity anomaly in mGal. The fifth column with the observed gravity anomaly is added automatically by the program. The Subsurface layout file has eight columns: \( x_1, x_2, y_1, y_2, z_1, z_2 \), density and layer ID of each block. Initially, to all blocks, the layer ID = −1 is assigned (no layer). The program does not check for the correctness of the input data. There should be neither gaps nor overlaps in the structure. Therefore, the Subsurface layout file is supposed to be generated by the external program called prism_generator. The structures generated by this program have the following features: all blocks at the same depth have the same size; height, width and length of the blocks can vary with depth. The program automatically extends the edge blocks into “infinity”. That means that the width or length of these blocks is multiplied by the product of model size and some predefined value.

### Table 1

<table>
<thead>
<tr>
<th>Structure</th>
<th>Mean error (mGal)/relative</th>
<th>Max error (mGal)/relative</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 m slab (not compressed)</td>
<td>( 2 \times 10^{-4}/5 \times 10^{-5} )</td>
<td>( 2 \times 10^{-4}/5 \times 10^{-5} )</td>
</tr>
<tr>
<td>100 m slab (compressed)</td>
<td>( 1 \times 10^{-3}/2.5 \times 10^{-4} )</td>
<td>( 2 \times 10^{-3}/6 \times 10^{-4} )</td>
</tr>
<tr>
<td>100 km slab (not compressed)</td>
<td>( 2 \times 10^{-1}/5 \times 10^{-5} )</td>
<td>( 2 \times 10^{-1}/5 \times 10^{-5} )</td>
</tr>
<tr>
<td>100 km slab (compressed)</td>
<td>( 1.1/2.7 \times 10^{-4} )</td>
<td>( 2.3/5.6 \times 10^{-4} )</td>
</tr>
<tr>
<td>Micro-structure</td>
<td>( 5.5 \times 10^{-2} )</td>
<td>( 1.5 \times 10^{-4} )</td>
</tr>
<tr>
<td>Macro-structure</td>
<td>( 5.5 \times 10^{-2} )</td>
<td>( 1.5 \times 10^{-1} )</td>
</tr>
</tbody>
</table>
The software offers several output possibilities. The whole structure can be saved to an ASCII file that has the same format as the input structure file. The interpreter can also export top or bottom of the surface of the chosen layer or the densities of the selected horizontal or a vertical slice. Our philosophy was to put no effort to the development of 3D views of the modeled structure, but to enable exporting data from the program and visualize it with an external software e.g. Generic Mapping Tools (GMT).

6. Density model of the Hellenic Subduction Zone

The presented software was developed during a work on inversion of gravity data from the Hellenic Subduction Zone. It is a region of a very complicated tectonic situation. The most significant tectonic activity is subduction of the African plate beneath the Eurasian plate along the Hellenic Arc (see e.g. Papazachos et al., 1995; Papazachos and Nolet, 1997). Other important tectonic activities in the region are the westward motion of Turkey along the North Anatolian fault and the south-east motion of the southern Aegean (see e.g. McClusky et al., 2000). All these processes are indicated by the seismic activity which is the highest in Europe. Fig. 4 shows distribution of hypocenters from...
Advanced National Seismic System (ANSS) catalog. The Bouguer gravity field (see Fig. 5) is characterized by regional anomaly variations from \(-40\) to \(+180\) mGal and very strong local horizontal gradients. All these data indicate a process of a retreating subduction with a crustal extension north of Crete.

A density model of the region was constructed to investigate the density structure of the first-order tectonic units of the region: sediments, oceanic and continental crystalline crust and upper mantle. The goal was to construct a model, which reflects the complexity of the tectonic structures and has a reasonable size i.e. it should fit in our computer memory (\(\approx 255\) MB). Because of the very high density

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curvature of the Wadati–Benioff zone (see e.g. Papazachos and Comninakis, 1971; Papazachos et al., 2000), and probably significant gravity effect of the subducting African lithosphere, the model must extend to a depth of 150 km i.e. the maximum depth of the oceanic slab in the region. We modeled the central part of the region with Crete in the center of a 400 × 500 km rectangle. The observed Bouguer anomalies were averaged on 10 × 10 km grid covering the modeling area which gave 2091 stations.

The heights of the blocks varied with depth and reflected complexity and relief of the modeled geological layers. The height of the prisms in the first 5 km was set to 1 km. Finally prisms constituting the upper mantle had heights: 5 km (between 55 and 100 km depth) and 10 km at the deepest part of the model. Hence, the model was divided into 50 × 40 × 39 = 78,000 blocks. Each prism could be assigned to one of the defined layers: seawater, sediments, upper and lower continental crust, oceanic crust and upper mantle (divided into African and Aegean mantle and asthenosphere; see Fig. 6). Densities of the layers are given in Table 2. The whole model (blocks + stations + kernel array) had the size of 150 MB. To minimize the time needed to calculate the anomaly, only modeling of the regional field of subducting slab was processed using this model. Basing on the information from seismology (see e.g. Papazachos et al., 2000; Endrun et al., 2004) the slab was modeled. The model did not include any information about crustal densities (except the subducted oceanic crust). In order to obtain the gravity effect of structures deeper than 50 km, densities of all blocks above this depth were set to the reference density. The resulted field was subtracted from the original Bouguer anomalies. The residual field was used in the further modeling i.e. will be called the observed field.

On account of the presented field separation, the model depth was reduced to 50 km. The structure of the model remained unchanged. In the obtained crustal model the upper part of the slab was still present but its geometry remained fixed and could be used as a constraint. Hence, the structures resulted from the crustal model could be easily reimported into the original model.

<table>
<thead>
<tr>
<th>Layer</th>
<th>Density (g/cm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seawater</td>
<td>2.67⁺</td>
</tr>
<tr>
<td>Sediments</td>
<td>1.9–2.6</td>
</tr>
<tr>
<td>Upper crust</td>
<td>2.6–2.8</td>
</tr>
<tr>
<td>Lower crust</td>
<td>2.75–2.9</td>
</tr>
<tr>
<td>African mantle</td>
<td>3.35–3.4</td>
</tr>
<tr>
<td>European mantle</td>
<td>3.3</td>
</tr>
<tr>
<td>Asthenosphere</td>
<td>3.35</td>
</tr>
</tbody>
</table>

⁺Bouguer reduction density.
7. Results

The resulting model is constrained by passive seismological observation (see e.g. Papazachos et al., 1995; Papazachos and Nolet, 1997; Meier et al., 2004; Endrun et al., 2004) and data from active seismic experiments (see e.g. Bohnhoff et al., 2001; Truffert et al., 1993; Fruehn et al., 2002) and is comparable with our previous modeling (see Casten and Snopek, 2005). The modeling was processed using absolute density values and a reference density $\rho_{\text{ref}} = 3.3\, \text{g/cm}^3$ (density of the European upper mantle). A constant shift value of 520 mGal has been added to the calculated anomalies.

Fig. 7 displays a map of differences between the observed and calculated anomalies and their statistical distribution. The map of misfits shows only high-frequency differences that reflect local, surfacenear structures. A standard deviation of the misfits is about 12 mGal. Because we are interested in the regional structures, it is a satisfying result. From the final model we have exported four horizontal cross-sections (see Fig. 8) as well as depths of the continental and oceanic Moho (see Fig. 9). Visualization of these data exported from 3GRAINS has been done with the use of GMT. The horizontal cross-sections show several tectonic features:

(a) At 10 km depth one can recognize different densities of the continental crystalline crust ($2.55-2.7\, \text{g/cm}^3$) and thick oceanic sediments ($2.10-2.5\, \text{g/cm}^3$).
(b) At 20 km depth we observe an uplift of the mantle north of Crete (high densities $3.2-3.3\, \text{g/cm}^3$). In the southern part, the zone of higher densities ($2.9-3.0\, \text{g/cm}^3$) indicates the oceanic crystalline crust. South of Crete a small mantle wedge is visible.
(c) At 30 km depth the mantle densities ($3.2-3.4\, \text{g/cm}^3$) and the thick continental crust beneath Crete ($2.8-2.9\, \text{g/cm}^3$) and south of the island are visible. A mantle wedge is located south-west of the Crete.
(d) At 40 km depth, mainly mantle densities ($3.2-3.4\, \text{g/cm}^3$) are dominant; cold, African, oceanic mantle is distinguishable from the European one; densities between 2.9 and $3.0\, \text{g/cm}^3$ indicate the subducted oceanic crust.

The same structures are displayed on the map of Moho boundary (see Fig. 9). The main features are: thick continental crust under Crete that extends about 100 km south of the island; strong variations of Moho around Crete; significant difference in density of African and European mantle. The presented model shows similar structure as that modeled with IGMAS (see Casten and Snopek, 2005). The use of rectangular blocks allowed, however, horizontal variation of layers densities. Application of this method enables also detailed interpretation by means of an automatic inversion.

8. Summary

A new software that allows interactive gravity modeling was presented. The simplicity in creation of the initial model and its modifications allows fast interpretation of gravity data. A size and resolution...
of models depend mainly on the CPU and RAM of user's computer. Application of compressing techniques enables the saving of the kernel array, which translates densities to gravity anomalies, in computer memory and speeds up the calculations. The presented density model of the Hellenic Arc can be considered as a relatively high-resolution one and has been processed on Pentium III 700 MHz with 256 MB of RAM. The resulting structure has a satisfying resolution enabling the investigation of the first order tectonic units of the region. In comparison to our previous modeling, which was done with IGMAS, the use of rectangular blocks allows horizontal density variations of selected layers and produces a more accurate model.

3GRAINS can be used as a standalone 3D modeling application or as a tool for creation of starting models for an automatic inversion as well as for visualization of inverted structures. It is especially suited for the latter, because most of the
algorithms for inversion of gravity data use the rectangular prism approach.

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References


Fig. 9. Depth of continental Moho (gray shaded relief) and oceanic Moho (isolines with 5 km depth interval).