GEODEZJA I KARTOGRAFIA
GEODESY AND CARTOGRAPHY
Vol. 55, No 4, 2006, pp. 175-191

Numerical analysis of crustal database CRUST 2.0 and comparisons with Airy defined Moho signatures

Dimitrios Tsoulis, Christos Venesis

Department of Geodesy and Surveying, Aristotle University of Thessaloniki
Univ. Box. 440, GR-54124, Thessaloniki, Greece
e-mail: tsoulis@topo.auth.gr

Received: 12 February 2007/Accepted: 1 March 2007

Abstract: The recently released global crustal model CRUST 2.0 has been validated both globally and regionally focusing on its information content regarding the crust-mantle boundary. The numerical assessment of the metric information given by the database in terms of thickness and position of individual crustal layers with respect to sea level takes place by investigating correlations with the surface topography and by comparing those values with known theoretical approaches that describe the compensation mechanism between crust and mantle. The investigations described focused especially on the last crustal layer of CRUST 2.0, which represents the boundary surface between crust and mantle, widely known as Mohorovicic discontinuity. A direct comparison of the Moho structure as given from the crustal model CRUST 2.0 with the respective compensation depths derived theoretically from the application of the Airy/Heiskanen hypothesis is carried out both globally and regionally. The comparisons, especially those referring to selected regions of the globe expressing characteristic tectonic features, such as mountain belts or oceanic ridges, enable both the numerical assessment of the database while giving at the same time a preliminary insight on the local and regional behaviour of known isostatic mechanisms.

Keywords: Global crustal models, Airy/Heiskanen isostasy, Mohorovicic discontinuity, crust-mantle boundary

1. Introduction

The recent developments in computer technology combined with the large availability of terrestrial and satellite data makes possible the efficient manipulation of huge amount of data originating from heterogeneous sources. It resulted in many new global datasets that describe both the geometric figure of the Earth's topography (global digital elevation models) as well as the structure and consistency of the Earth's interior, especially its crustal layers. Those databases are of global coverage and of constantly increasing resolution as even more data are taken into consideration. The availability of such databases leads Earth-oriented disciplines, such as geodesy and geophysics, to a new computational era. Forward modelling algorithms and interpretation techniques of the Earth's gravity field can be applied in the view of the new available data by means of exact analytical methods that incorporate this information. Furthermore, theoretical approaches that used to describe an up to now relatively unknown quantities, such as the structure of the boundary surface separating crust and mantle, can now be tested numerically using the direct data delivered by the new digital databases. Thus, theories such as the compensation mechanism describing the mass equilibrium between crust and mantle, which until recently expressed the product of scientific intuition combined with the evaluation of the sparse direct geodetic observations that were available, can now be validated both globally as well as regionally. The latter is of special interest, as local and regional settings of increased interest in the frame of the above mentioned considerations, such as orogenic belts or ocean ridges, are becoming available both in terms of their structure and their consistency through the new global datasets with an increasing spatial resolution.

In the present study the global crustal model CRUST 2.0, which is a global database of the Earth's crust with density and distinct layer thickness information was validated both globally and regionally. CRUST 2.0 is compiled and administrated by the US Geological Survey and the Institute for Geophysics and Planetary Physics at the University of California (Bassin et al., 2000). It is an updated version of CRUST 5.1, a global crustal model released in 1998 from the same institutions, which comprised almost identical crustal information globally, however with the coarser resolution of $5° \times 5°$ (Mooney et al., 1998). The aim of the present investigation is to proceed to a first numerical evaluation of CRUST 2.0 database, focusing especially on its local and regional characteristics. As the database offers geometric information concerning the structure as well as consistency of distinct crustal layers from the Earth's topography down to the crust-mantle boundary, it is obvious that such an information may be used directly in the frame of diverse geodetic and geophysical applications. Thus, one might use the CRUST 2.0 relevant data in order to compute the contribution of each individual layer to the observed gravity at the Earth's surface by employing one of the standard techniques in forward gravity field modelling. That forward application would be feasible, since both geometry and consistency of the hidden source consists in the case of CRUST 2.0 of known data. Furthermore, and this is the main focus of the present paper, using directly the data emerging from CRUST 2.0 one is allowed to validate local and regional crustal structures, especially those describing the crust-mantle boundary surface. This is of special importance, since the knowledge of the exact structure of this discontinuity boundary surface is a fundamental research topic to many different branches of Earth sciences.

There exist different established techniques for the computation of the Moho structure. There are for example methods that elaborate the inversion of recorded seismic data (e.g. Wilde-Piorko et al., 2005; Geissler et al., 2000) while there also exist methodologies for the estimation of the sea floor topography through a prediction process that involves heterogeneous data sources such as gravity anomalies and satellite altimetry data (e.g. Smith and Sandwell, 1997), a method that could be properly adapted to the problem of estimating the Mohorovicic boundary from the analysis of similar data types. However, the present study will deal solely with the direct information provided by CRUST 2.0 database with regard to the geometry of its final layer, which in itself defines the crust-mantle boundary. Since that information is vital to isostasy and to isostasy-relevant quantities, such as topographic/isostatic Earth gravity models, isostatic reduction processes etc (e.g. Kaban et al., 2004; Tsoulis, 2004), the CRUST 2.0 defined Moho structure will be compared with that emerging from the standard Airy/Heiskanen isostatic model. The global and especially the local comparisons between these two surfaces reveal some very interesting features of the recently released CRUST 2.0 model.

2. The CRUST 2.0 global crustal database

The construction of both CRUST 5.1 and CRUST 2.0 models is based on the analysis of seismic refraction data published up to 1995 and a detailed global compilation of ice and sediment thickness information. Taking advantage among others of a global digital sediment map defined on a $1^\circ \times 1^\circ$ grid, CRUST 2.0 offers a more detailed density structure of the crust and uppermost mantle than the one contained in CRUST 5.1, namely one at a $2^\circ \times 2^\circ$ scale. Averaging available data from active seismic methods and deep drilling over many regions of the Earth, the crustal structure was predicted for representative regions such as most of Africa, South America and Greenland, where direct seismic measurements were available. The final structure of CRUST 2.0 model consists of seven layers, all of them at a global resolution of $2^\circ \times 2^\circ$. Those layers are namely: (1) ice, (2) water, (3) soft sediments, (4) hard sediments, (5) upper crust, (6) middle crust and (7) lower crust. Generalizing the available field measurements into a limited number of primary crustal types by globally averaging data which refer to similar geological and tectonic settings, the model consists of global maps with the depths of the above mentioned layers with respect to mean sea level at a $2^\circ \times 2^\circ$ resolution, while it delivers values for compressional and shear wave velocity as well as density for each of the seven layers and explicitly for every one of the 16200 grid elements defining each layer. In particular, CRUST 2.0 delivers a total of eight topography maps t_i, $i = 0, 1, \ldots, 7$, as two-dimensional fields with elements corresponding to individual cells of dimensions $2^\circ \times 2^\circ$. The first of those maps describes the top of water and topography, while the rest correspond respectively to the bottom surface of water, ice, soft and hard sediments, upper, middle and lower crust. The maps define the geometry of the boundary surface between two neighbouring layers. In other words the aforementioned eight global maps define a total of seven distinct crustal layers. Each of those layers is accompanied by an extra map of the same dimensions containing $2^\circ \times 2^\circ$ block density values as an estimate for the respective crustal layer. It is important to stress, that those values vary within each layer, thus reflecting local and regional characteristics of the crustal structure. Mean water depth as well as topography within the $2^\circ \times 2^\circ$ tiles were adopted from the 5-arcminute resolution data set ETOPO-5 of the National Geophysical Data Center (1988).

From the total information content of model CRUST 2.0, here only that referring to the consistency and the geometry of each individual layer is going to be considered.

Table 1 presents the statistical information for the density values expressed in g/cm^3 describing the density distribution of each global crustal layer. It is important to note, that CRUST 2.0 offers density estimates for the upper mantle as well. Thus, Table 1's inclusion of an additional record referring to the upper mantle should not be misinterpreted as if the database included an additional (8th) crustal layer. The statistical quantities min, max, the mean and the standard deviation were computed over all 16200 grid values defining each layer in a global scale.

Table 1. Statistics of the density information for each CRUST 2.0 layer expressed globally [g/cm^3]

Layer	Min	Max	Mean	Std dev.
ice	0.92			
water	1.02			
soft sediments	1.70	2.30	1.99	0.22
hard sediments	2.30	2.60	2.35	0.06
upper crust	2.60	2.80	2.67	0.08
middle crust	2.80	2.90	2.89	0.03
lower crust	2.90	3.10	3.04	0.05
upper mantle	3.30	3.50	3.37	0.03

Except from ice and water, where constant density values of 0.92 g/cm^3 and 1.02 g/cm^3, respectively have been assigned to all relevant tiles of the first two layers of the database, this is not the case for the rest of the layers. The analysis and compilation of diverse primary and indirectly derived crustal data (a large amount of seismic refraction data combined with information steaming from digitizing geologic maps and atlases) as well as the application of established prediction methodologies that extend this information to areas were no crustal data exist, permits the construction of a 3-D crustal density model, that provides crustal density variations down to the crust-mantle boundary (Mooney et al., 1998). Although not directly provided by the model, the geometry of the boundary surface of each layer given from CRUST 2.0 in terms of the depth of each tile from sea surface, can be used to deduce another useful property of these layers, namely their thickness. Table 2 gives the resulting thickness information for each CRUST 2.0 crustal layer (except from ice and water) expressed globally. The thorough analysis of this information leads to first numerical assessment of the model, especially in view of its global coverage, general characteristics and topography or other tectonic related features. The ice and water layers have been obtained from the direct adaptation of the $5' \times 5'$ global elevation model ETOPO5 (NGDC 1988), who's information has been generalized to the sparser resolution $2^\circ \times 2^\circ$ of CRUST 2.0. That elevation data has been combined in the case of the ice layer with the information contained in global atlases for the global ice coverage. The information presented in Tables 1 and 2 as well as their assessment resulting from the representation of the respective fields in terms of global plots, allow some first interesting remarks concerning the overall quality and information content of CRUST 2.0 database. For example, according to the model, the thickness of the ice layer (information not present in Table 2) has a mean of 1.74 km with a maximum value of 3.5 km occurring at Antarctica.

Table 2. Layer thickness information resulting for each CRUST 2.0 crustal layer (except from ice and water) expressed globally [km]

Layer	Min	Max	Mean	Std dev.
soft sediments	0.0	2.0	0.575	0.549
hard sediments	0.0	18.0	0.546	1.368
upper crust	1.7	25.0	6.686	5.629
middle crust	2.3	25.0	6.778	5.033
lower crust	2.5	25.0	6.271	4.213

The detailed description of global sediment depositions was one of the main motivations striving the development of model CRUST 2.0. The depths of the soft sediments layer vary globally from 7.43 km with respect to mean sea level underneath oceanic parts of the globe down to 5.37 km at the Himalayas. At the continental parts the depths of this layer, also expressing its lower boundary with the follow-up layer of hard sediments takes values varying from 0.5 km up to 2.0 km below surface topography. The correlation of the soft sediments layer with topography is apparent, since the preliminary analysis of this information obtained from CRUST 2.0 model reveals a proportional relation between the topographic heights and the depth of the boundary surface between soft and hard sediments. The same relation holds consequently for the thickness of this layer. An overall glance on the global distribution of the thickness values for the soft sediments layer leads to the observation that such depositions are almost (although not completely) absent from the oceanic regions of the Earth. Furthermore, over the continental parts the soft sediments layer thickness obtains a mean value of roughly 1 km, whereas the maximum of these depositions occur at coastline regions, where the global mean thickness value of the soft sediments layer becomes 1.6 km. Interesting remarks can be drawn for the variations of the density values for this layer as well. Thus, according to model CRUST 2.0, the density of the soft sediments layer obtains its minimum value of 1.7 g/cm^3 over oceanic regions and becomes maximum in some areas of Greenland and Antarctica where it is reported to be equal to 2.3 g/cm^3. Greater density values occur for those areas, for which also greater thickness values are reported, such as continental and coastline regions. Similar observations seem to apply to the hard sediments layer of the CRUST 2.0 model as well. Hard sediments can be found occasionally down to 15 km below mean sea surface at coastline areas, where the maximum thickness values of this layer are reported with a global mean value of 10 km. The thickness of the hard sediments layer has a mean value of 3 km over continental parts of the globe, while over oceanic regions these depositions can only be scarcely tracked. The density of hard sediments obtains its smallest value of 2.3 g/cm^3 at the oceans and varies up to 2.6 g/cm^3, a value that can be traced sporadically at individual tiles at the north of Canada.

2.1. Upper, middle and lower crust

The lower boundary of the fifth in order layer of model CRUST 2.0, namely that of upper crust, reveals a rather homogeneous structure under oceanic regions with depth values of the order of magnitude of 6 km with respect to mean sea surface. On the other hand, underneath continental parts the depth of the same boundary surface reveals a much more uneven character with depth values that vary between 12 km and 25 km and change proportional to the elevation of the topographic relief. Thus, the maximum depth values of the upper crust layer are located under Himalayas, at profound orogenic structures at Chile and parts of North America, as well as at parts of the coastline region of the Atlantic Ocean. The density variations of 2.6 g/cm^3 up to 2.8 g/cm^3 for this layer are distributed rationally over the globe (smaller values occur under oceans, larger values appear under continents). Interestingly enough, the maximum density values for this layer occur at flat continental regions and not mountainous areas, as it would be perhaps expected. The thickness of the upper crust layer below oceans obtains relative small values with a mean equal to 2.5 km and a minimum of 1.7 km. The global statistics for the thickness of this layer are presented in Table 2, while for its global distribution the same remarks hold as the ones mentioned above for the structure of the lower boundary of this layer.

Similar features are revealed from the numerical assessment of the middle crust layer as well. The depth of that layer with respect to mean sea level exhibits a rather homogeneous feature beneath oceans having an almost constant value slightly perturbing around 8 km globally, while beneath continental regions the variations of the same boundary surface is much more intense with numerical values exceeding up to even 45 km at regions with rough topography, such as the Himalayas or parts of South and North America. The resulting depth of the same layer proves also to vary accordingly. Thus, at oceans it obtains small unperturbed values with a mean of the order of 3.5 km, while at the continental parts the variations of the middle crust layer thickness depend on the roughness of the surface terrain where it can reach in some cases the value of 25 km. The density of the middle crust varies globally between 2.8 g/cm^3 and 2.9 g/cm^3. However, in contrast to the upper crust layer, here greater density values occur at oceans and smaller beneath continents. A thorough analysis of the geographical distribution of these values led to the interesting remark, that the larger density values of this layer are reported at plane continental regions and beneath oceans and not, as perhaps expected below distinct orogenic formations.

The final CRUST 2.0 crustal layer is that of lower crust. The importance of this information is twofold. On the one hand it provides the detailed description of an independent crustal layer, while also expressing the boundary surface between crust and mantle, the known Mohorovicic discontinuity surface. The depth of that layer, which is the direct information of model CRUST 2.0 regarding the global Moho structure, varies rather homogeneously around 10 km at oceans, proving to vary much more roughly beneath continents, where it obtains values from 30 km up to 70 km at areas with increased topographic elevation, such as the Himalayas and South America. At these areas the greater thickness values of this layer occur as well, namely values of the order of 25 km. On the contrary over oceanic parts of the globe, the thickness of that layer reaches much smaller values having a mean equal to 4 km with a minimum of 2 km. The information regarding the distribution of density values, which for this layer vary globally between 2.9 g/cm^3 and 3.1 g/cm^3, can be exported, likewise with the previous layers, from the global representation of the 2-D field of 2° × 2° density values and the identification of the exact geographical location of the respective numerical values. In this manner, it has been found that smaller density values for the lower crustal layer occur at continental regions, while larger values occur underneath oceans. That remark comes in compliance with the density distribution of the middle crust layer; however it is the exact opposite distribution that takes place at the upper crust layer. In overall, large density values appear at roughly plane continental regions, while the largest values are reported over the majority of Europe and some parts of Southeast Asia, North America and Antarctica.

The CRUST 2.0 model concludes with the information regarding the density of the uppermost mantle. For that layer no geometrical data are accompanied, i.e. information concerning the depth and structure of that layer is absent. What is given for the material adjacent to the Moho boundary is a global 2° × 2° distribution of density values. The fact that this information is given in the same global resolution as the information on the rest of the crustal layers enables the evaluation of density contrast values between the lower crust and the upper mantle layer with a 2° × 2° global resolution and a geometric position with respect to the surface topography equal to the depth information of the lower crust layer. The distribution of the uppermost mantle density values does not present any special global feature. The values provided by CRUST 2.0 vary from 3.25 g/cm^3 up to 3.45 g/cm^3 with smaller values occurring over Europe, Antarctica and North America and larger values appearing at the Himalayas and the Andes.

3. Airy/Heiskanen Moho structure

The Airy/Heiskanen local isostatic model is based on the assumption that a crust of constant density and variable thickness floats in a state of hydrostatic equilibrium above a denser mantle having also a constant density value. The resulting constant density contrast between crust and mantle occurs at the base of the crust, while, in order to fulfil the hydrostatic equilibrium hypothesis, the boundary surface between crust and mantle varies according to the actual fluctuations of the surface topographic relief. Thus, crustal roots occur beneath continental regions with depth increasing with increasing elevation of the respective surface terrain, whereas so-called anti-roots should be present below oceanic regions. In other words the Airy/Heiskanen isostatic model implies a thick crust beneath continents and a thinner crust below oceans. The extension of the respective roots and anti-roots refers always to a certain depth with respect to sea surface, called compensation depth. Typical values for the compensation depth have an order of magnitude of 30 km, however many geodetic studies in the past have questioned the validity of such an assumption (e.g. Tscherning, 1985; Sünkel, 1986).

The derivation of explicit relations for the size of root and anti-root thicknesses in the Airy/Heiskanen theory elaborates the rigorous equilibrium mass condition between a mass element at the surface and its respective counterpart at a certain depth below sea level. Expressing this condition in a mathematically rigorous manner one obtains in spherical approximation the following equation

$$\iint_{\sigma} \int_{r=R}^{R+h} \rho_{cr} r^2 dr d\sigma = \iint_{\sigma} \int_{r=R-D-t}^{R-D} \Delta\rho r^2 dr d\sigma \tag{1}$$

where R is a mean radius value for an approximately spherical Earth, a quantity that coincides in that spherical model with global mean sea level, h denotes the elevation of topography and bathymetry with respect to the aforementioned mean Earth sphere, whereas ρ_{cr} and $\Delta\rho$ stand for the density and density contrast values of the surface mass element and its compensating counterpart, respectively. The assumption that both elements are characterized by a constant density distribution permits the placement of the density parameters ρ_{cr} and $\Delta\rho$ outside the respective integrals in (1). Furthermore, r in (1) is the radial distance with respect to the centre of the sphere expressing also the integration parameter in the radial direction, $d\sigma$ is the differential surface element of the elementary mass particle with respect to the total surface σ expressing the cross section of the elementary mass particle and finally the parameters D and t are linked directly with the definition of the Airy/Heiskanen model. Thus, D stands for the certain constant depth below sea surface called compensation depth. It is a reference surface with respect to which the actual extent of the crustal roots and anti-roots entering the theory are evaluated. The compensation depth has thus a concrete physical meaning in Airy/Heiskanen theory. However, its selection can be done arbitrarily. In other words, D is a user-defined parameter. Different values lead to a different realization of the Airy/Heiskanen model but not to a failure of the theory. Although 30 km is a typical value for D that is more often mentioned in the relevant literature, there have been several studies mainly in the frame of the analysis of a global elevation database for the evaluation of topographic/isostatic gravity models, that attempted to relate the selection of a specific numerical value for D with certain spectral characteristics of the respective elevation models (Sünkel 1986; Rummel et al., 1988).

The mass balance relation expressed by (1) relates ultimately the height of the topographic relief above sea level with the magnitude of sinking or emerging of the crustal masses with respect to a reference compensation level. Depending on whether one refers to a continental topographic column or to an oceanic mass element, the parameter t expresses the magnitude of the crustal root or anti-root respectively with respect to a predefined constant compensation depth D. The mathematical solution of (1) towards a rigorous relation for t leads to a solution of a third order polynomial equation in parameter $t/(R-D)$ (for details see Rummel et al., 1988; Claessens. 2003).

Retaining only the linear terms in the subsequent iterative solution of this equation one obtains the final expression for t (Lambeck, 1988; Tsoulis, 2001)

$$t = \left(\frac{R}{R-D}\right)^2 \frac{\rho_{cr}}{\Delta\rho} h \tag{2}$$

for the case of continental masses, and

$$t' = \left(\frac{R}{R-D}\right)^2 \frac{(\rho_{cr} - \rho_w)}{\Delta\rho} h \tag{3}$$

when referring to the anti-root crustal structure below oceans, with ρ_w denoting a constant water density value. Computing equations (2) and (3) for a given global elevation model and for a certain numerical value for the reference compensation level leads to an Airy-defined global Moho structure.

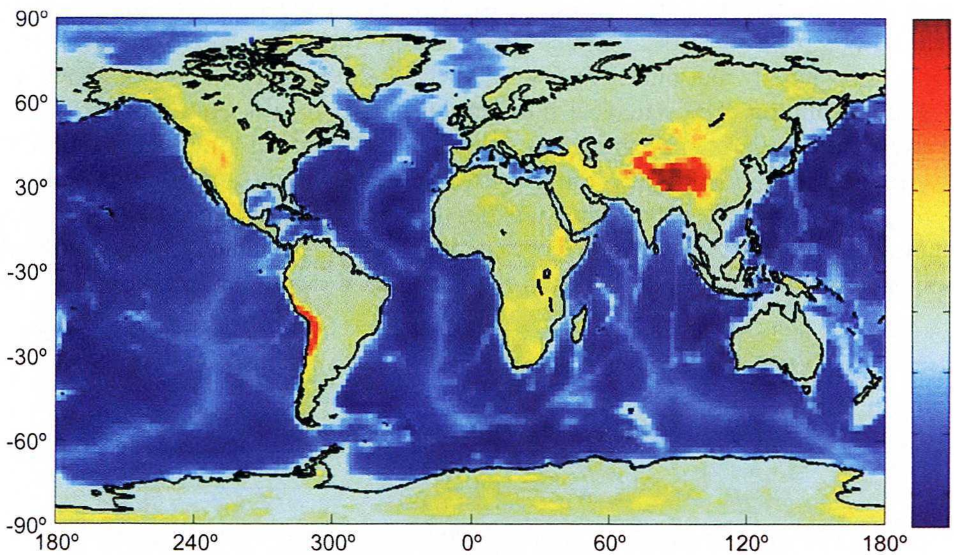

Fig. 1. Theoretical Airy/Heiskanen derived Moho depths at a global scale [km]

Figure 1 presents the aforementioned computations for the global elevation model that accompanies database CRUST 2.0. It is an elevation model given also at a $2° \times 2°$ resolution that resulted from the appropriate down-sampling of the much denser global terrain database ETOPO-5. The depth of the crust-mantle boundary with respect to mean sea level, which is presented finally in Figure 1, represents a theoretically computed surface, which complies with the Airy/Heiskanen isostatic theory, and was evaluated with (2) and (3) using the numerical values ρ_{cr} = 2.67 g/cm^3, ρ_w = 1.02 g/cm^3 and $\Delta\rho = \rho_m - \rho_{cr}$ = (3.4 – 2.67) g/cm^3 = 0.73 g/cm^3, with ρ_m an approximate numerical value for the density of the mantle taken here equal to 3.4 g/cm^3. The evaluated root and anti-root thicknesses t and t' were then added to and subtracted from respectively the globally defined compensation depth of D = 30 km to produce finally the Airy-defined and theoretically computed Moho depths. The global variation of this surface, as Figure 1 clearly demonstrates, is a solid manifestation of the Airy hypothesis as the Moho surface which is depicted in this global map undoubtedly mirrors the actual topography. The larger Moho depths occur according to the Airy theory there, were also the larger topographic elevations take place, while the smaller depths of the crust-mantle boundary are reported below deep oceans, were the anti-root thickness t' obtains large numerical values.

4. CRUST 2.0 Moho structure

The global Moho structure displayed in Figure 1 can be compared directly with the respective information of the CRUST 2.0 database. Therein the information for the crust-mantle boundary surface is expressed by the geometric data of the final layer of the database, namely that of lower crust. The data concerning the depth of each individual tile from mean sea surface gives readily the Moho depth of the specific station. Consequently that final 2-D field of CRUST 2.0 is merely a global Moho map at $2° \times 2°$ resolution. The statistical information of this data is presented in Table 3. Also presented in the same table is the respective theoretically derived Moho data, that were evaluated globally with the same resolution using the approach described in the previous section, as well as the statistics regarding the difference between these two fields, namely the Airy-defined Moho depths (equations (2) and (3) adapted to the compensation depth of D = 30 km) and the CRUST 2.0 Moho information.

Table 3. Depth of the Mohorovicic discontinuity with respect to mean sea level computed globally from the theory of Airy/Heiskanen and extracted from crustal model CRUST 2.0 as the direct information of its final layer [km]

	Min	Max	Mean	Std dev.
Airy model	12.29	54.11	24.50	6.82
CRUST 2.0	7.96	70.14	22.97	7.91
Airy – CRUST 2.0	0.00	30.61	6.42	3.72

The CRUST 2.0 Moho data reveal a global mean value of 22.97 km, several kilometers less that the respective value of the Airy-defined calculations for the same surface. The geographical distribution of the CRUST 2.0 Moho structure in overall comes in good agreement with the respective representation of the Airy-defined Moho depths, although some interesting remarks arise from the comparison of the two surfaces. Thus, for example the largest Moho depth in the Airy-defined surface equals 54.11 km, occurs at the Himalayas and is a whole 25 km less than the respective Moho depth of CRUST 2.0 database at the same geographical location. On the other hand, the smallest Moho depth values for the Airy-derived field are reported at the deepest oceanic regions, are of the order of magnitude of 12.5 km and are almost 4 km bigger than the respective CRUST 2.0 data. Apart from these local discrepancies, in overall the

CRUST 2.0 Moho structure complies with the general Airy concept (thick crust below continents, thin crust beneath oceans), however not verifying in a strict mathematical sense Airy's hypothesis. Large CRUST 2.0 Moho depths occur at profound orogenic formations, while the smallest values of the order of 8 km are reported here also at the deepest oceanic regions.

In order to visualize the behaviour of the data presented in Table 3 several global sections of these 2-D fields were taken along different geographical profiles. Figure 2 presents the results of such a section defined at latitude $\varphi = 41°$. The upper panel displays the variation of the topography, the next two panels give the Airy-derived and the CRUST 2.0 provided Moho structure for the same section respectively, while the last panel depicts the difference of the previous two. The latitude selection was made such, that a most representative cross-section of the global topography may be presented. Indeed, the section obtained for $\varphi = 41°$ contains both rough terrain as well as deep bathymetry and oceanic ridges at the Atlantic Ocean. The Airy-derived Moho depths presented at the second panel from the top clearly mirror the surface topography. The third panel demonstrates the restricted quality of CRUST 2.0 model over both oceanic parts (Pacific and Atlantic), where the lack of information leads to an almost plane representation of the Moho structure. For the continental parts on the other hand CRUST 2.0 database offers a rather detailed image of the Moho discontinuity, which in overall agrees in order of magnitude with the one calculated from the Airy model. Thus, crustal roots occur underneath continents, with growing magnitude with respect to the height of the visible topography. The $2° \times 2°$ resolution of CRUST 2.0 offers a fairly detailed Moho structure at the continental parts, as the third panel in Figure 2 soundly demonstrates. The final panel displays the differences between the data presented in the previous two panels. One remarks, that the difference between the two surfaces ranges along this specific profile from +15 km to −15 km. The positive maximum values, i.e. there, where CRUST 2.0 crustal roots grow deeper in the mantle than the respective Airy-defined quantities, take place over continents (North America and the Himalayas), while the negative maximum difference, there where Airy-defined crustal roots are thicker than those implied by the CRUST 2.0 database, can be found at oceans, in particular at the Atlantic Ocean and the Philippines.

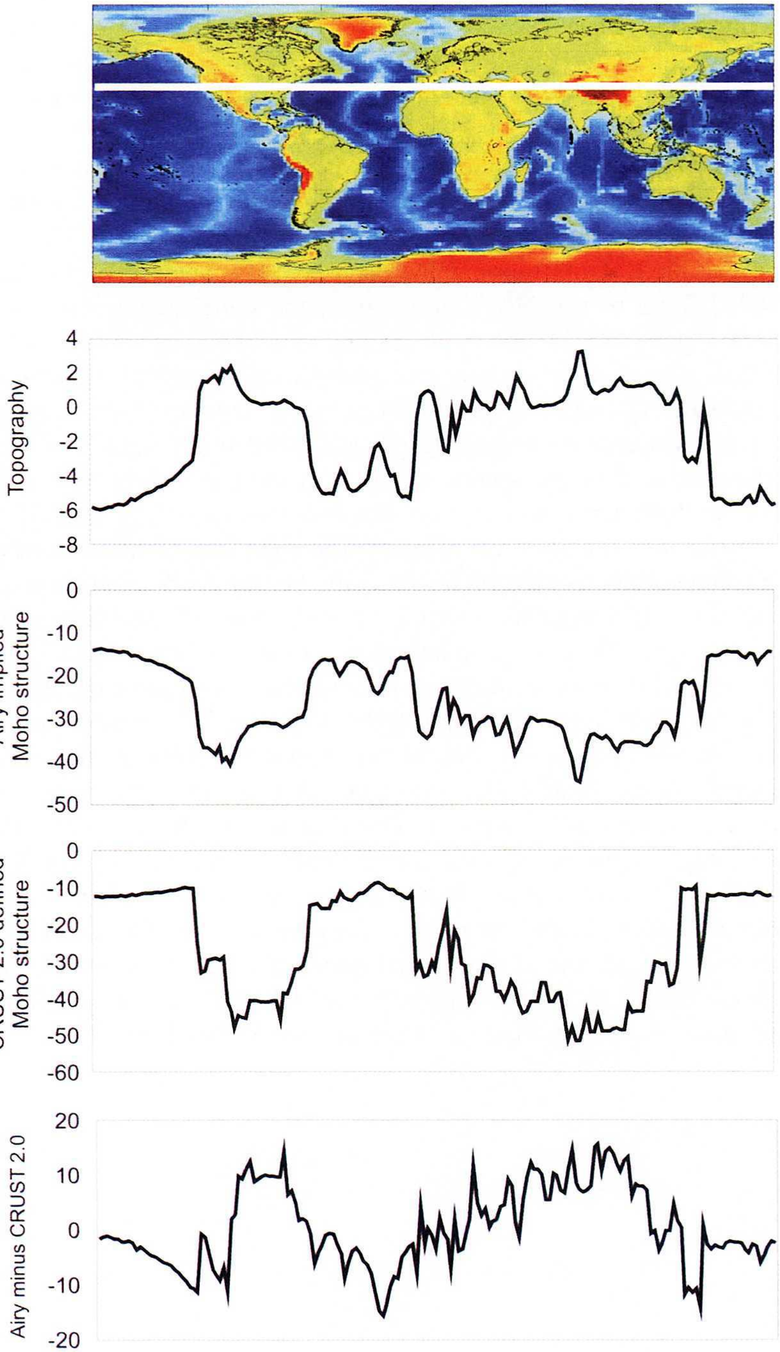

Fig. 2. Global profile for differences between theoretical Airy/Heiskanen and CRUST 2.0 defined Moho depths for $\varphi = 41°$ [km]

4.1. A test window for regional Moho structure

In order to obtain a regional glims of the above information as well as the comparison between Airy-defined and CRUST 2.0 Moho structure, a regional area was defined that stretches over $18^\circ \leq \lambda \leq 30^\circ$ and $32^\circ \leq \varphi \leq 44^\circ$. The area covers the southest part of the Balkan peninsula, i.e. the area surrounding Greece. This region is represented inside CRUST 2.0 database from a total of 100 tiles per crustal layer. Tables 4 and 5 present the respective statistical information.

Table 4. Statistics of the density information for each CRUST 2.0 layer for the region $18^\circ \leq \lambda \leq 30^\circ$ and $32^\circ \leq \varphi \leq 44^\circ$ [g/cm^3]

Layer	Min	Max	Mean	Std dev.
water	1.02			
soft sediments	2.10	2.20	2.13	0.05
upper crust	2.60	2.80	2.73	0.05
middle crust	2.80	2.90	2.86	0.05
lower crust	2.90	3.10	3.02	0.09
upper mantle	3.30	3.40	3.36	0.05

Table 5. Layer thickness information resulting for each CRUST 2.0 crustal layer (except from water) for the region $18^\circ \leq \lambda \leq 30^\circ$ and $32^\circ \leq \varphi \leq 44^\circ$ [km]

Layer	Min	Max	Mean	Std dev.
water	1.02			
soft sediments	0.5	1.5	1.125	0.351
upper crust	1.7	20.0	9.704	4.007
middle crust	2.3	20.0	9.796	3.569
lower crust	2.5	13.5	8.740	2.501

The hard sediments layer is absent from the defined window, something that is not rare in CRUST 2.0 database and occurs over regions that no relevant information exists on the specific layer. The density values appearing in all 100 tiles defining the test area devise very small variations from layer to layer. As Table 4 shows, the crustal density increases gradually from the surface of the topography to the crust-mantle boundary, not showing any large variations within each layer and having a total mean value of 2.69 g/cm^3. The thickness of the soft sediments layer proves to be directly correlated with the topographic variation of the test area, showing in general small numerical variations. In overall three numerical values for the thickness of this layer are present for the defined region, namely 0.5 km, 1.0 km and 1.5 km. The 1.5 km value is found at the area of the Ionian trench, while the thickness of the layer decreases constantly as the topographic elevation increases. The $2^\circ \times 2^\circ$ resolution of the database is unable to describe in detail the crustal properties of the very long and complicated coastal regions that appear in this part of the Mediterranean. The correlation of the thickness of individual crustal layers with variations in topography/bathymetry is confirmed for the rest CRUST 2.0 layers as well. Thus, the thickness of the upper crust layer proves to obtain a maximum value of the order of 12 km over continental parts, while a much smaller value is assigned at sea, where it obtains a mean value of 7 km. The middle crust layer reaches depths of almost 40 km at parts of eastern Turkey with a mean value over the continental part of Greece equal to 23 km. Moving towards the deeper crustal layers one verifies the general concept of the Airy hypothesis inside the distribution of the CRUST 2.0 data, as gradually a direct correlation of the depths of the individual layers with the variations of the surface topography can be detected.

The depth of the lower crustal layer for the test area, i.e. the crust-mantle boundary surface, obtains its largest values over the continental part of Greece and is of the order of 40 km, whereas the minimum values around 20 km occur at sea. Figure 3 presents a numerical comparison between those data and the respective Airy-computed Moho depths for the same region. The comparison demonstrates a fairly good agreement between the two datasets, outlining however a relative visible correlation of the magnitude of the differences in the Moho structure with the overall tectonic setting. Thus, although the difference between Airy-defined and CRUST 2.0 Moho depths takes numerical values of up to several kilometers, larger numerical values that reach up to 11 km are obtained along the Ionian trench. However, the sparse resolution of CRUST 2.0 and the unavailability of other independent sources for the evaluated or even predicted structure of the Moho surface over the specific region allow only a preliminary assessment of the quality of the CRUST 2.0 contained Moho-information for that region.

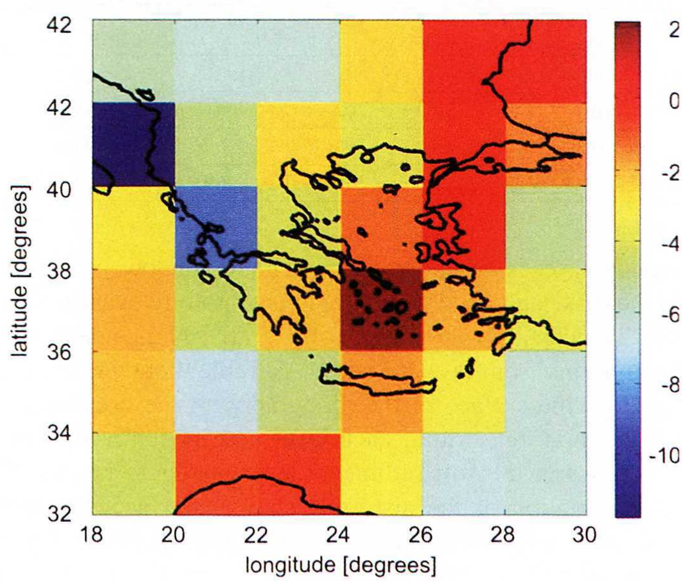

Fig. 3. Differences between Airy/Heiskanen induced and CRUST 2.0 defined Moho depths for the study area $18° \leq \lambda \leq 30°$ and $32° \leq \varphi \leq 44°$. Negative values denote locations where *Moho depth (Airy)* > *Moho depth (CRUST 2.0)* in absolute sense [km]

5. Conclusions – discussion

The numerical assessment of global crustal databases is an essential step prior to the direct application of their geometrical and physical features. Although representing a completely novel type of information with global coverage, this does not imply that their crustal estimates are errorless or apply everywhere. Seismic refraction data analysis, which builds the foundation of the primary data types that enter the evaluation algorithm of such databases, such as CRUST 2.0, can only represent locally defined crustal structures, although, due to the lack of the respective information in a global scale, they have been used to generalize homogeneous crustal types for different regions around the globe. In other words, the CRUST 2.0 data offer a very useful tool for gravity field related investigations, they should be opposed however, whenever this is possible, to independently estimated crustal characteristics for the same area or region. A further constraint of the CRUST 2.0 data results from their limited resolution. A $2° \times 2°$ sparse dataset can be used only approximately in the frame of gravity field modelling related applications, where normally increased resolution and accuracy are envisaged. On the other hand, for computations that refer to greater regions and cover large continental or oceanic parts of the Earth, one may easily rely on the gridded crustal information provided by model CRUST 2.0 for the computation for example of isostatic gravity anomalies according to some standard compensation mechanism. Furthermore, the availability of a variable density information given from CRUST 2.0 for every individual tile that build the individual crustal layers lead to a global three dimensional Digital Density Model of the crust. Although the sparse resolution of that model again limits the applicability of those data, there exist a number of applications, such as the analysis and assessment of gravity field models that could utilize this information. The numerical assessment of the CRUST 2.0 database led to some interesting remarks that hopefully can serve the efficient exploitation of its information for future applications. First of all, the lack of dense primary type data over the oceanic parts of the globe has led to a rather homogeneous representation of the crustal structure underneath the respective regions. On the contrary, the model offers a much more detailed structure of the individual crustal layers under continents, where both the variations of the respective boundary surfaces as well as the variations of the reported arithmetic density values are much more intense.

Acknowledgments

Financial support from the Greek Ministry of Education under the O.P. Education II program "Pythagoras II – Support to Research Teams in the Universities" is gratefully acknowledged. Thanks also go to the anonymous reviewer and the Editor-in-Chief for their helpful remarks.

References

Bassin C., Laske G., Masters T.G., (2000): *The current limits of resolution for surface wave tomography in North America*, EOS Trans AGU 81: F897 (http://mahi.ucsd.edu/Gabi/rem.html).

Claessens S.J., (2003): *A Synthetic Earth Model: analysis, implementation, validation and application*, Delft University Press, The Netherlands.

Geissler W., Plenefisch T., Kind R., Klinge K., Kampf H., Bouskova A., Nehybka V., Skacelova Z., Jacob B., (2000): *The Moho structure in the western Eger rift: a receiver function experiment*, Studia Geophys. Geod., Vol. 44, pp. 88-194.

Kaban M.K., Schwintzer P., Reigber C., (2004): *A new isostatic model of the lithosphere and gravity field*, Journal of Geodesy, Vol. 78, pp. 368-385.

Lambeck K., (1988): *Geophysical geodesy. The slow deformations of the Earth*, Clarendon Press, Oxford.

Mooney W.D., Laske G., Masters T.G., (1998): *CRUST 5.1: A global crustal model at* 5° × 5°, Journal of Geophys. Res., Vol. 103, pp. 727-747.

National Geophysical Data Center, (1988): *ETOPO-5, bathymetry/topography data, Data Announcement 88-MGG-02*, National Oceanic and Atmospheric Admin., US Dept of Commerce, Washington, DC.

Rummel R., Rapp R.H., Sünkel H., Tscherning C.C., (1988): *Comparisons of global topographic/isostatic models to the Earth's observed gravity field*, Report 388, Department of Geodetic Science and Surveying, The Ohio State University, Columbus.

Smith W.H.F., Sandwell D.T., (1997): *Global sea floor topography from satellite altimetry and ship depth soundings*, Science, Vol. 277, pp. 1956-1962.

Sünkel H., (1986): *Global topographic-isostatic models*, In: Lecture Notes in Earth Sciences, Vol. 7, Mathematical and Numerical Techniques in Physical Geodesy, (ed.) H. Sünkel, Springer Verlag, pp. 418-462.

Tscherning C.C., (1985): *On the long-wavelength correlation between gravity and topography*, Proc. of the 5th International Symposium 'Geodesy and Physics of the Earth', Magdeburg, 23-29 September 1984, Veröffentlichungen des Zentralinstituts für Physik der Erde, Nr 81, Potsdam, pp. 134-142.

Tsoulis D., (2001): *A comparison between the Airy/Heiskanen and the Pratt/Hayford isostatic models for the computation of potential harmonic coefficients*, Journal of Geodesy, Vol. 74, pp. 637-643.

Tsoulis D., (2004): *Spherical harmonic analysis of the CRUST 2.0 global crustal model*, Journal of Geodesy, Vol. 78, pp. 7-11.

Wilde-Piorko M., Saul J., Grad M., (2005): *Differences in the crustal and uppermost mantle structure of the Bohemian massif from teleseismic receiver functions*, Studia Geophys. Geod., Vol. 49, pp. 85-107.

Analiza numeryczna bazy danych gęstości skorupy ziemskiej CRUST 2.0 i porównanie wynikających z niej struktur Moho z obliczonymi z modelu izostatycznego Airy-Heiskanena

Dimitrios Tsoulis, Christos Venesis

Wydział Geodezji i Miernictwa, Uniwersytet Arystotelesa w Salonikach
Univ. Box. 440, GR-54124, Thessaloniki, Greece
e-mail: tsoulis@topo.auth.gr

Streszczenie

Udostępniony obecnie model gęstości skorupy ziemskiej CRUST 2.0 został poddany weryfikacji w aspekcie informacji na temat granicy skorupa-płaszcz zarówno w skali globalnej jak i regionalnej. Ocena numeryczna zawartej w bazie danych informacji dotyczącej gęstości i położenia poszczególnych warstw skorupy ziemskiej względem poziomu morza dokonywana jest w procesie badania korelacji z topografią

terenu i poprzez porównanie otrzymanych wartości ze znanymi teoretycznymi modelami opisującymi mechanizm kompensacji pomiędzy skorupą i płaszczem. Opisane badania skoncentrowane są w szczególności na ostatniej warstwie modelu CRUST 2.0, która reprezentuje powierzchnię graniczną między skorupą i płaszczem, znaną pod nazwą powierzchni nieciągłości Mohorovicica. Bezpośrednie porównanie struktury Moho wynikającej z modelu gęstości skorupy ziemskiej CRUST 2.0 z odpowiednią głębokością kompensacji wyznaczoną przy użyciu teorii Airy/Heiskanena przeprowadzono zarówno w skali globalnej jak i regionalnej. Porównania, szczególnie przeprowadzone w wybranych rejonach globu, o charakterystycznych cechach tektonicznych, takich jak pasma górskie, rowy oceaniczne, dają możliwość zarówno oceny numerycznej bazy danych jak i równoczesnego zobrazowania lokalnych i regionalnych cech znanych mechanizmów izostazji.