Density modeling of the lithospheric structure along the CELEBRATION 2000 seismic profile CEL01

M. Bielik
Department of Applied and Environmental Geophysics, Faculty of Natural Sciences, Comenius University[1]
Geophysical Institute of the Slovak Academy of Sciences[2]

T. Grabowska, G. Bojdys
Institute of the Geophysics, AGH University of Science and Technology[3]

K. Csicsay
Department of Applied and Environmental Geophysics, Faculty of Natural Sciences, Comenius University[1]

J. Šefara
Geophysical Institute of the Slovak Academy of Sciences[2]

E. Speváková
Department of Applied and Environmental Geophysics, Faculty of Natural Sciences, Comenius University[1]

Abstract: The paper deals with density modeling along the seismic refraction Profile CEL01 and finding out a possibility of application of special formulae for transformation of the P-velocities to densities. We present three variants of the resulting density models. In general, good agreement between the seismic and gravity interpretations of the lithosphere was acquired. The largest disagreement between the seismic and gravity interpretations is observed beneath the TESZ. To obtain good fit between data and model predictions it was necessary to increase densities and to adjust the geometry of the anomalous bodies of the lower part of the upper crust and the lower crust. The lithospheric structure is the most complicated in the TESZ and EEP junction. The upper (lower)

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[1] Mlynská dolina, 842 15 Bratislava, Slovak Republic; e-mail: bielik@fns.uniba.sk
[2] Dúbravská cesta 9, 845 28 Bratislava, Slovak Republic; e-mail: geofsefa@savba.sk
[3] al. Mickiewicza 30, 30-059 Kraków, Poland
e-mail: tgrabow@geol.agh.edu.pl; bojdys@geol.agh.edu.pl

crustal anomalous bodies with densities of 2.68 g.cm^{-3} and 2.62 g.cm^{-3} (3.05 g.cm^{-3}) were modeled. The high-density lower crustal anomalous body was modeled based on seismic and gravity interpretations. The large differences can be observed in the crustal thicknesses of the EEP and the microplate ALCAPA. The EEP crustal thickness (43 km on average) is larger in comparison with the ALCAPA crustal thickness (32 km on average). In the Western Carpathians the largest thickness (37 km) is indicated beneath the Pieniny Klippen Belt and Outer Western Carpathians Flysch zone junction (around of 400 km of the profile). The Pannonian Basin is characterized by thin crust (28 km on average only). The thickness of the lower crust beneath the Pannonian Basin is also very thin (8–10 km). The lower part of the lower crust of the TESZ and EEP with the seismic velocities 6.85–7.05 kms^{-1} and density $\rho \geq 3.00$ gcm^{-3} does not exist beneath the Pannonian Basin. The interpretation indicates that the thickness of the crust beneath the TESZ and EEP is thinner than it was suggested in the former seismic interpretation.

Key words: gravity, density modeling, lithosphere, East European platform, Western Carpathians, Pannonian Basin, CELEBRATION 2000 project

1. Introduction

In 2000, a consortium of European and North American institutions completed a huge active source seismic experiment focused on central Europe, the Central European Lithospheric Experiment Based on Refraction or CELEBRATION 2000 (*Grad et al., 2006*). This experiment primarily consisted of a network of seismic refraction profiles that extended from the East European platform (EEP) in Poland, along and across the Trans-European suture zone (TESZ) involving Tornquist-Teisseyre zone (TTZ) into the Bohemian Massif, the Western Carpathians, the Eastern Alps and into the Pannonian Basin (Fig. 1). The huge dataset resulting from this experiment is based on a network of seismic profiles (Fig. 2) with a total length of 8900 km *(Guterch, 2003a,b)* and will provide a 3D velocity image of the Central European crust. In the frame of CELEBRATION 2000 project seismic refraction measurements have been made at 16 profiles: CEL01, CEL02, CEL03, CEL04, CEL05, CEL06, CEL07, CEL08, CEL09, CEL10, CEL11, CEL12, CEL013, CEL14, CEL15 a CEL16 (Fig. 2). From these profiles seven are passing through Slovakia: CEL01, CEL04, CEL05, CEL06, CEL09, CEL11 and CEL15.

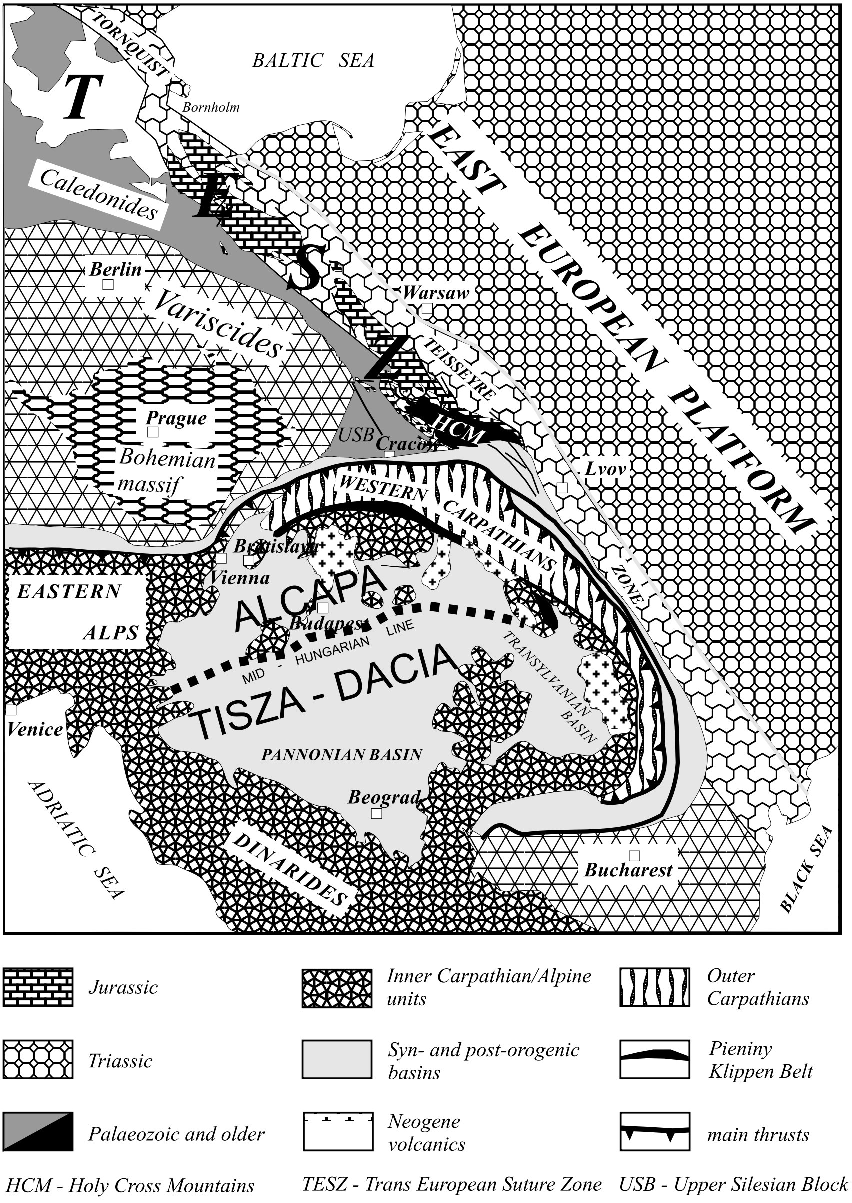

Fig. 1. Location of the profiles of the CELEBRATION 2000 seismic experiment (modified after *Guterch et al., 2003b*). The black circles show shot points. Profile CEL01 – interpreted density cross-section.

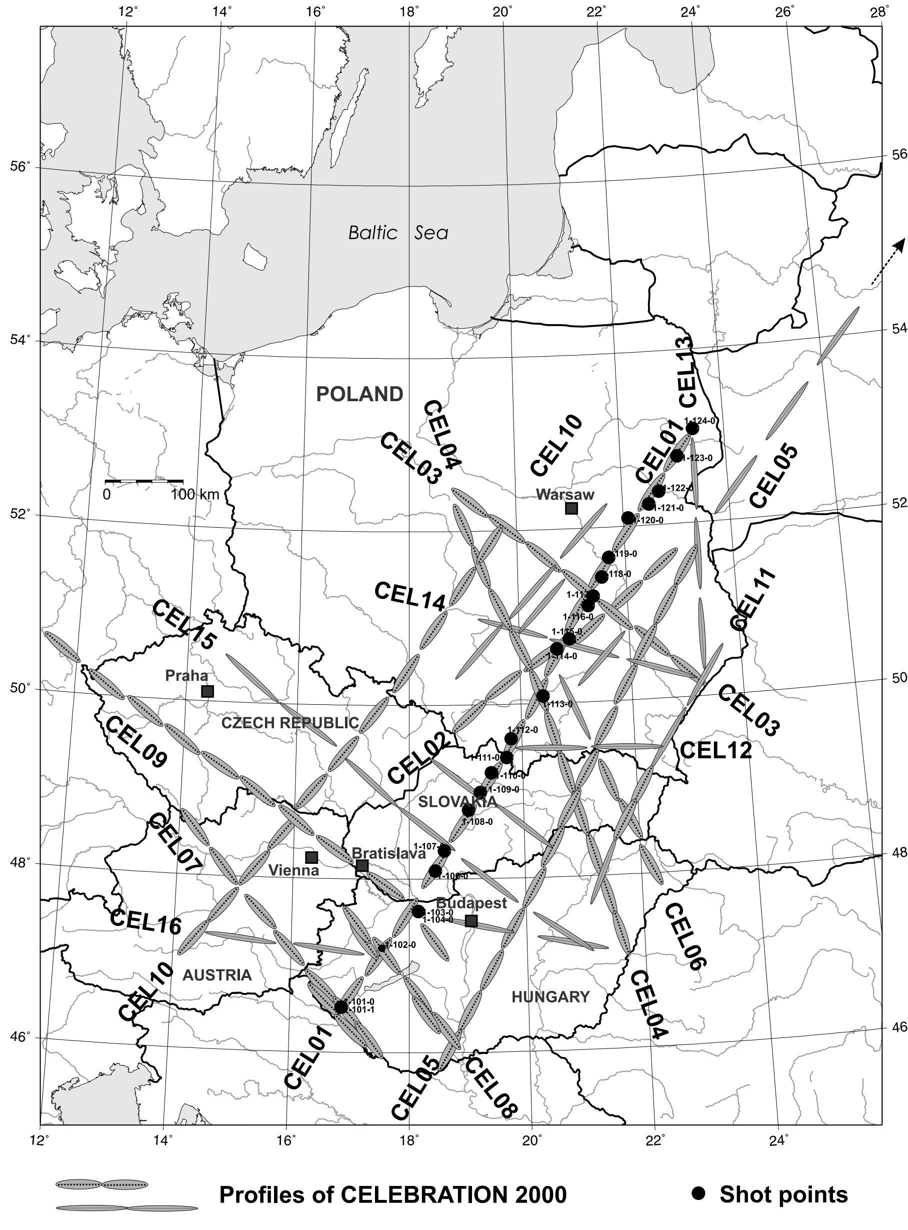

Fig. 2. Schematic tectonic map of the CELEBRATION 2000 seismic experiment region (modified after *Guterch et al., 2003a*).

The main goal of the CELEBRATION 2000 seismic experiment is to broaden the knowledge of deep-seated structures and of the geodynamics of the complex continental lithosphere, and to study the relationships between the main tectonic units of Central Europe.

For achieving the project goals it is necessary to integrate the seismic refraction data and their interpretation with the data of other geophysical fields (*Bielik et al., 2006).* From this point of view the goal of this paper is to carry out density modeling along the profile CEL01 and to find out a possibility of application of the formulae for transformation of the P-velocities (v_p) to densities published by *Sobolev and Babeyko (1994), Lachenbruch and Morgan (1990)* and *Christensen and Mooney (1995).*

Seismic profile CEL01 is one of the most representative profiles of the international seismic project CELEBRATION 2000 (Fig. 2). The length of the profile is 900 km. It starts in the Pannonian Basin, and then continues through the Western Carpathians and the Western Carpathian Foredeeep, southwestern portion of the Paleozoic Platform with the Holy Cross Mountains (HCM), the region of TESZ including the TTZ, and it ends in the EEP. The seismic refraction measurements used 22 shot points. Sampling was 10 ms and length of registration was 80–100 s. The distance between geophones was 3.0–3.5 km.

2. Geological setting of the CELEBRATION 2000 region

Geological structure of the Central Europe is very complicated. It consists of the EEP, TESZ, the Carpathians, the Bohemian Massif, the Eastern Alps and the Pannonian Basin.

The TESZ region (including the Caledonides and TTZ) is a broad zone of deformation that extends across Europe from British Isles to the Black sea region. It formed as Europe was assembled from a complex collage of terranes during the late Paleozoic. These terranes were accreted along the margin of Baltica (EEP) that was formed during the break-up of Rodinia. The TESZ is far more complex than a single suture. In a broad sense it is the boundary between the Paleozoic and the Proterozoic European platform.

The Bohemian Massif, whose origin can be traced to northern Gondwana

(Africa), is mostly located in the Czech Republic. In southern Poland, several structural blocks such as the Małopolska Massif (MM) are located. They were probably transported laterally along Baltica *(Guterch et al., 2003b)*.

The younger Carpathian Mountains and the Pannonian Basin are the result of intricate Mesozoic-Cenozoic plate interactions in the Mediterranean region as the Tethys Ocean closed during the convergence of Europe and Afro-Arabia. During the Cenozoic, complex interactions among microplates ALCAPA and TISZA–DACIA with the underthrusting European platform plate caused the Carpathian arc with strongly arcuate shape. This plate interaction consists of subduction of oceanic lithosphere, which produced considerable Neogen volcanism and subsequent collision of microplates ALCAPA and Tisza–Dacia with EEP *(Kováč, 2000)*. Back arc extension resulted in the Pannonian Basin (e.g., *Posgay et al., 1995; Kováč, 2000; Bielik et al., 2005*).

3. Seismic refraction Profile CEL01

Quantitative interpretation of the seismic refraction measurements along the profile CEL01 (Fig. 3) was made by *Šroda et al. (2003)*. The distribution of seismic velocities v_p indicates complicated structure and geodynamics of the lithosphere of the studied region.

The crustal thickness varies in an interval from 26 km (beneath the Pannonian Basin region) to 45 km (beneath TESZ). Large elevation of the Moho is observed beneath the region of the Małopolska Massif, which is also part of the TESZ (km of the profile: 420–570). The Moho is characterized by the jump increase of v_p from values of 6.65 up to 7.85 kms^{-1} (the Pannonian Basin), 6.85 up to 7.80 kms^{-1} (the Western Carpathians), 6.85 up to 8.11 kms^{-1} (the Małopolska Massif region), 6.85-7.05 up to 8.05 kms^{-1} (TESZ and EEP).

Upper crustal seismic velocities v_p of the Pannonian Basin attain the values of 5.85–6.30 kms^{-1} and its thickness is 17–20 km. The Tertiary sediments (uppermost part of the upper crust) of the Pannonian Basin have a velocity of 4.00 kms^{-1}. The lower crust is characterized by the velocity of 6.55 kms^{-1} with only 8–10 km thickness.

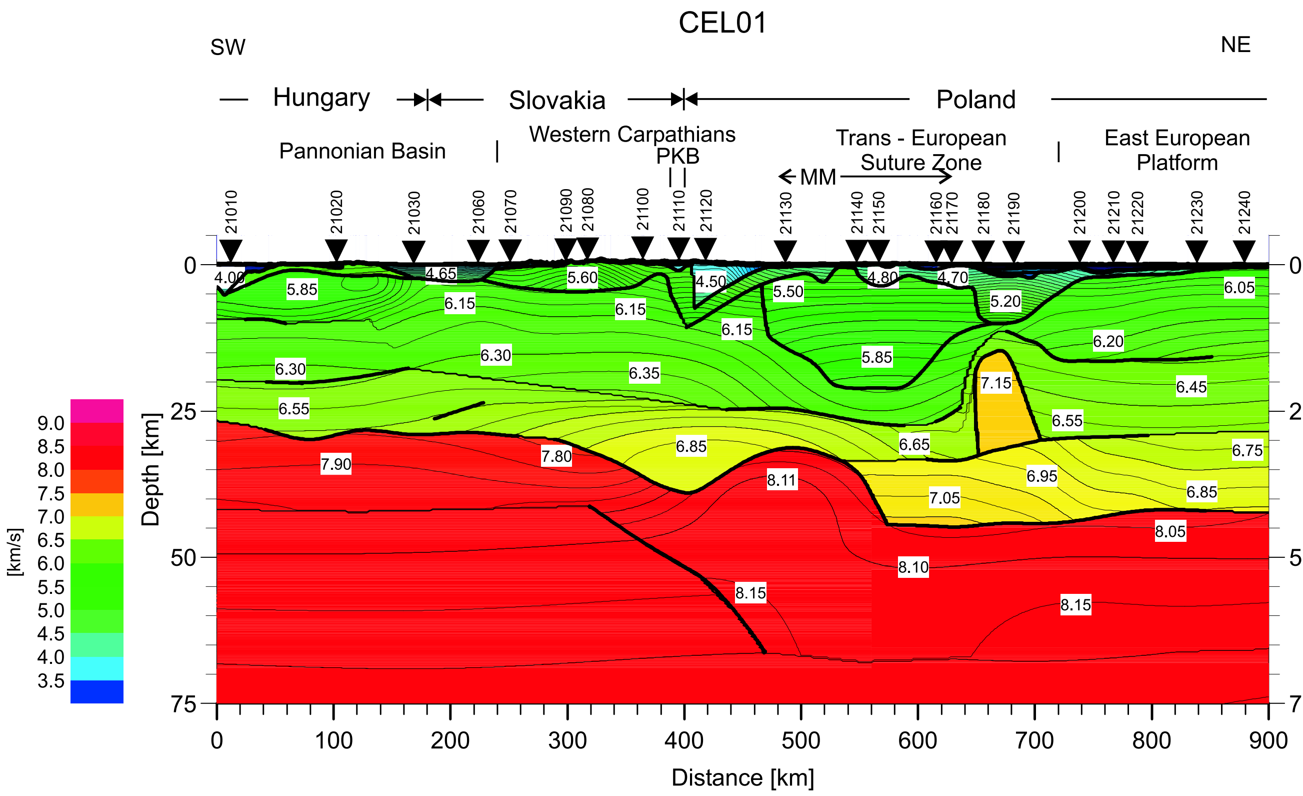

Fig. 3. Quantitative interpretation of the seismic refraction measurements along the profile CEL01. Keys: The black triangles show shot points, PKB – Pieniny Klippen Belt, MM – Malopolska Massif.

The velocities of the Western Carpathian upper (lower) crust are 6.15–6.35 kms^{-1} (6.85 kms^{-1}). The boundary between the upper crust and lower crust increases from 17 km beneath the Inner Western Carpathians up to 25 km beneath the Outer Western Carpathians. The sediments of the Outer Western Carpathian Flysch zone are characterized by a velocity 4.50 kms^{-1}.

Dominant features of the MM crust are three velocity bodies. One can be observed within the upper crust and the second is the Moho elevation mentioned above. The upper crustal body has a velocity 5.85 kms^{-1}. It forms practically the whole upper crust. The seismic velocities within the lower crust attain the values 6.65–7.05 kms^{-1}.

A further dominant of the crust can be seen beneath the TESZ. It is represented by a high velocity (7.15 kms^{-1}) body. Over this body a depression with a velocity 5.20 kms^{-1} is located.

The thickness of the upper crust of the EEP is about 28–30 km and the velocities are changing from 6.05 to 6.55 kms^{-1}. The lower crust velocities are characterized by the values 6.75–7.05 kms^{-1}. The lower crustal thickness is approximately 15 km.

4. Density modeling

The preliminary density model of this profile was constructed on the basis of the available geological data (e.g., *Żelichowski and Kozłowski, 1983; Šefara et al., 1987; Kilényi and Šefara, 1989; Poprawa and Nemčok, 1989; Rylko and Tomaš, 2005*) and geophysical data (e.g., *Dąbrowski, 1974; Šefara et al., 1987; Bielik, 1988; Ibrmajer and Suk, 1992; Szafián et al., 1997; Šefara and Szabó, 1997; Królikowski and Petecki, 2001; Bielik et al., 2005*). The depths of the sedimentary Basins were taken from the map of pre-Tertiary basement depth published by *Kilényi and Šefara (1989); Poprawa and Nemčok (1989); Rylko and Tomaš (2005).* The Moho boundary was defined by means of the interpretation of the seismic refraction profile CEL01. The lithosphere-asthenosphere boundary was taken from the papers of *Zeyen et al. (2002); Dérerová (2004)* and *Dérerová et al. (2006).*

The sedimentary crust of the EEP is built by Mesozoic and Paleozoic rocks. The density model assumes, that the lower boundary of the sedimentary complex coincides with the seismic velocity of $v_p = 6$ kms^{-1}. The boundary could correspond to the upper boundary of the crystalline basement with density of 2.685 g.cm^{-3}. The main constraint for the geometry of density inhomogeneities within the crust and lower lithosphere along the profile CEL01 was the seismic velocity model.

The sources of density parameters of anomalous bodies were different. The density of the sedimentary Basins, the Pieniny Klippen Belt, the Inner and Outer Flysch were defined by *Šefara et al. (1987), Królikowski and Petecki (2001); Bielik (1988); Bielik et al. (2005); Ibrmajer and Suk (1992); Šefara and Szabó (1997); Szafián et al. (1997).*

The topography was generated from the topographic map of Central Europe and the total Bouguer gravity anomalies were taken from the maps of the total Bouguer gravity anomalies in Hungary, Slovakia and Poland *(Bielik et al., 2006; Bronowska et al., 1972; Mikuška et al., 2004; Šefara et al., 1987; Szabó and Páncsics, 1999).*

Density of the lower part of the upper crustal and lower crustal anomalous bodies were defined by transformation of P–wave velocities to densities. This transformation was carried out by means of the formulae of *Sobolev and Babeyko (1994)* and *Lachenbruch and Morgan (1990).* Note that the formulae published in the paper of *Sobolev and Babeyko (1994)* are valid for crystalline rocks only.

Within the lithospheric mantle the influence of temperature is larger than the influence of the pressure, while in the upper crust and partly in the lower crust the effect of the pressure and temperature compensate one another. *Parsons and Sclater (1977)* and *Lachenbruch a Morgan (1990)* derived a formula, where density distribution in the lithosheric mantle results from the density of asthenosphere (taken as constant), when density with increasing temperature decreases:

$$\rho_m(z) = \rho_a(1 + \alpha[T_a - T(z)]),$$

where:

$\rho_m(z)$ – density of the lithospheric mantle (gcm^{-3} = 1000 kgm^{-3}),
ρ_a – density of asthenosphere (gcm^{-3}),
α – coeficient of heat expantion (K^{-1}); $\alpha \approx 3.4 \cdot 10^{-5} K^{-1}$,
T_a – temperature on the lithosphere–asthenosphere boundary (1300°C),
$T(z)$ – temperature within the lithospheric mantle (°C).

The results are shown in Table 1. The Lachenbruch-Morgan formula was used for the transformation of the P-velocities (v_p) to densities (ρ) in density models of the second and third variants. The Christensen-Mooney formula was applied in the first variant.

The gravity effects of the density models were calculated by GMSYS in Slovakia and Bojdys's *(Grabowska and Bojdys, 2001)* software in the Polish part of the profile CEL01.

The density-related parameters and geometry of the anomalous bodies were modified by trial-and-error until a reasonable fit between data and model predictions was obtained.

5. Interpretation of density models

In the paper we present three variants of the resulting density models. The first variant (Fig. 4) does not take into account the lithosphere-asthenosphere boundary and it also suggests horizontal variations of density in the upper mantle. The second and third variants (Figs 5, 6) suggest a continental collision between two lithospheric plates: the EEP (upper plate) and microplate ALCAPA (lower plate), and take into account the lithosphere-asthenosphere boundary. The second variant (Fig. 5) suggests: (a) the lower lithosphere of both plates has the same density 3.25 gcm^{-3}, (b) the lithosphere-asthenosphere boundary is a density discontinuity (−0.03 gcm^{-3} in the microplate ALCAPA *(Lillie et al., 1994)* but not in the EEP. The third variant (Fig. 6) predicts: (a) the lower lithosphere of both plates has a different density. The microplate ALCAPA and the EEP is defined by density of 3.25 gcm^{-3} and 3.24 gcm^{-3}, respectively, (b) the lithosphere-asthenosphere boundary is a density discontinuity in both collisional plates with the density contrast between the lower lithosphere and the asthenosphere of −0.03 gcm^{-3}. Each variant accepts the depth of the Moho boundary, which was determined by means of seismic interpretation. Adjusting the Moho boundary during density modeling was minimal.

In general, good agreement between the seismic and gravity interpretations of the lithosphere was achieved. The largest disagreement between the seismic and gravity interpretations is observed beneath the TESZ. To obtain a good fit between data and model predictions, it was necessary to

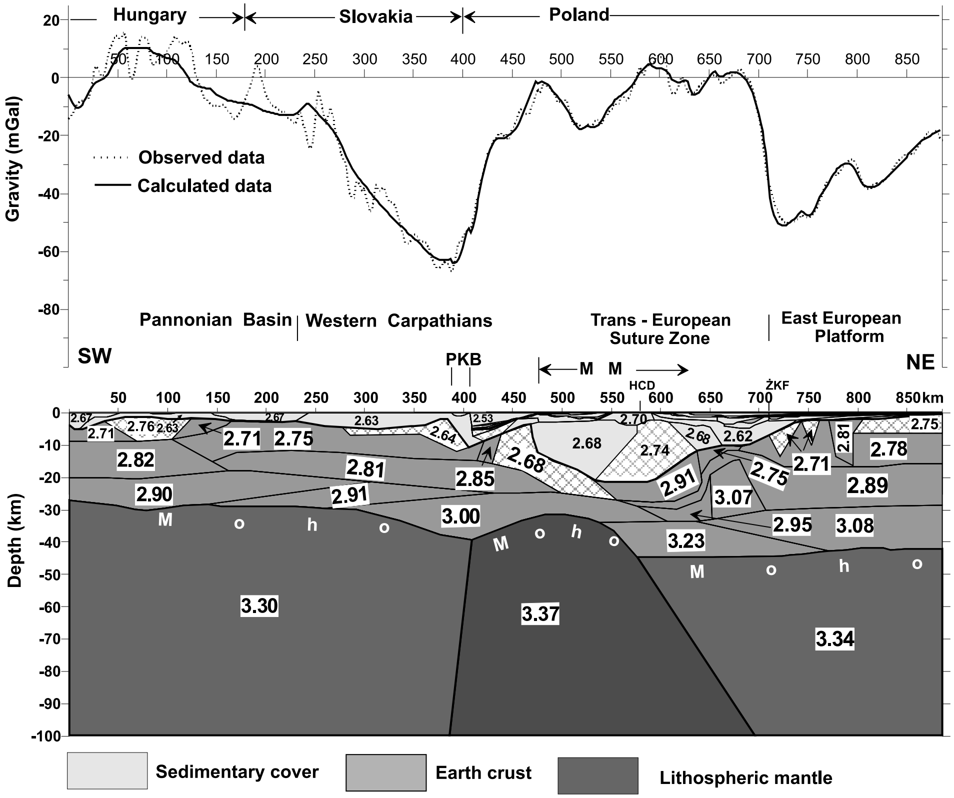

Fig. 4. Two-dimensional density model of the crust and uppermost mantle along Profile CEL01 – 1st variant. Density model constructed on the basis of geological data (sedimentary cover), seismic data (crystalline crust and upper mantle). Densities of the sedimentary rocks in the Polish part of profile are: in SW region: 2.33–2.73, in NE region: 2.11–2.67. Density contrasts are in gcm^{-3}. Christensen-Mooney's formula was used for transformation of the P-velocities (v_p) to densities (ρ) in the lower crust and lower lithosphere. Keys: PKB – Pieniny Klippen Belt, MM – Małopolska Massif, HCD – Holly Crust Dislocation, ŻKF – Żelechów-Kock fault.

increase a densities and to adjust the geometry of the anomalous bodies of the lower part of the upper crust and the lower crust. In the first variant of the density model based on drilling results in the sedimentary complex of the Mazowsze-Lublin Trough (MLT, km of the profile: 700–750) the basic body with density 2.71 gcm^{-3} (within EEP basement) was modeled.

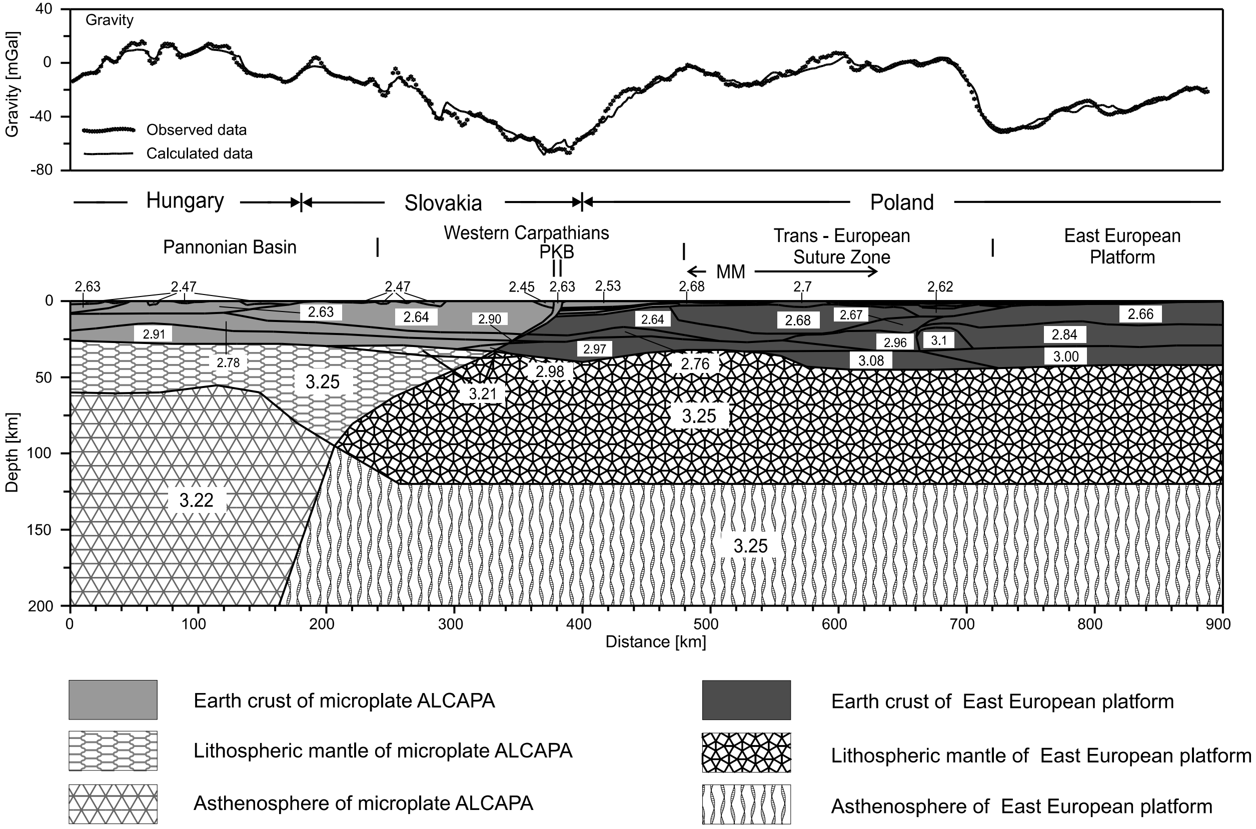

Fig. 5. Two-dimensional density model of the lithosphere along Profile CEL01 – 2$^{\mathrm{nd}}$ variant. Density contrasts are in gcm^{-3}. Sobolev-Babeyko's (Lachenbruch-Morgan's) formulae were used for transformation of the P-velocities (v_p) to densities (ρ) in the crust (lower lithosphere). Keys: PKB – Pieniny Klippen Belt, MM – Małopolska Massif.

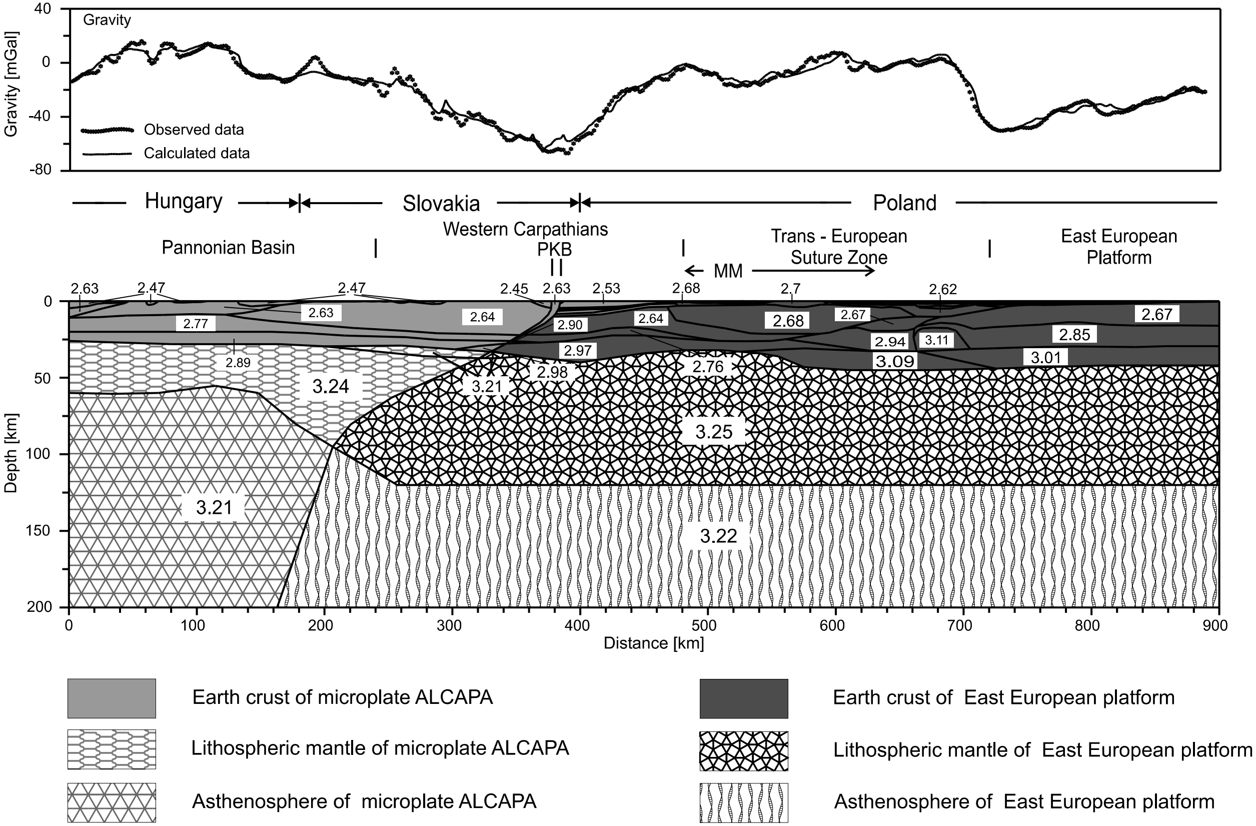

Fig. 6. Two-dimensional density model of the lithosphere along Profile CEL01 – 3rd variant. Density contrasts are in gcm^{-3}. Sobolev-Babeyko's (Lachenbruch-Morgan's) formulae were used for transformation of the P-velocities (v_p) to densities (ρ) in the crust (lower lithosphere). Keys: PKB – Pieniny Klippen Belt, MM – Małopolska Massif.

The lithospheric structure is the most complicated in the TESZ and EEP junction. The large anomalous bodies of the upper crust [km of the profile: 460–640 (and 640–740) with density of 2.68 gcm^{-3} (2.62 gcm^{-3})] and lower crust (km of the profile: 640–710 with density large than 3.05 gcm^{-3}) was modeled. It is worth to note that the high-density body within the lower crust (km of the profile: 640–710) was interpreted by both the seismic and gravity interpretation.

The large differences can be observed in the crustal thicknesses of the EEP and the microplate ALCAPA. The EEP crustal thickness (43 km on average) is visibly thicker in comparison with the ALCAPA crustal thickness (32 km on average). In the Western Carpathians the largest thickness (37 km) is indicated beneath the Pieniny Klippen Belt and the Outer Western Carpathians Flysch zone junction (around of 390 km of profile). The Pannonian Basin is characterized by thin crust (28 km on average only). The thickness of the lower crust beneath the Pannonian Basin is very thin (8-10 km). The lower part of the lower crust of the TESZ and EEP with the seismic velocities $v_P = 6.85\text{-}7.05\ \mathrm{kms}^{-1}$ and density $\rho \geq 3.00\ \mathrm{gcm}^{-3}$ does not exist beneath the Pannonian Basin.

6. Conclusions

The results of the density modeling brought the fruitful results that extend the knowledge on the deep-seated lithospheric structures, its geodynamics and the relationships between the main tectonic units of Central Europe. The interpretation indicates that the thickness of the crust beneath the TESZ and EEP is thinner than it was suggested in the former seismic interpretations (e.g., *Guterch et al., 1986; 1994*). This suggestion is also supported by our density modeling along the profile CEL01. In the future, it will be necessary to conduct geological interpretation of density and seismic modeling results and to explain the main anomalous density and seismic bodies.

Based on the achievement of a good agreement between the results obtained by independent seismic and density modeling, it seems to be that the application of Sobolev-Babeyko's *(Sobolev and Babeyko, 1994)*, Lachenbruch-Morgan's *(Lachenbruch and Morgan, 1990)* and Christensen-Mooney's *(Christensen and Mooney, 1995)* formulae for the transformation of the seismic velocities to densities is useful.

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