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Determination of rock densities in the Carpathian-Pannonian Basin lithosphere: based on the CELEBRATION 2000 experiment

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Abstract: The international seismic project CELEBRATION 2000 brought very good information about the P-wave velocity distribution in the Carpathian-Pannonian Basin litosphere. In this paper seismic data were used for transformations of in situ P-wave velocities to in situ densities along all profiles running across the Western Carpathians and the Pannonian Basin: CEL01, CEL04, CEL05, CEL06, CEL09, CEL11 and CEL12. The calculation of rock densities in the crust and lower lithosphere was done by the transformation of seismic velocities to densities using the formulae of Sobolev-Babeyko, Christensen-Mooney and in the lower lithosphere also by Lachenbruch-Morgan's formula. The density of the upper crust changes significantly in the vertical and horizontal directions, while the interval ranges of the calculated lower crust densities narrow down prominently. The lower lithosphere is the most homogeneous – the intervals of the calculated densities for this layer are already very narrow. The average density of the upper crust ($\bar{\rho} = 2.60$ g·cm^{-3}) is the lowest in the Carpathian Foredeep region. On the contrary, the highest density of this layer ($\bar{\rho} = 2.77$ g·cm^{-3}) is located in the Bohemian Massif. The average densities $\bar{\rho}$ of the lower crust vary between 2.90 and 2.98 g·cm^{-3}. The Palaeozoic Platform and the East European Craton have the highest density ($\bar{\rho} = 2.98$ g·cm^{-3} and $\bar{\rho} = 2.97$ g·cm^{-3}, respectively). The lower crust density is the lowest ($\bar{\rho} = 2.90$ g·cm^{-3}) in the Pannonian Basin. The range of calculated average densities $\bar{\rho}$ for the lower lithosphere is changed in the interval from 3.35 to 3.40 g·cm^{-3}. The heaviest lower lithosphere can be observed in the East European Craton ($\bar{\rho} = 3.40$ g·cm^{-3}). The lower lithosphere of the Transdanubian Range and the Palaeozoic Platform is characterized by the lowest density $\bar{\rho} = 3.35$ g·cm^{-3}.

Key words: density, seismic velocity, deep seismic sounding, transformation seismic velocity to density, Carpathian-Pannonian Basin region

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1. Introduction

The CELEBRATION 2000 Seismic Experiment (*Guterch et al. 2000; 2001; 2003a,b*) was located on the area of the southern portion of the Trans European Suture Zone (TESZ) region, the margin of Baltica (East European Craton), inversion structures along the TESZ, the Carpathian orogenic belt, the Pannonian Basin, and the Bohemian Massif (Fig. 1). The layout of the experiment was a network of interlocking profiles the total length of which was about 9000 km. One of the most fundamental goals of the CELEBRATION 2000 project was to research the structure and the dynamics of the lithosphere in the Carpathian-Pannonian Basin region. From this perspective, the seismic measurements along the seismic profiles CEL01, CEL04, CEL05, CEL06, CEL09, CEL11 and CEL12 and CEL28 (Figs. 1, 2) were the most important (*Grad et al., 2006, 2009; Środa et al., 2006; Malinowski et al., 2005, 2008, 2009; Hrubcová et al., 2005, 2008; Janik et al., 2009, 2011*).

The quantitative interpretation of gravity anomalies (as well as other geophysical fields) depends not only on the quality of methods for solution of direct and inverse gravimetric problems but significantly also on our knowledge of the rock densities (physical properties).

In general, the density modelling of the uppermost layer of the Earth's crust, down to a depth of about 5 km is based on current geological knowledge, borehole data, geophysical observations, which can be considered relatively reliable (e.g., *Burda et al., 1985; Bielik et al., 1987, 1990; Vyskočil et al., 1992*).

For deeper parts of the crust and lithosphere it is necessary to apply other approaches. If we have information available about the velocities of the seismic waves in the crust and/or lithosphere then the best approach to defining the most real densities is to use the suitable formulae for transformation of the in situ seismic velocities to the in situ densities.

The Carpathian-Pannonian Basin area is sufficiently covered by seismic measurements, which provide very high quality information on the velocities of seismic waves in the lithosphere. The results of the international seismic project CELEBRATION 2000 brought the latest and best knowledge on P-wave velocity distribution in the crust and in the upper part of the mantle (lower lithosphere) in this studied region. Therefore, the aim of this paper is

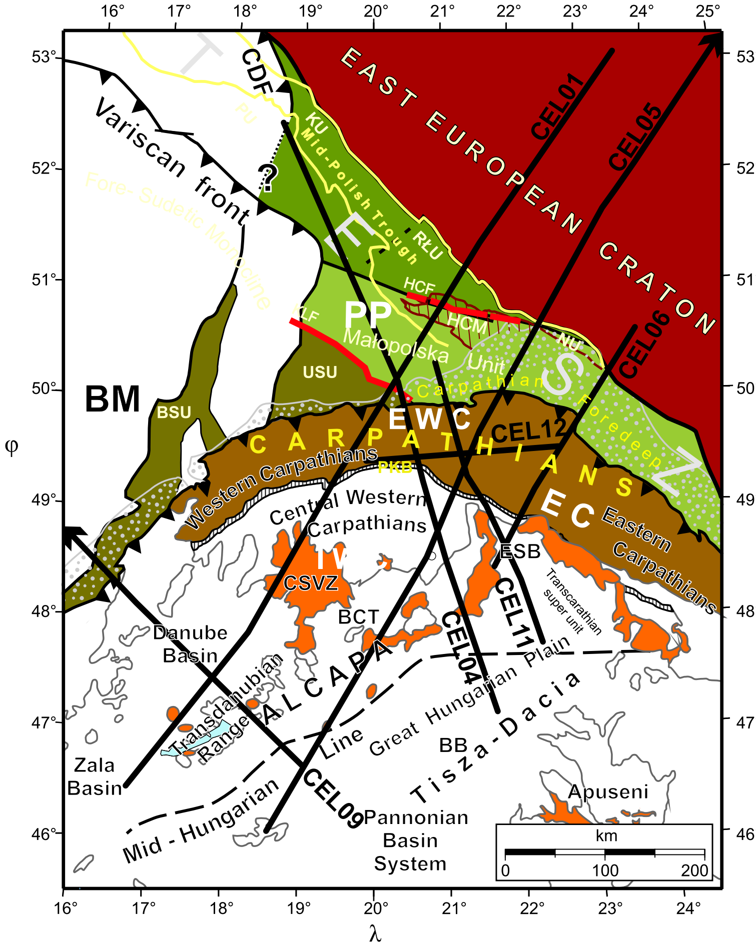

Fig. 1. Location of the seismic profiles CEL01, CEL04, CEL05, CEL06, CEL09, CEL11 and CEL12 on the background of a geological map of Central Europe (modified after *Janik et al., 2011* and references therein). BCT – Bükk Composite Terrane; BM – Bohemian Massif; BSU – Bruno-Silesian Unit; CDF – Caledonian Front; CSVZ – Central Slovak Volcanic zone; ESB – East Slovakian Basin; HCF – Holy Cross Fault; HCM – Holy Cross Mts.; IWC – Internal Western Carpathians; KLF – Kraków-Lubliniec Fault; KU – Kuiavian Unit; NU – Narol Unit; PKB – Pieniny Klippen Belt; EC – External Carpathians; EWC – External Western Carpathians; PP – Palaeozoic Platform; PU – Pomeranian Unit; RŁU – Radom-Łysogóry Unit; TESZ – Trans-European Suture Zone; USU – Upper Silesian Unit; areas covered by: brown – Outer Carpathians; blue – Central Western Carpathians, Eastern Carpathians, Alps, Apuseni and Transdanubian Range; yellow – Pannonian Basin; orange – Neogene volcanics.

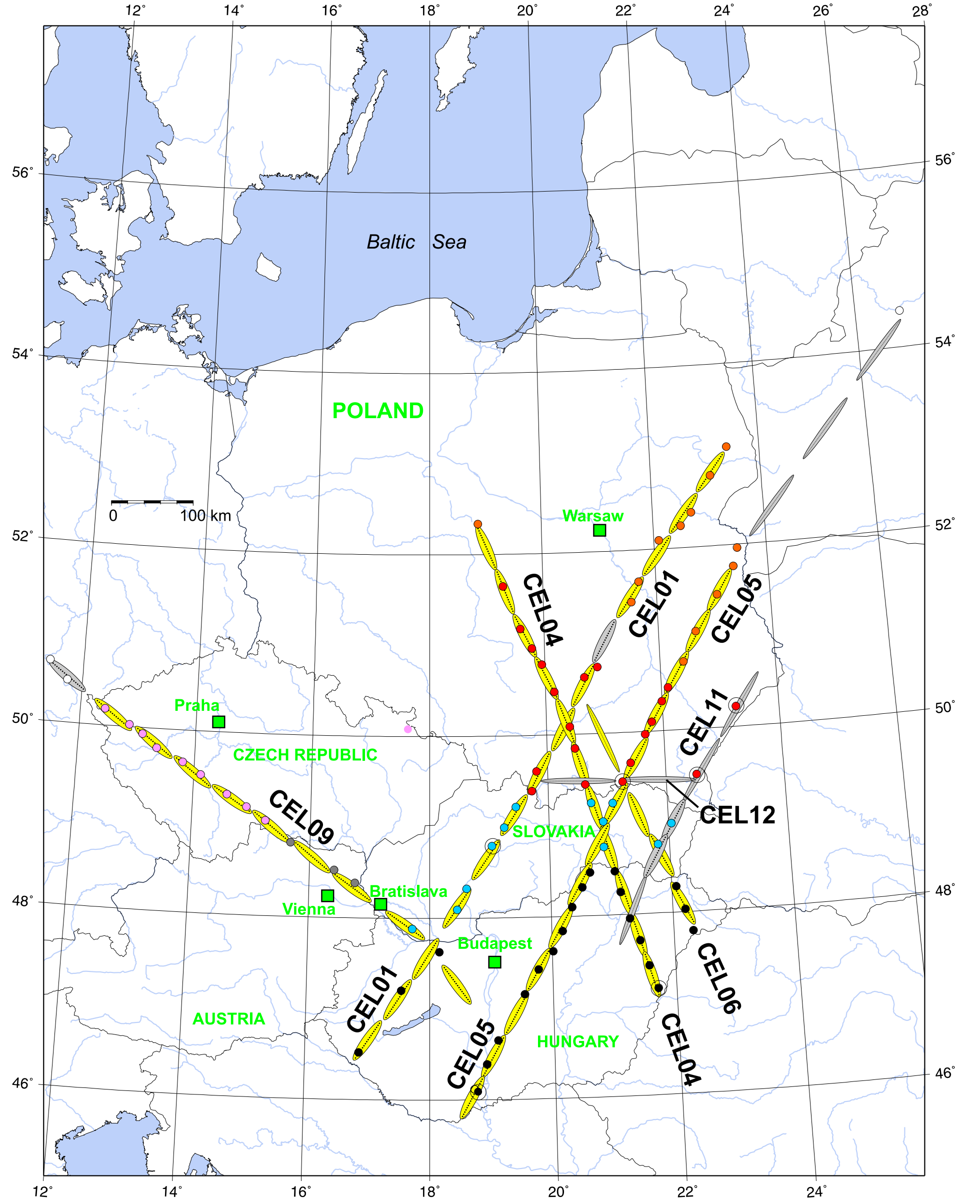

Fig. 2. Location of the profiles of the CELEBRATION 2000 experiment crossing the Western Carpathians and the Pannonian Basin region (modified after *Guterch et al., 2003a,b*). The red, pink, blue, black and grey coloured circles show shot points.

to calculate the densities of rocks forming the Carpathian-Pannonian Basin lithosphere based on the results of the seismic measurements (*Grad et al., 2006; Janik et al., 2009, 2011; Środa et al., 2006; Hrubcová et al., 2005, 2008*). The transformations of the in situ P-wave velocities to the in situ densities are made along all the sections of CELEBRATION 2000 which are running across the Western Carpathians: CEL01, CEL04, CEL05, CEL06, CEL09, CEL11 and CEL12. In this paper, the determined densities are also analysed.

2. CELEBRATION 2000 seismic experiment

In 2000, a consortium of European and North American institutions completed a huge active source seismic experiment focused on CELEBRATION 2000 (**C**entral **E**uropean **L**ithospheric **E**xperiment **B**ased on **R**efr**action**). This international project involved 28 institutions from Europe and North America. The experiment primarily consisted of a network of seismic refraction profiles (CEL01, CEL02, CEL03, CEL04, CEL05, CEL06, CEL09 and CEL10, CEL11, CEL12, CEL13, CEL14, CEL15, CEL16) that extended from the East European Craton, along and across the Trans-European suture zone (TESZ) region in Poland to the Bohemian Massif, and through the Carpathians and Eastern Alps to the Pannonian Basin (*Guterch, 2003a,b*). The fieldwork for the project was completed in June 2000, when 147 shots were fired along most of the recording profiles, which resulted in obtaining 160000 seismic records. The area of the CELEBRATION 2000 project is outlined by 45°– 54° N latitude and 12°– 24° E longitude. Later it was followed by the projects ALPS 2002, SUDETES 2003 and the BOHEMIA teleseismic experiment.

The CELEBRATION 2000 seismic experiment brought new knowledge on the deep-seated structures and the geodynamics of the complex continental lithosphere and the relationships between the main tectonic units of Central Europe.

For achieving the project goals it was necessary to integrate the seismic refraction data and their interpretation with the data of other geophysical fields too. In consequence the potential field working group was formed. This group consisted of representatives from five countries: Poland, Czech Republic, Slovak Republic, Austria and Hungary. The main goal of this working group was joint interpretation of potential field data (gravity, magnetic and geothermal) using CELEBRATION 2000 project seismic refraction results as base. For interpretation of the gravity field a unified complete Bouguer gravity anomaly map of high quality and accuracy was created (*Bielik et al., 2006*).

3. Methodology

The methods for determination of rock densities can be, in principle, divided into direct (laboratory) and indirect (geophysical). In general, the density data for the sediments, magmatic and metamorphic rocks located in the first five kilometres are based on laboratory measurements of samples taken from the surface, boreholes, and well-logging (e.g., *Eliáš and Uhman, 1968; Husák, 1977, 1986; Šefara et al., 1987; Ibrmajer and Suk, 1989; Królikowski and Petecki, 2001; Bała and Witek, 2007; Dabrowski, 1971, 1976*).

In our work we defined the density of rocks using four different approaches: (1) for sedimentary rocks by the analysis of existing knowledge of their densities, which have been carried out by laboratory measurements on samples taken from surface and boreholes, and from well-logging; (2) for the upper and lower crust and lower lithosphere by the transformation of the in situ P-wave velocities to the in situ densities using the formulae of Sobolev-Babeyko (*Sobolev and Babeyko 1994*); (3) Christensen-Mooney (*Christensen and Mooney 1995*); and (4) Lachenbruch-Morgan's formula (*Lachenbruch and Morgan, 1990*).

For evaluation of the density data of the Neogene and Palaeogene sediments (Tables 1, 2 and Fig. 3) we used the data published, for example, in the papers of *Eliáš and Uhman (1968), Dabrowski (1971, 1976), Husák (1977, 1986), Tomek et al. (1979), Šefara et al. (1987), Bielik (1988), Ibrmajer and Suk 1989; Bucha et al. (1994), Szafián et al. (1997), Šefara and Szabó (1997), Królikowski and Petecki (2001), Makarenko et al. (2002), Zeyen et al. (2002), Bielik et al. (2005, 2006), Dérerová et al. (2006), Bała and Witek (2007), Csicsay (2010), Csicsay et al. (2012), Grinč et al. (2013), Alasonati Tašárová et al. (2008, 2009, 2016*). We also take into account the results and knowledge published by *Nafe and Drake (1957,*

Table 1. The calculated in situ rock densities for the upper and lower crust along the seismic profiles CEL01, CEL04, CEL05, CEL06, CEL09, CEL11, CEL12. Keys: z – depth, P – Pressure, T – Temperature, $v_{p(insitu)}$ – longitudinal seismic velocity, ρ_{SB} – in situ density evaluated by Sobolev-Babeyko's formulae (*Sobolev and Babeyko, 1994*), ρ_{CHM} – in situ density evaluated by Christensen-Mooney's formula (*Christensen and Mooney, 1995*), ρ_{LACH} – density evaluated by Lachenburg-Morgen's formula (*Lachenburg and Morgen, 1990*), $\bar{\rho}$ – average density. See text for further details and references.

a)

CEL01			z [km]	P [GPa]	T [C°]	$V_{p(in\ situ)}$ [km·s^{-1}]	ρ_{SB} [g·cm^{-3}]	ρ_{CHM} [g·cm^{-3}]	ρ_{LACH} [g·cm^{-3}]	$\bar{\rho}$ [g·cm^{-3}]
Pannonian Basin	Transdanubian Range	Upper Crust	5 15	0.24 0.51	180 400	5.9 6.25	2.75	2.69 2.8		2.75
		Lower Crust	25	0.79	625	6.5	2.89	2.89		2.89
		Lower Lithosphere	30	0.93	740	7.9		3.3	3.36	3.33
	Pannonian Basin West	Upper Crust	5 10	0.24 0.38	180 300	6.1 6.2	2.66 2.72	2.76 2.78		2.73
		Lower Crust	25	0.79	625	6.55	2.91	2.91		2.91
		Lower Lithosphere	32	0.98	750	7.9		3.31	3.44	3.38
Internal Western Carpathians		Upper Crust	10	0.38	260	6.25	2.74	2.8		2.77
		Lower Crust	25	0.79	570	6.7	2.97	2.96		2.97
		Lower Lithosphere	35	1.06	770	7.9		3.32	3.36	3.34
External Western Carpathians		Upper Crust	5 15	0.24 0.51	100 290	5.6 6.3	2.76	2.58 2.82		2.72
		Lower Crust	30	0.93	540	6.85	3.04	3.02		3.03
		Lower Lithosphere	45	1.34	745	8.1		3.39	3.36	3.38
Paleozoic Platform	Lysogóry Unit	Upper Crust	5 10 15 25	0.24 0.38 0.51 0.79	80 180 250 375	5.5 5.75 5.85 6.2	2.73	2.54 2.62 2.65 2.79		2.67
		Lower Crust	30 40	0.93 1.2	445 550	6.65 7.05	2.94 3.13	2.95 3.1		3.03
		Lower Lithosphere	50	1.48	650	8.1		3.41	3.37	3.39
	Malopolska Unit	Upper Crust	5 10 15	0.24 0.38 0.51	80 180 250	5.5 5.75 5.85		2.54 2.62 2.65		2.6
		Lower Crust	25 30	0.79 0.93	375 445	6.2 6.75	2.73 2.98	2.79 2.99		2.87
		Lower Lithosphere	40 50	1.2 1.48	550 650	8.1 8.15		3.38 3.42	3.38 3.37	3.39
East European Craton	Lublin Trough	Upper Crust	5	0.24	80	5.3		2.45		2.45
		Lower Crust	20 20 35	0.65 0.65 1.06	300 300 450	7.15 6.45 6.95	3.13 2.83 3.07	3.08 2.87 3.06		3.01
		Lower Lithosphere	45	1.34	540	8.05		3.38	3.39	3.39
		Upper Crust	5 10	0.24 0.38	80 170	6.1 6.2	2.65 2.71	2.76 2.78		2.73
		Lower Crust	20 35	0.65 1.06	300 450	6.45 6.95	2.83 3.07	2.87 3.06		2.96
		Lower Lithosphere	45	1.34	540	8.1		3.39	3.39	3.39

b)

CEL04			z [km]	P [GPa]	T [C°]	$V_{p(in\ situ)}$ [km·s^{-1}]	ρ_{SB} [g·cm^{-3}]	ρ_{CHM} [g·cm^{-3}]	ρ_{LACH} [g·cm^{-3}]	$\bar{\rho}$ [g·cm^{-3}]
Pannonian Basin		Upper Crust	10	0.38	460	6	2.65	2.71		2.68
		Lower Crust	20	0.65	740	6.45	2.88	2.87		2.88
		Lower Lithosphere	30 40	0.93 1.2	950 1180	7.85 8		3.29 3.35	3.34 3.31	3.32
Internal Western Carpathians		Upper Crust	5 10	0.24 0.38	180 250	5.7 6	2.63	2.62 2.71		2.65
		Lower Crust	25	0.79	540	6.55	2.9	2.91		2.91
		Lower Lithosphere	40 50	1.2 1.48	780 930	7.9 8.05		3.33 3.4	3.36 3.34	3.36
External Western Carpathians		Upper Crust	8 10 15 25	0.32 0.38 0.51 0.79	150 270 370 570	5.2 5.85 6 6.3	2.64 2.79	2.38 2.66 2.71 2.82		2.67
		Lower Crust	30 38	0.93 1.15	780 835	6.6 6.8	2.95 3.05	2.94 3.02		2.99
		Lower Lithosphere	50	1.48	995	8.08		3.4	3.33	3.37
Paleozoic Platform	Lysogóry Unit	Upper Crust	5 15 25	0.24 0.51 0.79	80 260 420	5.65 6 6.3	2.78	2.6 2.71 2.82		2.73
		Lower Crust	30	0.93	490	6.75	2.98	2.99		2.99
		Lower Lithosphere	35 45	1.06 1.34	550 650	7 8.25	3.11	3.08 3.43	3.37	3.25
	Malopolska Unit	Upper Crust	5 15 25	0.24 0.51 0.79	80 260 420	5.8 6 6.28	2.77	2.66 2.71 2.82		2.74
		Lower Crust	25 30	0.79 0.93	420 490	6.8 6.85	3 3.03	2.99 3.02		3.01
		Lower Lithosphere	35 40	1.06 1.34	550 650	8.1 8.1		3.36 3.39	3.38 3.37	3.38

c)

CEL05			z [km]	P [GPa]	T [C°]	$V_{p(in\ situ)}$ [km·s^{-1}]	ρ_{SB} [g·cm^{-3}]	ρ_{CHM} [g·cm^{-3}]	ρ_{LACH} [g·cm^{-3}]	$\bar{\rho}$ [g·cm^{-3}]
Pannonian Basin		Upper Crust	10	0.38	460	6.03	2.66	2.72		2.69
		Lower Crust	20	0.65	750	6.35	2.84	2.84		2.84
		Lower Lithosphere	35	1.06	1000	8.05		3.35	3.33	3.34
Internal Western Carpathians		Upper Crust	5 15	0.24 0.51	180 375	5.85 6.05	2.66	2.68 2.72		2.69
		Lower Crust	25	0.79	575	6.55	2.91	2.91		2.91
		Lower Lithosphere	40	1.2	850	8.05		3.37	3.35	3.36
External Western Carpathians		Upper Crust	5 10 15 15	0.24 0.38 0.51 0.51	60 225 320 320	4.6 5 5.3 6	6.63	2.09 2.27 2.4 2.71		2.42
		Lower Crust	30	0.93	575	6.7	2.97	2.9		2.94
		Lower Lithosphere	50	1.48	720	8.05		3.4	3.45	3.43
Carpathian Foredeep		Upper Crust	5 5 10	0.24 0.24 0.38	80 80 190	5.05 5.6 5.7		2.33 2.58 2.6		2.5
		Lower Crust	20 30 35	0.65 0.93 1.06	345 490 550	6.1 6.7 6.8	2.68 2.96 3.01	2.74 2.97 3.01		2.9
		Lower Lithosphere	50	1.48	720	8.05		3.4	3.37	3.39
East European Craton	Lublin Trough	Upper Crust	5 10	0.24 0.38	80 125	5.2 6		2.41 2.71		2.56
		Lower Crust	15 20 35	0.51 0.65 1.06	190 230 355	6.45 6.52 6.9	2.82 2.85 3.04	2.87 2.89 3.05		2.92
		Lower Lithosphere	50	1.48	440	8.15		3.42	3.4	3.41
		Upper Crust	5 10	0.24 0.38	80 170	6.1 6.2	2.65 2.71	2.76 2.78		2.73
		Lower Crust	25 35 35	0.79 1.06 1.06	350 450 450	6.58 7 6.72	2.89 3.1 2.97	2.92 3.08 2.99		2.99
		Lower Lithosphere	50	1.48	570	8.25		3.44	3.38	3.41

d)

CEL06		z [km]	P [GPa]	T [C°]	$V_{p(in\ situ)}$ [km·s^{-1}]	ρ_{SB} [g·cm^{-3}]	ρ_{CHM} [g·cm^{-3}]	ρ_{LACH} [g·cm^{-3}]	$\bar{\rho}$ [g·cm^{-3}]
Pannonian Basin	Upper Crust	7.5	0.31	250	5.95		2.7		2.7
	Lower Crust	15	0.51	470	6.54	2.89	2.9		2.9
	Lower Lithosphere	30	0.93	820	7.9		3.33	3.5	3.42
Internal Western Carpathians	Upper Crust	10	0.38	320	5.9		2.68		2.68
	Lower Crust	25	0.79	680	6.55	2.92	2.91		2.92
	Lower Lithosphere	35	1.06	890	7.9		3.32	3.35	3.34
External Western Carpathians	Upper Crust	5 10 10 15	0.24 0.38 0.38 0.51	120 205 205 290	5.2 5.3 5.88 5.92		2.41 2.42 2.67 2.67		2.54
	Lower Crust	25 30 30	0.79 0.93 0.93	450 540 540	6.25 6.55 6.78	2.76 2.9 3	2.81 2.92 3		2.9
	Lower Lithosphere	30	0.93	540	7.9		3.3	3.39	3.35
Carpathian Foredeep	Upper Crust	10	0.38	320	5.9		2.68		2.68
	Lower Crust	25	0.79	680	6.55	2.92	2.91		2.92
	Lower Lithosphere	35	1.06	890	7.9		3.32	3.35	3.34

Table 1. Continued from the previous page.

e)

CEL09			z [km]	P [GPa]	T [C°]	$V_{p(in\ situ)}$ [$km\cdot s^{-1}$]	ρ_{SB} [$g\cdot cm^{-3}$]	ρ_{CHM} [$g\cdot cm^{-3}$]	ρ_{LACH} [$g\cdot cm^{-3}$]	$\bar{\rho}$ [$g\cdot cm^{-3}$]
Pannonian Basin	Transdanubian Range	Upper Crust	10	0.38	250	6	2.63	2.71		2.67
		Lower Crust	24	0.76	535	6.65	2.95	2.94		2.95
		Lower Lithosphere	40 45	1.2 1.34	785 870	7.95 8		3.34 3.37	3.36 3.35	3.36
	Pannonian Basin West	Upper Crust	5 12	0.24 0.43	150 350	6 6.2	 2.73	2.73 2.78		2.75
		Lower Crust	24	0.76	650	6.65	2.96	2.94		2.95
		Lower Lithosphere	40 45	1.2 1.34	900 1000	7.9 8.05		3.33 3.38	3.44 3.44	2.4
	Pannonian Basin East	Upper Crust	5 12	0.24 0.43	175 380	6 6.05	 2.66	2.73 2.73		2.71
		Lower Crust	24	0.76	750	6.65	2.97	2.94		2.96
		Lower Lithosphere	40 45	1.2 1.34	1000 1100	7.9 8.05		3.33 3.38	3.44 3.44	3.4
External Western Carpathians		Upper Crust	8 15	0.32 0.51	240 340	6 6.3	2.62 2.77	2.72 2.82		2.73
		Lower Crust	25	0.79	535	6.65	2.95	2.94		2.95
		Lower Lithosphere	40	1.2	780	8		3.35	3.36	3.36
Bohemian Massif		Upper Crust	5 15	0.24 0.51	120 310	6 6.3	 2.77	2.73 2.82		2.77
		Lower Crust	25	0.79	490	6.7	2.96	2.96		2.96
		Lower Lithosphere	45	1.34	800	8.05		3.38	3.36	3.37

f)

CEL11		z [km]	P [GPa]	T [C°]	$V_{p(in\ situ)}$ [$km\cdot s^{-1}$]	ρ_{SB} [$g\cdot cm^{-3}$]	ρ_{CHM} [$g\cdot cm^{-3}$]	ρ_{LACH} [$g\cdot cm^{-3}$]	$\bar{\rho}$ [$g\cdot cm^{-3}$]
Pannonian Basin	Upper Crust	10	0.38	350	5.95	2.61	2.69		2.65
	Lower Crust	20	0.65	470	6.5	2.87	2.89		2.88
	Lower Lithosphere	35 50	1.06 1.48	900 1100	8.05 8.4		3.35 3.47	3.34 3.32	3.37
Internal Western Carpathians	Upper Crust	5 10	0.24 0.38	150 320	5.5 5.9		2.54 2.68		2.61
	Lower Crust	20	0.65	560	6.6	2.93	2.92		3.93
	Lower Lithosphere	35 60	1.06 1.75	890 1310	8.05 8.4		3.35 3.51	3.35 3.3	3.38
External Western Carpathians	Upper Crust	5 10 15 20	0.24 0.38 0.51 0.65	90 190 265 350	5.2 5.3 5.7 6	 2.64	2.41 2.42 2.59 2.9		2.59
	Lower Crust	20 27	0.65 0.84	350 480	6.55 6.7	2.88 2.96	2.71 2.96		2.88
	Lower Lithosphere	45	1.34	660	8.15		3.4	3.37	3.39
Carpathian Foredeep	Upper Crust	5 10 15 20	0.24 0.38 0.51 0.65	110 150 210 265	5.55 5.6 5.9 6		2.56 2.55 2.67 2.71		2.62
	Lower Crust	25 30	0.79 0.93	310 360	6.6 6.7	2.9 2.95	2.93 2.97		2.94
	Lower Lithosphere	40	1.2	385	8.15		3.39	3.4	3.4
East European Craton	Upper Crust	5 15	0.24 0.51	90 265	5.6 5.9		2.58 2.67		2.63
	Lower Crust	25 30	0.79 0.93	420 490	6.53 6.8	2.88 3.01	2.9 3		2.95
	Lower Lithosphere	45	1.34	665	8.15		3.4	3.37	3.39

g)

CEL12		z [km]	P [GPa]	T [C°]	$V_{p(in\ situ)}$ [$km\cdot s^{-1}$]	ρ_{SB} [$g\cdot cm^{-3}$]	ρ_{CHM} [$g\cdot cm^{-3}$]	ρ_{LACH} [$g\cdot cm^{-3}$]	$\bar{\rho}$ [$g\cdot cm^{-3}$]
External Western Carpathians	Upper Crust	5 5 10 15 20 25	0.24 0.24 0.38 0.51 0.65 0.79	80 100 195 265 345 420	4.9 5.5 5.65 5.75 6 6.1	 2.64 2.69	2.26 2.54 2.58 2.61 2.82 2.71		2.61
	Lower Crust	15 20 25 30 30 35	0.51 0.65 0.79 0.93 0.93 1.06	265 345 420 490 490 550	6.3 6.35 6.45 6.55 6.75 6.8	2.76 2.79 2.84 2.9 2.98 3.01	2.84 2.75 2.88 2.92 2.99 3.01		2.89
	Lower Lithosphere	35 40	1.06 1.2	550 600	8 8.1		3.34 3.38	3.38 3.38	3.37

1963), Birch (1961), Ludwig et al. (1970), Gardner et al. (1974), Beyer et al. (1985), Granser (1987), Lillie et al. (1994), Kaban and Mooney (2001), Tesauro et al. (2008), Krysiński (2009), Krysiński et al. (2009), Kaban et al. (2010) and Bielik et al. (2013).

The densities of the crustal rocks located in depths of over 5 km were determined based on the formulae defined by *Sobolev and Babeyko (1994)* and *Christensen and Mooney (1995)*. The main reason for their applications is that these formulae take into account the in situ temperature and pressure conditions. Sobolev-Babeyko's formulae are applicable only to crystalline rocks, which means they cannot always be applied for the calculation of the in situ densities within the whole lithosphere. Where these formulae cannot be used the densities were determined on the basis of Christensen-Mooney's formula. In the lithospheric mantle (*Zeyen et al., 2002*) the density decrease due to temperature is usually supposed to be stronger than the increase due to pressure except for very low temperature gradients. Therefore, the den-

Table 2. Summary of the results for the major tectonic units through which profiles CEL01, CEL04, CEL05, CEL06, CEL09, CEL11 and CEL12 pass. Keys: z – depth, v_p – longitudinal seismic velocity, ρ – density, $\bar{\rho}$ – average density.

Tectonic Units	**Layer**	**z [km]**	**$v_{p(in\ situ)}$ [km·s^{-1}]**	**ρ [g·cm^{-3}]**	**$\bar{\rho}$ [g·cm^{-3}]**
Transdanubian Range	Upper Crust	0 – 20	5.90 – 6.25	2.69 – 2.80	2.75
	Lower Crust	17 – 32	6.50 – 6.65	2.89 – 2.94	2.92
	Lower Lithosphere	30 – 110	7.90 – 8.00	3.30 – 3.37	3.34
Pannonian Basin	Upper Crust	2 – 21	5.95 – 6.20	2.61 – 2.78	2.70
	Lower Crust	9 – 30	6.35 – 6.65	2.84 – 2.97	2.91
	Lower Lithosphere	21 – 100	7.85 – 8.40	3.29 – 3.47	3.38
Internal Western Carpathians	Upper Crust	2 – 25	6.05 – 6.25	2.66 – 2.80	2.73
	Lower Crust	13 – 36	6.55 – 6.70	2.90 – 2.97	2.94
	Lower Lithosphere	25 – 140	7.90 – 8.40	3.32 – 3.51	3.42
External Western Carpathians	Upper Crust	3 – 25	5.30 – 6.30	2.40 – 2.82	2.61
	Lower Crust	23 – 42	6.30 – 6.80	2.76 – 3.05	2.91
	Lower Lithosphere	35 – 170	8.08 – 8.05	3.30 – 3.45	3.38
Carpathian Foredeep	Upper Crust	3 – 25	5.55 – 6.00	2.56 – 2.71	2.64
	Lower Crust	23 – 42	6.10 – 6.80	2.68 – 3.01	2.85
	Lower Lithosphere	35 – 170	7.90 – 8.15	3.32 – 3.40	3.36
Paleozoic Platform	Upper Crust	3 – 27	5.50 – 6.30	2.54 – 2.82	2.68
	Lower Crust	20 – 44	6.65 – 7.05	2.94 – 3.13	3.04
	Lower Lithosphere	30 – 180	8.10 – 8.15	3.36 – 3.43	3.40
East European Craton	Upper Crust	4 – 22	5.20 – 6.20	2.41 – 2.87	2.64
	Lower Crust	10 - 51	6.45 – 7.15	2.83 – 3.13	2.98
	Lower Lithosphere	34 – 240	8.15 – 8.25	3.37 – 3.44	3.41
Bohemian Massif	Upper Crust	0 – 20	6.00 – 6.30	2.73 – 2.82	2.78
	Lower Crust	15 – 38	6.70	2.96	2.96
	Lower Lithosphere	30 – 140	8.05	3.36 – 3.38	3.37

sities in the lithospheric mantle were also calculated by using Lachenbruch-Morgan's formula (*Lachenbruch and Morgan 1990*), which takes into account the dependence of density on temperature through the coefficient of thermal expansion $\alpha = 3.5 \times 10^{-5}$ K^{-1}.

4. Results

The densities of the sedimentary rocks in the Pannonian Basin and in the intramontane depressions of the Internal Western Carpathians (Figs. 3b,c) vary in the range from 2.00 to 2.67 g·cm^{-3}. In the External Western

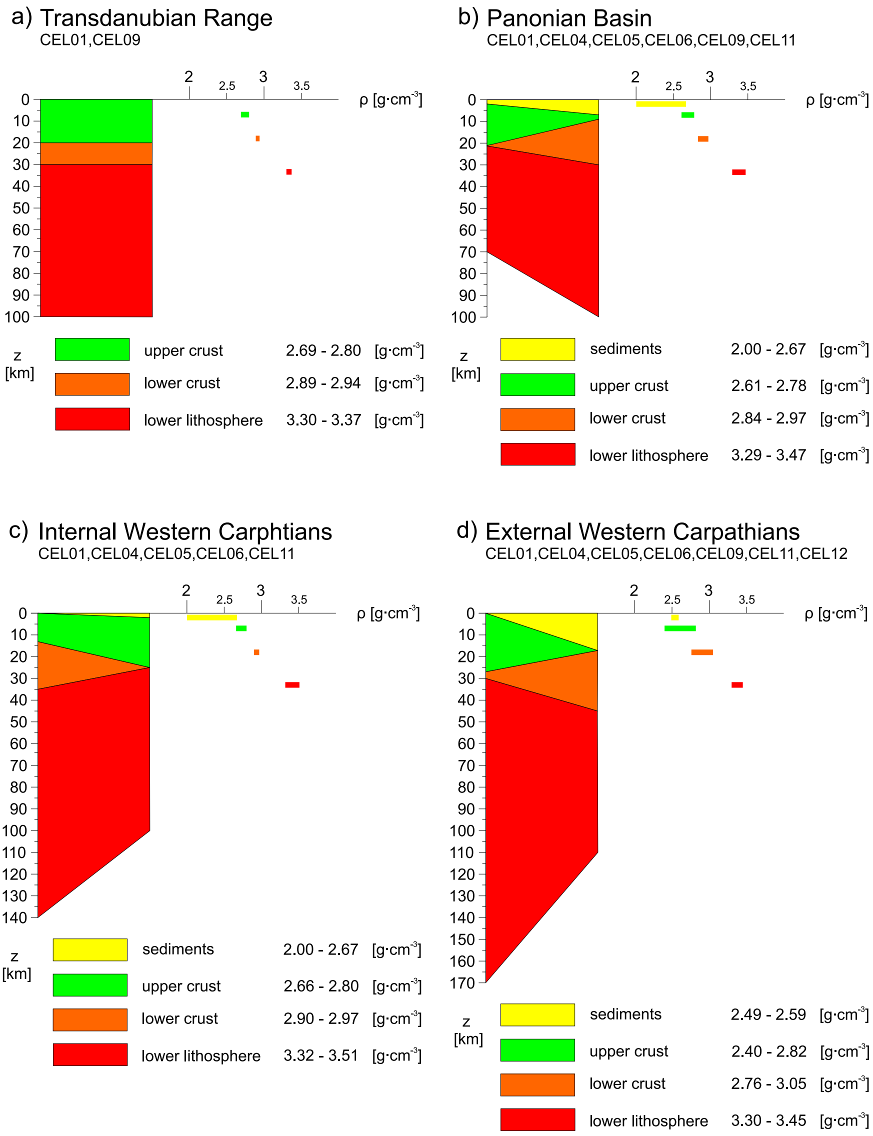

Fig. 3. Summary of the calculated rock density intervals and estimated thicknesses for the sediments, upper crust, lower crust and lower lithosphere (see text for further details and references).

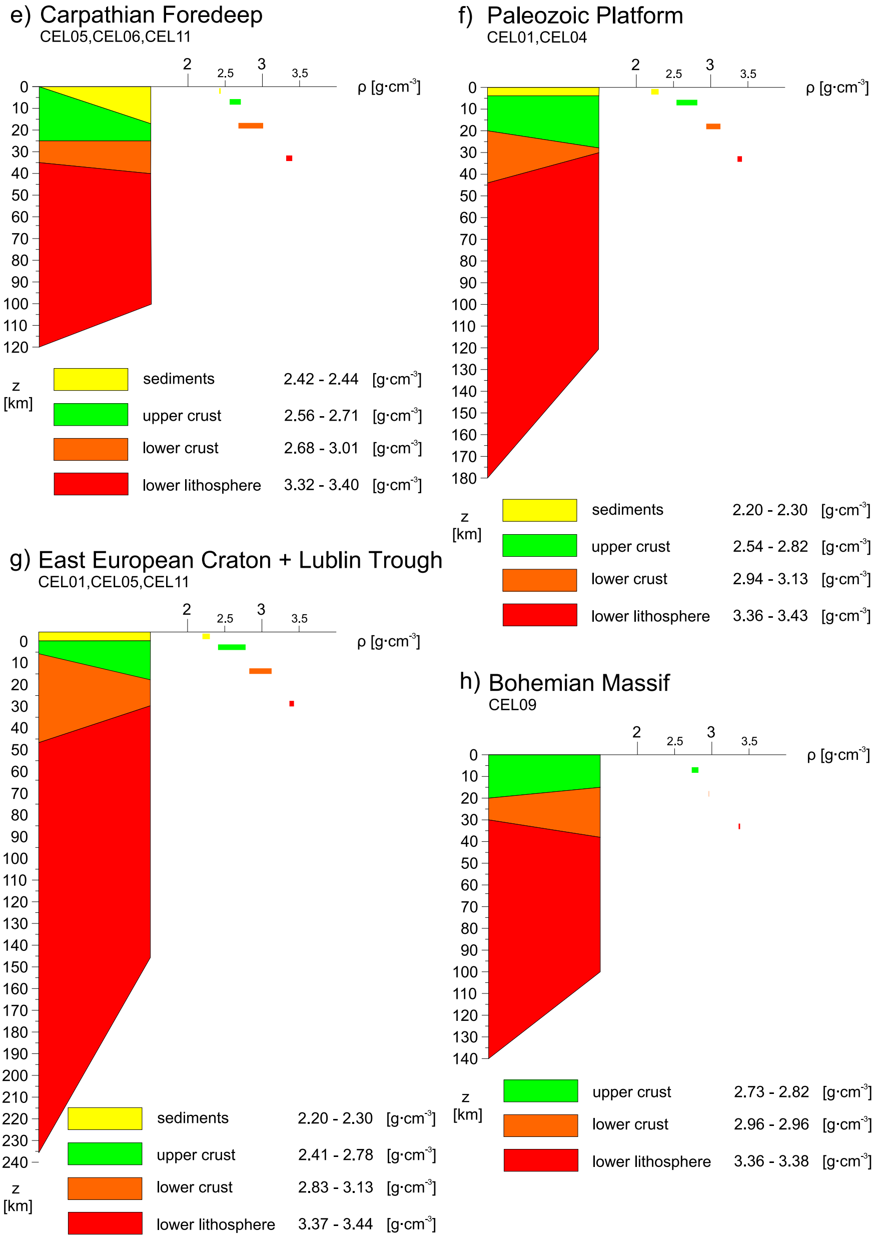

Fig. 3. Continued from the previous page.

Carpathians the average densities (Fig. 3d) were determined in the interval of 2.49–2.59 g·cm^{-3}. The average densities of the sedimentary filling in the Carpathian Foredeep range from 2.42 to 2.44 g·cm^{-3} (Fig. 3e), in the Palaeozoic Platform and the East European Craton (including the Lublin Trough) from 2.20 to 2.30 g·cm^{-3} (Figs. 3f,g).

The rock densities in the crust calculated by the transformation of the in situ P-wave velocities to the in situ densities using the formulae of Sobolev-Babeyko (*Sobolev and Babeyko, 1994*), Christensen-Mooney (*Christensen and Mooney, 1995*) and in the lower lithosphere by Lachenbruch-Morgan's formula (*Lachenbruch and Morgan, 1990*) are presented in Tables 1 and 2, and in Figure 3. The blank spaces in the column of ρ_{SB} of the Table 1 mean that Sobolev-Babeyko's formulae could not be applied. In these cases the densities were determined by Christensen-Mooney's formula. The rock densities in Table 1 are set up by major tectonic units through which profiles CEL01, CEL04, CEL05, CEL06, CEL09, CEL11 and CEL12 pass and given for the upper and lower crust, and lower lithosphere. Table 2 and Figure 3 provide a range of average densities for the upper and lower crust, and lower lithosphere in the individual tectonic units. Figure 3 also shows the minimum and maximum depths for the depth of the sedimentary basement (*Bielik, 1988; Kilényi and Šefara, 1989; Lenkey, 1999; Kováč, 2000; Bielik et al., 2005*), the top and bottom boundaries of the upper and lower crust (*Grad et al., 2006; Hrubcová et al., 2005; Środa et al., 2006; Janik et al., 2011*), and the lower lithosphere (*Zeyen et al., 2002; Dérerová et al., 2006; Grinč et al., 2013; Alasonati Tašárová et al., 2008, 2009, 2016*).

The analysis of the calculated in situ rock densities along the investigated profiles indicates that the average density of the upper crust ($\bar{\rho}$ = 2.60 g·cm^{-3}) is lowest in the Carpathian Foredeep region. On the other hand, the highest density of this layer ($\bar{\rho}$ = 2.77 g·cm^{-3}) is located in the Bohemian Massif. The External Western Carpathians have the second lowest density of the upper crust ($\bar{\rho}$ = 2.61 g·cm^{-3}). A relatively low density of the upper crust can be observed in the East European Craton ($\bar{\rho}$ = 2.62 g·cm^{-3}). However, it is due to the extremely low density of the upper crust in the Lublin Trough ($\bar{\rho}$ = 2.45 g·cm^{-3} – CEL01 and $\bar{\rho}$ = 2.56 g·cm^{-3} – CEL05). The rest of the East European Craton until the end of the profiles CEL01, CEL05 and CEL11 is already characterized by significantly higher average density, which varies from $\bar{\rho}$ = 2.63 to 2.73 g·cm^{-3}. The calculated average density in the Internal Western Carpathians is $\bar{\rho} = 2.68$ g·cm^{-3} and in the Palaeozoic Platform it is $\bar{\rho} = 2.69$ g·cm^{-3}. This tectonic unit is represented by the Malopolska and Lysogory units. Both are characterized by extremely strong low density upper crustal bodies ($\bar{\rho} = 2.60$ g·cm^{-3} – Malopolska unit and $\bar{\rho} = 2.66$ g·cm^{-3} – Lysogory Unit). This anomalous density body reaches in its centre a thickness of up to 20 km (CEL01). However, on the profile CEL04, both these tectonic units have higher densities ($\bar{\rho} = 2.73$ g·cm^{-3} and $\bar{\rho} = 2.74$ g·cm^{-3}). The density of the Pannonian Basin upper crust is $\bar{\rho} = 2.70$ g·cm^{-3}. A slightly higher density ($\bar{\rho} = 2.71$ g·cm^{-3}) of this layer characterizes the Transdanubian Range.

The average densities of the lower crust vary between 2.90 to 2.98 g·cm^{-3}. Clearly the Palaeozoic Platform and the East European Craton have the highest lower crust density ($\bar{\rho} = 2.98$ g·cm^{-3} and $\bar{\rho} = 2.97$ g·cm^{-3}, respectively). The Bohemian Massif is characterized by an average density of 2.96 g·cm^{-3}. The lower crust in the External Western Carpathians is characterized by a density of $\bar{\rho} = 2.94$ g·cm^{-3}. The Internal Western Carpathian lower crust has a slightly lower density ($\bar{\rho} = 2.93$ g·cm^{-3}), while the density of this layer in the Carpathian Foredeep and the Transdanubian Range is $\bar{\rho} = 2.92$ g·cm^{-3}. The Pannonian Basin lower crust is the lowest ($\bar{\rho} = 2.90$ g·cm^{-3}).

The range of calculated average densities for the lower lithosphere is changed in the interval from 3.35 to 3.40 g·cm^{-3}. The results show clearly that the heaviest lower lithosphere can be observed in the East European Craton, the densities of which are on average 3.40 g·cm^{-3}. The lower lithosphere of the Transdanubian Range and Palaeozoic Platform is characterized by the lowest density $\bar{\rho} = 3.35$ g·cm^{-3}. The Pannonian Basin, the External Western Carpathians and the Carpathian Foredeep have the same average density of $\bar{\rho} = 3.38$ g·cm^{-3}. A slightly lower density of $\bar{\rho} = 3.36$ g·cm^{-3} was evaluated for the Internal Western Carpathians. The Transdanubium Range and the Palaeozoic Platform have the lowest density of the lower lithosphere ($\bar{\rho} = 3.35$ g·cm^{-3}).

4. Conclusion

It is known that heterogeneity of the Earth's structure decreases from the surface with increasing depth. This phenomenon was also confirmed in the

Carpathian-Pannonian Basin area. While the density of the upper crust changes significantly in the vertical and horizontal directions, the interval ranges of the calculated densities for the lower crust narrow down prominently. One exception is the lower crust of the Carpathian Foredeep and External Western Carpathians, and partly the Palaeozoic Platform. But it may also have a significant geological aspect. The results of the interpretation of seismic sections along the studied seismic profiles CELEBRATION 2000 (*Janik et al., 2011*) as well as the results of our density interpretation indicate that the lower crust of these three tectonic units is different from the surrounding tectonic units. The lower lithosphere is the most homogeneous – the intervals of the calculated densities for this layer are already very narrow.

When comparing the results obtained with the results of previous works (e.g., *Zeyen et al., 2002; Grabowska and Bojdys, 2005; Bielik et al., 2006; Dérerová et al., 2006; Grabovska et al., 2011; Grinč et al., 2013; Alasonati Tašarová et al., 2008, 2009, 2016*) we can note that our results are in good agreement with the previous results. The results obtained in this paper extend our present information and knowledge significantly about the crustal and lower lithosphere densities of the Carpathian-Pannonian Basin area.

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