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IMPROVED GEOPHYSICAL IMAGE OF THE CARPATHIAN-PANNONIAN BASIN REGION

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Our paper presents the general overview of the current geophysical results, which helps to improve the geophysical image and the lithospheric structure of the Carpathian-Pannonian Basin region. Two different geophysical methods have been applied for the study of the structure and composition of the lithosphere as well as for determination of the lithospheric thermal structure. Firstly, integrated 2D modeling of gravity, geoid, topography and surface heat flow data was performed. Secondly, based on the results of the CELEBRATION 2000 seismic experiment, a large-scale 3D lithospheric gravity model was developed. The resulting map of the lithospheric thickness shows important variations in lithospheric thickness across the chain as well as along strike of the Carpathian arc. The sediment stripped gravity map is characterized by minima in the Eastern Alps and Western Carpathians. The maxima are observed in the Pannonian Back-arc Basin system, Bohemian Massif, Fore-Sudetic Monocline, Bruno-Silesian unit (BSU), Lublin Trough and partly in the Holy Cross Mts. and Malopolska unit. The Western Carpathian gravity minimum is a result of the interference of two main gravity effects. The first one comes from the low-density sediments of the Outer Western Carpathians and Carpathian Foredeep. The second one is due to the thick low-density upper and middle crust, reaching up to 25 km. The sediment stripped anomaly in the Pannonian Back-arc Basin system is characterized by gravity high that is a result of the gravity effect of the anomalously shallow Moho. The most dominant feature of the complete stripped gravity map is the abrupt change of the positive anomalies along the Pieniny Klippen Belt zone. The complete residual anomaly of the Pannonian Back-arc Basin system and the Western Carpathian orogen is characterized by a long-wavelength gravity low. The lowest values are associated with the thick low-density upper and middle crust of the Inner Western Carpathians. The European Platform is characterized by significantly denser crust with respect to the less dense crust of the microplates ALCAPA and Tisza-Dacia. That is why we suggest that the European platform represents consolidated, while the Carpathian-Pannonian Basin region un-consolidated crust.

Keywords: Carpathian-Pannonian Basin region; gravity; lithosphere; modeling; stripping

1. Introduction

The main goal of this paper is to present the current geophysical results together with an enhanced model of the Carpathian-Pannonian Basin lithosphere. For the development of the model, two different methods of the gravity field modeling were applied. In the first case we used the integrated lithospheric modeling that combines the interpretation of gravity, surface heat flow, geoid and topography data for the determination of the lithospheric thermal structure. The modeling was performed along nine profiles crossing the Western and Eastern Carpathians from the European Platform to the Pannonian Back-arc Basin system. A new map of lithospheric thicknesses was calculated and published in the papers of Zeyen et al. (2002) and Dérerová et al. (2006). The second method consisted of the application of 3D gravity modeling by means of the IGMAS software (Alasonati Tašarová et al. 2008, 2009). The resulting 3D density model was constructed based on the forward modeling of the newly compiled complete Bouguer anomalies (Bielik et al. 2006). The model includes most of the available geophysical constraining data (the previous geophysical studies and the results from several international seismic refraction experiments: CELEBRATION2000, POLONAISE'97, ALP 2002 and SUDETES 2003 — e.g., Šroda et al. 2006, Malinowski et al. 2005, Janik et al. 2005, Grad et al. 2006, Hrubcová et al. 2005). Additionally, thermal and density distributions of the shallow upper mantle were estimated using a combination of petrological, geophysical, and mineral physics information (LitMod algorithm — e.g., Afonso et al. 2008). As a result, this recent 3D gravity model combines geophysical and petrological data, by means of which improved density and thermal distributions in the crust and mantle were estimated and modeled. Moreover, based on the enhanced geometry of the lithospheric structure, gravity stripping was done in order to analyze the gravity field in more detail.

2. Geology

The Alpine-Carpathian-Pannonian (ALCAPA) region consists of the Carpathian orogen and Pannonian Back-arc Basin system (Fig. 1). It is a result of the Neogene evolution. In the beginning of this evolution (Neogene), the Inner Carpathian region consisted of two independently moving microplates, known as ALCAPA and Tisza-Dacia (Balla 1994, Csontos 1995). The extrusion of ALCAPA from Alpine region is studied by Kázmér and Kovács (1985). The northern boundary of the ALCAPA microplate is the Klippen Belt zone (KBZ) and the southern boundary is represented by the Balaton and Mid-Hungarian line, respectively having the insertion of the Sava unit between them (Haas 2001, Ádám et al. 2005). The Tisza-Dacia microplate consists of two separate lithospheric fragments, having different tectonic histories (Csontos 1995). The Tisza unit outcrops in the Mecsek, Villany, Papuk and Apusseni Mountains. The Dacia unit is formed by the Inner and Outer Dacides of the Eastern Carpathians and by the Southern Carpathian units. The third major microplate which has influenced the evolution of the Carpathian-Pannonian region is the Adriatic (Adria, Apulia) microplate (Kováč 2000).

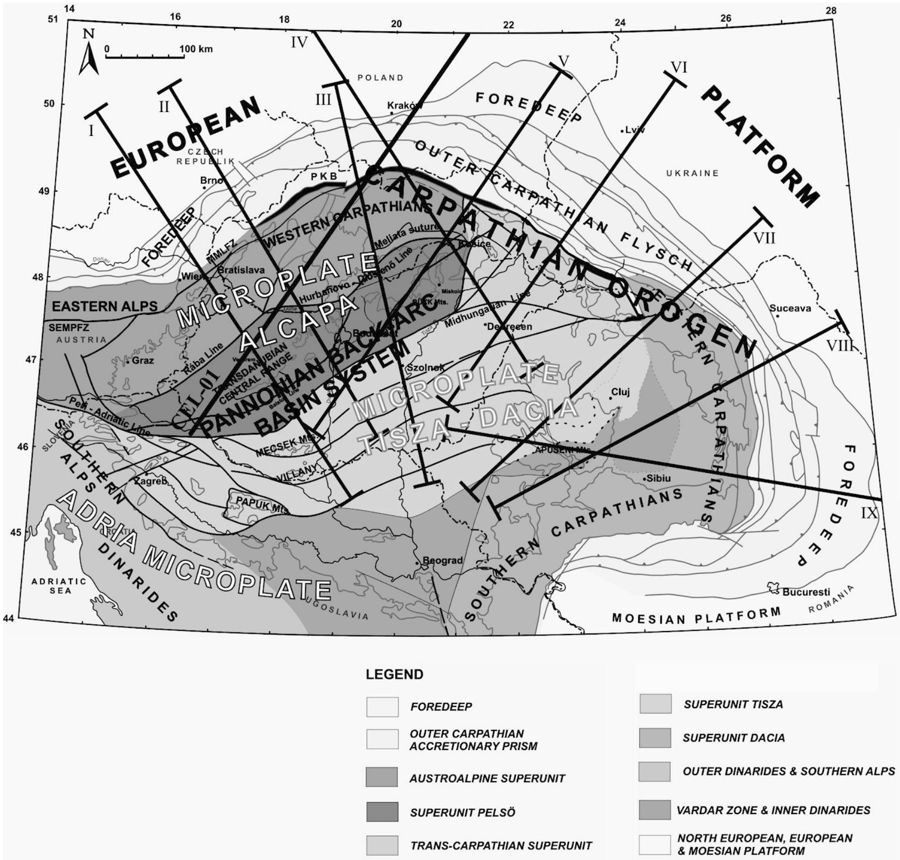

Fig. 1. Tectonic scheme of the Carpathian-Pannonian Basin region with the microplates ALCAPA, TISZA-DACIA and ADRIA and their division into geological superunits (modified after Kováč 2000). Location of the interpretation profiles, which were used for determination of the lithospheric thickness (modified after Zeyen et al. 2002 and Dérerová et al. 2006)

The evolution was caused and accompanied by the subduction of an oceanic/sub-oceanic lithosphere underneath the microplates, related to the closure of the remnant Neotethys Ocean. The slab roll-back at the orogenic front leading to the steepening of the slab and its detachment was associated with a contemporaneous asthenospheric upwelling and rifting in the Pannonian Back-arc Basin System region. The oblique collision of the microplates with the European Platform stopped the subduction (for more details see Ratschbacher et al. 1991a, 1991b, Lexa et al. 1993, Csontos 1995, Kováč 2000). This interpretation is supported to the volcanic activity in the region. During the Miocene-Pliocene time, the Carpathian arc migrated northward and eastward.

3. Determination of the Carpathian-Pannonian lithospheric thermal structure by means of the integrated geophysical modeling

The integrated modeling algorithm has been applied to nine profiles (Fig. 1). All profiles start in the Pannonian Back-arc Basin system and cross the Carpathian orogen and end on the European Platform. Profile VI passes through the Transcarpathian Basin and profiles VII and VIII cross the Apuseni Mountains and the Transylvanian Basin. Profile IX crosses the Apuseni Mountains and the Transylvanian Basin and then passes through the seismogenic Vrancea zone.

Input geophysical data using for the 2D integrated geophysical modeling are represented by the topography, gravity, geoid and surface heat flow. Topography has been taken from GTOPO30 database (Gesch et al. 1999). The free air gravity anomalies were taken from the TOPEX 1-min gravity data set (ftp: //topex.ucsd.edu/pub (Sandwell and Smith 1997). Geoid data are taken from the EGM96 global model (Lemoine et al. 1998). The surface heat flow data were compiled from the worldwide data set of Pollack et al. (1993) and the maps of heat flow of the Western Carpathians and their vicinity published by Čermák et al. (1992), Král (1995), Šefara et al. (1996), Gordienko and Zavgorodnyaya (1996), Majorowicz (2004), and Lenkey (1999). More detail information on the accuracy of these data can be found in the paper (Dérerová et al. 2006). The same paper also deals with about the geological and geophysical data (e.g., the thickness of the outer Carpathian foredeep sediments, the thickness of the Tertiary sediment of the Pannonian Back-arc Basin System, the depth of the boundary between upper and lower crust, the Moho discontinuity and the lithosphere thickness), which were applied for a creation of the starting model of our integrated geophysical modeling.

The applied integrated geophysical method has been explained in the papers of Zeyen and Fernàndez (1994), Zeyen et al. (2002) and Dérerová et al. (2006). The program uses a 2D finite element algorithm to calculate the temperature distribution based on a user-defined lithospheric structure, where each anomalous body is characterized by its density, thermal conductivity and heat production. The body structure is as much as possible constrained by existing seismic and other geophysical and geological data. The thermal boundary conditions are fixed temperatures at the upper limit (20°C on the Earth's surface) and the lower one (1300°C on the lithosphere-asthenosphere boundary (LAB)). No horizontal heat flow at the lateral and vertical boundaries is suggested. After the calculation of the temperature distribution, the gravity and geoid variations and the topography are calculated. The observed data (surface heat flow, free-air anomaly and/or complete Bouguer anomaly, geoid and topography) and model results are compared and the model is then changed interactively by trial and error until an acceptable fit is obtained (Fig. 2).

A general feature of the lithospheric thickness in the study region (Fig. 3) is its increase from the youngest and hottest tectonic units (the Pannonian Back-arc Basin system) to the oldest and coolest ones (the European Platform). The lithospheric thickness underneath the European Platform varies from 80–140 km in the Czech Republic (the Bohemian Massif), 120–140 km in the Poland up to 120–200 km in the Ukraine. Based on the results of Semenov et al. (2008) it can be expected that the lithospheric thickness would have increased from interpreted 140 km up to more than 200 km in direction from the Tornquist-Teisseyre line towards the East European Platform. Note that this part of the East European Platform is out of our interest. The Pannonian Back-arc Basin system is characterized by 70–80 km thick lithosphere increasing southward to 100 km. This thickness is larger than published earlier (e.g., Posgay 1975, Horváth 1993, Lenkey 1999, Ádám and Wesztergom 2001, Horváth et al. 2006). Reducing the lithospheric thickness to the published values 60 km would uplift 200 m the modeled topography, making it incompatible with the observed one. The lithospheric thickness underneath the Transylvanian Basin reaches in the models about 110 to 130 km. Underneath the Apuseni Mountains the lithospheric thickness increases to 90–130 km. The most interesting feature can be seen underneath the Eastern Carpathians and their foreland. Our models show a strong lithospheric thickening to more than 240 km along all transects. This pronounced thickening is needed to obtain a good correlation between the observed and modeled topography and geoid anomalies. Note that the calculated lithospheric thickness is not correct in the Vrancea zone, because the applied 2D finite element algorithm collapses if a structure (lithospheric slab) becomes much thicker than its width (Dérerová et al. 2006). It is known that the lithospheric thickness increases beneath the Vrancea zone to more than 300 km (Wortel and Spakman 2000).

Thickening of the lithosphere in the Eastern Carpathian foreland is only accompanied by small crustal thickening, except for the Vrancea zone. On all transects, the crustal thickening is shifted south-westward with respect to the lithospheric thickening toward the areas of highest topography in the central (inner) Eastern Carpathians (e.g. see Fig. 2). In the Vrancea area, we had to model a local thickening underneath the mountain chain to an intermediate thickness of 45 km. On all transects, crustal thickness beneath the European Platform is rather constant and has values around 37–38 km. Under the Pannonian Back-arc Basin system, the crust thins to 26–27 km with a clear increase underneath the Apuseni Mountains to more than 35 km.

4. 3D density modeling

The 3D gravity model was constructed using the Interactive Gravity and Magnetics Application System (IGMAS). IGMAS is a tool made for the interpretation of measured gravity and magnetic fields (e.g. Schmidt and Götze 1999). It works by means of a numerical simulation of geological structures that are described as closed polyhedrons of constant density/susceptibility (e.g. Götze and Lahmeyer 1988). 3D structure is achieved in IGMAS by defining several vertical planes parallel to each other, which are connected via triangulation into 3D structure. The 3D gravity model was developed along 36 profiles. The separation of the profiles in the area of the Pannonian Back-arc Basin system and Western Carpathians was set to 10 or 20 km and in the Eastern Alps and Bohemian Massif to 40 km. The crustal densities were calculated using the empirical P-wave velocity-density relationships of Sobolev and Babeyko (1994) and Christensen and Mooney (1995). The upper-mantle den-

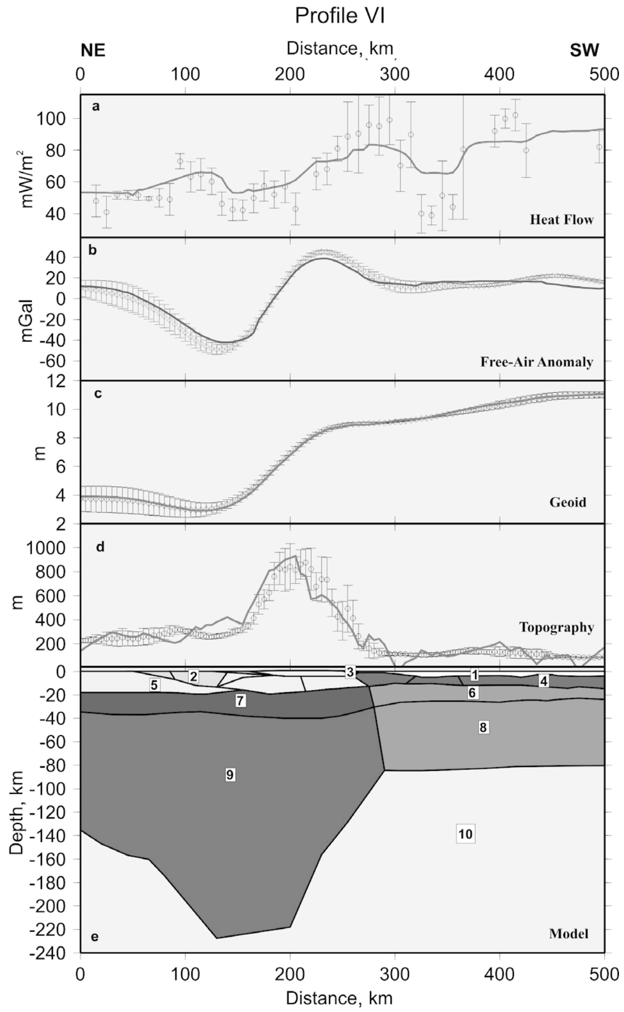

Fig. 2. Lithospheric models along Profile VI (modified after Dérerová et al. 2006). Dots corresponding to measured data with uncertainty bars and solid lines to calculated values. Keys: 1 – Pannonian Basin sediments, 2 – Outer Carpathian Molasse and Flysh, and sedimentary cover of European Platform, 3 – Volcanics, 4 – Carpathian Pannonian (microplates ALCAPA and TISZA-DACIA) upper crust, 5 – European Platform upper crust, 6 – Carpathian-Pannonian (microplates ALCAPA and TISZA-DACIA) lower crust, 7 – European Platform lower crust, 8 – Carpathian-Pannonian Lower Lithosphere, 9 – European Platform Lower Lithosphere, 10 – asthenosphere

sities were estimated based on the 2D approach LitMod (Afonso 2006), which combines the petrological, geophysical, and mineral physics information (Fig. 4).

Hence, a better control on possible temperature and density variations within the lithosphere is possible. This is particularly important for the Pannonian Back-arc Basin system, where a pronounced asthenospheric upwelling has been inferred (e.g. Csontos et al. 1992, Bielik et al. 2004). The LitMod modeling was performed along three selected profiles. The resulting densities were incorporated into the IGMAS

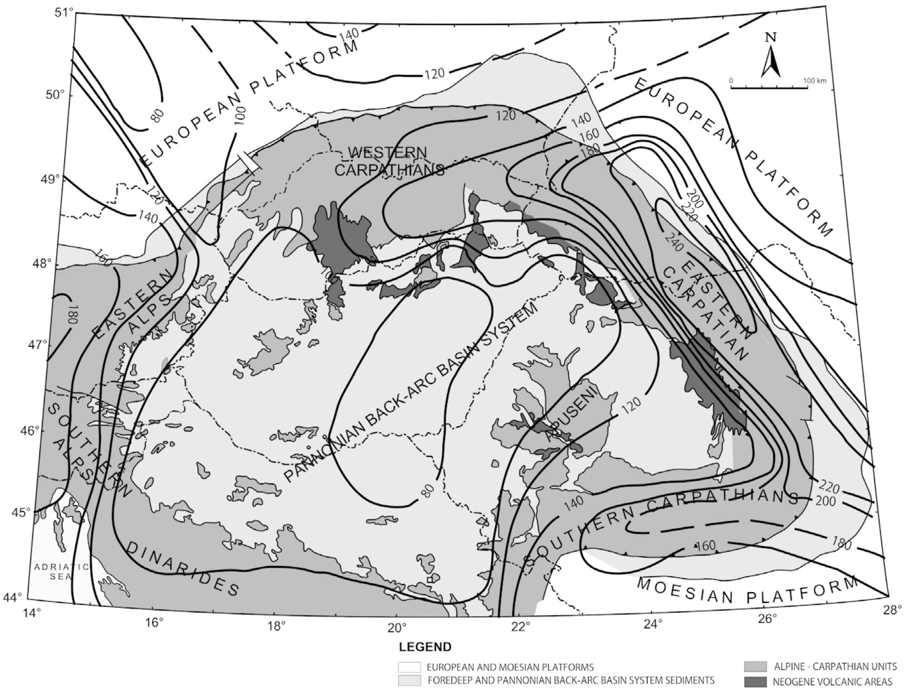

Fig. 3. Lithospheric thickness map of the Carpathian-Pannonian Basin region (compiled after Zeyen et al. 2002 and Dérerová et al. 2006 and completed by Babuška et al. 1988, Horváth 1993 and Lenkey 1999) in the region out of the profiles

3D gravity model. The structure was extrapolated along the remaining profiles and the model was refitted accordingly. For more details see Alasonati Tašárová et al. (2009).

The 3D gravity model integrates the results from previous petrological and geophysical investigations (e.g. Horváth 1993, Lillie et al. 1994, Konečný et al. 2002, Zeyen et al. 2002, Dérerová et al. 2006) with the more recent CELEBRATION 2000 seismic experiment (Środa et al. 2006, Malinowski et al. 2005, Janik et al. 2005, Grad et al. 2006, Hrubcová et al. 2005). The resulting 3D gravity model is an advance in the knowledge of the recent structure of the region. Moreover, it provides new insights into its tectonic evolution (Figs 5 and 6).

5. Interpretation and discussion

The resultant new map of the lithospheric thickness in the Carpathian-Pannonian Basin region (Fig. 3, Zeyen et al. 2002 and Dérerová et al. 2006) was constructed as a compilation of our results and partly the results published by Babuška et al. (1988), Horváth (1993) and Lenkey (1999). The compilation consisted of the interpolation of our profile data and the former data, which were used in the region out of the profile region. This map shows significant variations within the lithospheric thickness across the chain as well as along strike of the Carpathians arc.

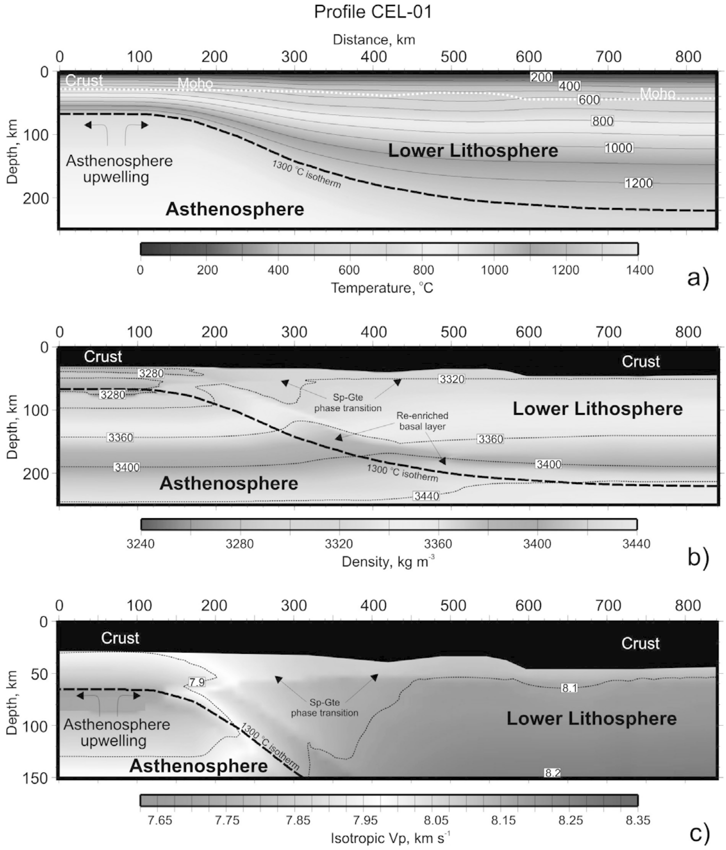

Fig. 4. The temperature, density and P-wave distribution in the shallow upper mantle along the CEL-01 calculated using the approach of Afonso (2006). The location of the profile is indicated in Fig. 1

The largest lithospheric thickness (240 km) can be observed beneath the Eastern Carpathians and its foreland. We suggest that this thickening of the lithosphere would be explained by the remnants of a slab, which started to break off in the Miocene. Our results of the integrated geophysical modeling are in good agreement with the results of seismic tomography by Wortel and Spakman (2000). Based on these results we also suggest the existence of the remnants of deep subduction and slab detachment from the European plate below the Carpathian-Pannonian Basin region (probably except for the seismogenic Vrancea zone, where the slab detachment has already not yet started and/or it is in the initial state, as well as in the Southeastern Carpathians). The remnants of the slab datachment would be represented by high-velocity anomaly at the bottom of the upper mantle (Wortel and Spakman 2000). We propose that the calculated lithospheric root is a result of the slab detachment along-strike of the Carpathians. After slab breaking-off its lower part sank into the deeper mantle beneath the Pannonian Basin, while its upper part started to create simultaneously the interpreted lithospheric root due to the con-

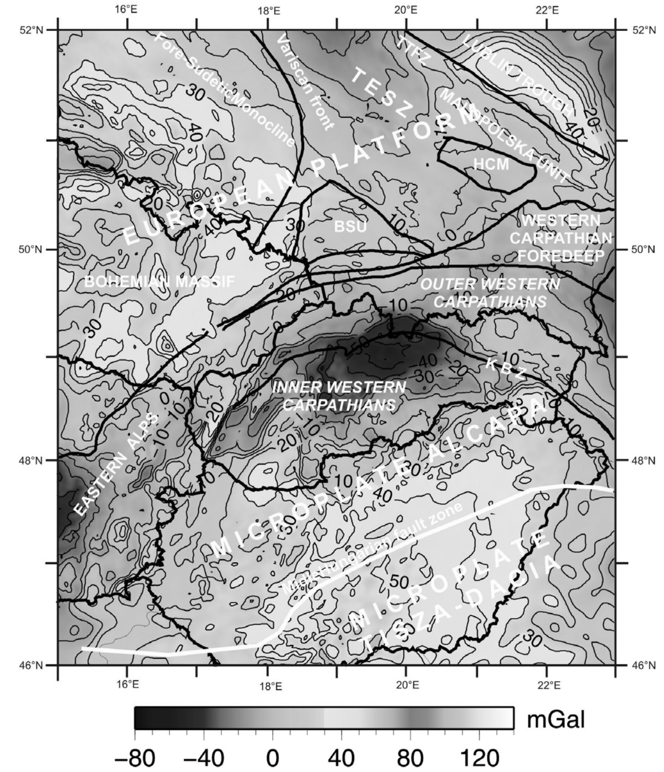

Fig. 5. Sediment stripped map calculated by subtracting the gravity effect of the sediments from the complete Bouguer anomaly. Acronyms stand for: TTFZ – Teyssere-Tornquist fault zone, TESZ – Trans European suture zone, HCM – Holly-cross Mts., BSU – Bruno-Silesian units, KBZ – Klippen Belt zone

tinuation of the convergence. The increasing thickness of the lithospheric slab from the Western Carpathians to the Eastern Carpathians supports the idea that the slab break-off started in the NW and propagated toward the SE. The seismogenic Vrancea zone is being inferred as the final expression of the progressive subduction, slab roll-back and plate boundary retreat. Similarly to Tomek and PANCARDI Working group (1996), we believe that these tectonic processes were responsible for the evolution of the Carpathian arc. Under the western part of the Western Carpathians no lithospheric thickening is observed. The values vary from only 100 to 120 km. Absence of the lithospheric slab can be explained by Miocene strike-slip extrusion of the microplate ALCAPA toward the east along the left-lateral strike-slip SEMPFZ in the Eastern Alps and along the similar MMLFZ to the northeast (Ratschbacher et al. 1991a, 1991b). It means that the relative movement changed from E to NE and it was mainly strike-slip along-strike the Leitha-Pericarpathian fault zone (MMLFZ) system (Fig. 7).

It is well-known that the magnetotelluric results (e.g., Horváth 1993, Ádám 1996, Lenkey 1999, Ádám and Wesztergom 2001, Horváth et al. 2006) suggest that the lithospheric thickness in the central part of the Pannonian Back-arc Basin system

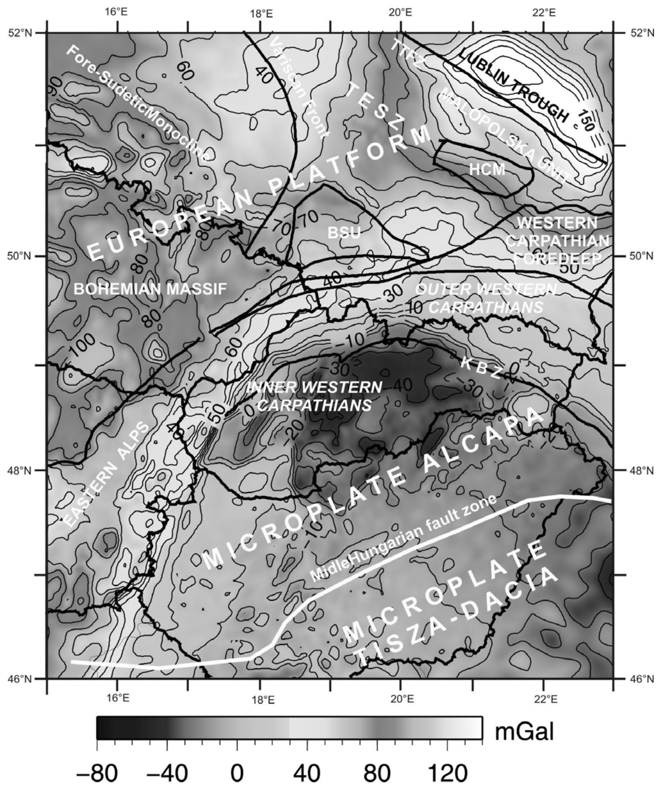

Fig. 6. Complete stripped map calculated by subtracting the gravity effects of the sediments (Fig. 5), the Moho and the uppermost part of the upwelling asthenosphere from the complete Bouguer anomaly. Acronyms stand for: TTFZ – Teyssere-Tornquist fault zone, TESZ – Trans European suture zone, HCM – Holly-cross Mts., BSU – Bruno-Silesian units, KBZ – Klippen Belt zone

is about 20 km less in comparison with our results. In spite of that we tried to take into account these results to our modeling, the integrated lithospheric modeling does not support a thinning to less than about 70 km. On the other hand, the valitidy of the magnetotelluric data is supported by the relation between the asthenospheric depth and the regional surface heat flow according to Ádám (1978). On the present, taking into account all existing geophysical results related to the determination of the lithospheric thickness models in the Carpathian-Pannonian Basin region, it is very hard to say which results reflect the real lithospheric thickness more correct. We can state only that the advantage of the magnetotelluric approach is the direct physical measurements, while the advantage of the integrated modeling consists in fitting of four different parameters: gravity, heat flow, topography and geoid at the same time.

The density model resulting from the 3D gravity modeling indicates the thinnest crust (22–28 km) underneath the Pannonian Back-arc Basin system, while it gradually thickens towards the European platform. The crust gradually thickens to 46 km in the Eastern Alps and 35-38 km in the eastern part of the Bohemian Massif. The

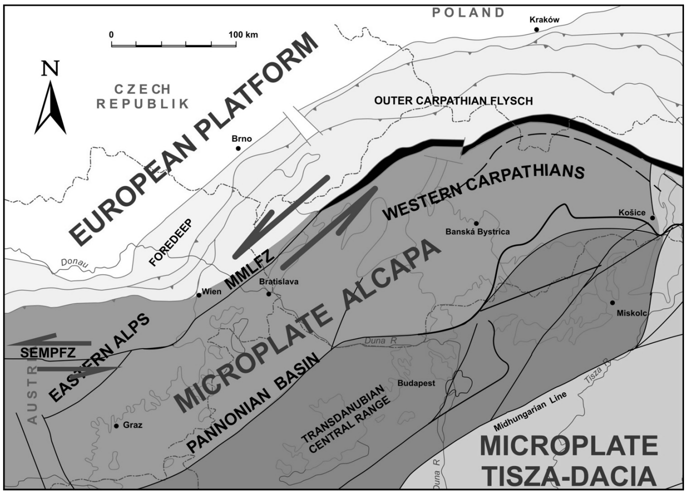

Fig. 7a. Schematic tectonic map of the Carpathian-Pannonian region (modified after Kováč 2000) with location the left-lateral strike-slip Salzachtal-Ennstal-Mariazell-Puchberg fault zone (SEMPFZ) in the Eastern Alps and the Mur-Mürz-Leitha fault zone (MMLFZ) and indication the movement of the lithospheric plates

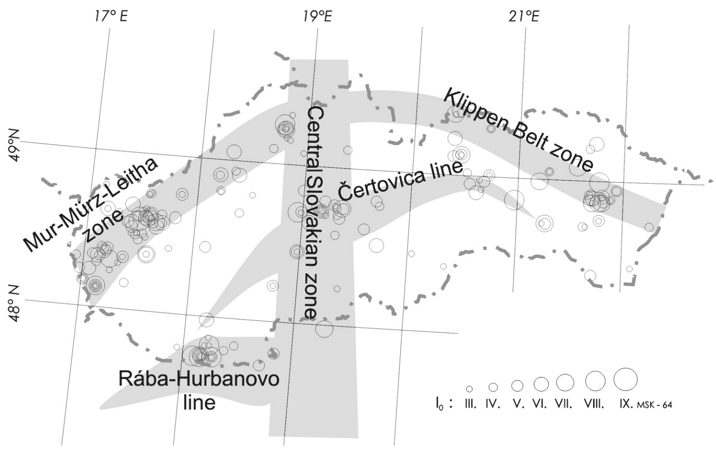

Fig. 7b. Map of the seismotectonic zones (modified after Hók et al. 2000) with epicenters of the macroseismically observed earthquakes in Slovakia during the period 1304–1990 (after Labák a Brouček 1996)

Western Carpathians are characterized by moderate crustal thickness. In general, the Inner Western Carpathians have 29 to 36 km thick crust, while underneath the Outer Western Carpathians and the Western Carpathian Foredeep it decreases from 30 to 45 km (Alasonati-Tašárová et al. 2009).

The thicknesses of the sedimentary units estimated by means of the 3D gravity modeling vary from 0–8 km in the Pannonian Back-arc Basin system, 0–2 km in the Inner Western Carpathians and a maximum of 21.5 km in the Outer Western

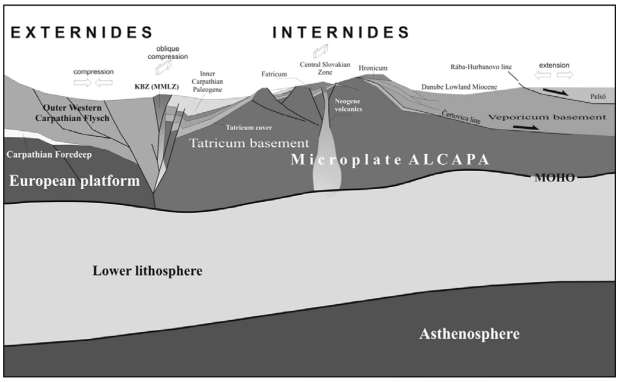

Fig. 7c. Scheme of the Western Carpathians geological structure with indication of the stress components and the directions of the movement main tectonic units (modified after Hók et al. 2000)

Carpathians Flysch zone. Note that the last value includes not only the sediments of the Outer Western Carpathian Flysch zone but also the Trans European suture zone (TESZ) cover, which contains the Upper Palaeozoic to Mesozoic strata (Środa et al. 2006). The Western Carpathian Foredeep is characterized by a thickness of 1–3 km.

To support the interpretation of the gravity field we calculated the sediment stripped gravity map (complete Bouguer anomalies are corrected for the gravity effect of the sediments – Fig. 5) and the complete stripped map (Fig. 6), which represents the crustal gravity effect (complete Bouguer anomalies are corrected for the gravity effects of the sediments, Moho and the low-density uppermost part of the asthenospheric upwelling.

On the sediment stripped gravity map, the Eastern Alps and Western Carpathians are characterized by minima, while the Pannonian Back-arc Basin system, Bohemian Massif, the Fore-Sudetic Monocline and the Lublin Through by maxima. The gravity low in the Eastern Alps is produced by the thick crust in this area (more than 45 km). The Western Carpathian gravity minimum is a result of the superposition of two gravity effects: 1. the low-density sediments of the Outer Western Carpathians and Western Carpathian Foredeep and 2. the thick low-density upper and middle crust, reaching up to 25 km. In contrary, the sediment stripped anomaly in the Pannonian Back-arc Basin system is characterized by positive values of 10–50 mGal, reflecting the anomalously shallow Moho in this region. Note that the Moho gravity effect of the shallow Moho is more dominate that the one coming from the sediments. The gravity maximum of ≈40 mGal along the Lublin through is associated with the high-velocity and high-density intrusive body, located below the sedimentary infill of the Lublin Trough. This 3D structure, which was clearly imaged along the CEL01 profile (Środa et al. 2006) is modeled in the middle crust of this transitional area between the European platform and TESZ. Therefore, the Lublin gravity high is a superposition of the positive gravity effect of the intrusion and the negative effect of the sedimentary infill, in which the intrusion effect is more pronounced.

The most dominant feature of the complete stripped gravity map is the abrupt change of the positive anomaly, which is observed in the region of the European platform (consisting of the Bohemian Massif, Fore-Sudetic Monocline, Variscan Front, Malopolska unit, Lublin Trough, Holy Cross Mts., Bruno-Silesian unit), along the KBZ (Fig. 6). The complete residual anomaly of the Western Carpathian orogen (ALCAPA and Tisza-Dacia microplates) and the Pannonian Back-arc Basin system is characterized by a relatively long-wavelength gravity low, with values varying from –10 mGal in the Pannonian Back-arc Basin system to –40 mGal in the Inner Western Carpathians. The lowest values are associated with the already mentioned thick low-density upper and middle crust of the Inner Western Carpathians. Additionally, we can also observe a difference between the residual gravity that characterize the microplates ALCAPA and TISZA-DACIA. The amplitude and the configuration of the microplate ALCAPA gravity field is obviously lower than in the TISZA-DACIA microplate. This can indicate the different structure and composition of the both microplates.

The major change in the complete residual anomaly takes place at the PKB. The complete stripped map shows a gradual increase of the residual anomaly from minimum of –40 mGal along the PKB to 30–60 mGal at the front of the Western Carpathian thrust (the border between the Outer Western Carpathian Flysch zone and the Western Carpathian Foredeep). This due to the fact that the Outer Western Carpathian Flysch zone is underlain by the older, denser and thicker crust of the European platform. The European Platform is characterized by a crust that is significantly denser with respect to the crust of the microplates ALCAPA and Tisza-Dacia. We suggest that the difference in the gravity fields of the European plate and microplates ALCAPA and Tisza-Dacia reflect a different consolidation of the crust in these tectonic units. It means that the Western Carpathian-Pannonian crust is less consolidated than the crust of the European platform.

6. Conclusions

The gravity stripping in the Carpathian-Pannonian region is essential, since its structures (e.g. thick sediments and very thin crust in the Pannonian Back-arc Basin system) cancel their gravity effects. The low values of the complete stripped map indicate rather less dense composition of the Western Carpathian-Pannonian Basin lithosphere, which probably is still unconsolidated. In contrary, the European platform lithosphere is much denser and mafic in composition. Hence, these observed differences in the complete residual anomaly clearly show that the Carpathian-Pannonian Basin region differs quite a lot from the older surrounding tectonic units. Our interpretation of the evolution of the Carpathian-Pannonian Basin region favors the 'traditional' subduction-collision models, due to the geological and petrological evidence (e.g. Lexa et al. 1993, Horváth 1993, Kováč 2000, Szabó et al. 2004).

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