DE GRUYTER
OPEN

Contributions to Geophysics and Geodesy Vol. 45/1, 2015 (13–23)

A new lithospheric model in the eastern part of the Western Carpatians: 2D integrated modelling

Petra HLAVŇOVÁ[1], Miroslav BIELIK[1,2], Jana DÉREROVÁ[2], Igor KOHÚT[2], Mariana PAŠIAKOVÁ[1]

[1] Faculty of Natural Sciences, Department of Applied and Environmental Geophysics
Comenius University, Mlynská dolina, pav. G, 842 15 Bratislava, Slovak Republic
e-mail: hlavnova@fns.uniba.sk; bielik@fns.uniba.sk; pasiakova@centrum.sk

[2] Geophysical Institute of the Slovak Academy of Sciences
Dúbravská cesta 9, 845 28 Bratislava, Slovak Republic
e-mail: geofjade@savba.sk; geofkohi@savba.sk

Abstract: Using 2D integrated geophysical modelling we recalculated lithospheric model along transect KP-X in the eastern part of the Western Carpathians. Our model takes into account the joint interpretation of the heat flow, free air anomalies, topography and geoid data. A more accurate model of lithospheric structure has been created, especially the lithosphere-astenosphere boundary. Lithosphere thickness in the study region increases from the area of the Pannonian Basin where we modelled it at the depth of 80 km towards the oldest and coolest area of the European Platform where it reaches about 150 km. In the Pannonian Basin the modelled Moho depths reach about of 25 km and it decreases towards the Western Carpathians. The Western Carpathian's crustal thickness varies from about 30 km to 45 km. The largest crustal thickness (45 km) has been located beneath the Externides (Carpathian Foredeep) of the Western Carpathians. In the direction of the European platform a Moho depth gradually increases until the end of the profile, where the crustal thickness reaches of about 42 km. Our modelling has confirmed the existence of an anomalous body with average density of 2850 $\mathrm{kg\,m^{-3}}$ seated mostly in the lower crust. Its uppermost boundary reaches a depth of about 12 km. The lower crust beneath the Western Carpathian Externides is much thicker (20 km) in comparison beneath the Pannonian Basin, where it is only 8 km on average.

Key words: integrated modelling, geoid, topography, gravity anomaly, heat flow, lithosphere, asthenosphere, the Western and Eastern Carpathian junction zone

1. Introduction

The Carpathian-Pannonian region offers an outstanding opportunity to study the interaction of asthenospheric and lithospheric processes and their

doi: 10.1515/congeo-2015-0010

mutual dependencies during the orogeny, volcanic arc and related fore-arc and back-arc basin development. However, most of the studies over the last years focused mainly on the investigations of the lithospheric structure in the Western and Eastern Carpathians (*Zeyen et al., 2002; Dérerová et al., 2006; Tašárová et al., 2009; Majcin et al., 1998*). For the complex overview of the tectonic development of the whole Carpathian arc it is necessary to provide an integrated geological-geophysical study of the Western and Eastern Carpathian junction area, because it represents an important part of the whole Carpathian-Pannonian system from the point of view of tectonic development. Based on the preliminary models published in the works by *Pospíšil et al. (1992)*, *Šefara et al. (1996)* and *Bielik (1998)*, we decided to apply the method of the integrated lithospheric modelling to determine a new model of the lithospheric structure in the Western and Eastern Carpathian junction area.

2. Geology

The recent Carpathian–Pannonian region consists of the Carpathian orogen and Pannonian back-arc basin. This geological structure is a result of the Neogene evolution. The tectonic evolution and present-day structure of the region is still a matter of discussion. Models proposed for its Tertiary evolution can be basically divided into two groups. One group interprets the evolution of the Carpathian–Pannonian Basin region in terms of gravitational collapse of the continental lithosphere (*Knapp et al., 2005; Gemmer and Houseman, 2007*). These recent works exclude the existence of the subduction underneath the Carpathian Mountains. The other group of models includes the subduction of oceanic lithosphere as a key process during the tectonic evolution of the Carpathian-Pannonian region (*Csontos et al., 1992; Kováč 2000, Lexa et al., 1993*). Due to the available geological and geophysical evidence, the latter interpretation is more commonly accepted (*Tašarová et al., 2009*).

The Pannonian Basin system has been formed as a back-arc system due to lithospheric extension and mantle upwelling behind the Carpathian arc (*Csontos et al., 1992; Horváth, 1993; Royden, 1993; Kováč, 2000*). Apart from the normal and listric faults, large horizontal movements along the margin of the microplates were also generated during the formation of this basin system. The Pannonian Basin systems are filled with Tertiary and Quaternary strata. The thickness of the sedimentary filing varies between 0 to 9 km, with average of 2.5–3.0 km (*Bielik, 1988; Kilényi and Šefara, 1989; Bielik et al., 2005*). The filling of the basin mainly consists of sands, clays, shales, sandstones with isolated limestones and evaporites, and also clays and marls in the layers closest to the surface. The evolution of this back-arc system has been accompanied by the Neogene–Quaternery volcanism, of which rocks are part of the Pannonian Basin sedimentary fill (*Lexa et al., 1993*).

The Western Carpathians are divided into two main parts (*Kováč, 2000*): the Outer (the Externides) and Inner (the Internides) Western Carpathians. They are separated by the Pieniny Klippen Belt (Fig. 1). Thrusting of the Internides was completed before the Upper Cretaceous (approximately 65 Ma ago), whereas the Externides were folded during the Tertiary (30–12 Ma). The Internides also contain relics of an older Hercynian tectogenesis, which was transformed and incorporated into Alpine units (*Tašarová et al., 2009*). The morphological and tectonic setting of the Western Carpathians was largely influenced by Tertiary tectonics. The Tertiary accretionary prism of the Externides is a tectonic element common to the whole Alpine-Carpathian mountain belt. It consists of several nappe units (the sub-Carpathian unit, Krosno-Menilite group and Magura group – *Kováč (2000)*) that were thrust onto the European Platform. The final process of accretionary prism formation was connected to the flexure of the platform margin onto which the Carpathian Foredeep was developed. The thicknesses of the Flysch sediments reach more than 15 km (*Makarenko et al., 2002; Rylko and Tomaš, 2005; Janik et al., 2011*). The Western Carpathian Foredeep is filled with Middle Miocene, mostly marine sediments (*Oszczypko, 1998*). The thickness of the sediments varies from 0 to 3 km in the studied area (*Poprawa and Nemčok, 1989; Makarenko et al., 2002*).

The European Platform comprises the Precambrian East European Craton in the NE and the younger Paleozoic Platform in the SW. These two units are separated by the Trans European Suture Zone, which is a broad (up to 200 km) zone.

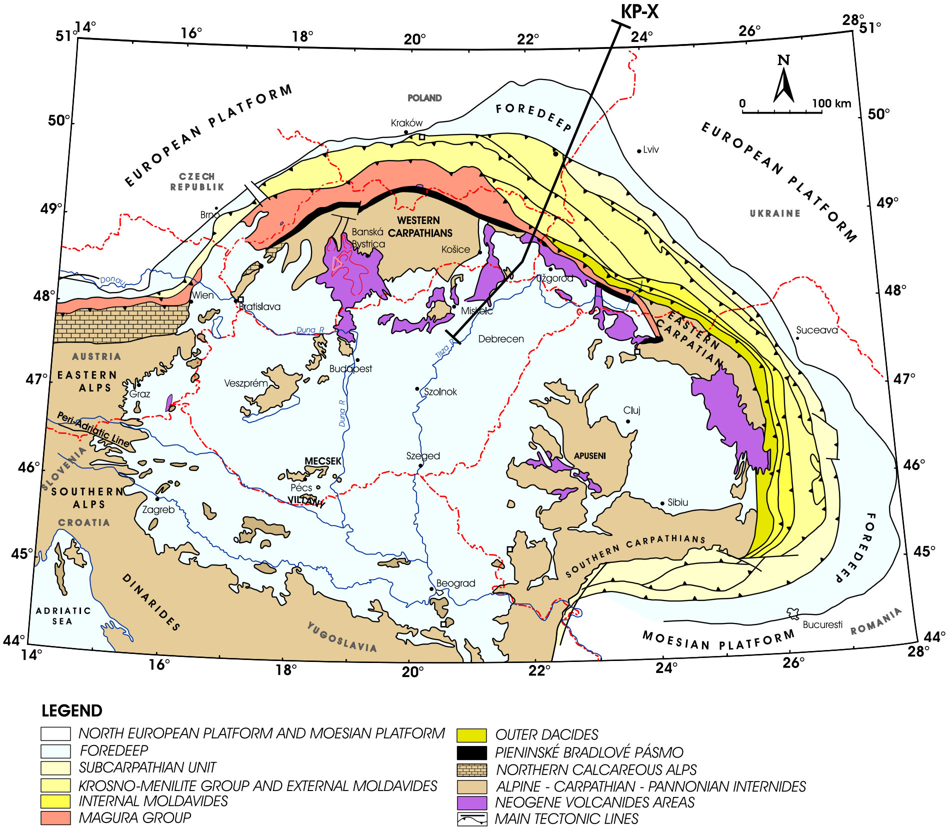

Fig. 1. Location of profile KP-X on the map of the Carpathian-Pannonian basin region (modified after *Bielik (1998)* and *Kováč (2000)*).

3. Profile KP-X

The profile KP-X (Fig. 1) starts in the Pannonian Basin 150 km southwest of the Slovak-Hungarian border. In a northeastern direction the profile runs across the Zemplínske vrchy Upland and through the East Slovak Basin. Then it enters the Vihorlatské vrchy Mts. and passes the Outer Carpathian Flysch Belt and Molasse Foredeep and terminates in the European Platform (200 km from the Slovak-Polish border). The length of profile is of 450 km.

4. Method

A detailed description of the method and its fundaments is given by *Zeyen and Fernàndez (1994)*. A finite element algorithm is used to calculate the two-dimensional temperature distribution in the lithosphere, given its thickness (here defined as the 1300 °C isotherm) and the distribution of heat production and thermal conductivity solving the steady state heat conduction equation:

$$\lambda \nabla^2 T = A ,$$

where λ is the thermal conductivity ($\mathrm{W m^{-1} K^{-1}}$), T the temperature (°C) and A the heat production ($\mathrm{W m^{-3}}$).

Once the temperatures are calculated at every node, densities are evaluated at the same nodes, depending on temperature and pressure and based on predefined densities at room conditions. In the upper crust, with relatively low temperatures and high porosities, pressure and temperature effects are supposed to balance each other. In the lower crust and lithospheric mantle, however, the density decrease due to temperature is usually supposed to be stronger than the increase due to pressure except for very low temperature gradients. In our calculations, we assumed a thermal expansion coefficient of $3{\cdot}10^{-5}\,\mathrm{K^{-1}}$. With this density distribution, we are able to calculate the gravity (Bouguer or free air) anomalies along the transects (*Talwani et al., 1959*) and, for every column of the model, the topography under the assumption of local isostatic equilibrium based on the formulas given by *Lachenbruch and Morgan (1990)*. The formulas used to calculate geoid have been published by *Zeyen et al. (2005)*.

The common use of gravity, topography and geoid data enables us to distinguish between density variations at different depths. Shallow (crustal) density variations are better controlled by gravity analyses, especially if the crustal structure is known. Density variations in the deeper lithosphere are supposed to be mainly due to temperature variations and have a strong influence on the topography, but relatively little effect on gravity. The geoid, reflecting variations of the elevation of the gravimetric isopotential surface corresponding to sea level depends on the distance to density variations by r^{-1}. The geoid is therefore more sensitive to near-surface density variations (specifically to topography) than to deep ones. However, the decay is relatively slow, and therefore geoid anomalies reflect crustal as well as mantle density variations.

5. Geophysical data

The initial model has been constructed based on the model published by *Bielik et al. (1998)*.

The Moho boundary has been adjusted based on the data published by *Csicsay (2010)*. The lithosphere-astenosphere boundary has been taken from the map of the lithospheric thickness published by *Dérerová et al. (2006)*. Topography has been taken from the GTOPO30 database (*Gesch et al., 1999*) having estimated errors of less than 20 m. The free air gravity anomalies were taken from the TOPEX 1-min gravity data set (accessible at ftp://topex.ucsd.edu/pub (*Sandwell and Smith, 1997*)). Geoid data are taken from the EGM96 global model (*Lemoine et al., 1998*) with errors of less than 30 cm (http://cddis.gsfc.nasa.gov/926/egm96/contents.html). In order to avoid effects of sublithospheric density variations on the geoid, we have removed the geoid signature corresponding to the spherical harmonics developed until degree and order 8 (*Bowin, 1991*). The surface heat flow data were compiled from the worldwide data set of *Pollack et al. (1993)*.

6. Results

On the basis of the geophysical data mentioned above we constructed initial density model. The thermal and density-related parameters were then modified by trial and error until a reasonable fit was obtained between data and model predictions (Fig. 2). The final densities and thermal parameters are given in Table 1. In our modelling we tried not to modify near surface structures like sediments and upper crust where we followed model by *Bielik (1998)* and focused our modelling on deeper structure of the crust, Moho and lithosphere-asthenosphere boundary.

Lithosphere thickness in the study region increases from the area of the Pannonian Basin where we modelled it at the depth of 80 km towards the

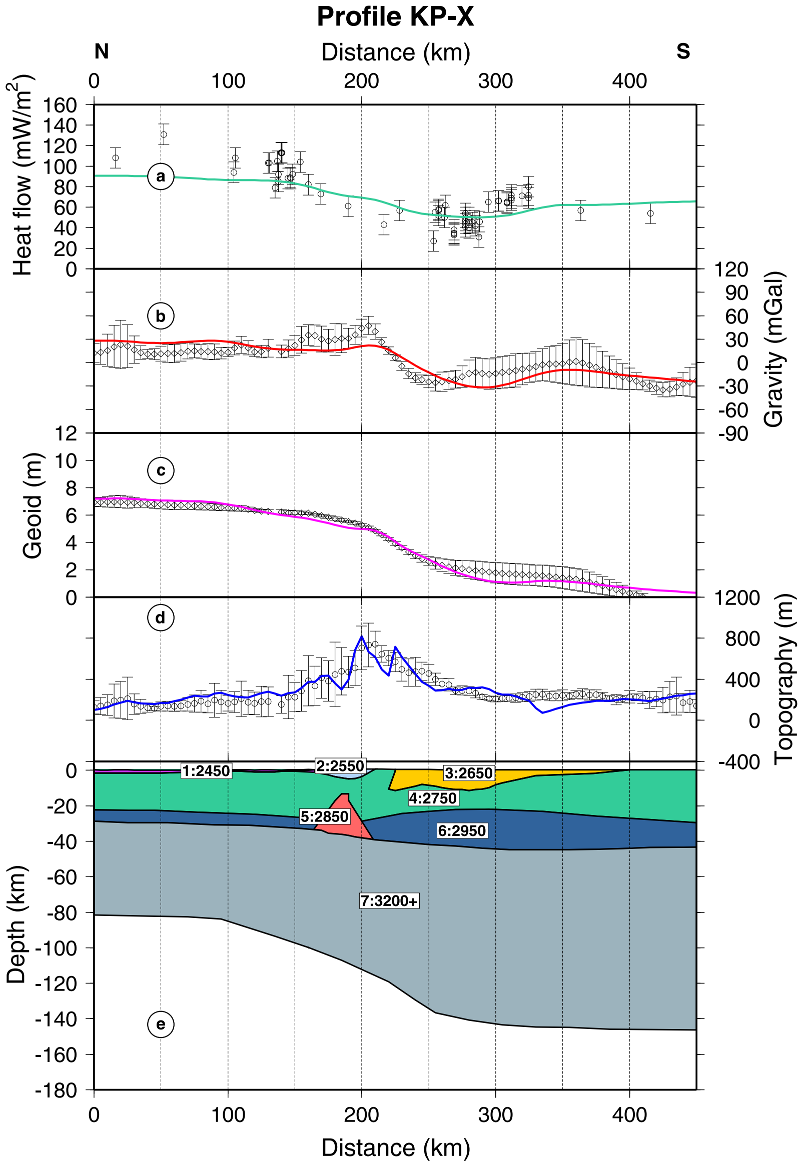

Fig. 2. Lithospheric model along transect KP-X. (a) Surface heatflow, (b) free air gravity anomaly, (c) topography with dots corresponding to measured data with uncertainty bars and solid lines to calculated values. Numbers in (d) correspond to material parameter values in Table 1 (*Zeyen et al., 2002*).

Table 1. Densities and thermal properties of different bodies used for modelling along transect KP-X; No.: Reference number in Fig. 2, HP: heat production (μW m^{-3}), TC: thermal conductivity (W m^{-1} K^{-1}), ρ_0: density at room temperature (kg m^{-3})

No.	Unit	HP	TC	ρ_0
1	Pannonian Basin sediments	3.50	2.5	2450
2	East Slovak Basin sediments	2.50	2.0	2550
3	Flysch sediments	2.00	2.0	2650
4	Upper crust	2.00	2.5	2750
5	High density anomalous body	0.20	2.0	2850
6	Lower crust	0.20	2.0	2950
7	Lower (mantle) lithosphere	0.05	3.4	3200

oldest and coolest area of the European Platform where it reaches about 150 km. In Bielik's model the thickness of the lithosphere beneath the Pannonian Basin reaches only about 60 km and beneath the European Platform 200 km while general shape of the lithosphere-asthenosphere remains unchanged. Our results are more in correlation with a previously published map of the lithospheric thickness (*Dérerová at al., 2006*).

In the Pannonian Basin the modelled Moho depths reach about of 25 km and it decreases towards the Western Carpathians. Underneath the Western Carpathians we can observed a drop of the Moho depth from about 30 km to 45 km. The largest thickness is located beneath the Externides (Carpathian Foredeep) of the Western Carpathians. In the direction of the European platform a Moho depth gradually increases until the end of the profile, where the crustal thickness reaches of about 42 km. These results correlate very well with the last seismic refraction results of *Janik et al. (2011)*.

An interesting feature of our model is the presence of a high-density anomalous body underneath the pre-Tertiary basement of the East Slovak Basin. This anomalous body was first suggested by *Pospíšil (1980)* and modelled by *Bielik (1998)*. Our modelling confirmed the existence of an anomalous body with average density of 2850 kg m^{-3} seated mostly in the lower crust. Its uppermost boundary reaches a depth of about 12 km.

It is also worth noting that the lower crust beneath the Externides is much thicker (20 km) in comparison with the lower crust beneath the Pannonian Basin. Here the thickness is only 8 km on average.

7. Conclusions

2D integrated geophysical modelling has brought valuable results about the deep seated structure of the lithosphere, which are in very good agreement with the seismic refraction measurements and their interpretation carried out within the International project CELEBRATION 2000 (*Janik et al., 2011*). In the paper it was modelled deep seated crustal structure and the courses of the Moho discontinuity, the lithosphere-asthenosphere boundary and the boundary between the upper and lower crust. The existence of the crustal heavy anomalous body under the East Slovak Basin has been proved, too. The results have showed clearly a significant difference in the structure and thickness of the crust and lithosphere in the Western Carpathian Internides and the Pannonian Basin, and the Western Carpathian Externides and European Platform.

Acknowledgments. This research has been supported by the Slovak Grant Agency VEGA, grants 1/0095/12, 2/0067/12 and 1/0131/14, and by the Slovak Research and Development Agency under grants APVV-0724-11, APVV-0194-10. Authors are grateful to Prof. Hermann Zeyen (Laboratoires IDES, Université Paris-Sud XI) for permission to use his 2D integrated modelling software.

References

Bielik M., 1998: Analysis of the gravity field in the Western and Eastern Carpathian junction area: density modeling. Geologica Carpathica, **49**, 2, 75–83.

Bowin C., 1991: The Earth's gravity field and plate tectonics. Tectonophysics, **187**, 69–89.

Csicsay K., 2010: Two-dimensional and three-dimensional integrated interpretation of field of attraction within the international framework CELEBRATION 2000 (Dvojrozmerná a trojrozmerná integrovaná interpretácia tiažového poľa v rámci medzinárodného projektu CELEBRATION 2000). Ph.D. dissertation, FNS UK Bratislava, 155 p. (in Slovak).

Csontos L., Nagymarosy A., Horváth F., Kováč M., 1992: Tertiary evolution of the intra-Carpathian area; a model. Tectonophysics **208**, 221–241.

Dérerová J., Zeyen H., Bielik M., Salman K., 2006: Application of integrated geophysical modeling for determination of the continental lithospheric thermal structure in the Eastern Carpathians. Tectonics, **25**, 3, Art. No. TC3009.

Gemmer L., Houseman G. A., 2007: Convergence and extension driven by lithospheric gravitational instability: evolution of the Alpine–Carpathian–Pannonian system. Geophys. J. Int. **168**, 1276–1290.

Gesch D. B., Verdin K. L. , Greenlee S. K. 1999: New land surface digital elevation model covers the Earth. Eos Trans. AGU, **80**, 69–70.

Horváth F.,1993: Towards a mechanical model for the formation of the Pannonian basin. Tectonophysics **226**, 333–357.

Janik T., Grad M., Guterch A., Vozár J., Bielik M., Vozárová A., Hegedus E., Kovacs C. A., Kovacs I., Keller G. R., 2011: Crustal structure of the Western Carpathians and Pannonian Basin: seismic models from CELEBRATION, 2000 data and geological implications. Journal of Geodynamics **52**, 2, 97–113.

Knapp, J. H., Knapp C. C., Raileanu V., Matenco L., Mocanu V., Dinu C., 2005: Crustal constraints on the origin of mantle seismicity in the Vrancea Zone, Romania: the case for active continental lithospheric delamination. Tectonophysics **410**, 311–323.

Kováč M., 2000: Geodynamic, paleographic and structural development of the Carpathian-Pannonian region in Miocene (Geodynamický, paleografický a štruktúrny vývoj karpatsko-panónskeho regiónu v miocéne). Veda Bratislava, 202 p.

Lachenbruch A. H., Morgan P., 1990: Continental extension, magmatism and elevation; formal relations and rules of thumb. Tectonophysics, **174**, 39–62.

Lemoine F. G., Kenyon S. C., Factor J. K., Trimmer R. G., Pavlis N. K., Chinn D. S., Cox C. M., Klosko S. M., Luthcke S. B., Torrence M. H., Wang Y. M., Williamson R. G., Pavlis E. C., Rapp R. H., Olson T. R., 1998: The development of the Joint NASA GSFC and NIMA geopotential model EGM96. NASA Goddard Space Flight Center, Greenbelt, Maryland.

Lexa J., Konečný V., Kalinčiak M., Hojstričová V., 1993: Distribution of volcanic rocks in the Carpathian-Pannonian region in space and time. Konf., Symp., Sem. GÚDŠ, Bratislava, 57–69 (in Slovak, English summary).

Majcin D., Dudášová V., Tsvyashchenko V. A., 1998: Tectonics and temperature field along the Carpathian profile 2T, Contrib. Geophys. Geod., **28**, 107–114.

Makarenko I., Legostaeva O., Bielik M., Starostenko V., Dérerová J., Šefara J., 2002: 3D gravity effects of the sedimentary complexes in the Carpathian-Pannonian region. Geologica Carpathica, **53**, special issue, CD ROM.

Oszczypko N., 1998: The Western Carpathian foredeep – development of the foreland basin in front of the accretionary wedge and its burial history (Poland). Geologica Carpathica, **49**, 6, 415–431.

Pollack H. N., Hurter S. J., Johnson J. R. 1993: Heat flow from the Earth's interior: Analysis of the global data set. Rev. Geophys., **31**, 267–280.

Poprawa D., Nemčok J., 1989: Geological atlas of the Western Outer Carpathians and their foreland. PIG Warszawa – GÚDŠ Bratislava, UÚG Praha, 9 p.

Pospíšil L., Buday T., Fusán O., 1992: Neotectonic movements in the Western Carpathians (Neotektonické pohyby v Západních Karpatech). Západné Karpaty, sér. Geológia, 16, 65–84 (in Slovak with English summary).

Rylko W., Tomaš A., 2005: Basement structure below the West Carpathian–East Carpathian orogen junction (Eastern Poland, Northeastern Slovakia and Western Ukraine). Geologica Carpathica, **56**, 1, 29–40.

Sandwell D. T., Smith W. H. F., 1997: Marine gravity anomalies from Geosat and ERS-1 satellite altimetry. J. Geophys. Res., **102**, 10039–10054.

Šefara J., Bielik M., Konečný P., Bezák V., Hurai V., 1996: The latest stage of development of the Western Carpathian lithosphere and its interaction with asthenosphere, Geologica Carpathica, **47**, 6, 339–347.

Talwani M., Worzel J. L., Landisman M., 1959: Rapid gravity computations for two-dimensional bodies with application to the Mendocino submarine fracture zone, J. Geophys. Res., **64**, 49–59.

Tašarová A., Afonso J. C., Bielik M., Gotze H. J., Hok J., 2009: The lithospheric structure of the Western Carpathian–Pannonian Basin region based on the CELEBRATION, 2000 seismic experiment and gravity modelling. Tectonophysics, **475**, 3-4, 454–469.

Zeyen H., Ayarza P., Fernandez M., Rimi A., 2005: Lithospheric structure under the western African-European plate boundary: A transect across the Atlas Mountains and the Gulf of Cadiz. Tectonics, **24**, TC2001, doi: 10.1029/2004TC001639.

Zeyen H., Dérerová J., Bielik M., 2002: Determination of the continental lithosphere thermal structure in the western Carpathians: Integrated modelling of surface heat flow, gravity anomalies and topography. Phys. Earth Planet. Inter., **134**, 89–104.