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Calculation of temperature distribution and rheological properties of the lithosphere along transect IV in the Western Carpathian-Pannonian Basin region

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Abstract: 2D integrated modelling algorithm was used to calculate the temperature distribution in the lithosphere along the transect IV located in the Western Carpathian-Pannonian Basin area. Based on the determined temperature field and given rheological parameters of the rocks, it was possible to calculate the strength distribution for both compressional and extensional regimes, construct the strength envelopes for chosen columns of the main tectonic units of the model, and thus construct a simple rheological model of the lithosphere along transect IV. The obtained results indicate decrease of the lithospheric strength from the European platform and the Western Carpathians towards the Pannonian Basin. The largest strength (valid for all tectonic units) can be observed within the upper crust with its maxima on the boundary between upper and lower crust, decreasing towards lower crust and disappearing in the lithospheric mantle, suggesting mostly rigid deformation occurring in the upper crust. A local increase in the values of strength can be observed in the eastern segment of the Western Carpathians where crustal thickening accompanies the lithospheric thickening (formation of the lithospheric root), unlike the previous models along transects I and II, that pass through the western segment of the Western Carpathians and their lithosphere-asthenosphere boundary is almost flat and therefore no accompanying crustal thickening is observed and the decrease in strength is slow and steady.

Key words: 2D integrated modelling, temperature field, rheological parameters, compressional and extensional strength, strength envelopes

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1. Introduction

The Carpathian-Pannonian Basin region together with its surrounding tectonic units is a very complex lithospheric system where many different tectonic units can be identified in a relatively small area. Therefore, it provides a great opportunity to study their mutual interactions, the interaction of lithosphere and asthenosphere as well as many geodynamic interactions within the lithosphere during volcanic arc and related fore- and back-arc basin development.

The Pannonian Basin is young and hot, while the Western Carpathians, although being young as well, are colder. The evolution of the Carpathian arc was driven by the inter-related processes of rift genesis, crustal thinning, lateral displacement, rotational movements, convergence, collisional suturing, accretion, transpressive–transtensive subduction, slab rollback, asthenospheric up-welling and lateral extrusion of the Eastern Alps and Dinarides-Balkan orogens, while formation of the Pannonian Basin is related to interplay of contraction, strike-slip and extension (*Ratschbacher et al., 1991a,b; Csontos et al., 1992; Horváth, 1993*).

The Carpathian-Pannonian Basin region has been covered by extensive geophysical surveys, and an enormous amount of geological and geophysical data such as deep seismic reflection and refractions data (*Mayerová et al., 1994; Tomek et al., 1989; Vozár and Šantavý, 1999*), gravity data (*Bielik et al.,2006; Alasonati Tašárová et al., 2009; Zahorec et al., 2013*), surface heat flow data (*Čermák et al., 1991; Majcin, 1993*), geoelectric data (*Putiška et al., 2012a,b*), magnetotelluric data (*Ádám, 1996*) has been collected and is available for calculations and modelling in order to reconstruct the structure of the lithosphere and geodynamical and tectonic processes within it. Despite the fact that the Carpathian-Pannonian Basin area becomes very well explored and studied, the main focus still lays on the lithospheric structure reconstruction (*Alasonati Tašárová et al., 2009, 2016; Grinč et al., 2013; Hrubcová et al., 2010; Dérerová et al., 2006; Grad et al., 2006; Bielik et al., 2005* and many others). We believe that rheological modelling can provide additional information to already existing lithosperic models and contribute to better understanding of interactions among different tectonic units from rheological point of view.

The very first rheological models of the lithosphere have been calculated by *Bielik and Striženec (1994)*, *Bielik and Ursíny (1997)* and *Lankreijer et al. (1999)*. 2-dimensional integrated modelling method has been used to calculate temperature distribution and construct the rheological model along transect I (*Dérerová et al., 2012*) and and transect II (*Dérerová et al., 2014*) passing through the Carpathian-Pannonian basin region. To improve the rheological model of the lithosphere in the study area, we decided to continue in our approach and calculate and construct rheological model along transect IV located in the same study area.

2. The Western Carpathian Transect IV

The studied transect IV (*Zeyen et al., 2002*) (Fig. 1) starts in the Polish European foreland, continues across the Western Carpathian molasse foredeep, the Outer Western Carpathian flysch, the Pienniny Klippen Belt, the Slovenské Rudohorie Mts. and finishes in the Pannonian Basin. From an interpretation point of view the direction of the transect IV is not optimal, since it is not perpendicular to the strike of the geological structures. We chose this profile nevertheless because it coincides with the international transect CEL04, which is one of the seismic profiles of the CELEBRATION 2000 project. Its length is 550 km and the layout of main geological structures it consists of can be seen on Fig. 2 (*Zeyen et al., 2002*).

3. Method

Lithospheric structure along Transect IV (Fig. 2) has previously been modelled as a part of a tectonic and geodynamical reconstruction of the Western Carpathians-Pannonian basin region (*Zeyen et al., 2002*), using 2D integrated geophysical modelling method. It is an algorithm that calculates lithospheric thermal structure based on the simultaneous interpretation of surface heat flow, gravity, and topography data. 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 (*Lachenbruch and Sass, 1977*):

$$\lambda \nabla^2 T = A\,, \tag{1}$$

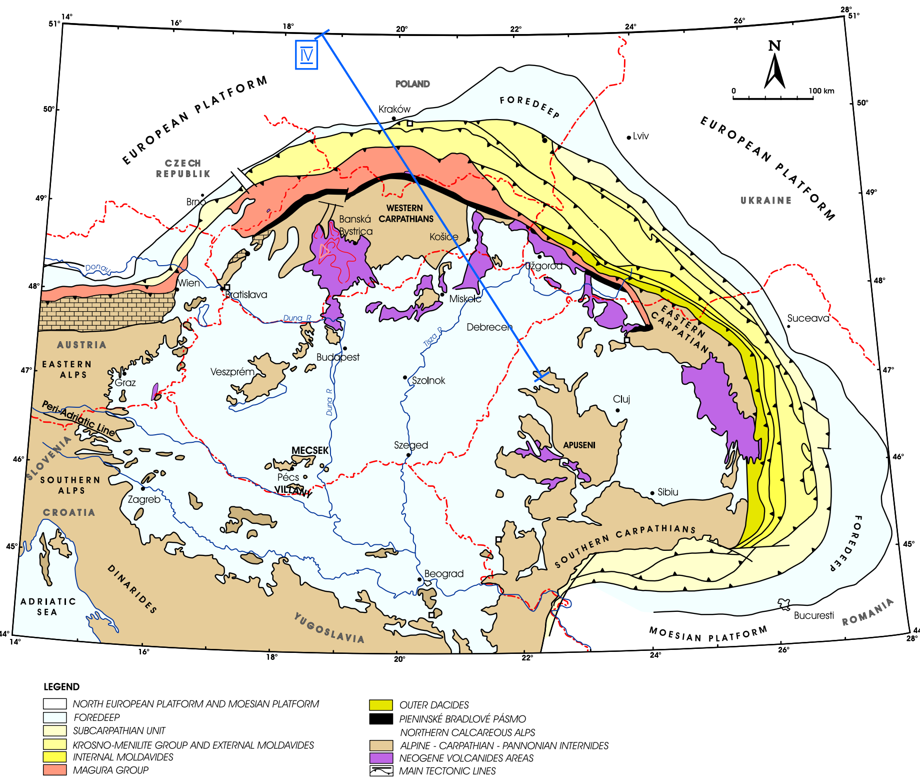

Fig. 1. Location of transect IV on the map of the Carpathian-Pannonian Basin region (modified after *Zeyen et al., 2002*).

where λ is the thermal conductivity [$\mathrm{Wm^{-1}K^{-1}}$], T is the temperature [K] and A the heat production [$\mathrm{Wm^{-3}}$]. More detailed description can be found in *Zeyen and Fernàndez (1994)*.

Based on the determined temperature distribution in the lithosphere, we can calculate the yield strength for a given distribution of rheological rock parameters. The strength is defined as the minimum of brittle and ductile strength at each point. For brittle strength calculation we have assumed that deformation occurs according to the frictional sliding law given by *Byerlee (1978)*:

$$\sigma_{brittle} = \alpha \rho g z (1 - \lambda) \,, \tag{2}$$

where $\sigma_{brittle}$ is brittle failure function [Pa], parameter $\alpha = R - 1/R$ is valid

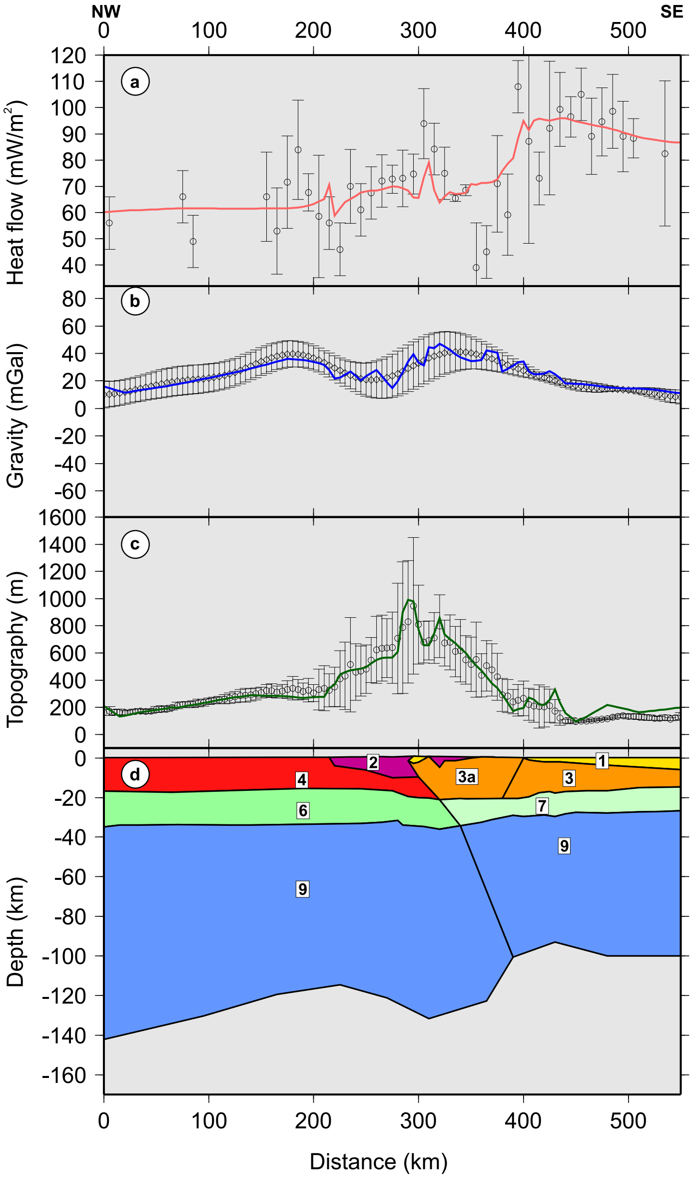

Fig. 2. Lithospheric model along transect IV. (a) Surface heatflow, (b) free air gravity anomaly, (c) topography with dots corresponding to measured data with uncertainty bars and solid lines to calculated values. Numbers in (d) correspond to material number in Table 1b (*Zeyen et al., 2002*).

for normal faulting, $\alpha = R - 1$ for thrust faulting, $\alpha = R - 1/[1 + \beta(R - 1)]$ for strike-slip faulting. Parameter $R = \left[(1 + f_s^2)^{1/2} - f_s\right]^{-2}$ depends on coefficient of static friction f_s, λ represents the hydrostatic pore fluid factor, ρ is material density [kg m^{-3}], g is acceleration of gravity [m s^{-2}], z is depth [m], β is extension factor.

Ductile strength is calculated assuming power-law creep deformation given as (*Lynch and Morgan, 1987*):

$$\sigma_{creep} = \left(\frac{\dot{\varepsilon}}{A_p}\right)^{1/n} \exp\left[\frac{E_p}{nRT}\right], \tag{3}$$

where σ_{creep} is power law creep function [Pa], $\dot{\varepsilon}$ denotes strain rate [s^{-1}], A_p is Dorn constant, n is power law exponent, E_p is power law activation energy [kJ mol^{-1}], R is universal gas constant [8.314 J mol^{-1} K^{-1}], T is temperature [K].

4. Results

2D integrated modelling algorithm has been used to calculate temperature distribution for a pre-modelled lithospheric structure of the transect IV (Fig. 3). The lower limit of the model corresponds to 1300 °C isotherm which represents the lithosphere-asthenosphere boundary in geotermics. On the surface (the upper boundary of the temperature model), the temperature 20 °C has been considered. The temperature distribution has been calculated for every node of the model. Temperature field reflects the distribution

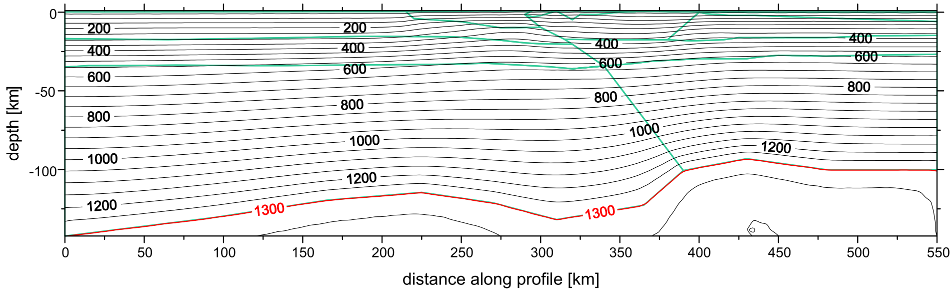

Fig. 3. Lithospheric temperature distribution calculated for transect IV, isoline values in °C. The bottom of the model corresponds to the 1300 °C isotherm (red line).

of the heat sources predominantly in the upper crust and background heat flow density from the lower mantle. The reliability of the temperature model usually depends on the accuracy and density of measurements of the surface heat flow density data but 2D integrated modelling algorithm ensures that our lithological model is constrained by calculation of free air anomaly and topography, which greatly increases the reliability of the model.

In the next step, the rheological parameters for every lithospheric unit of previously modelled transect IV has been assigned. These rheological parameters were carefully chosen based on the work of Carter and Tsenn (*Carter and Tsenn, 1987*) and Goetze and Evans (*Goetze and Evans, 1979*) and a previous rheological modelling in the Western Carpathians by *Lankreijer et al. (1999)*. We made sure that the assigned rheological parameters for transect IV were also in correlation with our previous rheological modelling on transects I and II (*Dérerová et al., 2012, 2014*). These parameters are shown in Table 1a and Table 1b together with densities and geothermal parameters of the 2D integrated lithospheric model of transect IV.

Table 1a. General properties used for calculation of rheological model.

Definition	**Parameter**	**Value**
Gravity acceleration [$\mathrm{ms^{-2}}$]	g	9.81
Universal gas constant [$\mathrm{J\,mol\,K^{-1}}$]	R	8.314
Temperature at the base of the lithosphere [°C]	T_m	1300
Static friction coefficient	f_s	0.6
Strain rate [$\mathrm{s^{-1}}$]	$\dot{\varepsilon}$	10^{-15}
Hydrostatic pore fluid factor	λ	0.35

With the assigned parameters we were able to calculate the strength distribution in the lithosphere for studied transect. Fig. 4 shows vertically integrated compressional and extensional strength calculated along transect IV. Fig. 5 and Fig. 6 show the calculated yield strength contour plot for compressional and extensional deformation. In our calculations a strain rate $10^{-15}\ \mathrm{s^{-1}}$ has been used because this value is commonly observed in compressional and extensional settings (*Carter and Tsenn, 1987*). We have calculated the strength envelopes for both compressional and extensional regimes in selected lithospheric columns of the model. We chose one column for each of the main tectonic units (European platform, the Western

Table 1b. Thermal and rheological parameters used for modelling along transect IV (after *Carter and Tsenn (1987)* and *Goetze and Evans (1979)*). HP: heat production [μWm^{-3}], TC: thermal conductivity [Wm^{-1}K^{-1}], ρ: density at room temperature [kg m^{-3}], A_p: power law pre-exponential constant, n: power law exponent, E_p: power law activation energy [kJ mol^{-1}].

Nr.	**Unit**	**HP**	**TC**	$\boldsymbol{\rho}$	$\boldsymbol{A_p}$	$\boldsymbol{n}$	$\boldsymbol{E_p}$
1	Neogene sediments	2.5 – 3.0	2.5	2400 – 2550	3.16E-26	3.30	186
2	Flysch and Volcanics	1.0 – 2.5	2.0 – 2.5	2550 – 2650	3.16E-26	3.30	186
3	Carpathian and Pannonian upper crust	3.0 – 3.5	3.0	2750	3.16E-26	3.30	186
3a	Inner Western Carpathian upper crust	2.0 – 2.5	3.0	2750	3.16E-26	3.30	186
4	European upper crust	0.5 – 2.0	2.5 – 3.0	2750 – 2800	3.16E-26	3.30	186
6	European lower crust	0.2	2.0	2960	6.31E-20	3.05	276
7	Carpathian and Pannonian lower crust	0.2	2.0	3000	6.31E-20	3.05	276
9	Lower (mantle) lithosphere	0.05	3.4	3325	7.94E-18	4.50	535

Carpathians and the Pannonian Basin). The strength distribution for given lithospheric columns is shown on Fig. 7.

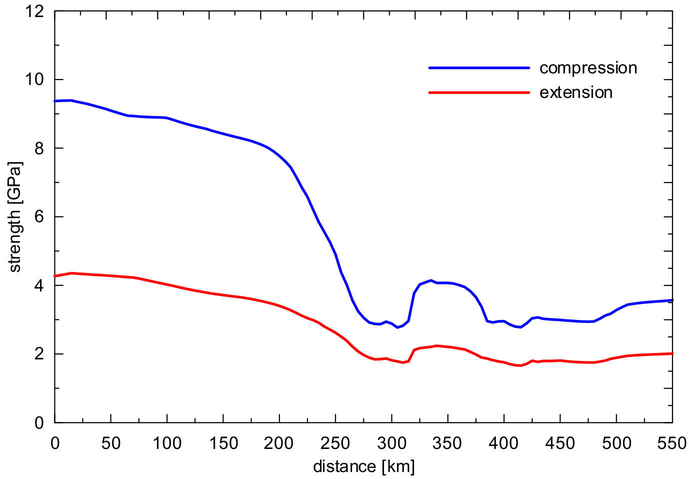

Fig. 4.Vertically integrated compressional (red line) and extensional (blue line) strength calculated along the transect IV.

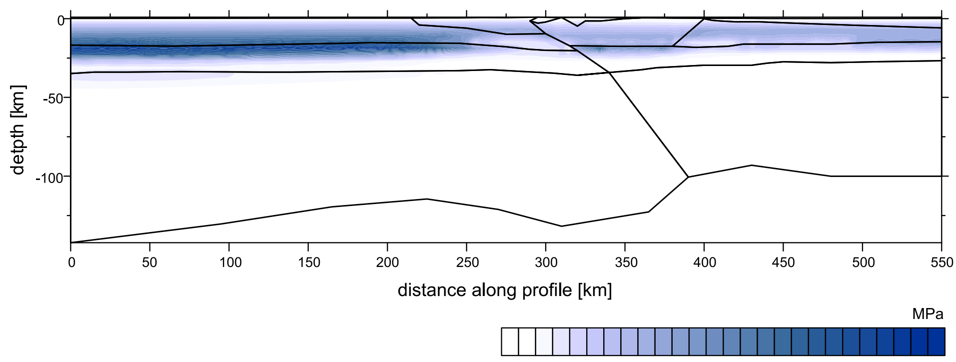

Fig. 5. Yield strength contour plot for compressional deformation calculated along transect IV calculated at a strain rate 10^{-15} s^{-1}.

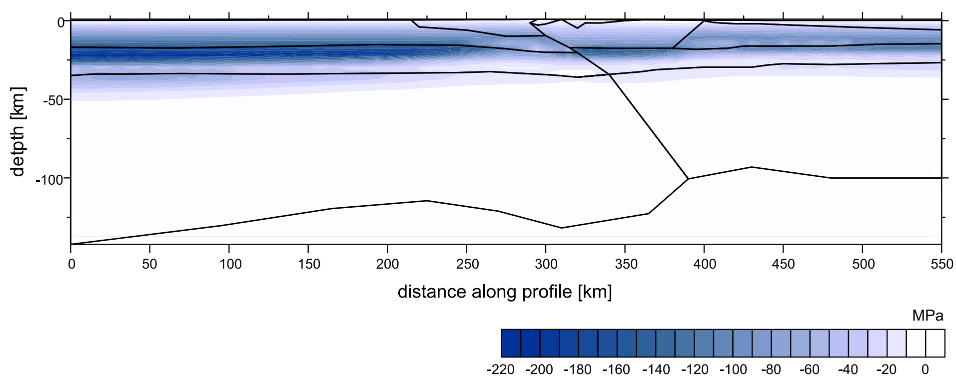

Fig. 6. Yield strength contour plot for extensional deformation calculated along transect IV calculated at a strain rate 10^{-15} s^{-1}.

5. Conclusions

Based on the results related to the vertically integrated compressional and extensional strength along transect IV (Fig. 4), we can say that the lithospheric strength decreases from the European platform and the Western Carpathians to the Pannonian Basin. Decrease is more prominent in the case of compressional strength. A local increase in the values of strength can be observed in the eastern segment of the Western Carpathians where the lithospheric thickening occurs. This thickening (forming of a lithospheric root), which is interpreted as a small remnant of a subducted slab, is also

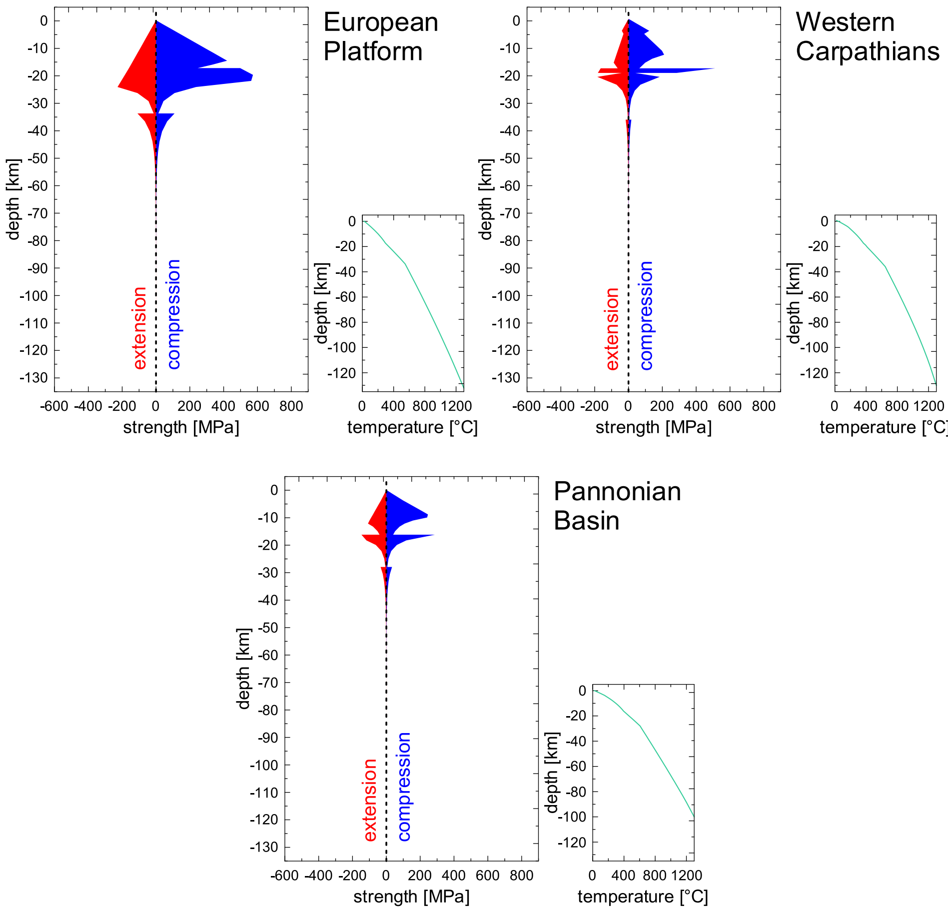

Fig. 7. Vertical strength distribution for different lithospheric columns calculated along transect IV. Negative and positive values correspond to extensional and compressional strength respectively.

accompanied by crustal thickening. If we look at the results of yield strength contour plot for compressional and extensional deformation (Figs. 5 and 6) and vertical strength distribution for different lithospheric columns (see the second strength envelope, where the column was chosen in the area of crustal and lithospheric thickening) for compressional and extensional deformation (Fig. 7), it shows that in the area of crustal thickening, the largest strength occurs on the boundary between upper and lower crust, causing the increase in the values that can be clearly seen on our calculated vertically integrated strength graph as an increase in both compressional (more prominent) and extensional strength. Along previously modelled transects I and II (*Dérerová et al., 2012, 2014)*, where the lithosphere-asthenosphere boundary is almost flat and therefore no accompanying by crustal thickening is observed, the decrease in strength is slow and steady.

As general result, for all tectonic units (European platform, the Western Carpathians and the Pannonian basin), the largest strength occurs within the upper crust with its maxima on the boundary between upper and lower crust. Towards the lower crust, the strength significantly decreases. Within the uppermost mantle (lower lithosphere) the lithospheric strength almost disappears. These results suggest predominantly rigid deformation in the upper crust and ductile deformation (as a result of higher temperatures) in the lower part of the lithosphere. Similar results have been obtained in previously modelled transects I and II.

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