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Calculation of temperature distribution and rheological properties of the lithosphere along transect I in the Western Carpathians

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Abstract: Using the 2D integrated modelling method, we calculated the temperature model of the lithosphere along transect I passing through the Western Carpathians. Based on the extrapolation of failure criteria, lithology and calculated temperature distribution, we derived the rheology model of the lithosphere in the area. Our results indicate clearly that the strength decreases from the Bohemian Massif via the Western Carpathians to the Pannonian Basin. The largest strength can be observed within the upper crust on the boundary between the upper and lower crust. This phenomenon is typical for all studied tectonic units: the Bohemian Massif, the Western Carpathians and the Pannonian Basin. These results suggest mostly rigid deformation in the upper crust of the units. By contrast, the lower crust in the Bohemian Massif and the Western Carpathians reflects significantly lower strength, while in the Pannonian Basin the strength is the smallest. In all tectonic units the strength within the uppermost mantle (lower lithosphere) disappears. It can be suggested that the ductile deformation dominates in this part of the lithosphere.

Key words: integrated modelling, temperature, rheology, strength, compression, extension, the Western Carpathians

1. Introduction

The Carpathian-Pannonian Basin region, due to its complexity, represents a challenging area to study the influence of different parameters on the lithospheric rheology. In a relatively small area, many different thermotectonic

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units occur. The Pannonian Basin is young and hot, whereas the Western Carpathians being also young are colder. The thermotectonically old lithosphere represented by the Bohemian Massif and the European platform, which underthrust beneath the Western Carpathians, forms a sharp rheological contrast to the former two lithospheric units. The first attempts on the rheological calculations of the lithosphere have been done by *Bielik and Stríženec (1994), Bielik and Ursíny (1997), Ursíny and Bielik (1997)* and *Lankreijer et al. (1999).*

Furthermore, the abundance of geophysical data *(Vozár and Šantavý 1999)* such as deep seismic reflection and refractions profiles *(Beránek and Zátopek, 1981; Mayerová et al., 1994; Tomek et al., 1987, 1989)*, gravity *(Bielik et al., 1990, 2006; Alasonati Tašárová et al., 2009)*, radiometric *(Mojzeš, 1998; Putiška et al., 2005)*, geoelectric *(Putiška et al., 2012)* and surface heat flow data *(Čermák et al., 1991; Majcin 1994; Majcin et al., 1998)* provide valuable constraints on tectonic models of the area. For that reason, we decided to apply 2-dimensional integrated modelling algorithm to calculate rheological model of the lithosphere along transect I passing through the Carpathian-Pannonian basin region.

2. Study area and method

Transect I starts in the Bohemian Massif, crossing the orogen between the Alps and the Western Carpathian Mts. in southeastern direction, passes through the Danube Basin and ends in the Pannonian Basin (Fig. 1).

Lithospheric structure along transect I (Fig. 2) has already been modelled using the 2D integrated geophysical modelling method that combines the interpretation of surface heat flow, gravity, and topography data for the determination of the lithospheric thermal structure. Detailed description of the method can be found in *Zeyen and Fernàndez (1994).* Modelling results for transect I were described in *Zeyen et al. (2002).* Based on the determined temperature field 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)*:

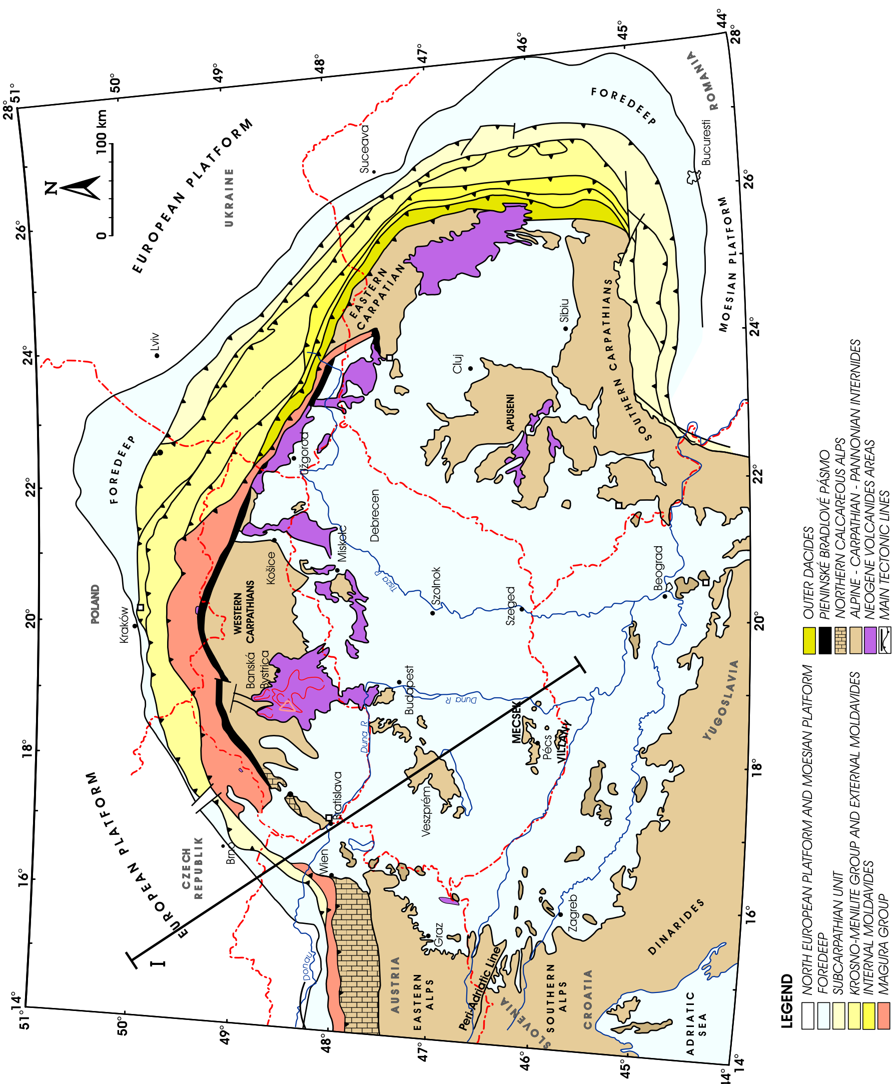


Fig. 1. Location of transect I in the Carpathian-Pannonian Basin region.

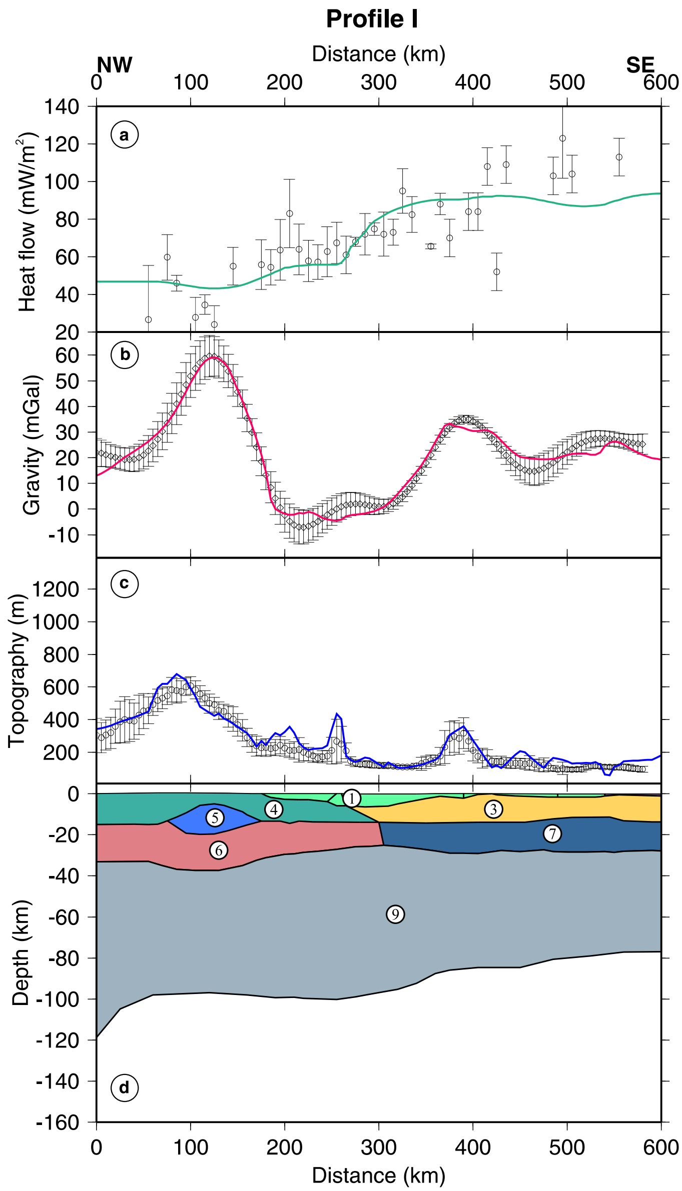


Fig. 2. Lithospheric model along Profile I: (a) Surface heatflow, (b) free air gravity anomaly, (c) topography with dots corresponding to measured data with uncertainty bars and solid lines to calculated values. Numbers in (d) correspond to material number in Table 1b *(Zeyen et al., 2002)*.

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

where, $\sigma_{brittle}$ is brittle failure function [Pa], parameter $\alpha = R - 1/R$ is valid 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 frictionf_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 a power-law creep deformation given as *(Lynch and Morgan, 1987)*:

$$\sigma_{creep} = \left(\frac{\dot{\varepsilon}}{A_p}\right)^{1/n} \exp\left[\frac{E_p}{nRT}\right], \tag{2}$$

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

3. Results

We have calculated the temperature distribution for a given model along transect I (Fig. 3), where the lower limit of the model corresponds to the 1300 °C isotherm. The resulting temperature field is determined by the effect of the heat sources and background heat flow density from the lower mantle. The reliability of the temperature model normally depends on the accuracy and density of measurements of the surface heat flow density. Since our lithological model is controlled by the calculation of free air anomaly and topography, reliability of the model increases greatly.

Based on the rheological parameters shown in Tables 1a and 1b, we have calculated strength distribution in the lithosphere. Fig. 4a shows vertically integrated compressional and extensional strength along transect I. Figure 5 and Fig. 6 show yield strength contour plot for compressional and extensional deformation along profile I. We adopted a strain rate 10^{-15} s^{-1}, which is commonly observed in compressional and extensional settings

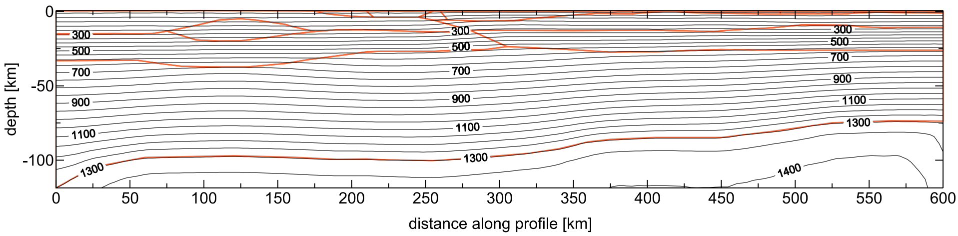


Fig. 3. Lithospheric temperature distribution for transect I. Isolines every 100 °C. The bottom of the model corresponds to the 1300 °C isotherm.

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

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

Table 1b. Thermal and rheological parameters used for modelling along transect I (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 (kgm^{-3}), A_p: power law pre-exponential constant, n: power law exponent, E_p: power law activation energy ($kJmol^{-1}$)

Nr.	**Unit**	**HP**	**TC**	**ρ**	A_p	**n**	E_p
1	Neogene sediments	2.5-3.0	2.5	2400-2550	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
4	European upper crust	0.5-2.0	2.5-3.0	2750-2800	3.16E-26	3.30	186
5	Anomalous upper crust (Bohemian Massif)	1.0	2.0	2900	6.31E-20	3.05	276
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

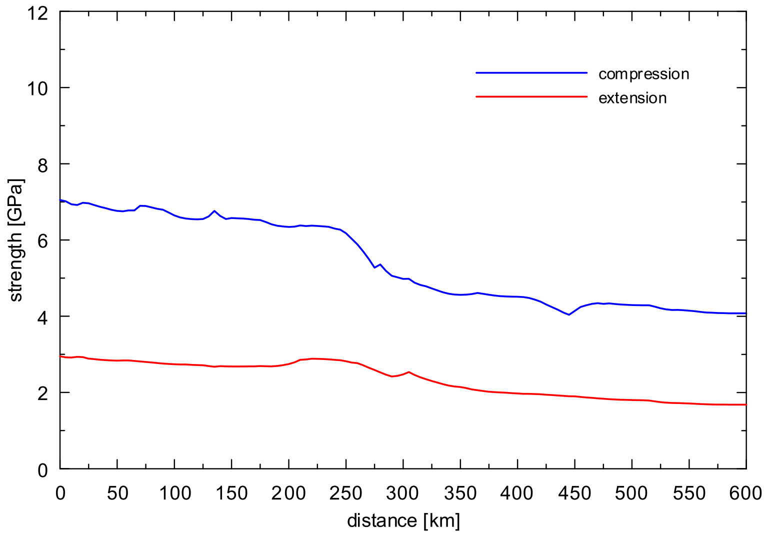


Fig. 4a. Vertically integrated compressional (blue line) and extensional (red line) strength calculated along transect I.

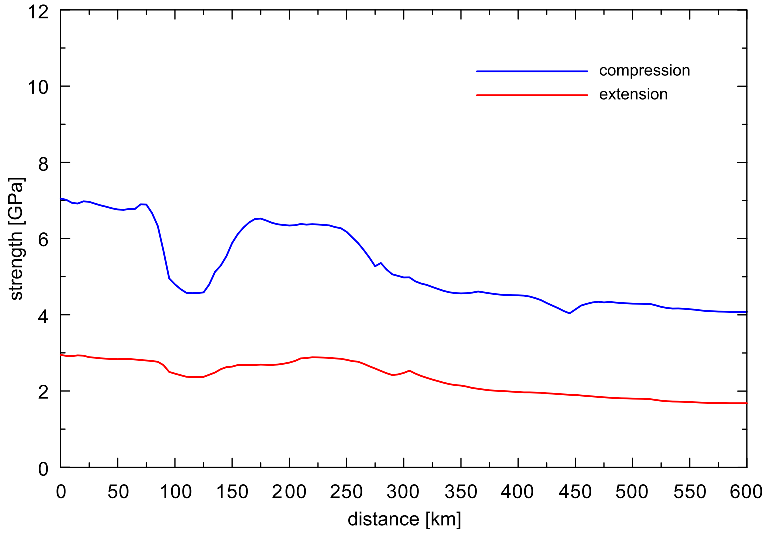


Fig. 4b. Vertically integrated compressional (blue line) and extensional (red line) strength calculated along transect I (rheological parameters for anomalous body 5 under the Bohemian Massif were considered as those of upper crust).

(Carter and Tsenn, 1987). The strength envelopes have been calculated for both compressional and extensional regimes. Fig. 7 shows strength distribution for selected lithospheric columns in the Bohemian Massif, the Western Carpathians and the Pannonian Basin.

The results related to the vertically integrated compressional and extensional strength along transect I (Fig. 4a) indicate clearly that the strength decreases from the Bohemian Massif via the Western Carpathians to the Pannonian Basin. We would like to mention that integrated modeling along transect I *(Zeyen et al., 2002)* indicated anomalous body (body 5 in Fig. 2) under Bohemian Massif at a mid-crustal level, suggesting a thickening of the lower crust, mainly at the expense of the upper crust. We have found out

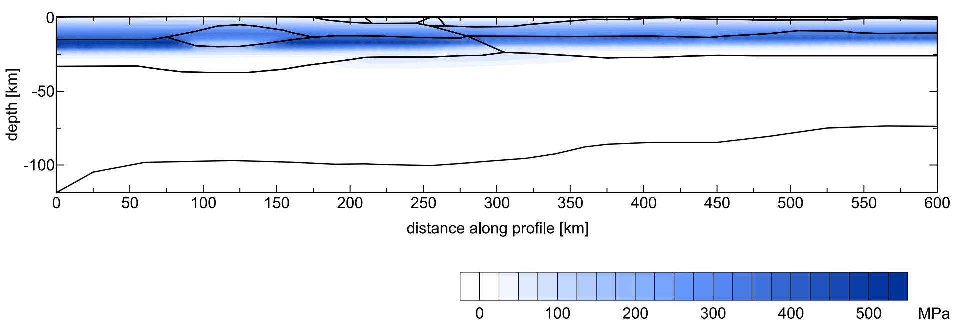


Fig. 5. Yield strength contour plot for compressional deformation calculated along transect I at a strain rate 10^{-15} s^{-1}.

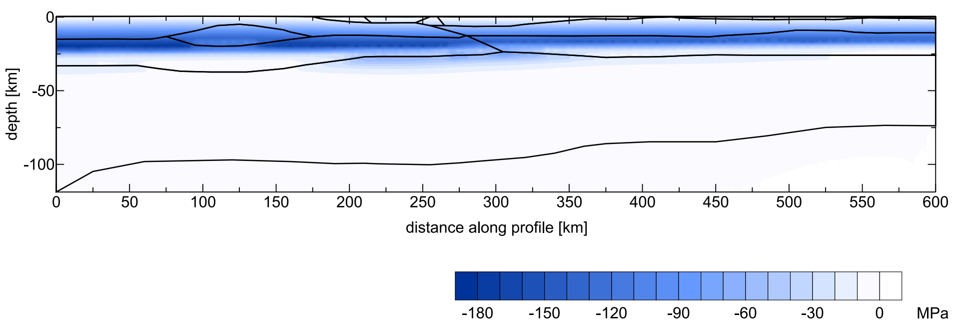
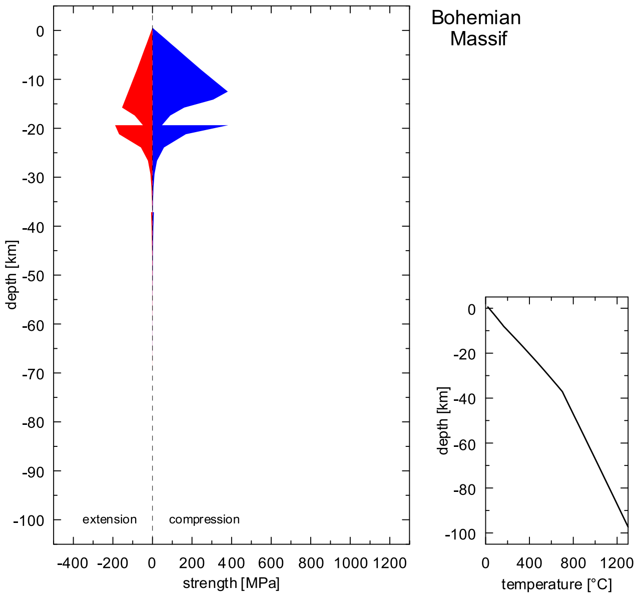
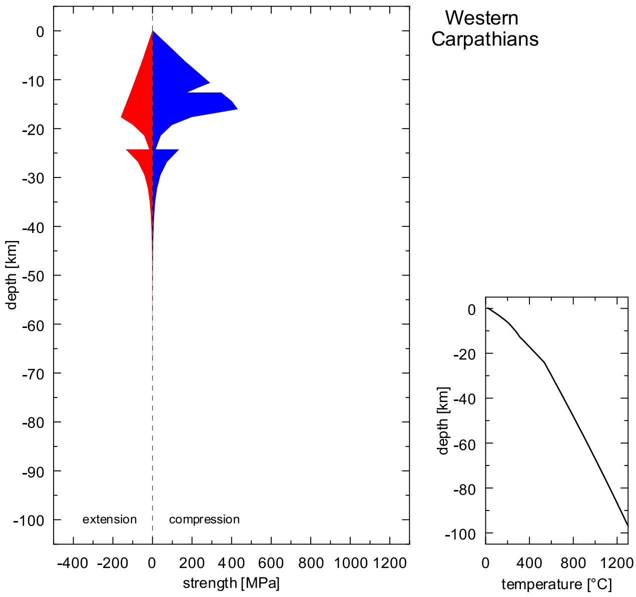


Fig. 6. Yield strength contour plot for extensional deformation calculated along transect I at a strain rate 10^{-15} s^{-1}.





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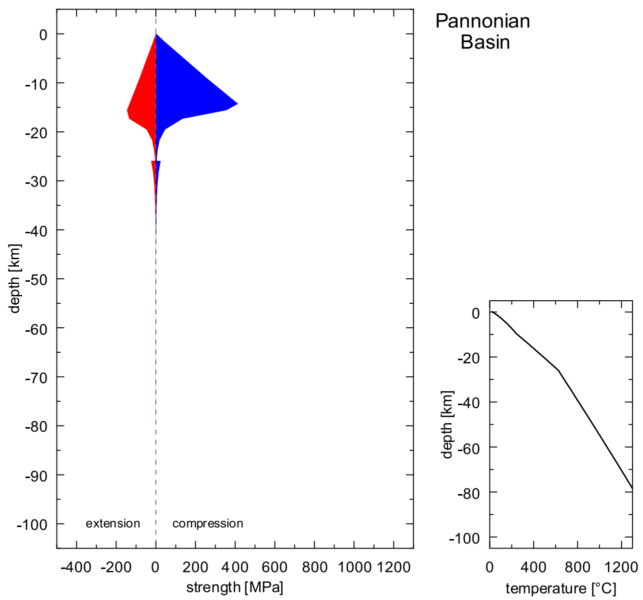

Fig. 7. Vertical strength distribution for different lithospheric columns calculated along transect I. Negative and positive values correspond to extensional and compressional strength respectively.

that this anomalous body is also from a rheological point of view closer to the lower crust. If we assign rheological parameters adopted for the upper crust to the anomalous body, the region over the anomalous upper crust (Bohemian Massif) is characterized by low strength (Fig. 4b), which is not in correlation with previous results of *Lankreijer et al. (1999)*. Therefore, the anomalous body was assigned parameters typical for the lower crust and all further calculations have been done under such consideration.

Based on analysis of the yield strength contour plot and vertical strength distribution for different lithospheric columns for compressional and extensional deformation calculated along transect I (Figs. 5 and 6), the largest strength can be observed within the upper crust with the maximum (400 MPa) on the boundary between the upper and lower crust. This phenomenon is typical for all studied tectonic units: the Bohemian Massif, the Western Carpathians and the Pannonian Basin. These results suggest mostly rigid deformation in the upper crust of the units. By contrast, the lower crust in the Bohemian Massif and the Western Carpathians reflects significantly lower strength, while in the Pannonian Basin the strength is the smallest. In all tectonic units the strength within the uppermost mantle (lower lithosphere) disappears. Based on this result it can be suggested that the ductile deformation dominates in this part of the lithosphere.

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