Integrated geophysical modelling of the lithosphere in the Carpathian–Pannonian region: A review

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Abstract: Over the past ten–fifteen years, new, original and extremely valuable results have been obtained about the geophysical–geological structure and dynamics of continental lithosphere in the Carpathian–Pannonian area. These results have been obtained by modern geophysical programs (e.g., CAGES, LitMod, IGMAS+), whose common denominator is that they are able to minimize uncertainties of the estimates derived from forward modelling of various data sets separately. To further constrain our 2D and 3D models we have made use of the vast geophysical and geological data based on experiments performed in Central Europe in the past decades. The paper illustrates resultant geophysical models of the structure and composition of the lithosphere in the Carpathian–Pannonian Basin region obtained by mentioned new integrated geophysical approaches.

Methodology

CAGES 2D approach

This approach of 2D modelling is based on the joint interpretation of gravity, geoid, topography and surface heat flow data with temperature-dependent density. A finite element algorithm is used to calculate the 2D temperature distribution in the lithosphere in the steady state regime, given its thickness — defined as the 1300 °C isotherm (Zeyen & Fernàndez 1994).

LitMod 3D approach

LitMod 3D has been developed to perform integrated geophysical–petrological LIThospheric forward MODeling of the lithosphere and the sublithospheric mantle down to the top of the transition zone at 410 km depth. The forward modelling is performed within a self-consistent thermodynamic framework, where essential physical properties in the mantle are determined as a function of the pressure, temperature, and bulk mineralogical composition. This is done by solving the appropriate heat transfer, thermodynamical, rheological, geopotential, and isostasy equations. The code allows modelling of several geophysical data sets simultaneously (Alasonati Tašarová et al. 2016).

LitMod 3-D uses the finite difference method to solve the thermal conduction equation (Fullea et al. 2010, 2014; Afonso et al. 2013a,b).

IGMAS+ 3D approach

The IGMAS+ 3D (Interactive Geophysical Modelling Assistant) program is based on simultaneous forward modelling of gravity, gravity gradients, and magnetic fields (Schmidt et al. 2011, 2015; Götze 2014). The software platform offers an interdisciplinary modelling approach integrating independent data sets from seismic, boreholes, and geology, and thus reducing the ambiguity of potential field inversion. The superposition of a voxel model and triangulated surfaces gives possibility to produce complex ("hybrid") models allowing to describe geological structures in a more realistic way (Schmidt et al. 2011; Alvers et al. 2014).

Results

Joint modeling of surface heat flow, gravimetric, geoid and topographic data (CAGES 2D software), using geological and crustal seismic data as constraints along transects crossing the Carpathians (Dérerová et al. 2006), allowed us to establish a new model of the lithospheric structure and the lithosphere thickness map of the Carpathian–Pannonian Basin region (Fig. 1), compiled after our results and results published earlier by Babuška et al. (1988), Horváth (1993), Lenkey (1999).

In the paper of Grinč et al. (2013) four new 2D another lithosphere-scale transects (Fig. 2) crossing central Europe from the West European Platform in the North to the Aegean Sea in the South and from the Adriatic Sea in the West to the East European Platform in the East were presented. As a case study the lithospheric model for transect B is shown in the Fig. 3.

The paper Alasonati Tašárová et al. (2016) presents the parameters and the structure of our preferred (best fitting) model obtained by LitMod 3D approach. Our lithospheric model of Central Europe combines a large number of geophysical, geological, and petrological data sets at various scales into one robust and self-consistent model.

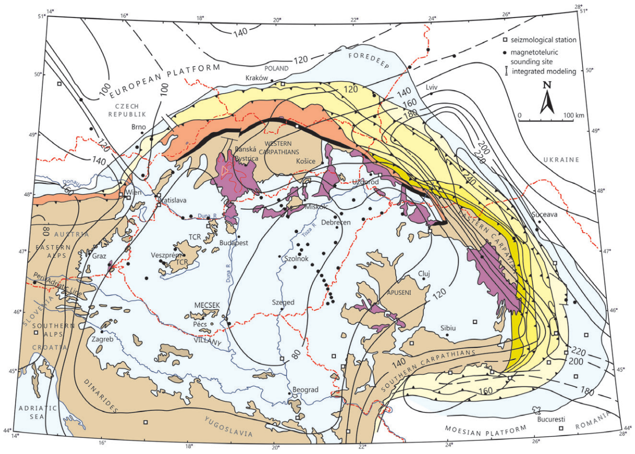

Fig. 1. Lithosphere thickness map of the Carpathian–Pannonian Basin region (modified after Dérerová et al. 2016).

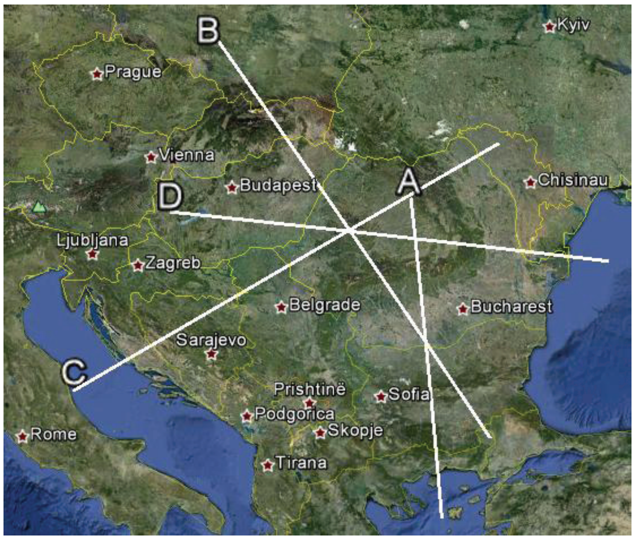

Fig. 2. Location of the interpreted transects A, B, C and D on Google Earth with overlain topography (modified after Grinč et al. 2013).

The model was divided into three main units: ALCAPA; EU, and EEC; and the location of the HVUM (red), slab (grey), and crustal EEC intrusion (blue). Note that the EU mantle has the same composition every where accept for the shallower part of the HVUM and EEC and the deeper part of the Eastern Alpian slabs (Fig. 4).

Based on the extended modelling (Fig. 5) the following conclusions can be drawn:

1. The lithosphere in Central Europe can be divided into three main tectonic domains, characterized by distinct features:
   - Thin, low density, young, hot, and fertile mantle in the Pannonian Basin. Upper/middle crust ~2750 kg/m^3; Lower crust <3000 kg/m^3, sediment infill up to 7–8 km locally, crust as thin as 22–32 km; and LAB depth varies between 70 and 100 km.
   - Thick, cold, dense, and old mantle in the East European craton north of the TESZ; 1–2 km sediments, three-layered and relatively fast and dense crust of up to 45 km thickness. The mantle contains an upper layer composed of depleted (low-density) material.
   - Neutral mantle (both in terms of composition and thickness) in the European Platform, Bohemian Massif, and Western Carpathians. No major crustal root is present underneath the Western Carpathians,

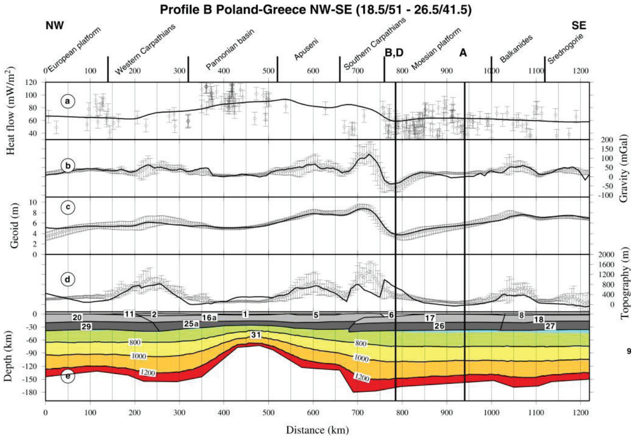

Fig. 3. Lithospheric model for transect B (modified after Grinč et al. 2013). a — Surface heat flow density; b — free-air gravity anomaly; c — geoid; d — topography with dots corresponding to measured data with uncertainty bars and solid lines to calculated values; e — lithospheric structure; numbers in (e) correspond to material number in table 1 of the paper Grinč et al. (2013). In the lithospheric mantle, isotherms are indicated every 200 °C. Numbers on top of the figures indicate the starting and end point coordinates of transects.

with the exception of some local extremes (e.g., ~45 km NE from High Tatras profiles CEL04 and CEL12, Janík et al. 2011).

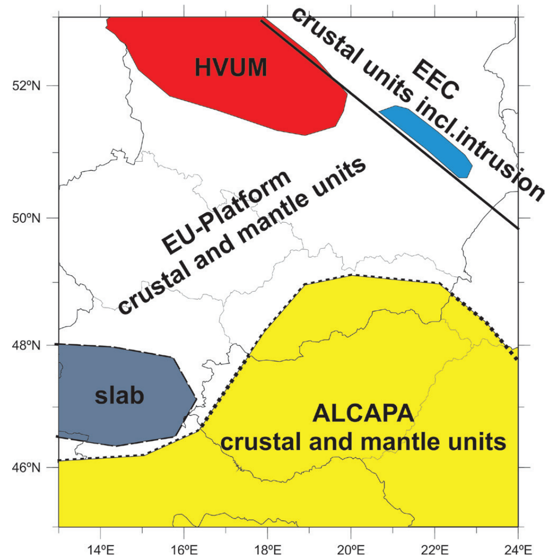

Fig. 4. The model consists of three main units (after Alasonati Tašárová et al. 2016): ALCAPA, European platform (EU) and East European craton (EEC); and the location of the HVUM (high velocity upper mantle — red), slab in the Eastern Alpine region (grey), and crustal EEC intrusion (blue).

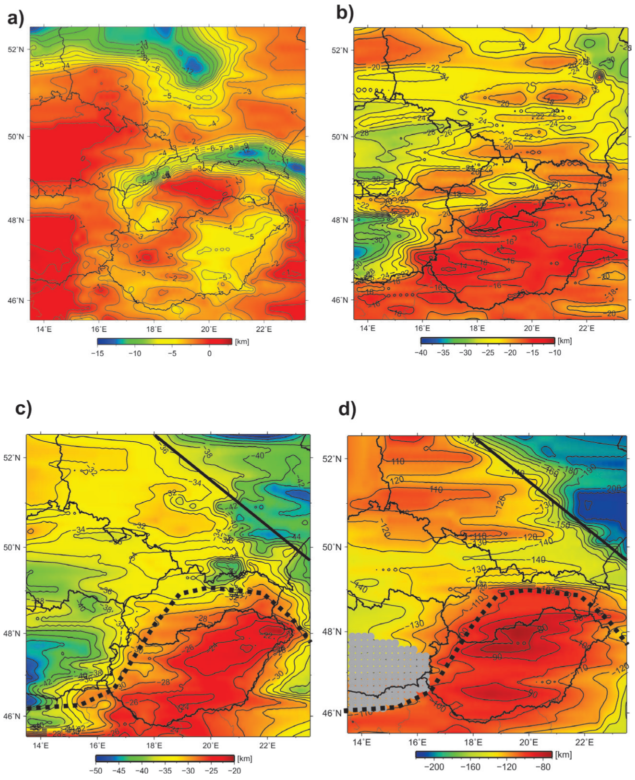

Fig. 5. Results of the modeling showing the depth to the (**a**) basement, (**b**) top of the lower crust, (**c**) Moho, and (**d**) LAB. The grey circles denote the area of the 360 km deep Alpian slab modeled. The black lines denote the three different mantle domains (after Alasonati Tašárová et al. 2016).

2. The Alps are typical collisional orogen, and in contrast to the Western Carpathians, a distinct crustal root is present in our model. The Alpian "suture" (slab junction) plays an important role. While the orientation of the slabs is still a matter of discussion, the presence of the cold, dense, and thick mantle lithosphere in the triple-junction area is clear from both seismic tomography and the gravity field anomalies.
3. The HVUM south of the TESZ is characterized by high-velocity and high-density material, which is interpreted to be eclogite. The very high values of seismic velocity observed and the high densities required to fit the observed topography and gravity field data rule out interpretation as an underplated magmatic body.
4. The combined geophysical-petrological modeling is a very effective tool and allows estimation of reliable mantle P/T dependent densities, temepratures and velocities (Fig. 6) in the upper mantle. Modeling of

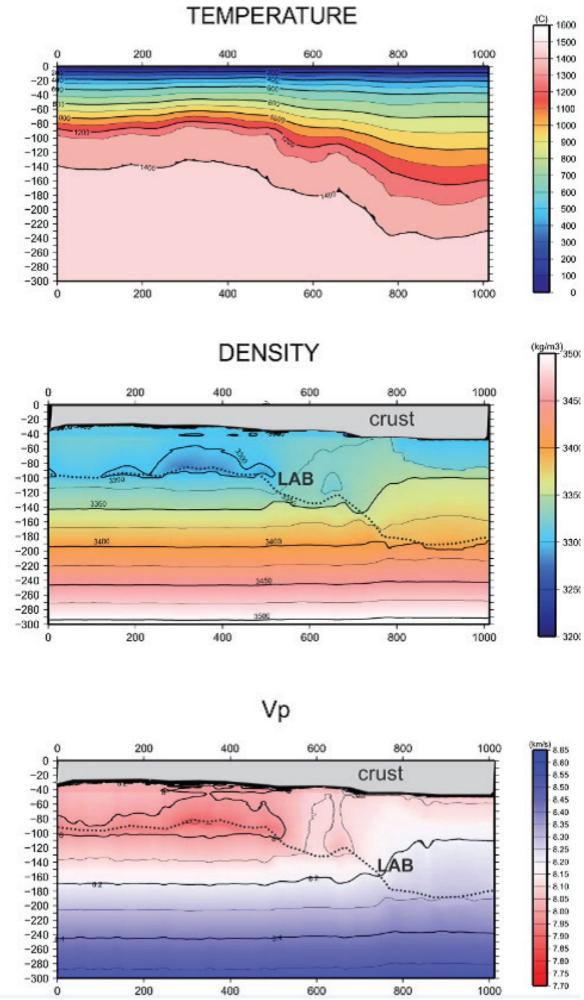

Fig. 6. Profile CEL01 showing the temperature, density and seismic distribution (published by Alasonati Tašárová et al. 2016).

several data sets simultaneously further reduces the ambiguity related to modelling/interpreting the different parameters /data sets separately.

The 3D geophysical modelling by IGMS+ 3D approach (Pánisová et al. 2018) was applied for interpretation of the early Late Miocene Pásztori volcano (ca. 11–10 Ma) and adjacent area in the Little Hungarian Plain Volcanic Field of the Danube Basin (Fig. 7). The gridded gravity and magnetic data (Fig. 8), interpreted seismic reflection sections and borehole data combined with re-evaluated geological constraints have been used. Based on petrological analysis of core samples from available six exploration boreholes, the volcanic rocks consist of a series of alkaline trachytic and trachyandesitic volcanoclastic and effusive rocks. The measured magnetic susceptibilities of these samples are generally very low suggesting a deeper magnetic source. The age of the modelled Pásztori volcano, buried beneath a 2 km-thick Late Miocene-to-Quaternary sedimentary sequence, is 10.4±0.3 Ma belonging to the dominantly normal C5 chron. Our model (Figs. 9, 10) includes crustal domains with different effective induced magnetizations and densities: uppermost 0.3–1.8 km thick layer of volcanoclastics underlain by a trachytic-trachyandesitic coherent and volcanoclastic rock units of a maximum 2 km thickness, with a top situated at minimal depth of 2.3 km, and a deeper magmatic pluton in a depth range of 5–15 km. The 3D model of the Danube Basin is consistent with observed high ΔZ magnetic anomalies above the volcano, while the observed Bouguer gravity anomalies correlate better with the crystalline basement depth. Our analysis contributes to deeper understanding of the crustal architecture and the evolution of the basin accompanied by alkaline intraplate volcanism.

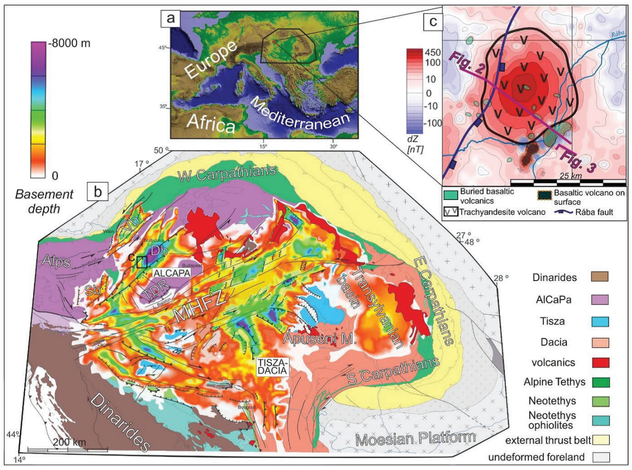

Fig. 7. a — Topography and location of the Pannonian Basin system of the Mediterranean region (after Pánisová et al. 2018). **b** — Simplified tectonic map of the Alps–Carpathians–Dinarides region overlain by the Miocene–Quaternary sedimentary thickness (in meters) of the Vienna (Vb), Pannonian and Transylvanian basins. MHFZ — Mid Hungarian Fault Zone, Db — Danube Basin, TDR — Trans-Danubian Range, Sb — Styrian Basin (modified after Balázs et al. 2017). **c** — Magnetic ΔZ anomaly map of the Danube Basin overlain by the location of surface and subsurface igneous bodies.

The refined Moho depth map in the Carpathian–Pannonian region

The paper of Bielik et al. (2018) published a new digital Moho depth map in the the Carpathian–Pannonian region (Fig. 11). The map was produced by compiling

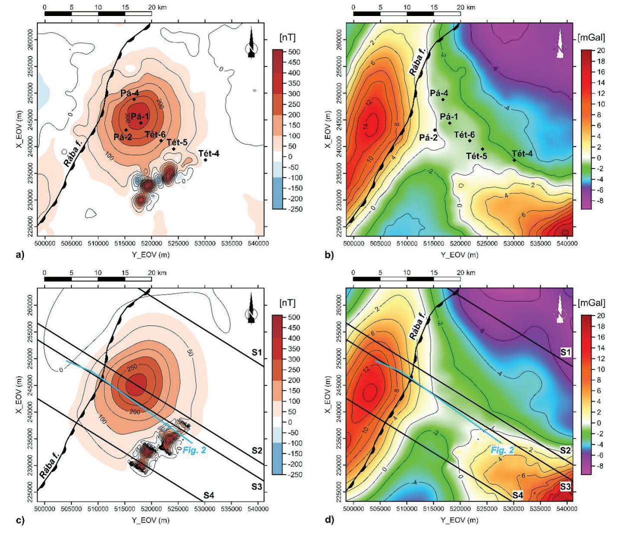

Fig. 8. a — Magnetic anomaly above the Pásztori volcano; **b** — Bouguer gravity anomaly map for a correction density of 2.0 g.cm^{-3}; **c** — modelled magnetic field; **d** — modelled gravity field. Positions of available wells are depicted by black dots with names (published by Pánisová et al. 2018).

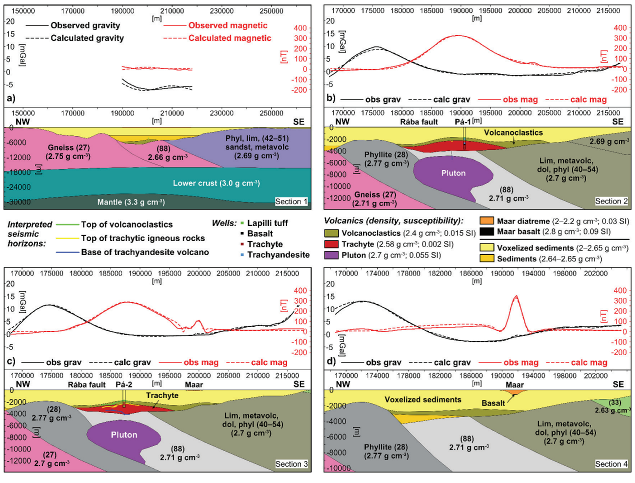

Fig. 9. Four selected cross sections of the final model in Section 1 (**a**), Section 2 (**b**), Section 3 (**c**) and Section 4 (**d**). Locations of particular sections (S1- oriented in NW-SE direction are drawn by black lines in Fig. 8 (published by Pánisová et al. 2018).

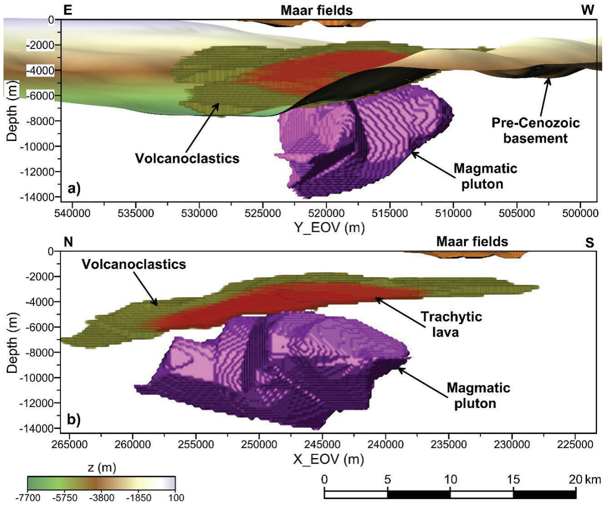

Fig. 10. 3D geophysical model of the Pásztori volcano (Pánisová et al. 2018): north view (**a**), west view (**b**).

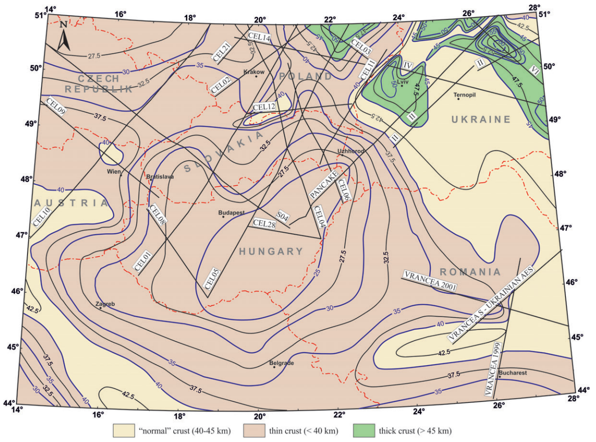

Fig. 11. The Moho depth map in the Carpathian–Pannonian region (modified after Bielik et al. 2018).

Moho discontinuity depth data, which were obtained by interpretation of seismic measurements taking into account the results of 2-D and 3-D integrated geophysical modelling. The resultant map is characterized by significant Moho depth variations. The trends and features of the Moho in this region were correlated with the main tectonic units, which built the studied area.

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