Determination of the lithosphere thickness in the Western Carpathians by means of geothermal-gravity-isostatic modeling

JANA DÉREROVÁ[1], HANS ZEYEN[2] and MIROSLAV BIELIK[1]

[1]Geophysical Institute of the Slovak Academy of Sciences, Dúbravská cesta 9, 842 28 Bratislava, Slovak Republic. E-mail: geofjade@savba.sk

[2]Départment des Sciences de la Terre, Université de Paris-Sud, Bat. 504, F-91504 Orsay Cedex, France. E-mail: zeyen@geol.u-psud.fr

Abstract: Differences in determination of the depths of the lithosphere-asthenosphere boundary by means of seismic, magnetotelluric and geothermal methods were found out in the Western Carpathian-Pannonian basin region. It leds us to the application of integrated lithosphere modeling of the surface heat flow, free-air anomalies and topography (local isostasy) to determine the continental lithospheric thermal structure along the profiles going through the Western Carpathians, the Eastern European platform, the Bohemian Massif and the Pannonian basin. The calculation of model of the structure and thickness of the lithosphere were performed along the profiles I, II, III and IV. The results indicate observably differences in the lithosphere thicknesses along the Western Carpathian orogen not only in N-S direction but in W-E direction orogen as well. The lithosphere thickness varies from about 120 to 90 km underneath the Bohemian Massif, 140-100 km beneath the Eastern European platform, 100 km to 90 underneath the Western Carpathians and 90 to 75 km beneath the Pannonian basin. Underneath ofthe central Western Carpathians a thickening of the lithosphere is indicated. This structure is interpreted as a small remnant of a subducted lithosphere slab. The lithosphere slab was not indicated in the western segment of the Western Carpathians. Taking into account this results we suggest that tectonic evolution of the continental collision along the Western Carpathian orogen has been changed in time and space.

Introduction

It is known that the lithosphere-asthenosphere boundary is a fundamental physical-chemical boundary in the upper mantle. It has been observed as a low P- and S- wave velocity layer, a change in seismic anisotropy, area of increased electrical conductivity, a rheological boundary, a thermal boundary layer, a phase change, and a geochemical boundary.

From geothermal point of view, the lithosphere can be understood as the layer down to the layer, where a change in physical properties of rocks, caused by their partial melting, occurs. In the present time this boundary is defined as the 1300°C isotherm. The first model of the lithosphere thickness in the central Europe, including the Western Carpathians, was determined by means of geothermal calculations and published by Čermák (1982).

The first seismological studies of the lithosphere thickness in the central Europe were performed by Babuška et al. (1987, 1988) through the interpretation of teleseismic P-wave delay times. The lithosphere is characterized as the layer down to the low-velocity layer. That is why seismic wave velocities are higher in the lower lithosphere than those in the asthenosphere.

Basing on the magnetotelluric sounding in irregular points of measurements, the lithosphere thickness data were completed in former Czechoslovakia by Praus et al. (1990) and in Hungary by Ádám et al. (1989).

Today, we have already suggested that the lithosphere-asthenosphere boundary can also be understood as a density discontinuity (e.g., Lillie et al. 1994, Bielik 1995).

In spite of independent knowledge about the lithosphere thickness coming from mentioned above sources, these determinations, however, do not necessarily coincide one another. In the central Europe large differences in the lithosphere thickness have been recognized (Zeyen and Bielik 2000, Bielik et al. 2000). The largest differences in the lithosphere thicknesses determined by means of the seismology and the magnetotelluric sounding were found out in the central Slovakia region (Babuška et al. 1988, Horváth 1993, Šefara et al. 1996). They attain over 40-50 km. Further it seems to be that the lithosphere underneath the European platform is deep about 100-110 km in model of Zeyen and Bielik (2000) and thinner than previously modeled. It was obtained in spite of implying a decrease in upper-crustal heat production in order to stay compatible with the measured heat flow data.

We would like to stress that, in generally, the determination of the lithosphere-asthenosphere boundary from all known geophysical boundaries within the whole lithosphere is the most unambiguous. The largest imperfection of its definition comes from limited numbers of observations. Up to now there are large differences in determination of the depths of the lithosphere-asthenosphere boundary by means of the different geophysical methods, too.

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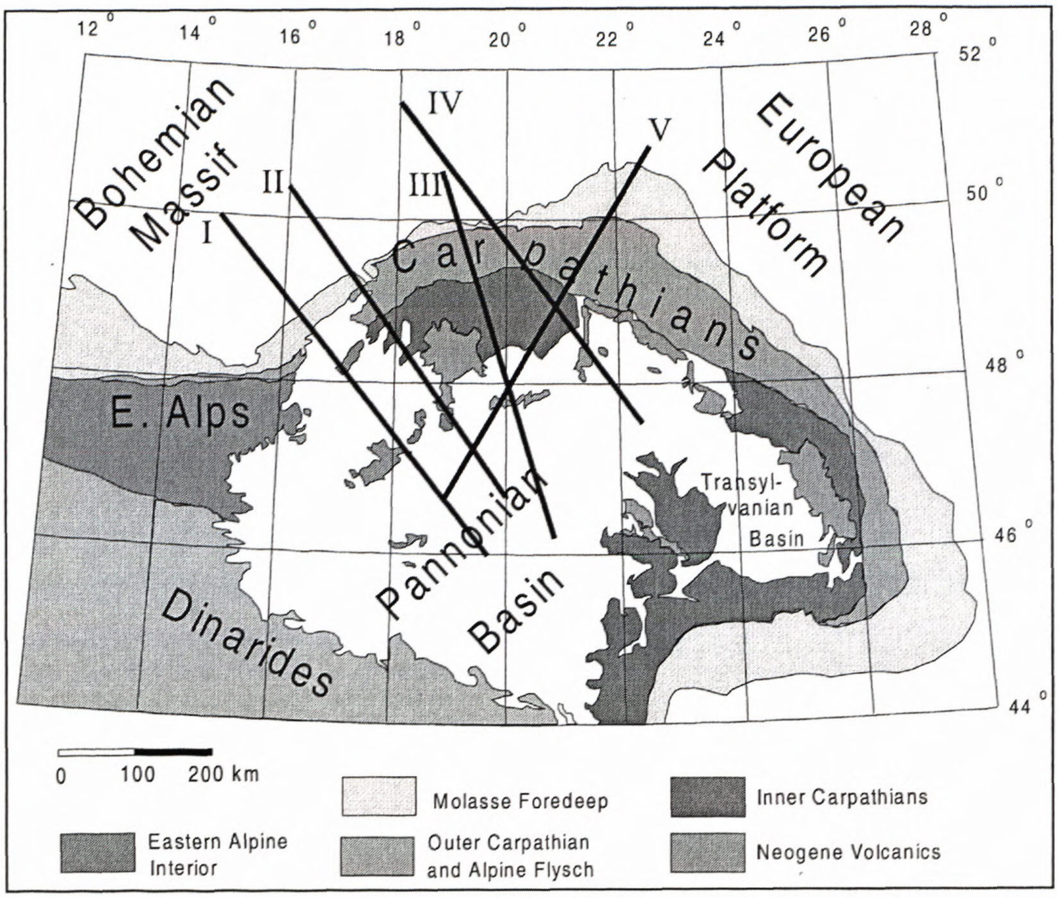

Fig. 1. A simplified tectonic map of the Eastern Alpine-Carpathian-Pannonian basin region (from Lillie et al. 1994). The cross-sections of profiles used in this study are shown by the bold line.

To improve the knowledge of the lithosphere thickness in the Carpatho-Pannonian basin region (Fig. 1) the integrated lithosphere modeling was applied in our paper. The determination of the continental lithosphere thickness was made by means of integrated geothermal-gravity-isostatic modeling along the profiles going through the Western Carpathians.

Method

The calculations of the models of the lithosphere thickness as a base for geodynamical reconstructions of the Western Carpathians were performed systematically along the profiles I, II, III and IV going through the Western Carpathians and its surrounding tectonic units - the Bohemian Massif, the Eastern European platform and the Pannonian Basin (Fig. 1).

To determine the lithosphere thermal structure, the method which was founded by Zeyen and Fernandez (1994) was applied. A finite element algorithm integrates the different physical concepts of gravity, local isostatic topography and conductive heat transport links the data sets through thermal expansion. This algorithm is used to calculate the two-dimensional temperature distribution in the lithosphere, given its thickness (in our study defined as the 1300 °C isotherm).

Once the temperatures are calculated at every node, densities are evaluated at the nodes, depending on temperature and pressure. In the crust, with relatively low temperatures and high porosities, pressure and temperature effects are supposed to balance each other. In the lower crust and lithosphere 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, a thermal expansion coefficient of $3*10^{-5}$ K^{-1} is assumed. With this density distribution, we are able to calculate the gravity (Free air or Bouguer) anomalies along the profile (Talwani et al., 1959) and, for every column of the model, the topography under the assumption of local isostatic equilibrium. The level of compensation is taken at the depth of thickest lithosphere in the model. The resulting profile of relative topography variations can then be compared to an area with well-known lithosphere structure in order to estimate absolute topography. Following Lachenbruch and Morgan (1990), this calibration is done at the mid-ocean ridges.

The mentioned thermal and density-related parameters were modified by trial-and-error until a reasonable fit was obtained between data and model predictions.

Results

As an examples of our integrated geothermal-gravity-isostatic modeling, the results obtained along the profiles I and IV (Figs. 2-3) are illustrated in our paper. The results

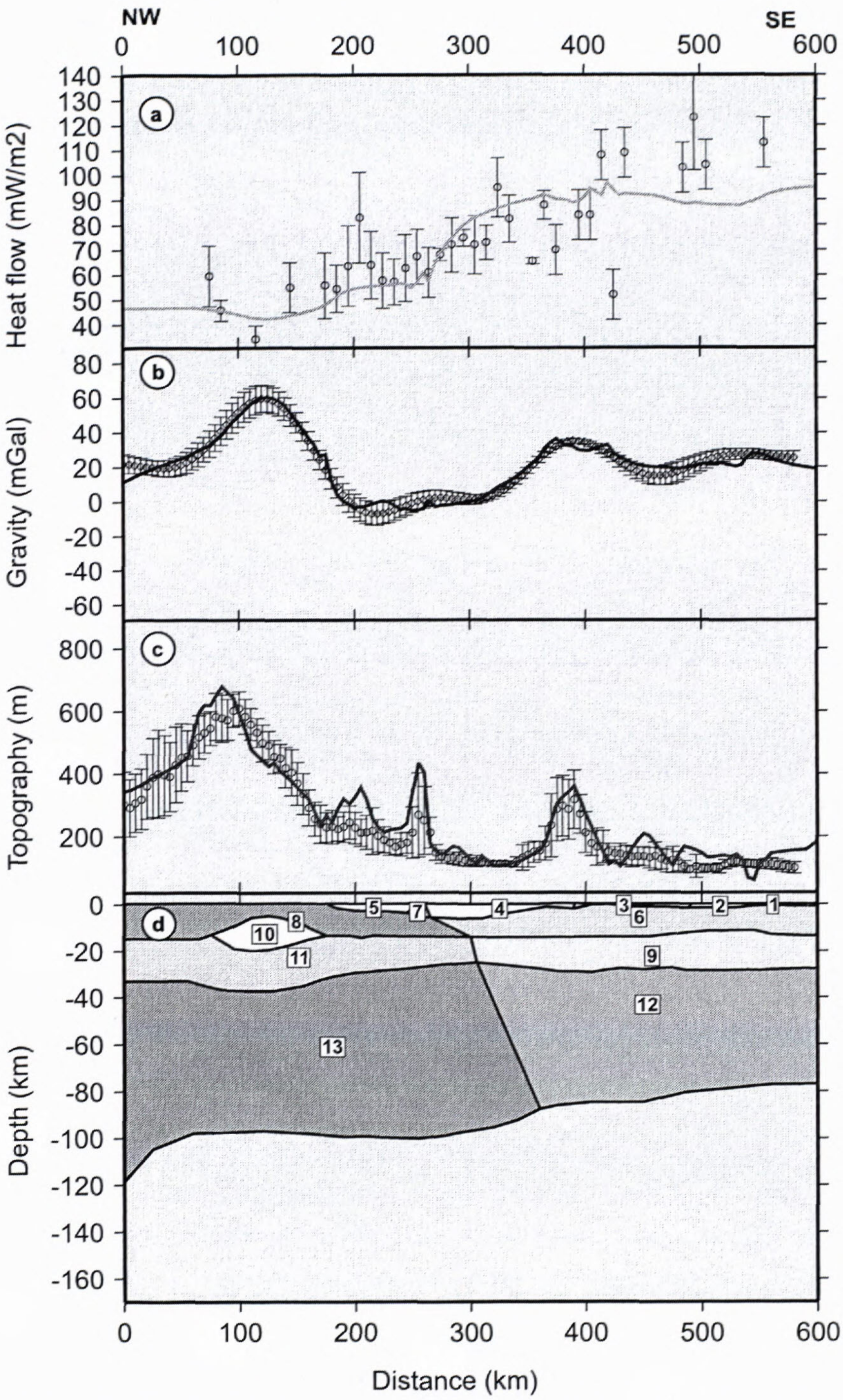

Fig. 2. Integrated modelling along the Profile I. Surface heat flow (a), Free-air gravity anomaly (b) and topography (c). Dots correspond to measured data with corresponding error bars and solid lines to calculated values. Keys: 1-2 – Sediments of the Pannonian Basin, 3 – Hungarian Central Mts. unit, 4 – Sediments of the Pannonian Basin, 5 – Outer Carpathian molasse and flysh and sediments of the Vienna Basin, 6 – Upper crust of the Carpatho-Pannonian plate, 7– Little Carpathian Mts. Unit, 8 – Upper crust of the Bohemian Massif, 9 – Lower crust of the Carpatho-Pannonian plate, 10 – Anomaly body within the Bohemian Massif crust, 11 – Lower crust of the Bohemian Massif, 12-13 – Lithoshere mantle.

indicate observably differences in the lithosphere thicknesses along the Western Carpathian orogen not only in N-S direction but in W-E direction orogen as well.
The lithosphere thickness underneath the Bohemian Massif (profiles I and II) is practically flat and/or it decreases slowly in the direction from the Bohemian massif to the Western Carpathians. It varies from about 120 to 90 km.

To fit the calculated and observed data along the profile I, an anomalous body located between the upper and lower crust (km 90-180) was needed to model. Underneath this anomalous body a small crustal thickening is indicated. In the cross-section of the lithosphere along profile II, a short wave-length Moho elevation (km 60-120) was observed. The lithosphere thickness beneath the western segment of the Western Carpathians deccreases clearly from about 100 km to 85 km.

Based on the results obtained along the profiles III and IV, the lithosphere thickness beneath the Eastern European platform can be observed at the depths of 140-100 km. Generally, the shallowing of the asthenosphere is in the direction to the Western Carpathians. Underneath the central Western Carpathians a thickening of the lithosphere is indicated. The thickening from about 100 km depth to about 120-140 km depth is needed to obtain good correlation between the observed and modeled data. This structure is interpreted as a small remnant of a subducted slab of the European plate. We would like to stress that the subducted lithosphere slab was not indicated in the western segment of the Western Carpathians. Taking into account this result we suggest that tectonic evolution of the continental collision along the Western Carpathian orogen has been changed in time and space. We speculate that the last stage of development of the lithosphere in the western segment of the Western Carpathians (and/or between the Western Carpathians and the Bohemian Massif) was influenced mainly by lateral extrusion, transpression and transtension, while in the central part of the Western Carpathians (and/or between the Western Carpathians and the European platform) the dominant features of the last stage of formation of the lithosphere was driven by the inter-related processes of convergence, subduction, collision suturing and accretion.

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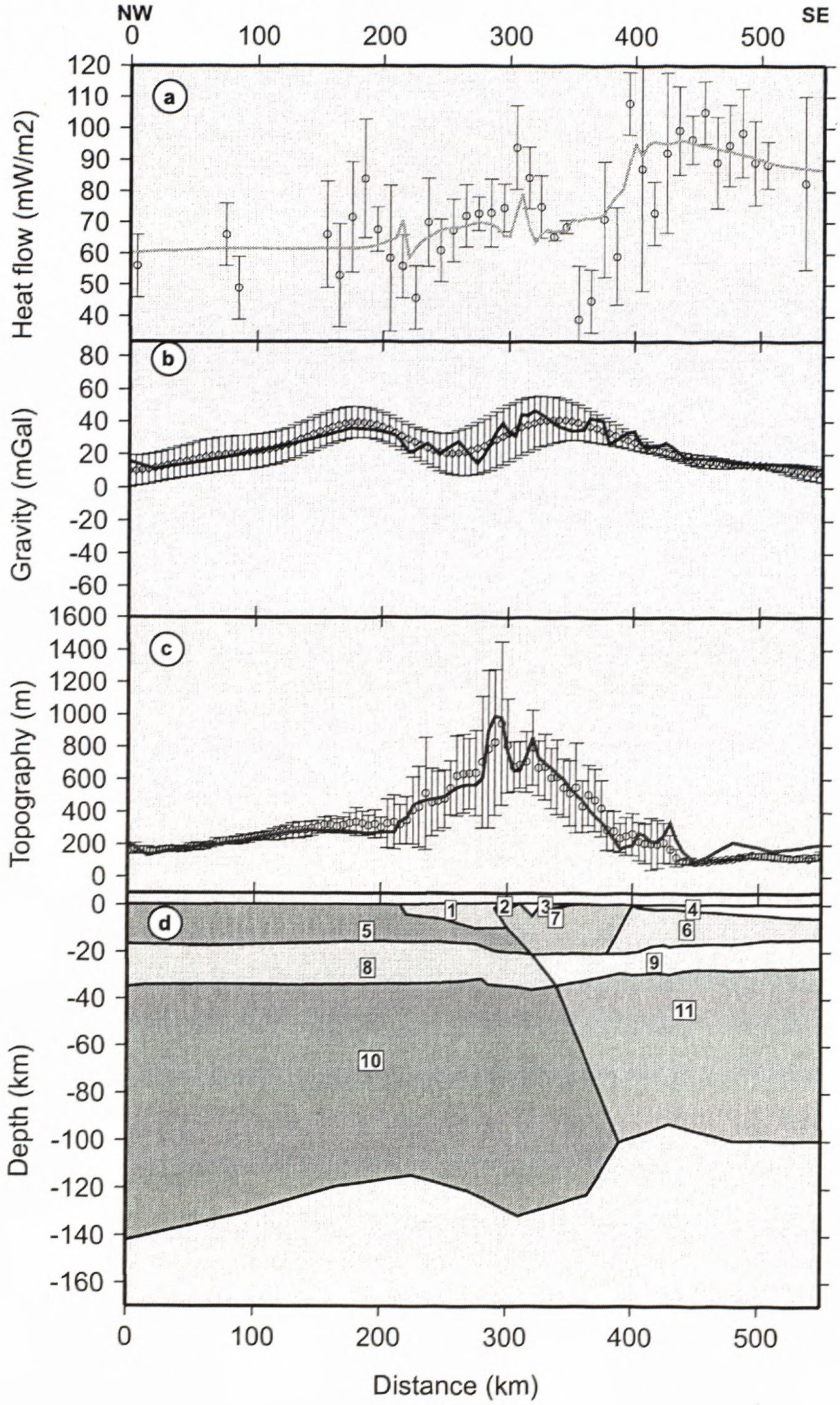

Fig. 3 Integrated modelling along the Profile IV. Surface heat flow (a), Free-air gravity anomaly (b) and topography (c). Dots correspond to measured data with corresponding error bars and solid lines to calculated values. Keys: 1 – Outer Carpathian molasse and flysh, 2-3 – Inner Carpathian flysh, 4 – sediments of the Pannonian Basin, 5 – Upper crust of the European platform, 6 – Pannonian Upper crust, 7 – Western Carpathian crust, 8 – Lower crust of the European platform, 9 – Lower crust of the Carpatho-Pannonian plate, 10-11 – Lithosphere mantle.

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