Geological Quarterly, 1999, **43** (3): 251–262

Geophysical features of the Slovak Western Carpathians: a review

Miroslav BIELIK

Bielik M. (1999) — Geophysical features of the Slovak Western Carpathians: a review. Geol. Quart., **43** (3): 251–262. Warszawa.

The article reviews the important results of the geophysical research in the Slovak Western Carpathians. As the Slovak Western Carpathians has been a target of intensive detailed gravimetric measurements for the last 20 years, an emphasis is given to the interpretation of gravity field. Analysis of the Bouguer gravity anomalies comes from density modelling in local isostatic equilibrium and 2 1/2 D forward density modelling. The results of density modelling together with other geophysical data were used for geological and geophysical interpretation of the lithospheric structure and its tectonics in the Slovak Western Carpathians. Rheology of the lithosphere based on extrapolation of failure criteria, lithology and temperature models is presented. Finally, the obtained results are discussed.

Miroslav Bielik, Geophysical Institute, Slovak Academy of Sciences, Dúbravská cesta 9, 842 28 Bratislava, Slovak Republic; e-mail: geofmiro@savba.sk (received: November 4, 1998; accepted: February 16, 1999).

Key words: Slovak Western Carpathians, geophysics, gravity modelling, local isostasy, lithosphere.

INTRODUCTION

The Western Carpathians are located in the Central Europe. They are characterized by relatively high average elevation (1200 m) and lie within the territories of four countries: Slovakia, Czech, Poland and Hungary. The Western Carpathian arc and the surrounding tectonic units: Bohemian Massif, European Platform, Pannonian Basin, Eastern Alps and Eastern Carpathians offer good opportunity to study continent collisional and extensional tectonics. The fundamental feature of the Western Carpathians (Fig. 1) is their nappe structure (O. Fusán *et al.*, 1987; A. Biely *et al.*, 1996). Rock complexes range from the Precambrian to Tertiary.

The Western Carpathians are divided into the externides (formerly called the outer Western Carpathians) and internides (formerly called the inner Western Carpathians). The externides represent the palaeo-Alpine and meso-Alpine consolidated part of the orogene. It is generally divided into the Variscan basement nappes and Mesozoic superficial ones. The externides are formed by the neo-Alpine accretionary prism of the flysch nappes thrust over the foredeep that covers the flanks of the European Platform (D. Andrusov, 1968; M. Kováč *et al.*, 1998).

Between the externides and internides the Pieniny Klippen Belt is located. The Pieniny Klippen Belt is one of the most complicated geological units in the Western Carpathians. Shortening of this zone was large and it was folded at least twice (in Upper Cretaceous and Tertiary). The result of this process is that the basement was entirely destroyed and subducted by continental collision. At present, the width of the Pieniny Klippen Belt is only several kilometers. Maximum width is about 20 km.

The goal of this paper is to give an overview of the regional geophysical data and to attempt to collect the most recent interpretation of gravity data and complitions. For that purpose results of 2 1/2 D gravity modelling, interpretation of all recent geophysical data, geological interpretation of the lithosphere structure and geodynamics, and rheology of the lithosphere in the Slovak part of the Western Carpathians are presented.

GEOPHYSICAL DATA

The Western Carpathians in Slovakia have been covered by extensive geophysical surveys. In the former Czechoslovakia, investigations of the deep structure of the upper lithosphere including Moho discontinuity started in 1962 (for summary see J. Šefara *et al.*, 1987; I. Ibrmajer *et al.*, 1994*a*; V. Bucha, M. Blížkovský, 1994).

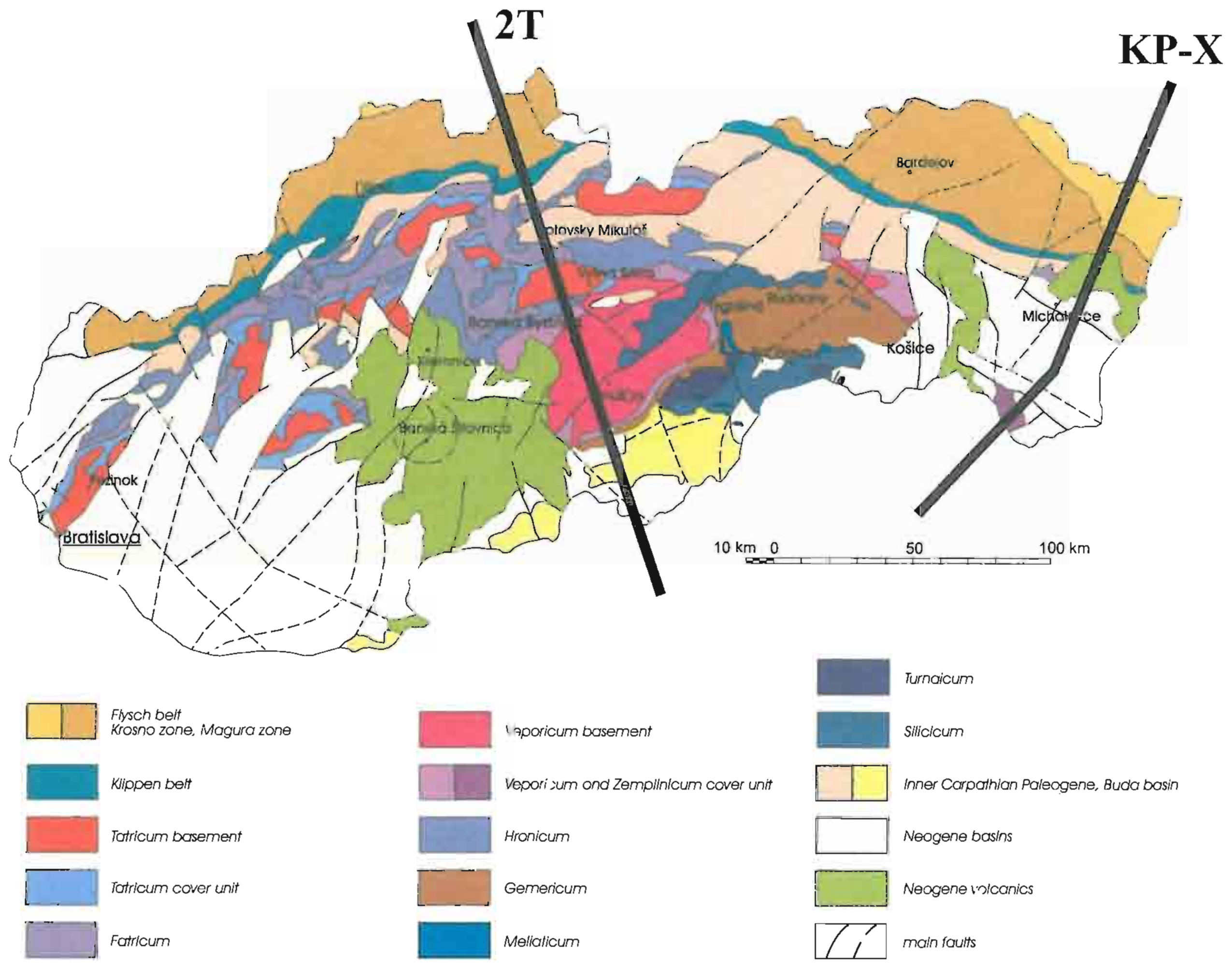

Fig. 1. Tectonic sketch of the Slovak part of the Western Carpathians (after A. Biely *et al.*, 1996)

Thick lines mark the locations of the cross-sections along which interpretation of the lithospheric structure made

SEISMIC REFRACTION MEASUREMENTS

The first seismic measurements (M. Mayerová *et al.*, 1994) to study the crust of the Western Carpathians were carried out along two international profiles designated by roman numbers V and VI (Fig. 2). They were followed by experiments along regional profiles KI, KII, KIII, 100R, 100B and F/75 (Fig. 2). These geophysical measurements provided the general velocity structure of the crust. The upper crust in the Slovak Western Carpathians is characterized by increased vertical gradient of velocity (Fig. 3). In the central part of the crust the low velocity channel can be observed. In the lower crust another zone of increased gradient of velocities was found. M. Mayerová *et al.* (1994) suggest that this zone is probably associated with the transition zone in the lower part of the crust. It may be noted that the Moho does not form a sharp boundary but rather a transient zone up to several kilometres thick (Figs. 3, 4). The course of the Moho is relatively complex and a group of layers exhibiting high a low

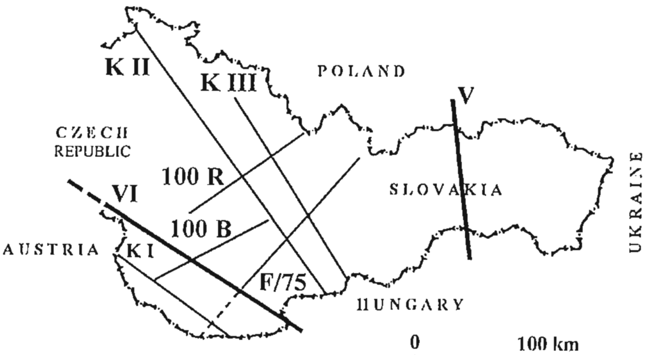

Fig. 2. Locations of DSS profiles in Slovakia

Thin lines represent national profiles and thick lines international profiles (modified after V. Bucha, M. Blížkovský, 1994)

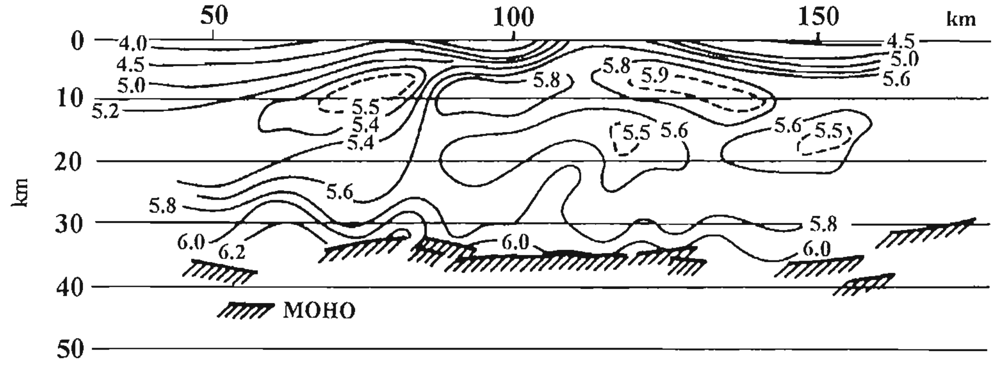

Fig. 3. Effective velocities pattern in KIII section (modified after V. Bucha, M. Blížkovský, 1994)

Velocities are in kms^{-1}

velocities form a lamellar character of the Moho discontinuity.

SEISMIC REFLECTION MEASUREMENTS

Deep seismic reflection sounding has brought a new insight into the understanding of the evolution the Western Carpathian lithosphere (for summary see I. Ibrmajer *et al.*, 1994*a*, *b*). The transect 2T proved the nappe structures of the Western Carpathians (Figs. 5, 6). The ideal geological model (Fig. 6) clearly showed two different segments of the Carpathian crust with different periods of a final deformation.

In the north (10 km on profile 2T/83, 84) the palaeosubduction zone occurs with an accretion complex of the Krosno flysch formation tilted, after bending, at an angle of 40°. Then, there are the frontal inner-Magura imbrications and backthrusts tilted at an angle of 30–40° on the Orava–Magura nappe, the Pieniny Klippen Belt, the Tatricum with the tectonic envelope of the sub-Tatric nappes, and the sedimentary cover of the central-Carpathian Paleogene. The northernmost overthrust at NE Orava are already covered by the Orava Basin of a probably Badenian to Sarmatian age (I. Ibrmajer *et al.*, 1994*b*).

In the southern half of the profile (from 10 km on partial section 2T/85) reflection segments dipping at angles of 20–30° to SSE predominate. Beneath the Veporicum they form a 20–30 km thick collision suture of the Carpathian Cretaceous orogene. As Veporicum and Gemericum have not been markedly affected by later deformation movements, the Mesozoic collision suture is well preserved in the time section.

The thrust of the Veporicum over Tatricum along the Čertovica fault and the root the Križna nappe in the North Vaporicum can be observed (Č. Tomek *et al.*, 1987, 1989). Gemericum covers the collisional complex of the Veporicum and Tatricum. The Veporicum was interpreted as an Upper Cretaceous whole-crust collisional suture. The whole crust flexure of the lower European plate was explained as a result of subduction movements when passive continental margin of the Krosno sea was subducted beneath the Carpatho-Pannonian plate (Č. Tomek, 1993). Beneath the area between Pilsko and Chabenec (I. Ibrmajer *et al.*, 1994*b*), the reflection elements in the upper plate consisting of the Magura–Pieniny complex (Magura–Rhenodanubian flysch — in the sense of Č. Tomek, 1993 and P. Szafián, 1999) and the Inner Carpathians probably correspond to the phenomena which originated prior to the subduction although the elements in some imbricated backthrusts could have originated during the subduction.

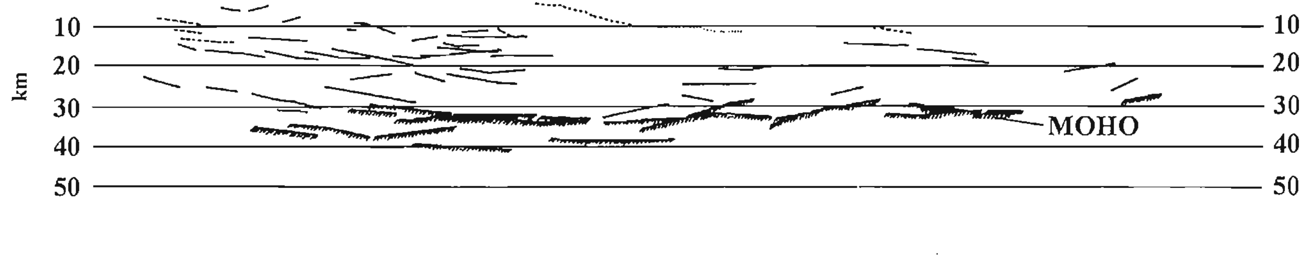

Fig. 4. Courses of seismic boundaries including the Moho discontinuity along of the profile KII (modified after V. Bucha, M. Blížkovský, 1994)

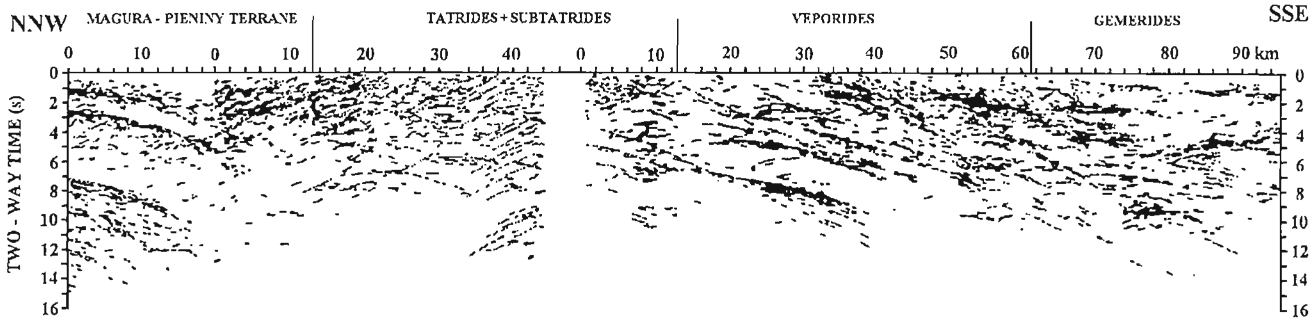

Fig. 5. Selected reflections along deep reflection seismic transect 2T (Č. Tomek *et al.*, 1987, 1989)

SEISMICITY

Earthquake activity in the Western Carpathians in Slovakia is determined by its geological history and tectonics. The latest version of the map of earthquake epicentres in Slovakia and its surroundings (P. Labák, F. Brouček, 1996) indicates that the most seismically active unit is the belt stretching rouhgly along the Pieniny Klippen Belt. As a rule the earthquake foci occur within the upper part of the crust, i.e. at depths smaller than 15 km, except for the area in the central part of Slovakia where this depth is probably in order of 20 km (D. Procházková *et al.*, 1994).

CRUSTAL STRUCTURE

Previous data on the Moho discontinuity obtained along the international and regional profiles and by industrial explosions were reinterpreted for the territory of the Slovak Western Carpathians taking into account the results of deep seismic profiles with extended recording time. Map of the Moho depth in the Western Carpathians and surrounding regions (Fig. 7) was modified after F. Horváth (1993), J. Šefara (1993) and J. Šefara *et al.* (1996).

The Western Carpathians in Slovakia (Č. Tomek *et al.*, 1987, 1989) are characterized by normal crustal thickness of

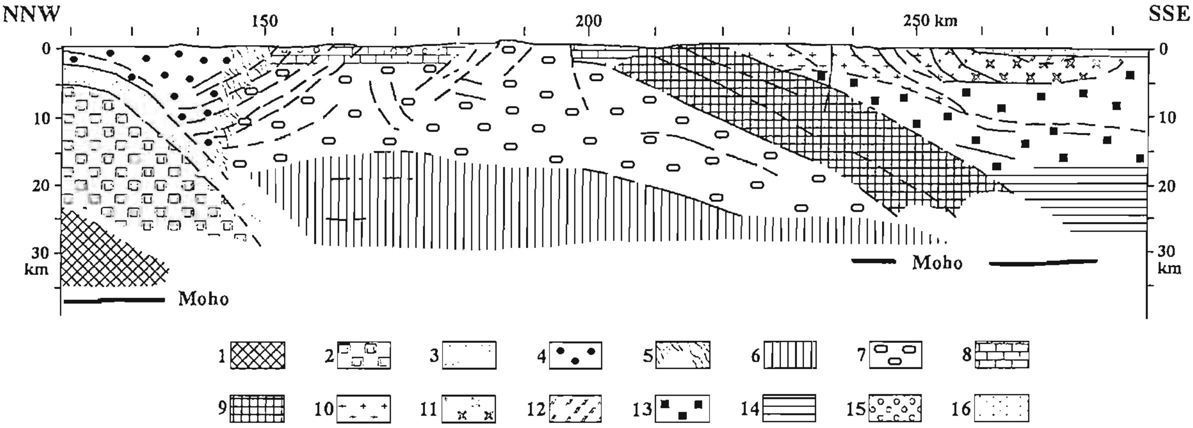

Fig. 6. Geological interpretation of the 2T deep reflection seismic transect (modified after Č. Tomek *et al.*, 1989; P. Szafián, 1999)

1, 2 — lower and upper crust of the subducted European Foreland (Bohemian Massif); 3 — subduction accretion complex of the Krosno sea (in the sense of I. Ibrmajer *et al.*, 1994*b*) and/or Moldavian Flysch wedge (in the sense of Č. Tomek, 1993 and P. Szafián *et al.*, 1997), and/or Gribowska unit or Silesian unit (M. Potfaj, pers. com.); 4 — Inner Magura-Pieniny subduction accretion complex (in the sense of I. Ibrmajer *et al.*, 1994*b*) and/or Magura-Rhenodanubian Flysch (in the sense of Č. Tomek, 1993 and P. Szafián *et al.*, 1997); 5 — Pieniny Klippen Belt; 6 — crust of the Tatricum; 7 — crystalline complexes of the Tatricum; 8 — Mesozoic nappes of the North Pannonian unit; 9 — crystalline complexes of the Veporicum; 10 — granitoid rocks of the Veporicum; 11 — Palaeozoic rocks of the Gemericum; 12 — Mesozoic rocks of the Gemericum; 13 — crystalline rocks of the southern Veporicum; 14 — lower crust of the Veporicum and Gemericum; 15 — Central Carpathian Paleogene; 16 — Neogene fill of the Pannonian Basin

30–36 km and by the formation of new Moho after the cessation of subduction beneath the Carpathian orogen. In the Bohemian Massif region the crustal thickness reaches about 32.5 km. Very thick crust can be observed in the Teisseyre-Tornquist Zone (A. Guterch *et al.*, 1984, 1986). The thick crust is, therefore, a Palaeozoic feature inherited from the collision between the European plate (Avalonia) and the Ukrainian Platform (Laurussia) (L. Lenkey *et al.*, 1998). In the Pannonian Basin the Moho undulates around 25 km and after the newest results along the PGT-1 line (K. Posgay *et al.*, 1995, 1996) it steeply rises to less than 22 km depth beneath the Békés Basin.

LITHOSPHERIC THICKNESS

The fundamental lithospheric thickness data come from seismic observations, magnetotelluric sounding and geothermal measurements. V. Babuška *et al.* (1987) calculated the first model of the lithospheric thickness in the Carpatho-Pannonian region. This map was later completed by magnetotelluric sounding data (O. Praus *et al.*, 1990; V. Babuška *et al.*, 1994). W. Spakman *et al.* (1993) applied a 3D model to project the velocity of seismic waves.

The lithospheric map in Figure 8 is modified according to F. Horváth (1993). The Western Carpathians are located over the zone of gradual increase of the lithospheric thickness from the Pannonian Basin to European Platform. The lithospheric thickness is 50–60 km beneath the Pannonian Basin. The rigid and older European Platform in Poland is characterized by thicker lithosphere (140–180 km). The thickness of the lithosphere beneath the Bohemian Massif varies from about 120 to 140 km.

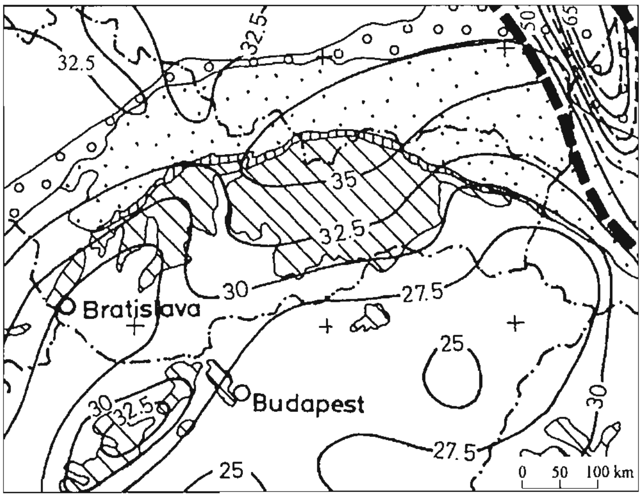

Fig. 7. Crustal thickness map of the Western Carpathians and the surrounding territories (modified according to F. Horváth, 1993; J. Šefara *et al.*, 1996)

The thickness is given in kilometres; simplified geological-tectonic map showing the outer molasse (circles), Outer Carpathian Flysch (dots), Pieniny Klippen Belt (vertical lines), pre-Neogene units (oblique lines); Neogene basins including neovolcanites and the units of the Alpine-Carpathian Foreland are not distinguished

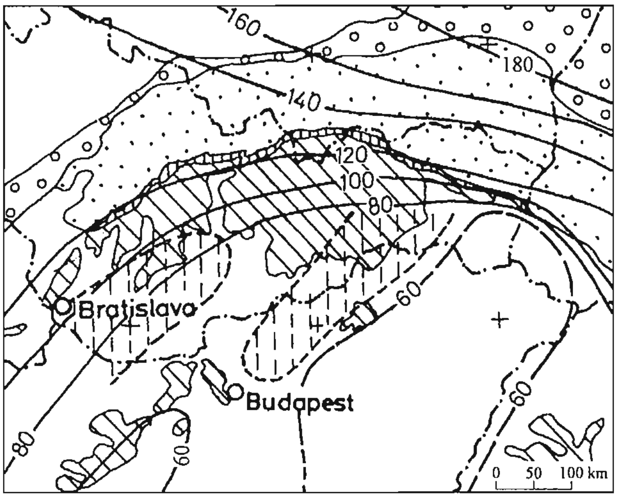

Fig. 8. Contour of the lithosphere-asthenosphere boundary in the Western Carpathians and their vicinity (after F. Horváth, 1993; J. Šefara *et al.*, 1996)

Regions of dashed lines have considerable uncertainty in determination of the lithospheric thickness; other explanations — see Fig. 7

HEAT FLOW

In spite of that the error bars of the surface heat flow density measurements are relatively large and heat distribution and thermal conductivity are usually not well known they are very valuable geophysical parameters for study of geodynamics of the lithosphere.

The map of heat flow density distribution in Slovakia (Fig. 9 after J. Šefara *et al.*, 1996) was based on results by J. Jančí (1994 — not published), and in surrounding areas by V. Čermák *et al.* (1992). The general increase of the heat flow density in direction from the European Platform *via* the externides of the Western Carpathians towards the inner tectonic units of this mountain belt and the Pannonian Basin is dominant feature in the whole map. The heat flow in the European Platform and the externides is only 40–60 $\mathrm{mWm^{-2}}$, but it attains over 100 $\mathrm{mWm^{-2}}$ in the Eastern Slovakian Basin and Pannonian Basin. The central Slovakian Neovolcanics are also characterized by high heat flow (about 100 $\mathrm{mWm^{-2}}$).

GEOMAGNETIC AND PALAEOMAGNETIC FIELDS

Geomagnetic anomalies compiled from the results of ground and aerial magnetic mapping (M. Filo, P. Kubeš, 1994) demonstrate that the highest magnetic field can be observed over the neovolcanic zones. The interpretation of geomagnetic anomaly confirmed the existence of a striking magnetized zone at southern margin of the central Western

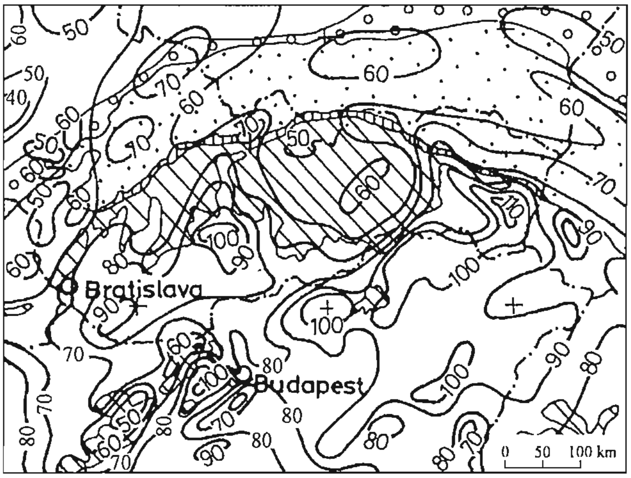

Fig. 9. Map of the heat flow density distribution in the Western Carpathians and the surrounding territories (modified according to V. Čermák *et al.*, 1992; J. Jančí, 1994 — not published)

For explanations — see Fig. 7

Carpathians which represents its contact with the Pannonian block (M. Filo, P. Kubeš, *op. cit.*).

The palaeomagnetic research in Slovakia showed the different rotation of particular geological units of the Western Carpathians. More detailed palaeomagnetic results in the Slovak part of the Carpathian belt were published by P. Muška (1994*a*, *b*), M. Krs (1994) and M. Kováč *et al.* (1998).

GRAVITY DATA

The Western Carpathians in Slovakia have been a target of intensive detailed gravimetric measurements (scale 1:25,000) for the last 20 years. Almost the whole territory of Slovakia is covered by this new mapping (J. Šefara *et al.*, 1987; I. Ibrmajer *et al.*, 1994*a*; M. Blížkovský *et al.*, 1994) with density of measurements about 4–6 points per km^2 and accuracy of measurements from 0.01 to 0.1 mGal.

In Figure 10 the sketch of the Bouguer gravity anomaly map in Slovakia (after J. Šefara *et al.* in: I. Ibrmajer *et al.*, 1994*a*) is presented. The long-wavelength anomalies essentially form two continuous zones. The zone of negative gravity anomalies extends along the arc of the mountain belt and includes: Carpathian Foredeep, outer Flysch Belt, the Pieniny Klippen Belt and the northern part of the central Western Carpathians. The zone of positive anomalies includes mainly the southern and eastern territory of Slovakia. Constructed stripped gravity map (M. Bielik, 1988, 1991) — map of Bouguer gravity anomaly corrected for gravity effect of the sedimentary cover — showed increased differences between both zones and proved this relationship.

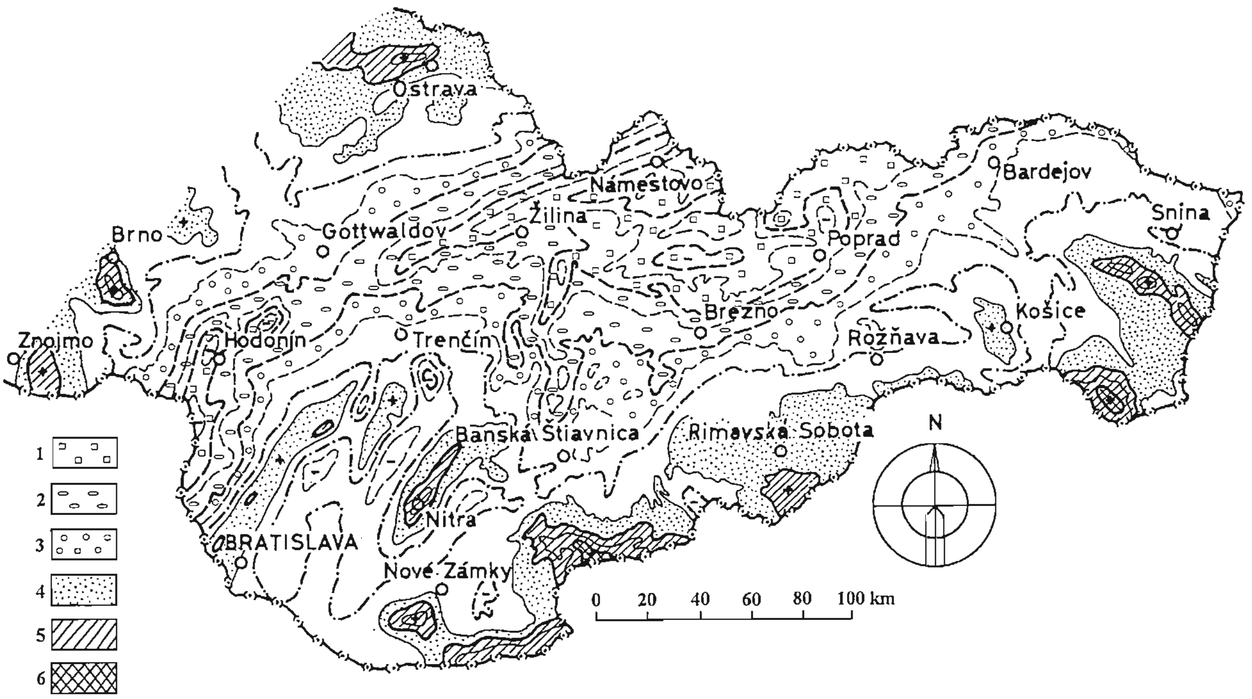

Fig. 10. Sketch of the Bouguer anomaly map of Slovakia (after I. Ibrmajer *et al.*, 1994*a*)

1 — less than –40 mGal; 2 — from –40 to –20 mGal; 3 — from –20 to –10 mGal; 4 — from –10 to 10 mGal; 5 — from 10 to 20 mGal; 6 — more than 20 mGal

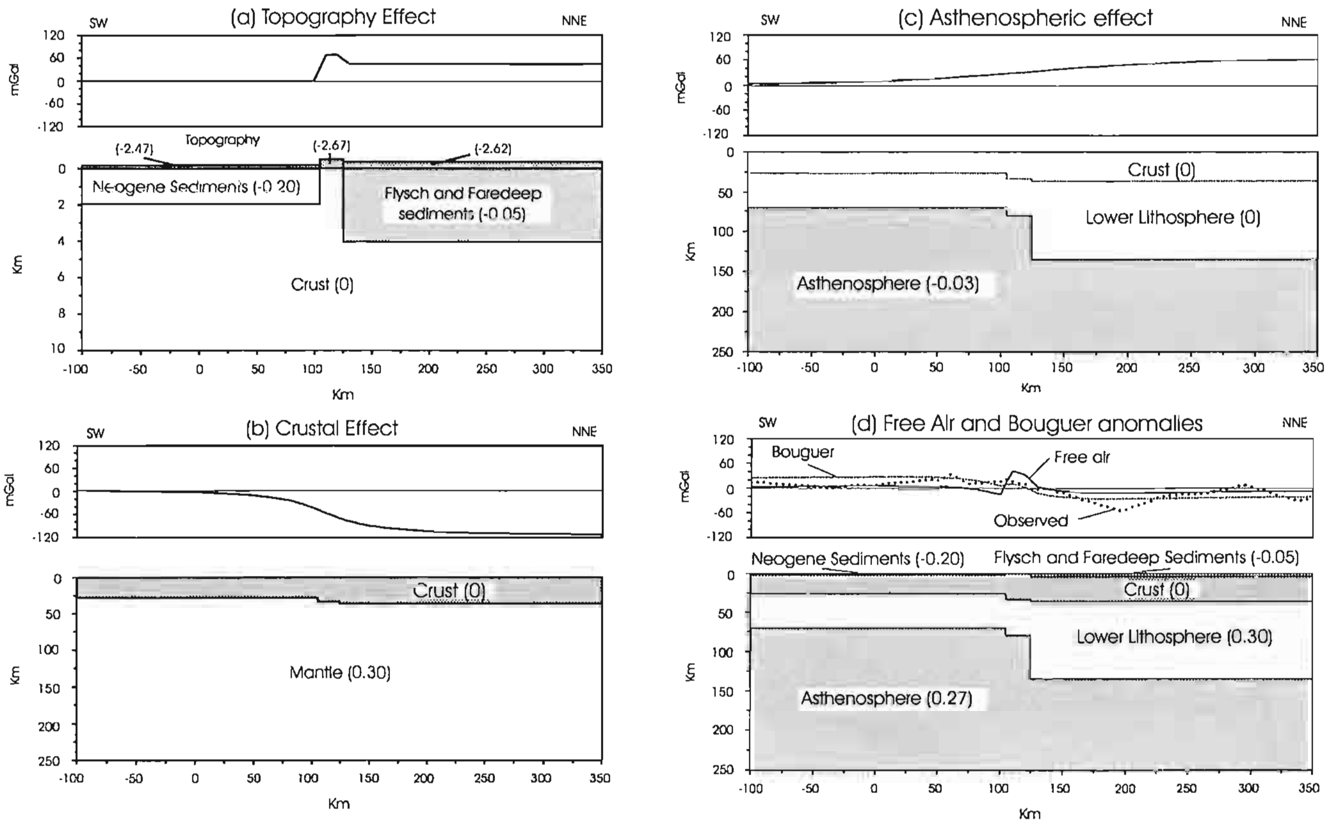

Fig. 11. Model in local isostatic equilibrium (after M. Bielik, 1998) showing gravity contributions from different level

The anomaly due to the topography (a), crustal thickness (b) and the lithosphere-asthenosphere boundary (c); free air gravity anomaly (d) calculated by summing the three components; for this model a Bouguer reduction densities of -2.67 gcm^{-3} for crust, -2.47 gcm^{-3} for Neogene sediments, -2.62 gcm^{-3} for outer flysch and molasse sediments remove the effect of topography, resulting in a Bouguer anomaly which is similar to the observed Bouguer anomaly in the studied area; the depth of compensation is 250 km; density contrasts are in gcm^{-3}

LOCAL ISOSTASY

Available tool for a study and analysis of observed gravity anomalies is a calculation of a simple density models in local isostatic equilibrium (R. J. Lillie *et al.*, 1994; M. Bielik, 1998; M. Bielik *et al.*, 1995, 1998). This approach also provides a possibility to calculate the contributions of these main anomalous zones to the free-air and Bouguer anomalies. Density models take into consideration topography, gravity and density data together with thickness of the main anomalous layers in the lithosphere. Mostly they are represented by young sediments, mantle part of the lithosphere and asthenosphere.

On the basis of density modelling in local isostatic equilibrium the density contrast between asthenosphere and lower lithosphere of -0.03 gcm^{-3} for the Alpine-Carpathian–Pannonian region was determined (R. J. Lillie *et al.*, 1994). This density contrast results in local isostasy for approximately 9 km shallowing of the Moho and 60 km shallowing of the lithosphere-asthenosphere boundary in the Pannonian region against the Alpine-Carpathian mountain belt.

Density modelling in local isostasy was carried out along profile KP-X (M. Bielik, 1998). This profile is passing through important area of the Western and Eastern Carpathian junction (Fig. 1). Four anomalous bodies and their density contrasts (Fig. 11) relative to "typical crust" (after R. J. Lillie *et al.*, 1994) are considered: (1) Neogene sediments of the East Slovakian Basin and the Pannonian Basin (-0.20 gcm^{-3});

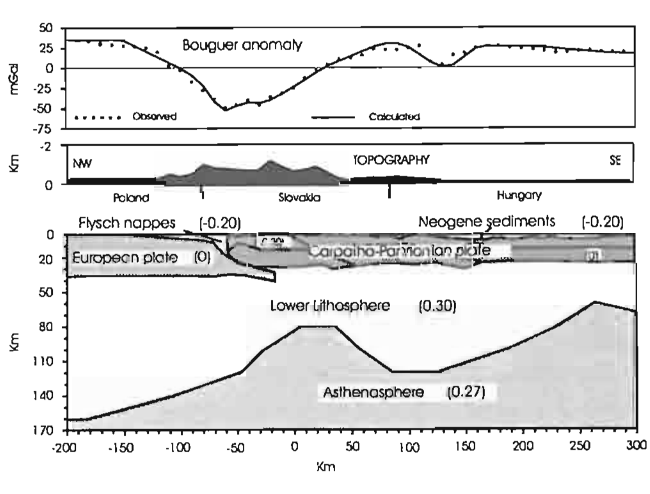

Fig. 12. Two-dimensional density model of the lithosphere along the transect 2T (according to M. Bielik, 1995*b*)

Density contrasts are in gcm^{-3}

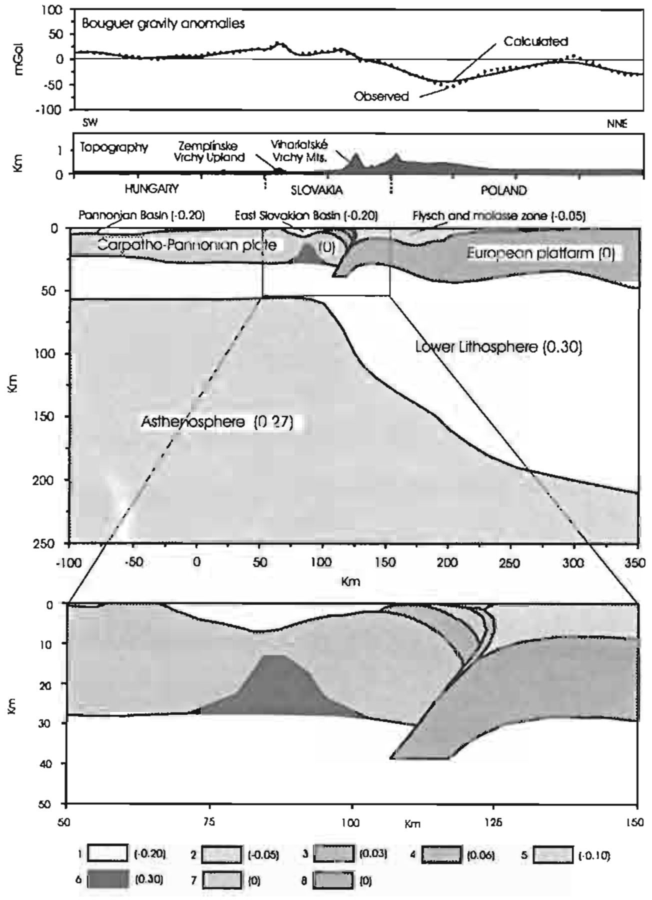

Fig. 13. Two-dimensional density model of the lithosphere along the transect KP-X

1 — Neogene sediments; 2 — Carpathian Flysch Belt and molasse foredeep sediments; 3 — Pieniny Klippen Belt; 4 — Mesozoic of the Humenské Vrchy Upland; 5 — Neogene volcanics; 6 — high-density anomalous body; 7 — Carpatho-Pannonian plate; 8 — European platform; density contrasts are in gcm^{-3}

(2) flysch and foredeep sediments of the Carpathian Foreland (–0.05 gcm^{-3}); (3) mantle part of the lithosphere (0.30 gcm^{-3}); (4) asthenosphere (0.27 gcm^{-3}).

Density contrasts for topographics relief relative to air are as follows: –2.67 gcm^{-3} for crust, –2.47 gcm^{-3} for Neogene sediments, and –2.62 gcm^{-3} for flysch and molasse sediments. The three mean topographic data are: (1) 0.2 km for the East Slovakian Basin and the Pannonian Basin; (2) 0.6 km for the contact zone between the externides and internides of the Western Carpathians (Carpathian collision region); (3) 0.4 km for the region of the Outer Carpathian Flysch Belt and molasse foredeep. The reference level for local isostatic equilibrium is at 250 km depth.

The above density contrasts between crust and upper mantle and lower lithosphere and asthenosphere result in isostatic equilibrium (Fig. 11d) for an approximately 10 km deeping of Moho (Fig. 11b) and about 70 km deeping of the lithosphere-asthenosphere boundary from the Pannonian Basin to the European Platform (Fig. 11c). Contribution of the Moho (Fig. 11b) is not fully compensated by the sediments and its topography (Fig. 11a). The compensation is about a half. For the second part of compensation it is necessary to take into account the gravity effect of the lithosphere-asthenosphere boundary (Fig. 11c). The resulting free-air and Bouguer anomalies are composed of added of gravity effects of all anomalous zones. It follows from the analysis that in spite of rough approximation of the crustal and lithospheric geometry the calculated Bouguer anomaly fits relatively well with the observed gravity effect.

INTERPRETATION OF THE WESTERN CARPATHIAN LITHOSPHERE

For a perspective of the current structure of the lithosphere in the Slovak part of the Western Carpathians two lithospheric density models (Figs. 12, 13) were calculated along deep reflection seismic transect 2T (M. Bielik, 1995*b*) and KP-X (M. Bielik, 1998). The transect 2T crosses the central part of the Western Carpathians (Fig. 1). The initial structural density models were constructed on the basis of published geophysical and geological data. The principal geophysical methods which were used are: refraction and reflection seismic profiling, gravimetry, magnetometry, magnetotellurics, geotermics and boreholes. The trial and error method and 2 1/2 D foward gravity modelling, using the GM-SYS set of programms were applied for calculation of density models.

The results of density modelling were used for interpretation of other geophysical data (V. Bezák *et al.*, 1997; J. Šefara *et al.*, 1996). The chosen results include geophysical model along profile KP-X (Fig. 14), which illustrates density and magnetic boundaries, low resistivity and low velocity zones interpreted from seismic and magnetotelluric soundings, calculated Curie isograde (575°C), upper-lower crustal boundary and lithosphere-asthenosphere boundary. The geological interpretation of the lithosphere structure and its kinematics (J. Šefara *et al.*, 1996; V. Bezák *et al.*, 1997) are presented on Figure 15.

In the last years a study of rheology of the lithosphere in the Western Carpathians has brought a new insight into the mechanical properties of the continental lithosphere (M. Bielik, 1995*a*; P. Krzywiec, P. Jochym, 1997; A. C. Lankreijer, 1998; A. Lankreijer *et al.*, in print). Based on extrapolation of failure criteria, lithology and temperature models the rheology of the lithosphere for several sections through the Western Carpathians and surrounding regions was predicted (A. Lankreijer *et al.*, in print). Selected results presented in this paper will show rheological cross-section along transect 2T (Fig. 16).

RESULTS AND DISCUSSION

The results demonstrate that the present day structure of the lithosphere in the Slovak part of the Western Carpathians is a result of the continental collision between European and Carpatho-Pannonian plates. Density modelling indicates the

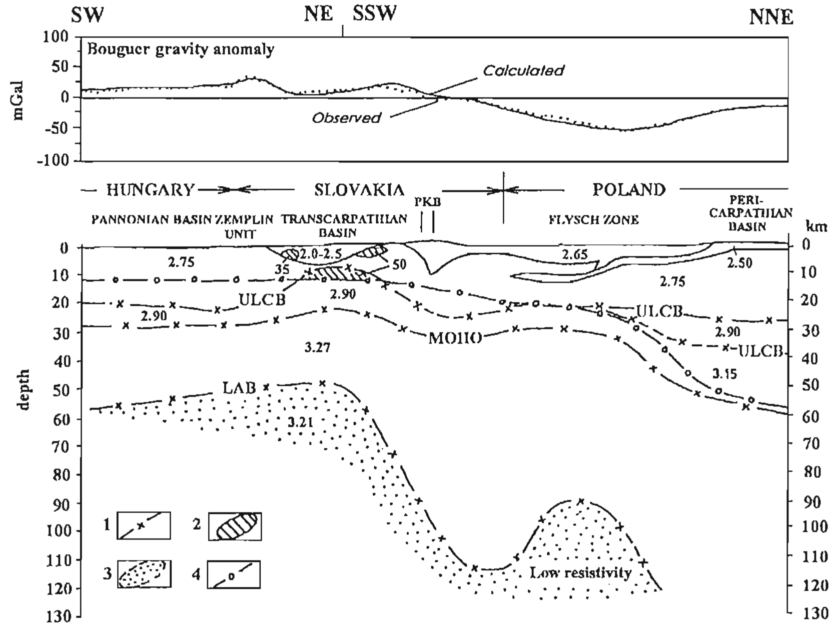

Fig. 14. Geophysical model of the lithosphere along the transect KP-X (modified according to V. Bezák *et al.*, 1997)

1 — density boundaries (numbers — absolute densities in gcm^{-3}); 2 — magnetic bodies (units are in 10^{-3} SI); 3 — low resistivity layers from magnetotelluric soundings (after V. Červ *et al.*, 1994; G. Varga, F. Lada, 1988); 4 — Curie isograde (575°C); PKB — Pieniny Klippen Belt; LAB — lithosphere-asthenosphere boundary (modified after V. Babuška *et al.*, 1987; F. Horváth, 1993); ULCB — upper-lower crust boundary; vertical and horizontal scales are the same

crustal slab-like structure under the Western and Eastern Carpathian junction area dipping beneath the overthrusted plate. The existence of the crustal slab in the central part of the Western Carpathians is questionable. P. Szafián *et al.* (1997) suggest that the subducted slab in this region has been detached and sunk into the deeper asthenophere or has been heated up and largely assimilated to the surrounding asthenosphere. On the other hand an expressionless slab of crust can

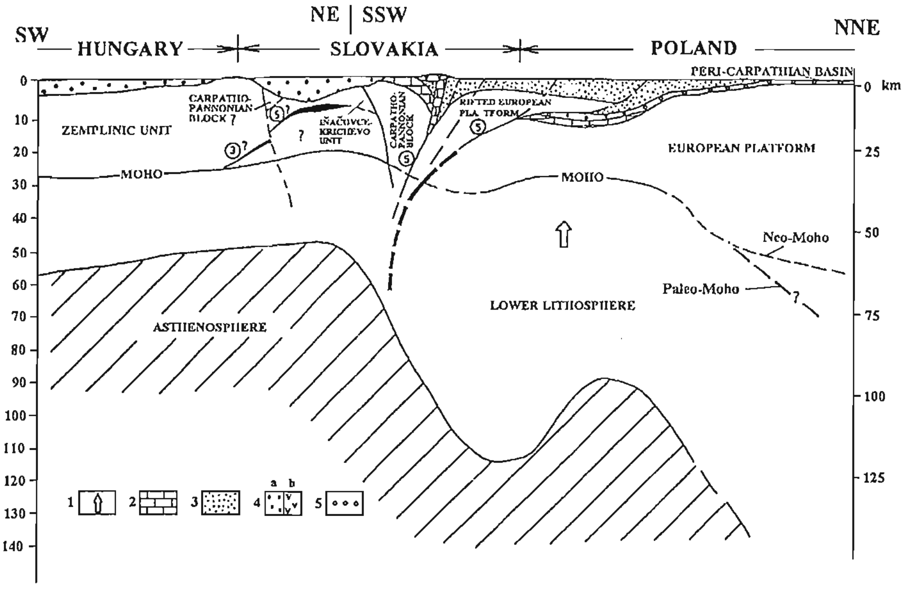

Fig. 15. Geological model of the lithosphere along the transect KP-X (modified according to V. Bezák *et al.*, 1997)

3, 5 — remnants of proposed sutures: 3 — Jurassic, 5 — Tertiary sediments of peri-Carpathian basin; 1 — updoming; 2 — Mesozoic; 4: a — Neogene, b — neovolcanics

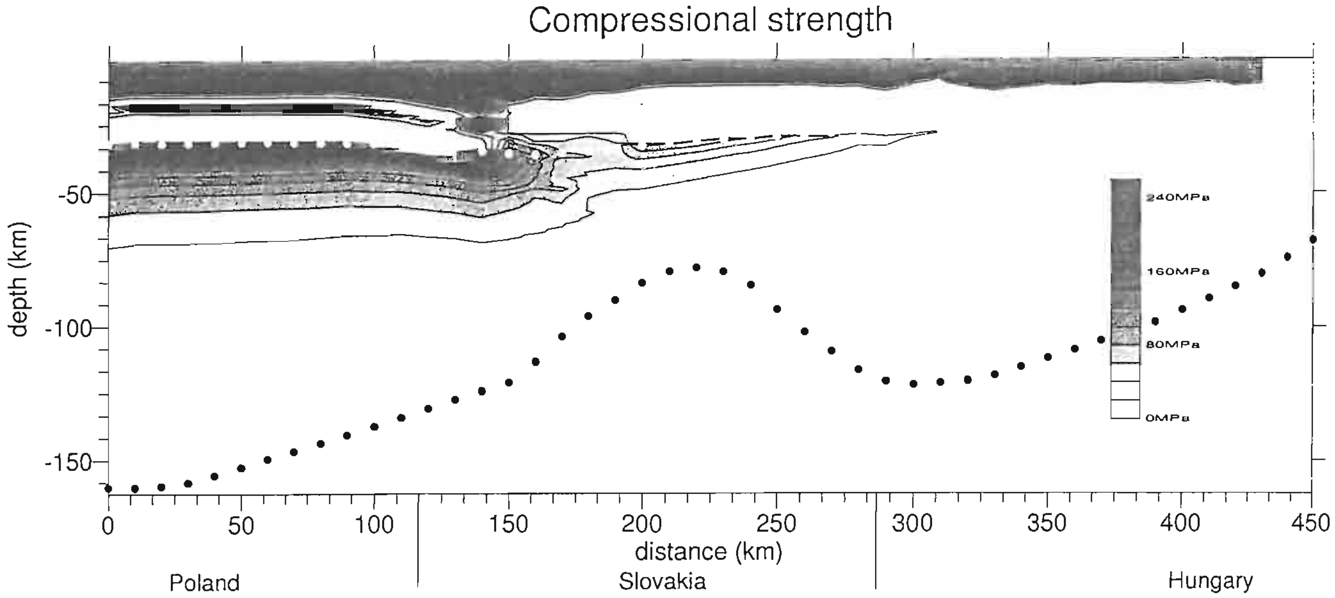

Fig. 16. Rheological cross-section along the transect 2T (after A. Lankreijer *et al.*, in print)

Yield-strength contour plot for compressional deformation, at a strainrate of $\varepsilon = 10^{-15}s^{-1}$; Moho and lithosphere-asthenosphere boundary (after M. Bielik *et al.*, 1995) is indicated by light grey and black dots, respectively

be modelled (Fig. 12). It is very probable that during initial stage of subduction the slab submerged into the deeper parts of the lower lithosphere and asthenosphere. During subduction the slab in oceanic form resulted in melting of andesite magma at a depth of about 150 km. It is speculated that modelled crustal slab would be a remnant after breaking and submerging of the subducted plate. The margin of the European basement bends down into the Carpathian subduction system. This result is in accordance with deep seismic reflection profiling. Probably, due to the rollback effect the slope of the underthrusted lower European Platform is very steep.

The high-density anomalous bodies were necessary to interpret within the lower crust in the Danube Basin and the East Slovakian Basin, where they were also found out by magnetic modelling (P. Kubeš, 1997 — not published). The anomalous body in the East Slovakian Basin correlates with so-called Iňačovce–Krichevo unit defined by J. Soták *et al.* (1995). L. Pospíšil (1980) explained these anomalous bodies by a suture associated with basic and ultrabasic rocks and/or a diapiric intrusion of the upper mantle material into the lower crust. J. Soták (in: M. Bielik *et al.*, 1998) suggests that it could represent a detached part of an older and shallower subducted plate, when its higher crustal position is a result of the tectonic exhumation and extensional unroofing. Similar geodynamic scenario was suggested by Č. Tomek *et al.* (1997) for the Danube Basin.

In the Slovak Western Carpathians the remnants of suture zones were also interpreted (V. Bezák *et al.*, 1997). In generaly, five remnants of sutures were interpreted: Palaeo-Hercynian, Neo-Hercynian, Jurassic (Meliata), Cretaceous (Tatric or Pieninic) and Tertiary.

For the Western Carpathians (Fig. 15) a general decrease in strenght from the Polish Foreland arc *via* the Western Carpathians towards the Pannonian Basin is predicted. In the Polish Foreland area mechanically strong behaviour is predicted for the upper part of the upper crust, the uppermost parts of the lower crust and mantle. The weak lower part of the upper crust is predicted as the most obvious detachment level. In the Western Carpathians lower crustal strenght completely disappears as a results of the crustal thickening and increased crustal temperatures. The lithospheric strength gradually decreases towards SE along this profile. This is a result of the increasing temperatures and decrease of the (thermaly defined) lithospheric thickness. The Pannonian rheological structure is characterized by one relatively thin strong layer in the uppermost 10–15 km of the crust and complete absence of strength in the lower crust and lower lithosphere. The extreme weakness of the lithosphere is a direct result of the high heat flow density and extremely shallow asthenosphere in the Pannonian Basin (A. Lankreijer *et al.*, in print).

The results also indicate that the Western Carpathians are very complicated geological area in which interaction of compression, strike-slip and extension can be observed. Immediately after cessation of subduction processes intensive processes of transpression started. These transpressional processes result in significant relocation of the crustal fragments of different palaeotectonic units. In the last stage of evolution this interplay led to the extensional processes in hinterland accompanied by tectonic exhumation of high-density and magnetic anomalous masses into the lower crust.

Acknowledgements. The author is grateful to the VEGA (grant no. 2/4047/98) for the partial support of this study. Nestor Oszczypko provided comments that helped to improve the original manuscript.

REFERENCES

ANDRUSOV D. (1968) — Grundriss der Tektonik der Nördlichen Karpaten. Vyd. Slov. Akad. Vied. Bratislava.

BABUŠKA V., PLOMEROVÁ J., PETR V., PĚČOVÁ J., PRAUS O. (1994) — Contribution of the MTS to the study of lithosphere in Central Europe. In: Crustal structure of the Bohemian Massif and the West Carpathians (eds. V. Bucha, M. Blížkovský): 157–160. Springer-Verlag. Praha–Heidelberg.

BABUŠKA V., PLOMEROVÁ J., ŠÍLENÝ J. (1987) — Structural model of the subcrustal lithosphere in Central Europe. In: Composition, structure and evolution of the lithosphere-asthenosphere system (eds. K. Fuchs, C. Froidevaux). AGU Geodyn. Ser., **16**: 239–251.

BEZÁK V., ŠEFARA J., BIELIK M., KUBEŠ P. (1997) — Models of the Western Carpathian lithosphere. In: Paleozoic geodynamic domains and their Alpidic evolution in the Thetys (eds. P. Grecula *et al.*): 25–34. Miner. Slov. Corpor.-Geocomplex, a.s., Geofyzika Bratislava and Geological Survey of Slovak Republic. Bratislava.

BIELIK M. (1988) — Analysis of the stripped gravity map of the Pannonian basin. Geol. Carpath., **39**: 99–108.

BIELIK M. (1991) — Density modelling of the Earths's crust in the intra-Carpathian basins. In: Geodynamic evolution of the Pannonian basin: 123–132. SASA. Beograd.

BIELIK M. (1995*a*) — Estimation of the effective elastic thickness and flexure rigidity in the Western Carpathians. Contr. Geophys. Inst. Slov. Acad. Sc., **25**: 81–93.

BIELIK M. (1995*b*) — Continental convergence in the Carpathian region by density modelling. Geol. Carpath., **46**: 3–12.

BIELIK M. (1998) — Analysis of the gravity field in the western and eastern Carpathian junction area: density modelling. Geol. Carpath., **49**: 75–83.

BIELIK M., DYRELIUS D., LILLIE R. J. (1995) — Caledonian lithosphere — gravity structure and comparison with Carpathian lithosphere. Contr. Geophys. Inst. Slov. Acad. Sc., **26**: 72–84.

BIELIK M., MOCANU V. (1998) — Deep lithospheric structure of the Eastern Carpathians: density modelling. Contr. Geophys. Geodesy, **29**: 95–100.

BIELIK M., SOTÁK J., ŠEFARA J., BEZÁK V. (1998)— Lithosphere structure in the west Carpathian-Pannonian-east Carpathian triple junction area based on geophysical data. Ann. Geophys., Part I, EGS, **16**: C110.

BIELY A., BEZÁK V., ELEČKO M., KALIČIAK M., KONEČNÝ V., LEXA J., MELLO J., NEMČOK J., POTFAJ M., RAKÚS M., VASS D., VOZÁR J., VOZÁROVÁ A. (1996) — Geological Map of Slovakia. MŽP SR–GS SR. Bratislava.

BLÍŽKOVSKÝ M., IBRMAJER I., NOVOTNÝ A., SUK M., ŠEFARA J. (1994) — Explanation of the main gravity structures in the Czechoslovak territory and in its close vicinity. In: Crustal structure of the Bohemian Massif and the West Carpathians (eds. V. Bucha, M. Blížkovský): 174–177. Springer-Verlag. Praha–Heidelberg.

BUCHA V., BLÍŽKOVSKÝ M. eds. (1994) — Crustal structure of the Bohemian Massif and the West Carpathians. Springer-Verlag. Praha–Heidelberg.

ČERMÁK V., KRÁL M., KUBÍK J., ŠAFANDA J., KREŠL M., KUFEROVÁ L., JANČÍ J., LIZO I., MARUŠIAK I. (1992) — Subsurface temperature and heat flow density maps on the territory of the Czechoslovakia. In: Geothermal Atlas of Europe (eds. V. Hurtig, V. Čermák): 21–24. Gotha.

ČERV V., PEK J., PÍCHA B., PRAUS O., TOBIÁŠOVÁ M. (1994) — Magnetotelluric models of inhomogenity zones. In: Crustal structure of the Bohemian Massif and the West Carpathians (eds. V. Bucha, M. Blížkovský): 147–157. Springer-Verlag. Praha–Heidelberg.

FILO M., KUBEŠ P. (1994) — Geologic interpretation of the geomagnetic anomalies in the Western Carpahians. In: Crustal structure of the Bohemian Massif and the West Carpathians (eds. V. Bucha, M. Blížkovský): 200–206. Springer-Verlag. Praha–Heidelberg.

FUSÁN O., BIELY A., IBRMAJER I., PLANČÁR J., ROZLOŽNÍK L. (1987) — Podložie terciéru vnútorných Západných Karpát (in Slovak with English summary). Monogr. GÚDŠ. Bratislava.

GUTERCH A., GRAD M., MATERZOK R., PAJCHEL J., PERCHUĆ E., TOPORKIEWICZ S. (1984) — Deep structure of the Earth's crust in the contact zone of the Paleozoic and Precambrian Platforms and the Carpathian Mts. in Poland. Acta Geophys. Pol., **32**: 25–41.

GUTERCH A., GRAD M., MATERZOK R., PERCHUĆ E. (1986) — Deep structure of the Earth's crust in the contact zone of the Paleozoic and Precambrian Platform in Poland (Teisseyre-Tornquist zone). Tectonophysics, **128**: 251–279.

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

IBRMAJER I. *et al.* (1994*a*) — Geofyzikální obraz ČSSR. Monograph. Academia. Praha.

IBRMAJER I., TOMEK Č., KORÁB T., DVOŘÁKOVÁ L. (1994*b*) — Deep reflection seismic profiling in Czechoslovakia — the ČESLOKORP (Czechoslovak crustal reflection profiling project). In: Crustal structure of the Bohemian Massif and the West Carpathians (eds. V. Bucha, M. Blížkovský): 21–45. Springer-Verlag. Praha–Heidelberg.

KOVÁČ M., BIELIK M., LEXA J., PERESZLÉNYI M., ŠEFARA J., TÚNYI I., VASS D. (1998) — The Western Carpathian intramountane basins. In: Paleozoic geodynamic domains and their Alpidic evolution in the Thetys (eds. P. Grecula *et al.*): 43–64. Miner. Slov. Corpor.-Geocomplex, a.s., Geofyzika Bratislava and Geological Survey of Slovak Republic. Bratislava.

KRS M. (1994) — Palaeomagnetic investigations of the flysch belt of the West Carpathians. In: Crustal structure of the Bohemian Massif and the West Carpathians (eds. V. Bucha, M. Blížkovský): 226–228. Springer-Verlag. Praha–Heidelberg.

KRZYWIEC P., JOCHYM P. (1997) — Characteristics of the Miocene subduction zone of the Polish Carpathians: results of flexural modelling (in Polish with English summary). Prz. Geol., **45** (8): 785–792.

LABÁK P., BROUČEK F. (1996) — Catalogue of macroseismically observed earthquakes on the territory of Slovakia (Version 1996) (manuscript). Geophys. Inst. Slov. Acad. Sc. Bratislava.

LANKREIJER A. C. (1998) — Rheology and basement control on extensional basin evolution in Central and Eastern Europe: Variscan and Alpine-Carpathian-Pannonian tectonics. Ph.D. thesis. Vrije Universiteit.

LANKREIJER A., BIELIK M., CLOETINGH S., MAJCIN D. (in print) — Rheology predictions across the Western Carpathians, Bohemian massif and the Pannonian basin: implications for tectonic scenarios. Tectonics.

LENKEY L., HORVÁTH F., DÖVÉNYI P., SZAFIÁN P. (1998) — Geophysical features and structural conditions of the Pannonian basin and its surroundings: a review. Reports on Geodesy — The Pannonian Basin, **5**: 11–34.

LILLIE R. J., BIELIK M., BABUŠKA V., PLOMEROVÁ J. (1994) — Gravity modelling of the lithosphere in the Eastern Alpine-Western Carpathian — Pannonian Basin region. Tectonophysics, **231**: 215–235.

MAYEROVÁ M., NOVOTNÝ M., FEJFAR M. (1994) — Deep sesmic sounding in Czechoslovakia. In: Crustal structure of the Bohemian Massif and the West Carpathians (eds. V. Bucha, M. Blížkovský): 13–20. Springer-Verlag. Praha–Heidelberg.

MUŠKA P. (1994*a*) — The Early Palaeozoic of the West Carpathians. In: Crustal structure of the Bohemian Massif and the West Carpathians (eds. V. Bucha, M. Blížkovský): 222–223. Springer-Verlag. Praha–Heidelberg.

MUŠKA P. (1994*b*) — The Late Palaeozoic of the West Carpathians. In: Crustal structure of the Bohemian Massif and the West Carpathians (eds. V. Bucha, M. Blížkovský): 222–225. Springer-Verlag. Praha–Heidelberg.

POSGAY K., BODOGY T., HEGEDÜS E., KOVÁCSVÖLGYI S., LENKEY L., SZAFIÁN P., TAKÁCS E., TÍMÁR Z., VARGA G. (1995) — Asthenospheric structure beneath a Neogene basin in SE Hungary. Tectonophysics, **252**: 467–484.

POSGAY K., TAKÁCS E., SZALAY I. *et al.* (1996) — International deep reflection survey along the Hungarian Geotraverse. Geophys. Transactions, **1–2**: 1–44.

POSPÍŠIL L. (1980) — Interpretation of gravity field in the Eastern Slovak Neogene region. In: Výskum hlvbinné geologické stavby Československa: 59–66. GFOČSAV. Praha-Geofyzika. Brno.

PRAUS O., PĚČOVÁ J., PETR V., BABUŠKA V., PLOMEROVÁ J. (1990) — Magnetotelluric and seismological determination of lithosphere-asthenosphere transition in Central Europe. Phys. Earth Planet. Inter., Amsterdam, **60**: 212–228.

PROCHÁZKOVÁ D., SCHENK V., SCHENKOVÁ Ż. (1994) — Seismicity and seismotectonics. In: Crustal structure of the Bohemian Massif and the West Carpathians (eds. V. Bucha, M. Blížkovský): 63–75. Springer-Verlag. Praha–Heidelberg.

SOTÁK J., BIRO A., KOTULOVÁ J., RUDINEC R., SPIŠIAK J. (1995) — Geological structure of the East Slovakian basin basement in the light of facts and regional tectonic context (in Slovakian with English summary). Miner. Slov., **27**: 1–8.

SPAKMAN W., VAN DER LEE S., VAN DER HILST R. (1993) — Travel-time tomography of the European — Mediterranean mantle down to 1400 km. Phys. Earth Planet. Inter., Amsterdam, **79**: 3–74.

SZAFIÁN P. (1999) — Gravity and tectonics: a case study in the Pannonian Basin and the surrounding mountain belt. NSG Amsterdam, no. 990 112.

SZAFIÁN P., HORVÁTH F., CLOETINGH S. (1997) — Gravity constrains on the crustal structure and slab evolution along a Trans-Carpathian transect. Tectonophysiscs, **272**: 233–247.

ŠEFARA J. (1993) — Deep seated structures and their role during extension in the western part of the Inner Western Carpathians. Terra Abstr., Terra Nova, **5**: 32.

ŠEFARA J., BIELIK M., BODNÁR J. *et al.* (1987) — Structural-tectonical map of the Inner Western Carpathians for the purposes of prognose deposits — geophysical interpretations (in Slovakian). Text to the colection of maps (manuscript). Geofond.

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. Geol. Carpath., **6**: 339–347.

TOMEK Č. (1993) — Deep crustal structure beneath the Central and Inner West Carpathians. Tectonophysics, **226**: 417–431.

TOMEK Č., BIELIK M., SITÁROVÁ A. (1997) — Kolárovo gravity high and its relationship to the Miocene-recent extension of the Danube Basin. Terra Nova, **9**: 159.

TOMEK Č., DVOŘÁKOVÁ L., IBRMAJER I., JIŘÍČEK R., KORÁB T. (1987) — Crustal profiles of active continental collision belt: Czechoslovak deep seismic reflection profiling in the West Carpathians. Geophys. J. R. Astr. Soc., **89**: 383–388.

TOMEK Č., IBRMAJER I., KORÁB T., BIELY A., DVOŘÁKOVÁ L., LEXA J., ZBOŘIL A. (1989) — Crustal structures of the West Carpathians on deep seismic line 2T (in Slovakian with English summary). Miner. Slov., **21**: 3–26.

VARGA G., LADA F. (1988) — Magnetotelluric measurement on the profile 2T (manuscript). ELGI Budapešt', Geofyzika. Brno.

PRZEGLĄD DANYCH GEOFIZYCZNYCH W SŁOWACKIEJ CZĘŚCI KARPAT ZACHODNICH

Streszczenie

Praca poświęcona jest podsumowaniu istotnych wyników badań geofizycznych słowackich Karpat Zachodnich. Obszar ten był przedmiotem intensywnych, szczegółowych pomiarów grawimetrycznych w ostatnich 20 latach, stąd w artykule położono nacisk na interpretację pól grawitacyjnych. Analiza anomalii Bouguera została wykonana na podstawie modelowania gęstości w warunkach lokalnej równowagi izostatycznej oraz na progresywnym modelowaniu gęstości 2 1/2 D. Wyniki modelowania gęstości wraz z innymi danymi geofizycznymi, w tym głównie sejsmicznymi, są punktem wyjścia do geologicznej i geofizycznej interpretacji struktury litosfery na analizowanym obszarze. Przedyskutowano ponadto zagadnienia reologii litosfery na podstawie ekstrapolacji kryteriów zniszczenia, litologii i modeli termicznych.