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THE LATEST STAGE OF DEVELOPMENT OF THE LITHOSPHERE AND ITS INTERACTION WITH THE ASTHENOSPHERE (WESTERN CARPATHIANS)

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Abstract: The latest stage of the development of the Western Carpathian arc and the Pannonian Basin was characterized by a lithospheric disintegration which occurred as a consequence of the transition from a transpressional to an extensional regime. This process was accompanied by both crustal thinning and, what is more important by thinning of the lithosphere. The thinning of the lithosphere was associated with an uplift of asthenospheric, partially molten masses, accompanied by local asthenoliths. This paper discusses the geological features and the development of processes involved in the ascension of partially molted masses into subcrustal levels through the older discontinuities. Geophysical and petrological evidence have shown that the uplift of these local partially molten masses nearly reached the Moho discontinuity. The mantle xenoliths transported to the surface by the youngest alkaline basalts and the study of their phase transition give petrological evidences for this process. Further geophysical indications of this process are seismic and magnetotelluric sounding (MTS) anomalies and geothermal conditions. The interpretation of other seismic profiles with prolonged registration, density and partly geomagnetic modelling have also been used in the interpretation. These data are discussed in the light of present knowledge of the tectonic development of Western Carpathians and the Pannonian Basin.

Key words: Western Carpathians, lithosphere, asthenosphere, geodynamics, geophysical interpretations, mantle xenoliths.

Introduction

A thin crust, reduced to 24–26 km in its apical parts (Fig. 1) is a typical feature of the southern part of the Western Carpathians and the Pannonian Basin area. One reasons for this thinning is an intense geothermal activity, widespread practically throughout the Pannonian area (Fig. 2), which has been caused by an uplift of asthenospheric, partially molten, masses into relatively shallow levels. The model shown in Fig. 3 displays this uplift at depths of approximately 80–60 km. However analysis of the geophysical fields suggests that their local uplift could reach even higher levels.

The diapiric models for the development of the Pannonian area presented by Stegena et al. 1975, McKenzie 1978, Sclater et al. 1980, were later updated using the strike-slip tectonics (Royden et al. 1989; Horvath & Royden 1981 etc.). Horvath (1993) used this model for the whole crustal detachment fault, running through the Danube Basin and the Makó Basin areas.

There are some new geophysical data, which throw light on the relation between the lithosphere and the asthenosphere in both regions, the Western Carpathians and the Panonian Basin. In this work we attempt to interpret these data as well as the complicated structure of the lithosphere-asthenosphere boundary which developed in the studied area as a consequence of younger and older tectonic processes.

The Earth's crust in the Carpathian-Pannonian area

There are indications that the Moho discontinuity is characterized by a distinct flexibility, related predominantly to the thermal conditions at depth. Seismic sections exist (e.g. Tomek & Hall 1993) at places with pronounced reflections, which accompany the Moho and are oblique to the reflections situated either above, or below the Moho. On the other hand sections also exist (e.g. Tomek et al. 1989) characterized by an absence of distinct reflection from the Moho. These results indicate a general non-horizontal trend of material (phase) changes which accompany this boundary including transitional zones of variable thicknesses in some case reaching up to several kilometers.

The Moho was reinterpreted for the territory of the Western Carpathians on the basis of new data obtained from the seismic reflection profiles with prolongated registration, also taking into account the qualitative and quantitative analysis of the stripped gravity map (Šefara 1993), especially of its western part, characterized by a remarkable decrease of the crustal thickness towards the Outer Carpathians (Fig. 1).

This area, especially the southern part of the Danube Basin, is accompanied by an increased heat flow density (Fig. 2), which continues as far north as the Hercynian region of the North European Platform, and correlates with an elevated Moho.

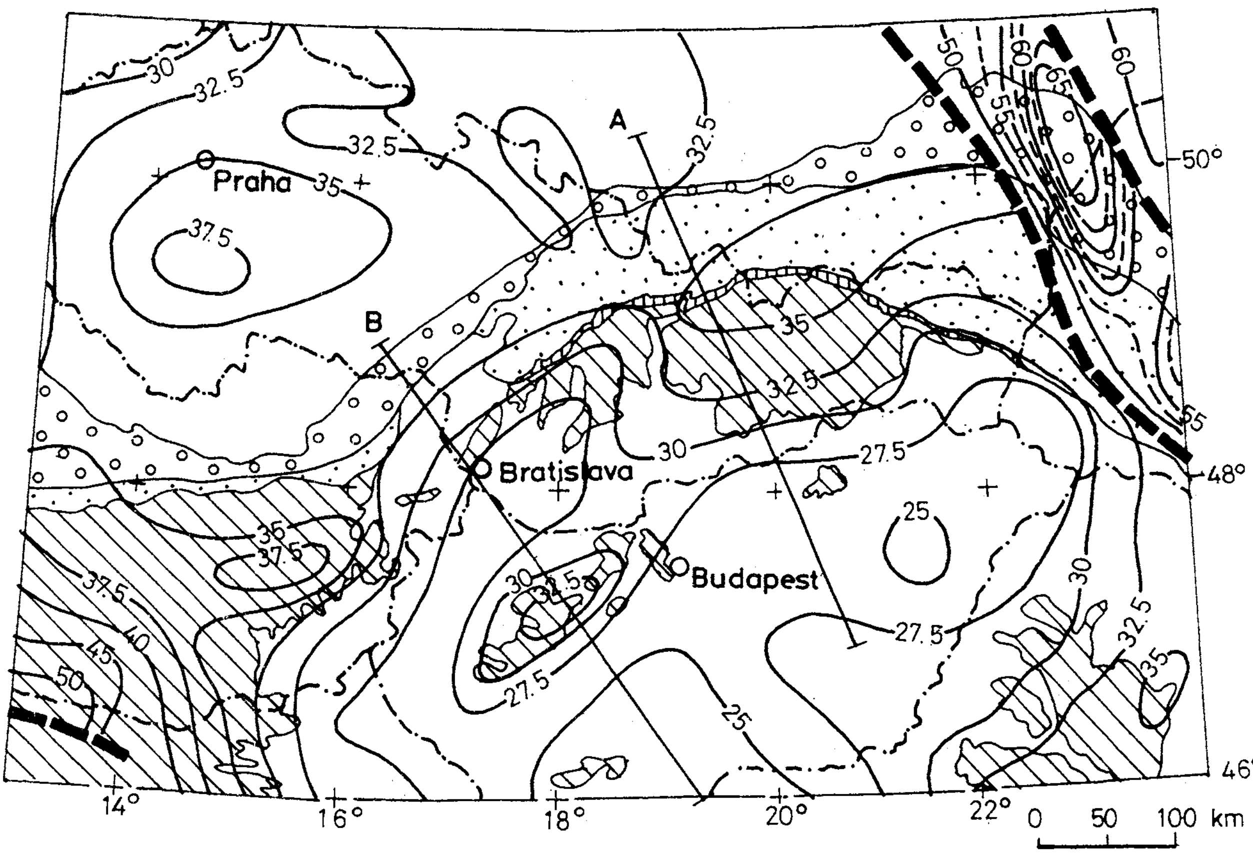

Fig. 1. Map of the thickness of the Earth's crust in the Western Carpathians and their vicinity. The thickness is given in km. The thick short lines indicate significant changes in the course of the crust thickness. Modified according to Horvath (1993) and Šefara (1993). The foundation is created by simplified geological-tectonic map showing the outer molasse (circles), outer Carpathian flysch (points), Klippen Belt (vertical lines) and pre-Neogene units (oblique lines). Internal basins including neovolcanites are not distinguished, as well as all units of the Alpine-Carpathian foreland. A, B interpreted profiles (Figs. 6 and 7).

This remarkable crustal feature could be explained by a mechanism of a later (probably younger than Lower Badenian) crustal extension, which followed the diagonal collision as soon as the transpressional processes in its hinterland ceased. Actually a similar process is applicable for the Eastern Slovak Basin in spite of the fact that the dependency of the Moho's elevation on the geothermal conditions may be different.

The lithosphere-asthenosphere boundary

The data related to the boundary between the lithosphere and asthenosphere and its course were obtained from two sources. The first data refer to the delay time of seismic waves (Babuška et al. 1984, 1994; Spakman et al. 1990, 1993 etc.) and their interpretation using various models for the low velocity horizons. The second source are the results of MTS (Červ et al. 1994; Praus et al. 1990, 1994; Ádam et al. 1990; Varga et al. 1993 etc.). Considerable decreases of resistivity (increase of conductivity) at depths, comparable to those of the zones of low velocity, may then be identified with the asthenosphere, or with its local uplifts (diapir style ?).

Low velocity zones

Any concept designed to outline the boundary between lithosphere and asthenosphere can be influenced by two circumstances. The first is the density of observations. If it is insufficient it will only permit the drawing of schematic boundaries. The density of observations depends mainly on the distribution of seismic stations, which register the delays of the seismic waves. The second circumstance implies an apriori model, used to invert the geophysical anomaly into a preconceived geological form.

Babuška et al. (1990, 1994) interpreted the seismic waves delay as a boundary with a relatively smooth outline. The ambiguous interpretation of this approach results from meagre data on one hand and the high standard deviation of registered seismic wave delays on the other. A typical example is the NE part of the Pannonian area. The lithosphere-asthenosphere boundary has been inferred at a depth of more than 100 km (Babuška et al. 1984) on the basis of two residual data (-0.04 ± 0.20 and -0.02 ± 0.36 s respectively). Unlike Horvath (1993) we presume that this phenomenon can be interpreted as a distinct directional anisotrophy of the upper mantle and/or asthenosphere which originates quasi vertical and considerably elongated beds with

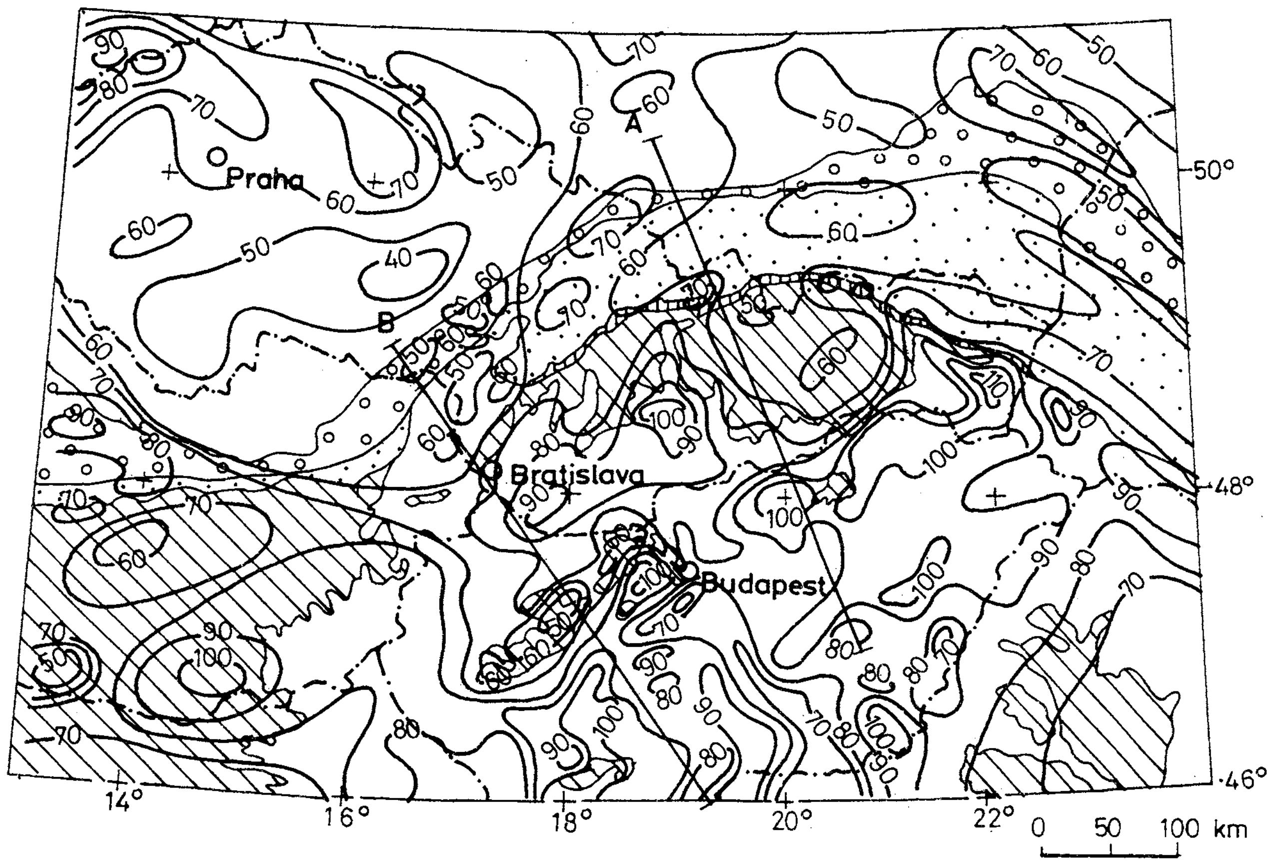

Fig. 2. Map of the heat flow density of the Western Carpathians and their vicinity. Contours are given in mWm^{-2}. According to Čermák et al. (1992) in Slovakia according to Janči (1994 — not published), modified. Other comments see Fig. 1.

higher and lower velocity. The phenomenon of considerably increased standard deviation can also be observed in other areas (e.g. Friuli Zone, station Zagreb). The above mentioned presumption valid for the NE part of the Pannonian Basin, suits the type of inhomogeneities, defined by MTS. Thus both methods of identifying the lithosphere-asthenosphere boundary (Babuška et al. 1984; Horvath 1993) are problematic.

Spakman et al. (1993) applies a 3D model to project the velocity of seismic waves. Although it lacks details of surface structures, it gives a reasonable picture of the subduction relicts within the Alpine-Carpathian lithosphere approximately down to the depth of 200 km. These indications of the relicts of subducting plates do not resemble the others (e.g. from Aegean Sea), which are usually very steep, or almost vertical and reach shallow levels. Velocity deviations occur above these relicts (from the standpoint of a mountain belt on the internal side), which would shift the zone of low velocity (asthenosphere) from the reference depth of 145-247 km (model PM2) to a depth an order lower (some 50 km).

Zones of high conductivity

The electric conductivity measurements are concentrated mainly within the Danube and Vienna Basins. Similarly the information on the conductivity zones is distributed irregularly. Moreover, many of the used methods (Varga & Lada 1988; Varga et al. 1993 etc.) unable us to reach the presumed lower boundary of the lithosphere. In spite of this fact these measurements unequivocally indicate that the zones of high conductivity are situated in the upper mantle.

Several anomalous conductive horizonts (Červ et al. 1994; Bucha et al. 1994) can be distinguished throughout the lithosphere. The zone situated below the Moho at a depth of approximately 40 km, separated from the original lithosphere-asthenosphere boundary of approximately 100-150 km, seems to be the most interesting (in the sense of original concept). The same type of conductive zone (Varga & Lada 1988), was also registered in the profile 2T (Tomek et al. 1989, 1993; Pospíšil et al. 1992).

We presume that the zones of very low resistivity in the profile A (Fig. 6) represent the asthenospheric masses with signs of partial melting. They can be identified with conduits of the latest neovolcanic rocks — basalts, which are practically independent from the subduction zones.

Indications of an upper mantle diapir in Southern Slovakia

The products of alkaline-basaltic volcanism (Fig. 4) are widespread in the Cerová vrchovina Upland of Southern Slovakia. Several lava flows contain the mantle ultramafic xenoliths that offer some information on the structure and the state of the upper mantle masses. The xenoliths have mostly the composition of spinel lherzolites, however, rare harzburgites, wehrlites and dunites also occur.

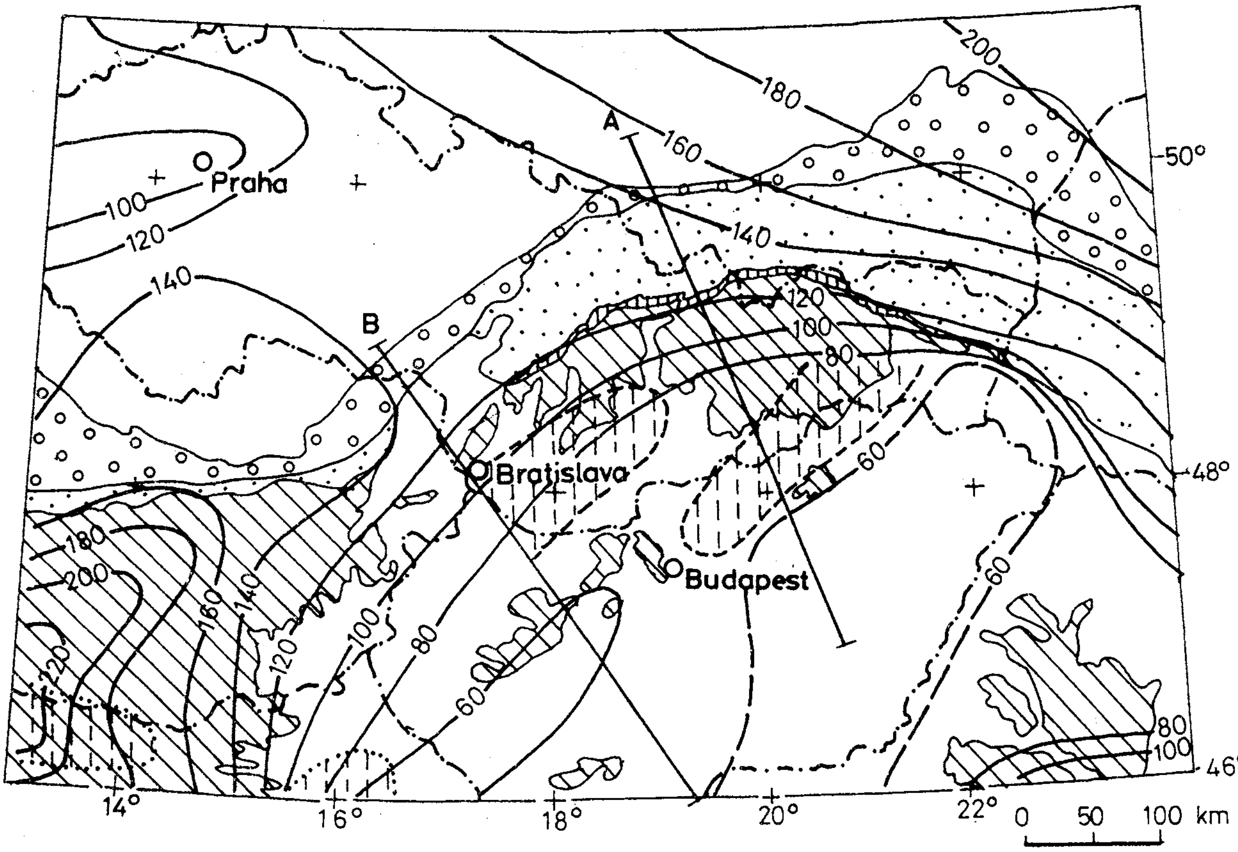

Fig. 3. Map of the lithospheric thickness of the Western Carpathians and their vicinity. Modified according to various authors mentioned in Horvath (1993). Areas marked with dashed lines have considerable uncertainity in determination of this boundary, including several possible separated environment, situated one above another. Other comments see Fig. 1.

In mineralogical terms, the lherzolites are composed of olivine, orthopyroxene, clinopyroxene and spinel. Owing to the variations in physical conditions in the upper mantle the equilibria among minerals have also changed, which is mainly due to the diffusion, or recrystallization. The structure of lherzolites also adapts to these changes. As a result of pressure originally protogranular texture is converted into a porphyroclastic one. Progressive deformation results in formation of equigranular structure and final intensive recrystallization gives rise to a secondary protogranular texture.

Vertical ascension of the upper mantle masses is assumed to have occurred in the southern part of the Cerová vrchovina Upland (Huraiová & Konečný 1994) in the form of a small scale upper mantle diapir. The distribution of the deformed xenoliths provides information on the location of such diapirs (Nicolas et al. 1987). Intensively deformed xenoliths in the centre of the upwelled area, should be surrounded by protogranular xenoliths. The most tectonized xenoliths in the Cerová vrchovina Upland occur at the Mačacia locality, thus, the centre of the diapir should be located near the Stará Bašta and Medvedia výšina (Fig. 4).

The pressures and the temperatures for the spinel lherzolite four-phase mineral assemblage have been calculated using the methods of Köhler & Brey (1990) and Brey & Köhler (1990). The xenoliths were torn out from various depths, therefore the P-T conditions for individual xenoliths give the geothermal gradient for the upper mantle. Fig. 5 shows the geotherms for the thick continental crust as well as for the provinces with alkaline-basaltic volcanism. In analogy to South Australia (O'Reilly & Griffin 1985), characterized by the high heat flow we can expect similar geotherm courses in Southern Slovakia. However the geotherm reminds rather an adiabatic uplift of the upper mantle masses, which also confirms the upper mantle situation.

The updoming of the upper mantle is also indicated by the paleorelief change and by basaltic volcanism. Konečný et al. (1996) used K/Ar radiometric data to reconstruct the basaltic volcanism in time and space. Initial manifestations dating back to the Pannonian-Pontian occur outside the Cerová vrchovina Upland. The gradual updoming of the mentioned area spanned the time from Pliocene to Lower Pleistocene. Simultaneously with updoming the volcanic activity first broke out in the central part and gradually moved outwards, while that in the centre continued only to a limited extent. The updoming is documented by radial distribution of the lava flows and by intense erosion in the updoming centre (diatrems as maar remains, lava necks etc.). The height of updoming, deduced from the height difference of the lava flows bases in the middle and outside updoming, has been estimated to range from 350 to 400 m.

Geotectonic aspects of lithosphere and asthenosphere interaction

Dewey's model (Dewey et al. 1989; Royden 1993) of oblique collision seems to be applicable for the plate interac-

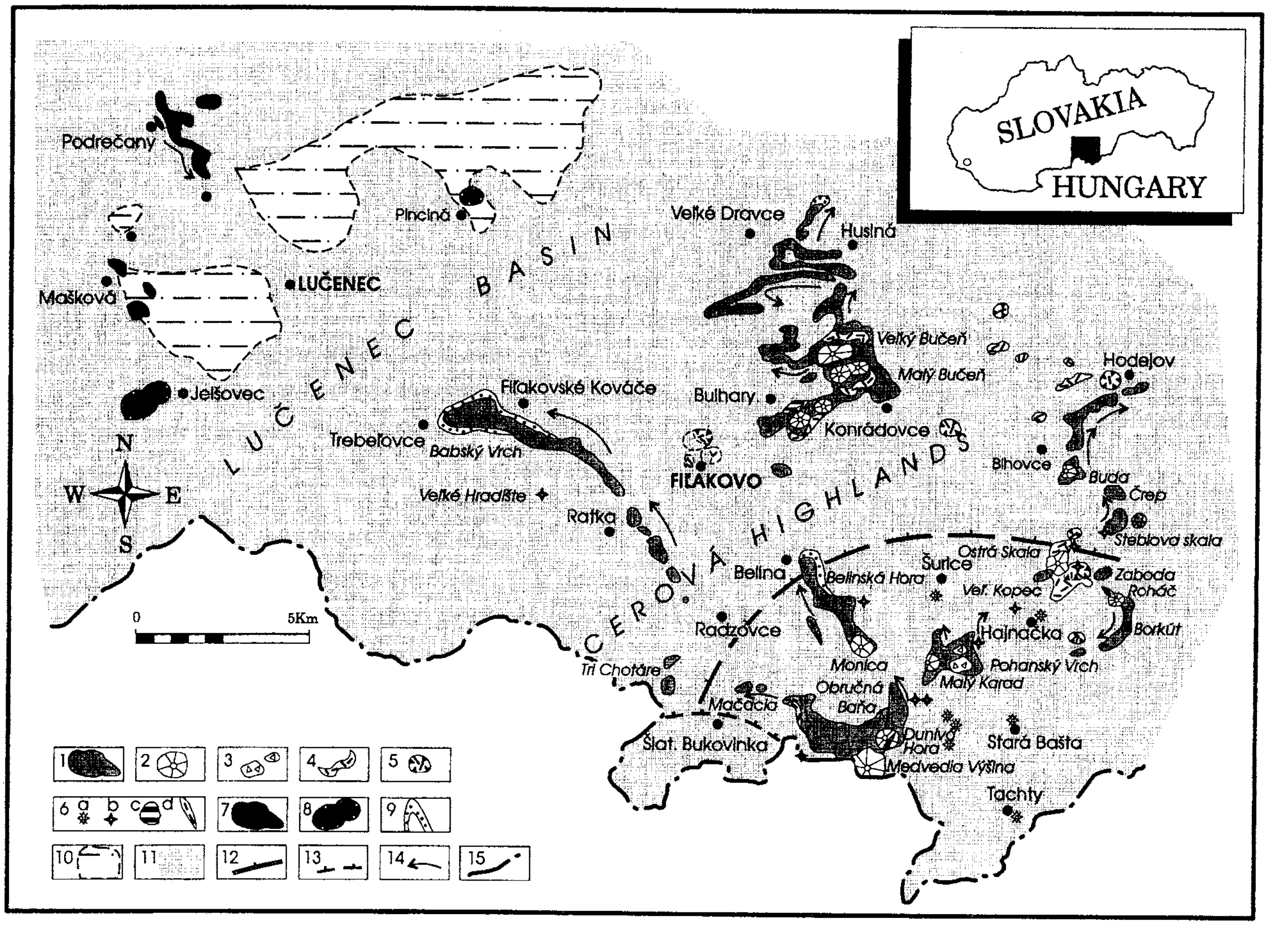

Fig. 4. Distribution of products of alkali basalt volcanism of Southern Slovakia. **Cerová Formation** (Middle Pliocene-Pleistocene): **1** — lava flow, **2** — scoria cone, **3** — agglomerates, **4** — lapilli tuffs, **5** — maar, **6** — eruptive centres; *6a* — diatreme, *6b* — neck, *6c* — extrusion, *6d* — dyke. **Podrečany Formation** (Early Pliocene): **7** — lava flow, **8** — diatreme, **9** — gravels, clays, sands, Belina beds (Romanian?). **Poltar Formation** (Pliocene): **10** — clays, sands, gravels, rare lignite lenses, **11** — Early Miocene sediments. **Other symbols**: **12** — updomed area, **13** — local scale elevation, **14** — orientation of lava flows, **15** — state boundary.

tion in the West-Carpathian region. This type of model has been proposed for the studied area with an objection that the rate of subduction and lateral replacement is lower than the rate of convergence. In this case horizontal extension must have occurred in the overriding plate. A similar conclusion was also reached by Lillie (1991) and Lillie et al. (1994), who compared the character of the Bouguer anomalies above the various collisional zones of the Alpine-Himalayan system.

This form of the plate interaction can also be applied to the SE margin of the Bohemian Massif (see Fig. 1), in which the extensional zone with Moho shallowing have been affected by the shape of the North European foreland (bent to NE) and its orientation towards the plate contact.

From this point of view it is important to explain the volcanic succession in the Pannonian area, in which rhyolite and andesite volcanism indicate a relation to the subduction processes (e.g. Lexa et al. 1993), while the final basaltic one can be related to diapirism. It is interesting to note that, apart from smaller occurrences in the Danube Basin, the entire volcanic development probably connected with the subduction is shifted outside the areas of the shallowing Moho into the Middle Slovak area.

Two factors are important for the further tectonic development, of practically the whole Pannonian Basin, characterized by extension. The first is the change of stress conditions dur-

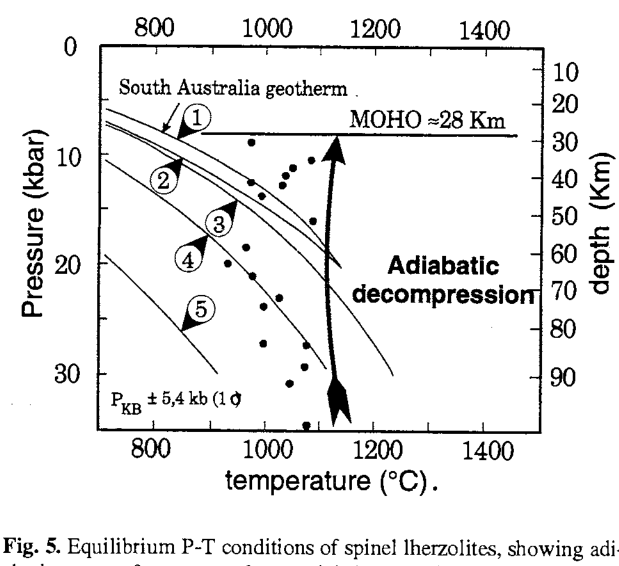

Fig. 5. Equilibrium P-T conditions of spinel lherzolites, showing adiabatic ascent of upper mantle material. **1** — South Australia geotherm (O'Reilly-Griffin 1985; O'Reilly 1990); **2** — alkanine province geotherm after Jones et al. (1982); **3-5** — oceanic geotherms (low and high temperature) and continental geotherms (thick crust) after Merciér & Carter (1975).

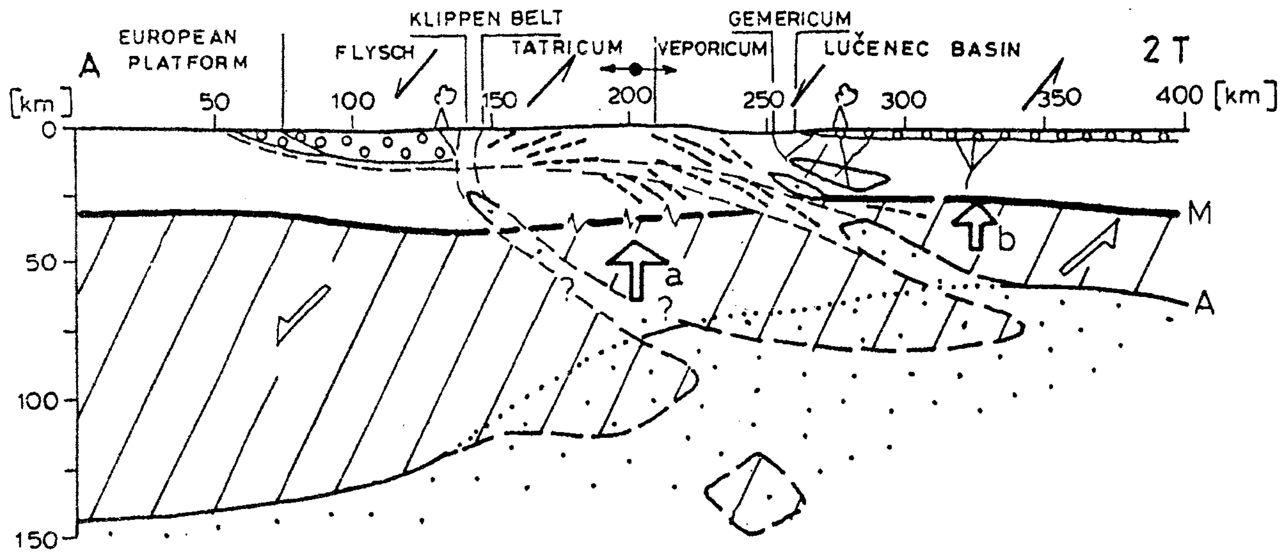

Fig. 6. Interpretation lithospheric section in the central part of the Western Carpathians, line A, see Fig. 1. Explanations see Fig. 7.

ing the Sarmatian up to Pannonian (Nemčok et al. 1993) and the confirmation that extension also occurred in the central part of the Western Carpathians (Bezák et al. 1993). The form of disintegration of the upper plate is documented in the profiles (sections) A and B (Figs. 6 and 7). We can observe that the reflection elements of the upper crust dip to the north in the northern part of the Central Carpathians while those in the southern sector dip to the south, or southeast (Fig. 6). The Moho is intersected below this zone by distinct reflection elements, in the continuation of which we can observe in the upper mantle a zone of very low resistivity. On the basis of the analysis of geophysical and geological data it is assumed that the very low resistivity zone could correspond to the asthenospheric masses.

A more complicated mechanism of lithospheric disintegration is found in the Danube Basin basement (western part of the profile B, Fig. 7), characterized by a similar peak of the seismic reflection boundary (low angle fracture — Ibrmajer et al. 1994). Moreover, a very low resistivity horizon, was defined, using the MTS method, in the eastern part of the profile (Varga et al. 1993). This pattern is in good agreement with the unroofing mechanism. The same indicate also the Badenian sedimentary depocentres, in which we observe a thermal subsidence at the end of the sedimentation period (from the Lower Pannonian).

The lithospheric structure, interpreted as unroofing, occurs on the profile B (Fig. 7). Its formation was probably due to an extensive development in this area, provoked by a process of oblique collision. The other tectonic elements are similar in both profiles, thus on the basis of the relation crust-lithosphere it is possible to interprete the lithospheric detachment faults as a whole in both profiles, running towards the Pannonian Basin interior.

The results of our interpretation indicate that the updoming and unroofing was due to the readjustment of the disturbed isostatic equilibrium in the central part of the Western Carpathians, including the NE margin of the Alps. The break of the isostatic equilibrium probably resulted from the collision and partial overthrusting of the Carpathian-Pannonian and Alpine plates. Another reason for the break of isostatic equilibrium could result from the asthenospheric ascent into shallow levels (sedimentation conditions have changed from marine to terrestrial).

The formation of the detachment faults was predestined by the existence of weakened zones located mainly in the upper part of lithosphere. According to preliminary estimates the thickness of the elastic layer in the Carpathians area ranges from 15 to 25 km (Bielik & Střiženec 1994). On the basis of the displayed profiles it is more realistic to consider the rheological characteristics of the lithosphere and asthenosphere in a concept of separated, oblique and elastic plates. Zones of weakened internal coherence, representing the relicts of older sutural zones of various Alpine ages (Jurassic, Cretaceous, Tertiary — Bezák et al. 1995) are situated between them. The mode of mutual movement and the differences in the load of individual plates upon the asthenosphere may result in a release of stress between them (extension in the lower part of lithosphere) with following upwelling of the asthenospheric material along these zones into the upper mantle, the crust or even to the surface. Should this event happen there due to a predisposition of the zones with weakened bonding only in the elastic layer ("memory" of the lithosphere).

Identification of zones with weakened internal coherence is based on the interpretation of existing high conductivities in the crust, regardless of the accepted geological concept (zones with deep-seated fluids — Bailey et al. 1989; graphitic coatings of the rock grains — Frost et al. 1989; clayey admixtures in ultramylonites, or clays of sedimentary origin) and lead to the definition of zones and layers with reduced coefficients of friction. The high reflective horizons are similar indicators.

Discussion and conclusion

Our interpretation is supported by further results obtained by means of density modelling of the lithospheric inhomogenities and their influence on the isostatic reequilibration (Šefara 1986; Lillie et al. 1994).

The magnetic anomalies originating from the deep-seated sources have shown a linear correlation betwen the magnetization and thermal conditions of the Earth' crust (up to the

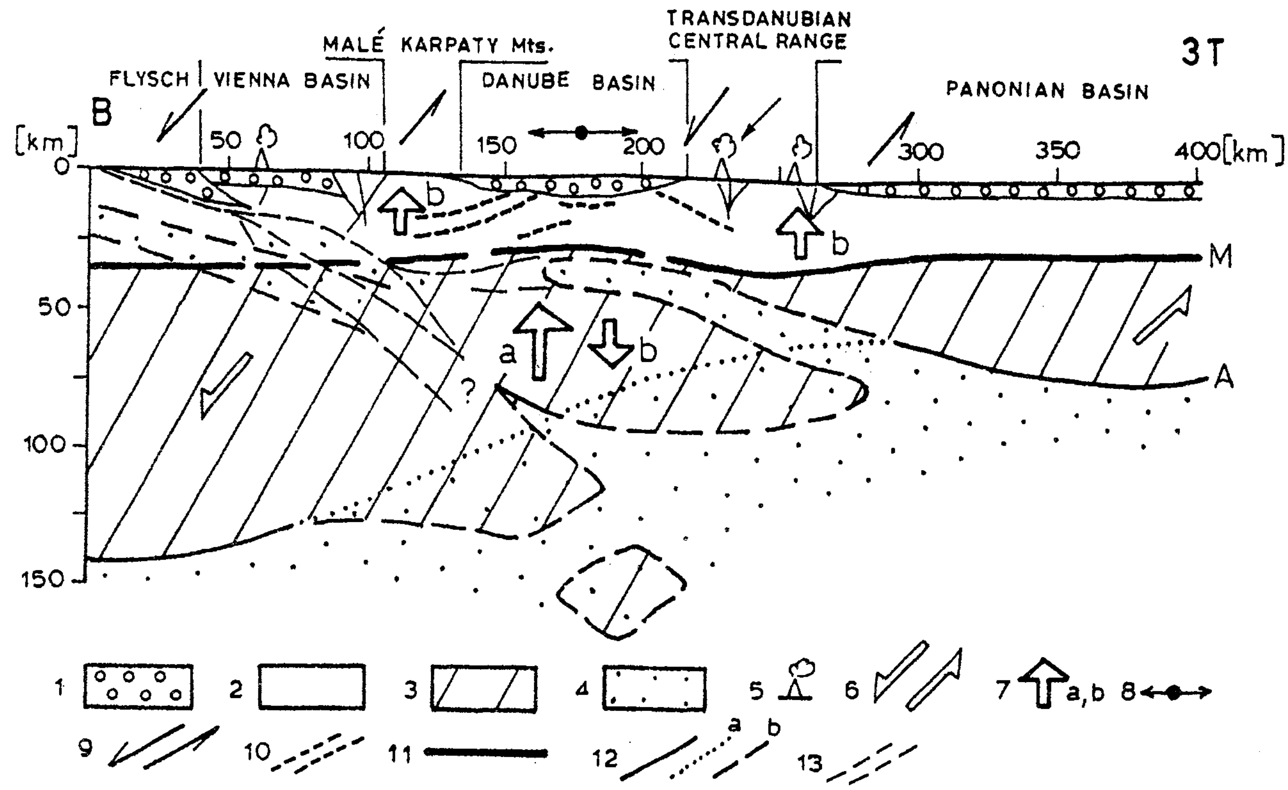

Fig. 7. Interpretation lithospheric section in the western part of the Western Carpathians, line B, see Fig. 1. ***Explanations:*** **1** — Tertiary sediments and the Cretaceous-Paleogene accretional wedge; **2** — Earth's crust, **3** — lower lithosphere, 1-3 lithosphere; **4** — astenosphere and astenospheric masses in lithosphere; **5** — basaltic volcanism on the surface; **6** — kinematics of the plates interaction oblique; **7** — vertical movement tendencies: a — derived from the crustal structures, b — derived from the map of vertical movement tendencies; **8** — extensive regime in the upper crustal part; **9** — strike-slip movement tendencies in the upper crustal part; **10** — significant sets of reflectors, or high conductive zones according to MTS (under TCR) in the crust; **11** — Moho discontinuity; **12** — boundary between lithospheric and asthenospheric masses: in the central part according to Horvath (1993) — a, newly interpreted — b; **13** — detachment course with various probability.

Curie isotherm). There are two possibilities to explain this phenomenon. The first implies a normal increase of mineral susceptibility in response to heat. The second may be the changes of mineral associations in consequence of older, and later metamorphism, alike, both being responsible for the conversion of minerals from poorly magnetic to highly magnetic minerals.

The first type of magnetic anomalies with the shape resembling that of the Curie isotherm (Bezák et al. 1995) is expected to occur in the Danube Basin basement (Gabčíkovo anomaly). The anomalies in the southern part of Slovakia (Filo & Kubeš 1994) represent the second type. As the drillings did not intersect any adequate potential sources, these must be sought in the deeper horizons. The second phenomenon is also not exluded in other areas which are influenced by high geothermal activity.

Heat transfer from the asthenosphere along the tectonicaly controlled zones (hot lines) takes place by convection, whereby the media are not necessarily basaltic magmas. Such a process accelerates the geothermal reworking of the lithosphere, its heating changes within the Moho, or rheologic lithospheric characteristics. The review of the map of the heat flow density (Fig. 2) shows that several such zones, may exist e.g. in the Danube Basin, in the Central Slovak Neovolcanites, with possible continuation south westwards (into the Peri-Adriatic Zone). A similar zone runs southwards at the margin of the Hungarian Midmountains, up to the NE part of the Pannonian area.

The rheology of the upper lithosphere influences the accumulation of the potential energy in its elastic layer. Earthquake epicentres exist in the majority of the studied areas at depths ranging from approximately 1.5 km to some 30 km, whereby some of the deep-seated ones are situated in the areas of increased geothermal activity at the surface. In cases of oblique zones with the transfer of heat to the surface the elasticity of the subducted plate can be sustained at relatively great depths elastic "plate". The depth differences among various rheologically defined zones (Figs. 6 and 7) enable the movement not only along their dip, but also parallel to it, in the form of strike-slip tectonics, observed very frequently up to the youngest periods of evolution.

The recent movement tendencies (Figs. 6 and 7) determined mainly by means of geodetic measurements (Joó et al. 1985), are in accord with this kinematic model. Even more distinct positive vertical movement tendencies were observed in the Eastern Carpathians. In spite of this fact it seems that the zones with a positive vertical movement tendency are connected with the NE margin of the Alps, or with the northern margin of the Central Western Carpathians. These tendencies are probably caused by isostatic readjustment of the regions, which were formerly subject to the compressive state regime, and had partly duplicated continental crust, or crust of intermediate type. The second type of uplift zone is identical with the latest basaltic volcanism. Regions of the positive movement tendency can be influenced not only by the tectonic updoming but also by the processes of density changes uplifting molten masses (see Fig. 4). The present negative movement tendency as a consequence of the thermal subsidence in the western part of the profile is indicated (Fig. 7).

In conclusion we would like to add that the model of the latest lithospheric development of the Western Carpathians and adjacent areas described above does not claim to solve all the problems of the geodynamic development of the studied area. We would like to stress that for study of the tectonics of the lithosphere it is necessary to take into account inherited lithospheric predispositions and their influence on lithosphere-asthenosphere interaction. Proposed convection heat production from the asthenosphere through the mentioned zones accelerates the processes of geodynamic development and gives the physical support for tectonic lithospheric disintegration in the form of detachment and strike-slip tectonics.

References

Ádam A., Nagy, Nemesi L. & Varga G., 1990: Electrical conductivity anomalies along the Pannonian Geotraverse and their geothermal relation. *Acta Geod. Geophys. Mont. Hung.*, 25, 291-307.

Babuška V., Plomerová J. & Šilený J., 1984: Spatial variation of P residuals and deep structure of the European lithosphere. *Geophys. J.R.A str. Soc. (Oxford)*, 79, 363-383.

Babuška V., Plomerová J., Petr V., Pěčová J. & Praus O., 1994: Contribution of the MTS to the study of lithosphere in Central Europe. In: Bucha & Blížkovský M. et al. (Eds.): *Crustal Structure of the Bohemian Massif and the West Carpathians.* Praha-Heidelberg, 157-160.

Bailey R.C., Craven J.A., Macnal J.C. & Polzer B.D., 1989: Imagin of deep fluids in Archean crust. *Nature*, 34, 136-139.

Brey G.P. & Köhler T., 1990: Geothermobarometry in four-phase lherzolites II. New thermobarometers, and practical assessment of existing thermobarometers. *J. Petrology,* 31, 6, 1353-1378.

Bezák V., Hók J., Kováč P. & Madarás J., 1993: The possibilities of the interpretation of seismic profile 2T. In: Rakús M. & Vozár J. (Eds.): *Geodynamical model and deep structure of Western Carpathians. GÚDŠ*, Bratislava, 287-290 (in Slovak).

Bezák V., Šefara J., Bielik M. & Kubeš P., 1995: Lithospheric structure in the Western Carpathians: geophysical and geological interpretation. *Miner. slovaca,* 27, 169-178 (in Slovak, English summary).

Bielik M., 1991: Density modelling of the Earth´s crust in the intra-Carpathian basin. In: Karamata S. (Ed.): *Geodynamic Evolution of the Pannonian Basin Acad. Conf. 62, Serb. Acad. Sci. Arts,* Beograd, 123-132.

Bielik M. & Střiženec P., 1994: Flexure of the lithosphere beneath the Pannonian Basin. *Contr. Geophys. Instit. Slov.Acad. Sci.*, 24, 87-104.

Bucha V., Blížkovský M., Burda M., Krs M., Suk M. & Šefara J. (Eds.), 1994: Crustal Structure of the Bohemian Massif and the West Carpathians. *Academia* Praha, *Springer-Verlang*, Heidelberg, 1-355.

Čermák V., Král M., Kubík J., Šafanda J., Krešl M., Kuferová L., Janči J., Lizoň I. & Marušiak I., 1992: Subsurface temperature and heat flow density maps on the territory of Czechoslovakia. In: Hurtig V., Čermák V., Halnel R. & Zuri V.I. (Eds): *Geothermal Atlas of Europe. Hermann Haack, Geogr.-Kart. Anstalt,* Gotha, 21-24.

Červ V., Pek J., Pícha B., Praus O. & Tobyášová M., 1994: Magnetotelluric: Models of Inhomogeneity zones. In: Bucha V. & Blížkovský M. et al. (Eds): *Crustal Structure of the Bohemian Massif and the West Carpathians. Academia*-Praha, *Springer-Verlag*-Heidelberg, 147-157.

Dewey J.F., Helman M.L., Turco E., Hutton D.H.W. & Knott S.D., 1989: Kinematics of the Western Mediterranean. In: Coward M.P., Dietrich D. & Park R.G. (Eds): *Alpine Tectonics. Spec. Publ. Geol. Soc. London,* 45, 265-283.

Dvořáková V., Tomek Č. & Vozár J., 1992: Late Cretaceous Intra - Austroalpine collisional events as evidenced in the Veporic and Gemeric Terranes in Slovakia. *Terra Abstr.,* Suppl. 2 to Terra Nova 4, 19.

Frost B. R., Fyfe W.S. Tazaki K. & Chan T., 1989: Grain boundary graphite in rocks and implication for high electrical conductivity in the lower Crust. *Nature,* 340, 134-136.

Horvath F., 1993: Towards a mechanical model for the formation of the Pannonian basin. *Tectonophysics,* 226, 333-357.

Horvath F. & Royden L., 1981: Mechanism for the formation of the intra-Carpathian basins: A review. *Earth Evol. Sci*, 1, 3-4, 307-316.

Huraiová M. & Konečný P., 1994: Pressure-temperature conditions and oxidation state of upper mantle in the southern Slovakia. *Acta Geol. Hung.*, 37, 1-2, 33-44.

Ibrmajer I., Tomek Č., Koráb T. & Dvořáková L., 1994: Deep reflection seismic profiling in Czechoslovakia — the ČESLOKORP (Czechoslovak Crustal Reflection Profilong Project). In: Bucha V. & Blížkovský M. et al. (Eds): *Crustal Structure of the Bohemian Massif and the West Carpathians. Academia*-Praha, *Springer-Verlag*-Heidelberg, 21-45.

Jones A.P., Smith J.V., Dawson J.B. & Hansen E.C., 1982: Metamorphism, partial melting, and K-metasomatism of garnet-scapolite-kyanite granulite xenoliths from Lashaine, Tanzania. *J. Geol.*, 91, 143-165.

Joó I., Arabadzijski D., Mladenovski M.M., Vanko J., Füry M., Thury J., Mihalia M., Wyrzykovski T., Meščerskij I.M. & Semič V.S., 1985: Map of the recent vertical movements in the Carpatho-Balcan Region. Scale 1:1,000,000, Budapest.

Kilényi E., Kröll A., Obernauer D., Šefara J., Steinhauser P., Szabó Z., & Wessely G., 1991: Pre-Tertiary basement Contour map of the Carpathian Basin beneath Austria, Czechoslovakia and Hungary. *Geophys. Transact.* 36, 1-2, 15-36.

Konečný V., Lexa J., Balogh K. & Konečný P., 1996: Alkali basalt volcanism in southern Slovakia: volcanic forms and time evolution. *Special Issue of Acta Volcanologica,* in print.

Köhler T. & Brey G.P., 1990: Calcium exchange between olivine and clinopyroxene as a geothermobarometer for natural peridotites from 2 to 60 kb with aplications. *Geochim. Cosmochim. Acta,* 54, 2375-2388.

Lexa J., Konečný V., Kaličiak M. & Hojstričová V., 1993: Distribution of volcanites of Carpatho-Pannonian region in time-space. In: Rakús M. & Vozár J. (Eds): *Geodynamical model and deep structure of Western Carpathians. GÚDŠ*, Bratislava, 57-70 (in Slovak).

Lillie J.R. & Bielik M., 1992: Crustal development and tectonics models of Western Carpathians from Gravity interpretation. *Geol. Carpathica,* 43, 2, 63-68.

Lillie J.R., Bielik M., Babuška V. & Plomerová J., 1994: Gravity modelling of the lithosphere in the Eastern Alpine - Western Carpathians - Panonian Basin Region. *Tectonophysics,* 231, 215-235.

McKenzie D., 1978: Some remarks on the development of sedimentary basins. *Earth Planet. Sci. Lett.*, 40, 25-32.

Merciér J.C. & Carter N.L., 1975: Pyroxene geotherms. *J. Geophysical Research,* 80, 23, 3349-3362.

Nemčok M., Hók J., Kováč P., Marko F., Madarás J. & Bezák V., 1993: Tertiary tectonics of Western Carpathians. In: Rakús M. & Vozár J. (Eds): *Geodynamical model and deep structure of Western Carpathians. GÚDŠ*, Bratislava, 263-267 (in Slovak).

Nicolas A., Lucazeau F. & Bayer R., 1987: Peridotite xenoliths in Massif Central, France: textural and geophysical evidence for astenopheric diapirism. In: P.H. Nixon (Ed.): *Mantle Xenoliths. J. Wiley & Sons Ltd.*, 563-573.

O´Reilly S.Y. & Griffin W.L., 1985: A xenolith-derived geotherm for southeastern Australia and its geophysical implications. *Tectonophysics*, 111, 41-63.

O´Reilly S.Y., 1990: Equilibration temperatures and elastic wave velocities for upper mantle rocks from eastern Australia: implications for the interpretation of seismological models. *Tectonophysics,* 185, 67-82.

Pospíšil L., Buday T. & Fusán O., 1992: Neotectonical movements in Western Carpathians. *Západ. Karpaty*, 16, 65-84 (in Slovak).

Praus O., Pěčová J., Petr V., Babuška V. & Plomerová J., 1990: Magnetotelluric and seismological determination of lithosphere-asthnosphere transition in Central Europe. *Phys. Earth Planet. Inter.*, 60, 212-228.

Praus O., 1971: Electric conductivity of the Earth in the Czechoslovakia studied by magnetotelluric and geomagnetic methods. In: *Upper Mantle Project Programme in Czechoslovakia 1962-1970. Geophysics, Final Report, Academia,* Praha, 162-184.

Royden L.H., 1993: The tectonic expression of slab pull at continental convergent boundaries. *Tectonies,* 12, 303-325.

Royden L.H. & Karner G., 1984: Flexure of lithosphere beneath Apennine and Carpathian foredeep basins: evidence for an insufficient topographic load. *Am. Assoc. Petr. Geol. Bull.,* 68, 704-712.

Royden L. H., Horvath F. & Burchfield B.C., 1982: Transform faulting, extension and in the Carpatho-Pannonian region. *Geol. Soc. Am. Bull.,* 73, 717-725.

Sclater J.G., Royden L., Horvath F., Burchfield B.C., Lekmen S. & Stegena L., 1980: The formation of the intra - Carpathian basins as determined from subsidence data. *Earth Planet. Sci. Lett.,* 51, 139-162.

Spakman W., van der Lee S. & van der Hilst R., 1993: Travel-time tomography of the European-Mediterranean mantle down to 1,400 km. *Phys. Earth. Planet. Inter.,* 79, 3-74.

Spakman W., 1990: Images of the upper mantle of central Europe and the Mediterranean. *Terra Nova,* 2, 542-553.

Stegena L., Géczy B. & Horvath F., 1975: Late Cenozoic evolution of the Pannonian basin. *Tectonophysics,* 26, 71-90.

Šefara J., Bielik M., Bodnár J., Čížek P., Filo M., Gnojek I., Grecula P., Halmešová S., Husák Ľ., Janoštík M., Král M., Kubeš P., Kurkin M., Leško B., Mikuška J., Muška P., Obernauer D., Pospíšil L., Putiš M., Šutora A. & Velich R., 1987: Structural-tectonical map of the Inner Western Carpathians for the purposes of prognose deposits — geophysical interpretations. Text to the collection of maps. 1-267 (in Slovak).

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. & Kubeš P., 1994: Complex geophysical interpretation of the 2T profile. In: Bezák V. & Lukáčik E. (Eds.): *Hercynian development of the Western Carpathians and some others segments of European Hercynides. Abstracts, GÚDŠ,* Bratislava, 33.

Tomek Č., Ibrmajer I., Koráb T., Biely A., Dvořáková L., Lexa J. & Zbořil A., 1989: A core structures of the Western Carpathians on deep reflection seismic profile 2T. *Miner. slovaca,* 21, 3-26 (in Slovak).

Tomek Č., 1993: Deep crustal structures beneath the Central and Inner West Carpathians. *Tectonophysics,* 226, 417-431.

Tomek Č. & Hall J., 1993: Subducted continental margin imaged in the Carpathians of Czechoslovakia. *Geology,* 21, 535-538.

Varga G. & Lada F., 1988: Magnetotelluric measurement on the profile 2T. *Manuscript ELGI* Budapest - Geofyzika Brno (in Czech).

Varga G., Lada F. & Verö L., 1993: Magnetotelluric measurement on the project DANREG. In: Džuppa (Ed.): *Geophysical survey in the area Podunajsko. DANREG — partial final report. Manuscript, Geofond,* Bratislava (in Slovak).