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CONTINENTAL CONVERGENCE IN THE AREA OF THE WESTERN CARPATHIANS ON THE BASIS OF DENSITY MODELLING

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Abstract: The dominant feature of the gravity field of the Western Carpathians is its significant decrease from the area of the East European Platform to the Outer and Central Carpathians and its increase in the direction of the Pannonian Basin. This course is connected with underthrusting of the European Plate under the Carpathian-Pannonian Plate, and its flexure as a result of the loading of its southernmost passive margin. The result of this is the existence of the foredeep basins of the Western Carpathians with significant thickness. According to the inclination of the subducted plate, the lithospheric models can be divided into two groups. In the first the inclination is large and in the second it is substantially smaller. The results of density modelling assume crustal shortening in the neo-Alpine development by only about 40-60 km. Shortening appears only in the narrow zone of the front of the overthrusting plate. In spite of the existence of the overthrust zones and local horizontal shortenings in the Carpathian-Pannonian Plate, it is possible to assume an extensional form of regional deformation. The difference in the process of continental convergence in time, but also space also confirms the density models. Differences of collision in the lower lithosphere are also evident. Profile 2T shows striking agreement of the continuation of the direction of the subduction of the European Plate, with the direction of deepening of the lithosphere-astenosphere boundary. It is possible that in this case, it is a relict of the southern continuation of the subduction zone to greater depths. However this fact is not observed on Profile 3T.

Key words: Western Carpathians, lithosphere, convergence, density model, gravity.

Introduction

The Western Carpathians are part of the northern branch of the mountain system of the Mediterranean European Alpides, which originated between the Middle Cretaceous and Miocene, from the Mediterranean section of the Tethys collision of the African and North European continent. In the neo-Alpine development of the Western Carpathians, convergence of the mountain massif and the North European Platform with the Alpine-Carpathian orogen occurred (Kováč et al. 1993). During the collision of continental plates, the Carpathian orogenic complex of the original active continental margin of the upper plate (Carpathian-Pannonian in the sense of Tomek et al. 1989) was overthrust onto the passive continental margin of the lower (North European, European) plate (brunia in the sense of Tomek et al. 1989), so that only complexes of the original accretional (flysch belt) were overthrust.

Deep seismic reflection profiles have brought very valuable results to the study of the crustal structure of the Western Carpathians. Among them, it is especially necessary to recall Profile 2T and Profile 3T (Tomek et al. 1987, 1989). It is necessary to state objectively that interpretation of seismic data from such a complex collisional environment as the Western Carpathians, is very difficult. It is therefore natural that apart from the original, elementary interpretation of the seismic reflection data, various suggestions, additions, and other views on the geological interpretation of these measurements also exist.

Šefara & Kubeš (1993) mention the objections of Buday et al. (1992) to the definition of the structure below the Klippen Belt, and the comments of Nemčok et al. (1992) on the measurement of tectonic elements, and the resulting transpressional and transtensional regime (Bezák et al. 1992). One of the further, naturally discussable phenomena is the flexure of the European Plate, and its descent to the depths.

The aim of this work is to continue the study of the gravity field of the Western Carpathians, in which the dominant factor is its significant decrease from the area of the East European Platform to the Outer and Central Carpathians (gravity minimum), and its increase in the direction of the Pannonian Basin. There is the further aim of studying the form of the flexure of the subducted lower European Plate, and its extent below the upper Carpathian-Pannonian Plate, on the basis of density modelling. It is necessary to emphasize that this concerns exclusively the solution of the regional problem, that is modelling of the gravity anomalies of significant wave length, at the same time taking into account the results of seismic reflection profiling, with an original addition about the density inhomogeneities represented by the upper mantle (the lower lithosphere and astenosphere), as well as data about the thicknesses of the frontal foredeep and the flysch zone of the Outer Carpathians, Neogene sediments of the Inner Carpathians, the Pannonian Basin and crust, including the use of information from other regional geophysical data and geological works.

Input data

To solve the problem of density modelling of the whole continental lithosphere, it is necessary to start from gravity anoma-

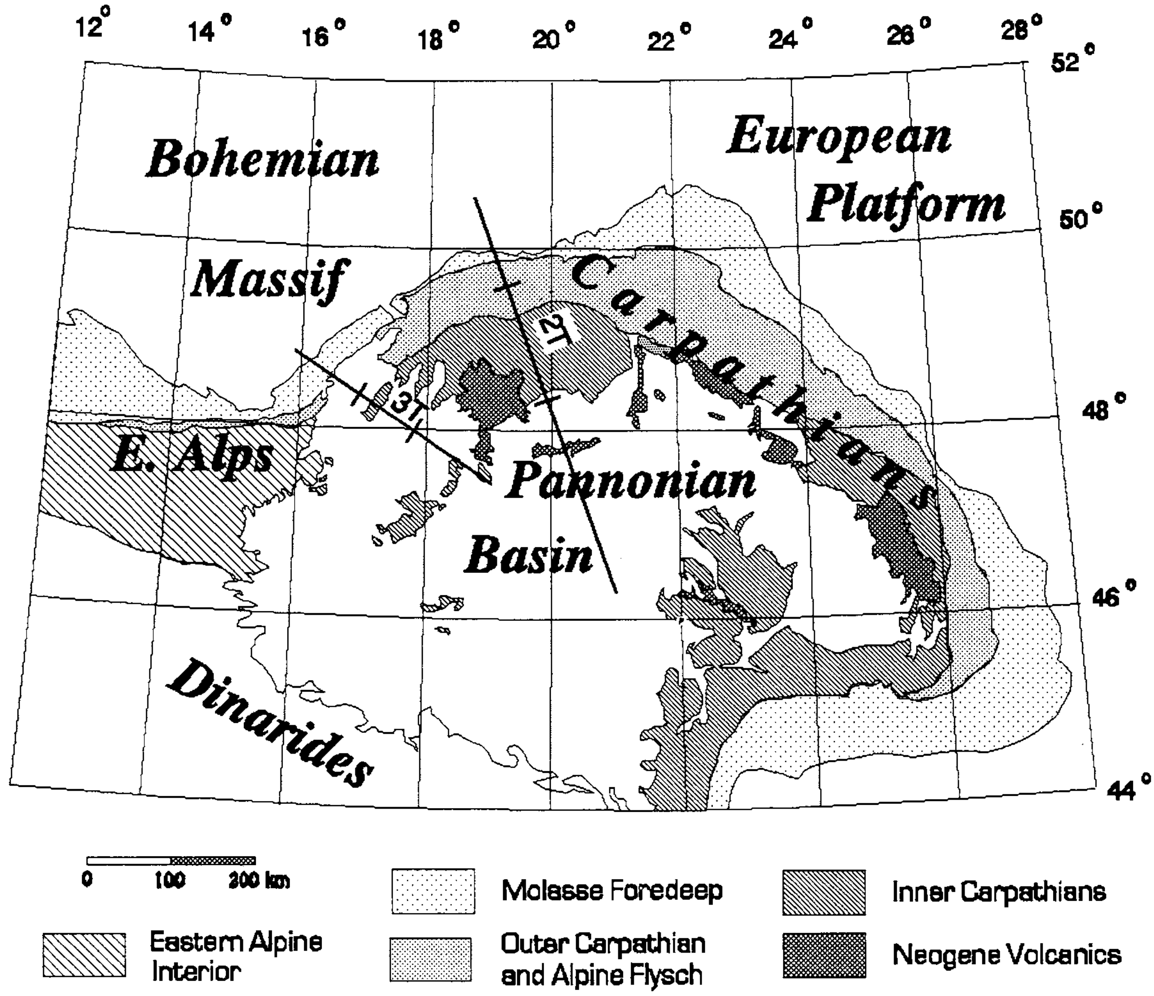

Fig. 1. Schematic tectonic map of the Eastern Alps, Carpathians and Pannonian Basin. The courses of the interpreted profiles are marked by continuous lines. The marked sections 2T and 3T coincide with the course of the seismic reflection Profiles 2T and 3T.

lies, which are characterized by large wave length. It is appropriate to simplify such models to an area representing the main density (anomalous) zones.

The density contrasts of these anomalous zones are related to the average density of the "typical" continental crust. In our case the main anomalous bodies were:

a - the sediments of the flysch nappes and frontal foredeep of the Western Carpathians,
b - the sediments of the Pannonian Basin,
c - the lower lithosphere,
d - the astenosphere.

The density contrasts (–0.20 and –0.21 g/cm^3) for the sediments of the flysch nappes, the frontal foredeep of the Western Carpathians and the sediments of the Pannonian Basin were relative to the average density of the upper crust, while the density contrasts for the upper mantle (that is the lower lithosphere and astenosphere) were relative to the average density of the lower crust. The density contrast for the lower lithosphere was fixed at +0.30 g/cm^3, and for the astenosphere at +0.27 g/cm^3 (compared to the covering lithosphere, this is –0.03 g/cm^3). In the case of such a definition of density contrasts, we practically introduce the assumption of increasing of the density of the earth's crust with depth, which has a rational basis.

The density contrasts of the main anomalous zones were chosen on the basis of the results of measurement of the density parameters of the rocks forming the Western Carpathians (Eliáš & Uhman 1968; Husák & Muška 1984; Husák 1977; Šefara et al. 1987), and data about the average density of "typical" continental crust and upper mantle. The density contrast for the astenosphere was defined on the basis of use of the validity of the Airy local isostatic balance (Lillie et al. 1993).

The topographic profiles and depths of the above mentioned anomalous zones were other basic data. The topographic data were taken from the Geodatischen Dienste (1979), the thickness of sediments of the Outer Western Carpathians, the depth of the Moho, and the thickness of the inner Paleogene were taken from seismic reflection measurements (Tomek et al. 1989). We used the work of Babuška et al. (1987, 1988) to trace the course of the lithosphere-astenosphere boundary. A map of the pre-Tertiary relief of the Pannonian Basin (Kilényi et al. 1989) was used to determine the thickness of the Neogene fill. Gravimetric data from the area of Slovakia were taken from maps of the complete Bouguer anomalies (Šefara et al. 1987). The same data for the territories of Czechland, Poland and Hungary were taken from the work of Ibrmajer (1978).

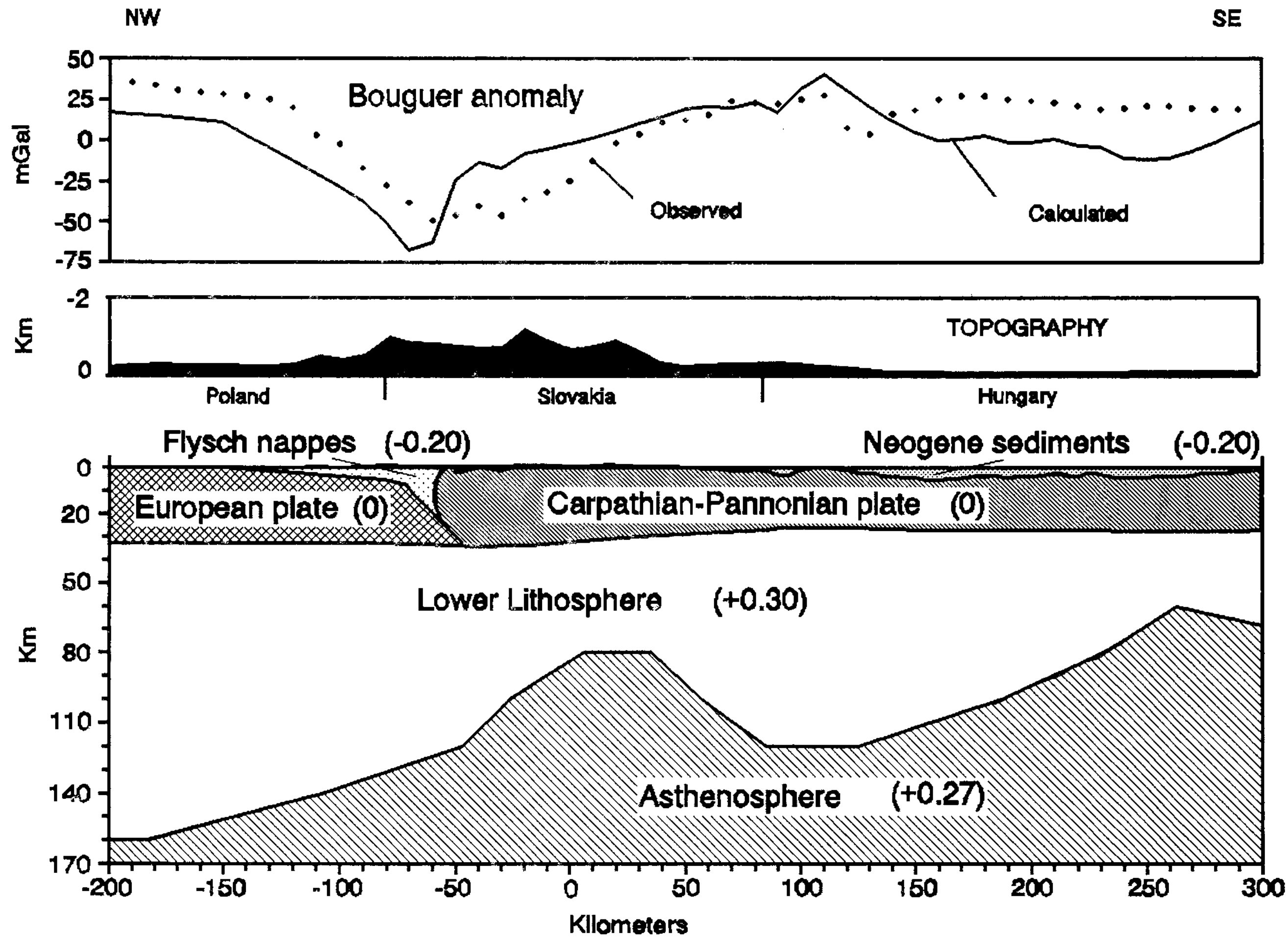

Fig. 2. Initial two-dimensional density model of the lithosphere along Profile 2T. Density contrasts are expressed in g/cm^3.

Course of the profiles

The choice of the course of both interpreted profiles (Fig. 1) was significantly purposeful, since we wanted to use the seismic reflection data from Profile 2T and Profile 3T for density modelling.

The first profile, along which a density cross section was calculated through the whole lithosphere, runs along the line Tworog (Poland)-Chabenec-Gemerský Jablonec-Battonya (Hungary). Its length is 500 km. We state that the Slovak part of the profile is identical with the seismic reflection Profile 2T. From the geological point of view the profile begins in the area of the Eastern European Platform (Poland), and towards the south east crosses the basic tectonic units of the Western Carpathians, to end in the Neogene of the Pannonian Basin.

The second profile extends along the line Moravské Budějovice (Czechland)-Pezinok-Kolárovo-Budapest (Hungary). Its length is 300 km. The localization of the profile was determined so that part of it covered the course of the other seismic reflection Profile 3T. The profile begins on the southern margin of the crystalline complex of the Czech Massif, and crosses the Carpathian frontal foredeep and flysch zone, the core mountain range of the Malé Karpaty, the Danubian Plain, and ends in the Pannonian Basin.

The interpretive approach

To study gravity anomalies with a large wave length, it is necessary for the interpretated profile to have sufficient length. This is necessary to fulfill both the conditions of two dimensionality of the solution of problems, and to eliminate unreal gravitational effects (gradient) from the final profile.

The method of density modelling was carried out with the help of a direct 2 ½ D gravimetric problem, using the GM-SYS (version 2.0) set of programmes. The set of programmes was worked out by the company, Northwest Geophysical Associates Inc. of the USA. Optimalization between the observed and calculated anomalies is fully automatized. The advantage of this set of programmes resides in the fact that the user has the opportunity of immediately choosing to accept the changes carried out.

Individual models of the lithosphere along both profiles were calculated on the basis of the trial and error method. Apart from the already mentioned density models, the topography and gravity anomalies, observed and calculated are also illustrated on Figs. 2-8.

The results of seismic reflection modelling are the most widely accepted basic strategy for solving the density modelling of the structure of the lithosphere, since the ambiguity of the solution with

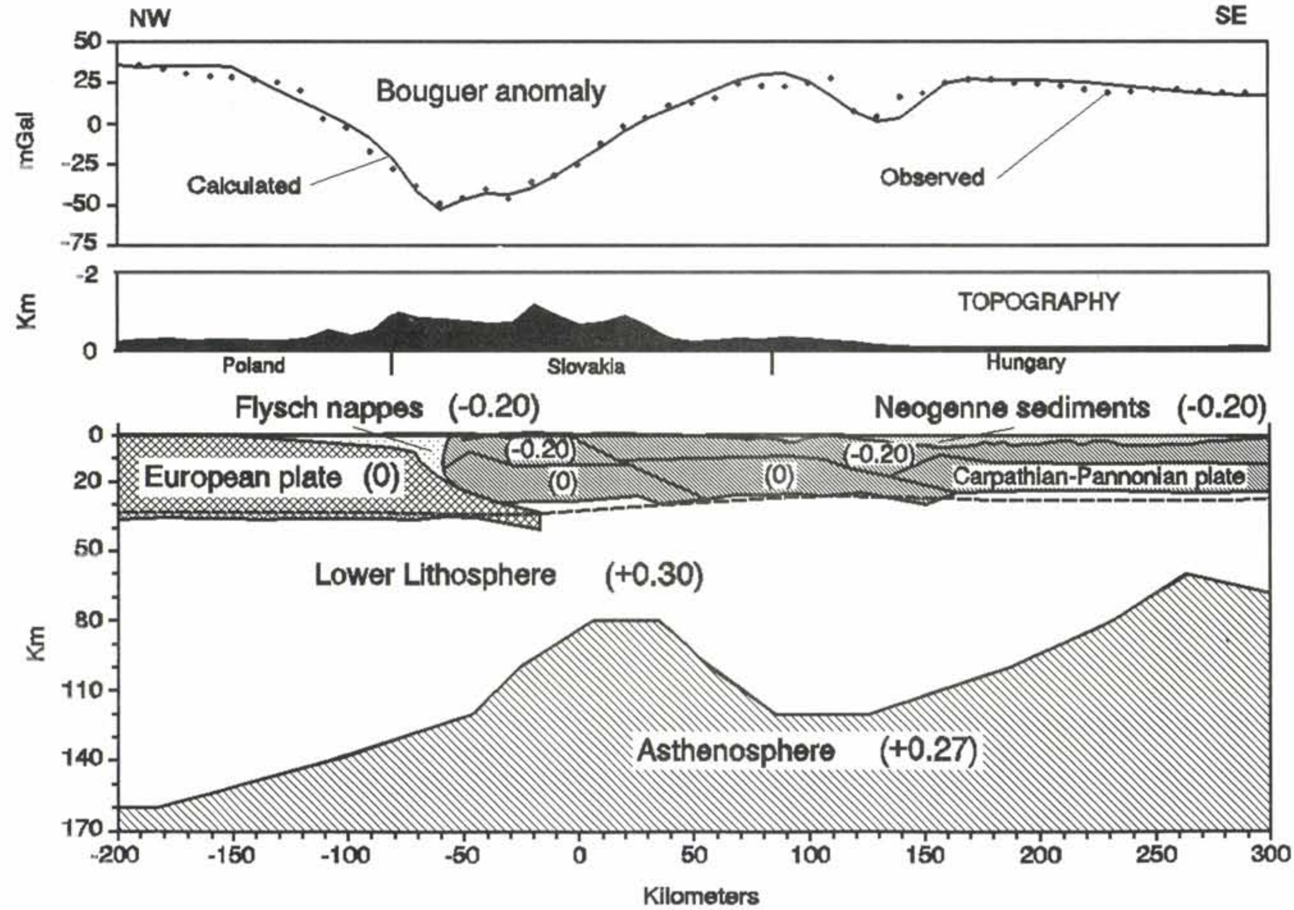

Fig. 3. Schematic two-dimensional density cross section of the lithosphere along Profile 2T.

the help of seismic methods is less in comparison with other potential methods. However considering the fact that the interpretation of seismic reflection measurements is also often very difficult (especially in continental collision areas), we decided that as far as modelling of the gravity field allowed, we would also prepare density models which are not in complete harmony with the seismic reflection data, and with their elementary interpretation (Tomek et al. 1987, 1989). This decision is justified especially by the problematic interpretation of the deeper parts of the crust, Moho depth and the mantle lithosphere in convergent areas, on the basis of seismic reflection data. In addition this was not its main aim on the Profile 2T and Profile 3T, and many recent geophysical and geological data give the possibility of another variant in interpreting these data.

Two important facts led us to a solution of the density modelling, practically up to the lithosphere-astenosphere boundary. The first was that in the studied area, the thickness of the lithosphere is "known". It was calculated by Babuška et al. (1987, 1988). The second is that, on the basis of the results of Lillie et al. (1993), it was proved that the gravitational effect of this boundary on the total gravity field is significant, although substantially smaller in comparison with the Moho. Therefore in density modelling of the wider region of the Western Carpathians (especially in the direction of the Pannonian Basin), this gravitational effect needs to be taken into account.

The basic density cross section through the lithosphere on Profile 2T (Fig. 2) showed that agreement between the observed and calculated gravity anomalies is not great, and it changes along the profile. The difference on some sections reached almost 350 μms^{-2} (35 mgl). Although it is necessary to add that the overall regional character of the field was preserved. We state that a gravity minimum, spreading over the Outer and Central Western Carpathians is a dominant feature of the gravity field.

For good correlation between the observed and calculated gravitational effect, it was therefore necessary to begin adjusting an initial density model. On the basis of study of the gravity contributions of individual anomalous zones and the validity of Airy's isostatic equilibrium, it was found that the overall gravity field is most influenced by the Moho discontinuity. Substantially smaller gravity contributions mark other anomalous bodies (Lillie et al. 1993). As a result, agreement between observed and calculated gravity anomalies can be achieved very simply with only an adjustment to the Moho boundary. We also think that the present published maps of the Moho represent a very flattened and simplified form, and do not reflect its local short wave-length changes. A change in the thickness of the Earth's crust by ± 1 km at a given difference of density (+0.30 g/cm^3) causes a change in the gravitational effect of around ± 5 mgl. In our case, we also partly corrected the thickness of sediments of the flysch zone and frontal foredeep. However this only concerned small adjustments to the thickness of the accretional prism, and local changes of the gravity field. The geometry and density of the anomalous zones representing the sediments of the Pannonian Basin, the Inner Carpathian Paleogene and the lithosphere-astenosphere boundary were practically unchanged

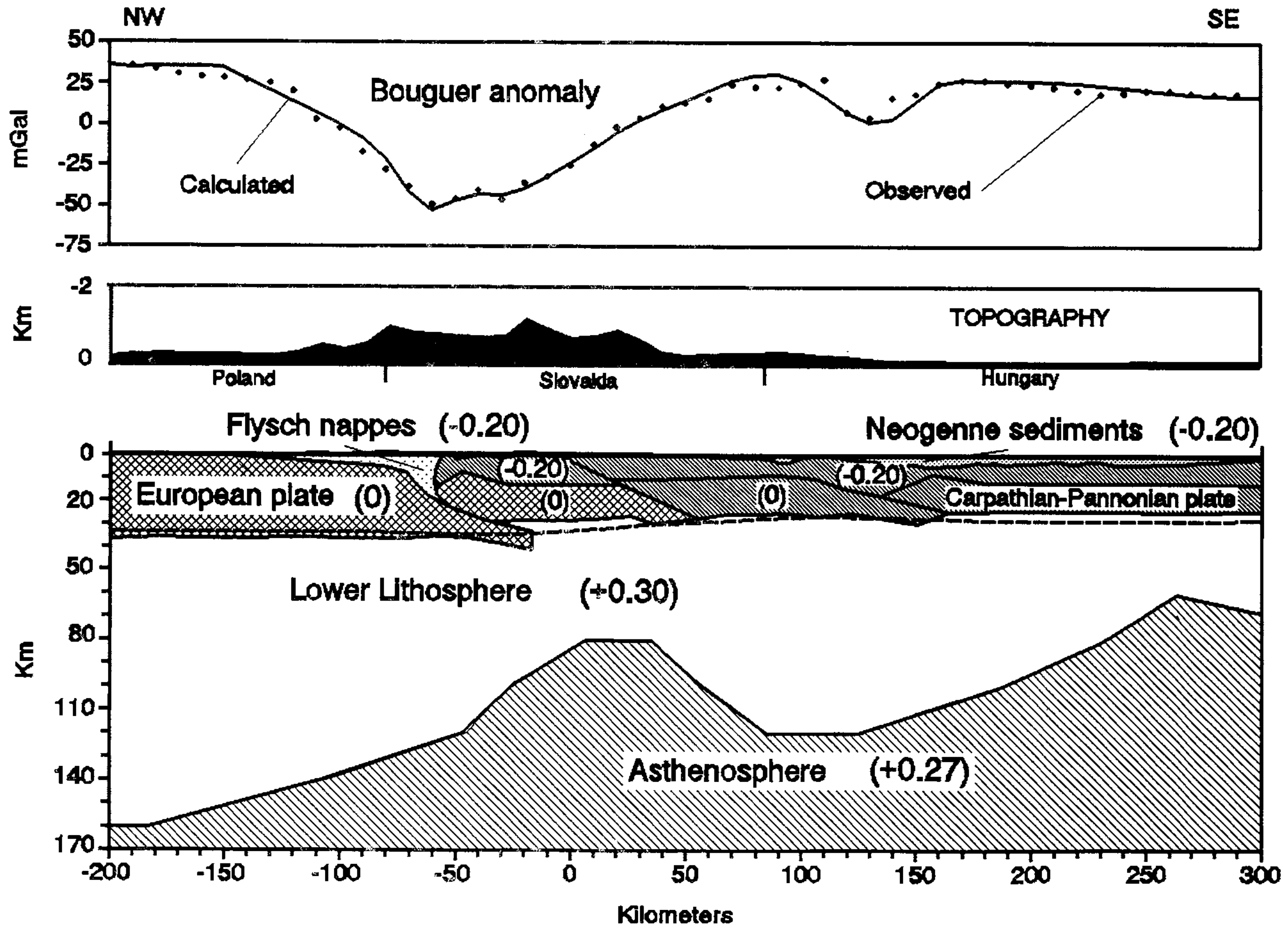

Fig. 4. Schematic two-dimensional density cross section of the lithosphere along Profile 2T.

by modelling. The cause of this decision concerning individual geological units was different. In the case of the sediments of the Pannonian Basin, the Inner Carpathian Paleogene, the flysch zone and the frontal foredeep, we emphasized the quality of their seismic interpretation. It concerns near-surface inhomogeneities, which can be considered relatively reliably known. However, this does not apply in the case of the lithosphere-astenosphere boundary. The uncertainty in determining its course is clearly greater. However, the already ascertained fact, that changes in the course of the lithosphere-astenosphere boundary have substantially less influence on the overall gravitational effect of the density models, than, for example, the Moho, influenced our decision.

The results of density modelling

The specific feature of this study is that it is not limited only to one variant of the density model along both interpreted profiles, but uses the basic property of solution of potential problems, and this is its ambiguity. This means that various density models were proposed, that on the one hand agreed with the course of the observed gravity field, and on the other also accepted previous geophysical and geological data.

The achieved result showed that the decrease in the gravity field from the area of the Eastern European Platform to the area of the Outer and Central Carpathians (Carpathian gravity minimum), and its subsequent increase towards the Pannonian Basin, is connected with the subduction of the European Plate under the Carpathian-Pannonian Plate, and its flexure as a result of loading of the southernmost part of this passive margin.

According to the inclination of the subduction of the passive margin of the European Plate, the constructed lithosphere density cross-sections may be divided into two groups:

1 - Models where the subducted plate has a large inclination (Figs. 3-5).

2 - Models where the subducted plate has a much smaller inclination (Figs. 6-8).

In the first group, the inclination of the deepening of the lower plate varies. From the overthrust front of the Carpathians ca. −150 km to −75 km on Profile 2T and from ca. −30 km to −5 km on Profile 3T there is a very shallow inclination of about 5-10°. This increases, so that it reaches around 40° in the middle section on Profile 2T, and around 25°. In the final section of the deepening of the European Plate on Profile 2T in the direction under the Central Carpathians, the inclination is again partly diminished, to about 20°. On the other hand, on Profile 3T the inclination increases to 60°.

In the second group, the inclination of deepening of the European Plate on Profile 3T, not taking into account local changes in the area of the Vienna Basin and its contact with the Malé Karpaty Mts., varies in the range of only about 8-12°. In this group, on Profile 2T, it was also necessary to partly adjust the initial seismic data on the form and inclination of the accretion-

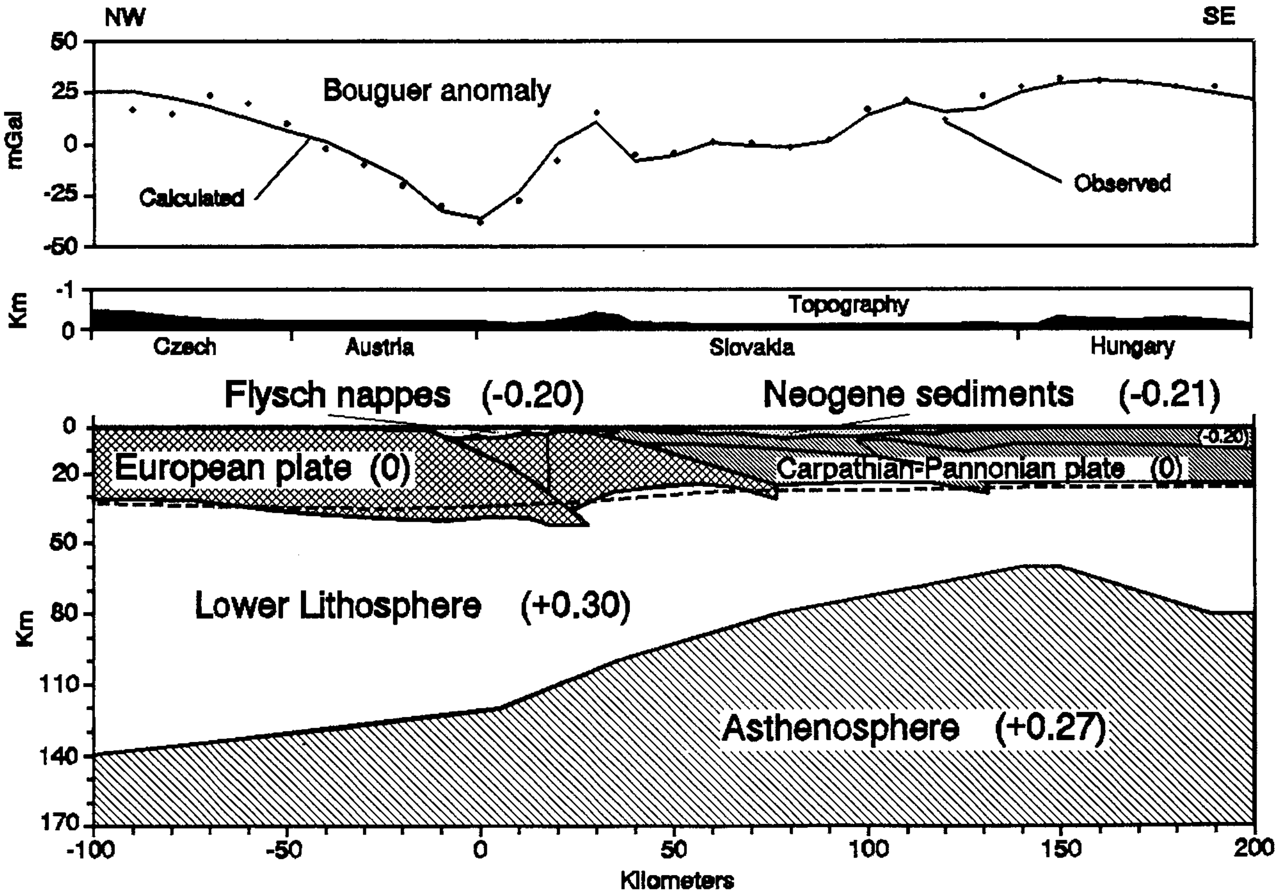

Fig. 5. Schematic two-dimensional density cross section of the lithosphere along Profile 3T.

ary prism (the flysch zone and foredeep). However in this case, there was only a small change in its deepest part. The greatest depth of the accretionary prism, in the section from −70 to −58 km was reduced from 15 km to about 11-12 km.

In practically all cases, for reasons already mentioned above, it was necessary to change or at least partly adjust the course of the Moho. For comparison, its course taken from publications (Posgay et al. 1989; Tomek 1988) is also given on the density cross sections of the lithosphere. We consider that local changes of the Moho are very important from the point of view of tectonic development. However in general, the regional trend of the course of the Moho is preserved, that is a gradual decline in its depth from the Outer Western Carpathians to the Pannonian Basin. The illustration of the chosen possibilities for the configuration of the Moho in the collisional area of both plates, determined on the basis of the results of the density model, is summarized on Fig. 9. Analysis of them shows that in the collisional area at the contact of both colliding plates, cases of the doubling of the Moho boundary are possible (e.g. Fig. 9a-d, g, h). The character of the course of the Moho illustrated on the geological cross sections through the northernmost part of the Malé Karpaty (Plašienka et al. 1991) is very similar to the configuration of the Moho given on Fig. 9d, g, h. In the collisional area, the subduction of the European Plate under the upper Carpathian-Pannonian Plate is evident. Crustal shortening varies around 40-60 km. The striking agreement of the supposed south-eastern continuation of the continental-oceanic transitional zone, towards greater depths, with a southward deepening of the lithosphere-astenosphere boundary in the section from about 30 to 85 km, can be considered as a very significant phenomenon on Profile 2T, for the case of steep subduction of the European Plate.

The relative gravity highs, such as the Kolárovo gravity anomaly on Profile 3T, and also the gravity high extending over the area of the Rimava Basin and Cerová Mts., were interpreted in the light of the latest data on the form of obducted crustal blocks, especially their upper boundaries.

The results of density modelling along Profile 2T confirm that the gravity minimum in this area of the Western Carpathians, is by superposition, not only of the gravitational effects of the flysch sediments and sediments of the frontal foredeep, but also the gravity effects of the rocks forming the upper and lower crust under the Tatric Unit and Veporic Unit. The assumption that the gravity minimum is caused only by the flysch sediments of the frontal foredeep applies only to the area of their actual surface outcrop (approximately from −160 km to −55 km).

Analysis of the density models assumes that the oceanic crust existing between both colliding plates, was largely or completely absorbed into the mantle, even before the closure of the ocean, or it could be found in fragments at greater depths under the units of the Central Western Carpathians, most probably under their northernmost parts, close to the Klippen Belt.

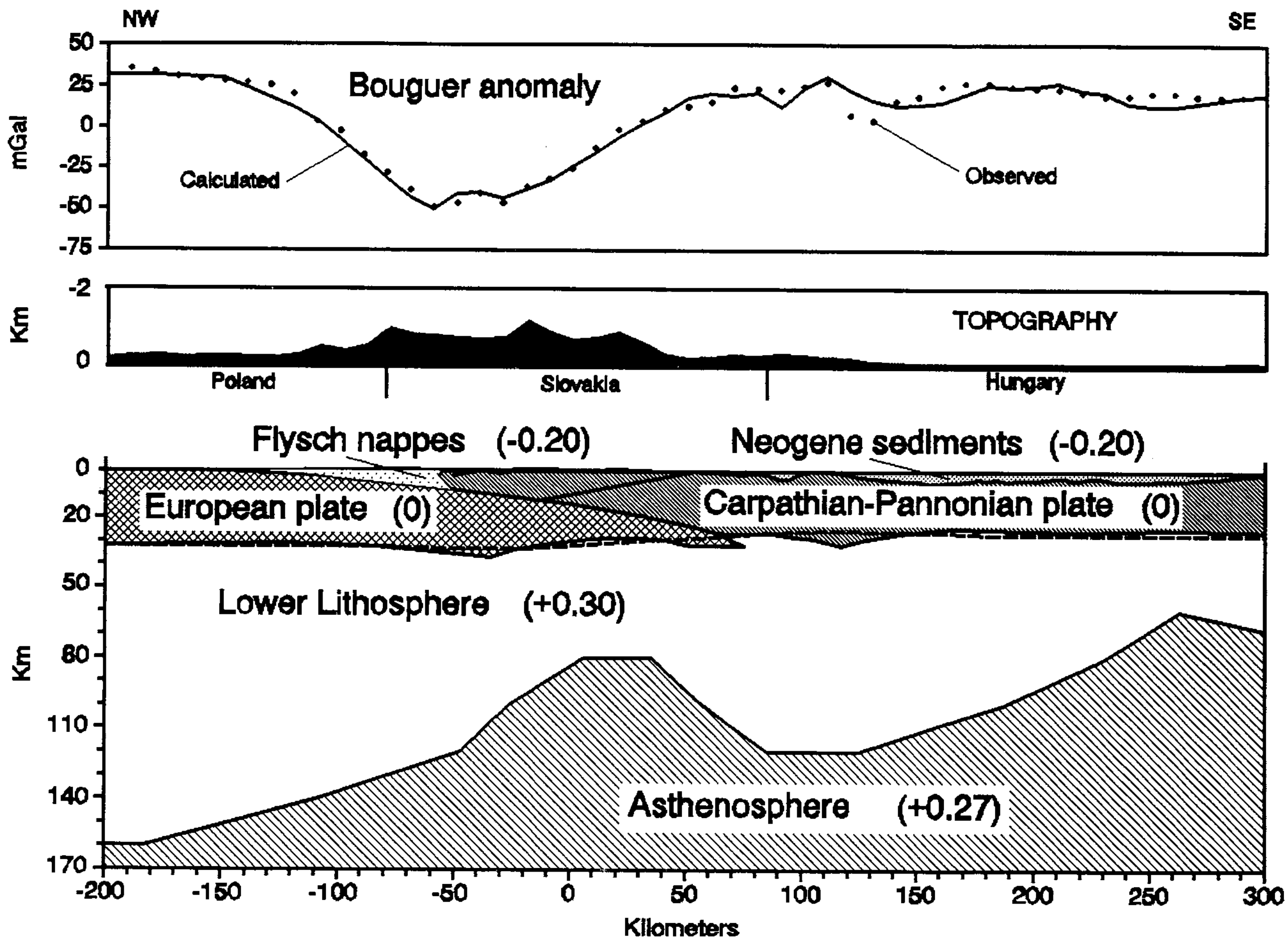

Fig. 6. Schematic two-dimensional density cross section of the lithosphere along Profile 2T.

Discussion

In introduction, it is immediately necessary to state that, it is not possible, to unambiguously answer the question of whether the subduction of the lower European Plate under the upper Carpathian-Pannonian Plate is shallow or steep, on the basis of the method of density modelling. This is still the case with a maximum effort to use recent and the latest geophysical and geological data. In a preceding chapter it was clearly shown that both the above mentioned cases can be modelled in accord with the observed gravity field.

Šefara & Kubeš (1993) emphasized in their interpretation of Profile 2T, the gradual sinking of the European Plate, by which in the whole section from the Klippen Belt to the northern margin of the Veporic Unit, the contact between the colliding plates is practically horizontal, and then its inclination is steep and it rapidly deepens into the depths. Some geological interpretations support their model (e.g. Bezák et al. 1992). The density model given on Fig. 4 most closely approximates to their solution. In the density model of Profile 2T (Šefara & Kubeš 1993), the density contrasts are less in the upper crust, than in the lower lithosphere, or between the lower lithosphere and astenosphere. From the physical point of view and the application of P-T conditions at great depths, it is possible to suppose that the density contrasts should decrease with depth, in spite of the proved anizotrophy of the lower lithosphere and astenosphere.

In our models it is accepted that the course of the lithosphere-astenosphere boundary, determined from seismic observations (Babuška et al. 1987, 1988). Šefara & Kubeš (1993) divided the astenosphere density into two anomalous zones, and interpreted the zone with greater density as the astenospheric part of the southern lithosphere plate.

It is necessary to comment that in calculation of a lithosphere density model, it should also be possible to find a good agreement between the calculated and observed gravity field with a change of other density boundaries, as was done in this study. It would mainly concern the possibility of changes of form and density of the boundaries between the upper and lower crust of the Western Carpathians and, between the lithosphere and astenosphere. However we again recall that in relation to their proved smaller gravitational effect in comparison with the Moho, it is necessary to consider moderately significant changes, since these could more significantly influence the overall gravity field.

The following facts are against the idea that the subduction of the European Plate under the upper Carpathian-Pannonian Plate is shallow, so that it extends to the southern area of the Central Western Carpathians, or the northern part of the Pannonian Basin (that is, the neo-Alpine convergence would be more than 100 km):

a – The small amplitude and short wave length of the gravity minimum (Lillie et al. 1993).

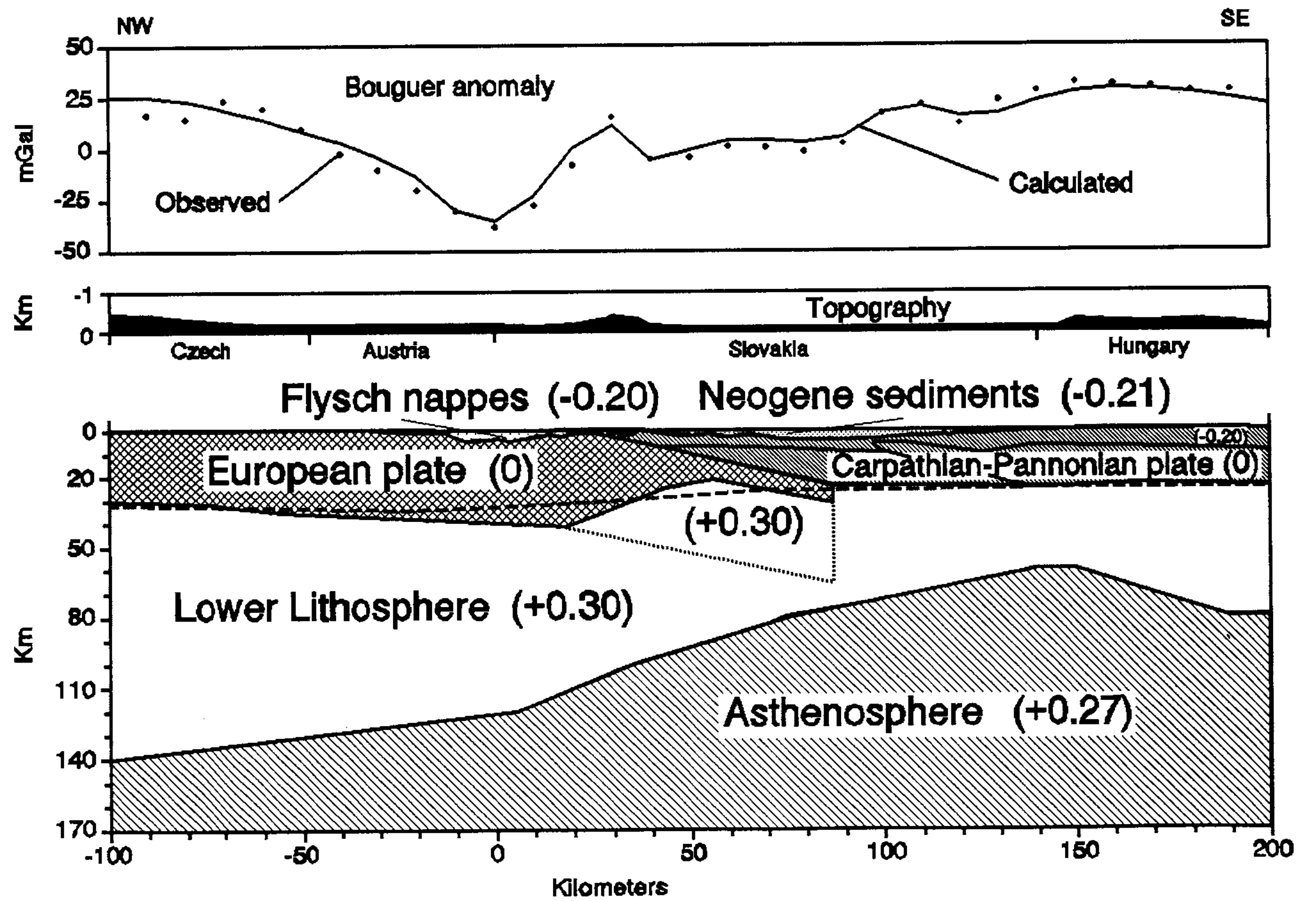

Fig. 7. Schematic two-dimensional density cross section of the lithosphere along Profile 3T.

b – In such a case, the collisional areas are characterized by high topography, significant erosion and denudation (Karner & Watts 1983).

c – The substantially smaller thickness of the foredeep basins (Royden 1993).

d – The occurrence of rocks on the surface with a high degree of metamorphosis (Royden 1993).

The work of Lillie et al. (1993) showed that it is precisely the difference of size of amplitude and wave length of a gravity minimum which determines the difference in size of convergence followed by erosion and crustal rebound. Crustal shortening in the neo-Alpine development of the Western Carpathians was determined as around 50 km, while in the Eastern Alps it was around 175 to 200 km. This result supposes only a partial underthrusting of the continental-oceanic transitional zone. The results of Royden (1993), which assume that the rate of overall plate convergence is less than the rate of subduction, also correspond to this. This type of subduction boundary is called a retreating plate boundary. In the type of mountain chain, to which the Carpathians also belong, the extensional form of regional deformation prevails, in spite of the existence of overthrust zones and local horizontal shortening in the upper plate.

Shortening appears only in the narrow zone of the front of the overthrusting plate, where the sedimentary rocks are scraped from the subducting plate and accreted onto the base of the overthrusting plate in the continental equivalent of an accretionary prism.

It appears quite probable that the result of a steep inclination of the subducted plate is a significant thickness of flysch sediments, while precisely this great thickness is a characteristic feature of a small continental convergence (Royden 1993).

Comparison of the lithospheric density models of the Western Carpathians and Eastern Alps, and also geological profiles across the Alps (Pfiffner 1993; Ratschbacher & Frisch 1993; Zillie et al. 1993; Raumer & Neubauer 1993) show that in contrast to continental convergence in the Western Carpathians, continental convergence in the area of the Eastern Alps is accompanied not only by significant crustal shortening (approaching a depth of 50 km) but also lithospheric roots. Therefore a double thickening (crust and lithosphere) exists here. The amount of crustal shortening is also greater here. The result of this is a substantially greater amplitude (around 150 mgl) and wave length (around 400 km) of the measured gravity field in comparison with the Western Carpathians.

We are fully aware that the continental convergence (collision) in the area of the Western Carpathians was substantially more complicated and variable during its development. The accretionary wedge of flysch and foredeep sediments is a result only of the youngest (Tertiary) phase of the collision. Therefore figures 3-4, at least in outline, also indicates the movement of the Veporic Unit onto the Tatric Unit, and therefore that the process of lithosphere convergence was not a single event. In other words the overthrusting of the basic tectonic units of the Western Carpathians was a much more complicated process than the density models show.

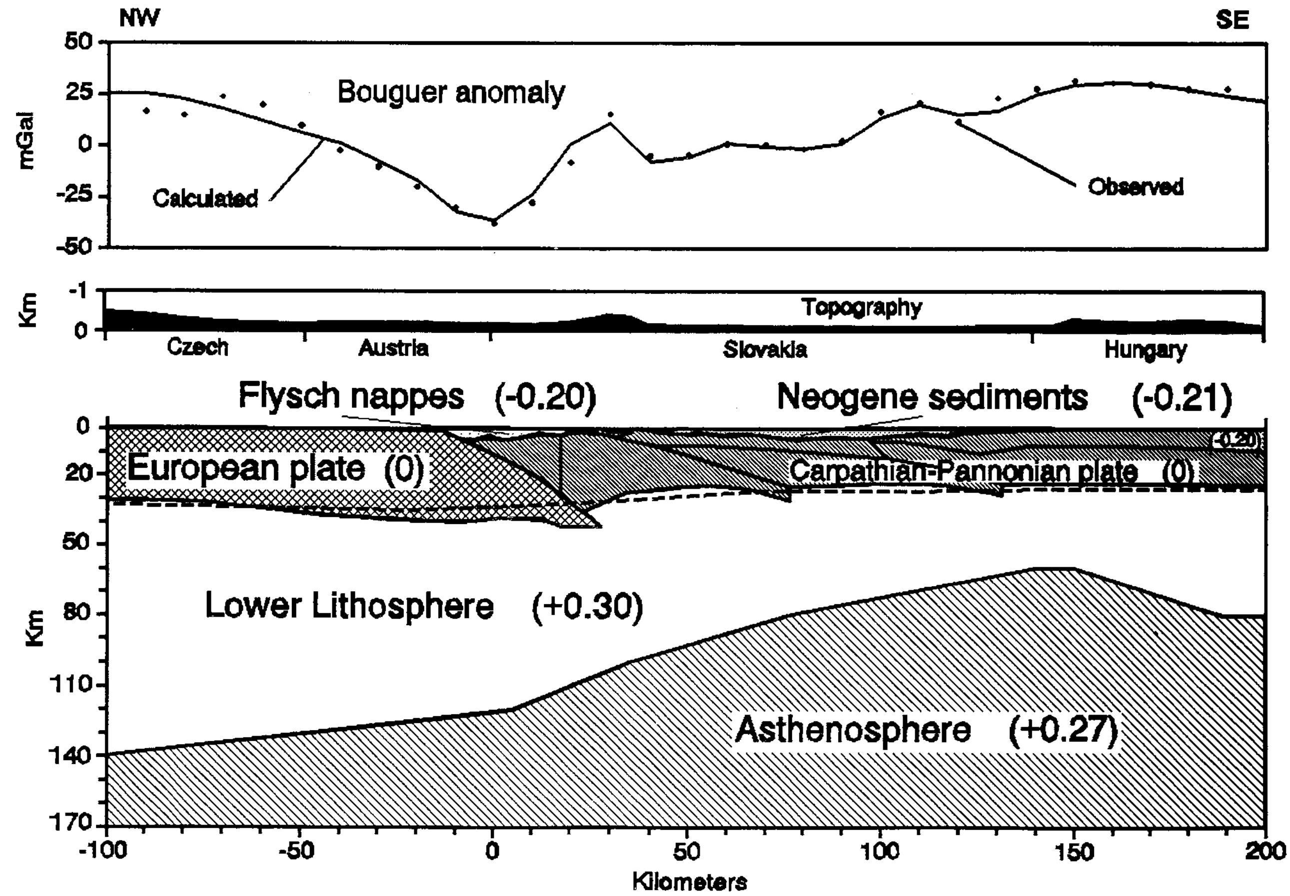

Fig. 8. Schematic two-dimensional density cross section of the lithosphere along Profile 3T.

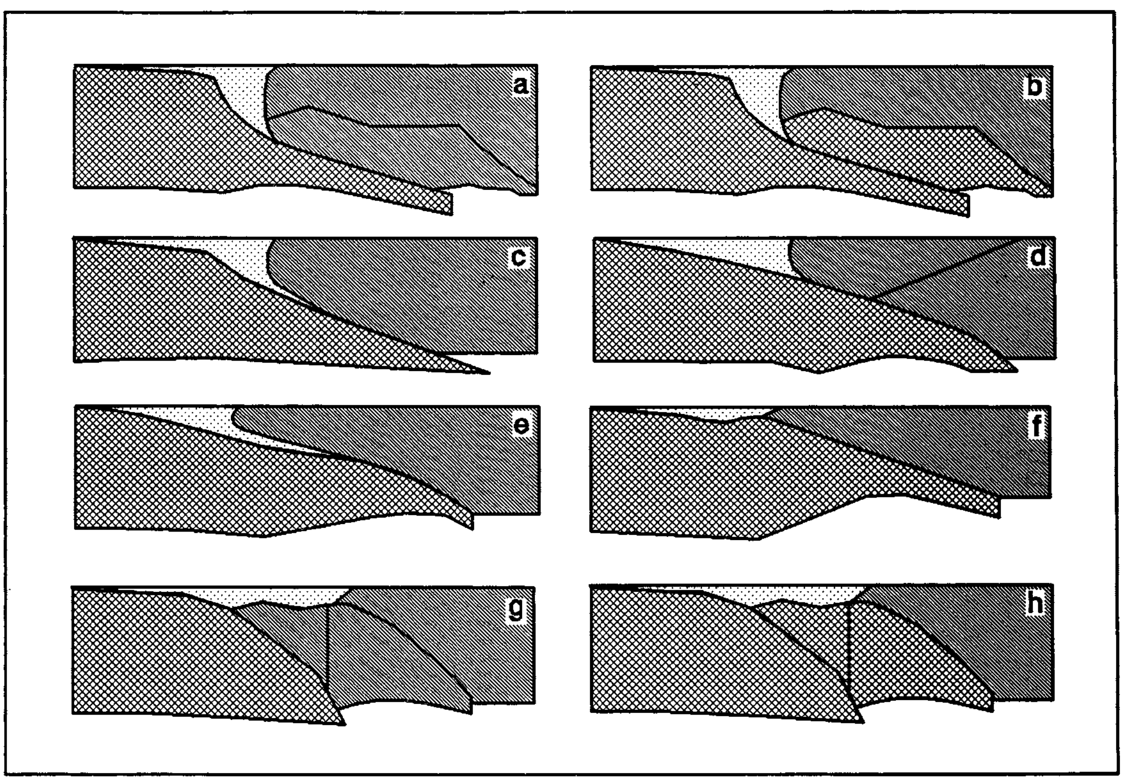

Fig. 9. Schemes of the possible configuration of the Moho at the contact of the colliding plates, determined on the basis of the results of density modelling. Schemes 9 a–e represent possible cases of the course of the Moho along Profile 2T, while schemes 9 f–h along Profile 3T.

Conclusion

Solution of the problem of continental collision of two lithosphere plates (the European and Carpathian-Pannonian), which resulted in the Western Carpathian mountain range, on the basis of density modelling (in combination especially with seismic data and other geological-geophysical data) produced a whole series of findings. However unambiguous answers to the many questions is not possible from the principal argument. The density models of both interpreted profiles also confirms the variation in the process of collisional orogenesis in time, and especially in space. The specificness of each of them, with one profile passing through the south-west part and the second through the northern part of the Western Carpathians, is evident.

Differences in the continental collision in the lower lithosphere are also evident. On Profile 2T, there is striking agreement of the continuation of the direction of subduction of the European Plate, with the direction of inclination of the deepening of the lithosphere-astenosphere boundary. This agreement could be a result of a relict of the southern continuation of the subduction zone to greater depths. The latest results of seismic tomography in the wider Mediterranean region support this result (Spakman et al. 1993). Their results clearly show that, for example in the area of the Aegean Sea, subduction is traceable up to depths of 800 km. However this fact is not observed on Profile 3T.

Density modelling also strikingly points to the fact that the foredeep basins of the Western Carpathians (frontal foredeep and flysch zone) are the result of flexural loading of the foreland lithosphere.

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