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CRUSTAL DEVELOPMENT AND TECTONIC MODELS OF WESTERN CARPATHIANS FROM GRAVITY INTERPRETATION

ROBERT J. LILLIE[1] and MIROSLAV BIELIK[2]

[1]Department of Goesciences, Oregon State University Corvallis, Oregon, 97331, U. S. A.
[2]Geophysical Institute, Slovak Academy of Sciences, Dúbravská cesta 9, 842 28 Bratislava, CSFR

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Abstract: A series of density models illustrating the gross form of Bouguer anomalies developed during continental collision is compared to Bouguer profiles observed across the Western Carpathians. Gravity models and maps of crustal thickness in Central Europe show that the Moho deepens southward from the European platform to the Outer Carpathians, then rises by more than 10 *km* across the mountains to the Pannonian Basin. Comparing this overall geometry and Bouguer profiles to the hypothetical models suggests that Tertiary convergence in the Western Carpathians stopped just after ocean basin closure. By this interpretation, the zone of thicker crust beneath the foreland is a geometric consequence of underthrusting the continental edge beneath thick flysch deposit, while crustal thinning to the south may have two components: 1 - original thinning preserved from the Mesozoic continental edge of Europe; and 2 - additional thinning during Neogene opening of the Pannonian Basin. Preserved Mesozoic crustal thinning in the Carpathians would suggest that only a moderate degree of continental underthrusting has occurred, so that the gross form of the continent to ocean transition zone may be intact beneath the mountains.

Key words: density and tectonic models, crustal convergence, the Western Carpathians.

Introduction

The late Cretaceous to Recent collision zone in Central Europe may represent differing degrees of destruction of the Mesozoic passive continental margin. In the Alps, collision progressed to an advanced stage with large amounts of crustal thickening, while the Carpathians show evidence of only slight convergence after ocean basin closure (Tomek 1988). Neogene extension that led to development of the Pannonian Basin is coincident with the later phases of collision, particularly in the Eastern Carpathians (Royden, Horváth & Rumpler 1983; Royden et al. 1983). But we must state that the process of continental collision in the Western Carpathians was much more complicated and there are many questions which are not answered up to the present.

This paper shows preliminary results of a study of the structure and evolution of the lithosphere in the eastern Alpine-Carpathian-Pannonian Basin region. It briefly presents models that may be considered working hypotheses about the crustal structure and tectonics of the Western Carpathians.

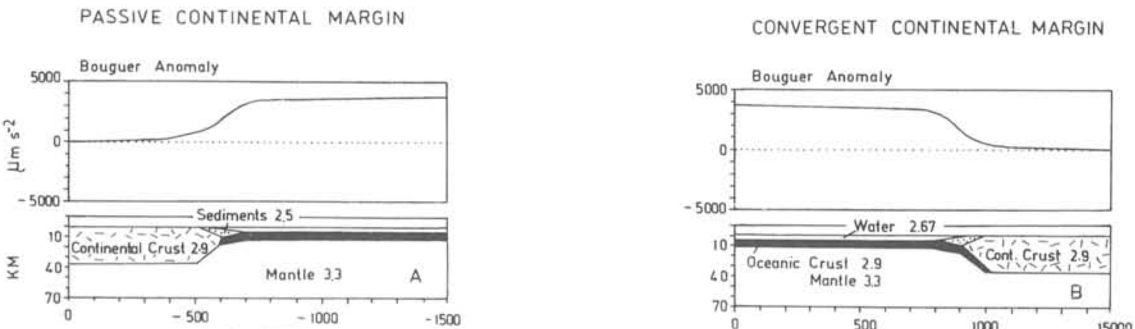

Fig. 1. Density configurations (in g/cm^3) assumed as starting positions for models of continental collision depicted in Fig. 2. The models for the passive and convergent margins are simplified so that they are mirror images. Note that a density of 2.67 g/cm^3 is used in compating the Bouguer gravity anomaly according to the method of Talwani et al. (1959).

Hypothetical Bouguer anomalies resulting from closure of an ocean basin and continued continental convergence

Model representing stages of development of collisional mountain belts (Stockmal, Beaumont & Boutilier 1986; Stockmal & Beaumont 1987) illustrate time sequences showing ocean basin closure and consequent crustal thicking, tectonic and sedimentary loading of the underthrusting margin, and erosion of the upper plate. Lillie (1991) developed models depicting changes in density distributions and consequent gravity anomalies from such processes.

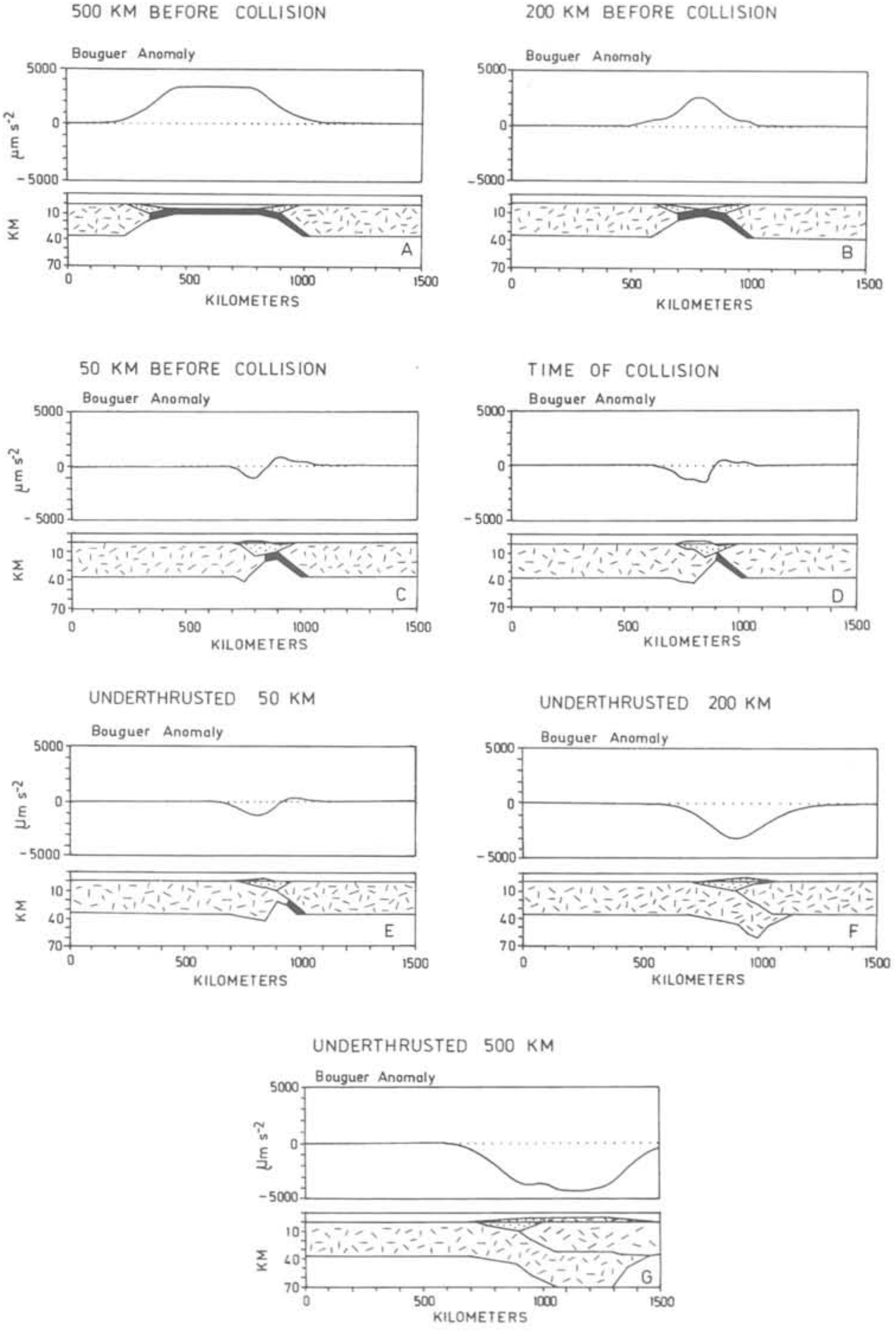

Fig. 2. Bouguer gravity anomalies resulting from ocean basin closure and consequent collision of passive and active continental margins. Assumed densities are the same as those illustrated in Fig. 1. After Lillie (1991).

Simplified density models of passive and active continental margins, from that study are shown in Fig. 1. The models are in Airy isostatic equilibrium, so that mass columns are equal at the base of each model (70 *km*). This state of equilibrium is maintained throughout a sequence of models representing closure of the ocean basin and collisional mountain belt development (Fig. 2).

The Bouguer gravity anomalies resulting from this process are in a gross sense directly related to Moho depth and inversely related to topography and bathymetry (Fig. 2). They are initially near zero over the continents and rise to about 3500 $m.s^{-2}$ over the ocean (Fig. 2A), as in the example from the Atlantic passive margin (Fig. 3). On land the Bouguer correction attempts to remove contributions of material above a sea-level datum and the resulting anomaly also mimics the general configuration of the crust/mantle boundary (Fig. 2 F, G). Critical deviation from this simple relationship appears in the initial stages of collision. In this case the Bouguer anomaly results from the interference of the thick (negative) sedimentary contribution and the (positive) mantle contribution (Fig. 2C-E). At this stage, the Bouguer anomaly changes from a high (Fig. 2B) to a low/high couple (Fig. 2C, D, E) to a low (Fig. 2F).

As the continents converge, the Bouguer anomaly lessens as the ocean Moho is depressed and the ocean filled with more sediments (Fig. 2B). Approaching collision, the continental Moho becomes depressed and mountains begin to grow in sediments over transitional crust of the passive margin, resulting in a Bouguer low over the foreland and high toward the interior (Fig. 2C,D,E). This stage may in a general sense explain the "low-high couple" observed in some mountain ranges that have experienced only "soft" collision, such as the Ouachita Mountains of the southern United States and Sulaiman Range of Pakistan (Lillie 1991). As discussed below, we interpret that a similar Bouguer gravity expression in the Western Carpathians suggests a similar crustal structure and stage of development.

As convergence continues, the ocean water is completely replaced by sediments, further depressing the Moho and leading to mountains comprised mainly of uplifted sediments, with a moderate Bouguer gravity low (Fig. 2F). At an advanced stage, further underthrusting leads to doubling of continental crustal thickness (to 70 *km*), with mountains of uplifted crust abut 4 *km* high and a broad Bouguer gravity low of about - 4500 $m.s^{-2}$- (Fig. 2G). The Himalaya represent this more advanced stage (Fig. 3).

Western Carpathian gravity model

Šefara (1984) and Bielik et al. (1990) have presented density models of the Western Carpathians based on gravity and other geophysical and geological constraints. Location of gravity profile A-A modelled in Figs. 5 and 7 is shown in Fig. 4. The model (Fig. 5) is similar to these earlier models, in that it shows southward crustal thinning from the European platform, across the Carpathians to the Pannonian Basin, and thick flysch deposits beneath the Outer Carpathians. This model is presented as an example of the general structure of the Western Carpathians that ongoing studies will build upon.

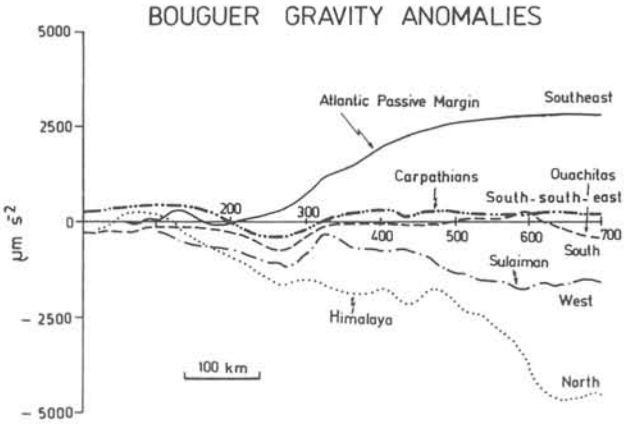

Fig. 3. Comparison of the four Bouguer gravity anomaly profiles from the Ouachita Mountain, Sulaiman Range, the Western Himalaya and the Western Carpathians. For further comparison, the Bouguer anomaly along U.S.G.S. seismic line 5 off the Atlantic coast of the United States is shown (after Grow et al. 1979), extended landward (northwestward) and seaward (southeastward) according to map of Woollard & Joesting (1964); compare to Fig. 1A. The anomalies are oriented so that the craton ("foreland") of the interpreted downgoing plate is to the left. Note that the Ouachiteas, Sulaiman and Western Carpathians may correspond to very early stages of collision (Fig. 2C,D,E) while the Himalaya represent a more advanced stage (Fig. 2G).

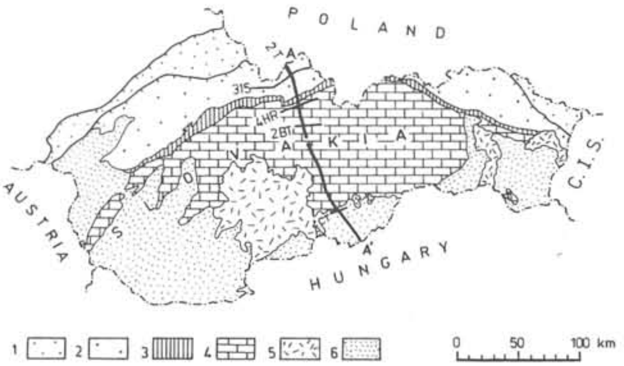

Fig. 4. Gravity profile A-A' modelled in Figs. 5 and 7. Note location of deep crustal seismic profile 2T (Tomek et al. 1987, 1989), described as "CZESLOCORP SURVEY" in Fig. 5.

1 - outer of Krosno (flysch); 2 - inner of Magura (flysch); 3 - Pienniny Klippen Belt; 4 - Inner Carpathians (undivided); 5 - Miocene subduction volcanics; 6 - Neogene.

Fig. 5A illustrates the effects of gross density changes in the upper part of crust. The model shows a gentle decrease in values going from the crust of the European plate (2.76 g/cm^3) to crust of colliding terranes (2.72 g/cm^3), with a shorter wavelength low associated with thick flysch between the plates (2.62 g/cm^3). The zone of the lowest gravity values belongs after Šefara & Obernauer et al. (1989) to region of negatively disturbed gravity field. The effect of the Moho shallowing by about 10 *km* from the European platform to the Pannonian Basin is modelled in Fig. 5B. Positive gravity values in SSE part of profiles belong to region of positively disturbed gravity field of southern and southeastern Slovakia (Šefara & Obernauer et al. l.c.) and Pannonian Basin. A density contrast of 0.2 g/cm^3 is assumed for the lower crust (3.0 g/cm^3) versus the upper mantle (3.2 g/cm^3). Fig. 5C represents the effects of models 5A and 5B added together, showing close agreement between calculated and observed anomalies. A generalized interpretation of the total density model is presented in Fig. 5D. This interpretation is consistent with current models of crustal structure and tectonic development of the Western Carpathians that involve steep subduction just before convergence ceased (Royden, Horváth & Rumpler 1983; Tomek 1988).

Comparison between observed and hypothetical Bouguer anomalies

Examples from specific mountain belts (Ouachita Mountains, in the southern United States, Sulaiman Range and the western Himalaya in Pakistan) have been published by Lillie (1991). A comparison of the Bouguer anomalies for these three zone and for the Western Carpathians is shown in Fig. 3. The Western Carpathians are interpreted as evolving to a very early stage in the collision process, so that convergence stopped just after ocean basin closure. Hence, the Western Carpathian share the following attributes with the Ouachita Mountains and Sulaiman Range:

1 - The mountains are relatively low ($<3km$).

2 - There is a very thick sedimentary section preserved (10 - 15 *km*).

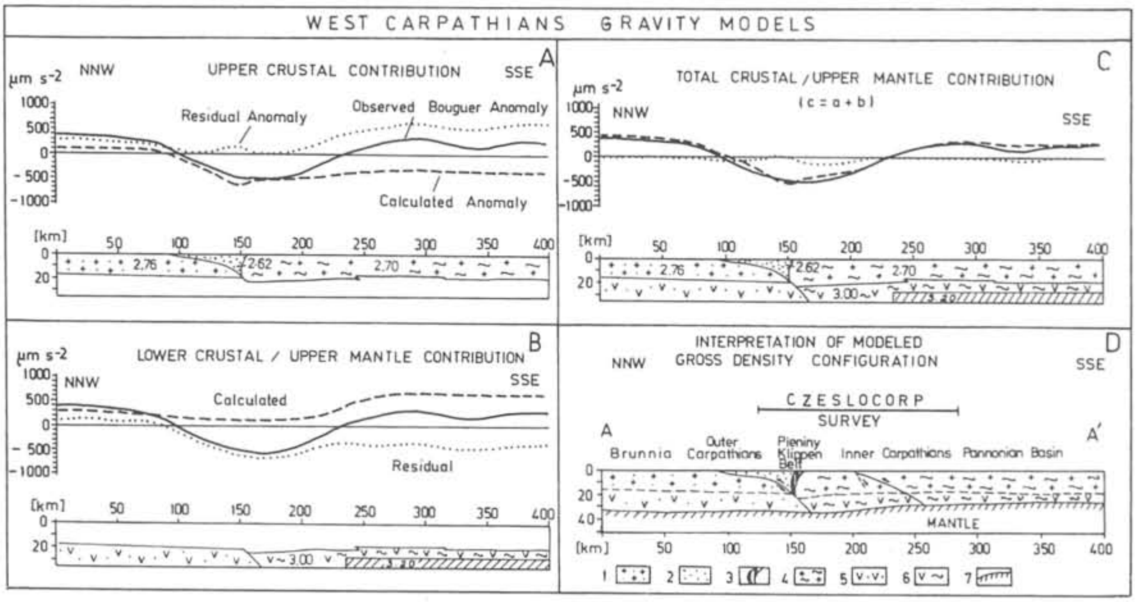

Fig. 5. Two-dimensional density models for Bouguer gravity profile 2T (A-A'). The calculated anomaly for each model was determined using the method of Pohánka (1988). Densities are in g/cm^3. The residual anomaly is the observed Bouguer anomaly minus that calculated from the model. Note position of seismic profile 2T (CZESLOCORP SURVEY).

1 - upper crust of the European plate passive margin; 2 - flysch sediments of the Outer Carpathians; 3 - Pienniny Klippen Belt; 4 - upper crust of the Carpathian-Pannonian plate; 7 - mantle.

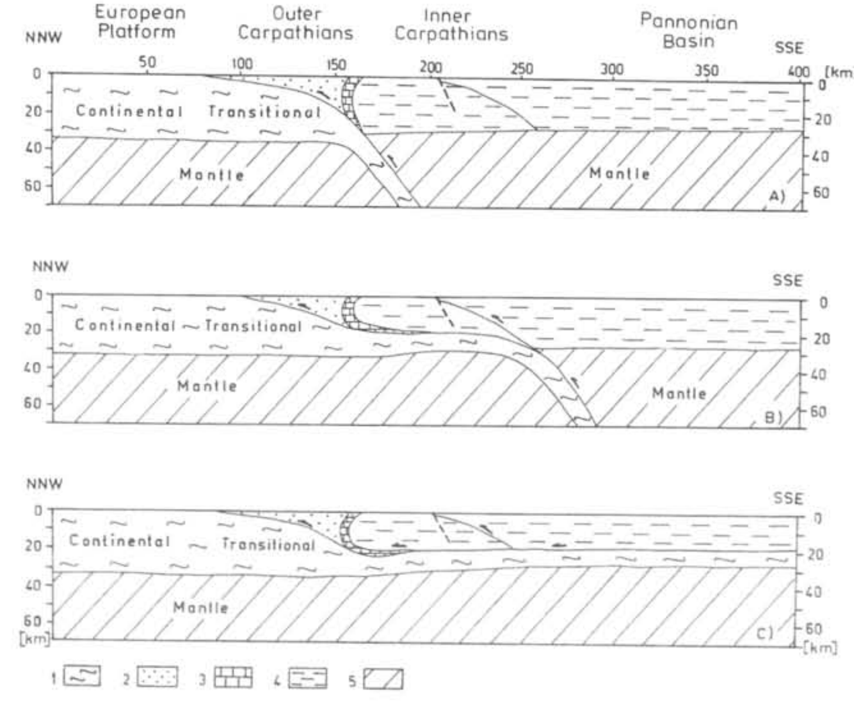

Fig. 6. Potential tectonic models along profile 2T (A-A') based on gross crustal structure modelled in Fig. 5.

1 - crust of the European plate passive margin; 2 - flysch sediments of the Outer Carpathians; 3 - Pienniny Klippen Belt; 4 - crust of the Carpathian-Pannonian plate; 5 - mantle.

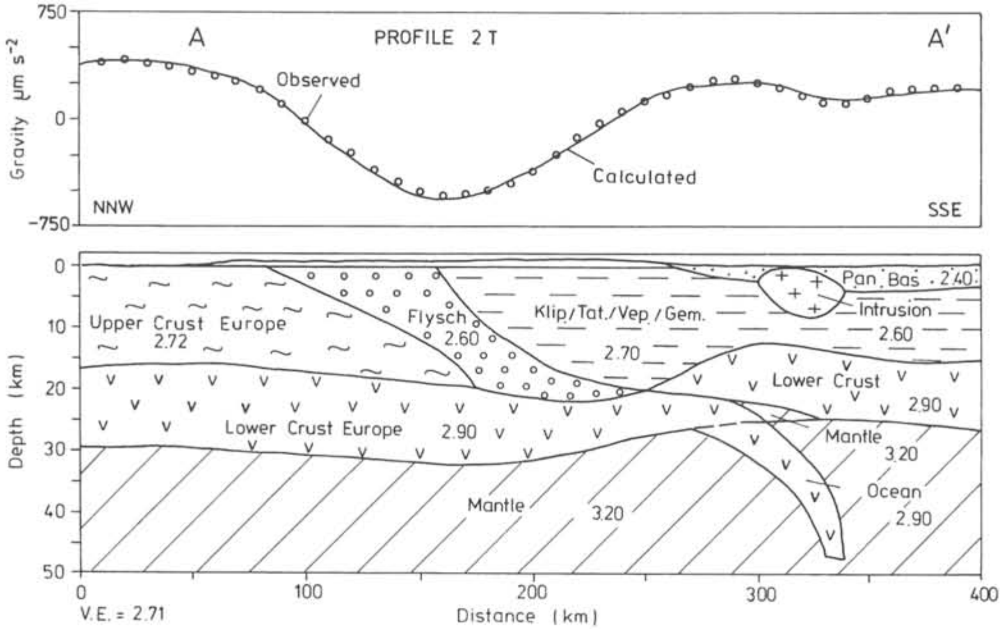

Fig. 7. Reinterpretation of gravity profile 2T (A-A'). Densities in *g/cm*^{3}. This is a preliminary model intended to illustrate a concept that will be further examined in ongoing studies.

3 - There is a very shallow erosion level in the hinterland, with very little basement exposure.

4 - Toward the hinterland, the Moho is at, or shallower than, that of normal continental crust (30 - 35 *km*).

5 - Bouguer anomalies are low over the foreland, but rise toward the hinterland.

Fig. 2 E suggests that underthrusting of a passive continental margin after ocean closure might produce a geometry in which the Moho deepens beneath the foreland, but then shallows toward the overriding plate (Stockmal, Beaumont & Boutilier 1986). The resulting Bouguer gravity anomaly consists of a broad low due to the thick sediments and moho depression in the foreland, and a gentle high resulting from the shallow mantle material in the hinterland. This gravity expression is similar to the observed Bouguer gravity profiles across the Western Carpathians (Figs. 3, 5). Thus, the Western Carpathians appear to have progressed only to a stage of very soft collision, with attributes of low mountains and the preservation of the passive continental margin beneath a thick sedimentary section.

Alternative tectonic hypotheses

Three differing interpretations of the shallow Moho beneath the Inner Carpathian - Pannonian Basin region are shown in Fig. 6. The standard interpretation (Fig. 6A) involves steep subduction of the crust at the Pieniny Klippen Belt (Tomek et al. 1989). Shallow mantle material beneath the Tatricum therefore belongs to the overriding plate. In Fig. 6B, shallow underthrusting occurs in the foreland, with steep subduction of the crust at the position of the older suture zone between the Tatricum and Veporicum. Shallow mantle material beneath the Tatricum in this case belongs to transitional crust of the European plate. The model in Fig. 6C shows shallow underthrusting of the crust beneath the entire region, including the Pannonian Basin; shallow mantle material therefore belongs entirely to the European plate.

Model 6C is considered unreasonable, while 6A and 6B represent "end-member" hypotheses under evaluation in ongoing studies. In 6A the shallow Moho beneath the Inner Carpathians may be attributable to thinner crust of the overriding plate and/or Neogene Pannonian Basin extension. In 6B the shallow Moho is inherited from the geometry of the Mesozoic continent to transition zone, and Neogene extension affects only the region south of the Inner Carpathians. While 6A is an acceptable interpretation of the current structure and tectonic evolution, we feel that 6B should be considered as an alternative for reasons discussed below.

Fig. 7 is a revision of the gravity model in Fig. 5, showing that the crustal structure in the Western Carpathians may be similar to the underthrusting model presented in Fig. 2F. The model shows thinning of the crust of the downgoing plate form continental thickness beneath the European platform on the north, to Pess thickness beneath the Inner Carpathians (Klippen Belt/Tatricum/Veporicum/Gemericum). Furthermore, the model incorporates a zone of relatively thick crust that follows outer portions of the Eastern and Western Carpathians on Moho depth maps (Mayerová et al. 1985; Tomek 1988) and on cross sections based on refraction interpretations (Lefeld & Jankowski 1985). As shown in Fig. 2C, D, E this geometry may be a consequence of only partially underthrusting the continent to ocean transition zone.

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