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An Ivrea-type Structure in the Alpine –Carpathian Junction Area?

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With 21 Text-Figures and 1 Table

Österreich
Ungarn
Slowakei
Ivrea-Zone
Geophysik
Gravimetrie

Inhalt

Eine Struktur vom Ivrea-Typ im Grenzbereich Alpen/Karpaten?

Zusammenfassung

Die Verbindung zwischen Alpen und Karpaten erstreckt sich über die drei Länder Österreich, Slowakei und Ungarn. Eine Detailanalyse des Schwerefeldes unter Berücksichtigung von reflexionsseismischen Profilen und von Dichtewerten aus Kernbohrungen ließ zum Schluß gelangen, daß – nach Korrektur des topographischen Effekts des Basements – eine deutliche Restanomalie (etwa 15 mGal) über dem Mihályi Rücken in Ungarn verbleibt. Iterative Schweremodelle entlang reflexionsseismischer Profile zeigten, daß unter der Annahme einer normalen kontinentalen Kruste für die transdanubischen Ketten dieser Rücken aus anomaler Kruste – mit dichterem Material – aufgebaut ist.

Ein isometrisches Schwerehoch bei Kolarovo (Slowakei) im nordöstlichen Donau–Raab-Becken wird als miozäne Andesitintrusion in das tertiäre Basement interpretiert. Die südburgenländische Schwelle in Österreich wird als Aufragung des prätertiären Basements aufgefaßt, entlang der eine zusätzliche Erhöhung des regionalen Schweregradienten vermutet wird. Slowakische und österreichische Daten wurden unter Zuhilfenahme der Ergebnisse aus ungarischen Profilen re-interpretiert: es resultierte daraus eine Zone anomaler Krustendichte über etwa 200 km im genannten Bereich aller drei Länder. Eine mögliche Erklärung hiefür ist die Annahme der Existenz einer Struktur analog der westalpinen Ivrea-Zone mit signifikanter Reduzierung der Krustendicke im Alpen/Karpaten-Grenzbereich in der Folge eines neogenen Extensionsregimes und nachfolgender Subsidenz; alle diese Faktoren modifizierten die Topographie der Kruste in diesem Gebiet.

Sowohl die Ivrea- als auch die Mihályi-Struktur liegen an der Insubrischen Linie, an der eine sich über mehr als 400 km erstreckende dextrale Verschiebung stattfand, die mit einer Ausquetschung ostalpiner Einheiten in Folge einer obereozänen Kontinent-Kontinent-Kollision in Zusammenhang stehen dürfte. Die genannten Dichteanomalien Ivrea und Mihályi entstanden somit nach einem frühkretazischen Kollisionsereignis, welches wiederum Folge der Schließung des Penninischen Ozeans war.

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Ivrea-típusú szerkezet az Alpok-Kárpátok csatlakozási övében?

Összefoglalás

Az Alpok és a Kárpátok csatlakozási öve három országra esik: Ausztriára, Magyarországra és Szlovákiára. A gravitációs tér reflexiós szeizmikus szelvényekre és fúrómagokon kapott sűrűség-adatokra támaszkodó speciális elemzése arra a felismerésre vezetett, hogy az aljzat-domborzat hatásának eltávolítása után a Mihályi-hátság felett jelentős (kb. 15 mGal) anomália marad. A gravitációs tér szeizmikus szelvények menti iterációs modellezésével kimutattuk, hogy amennyiben a Dunántúli-középhegység alatt normális kontinentális kéreg van, a Mihályi-hátság alatti földkéreg anomális felépítésű, s az aljzat felszíne alatt 3 km-rel nagysűrűségű tömeg települ benne.

Szlovákiában Gútánál (Kolarovo) egy izometrikus gravitációs maximum van, amelyet egy aljzaton belüli miocén andezit-intrúzióval magyaráztak. Ausztriában a Dél-Burgenlandi-küszöb egy aljzatkiemelkedést képez, amely felett a regionális gravitációs tér emelt voltát tételezték fel.

A magyar szelvényeken szerzett tapasztalatok alapján mind a szlovákiai, mind az ausztriai adatokat egy földkérgen belüli sűrűséganomáliaként értelmeztük újra, amely így három országon át kb. 200 km-en át követhetőnek bizonyult. Egy értelmezési lehetőség az, hogy a földkérgen belüli sűrűség-anomália a Nyugati Alpokból jólismert Ivrea-szerkezet analógja. A két terület között jelentős eltérés van, amely azonban visszavezethető lenne arra, hogy az Alpok és a Kárpátok csatlakozási övében a kéregvastagság a neogén extenzióval és besüllyedéssel kapcsolatban erősen lecsökkent, ami nyilvánvalóan módosította az eredeti kéregszerkezetet.

Mind az Ivrea-, mind a Mihályi-szerkezet az Inszubriai-vonal mentén helyezkedik el, több mint 400 km-es jobbos eltolódásnak megfelelő elrendeződést mutatva, ami az Alpoknak a késő-eocénben lejátszódott kontinens-kontinens ütközéssel kapcsolatos szétnyomódására vezethető vissza. Az Ivrea–Mihályi földkérgen belüli sűrűség-anomália valószínűleg egy kora-kréta kollíziós övből – a Pennini-óceán záródási övéből – keletkezett.

Abstract

The Alpine–Carpathian junction area spreads over three countries: Austria, Hungary and Slovakia. A special analysis of the gravity field based on reflection seismic profiles and density data from boreholes resulted in the conclusion that after removal of the basement topography effect a significant (about 15 mGal) anomaly remains above the Mihályi Ridge in Hungary. By means of iterative modeling of the gravity field along reflection seismic profiles it has been shown that if the Transdanubian Range is of normal continental crust the Mihályi Ridge is of anomalous crust with high-density masses from about 3 km below the basement surface.

In Slovakia, an isometric gravity high (Kolarovo) in the northeastern Danube–Rába Basin was interpreted in terms of a Miocene andesite intrusion within the pre-Tertiary basement. In Austria, the South Burgenland Swell is expressed as an elevation of the pre-Tertiary basement, and an additional elevation of the regional gravity field was supposed on it.

Based on the experience from Hungarian profiles both the Slovak and Austrian data have been reinterpreted in terms of a crustal density anomaly which turned to be traceable for about 200 km over all the three countries. A possible explanation for the crustal density anomaly is that it is an analog of the well-known Ivrea structure of the Western Alps. Significant differences are observable between these areas, but they may be due to sharp reduction of the crustal thickness in the Alpine–Carpathian junction area in connection with Neogene extension and subsidence which obviously modified the primary structure of the crust.

Both the Ivrea and Mihályi structures are located along the Insubric line displaying >400 km of dextral offset which may be related to the squeezing out of the Alps due to continent-continent collision in the Late Eocene. The Ivrea–Mihályi crustal density anomaly seems to have originated from an Eo-Cretaceous collision zone (closure of the Penninic ocean).

1. Introduction

The Bouguer-anomaly maps are extremely useful in evaluating regional structures. Unfortunately, in the former socialist countries, gravity data were for a long time secret, and maps based on recent measurements have not been published yet. In the Bouguer anomaly map (scale around 1 : 2,200,000) published by SCHEFFER (1957), the Alpine–Carpathian mountain range appears as a chain of well-expressed gravity lows (<–30 mGal) which probably reflect the mountain root in the Alps and underthrust sedimentary sequences in the Carpathians. East of the Eastern Alps and south of the northern West Carpathians the more-or-less uniform gravity high (>+10 mGal) of the Transdanubian and North Hungarian ranges is situated.

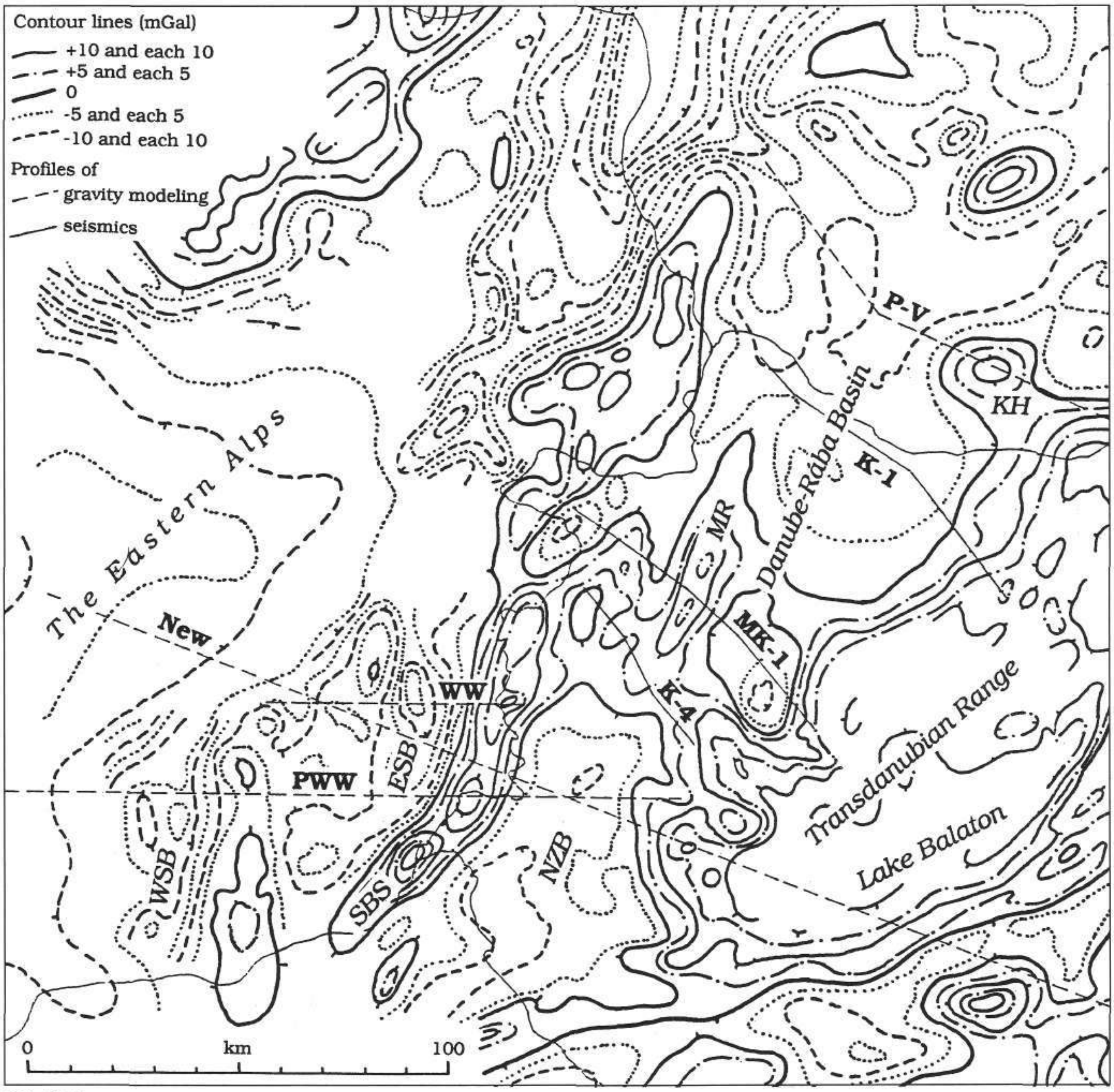
The intermediate belt displays a dismembered anomaly pattern with local highs and lows (Text-Fig. 1). In the first approximation, the anomaly pattern seems to reflect the pre-Cenozoic basement topography: gravity highs coincide with superficial outcrops or basement highs whereas gravity lows fall on basement lows. In a qualitative sense this reflects the sharp density difference between the basement and basin fill, i.e. the density excess of the basement rocks and the density deficiency of the sediments. Consequently, the gravity anomaly pattern can help in delineating the young structures connected with the subsidence.

It is remarkable, however, that the Mihályi Ridge (Text-Fig. 2) buried by a 1.5 km thick Neogene sequence coincides with a gravity high of the same value (>+15 mGal) as those on neighbouring basement outcrops in the Rechnitz – Kőszeg, Sopron – Hainburg or Bakony areas. In the next approximation, this fact seems to reflect the presence of anomalous, dense masses on the Mihályi Ridge or below it.

2. An Intra-Crustal High-Density Body in Hungary

The reflexion seismic section MK-1 crosses the Mihályi Ridge in the middle. Bouguer anomalies in general follow the basement topography (Text-Fig. 3). Procedures outlined in Appendix 1 resulted in separation of the regional gravity field independent of the basement topography and reflecting intra-crustal density inhomogeneities. The corresponding anomaly path shifted to the depth 2.6 km b.s.l. (Text-Fig. 4) displays a high with a flat slope in the northwest and a steep slope in the southeast. By means of computer modeling a lot of various models have been checked, density data having been taken from direct measurements (Table 1), and the Moho surface, mainly from POSGAY et al. (1991).

The most probable version is presented in Text-Fig. 5. The southeastern half of the section (Transdanubian Range unit) seems to be of normal continental crust whereas in the middle of the section high-density masses are in about 3 km from the basement surface, their top gently going down towards the northwest. The



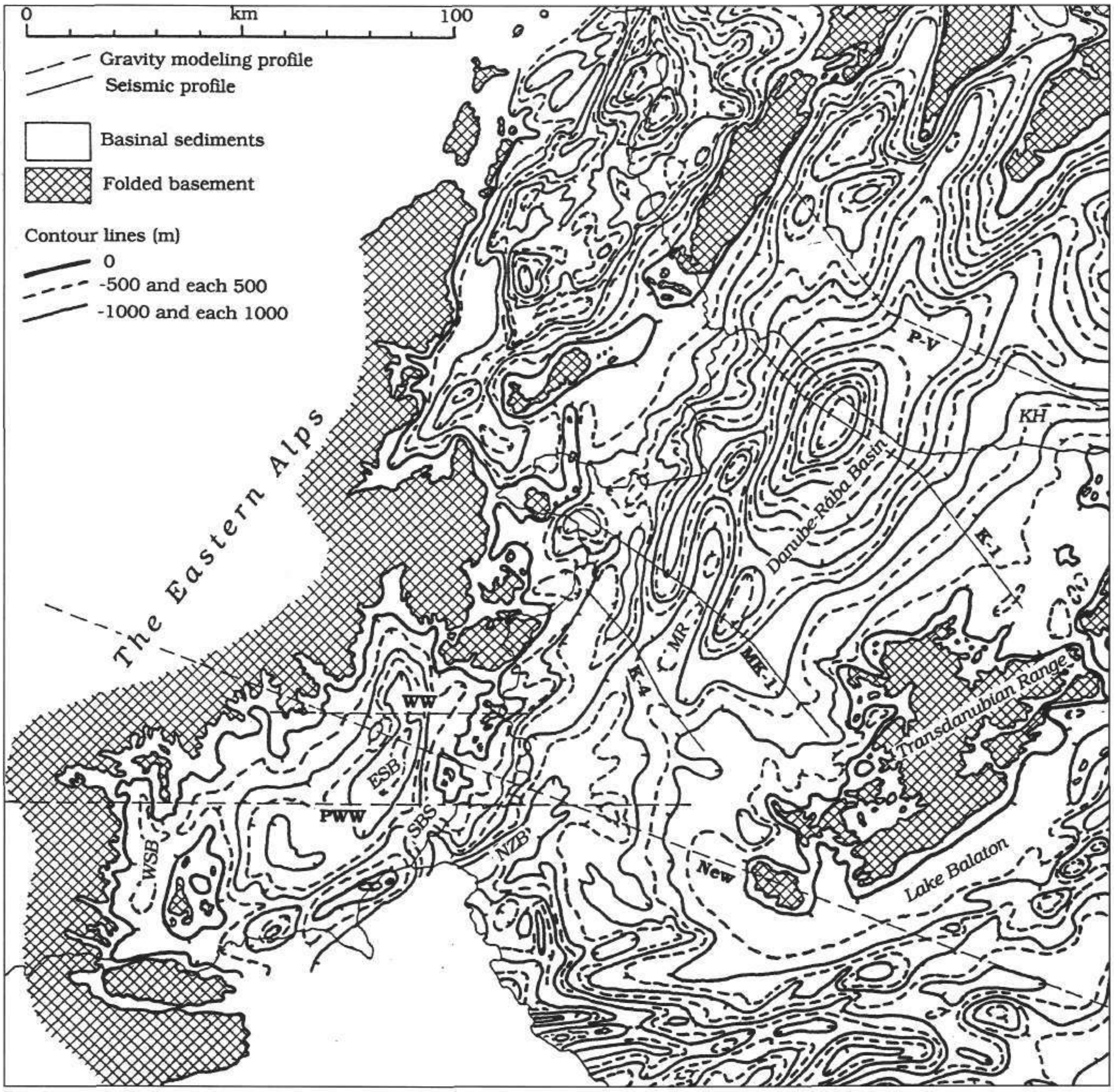
Text-Fig. 1.
Gravity anomaly map of the Alpine–Carpathian junction area after SCHEFFER (1957).
WW = profile in Fig. 5 of WALACH & WEBER (1987); PWW = profile in Text-Fig. 3 of POSCH et al. (1989); KH = Kolarovo high; MR = Mihályi Ridge; NZB = North Zala Basin; SBS = South Burgenland Swell; ESB and WSB = East and West Styrian basins.

boundary between these units is steep, is traceable for at least 12–13 km towards the depths and may cross even the Moho. This boundary coincides with the Rába line of Hungarian authors (see in KÁZMÉR, 1986).

Most of Hungarian geologists believe the low-metamorphic rocks in boreholes on the Mihályi high to be analogs of the Graz Paleozoic (Upper Austroalpine: see in KÁZMÉR, 1986). In our section, however, there is no place for the East Alpine nappe pile. On the contrary, these sequences seem to dip under, not over the Lower Austroalpine crystalline complex of the Sopron Hills, i.e. probably belong to the Penninics.

Formally, "basaltic layer" is displayed in high position in the middle of the section (Text-Fig. 5) but that is not the only possible interpretation of the modeling results. "Basaltic" density (2.9 g/cm³) is the minimum value required in modeling, any higher value being acceptable, up to the "mantle" ones, with corresponding increase of the depth to the top of the high-density body. On the other hand, the topography of the top of the high-density body is less constrained below the Lower Austroalpine crystalline complex due to the uncertainty of the thickness of the latter.

Modeling of gravity data along the seismic profile K–4 25 km southwest of the profile MK–1 confirmed existence of a high-density body. The density model (Text-Fig. 6) is rather detailed due to high resolution of the seismic section and presence of numerous boreholes near the profile, but due to the flatter basement topography position and geometry of the deep-seated high-density body is less constrained than in MK–1. In the seismic profile K–1 55 km northeast of the profile



Text-Fig. 2.
Pre-Tertiary basement contour map of the Alpine–Carpathian junction area. After KILÉNYI & ŠEFARA (1991).
WW = profile in Fig. 5 of WALACH & WEBER (1987); PWW = profile in Fig. 3 of POSCH et al. (1989); KH = Kolarovo high; MR = Mihályi ridge; NZB = North Zala Basin; SBS = South Burgenland Swell; ESB and WSB East and West Styrian basins.

MK–1 (HOBOT et al., 1987), the basement surface has been lost at extremely great depths (>8 km) so that position and geometry of the deep-seated high-density body is still less constrained. Nevertheless, the intra-crustal high-density body is traceable in Hungary for a distance over 80 km.

3. Intra-Crustal High-Density Bodies in Slovakia and Austria

In Slovakia, 50 km east of the northeastern closure of the Mihályi Ridge, the Kolarovo gravity high (see in Text-Fig. 1) displays >+10 mGal at 2–3 km basement depth. In a gravity modeling profile (P–V, Text-Fig. 7) it was related to a hypothetical Miocene andesitic intrusion, but equally can be regarded as the continuation of the Mihályi high-density body within the basement.

In Austria, southwest of the Mihályi Ridge, the South Burgenland Swell is well expressed in the gravity anomaly pattern. Attempts to evaluate the gravity high were made along two W–E profiles across the East Styrian Basin. In the Bouguer anomaly pattern of the longer profile (PWW), two different sections were distinguished (Text-Fig. 8): a slope with a 1 mGal/km gradient west of the Mur valley and a dismembered section with an assumed mean gradient of about 0.2 mGal/km. It was stated (POSCH et al., 1989) that gravity highs and lows on the dismembered section correspond to basement highs and lows, but no further calculations were performed.

A shorter profile about 20 km north of the previous one (WW) was interpreted in another way (Fig. 9). A tangent was applied to the peaks at the ends of the section and was accepted as the regional field with a 0.5 mGal/km

Table 1.
Thicknesses and densities applied in gravity model calculations along the profile MK-1.
Table III. of BALLA et al. (1989).

Depth interval	Thickness		Sequence	Density		
	total	partial		measured	calculated	corrected
Cenozoic basinal sediments						
0-1000	1000	1000	Upper Pannonian	1.99	1.99	2.10
1000-2000	1000	500	Upper Pannonian	1.99	2.08	2.24
		500	Lower Pannonian	2.17		
2000-3000	1000	500	Lower Pannonian	2.17	2.17	2.34
3000-4000	1000	500	Lower Pannonian	2.17	2.25	2.42
		500	Miocene	2.33		
4000-5000	1000	1000	Miocene	2.33	2.33	2.48
5000-6000	1000	1000	Miocene	-	2.40	2.53
6000-7000	1000	1000	Miocene	-	2.46	2.56
Basement of Transdanubian Range type						
-	-	-	Upper Cretaceous	2.56	2.56	-
-	800	400	L. Cretac. - Juras.	-	2.62	-
		200	Dachstein Limest.	2.62		
		200	Kössen beds	-	2.62	
-	1200	1200	Main Dolomite	2.76	2.76	-
-	2200	600	Veszprém Marl	2.54	2.57	-
		1100	Low.-Mid. Triassic	2.62		
-		500	Permian	2.49		
-	-	-	Metamorphic basem.	-	2.63	-

gradient. Two-dimensional calculations (WALACH & WEBER, 1987) resulted in the coincidence of the basement topography effect with the residual anomaly.

The attempts above clearly demonstrated the presence of dense masses below the Styrian Basin and the Swell expressed in the increase of the regional field. The most obvious component of the latter is connected with the Moho topography. If the whole of the regional field is due to this effect, the evaluation of the South Burgenland Swell gravity high will depend on the gradient of the regional field: if the latter is of about 0.5 mGal/km (Text-Fig. 9), no additional dense masses below the Swell are required to generate the observable gravity values, whereas at about 0.2 mGal/km of the regional gradient a >20 mGal local anomaly falls on the Swell (Text-Fig. 8) pointing to the existence of a high-density body within the earth crust (the corresponding local low of the East Styrian Basin can be related to density deficiency due to sedimentary fill).

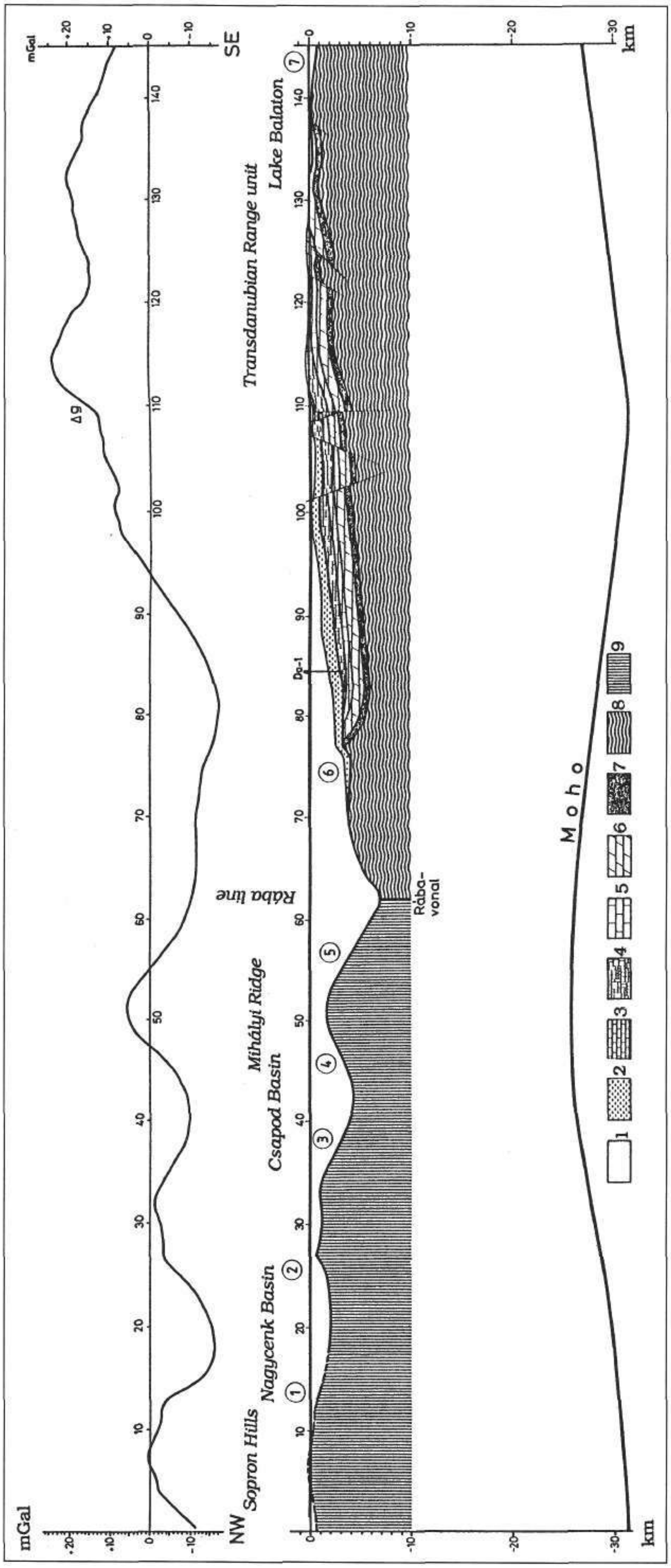
Gravity modeling (for details, see Appendix 2) resulted in revealing intra-crustal high-density bodies below the East Styrian and North Zala basins and their surroundings (Text-Figs. 10–12). Two principal cases have been outlined, an about 100 km wide horizontal sheet which (from the point of view of the gravity modeling) equally can be isolated from-below or attached to an underlying high-density layer forming elevation of this layer (Text-Figs. 10 and 11), on one hand, and a series of vertical sheets (Text-Fig. 12), on the other.

It should be mentioned, that the outer two vertical appendices/sheets are much less convincing than the central one. The existence of the eastern one of them is doubtful since the corresponding dense masses may be also represented by the thick limestone–dolomite sequence of the Transdanubian Range, not by a deep-seated source.

The western vertical appendice/sheet may reflect defects in both the density model of the Alpine root and in corresponding Moho topography.

The middle part of the horizontal sheet below the East Styrian Basin, South Burgenland Swell and axial zone of the North Zala Basin or its equivalent, the middle vertical sheet, only seems to be more-or-less confirmed by checking considerations, the lateral boundaries and the topography being not constrained.

As seen, there is a great number of models which reproduce the measured gravity anomalies, and there are no real constraints for selecting one of them on the basis of modeling. Thus, geological considerations must be taken into account in evaluation of the modeling results.



Text-Fig. 3.
Geological section along the reflexion seismic line MK–1.
For location, see Text-Figs. 1 and 2 (Fig. 8 of BALLA et al., 1991).
1 = Neogene–Quaternary basinal sediments; 2 = Upper Cretaceous (Senonian) sediments; 3 = Jurassic to Lower Cretaceous sediments; Upper Triassic Dachstein Limestone and Cassian Beds; 4 = Upper Triassic Main Dolomite; 5 = Upper Triassic Veszprém Marl; 6 = Lower–Middle Triassic; 7 = Permian; 8 = Paleozoic metamorphic basement of the Transdanubian Range; 9 = Austro-Alpine and Penninic formations.
In circles = serial numbers of slopes; Da–1 = borehole Dabrony-1.

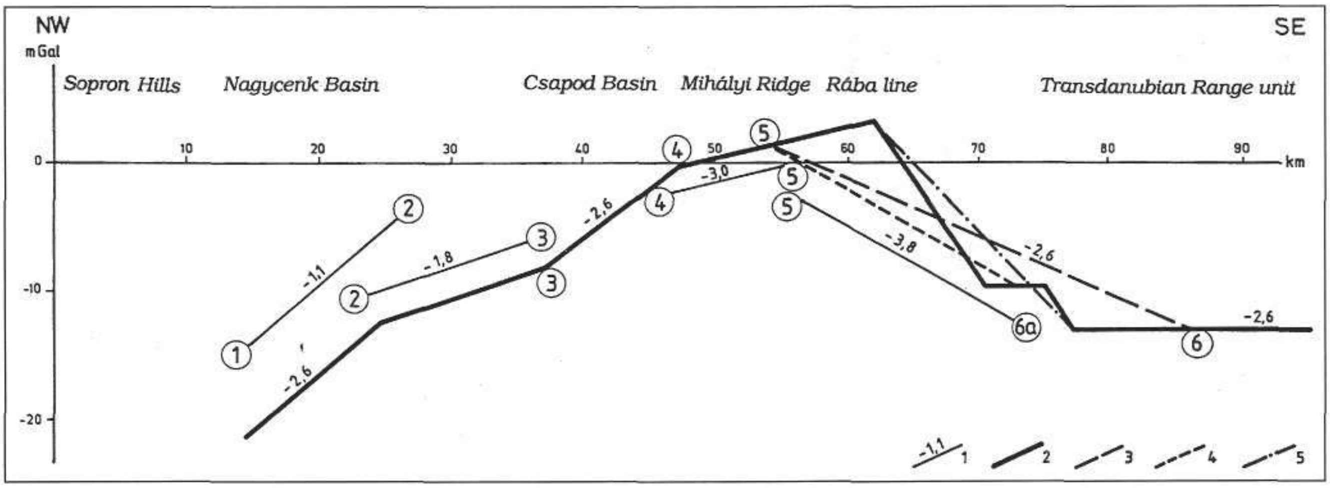
4. Geological Interpretation

Within the upper crust of granite-gneiss composition and average density around 2.7 g/cm^3 the most probable high-density bodies are of mafic or ultramafic composition with average densities around 2.9–3.1 g/cm^3. Thus, a density excess of 0.2–0.4 g/cm^3 seems to be most acceptable.

In a geological sense, the vertical-sheet model (Text-Fig. 12) would mean "mantle dikes" intruded or protruded during the extension which resulted in basin subsidence. In that case approximate coincidence of the dikes with basin axes would be expectable. In reality, however, only the middle "dyke" is close to a basin axis, the two others fall on the middle of slopes. Consequently, the vertical-sheet model seems to be unconvincing at least for the two outer bodies.

The horizontal-sheet model may have numerous geological applications. Its version with a body isolated from below would mean a specific horizon composed of high-density magmatic or metamorphic rocks, e.g. a series of intrusions arranged in a horizontal chain or an ophiolitic nappe. In a geological sense, the body attached to the underlying layer can only be identified with an elevation of the "basaltic layer". The latter, however, is expectable at about 15 km depths (see Text-Fig. 5) below the Transdanubian Range. Therefore, the position of the body in question (+0.2 g/cm^3) is probably similar to that in Text-Fig. 11C. The topography of the elevation is, however, unconstrained due to the absence of seismic profiles and density determinations.

Intra-crustal high-density bodies have been outlined in each of the five profiles studied from this point of view in the Alpine–Carpathian junction area. On the



Text-Fig. 4.
Residual gravity anomaly reflecting a deep structure along the profile MK–1 (Fig. 11 of BALLA et al., 1991).
Figures in circles = serial numbers of slopes; 1 = straight connecting points plotted with their g and km values read on Text-Fig. 17 in the depth indicated above the line; 2 = residual gravity anomaly mechanically shifted to the depth -2.6 km and corrected on the basis of the Δg–h curve; 3 = initial gravity step between slopes 5 and 6; 4 = gravity step between slopes 5 and 6a shifted to the depth -2.6 km; 5 = residual anomaly corrected on the basis of the Δg–h curve neglecting the slope 6a.

basis of the regional gravity anomaly pattern (Text-Fig. 1) it can be supposed that the same body has been detected in all five profiles, in other words it is traceable for about 200 km. This fact may help in the limitation of the number of possible models by means of comparisons.

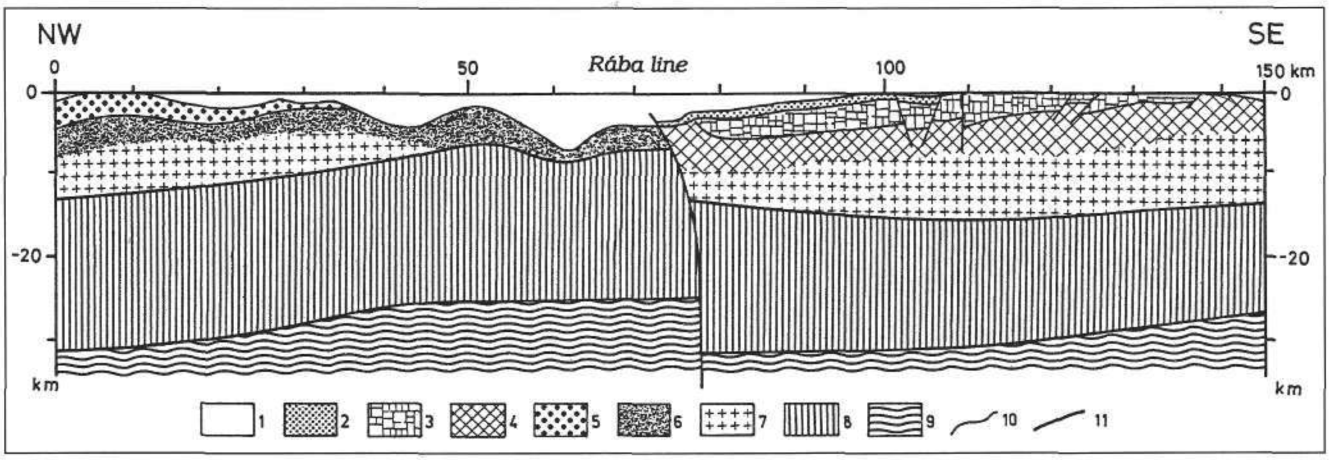
In the profile P–V (Text-Fig. 7), the high-density body falls below the slope and in the profile K–1, below the deepest part of the basin. In the profile MK–1 (Text-Fig. 5), it spreads far beyond the deepest part especially towards the northwest, and in the profile K–4 (Text-Fig. 6), it is located within a flat and comparatively shallow part of the basin, below the closure of the Mihályi Ridge. Consequently, in spite of the situation of the high-density in a basinal area, its location is only sometimes controlled by basin axes.

In the profiles MK–1 and K–4 (Text-Figs. 5 and 6) the intra-crustal high-density body is limited in the southeast by the Rába line, one of the most important lineaments of Hungary (see in KÁZMÉR, 1986). Similarly, in the profile K–1 it is located northwest of the Rába line. In the profile P–V (Text-Fig. 7) the high-density body is situated on the northwestern flank of the Hurbanovo line which is usually correlated with the Rába line (e.g. KÁZMÉR & KOVÁCS, 1985). Thus, the position of the intra-crustal body in question is clear in a tectonic sense: it accompanies the Rába–Hurbanovo line from the northwest.

No correspondence of the high-density body to Neogene basin axes makes unconvincing the "mantle dyke" model, on one hand, and its control by the pre-Neogene Rába–Hurbanovo line points to an old age, on the other. In our opinion, the isolated-from-below models are of low probability, thus, we regard the layer-elevation model as the most acceptable one. In its frame, two principal versions can be outlined: an oceanic-lithosphere inclusion and an Ivrea-type situation.

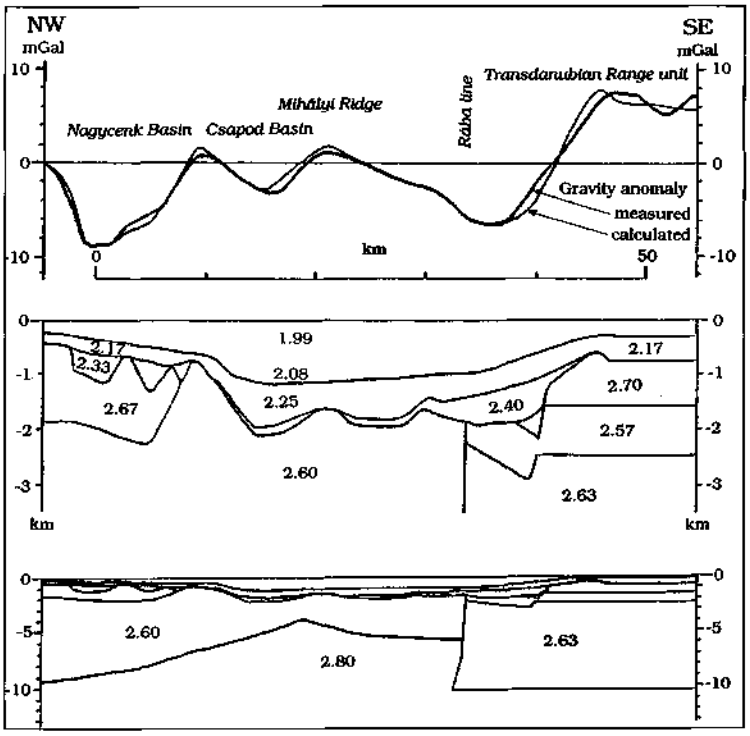
4.1. Inclusion of the Oceanic Lithosphere?

In both the Western Alps and the Tauern Window, the bottom of the Penninic ophiolite sequence is visible: it



Text-Fig. 5.
Crustal structure along the profile MK–1 (Fig. 16 of BALLA et al., 1991).
1 = Cenozoic (mainly Neogene) sediments; 2 = Upper Cretaceous (Senonian) sediments; 3 = Permian to Lower Cretaceous formations; 4 = Paleozoic of the Transdanubian Range; 5 = Lower Austro-Alpine nappe; 6 = Penninics; 7 = "granitic layer"; 8 = "basaltic layer" and other formations of similar density; 9 = upper mantle; 10 = geological boundary; 11 = intra-crustal boundary.

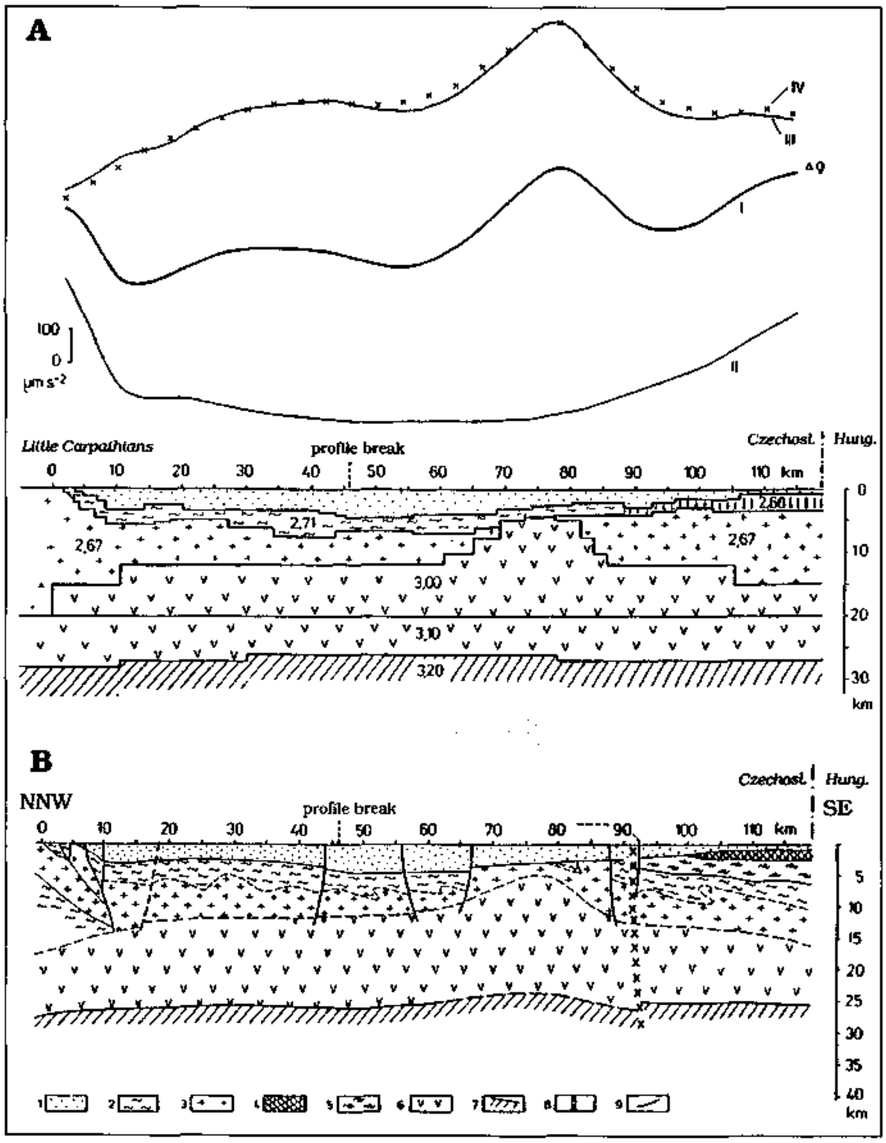
Text-Fig. 6.
Density model for the seismic section K–4.
For location, see Text-Figs. 1 and 2. Calculated by author using Pápa's seismic interpretation (Fig. 7 of Hobot et al., 1991).
A = gravity anomalies; B = upper part of the density model, vertical exaggeration 1 : 5; C = density model, no vertical exaggeration.



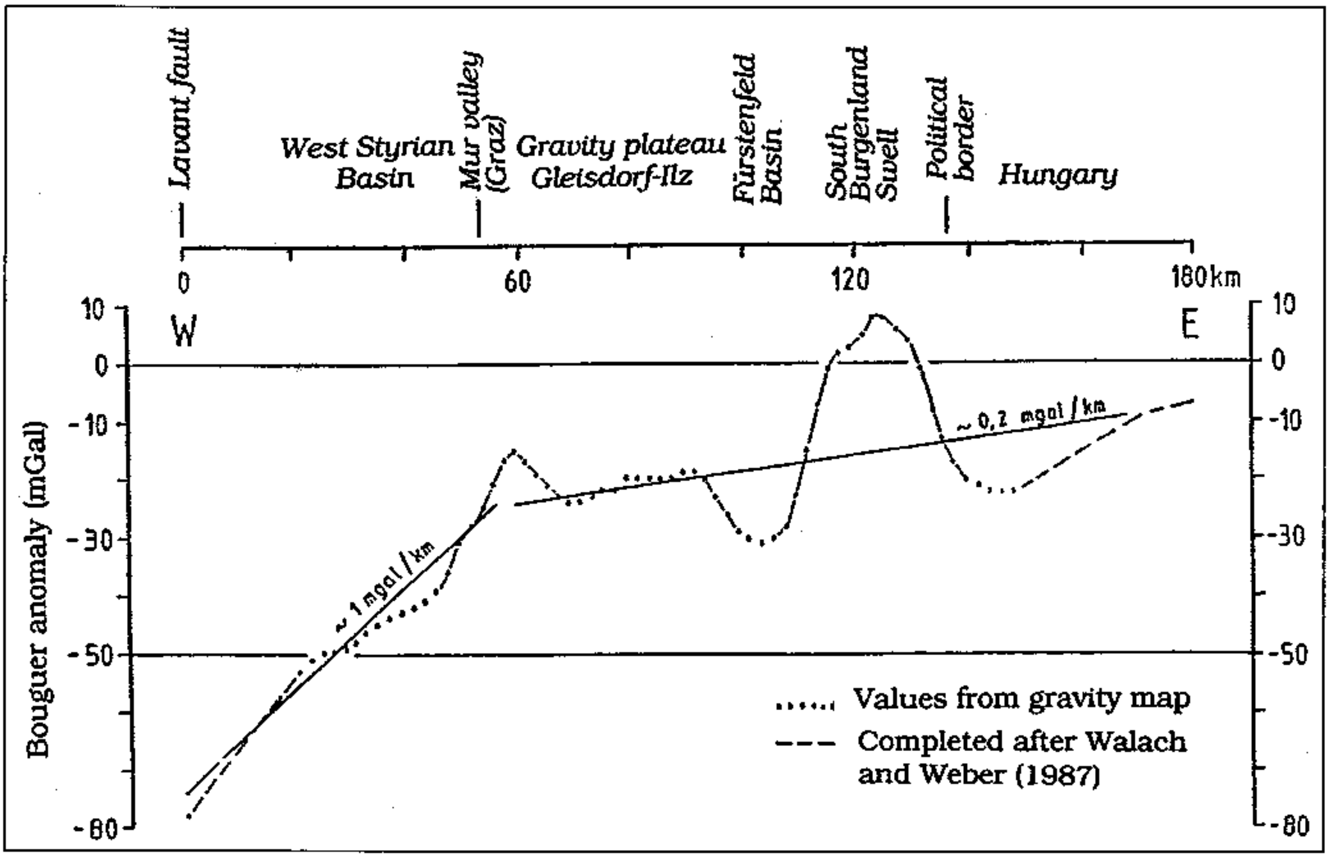
is represented by the underthrust European continental crust. It is usually believed that this is also the situation in the Kőszeg–Rechnitz area where the ophiolitic sequence lies on top of the Penninic sediments (Pahr, 1980, 1982, 1984).

For the area in question, intense magnetic anomalies are characteristic (Seiberl, 1988; Haáz & Komáromy, 1967). They are frequently related to the Penninic ophiolites (e.g. Hoffer et al., 1990) but this is not the only interpretation. Based on model calculations Posgay (1967a-b) located the top of magnetic sources in 1.3–2.3 km below the basement surface. Oberladstätter et al. (1979) also were of the opinion that the source of magnetic anomalies lies at considerable depths.

It is remarkable that in the Rechnitz area of outcropping ophiolites negative magnetic anomalies of low intensity (up to –60 nT, see in Seiberl, 1988) have been only detected whereas in the surrounding basinal areas positive anomalies up to 360 nT in Austria (ibid.) and over 300 nT (>3 mOe) in Hungary (Haáz & Komáromy, 1967) are observable. Thus, it should be clear that intense positive magnetic anomalies cannot be related to the ophiolites which lie as thin nappes above the Penninic sedimentary sequences, on the contrary, they must be connected with sources in the bottom of the Penninic sedimentary sequences.

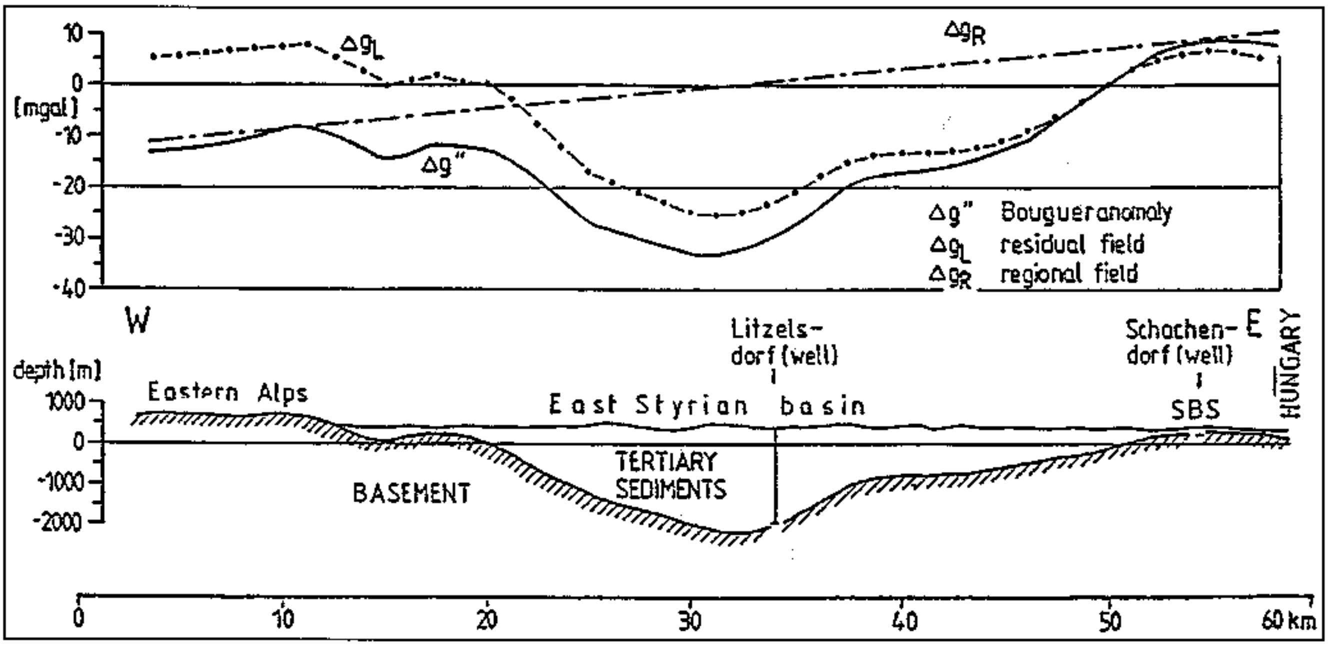


Text-Fig. 7.
The gravity modeling profile P–V and its interpretation.
For location, see Text-Figs. 1 and 2 (Figs. 8 and 9 of Bielik et al., 1986).
A = Density model; I = Bouguer anomalies; II = gravity effect of Tertiary sediments; III = values from the gravity map; IV = calculated gravity effect of the density model. B = Schematic geological section.
1 = Tertiary sediments; 2 = crystalline schists; 3 = West Carpathian granitoid rocks; 4 = Mesozoic of the Transdanubian Range; 5 = Paleozoic of the Transdanubian Range; 6 = "basaltic layer"; 7 = upper mantle; 8 = deep-seated fault; 9 = fault.



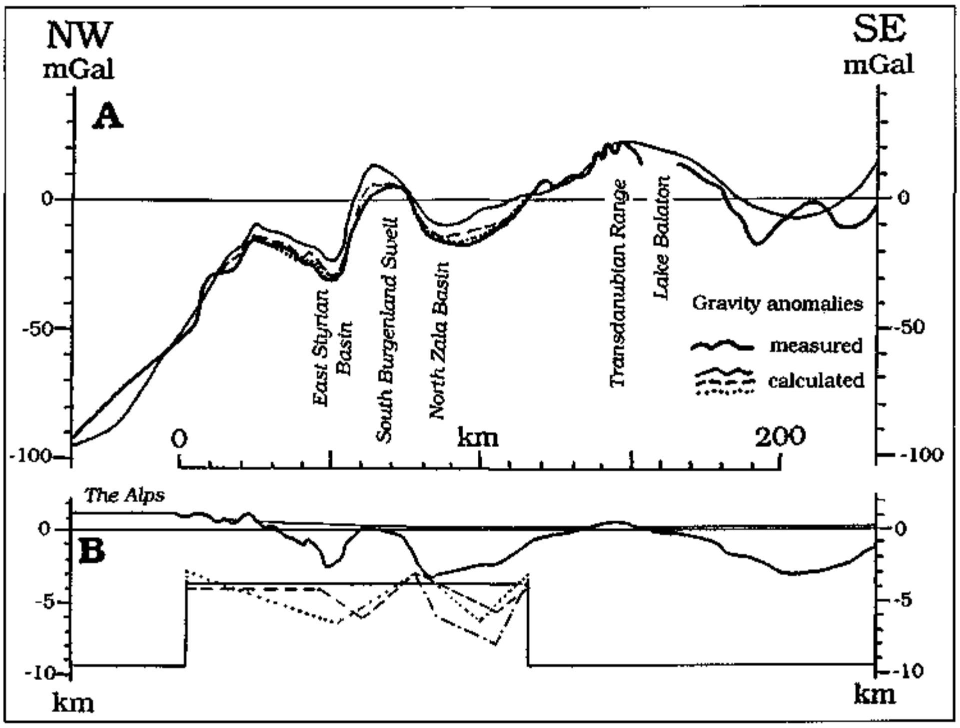
Text-Fig. 8.
Bouguer anomaly along the profile PWW.
For location, see Text-Figs. 1 and 2 (Fig. 3 of POSCH et al., 1989).

The question arises, what complexes underlie the Penninic sediments in the present-day structure. The traditional answer is "continental crust" but it does not explain intense magnetic anomalies. The primary oceanic crust of the Penninic basin in turn could be responsible for magnetic anomalies. The latter are restricted to the area of the deep-seated high-density body, consequently, their sources can be related to this body (the ragged magnetic anomaly pattern may reflect inhomogenous magnetization of the high-density body). Increased density of magnetic sources would be in harmony with the relation of them to the oceanic crust.



Text-Fig. 9.
Gravity distribution and calculated 2d-model along the profile WW.
For location, see Text-Figs. 1 and 2 (Fig. 5 of WALACH & WEBER, 1987).

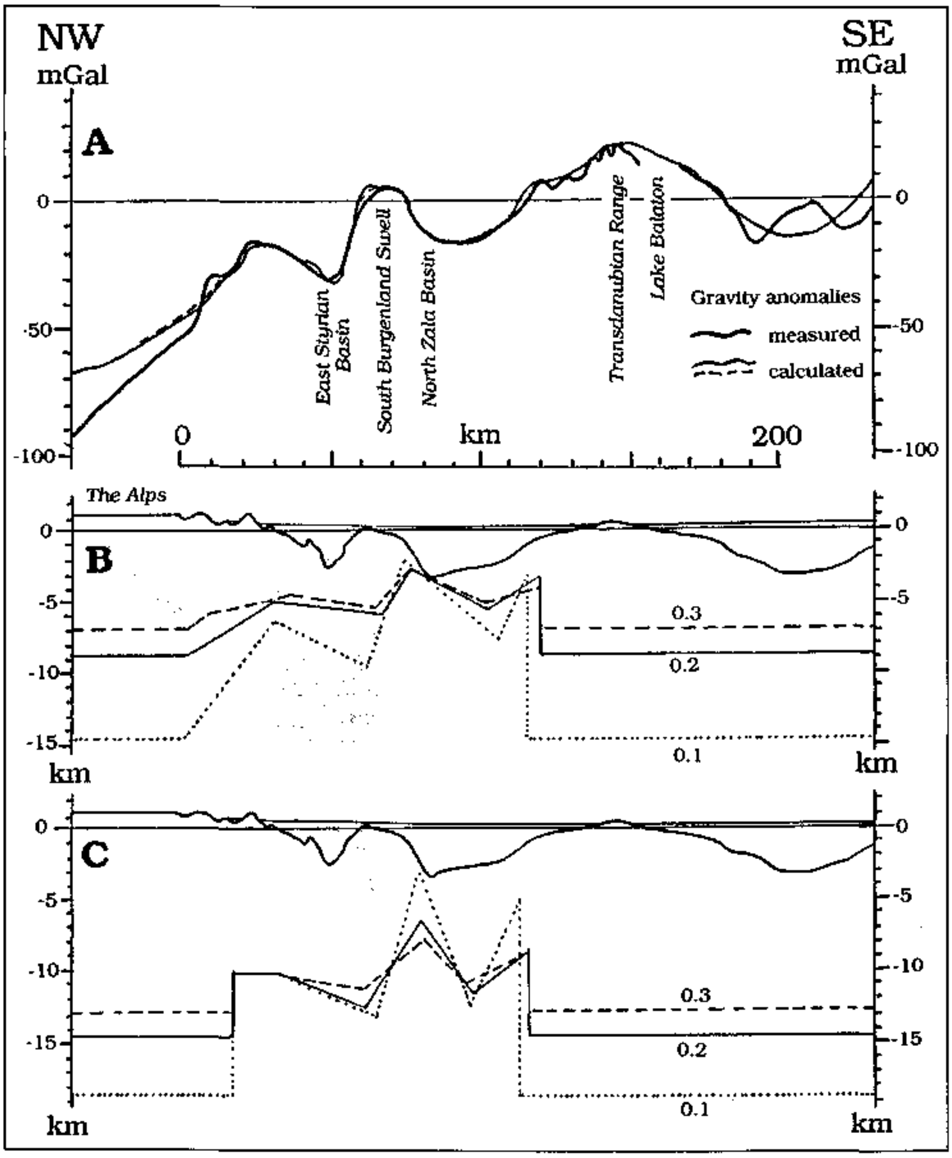
Text-Fig. 10.
Calculated two-dimensional gravity effect along the new profile (A, for location, see Text-Figs. 1 and 2) for 0.4 g/cm³ density contrast on the Moho and for various shapes of the intra-crustal dense body (+0.2 g/cm³) in its highest position and various density deficiencies of the sedimentary fills of the East Styrian and North Zala basins. Gravity curves shifted to coincide on the top of the Transdanubian Range gravity high. Vertical exaggeration of the depth model (B) 1 : 5.
Captions for the model (B): dashed = density deficiency diminished by 0.1 g/cm³ for the East Styrian Basin relative to that in Table 1; dots = same diminished by 0.2 g/cm³; dash-dot = deficiency diminished by 0.1 g/cm³ for the North Zala Basin.



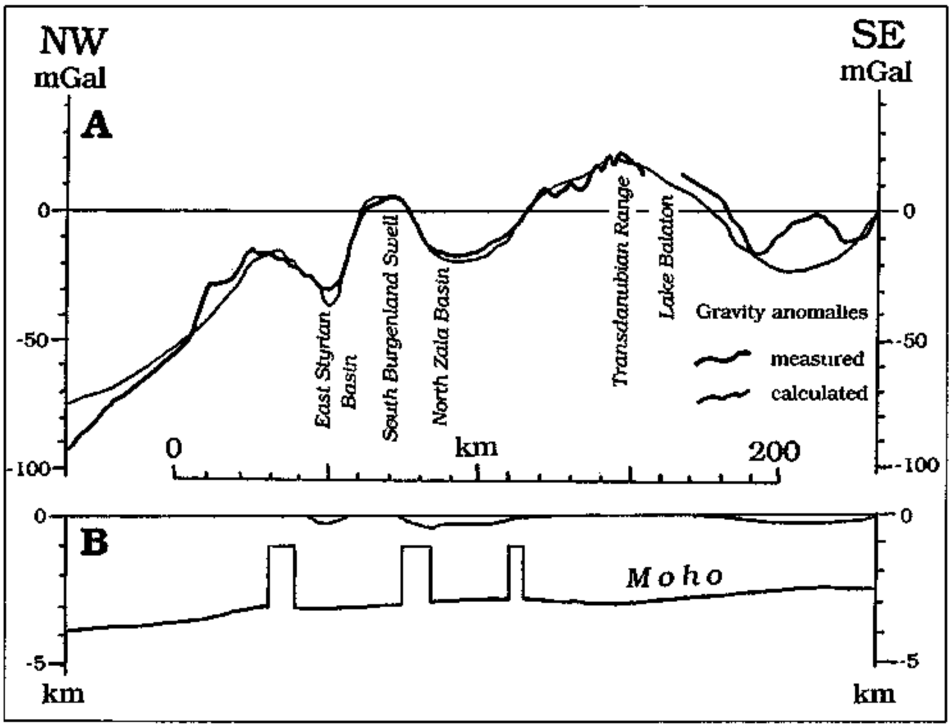
The present-day 31 km thick crust of the Rechnitz area (Posgay et al., 1991), however, cannot be of oceanic type as a whole, thus, the only acceptable model of this type is that in which a piece of oceanic crust in the bottom of the Penninic sedimentary sequence is incorporated into the present-day continental crust.

In other words, an ophiolitic complex of great thickness (>7 km in MK–1) can be assumed which is detached from its primary lithosphere and now is limited from-below tectonically at >10–12 km depth.

This oceanic-inclusion model would differ from the traditional concept of the Penninic Nappe System first of all in great thickness of the latter and in possible preservation of ophiolitic complexes below the sediments.



Text-Fig. 11.
Calculated two-dimensional gravity effect along the new profile (A, for location, see Text-Figs. 1 and 2) for 0.3 g/cm³ density contrast on the Moho and various density excesses of the intra-crustal body in its highest (B) and a deeper (C) position. Gravity curves shifted to coincide on the top of the Transdanubian Range gravity high. Vertical exaggeration of the depth models (B-C) 1 : 5.



Text-Fig. 12.
Calculated two-dimensional gravity effect along the new profile (A, for location, see Text-Figs. 1 and 2) for 0.3 g/cm³ density contrast on the Moho and of the "mantle dikes".
No vertical exaggeration of the depth model (B).

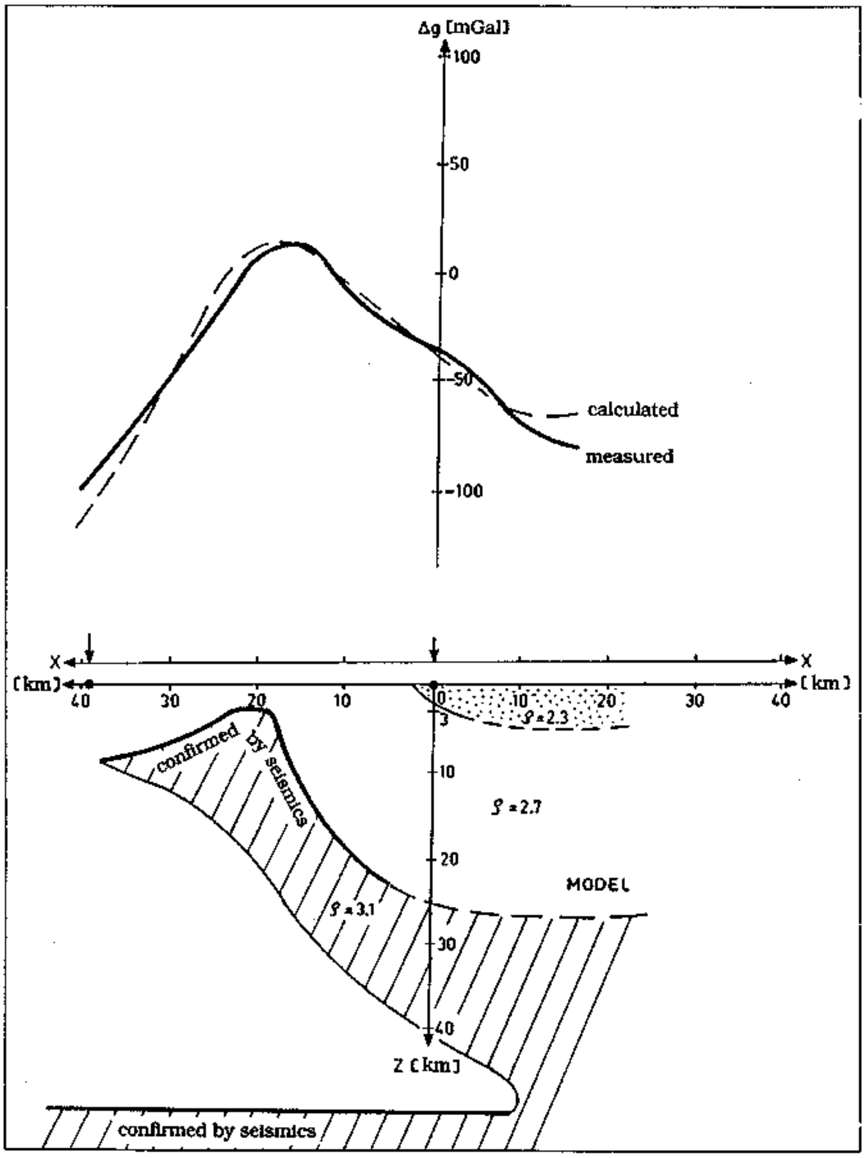
4.2. An Ivrea-Type Situation?

Along the northeast–southwest oriented section of the Western Alps, an intense gravity high is traceable for more than 200 km (VECCHIA, 1968). On the basis of refraction seismic profiling it was interpreted in terms of doubled Moho (BERCKHEMER, 1968) connected with an ancient subduction zone (SCHMID et al., 1987). This Ivrea zone (Text-Fig. 13) follows the Insubric line from the southeast and plunges beneath the Alps on the west–east-directed section of the line.

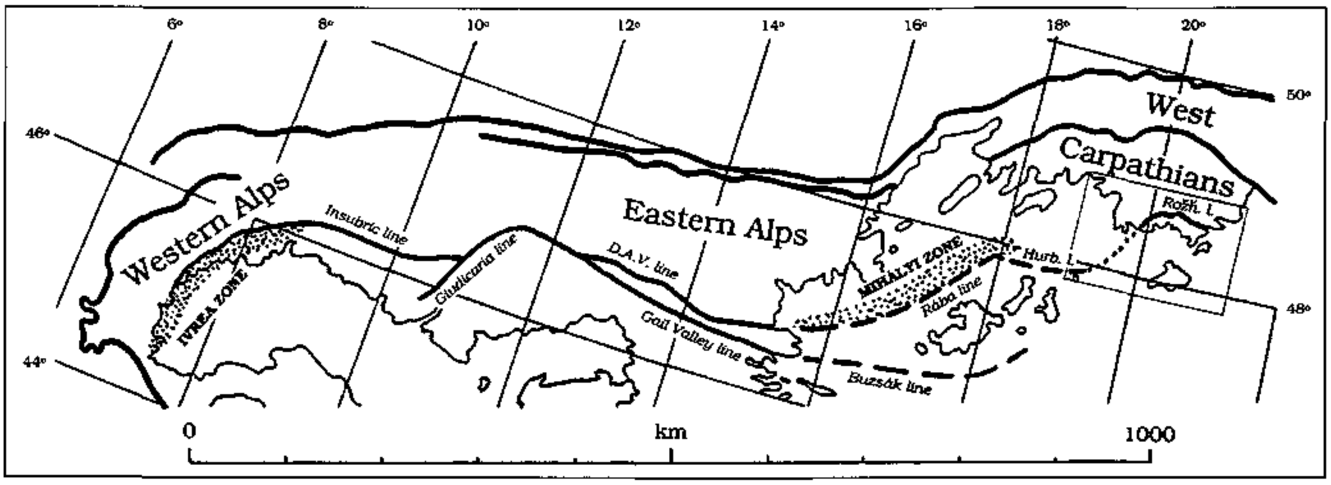
In the sense of the southern boundary of the Alpine metamorphism on the surface, the Insubric line countinues in the D.A.V. line of the Eastern Alps (SASSI et al., 1978) which in turn can be correlated with the Rába line of Hungarian authors (KOVÁCS, 1983). Consequently, the Insubric – D.A.V. – Rába line is traceable along the whole of the Alps and even beyond them.

It is remarkable that after the long and straight west–east-oriented section (displaced by the young Giudicaria strike slip) that line turns towards the northeast, and on this section, arranged quasi-symmetrically to the Ivrea zone, another intra-crustal high-density body appears on the opposite, northwestern side of the line (Text-Fig. 14) which can be named "Mihályi zone".

Despite the obvious analogy in maps, there are significant differences in vertical sections of the Ivrea and Mihályi zones. The thickness of the crust is more than 50 km beneath Ivrea and only 26 km beneath Mihályi. It should be clear, however, that this



Text-Fig. 13.
Model of the density structure of the Ivrea Zone.
After BERCKHEMER (1968).



Text-Fig. 14.
Position of the Ivrea and Mihályi zones in the general structure of the Alps after BALLA (1992).
Box in the West Carpathian area indicates frame of Text-Fig. 19.
Hurb. l. = Hurbanovo line; Rožň. l. = Rožňava line.

difference is due to the different Neogene history of the two regions, compressional in the Western Alps and extensional in the Danube – Rába Basin, and cannot be used as an argument against the correlation of obviously pre-Neogene structures.

A problem of the correlation consists in what to think about the mechanism which resulted in the present-day reduced crustal thickness in the Mihályi area.

On one hand, subcrustal erosion (ARTYUSHKOV & BAER, 1984) can be imagined, and in that case loss of the lower half of the Ivrea structure due to removal will be an explanation of the present-day Mihályi structure.

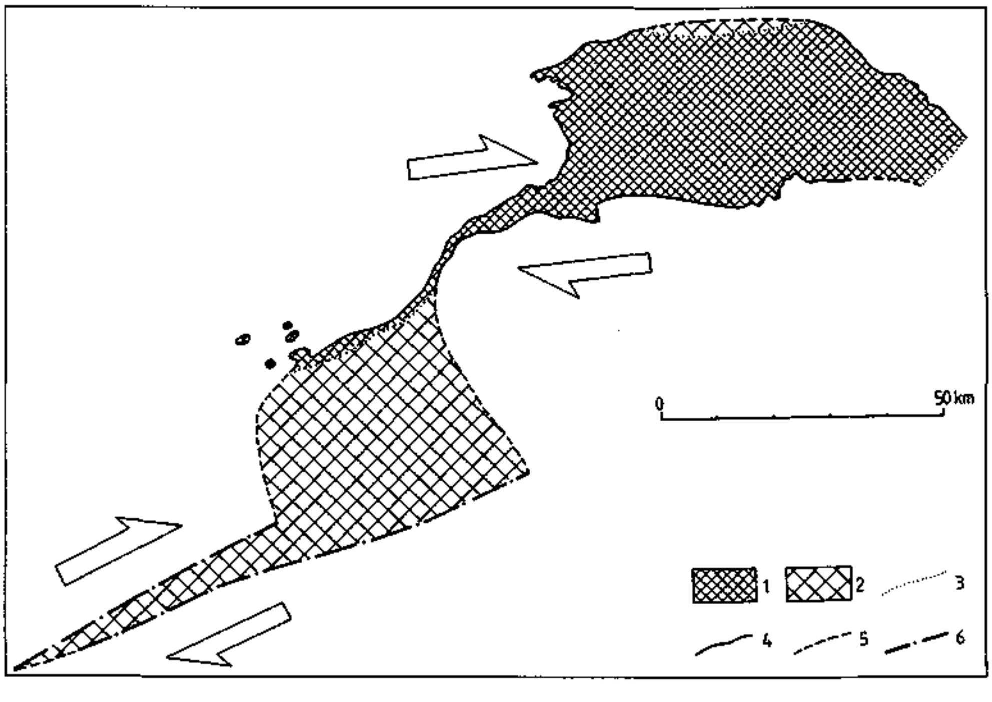
On the other hand, crustal attenuation (ROYDEN & DÖVÉNYI, 1988) is also imaginable, and in this case horizontal stretching of the Ivrea structure with no loss of material will serve as a model for the present-day Mihályi structure.

In both cases significant differences in corresponding gravity fields and models of the Ivrea and Mihályi zones are expectable, and obvious differences in vertical sections and gravity features are not necessary arguments against the correlation.

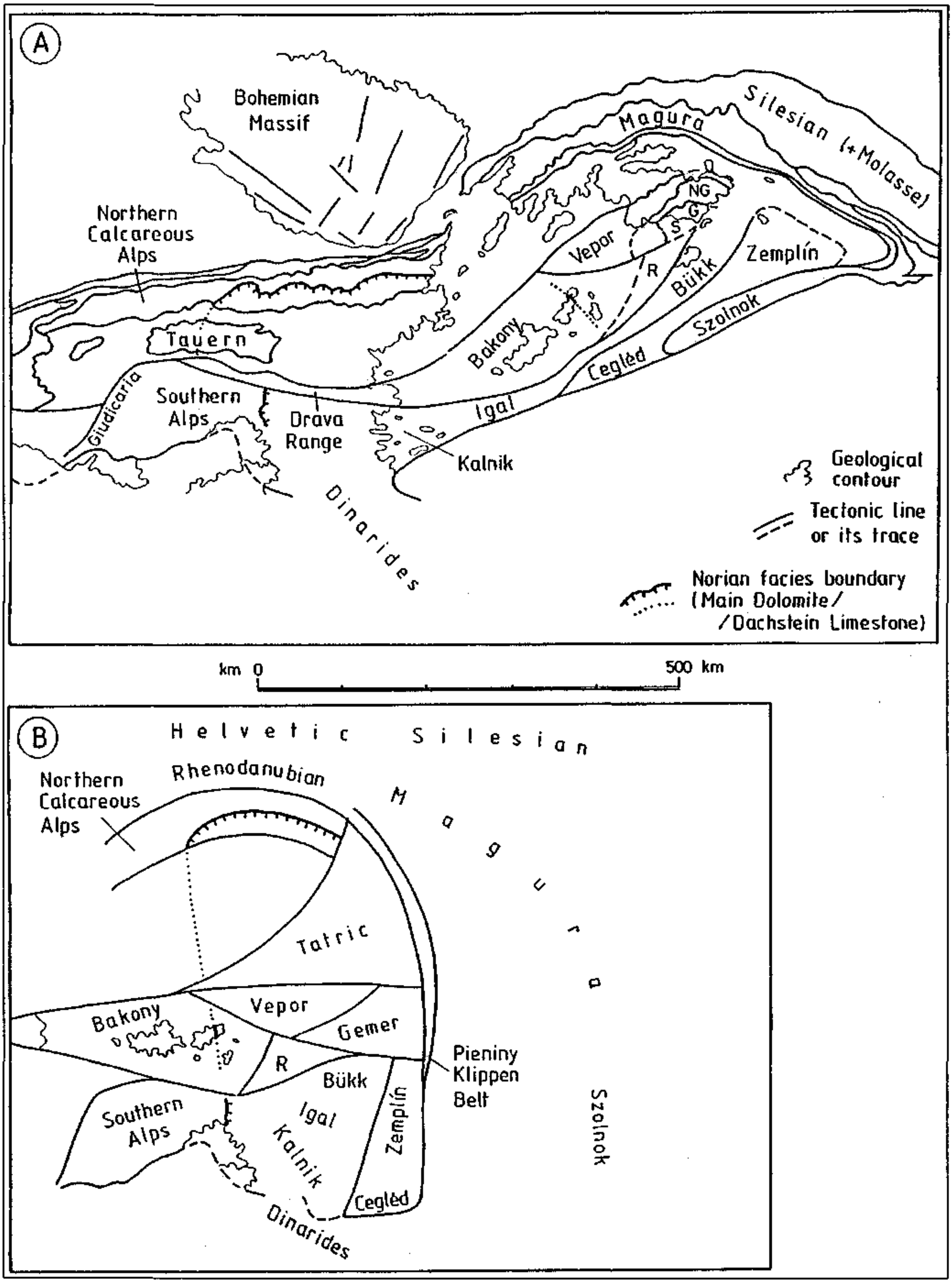
4.3. Discussion

In the framework of the Alpine–Carpathian junction, inclusion of both a relatively thick fragment of the oceanic crust or a promontory of the continental upper mantle within the present-day continental crust seem to be equally probable sources for both the gravity and magnetic highs concerned above. In a wider aspect, however, the Ivrea – Mihályi correlation along the Insubric – D.A.V. – Rába Line appears to be more convincing.

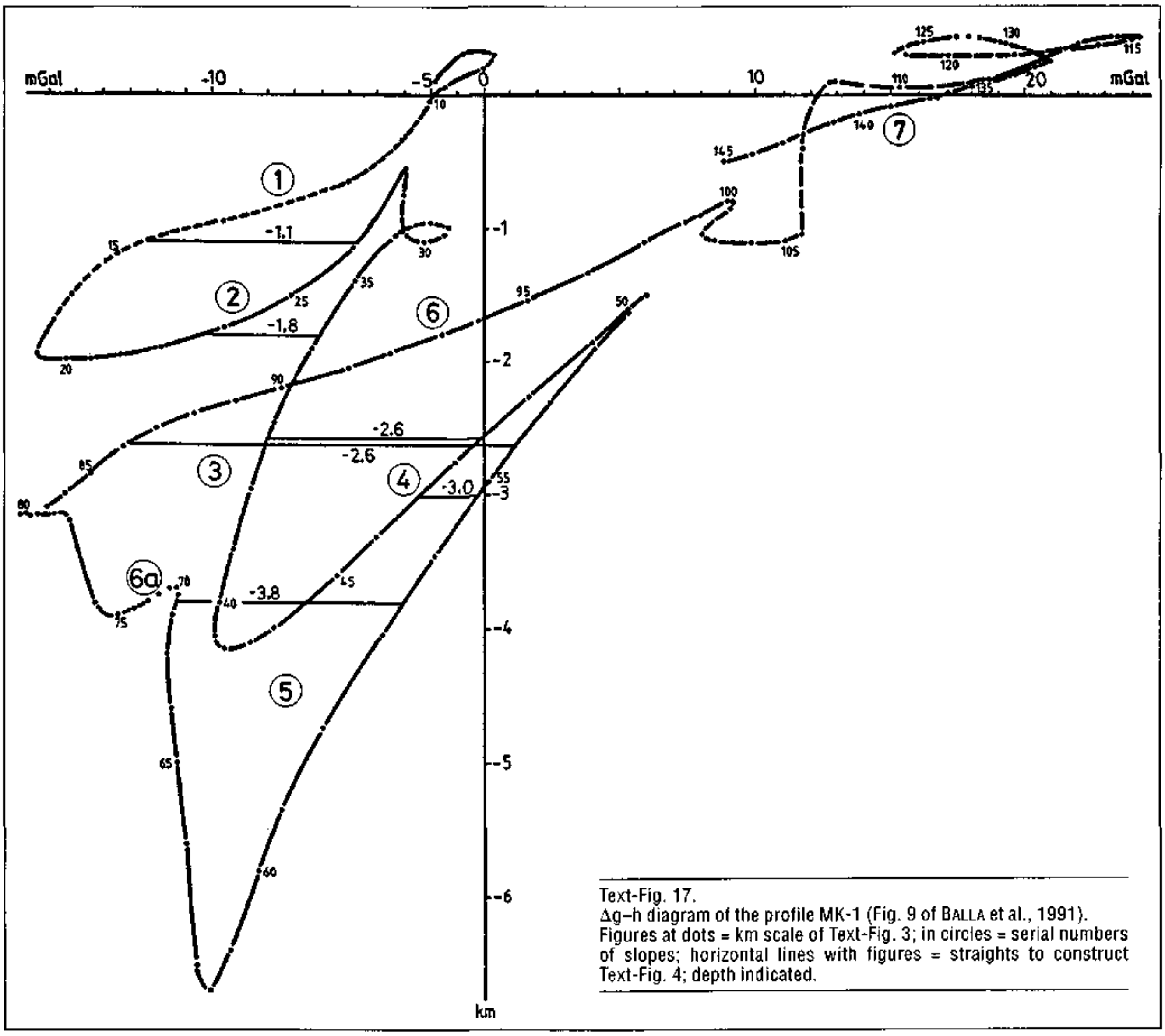
Doubts may be connected with specific gravity features of the Pannonian Basin. According to BIELIK's (1988) investigation, all the deep basins of the Carpatho-Pannonian region reveal residual gravity highs after removal of the gravity effect of the sedimentary fill. This concerns the gravity field of the Danube – Rába Basin as well, thus, in some profiles (K–1, MK–1 and New?) contribution of Neogene "mantle dikes" to the intra-crustal dense masses below the deep basin axes cannot be excluded. We do not imagine, however, any method



Text-Fig. 15.
Dextral strike slips assumed on the basis of the present structural pattern of the Gemericum (Fig. 32 of BALLA, 1989b).
For location, see Text-Fig. 14.
1–2 = areas of the Gemericum (earlier name: Gemeric Paleozoic): 1 = exposed; 2 = covered; 3 = boundary of exposed areas; 4–6 = boundary of the Gemericum: 4 = exposed (overthrust); 5 = covered (overthrust or of uncertain type); 6 = along axes of magnetic anomalies (strike-slip).



Text-Fig. 16.
Present-day (A) and Late Eocene (B) configuration of the East and South Alpine, West Carpathian and North Pannonian domains (Figs. 3A and 9D of BALLA; 1989c). Note how much the East Alpine and West Carpathian domains are shortened in the reconstruction, i.e., how much squeezing out of them is needed to achieve the present-day configuration.



Text-Fig. 17.
Δg–h diagram of the profile MK-1 (Fig. 9 of BALLA et al., 1991).
Figures at dots = km scale of Text-Fig. 3; in circles = serial numbers of slopes; horizontal lines with figures = straights to construct Text-Fig. 4; depth indicated.

for distinction between the "mantle dikes" and Ivrea-type bodies of the area studied and pass over to the discussion of the Ivrea-type body.

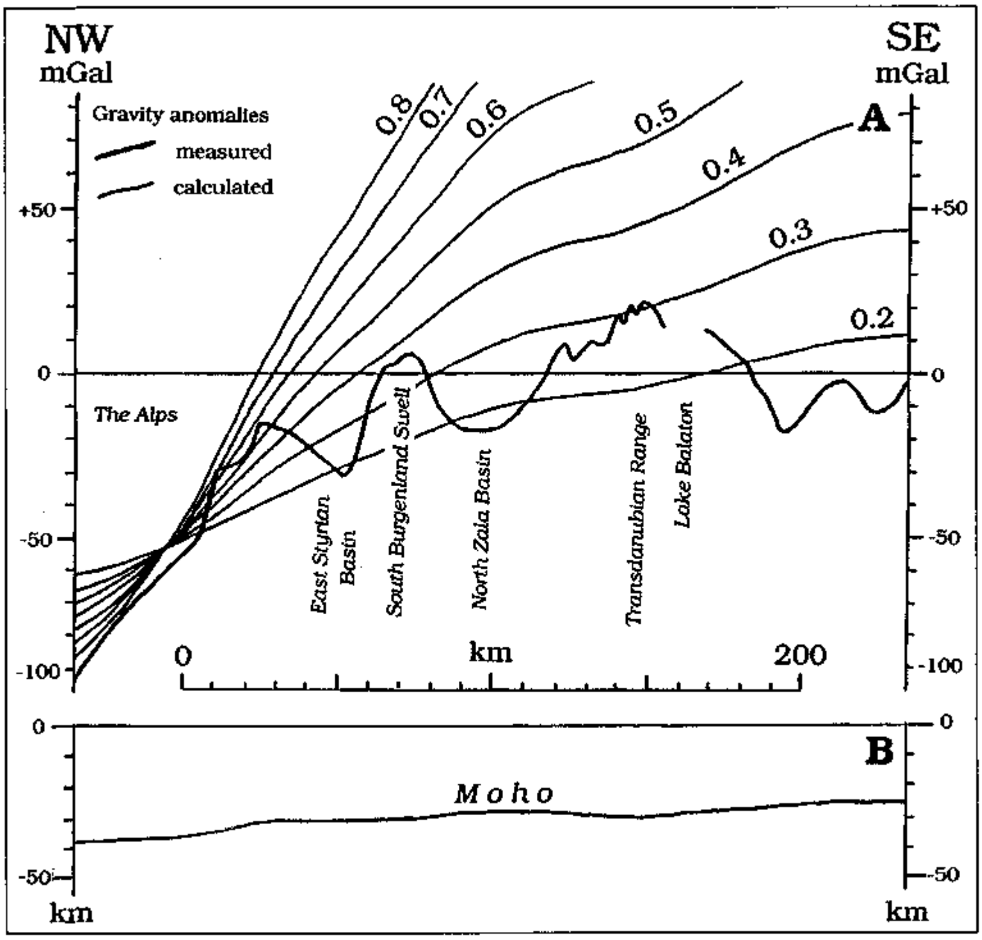
If the correlation of the Mihályi and Ivrea zones (Text-Fig. 14) is valid it would be explainable in terms of a >400 km dextral strike slip on the west–east-directed section of the Insubric – D.A.V. – Rába line which had crossed the Ivrea – Mihályi zone at a very small angle in a situation prior to the displacement. The direction of the strike slip is opposite to that postulated in the model of the escaping-to-the-east Transdanubian Range ("Bakony") unit (KÁZMÉR & KOVÁCS, 1985) but is consistent with the situation outlined for the eastern continuation of the Hurbanovo line (Text-Fig. 15).

The dextral strike slip in Text-Figs. 14–15 does not necessarily contradict the escape model in which a sinistral strike slip is needed between the area of Salzburg and the eastern Transdanubian Range (KÁZMÉR & KOVÁCS, 1985), not between the latter and the West Carpathians. A kinematic analysis (BALLA, 1988a, 1989a) revealed that the escape had to be accompanied by squeezing out of the East Alpine and West Carpathian domains and by their movement to the east relative to Europe (Text-Fig. 16), i.e. these domains moved in the same direction as the Transdanubian Range. As a consequence, the displacement on the Insubric – Rába line between the Alpine–Carpathian and Transdanubian domains diminishes towards the east due to lengthening of the Eastern Alps, and there are no constraints in the frame of the escape model on the movement of the West Carpathians relative to the Transdanubian Range.

If the West Carpathians were displaced towards the east more than the Transdanubian Range, the resulting movement between them would be of dextral sense, and the situation in Text-Fig. 15 would fit in the picture. That would only mean that the movement picture during the escape was much more complicated than it was primarily supposed (KÁZMÉR & KOVÁCS, 1985), first of all due to strong deformation of the East Alpine and West Carpathian domains in the course of the escape (BALLA, 1988a). If the West Alpine domains also moved towards the west during the squeezing out, the present-day >400 km displacement between the Ivrea and Mihályi Zones would reflect increase of the distance between the Western Alps and the West Carpathians due to lengthening, not a rigid strike-slip.

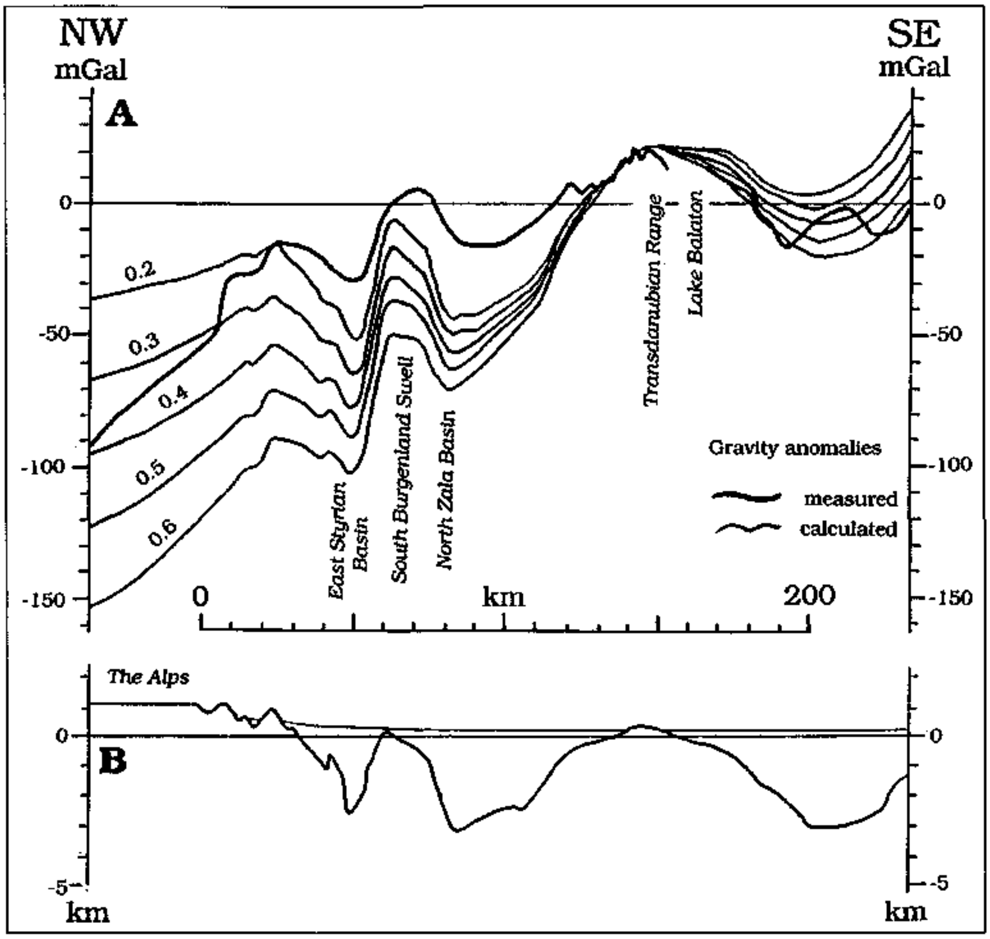
In the east, the closure of the Mihályi Zone at the Kolarovo high is not confirmed. The gravity step 60 km east of

Text-Fig. 18.
Calculated two-dimensional gravity effect of the Moho topography along the new profile (for location, see Text-Figs. 1 and 2) for various values of the density contrast.
"Measured" values taken from SCHEFFER 1957 (first 45 km), WALACH & ZYCH 1988 (Austria), SZABÓ & SÁRHIDAI (1985, Hungary), basement topography, from KRÖLL (1988, Austria), KILÉNYI & ŠEFARA (1991, Hungary), Moho topography, from POSGAY et al. (1991).
Gravity curves (A) shifted to coincide in a point above the Alpine root gravity slope. No vertical exaggeration of the depth model (B).

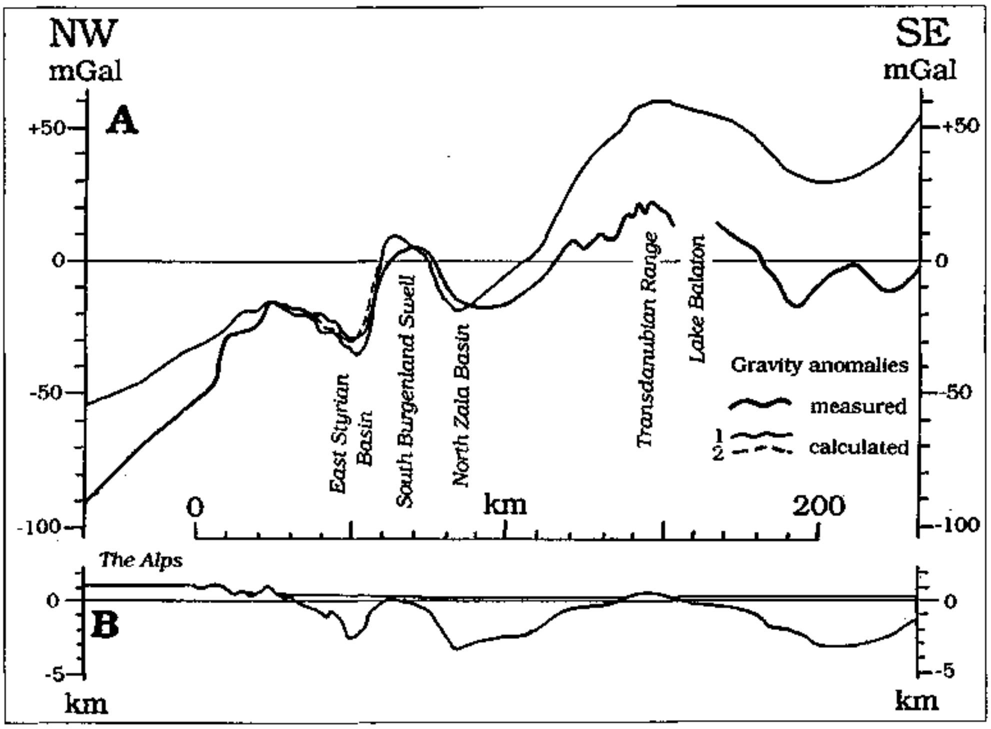


Kolarovo was interpreted in terms of stratigraphic and lithologic differences on the continuation of the Hurbanovo line (BALLA et al., 1978), but the step (elevation by 9 mGal on the northern side of the line) equally might be interpreted as the continuation of the Mihályi zone. The further continuation of the same tectonic zone is marked by intense magnetic anomalies which enter into the area of the Meliata Formation (mainly south of the Rožňava line in Text-Fig. 14; BALLA, 1989b).

The Ivrea structure can be regarded to be a collision zone (closure of the Penninic ocean) of Middle Cretaceous age. In Alpine geology, there are usually no doubts about correlation of the Rechnitz sequences with the Penninic ones and about Middle Cretaceous age of the first orogeny (PAHR, 1980, 1984; KOLLER, 1985; KOLLER & HÖCK, 1987). On the other hand, the Late Jurassic



Text-Fig. 19.
Calculated two-dimensional gravity effect along the new profile (A, for location, see Text-Figs. 1 and 2) for various values of the density contrast on the Moho and for the densities in Table 1.
Gravity curves shifted to coincide on the top of the Transdanubian Range gravity high. Vertical exaggeration of the depth model (B) 1 : 10.



Text-Fig. 20.
Calculated two-dimensional gravity effect along the new profile (A, for location, see Text-Figs. 1 and 2) for 0.4 g/cm³ density contrast on the Moho.
1 = for initial deficiency of sediment densities (Table 1); 2 = for those diminished by 0.1 g/cm³ in the East Styrian Basin.
Gravity curves shifted to coincide on the top of the gravity high between the East Styrian Basin and the Alpine root gravity slope.
Vertical exaggeration of the depth model (B) 1 : 5.

closure of the Meliata Ocean seems to be more or less clear (BALLA, 1988b). The geological relationships between the probably Eo-Alpine Mihályi zone with the Late Cimmerian Meliata collision structure wait for elucidation in the future.

5. Conclusions

Geological interpretation of gravity data has revealed a formerly unknown feature in the comparatively well studied area of the Alpine–Carpathian junction, i.e. an intracrustal density anomaly which is traceable for more than 200 km in all three countries. This fact demonstrates the necessity of more extensive use of geophysical data in geological investigation.

The density anomaly may be interpreted in various ways, nevertheless, an analog of the Ivrea structure, strongly modified by Neogene extension and subsidence processes, seems to be most probable. This interpretation is consistent with the idea of squeezing out of the Alpine domains during the Late Eocene continent-continent collision and raises the problem of spatial and structural relationships between the Eo-Alpine Penninic (Eastern Alps) and Late Cimmerian Meliata (Inner West Carpathians) collision structures.

Appendix 1
Brief Description of Gravity Modeling Along the Seismic Profile MK-1

Depths to the basement and Bouguer values from each km of the section were taken and plotted on the cross-plot (Text-Fig. 17). However, in contrast with the usual procedures of statistical evaluation we linked dots with lines sequentially as they follow each other along the seismic profile. Numbers in circles indicate slopes in Text-Fig. 3 and corresponding curve sections in text-Fig. 17. As seen, each of the slopes 1–5 display a normal path, i.e. increase of the Bouguer anomaly with decrease of the depths, whereas the sequence of these slopes displays a permanent increase of the regional gravity field towards the southeast. The path on Text-Fig. 17 turns to be abnormal between points 62 and 80, then slopes 6 and 7 together display a normal path, and disturbances between them probably reflect superficial lithological inhomogeneities.

If we cross the curve in Text-Fig. 17 by a series of horizontal lines, the distances in mGal between the neighbouring slopes will reflect a change in the regional gravity field. Sections of horizontal lines across the middle of slopes indicated in Fig. 17 were used to illustrate residual anomaly paths which correspond to the regional field (Text-Fig. 4). This path was constructed by shifting all lines to the same 2.6 km depth b.s.l.

Appendix 2
Description of Gravity Modeling along a New Profile across the South Burgenland Swell

The two-dimensional gravity effect of the Moho topography (Text-Fig. 18) strongly depends on the density excess of the masses below the Moho. The corresponding curve is as steep as the gravity slope of the Alpine root at values of 0.6 g/cm³ and higher whereas values >0.4 g/cm³ are in reality unacceptable. Consequently, the gravity slope in question is too steep and seems to need intra-crustal dense masses.

We constructed a simple density model for the East Styrian basin using density distribution within the sedimentary fill of the Danube–Rába Basin (Table 1) and accepting 2.67 g/cm³ for the density of the basement. A series of gravity curves calculated for various density contrasts on the Moho have been shifted to coincide on the top of the gravity high of the Transdanubian Range (Text-Fig. 19).

It is remarkable that the gravity low southeast of Lake Balaton is best reproducible at a density contrast of 0.2 g/cm³ or less (the small high inside the gravity low is due to the lateral effect of a basement high west of the profile, comp. Text-Figs. 1 and 2, thus, can be abandoned). This value was used in calculations for the sections MK-1 (Text-Fig. 5) and K-4 (Text-Fig. 6). At the same time, the gravity slope related to the Alpine root, again, requires at least 0.6 g/cm³ density contrast on the Moho. Consequently, there is no possibility to relate even the most principal features of the gravity profile to the topography of the Moho surface with a uniform gravity contrast on it.

A look at the gravity curves (Text-Fig. 19) reveals that the gravity field of the North Zala and East Styrian Basin area is too low relative to that of the Transdanubian Range, the difference increasing with increase of the density contrast on the Moho. Equalization would be possible by an effect from dense masses below the North Zala and East Styrian Basin area. The location of the western boundary of these masses seems to depend on the Moho gravity contrast, whereas the location of the corresponding eastern boundary may be independent of this contrast. Moho density contrasts of 0.3–0.4 g/cm^3 only seem to be acceptable in modeling.

Prior to further modeling we check the density distribution within the East Styrian Basin by shifting the gravity curve for 0.4 g/cm^3 density contrast on the Moho onto the gravity high west of the East Styrian Basin (Text-Fig. 20). We can conclude that the gravity slope between the Basin and the South Burgenland Swell is too high, i.e. it seems reasonable to diminish it by decreasing the density contrast between the sediments and the basement. It may equally mean increasing of sediment densities (Table 1, Text-Fig. 20), e.g. due to the presence of volcanic rocks in the sequence, or decrease of basement density due to the presence of low-metamorphic rocks (basement density 2.67 g/cm^3 would mean granite or gneiss). Now we are ready to start modeling of intra-crustal dense masses.

In the first step we placed a brick-like body with 0.2 g/cm^3 density excess immediately below the deepest point of the section and selected its appropriate height and width to fit the gravity anomaly with the Alpine root slope and with the Transdanubian Range high (Text-Fig. 10, continuous line), then modified its topography (dashed line) to improve the fit above internal areas of the body. A remarkable negative correlation between the topography obtained and the basement topography forced us to check sediment densities.

An attempt of further decrease of the sediment/basement density contrast in the East Styrian Basin by 0.1 g/cm^3 has resulted in positive correlation between the basement topography and the topography of the top of the high-density body (dotted line). A similar result has been obtained for the decrease of the sediment/basement density contrast in the North Zala Basin by 0.1 g/cm^3 (dot-dash line). Consequently, the topography of the high-density body is highly sensitive to the sediment/basement density contrast and cannot be defined precisely without precise data on densities. That is why in the course of further modeling we only tried to reveal principal features.

The selection of 0.3 g/cm^3 for density contrast on the Moho and increased by 0.1 g/cm^3 sediment/basement density contrast in the East Styrian Basin has not significantly changed the topography of the high-density body (Text-Fig. 11B, continuous line). Increase of the density excess from 0.2 to 0.3 g/cm^3 (dashed line) smooths, and its decrease from 0.2 to 0.1 g/cm^3 (dotted line) more dismembers topography of the high-density body.

Pushing down the whole body results in more contrasting topography (Text-Fig. 11C), and this fact induces an idea that the high-density body may be replaced by three vertical plates. Gravity modeling confirmed the possibility of this replacement (Text-Fig. 12) which, however, obviously highly depends on the sediment/basement density contrast.

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