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Crustal structure of the Alpine–Pannonian transition zone: a combined seismic and gravity study

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Abstract The crustal structure of the transition zone between the Eastern Alps and the western part of the Pannonian depression (Danube basin) is traditionally interpreted in terms of subvertical Tertiary strike-slip and normal faults separating different Alpine tectonic units. Reevaluation of approximately 4000-km-long hydrocarbon exploration reflection seismic sections and a few deep seismic profiles, together with data from approximately 300 wells, suggests a different structural model. It implies that extensional collapse of the Alpine orogene in the Middle Miocene was controlled by listric normal faults, which usually crosscut Alpine nappes at shallow levels, but at depth merge with overthrust planes separating the different Alpine units. The alternative structural model was tested along a transect across the Danube basin by gravity model calculations, and the results show that the model of low-angle extensional faulting is indeed viable. Regarding the whole lithosphere of the western Pannonian basin, gravity modelling indicates a remarkable asymmetry in the thickness minima of the attenuated crust and upper mantle. The approximately 160 km lateral offset between the two minima suggests that during the Miocene extension of the Pannonian basin detachment of the upper crust from the mantle lithosphere took place along a rheologically weak lower crust.

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Introduction

The Danube basin of Hungary and Slovakia is one of the deepest subbasins of the Pannonian basin. It was formed during the Middle Miocene at the transition zone between the Eastern Alps, the Western Carpathians and the Transdanubian Range (Fig. 1). The Hungarian part of the basin is usually called the Little Hungarian Plain, and this name illustrates the fact that the basin is indeed very flat due to ongoing subsidence in its central part. In the substrata of the Danube basin several major faults were postulated during the past decades (for an overview see Tari 1994). Especially one of these faults, the Rába line (for location see Figs. 2, 3), has been much debated during the past decade regarding its exact position, structural style and the role it played in the evolution of the Alps and the western Pannonian basin.

This paper presents the results of a combined seismic and gravity modelling study along a dip-oriented transect in the Hungarian part of the Danube basin (Fig. 2). The structure of the basin along this transect is well constrained by different geophysical data sets, such as deep reflection seismic profiles (Ádám et al. 1984; Posgay et al. 1986; Horváth et al. 1987), industry reflection seismic profiles (Horváth and Rumpler 1984; Rumpler and Horváth 1988; Mattick et al. 1996, unpublished data; Tari 1994, 1996) and magnetotellurics (Ádám et al. 1990; Nemesi et al. 1994). The gravity anomalies along the transect were previously interpreted by Dudko et al. (1990).

It is our aim to suggest an alternative model to that of Dudko et al. (1990) regarding the deep structure of the Danube basin. We combined the structural results of an extensive seismic reflection study (Tari 1994, 1996) with gravity modelling in order to find out

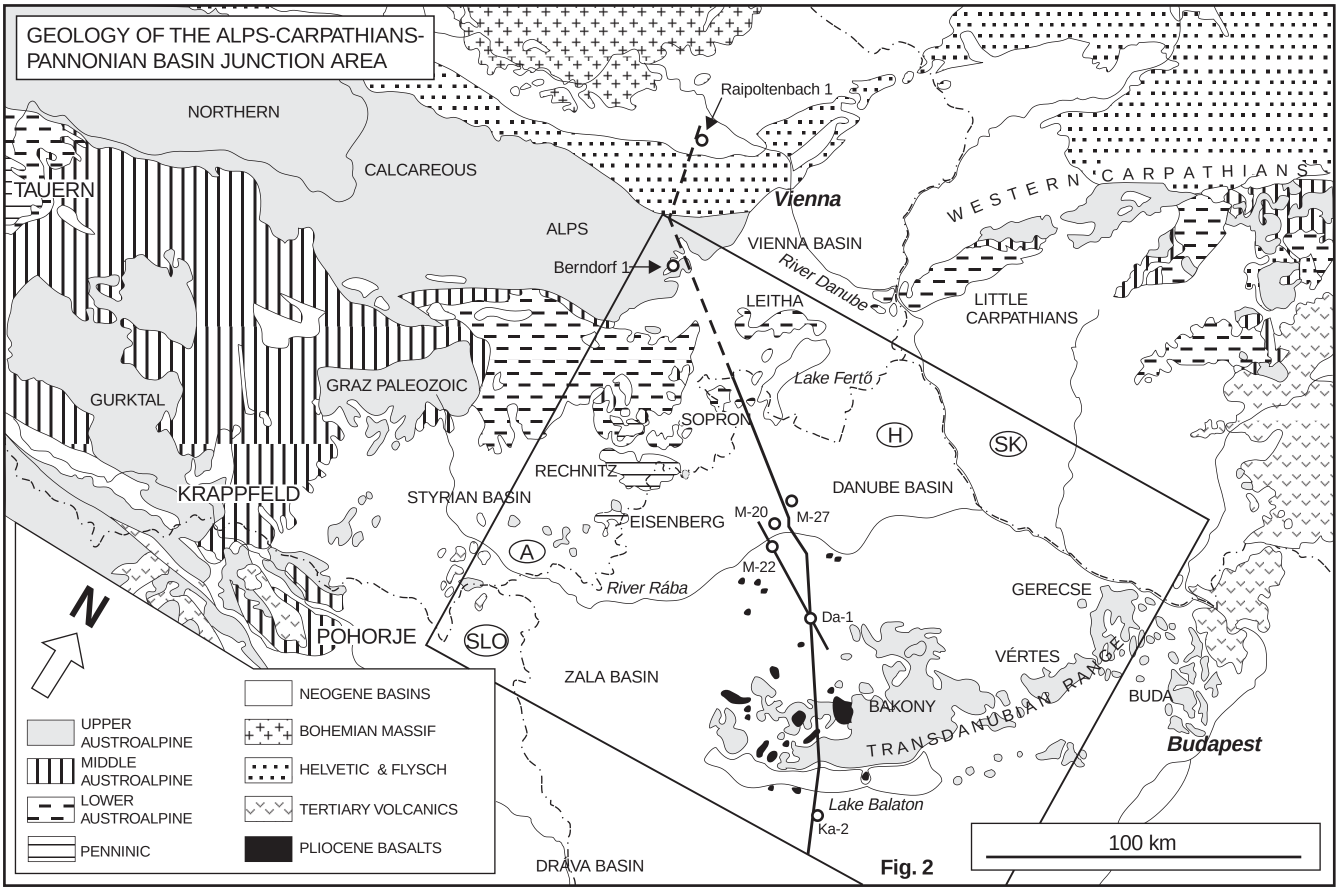

Fig. 1 Major tectonic units of the Alps–Carpathians–Pannonian basin junction area. *Thick lines* indicate the trace of the transect (*dashed* where no gravity model calculations were carried out) and the seismic line in Fig. 7. *Circles* show localities of wells discussed in the text

whether our remarkably different structural model of the basin evolution and the inferred crustal structure can reproduce the observed gravity anomalies. Moreover, we briefly discuss some of our results on lithospheric scale structures beneath the western Pannonian basin.

The problem of the Rába line

The much-debated Rába line trends to the NE beneath the centre of the Hungarian part of the Danube basin (Figs. 2, 3) and turns eastward below the Slovakian part. The Rába line was introduced by Scheffer and Kántás (1949) and Scheffer (1960), who studied the magnetic and gravity anomalies of NW Hungary and found that this line represented a boundary between blocks of very different characters in the potential fields. In the description of Kõrössy (1958, 1965) the Rába line is an important fault in the pre-Neogene basement separating a metamorphosed Paleozoic and Mesozoic area in the northwest (Austroalpine nappes) from a predominantly unmetamorphosed late Paleozoic and Mesozoic area in the southeast (Transdanubian Range; see Fig. 3). This definition became widely accepted and used mostly in studies on the metamorphic history of the area (e.g. Balázs 1971, 1975; Árkai et al. 1987; Árkai and Balogh 1989). Based on reflection seismic data, Ádám et al. (1984), Horváth and Rumpler (1984), and Rumpler and Horváth (1988) interpreted a southeast-dipping fault at the southeastern flank of the Mihályi high as the Rába line separating Austroalpine nappes from rocks of the Transdanubian Range in the basement. Horváth et al. (1987) using a deep seismic reflection line interpreted this fault as a flower structure suggesting oblique-slip movements, i.e. a combination of normal and sinistral strike-slip faulting. More recently, Horváth (1993) has carried out a systematical reinterpretation of previously published seismic sections and concluded that the Rába line is a pre-existing compressional detachment plane that reactivated as a listric normal fault during the Middle Miocene extension of the Pannonian basin. Mattick et al. (1996) analysed industrial seismic and borehole information and found no evidence that this normal fault, the Rába line, had a strike-slip component of displacement across the entire Little Hungarian Plain.

Further debate was generated by a different attempt to locate the Rába line. Magnetotelluric soundings in the Danube basin revealed a highly conductive layer at a depth of 5–10 km all over the northwestern flank of

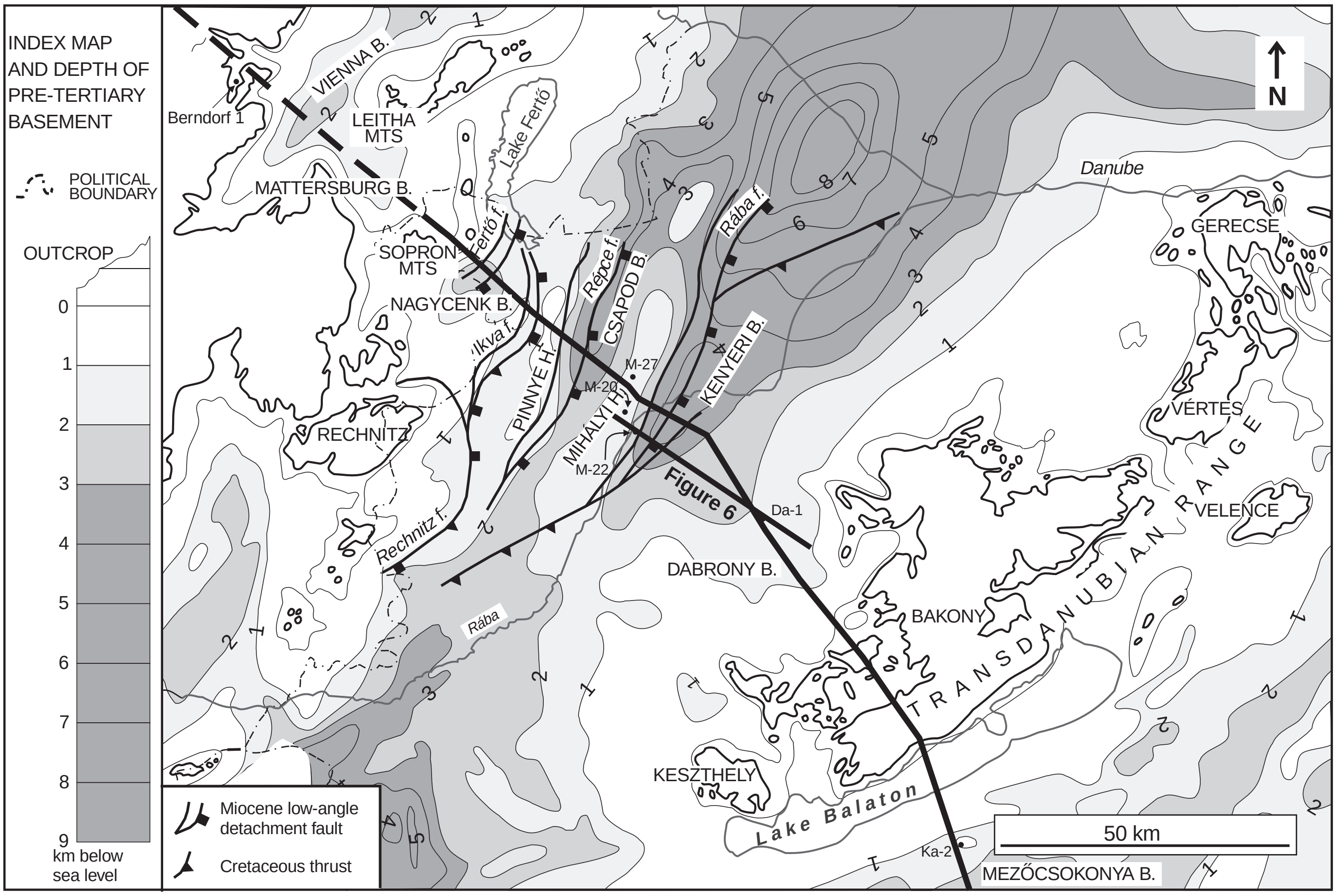

Fig. 2 Index map and depth of pre-Neogene basement in the northwest Pannonian basin (after Kilényi and Šefara 1989). For location see Fig. 1. *Thick lines* indicate the trace of the modelled transect (*dashed* where no gravity model calculations were carried out) and the seismic line in Fig. 7. The tectonic interpretation reflects the concept accepted in this paper (after Tari 1994). Miocene low-angle detachment faults are represented by two lines which indicate the amount of extension along them. Localities of wells discussed in the text are also shown

the Transdanubian Range, and nowhere in the area of the Alpine nappes. Based on several magnetotelluric transects across the area, the Rába line was defined as the boundary separating a "normal" basement complex on the northwest from another one on the southeast comprising an upper crustal layer with anomalously high electric conductivity. The magnetotelluric boundary defined this way (Pápa et al. 1990; Nemesi et al. 1994), however, deviates remarkably at places from the Rába line defined on the basis of distribution of metamorphic rocks. For example, Dudko et al. (1990) found an 8-km mismatch between the metamorphic and magnetotelluric Rába lines at the southeastern flank of the Mihályi high. They favoured the magnetotelluric definition and argued that this Rába line represented a major subvertical dislocation zone crossing the whole crust and offsetting by more than 6 km even the Mohorovičić discontinuity (Fig. 4). These crustal features were derived entirely from gravity model calculations along a single seismic line, which otherwise did not image at all this subvertical dislocation zone itself. Following the earlier notion of Kázmér and Kovács (1985) they interpreted the dislocation zone as the boundary of the Transdanubian Range unit which they considered as an exotic terrane escaped from the Periadriatic area during the Oligocene and early Miocene. According to this view the Rába line is the most important tectonic feature in the basement of the Danube basin, as it represents a subvertical strike-slip fault along which two crustal domains with completely different origin and internal structure are now juxtaposed. Balla (1994) has gone even further and suggested that the Rába line is accompanied by a high-density intracrustal body, very much like in the Ivrea zone of the Western Alps. Note also in Fig. 4 that the Mihályi high and its surroundings were postulated by Dudko et al. (1990) and Balla (1994) as Penninic unit, in contrast to all previous studies of the same rocks that correlated with the Upper Austroalpine domain exposed in the vicinity of Graz in the Eastern Alps (Balázs 1971, 1975; Árkai et al. 1987; Árkai and Balogh 1989).

This paper relies on an extensive seismic and borehole database acquired mostly during recent hydrocarbon exploration in the area. Seismic interpretation leads to a redefinition of the Rába line in terms of a southeast-dipping low-angle detachment plane which

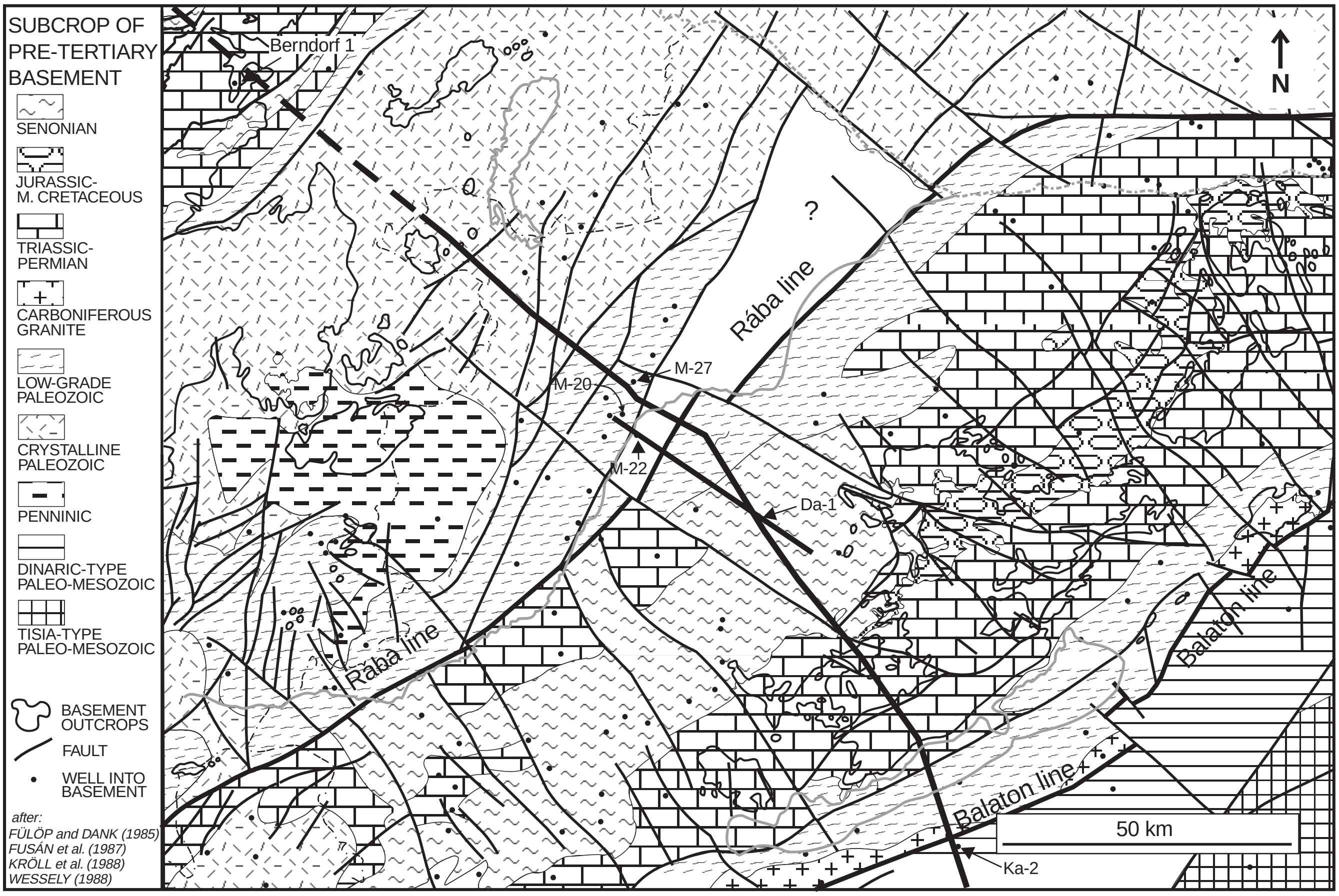

Fig. 3 Subcrop of pre-Tertiary basement in the northwest Pannonian basin. Same map frame as in Fig. 2. The map shows the "traditional" interpretation of the Rába line

soles out in the ductile lower crust. We show that there are a few other similar detachment planes in the basement of the Danube basin and, hence, the Rába line is not a unique feature of "megatectonic" significance; therefore, we call it Rába fault (see Fig. 2). Finally, we present a 2D gravity model calculation along the same transect as that of Dudko et al. (1990), and show that our remarkably different tectonic model is fully compatible with the gravity data.

Regional structural transect

The gravity model calculations were carried out along a regional transect compiled by Tari (1994) and, in the Hungarian part, it is based primarily on reflection seismic and well data (see Fig. 9). The section starts in the north on the European foreland, which was the northern passive margin of the Tethys that subducted southward beneath the Alps and Carpathians following the Tertiary collision between Europe and Africa (Dewey et al. 1989) and terminates to the south of Lake Balaton.

Northwestern part of the section

In the north the transect is based on a section published by Wessely (1983, 1988). It starts on the gently southward-dipping European foreland, which is built up of Hercynian and older crystalline rocks. Below the Vienna basin the autochthonous Mesozoic cover of the foreland is also usually preserved. This cover, however, is missing in the crest of the Bohemian basement promontory (Wessely 1987). The European foreland is overlain by a thin succession of autochthonous and allochthonous molasse and allochthonous flysch. Borehole information prove that molasse and flysch sediments are found as far as 35 km to the southeast from the leading edge of the overthrust Alpine units (e.g. Berndorf 1 well; see Figs. 2, 9; Table 1).

The upper part of the allochthonous Alpine nappe complex, which outcrops to the west of Vienna, belongs to the Upper Austroalpine system. The Upper Austroalpine system consists exclusively of unmetamorphosed Mesozoic sequences, except for the uppermost unit of the complex which has a low-grade metamorphic Paleozoic substratum. These units are structurally underlain by Middle and Lower Austroalpine thrust sheets which also outcrop along strike. The presence of the Penninic unit at depth is not known in the area of the Vienna basin due to the lack of well control (Wessely 1988; Zimmer and Wessely 1996).

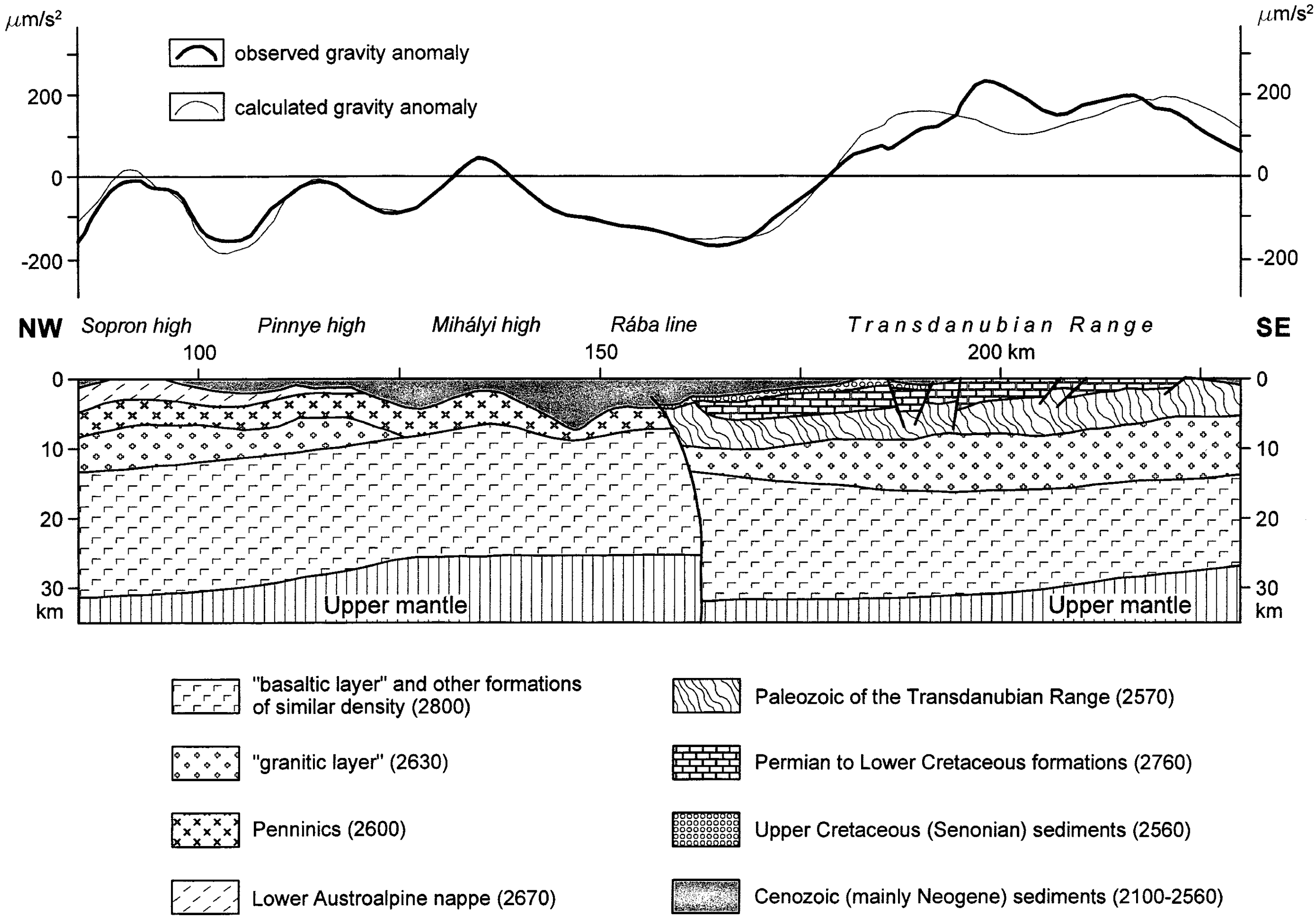

Fig. 4 The crustal structure of the Hungarian part of the Danube Basin according to Dudko et al. (1990) along the MK-1 crustal reflection profile. The location is shown in Figs. 2 and 3 by a *continuous thick line*. Note the subvertical nature of the Rába line offsetting the Mohorovičić discontinuity. *Numbers in parentheses* indicate densities used in the modelling (in kilograms per cubic metre)

The youngest strata are represented by the Neogene sedimentary rocks of the Vienna basin. The section crosses the southwestern corner of this basin (Fig. 2), where normal faults border a 2- to 3-km deep basin. These normal faults are shown to sole out and merge with the base of the underlying Alpine nappe complex in Figs. 5 and 9. Note that this is the only modification we made on the original sections of Wessely (1983, 1988) who thought that the normal faults also cut and offset the European foreland. According to many authors (Royden et al. 1982; Fodor et al. 1990; Fodor 1995) these normal faults accommodated the sinistral strike-slip motion during the opening of the Vienna pull-apart basin.

The Vienna basin is separated from the Danube basin by a basement high trending perpendicular to the section. The basement here consists of Lower Austroalpine units outcropping in the nearby Leitha Mountains. Farther to the south the smaller Mattersburg basin (Figs. 2, 9) appears to be bordered by a south-dipping normal fault.

Central part of the section

The section crosses the Austrian/Hungarian border just to the north of Sopron. Between the Sopron area and the Dabrony-1 well (Da-1; see Figs. 2, 8; Table 1) the section is based on the deep reflection seismic section MK-1 (Ádám et al. 1984; Posgay et al. 1986). Farther to the south the section follows the continuation of MK-1 line through the Bakony Mountains, which was processed only to 4-s two-way-travel time (Ádám et al. 1985). This part of the section, however, is constrained by surface geological data, as well (Császár et al. 1978; Bencze et al. 1990). After interpretation the seismic horizons were converted into depth using velocities shown in Fig. 6.

In the northwestern part of the Danube basin, the pre-Neogene basement exhibits a characteristic basin-and-range morphology. Subbasins, such as the Mattersburg, Nagycenk, Csapod, Kenyeri basins, are separated by basement highs (Leitha, Sopron, Pinnye, Mihályi; see Figs. 2, 5). All of these subbasins are controlled by major southeast-dipping synrift normal faults of Middle Miocene age. The crustal seismic section (Fig. 5) clearly

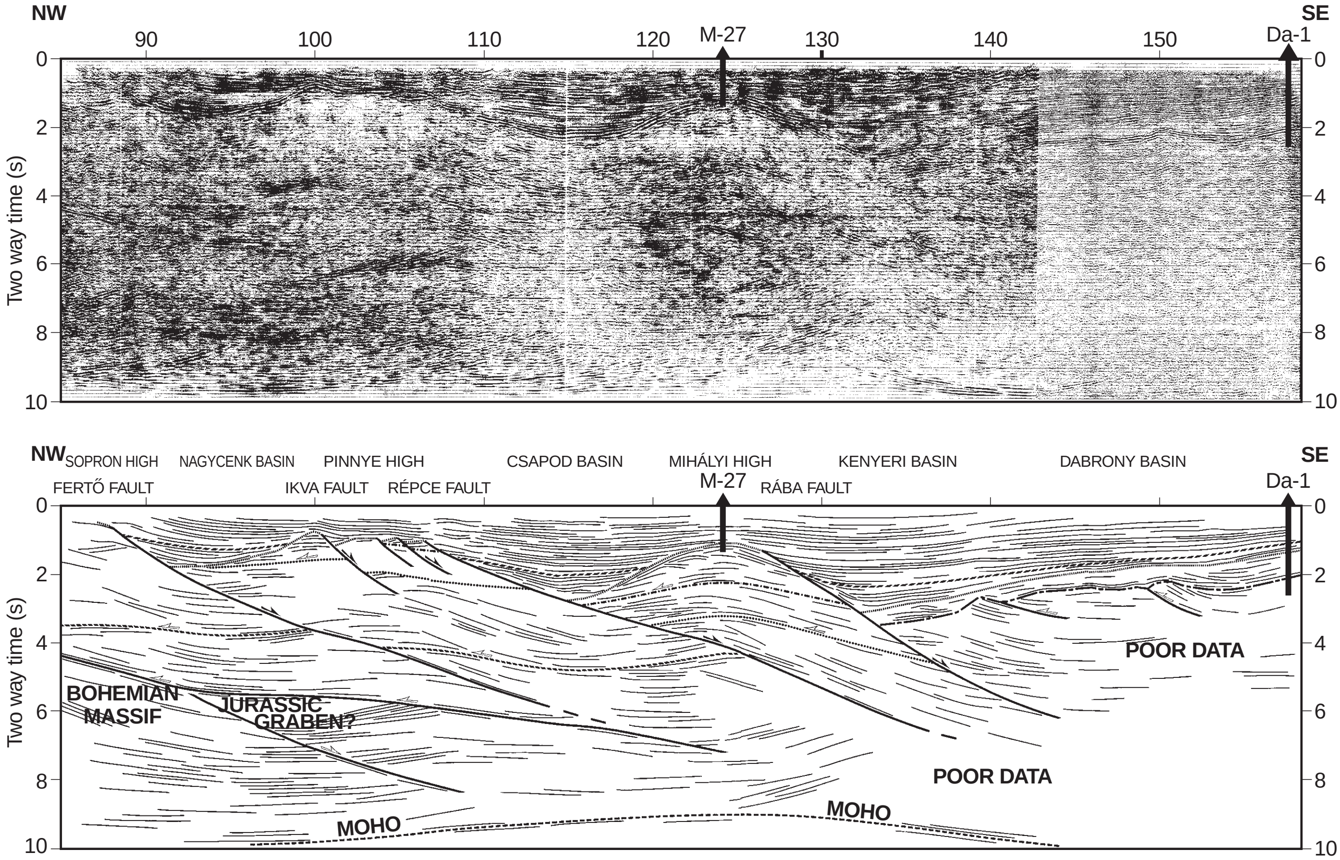

Fig. 5 MK-1 crustal reflection profile from Posgay et al. (1986) and its interpretation by Tari (1994, 1996)

shows that at least two of these faults (Fertő and Répce) maintain their low-angle dip (~30–40°) to middle crustal depth. Moreover, the Fertő fault appears to merge into a prominent surface which Tari (1994) considered the base of the Austroalpine nappe complex. The midcrustal geometry of the Rába fault is not clear because the data are poor in the southeastern part of the crustal profile.

However, the general structural picture is by far the best constrained along this part of the section, since the Little Hungarian Plain was the subject of a very detailed study using 4000 km of hydrocarbon exploration seismic lines and all available borehole information (Tari 1994, 1996). This study resulted in a series of structural maps (e.g. Fig. 2) and dozens of interpreted seismic sections (e.g. Figs. 5, 7), and allowed the following conclusions to be drawn for the whole Little Hungarian Plain:

1. Besides the several low-angle normal faults, there are apparently no synrift strike slip structures, which suggests a primarily extensional origin for the basin.
2. The compressionally pre-conditioned basement of the basin influenced the geometry of the Neogene extension, and newly forming extensional faults were guided by reactivation of pre-existing regional compressional décollement levels.

An average dip of ~5–7°of the European foreland at the northwestern end of the section is well constrained by the Raipoltenbach 1 and Berndorf 1 wells (see Fig. 1 and Table 1). Extrapolating this dip further to the southeast, the top of the European foreland can be tied into the northwestern end of the crustal seismic section along a reflection doublet at 4.2 s TWT time (~11 km depth). This reflection is interpreted as the boundary between the autochthonous European foreland and the overriding Alpine nappes. This reflection event can be correlated further SE to approximately 7 s TWT time (20 km depth) beneath the Mihályi high. Beneath the Pinnye high some strong northwest-dipping reflectors are tentatively interpreted as being related to a 10- to 15-km-wide Mesozoic half-graben on the distal edge of the European passive margin (Fig. 5).

Regarding the depth of the Mohorovičić discontinuity along the section, the map of Posgay et al. (1991) shows this surface in an elevated position beneath the Mihályi high. In the central part of the deep seismic section very-low-frequency reflectors between 9 and 10 s TWT may correspond to the Mohorovičić discontinuity. In the northwestern part of the section, below the Vienna basin and the Eastern Alps, the depth of the Moho descends to >30–35 km (Meissner et al. 1987).

Table 1 Description of the wells discussed in the text. For location of the wells see Figs. 1, 2 and 3. After Kőrössy (1987, 1990), Malzer et al. (1993), and Wessely and Wagner (1993)

Raipoltenbach 1	To SL	To KB
Kelly bushing	231	0
Quaternary	219	12
Molasse	– 508	739
Crystalline basement	– 514	745
Berndorf 1	To SL	To KB
Kelly bushing	454.2	0
Calcareous Alpine units	–5185.8	5640
Flysch	–5455.8	5910
Molasse	–5490.8	5945
Crystalline basement	–5574	6028.2
Mihályi-20 (M-20)	To SL	To KB
Kelly bushing	142	0
Upper Pannonian	–1114	1256
Lower Pannonian	–1332	1474
Crystalline basement	–1391	1533
Mihályi-22 (M-22)	To SL	To KB
Kelly bushing	142	0
Upper Pannonian	–1370	1512
Lower Pannonian	–2245	2387
Crystalline basement	–2350	2492
Mihályi-27 (M-27)	To SL	To KB
Kelly bushing	95	0
Upper Pannonian	–1249	1344
Lower Pannonian	–1458	1553
Miocene	–1542	1637
Crystalline basement	–1694.5	1789.5
Dabrony-1 (Da-1)	To SL	To KB
Kelly bushing	152.24	0
Quaternary	135.24	17
Upper Pannonian	– 492.76	645
Lower Pannonian	– 810.76	963
Miocene	–1592.76	1745
Upper Cretaceous	–2744.76	2897
Upper Triassic	–3848.26	4000.5
Karád-2 (Ka-2)	To SL	To KB
Kelly bushing	270.33	0
Upper Pannonian	– 130.67	401
Lower Pannonian	– 201.67	472
Miocene	– 746.67	1017
Mesozoic (Dinaric type)	– 755.67	1026

To SL means depths are relative to sea level; To KB means depths are relative to kelly bushing

In the southeastern part of the Danube basin the pre-Neogene basement displays a monoclinal dip to the northwest. Here the basement structure is reasonably well known based on the interpretation of industry seismic profiles by Tari (1995a). There are numerous northwest-verging nappe structures that display an Eoalpine (Cretaceous) deformational style similar to that of the Upper Austroalpine nappes of the Eastern Alps. These features are illustrated well by Fig. 7, which shows an interpreted industry seismic profile (after Tari 1994; for location see Fig. 2), and by other seismic sections published by Horváth (1993) and Mattick et al. (1996).

Southeastern part of the section

There are two synclines (Devecser and Halimba) superimposed on the overall NE-trending synclinal shape of the Bakony Mountains. In map view these synclines are flanked by anomalously wide (10–15 km) Hauptdolomite successions. Allowing for an average 30° dip of the Hauptdolomite as reported from both

Table 2 Densities of the sediments used in the gravity calculations. (After Bielik 1988, 1991; Dudko et al. 1990; Szafián et al. 1997; and unpublished data)

Depth interval (km)	Density (kg m^{-3})
0–1	2100
1–2	2300
2–3	2440
3–4	2580
4–5	2640
5–6	2660
6–7	2670

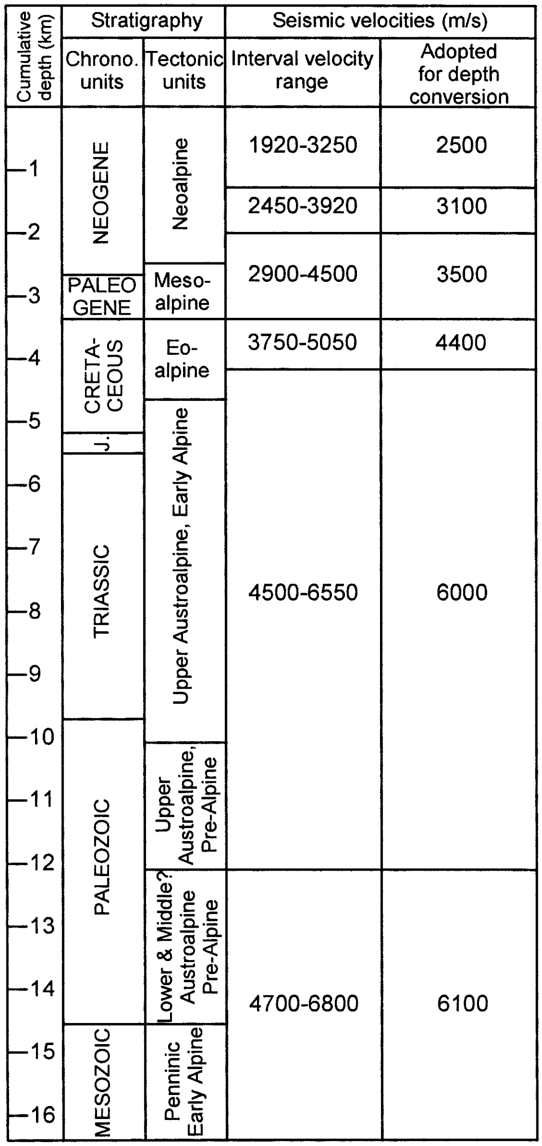

Fig. 6 Seismic interval velocities of the different tectonic units, and velocities adopted for depth conversion. (After Tari 1994, 1996)

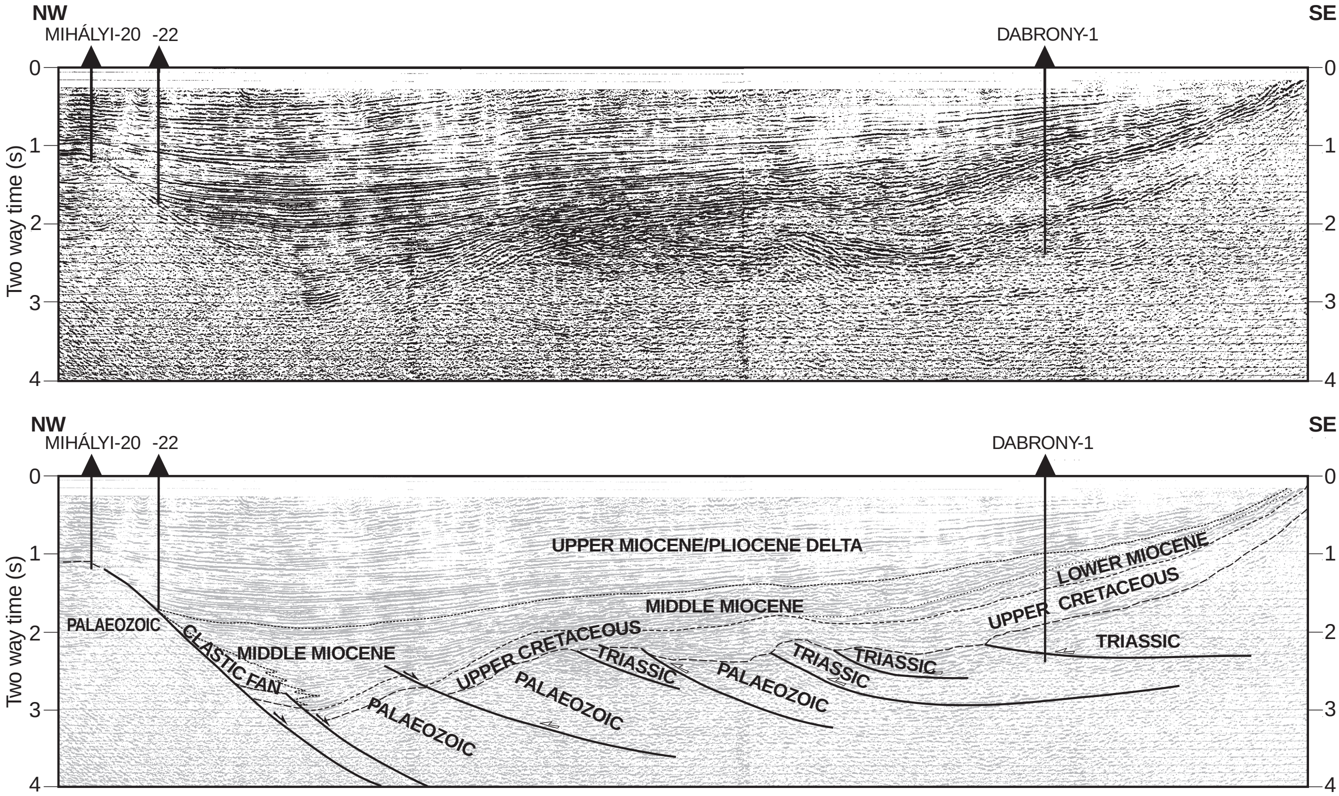

Fig. 7 Industry seismic line in the Dabrony basin and its interpretation. (After Tari 1994)

outcrops and wells (e.g. Bencze et al. 1990; Kőrössy 1987), this would mean a 5-km-thick sequence. Since the maximum observed thickness of the Hauptdolomite is 1500 m (Tari 1995b), we inferred its internal repetition by thrusting (see Fig. 10). The available poor seismic reflection data unfortunately do not support any interpretation. Backthrusting at the southern edge of the Devecser syncline over the northern margin of the Halimba syncline is documented in outcrops (see the map of Császár et al. 1978). The detachment of the Hauptdolomite from its base occurred along the Carnian Veszprém Marl which might have accumulated in a triangle shape subsurface area between the two synclines (see Fig. 10). The two synclines appear to float above two regional thrust surfaces correlatable from their outcrops in the Balaton Highland to their subcrop in the Danube basin: the structurally higher Veszprém thrust is associated with a Carnian detachment surface, and the deeper Litér thrust generally follows a Middle Triassic detachment level (see Fig. 10).

At the southeastern end of the transect the Early Miocene Balaton line has a reverse fault character at shallow depth as it was documented by drilling (Balla et al. 1987; Kőrössy 1990). In the transect the Balaton fault was placed immediately to the north of the Karád area (e.g. Ka-2 in Figs. 2 and 9; Table 1) where Dinaric-type Paleozoic carbonates were found (Bérczi-Makk 1988). At depth Tari (1994, 1996) postulated the flattening of the Balaton line at the base of the Austroalpine nappe system.

Gravity model calculation

The Bouguer anomaly map of NW Hungary is shown in Fig. 8. Unfortunately, there is no unified, detailed Bouguer anomaly map available for the whole territory of our study; therefore, we used only the Hungarian data (Szabó and Sárhidai 1985). This means that we have no gravity control for the shallow structure of the Austrian part of the section (0–85 km). Nevertheless, we show the Bouguer anomalies for the Austrian part, as well, in Fig. 9, although these data were not incorporated in the calculations, because the use of different reduction densities resulted in a significant misfit at the boundary of the Alps and the Danube basin. As our section runs approximately perpendicular to the strikes of the major anomaly stripes (Fig. 8), the two-dimensional modelling approach represents a good approximation.

The geometry of the upper 20–22 km of the profile was constructed following the structural interpretation of Tari (1994), in a somewhat simplified manner. The first deep seismic studies in the region (Gálfi and Stegena 1959) had already proven that there was a distinct lower crust in the Pannonian basin; therefore,

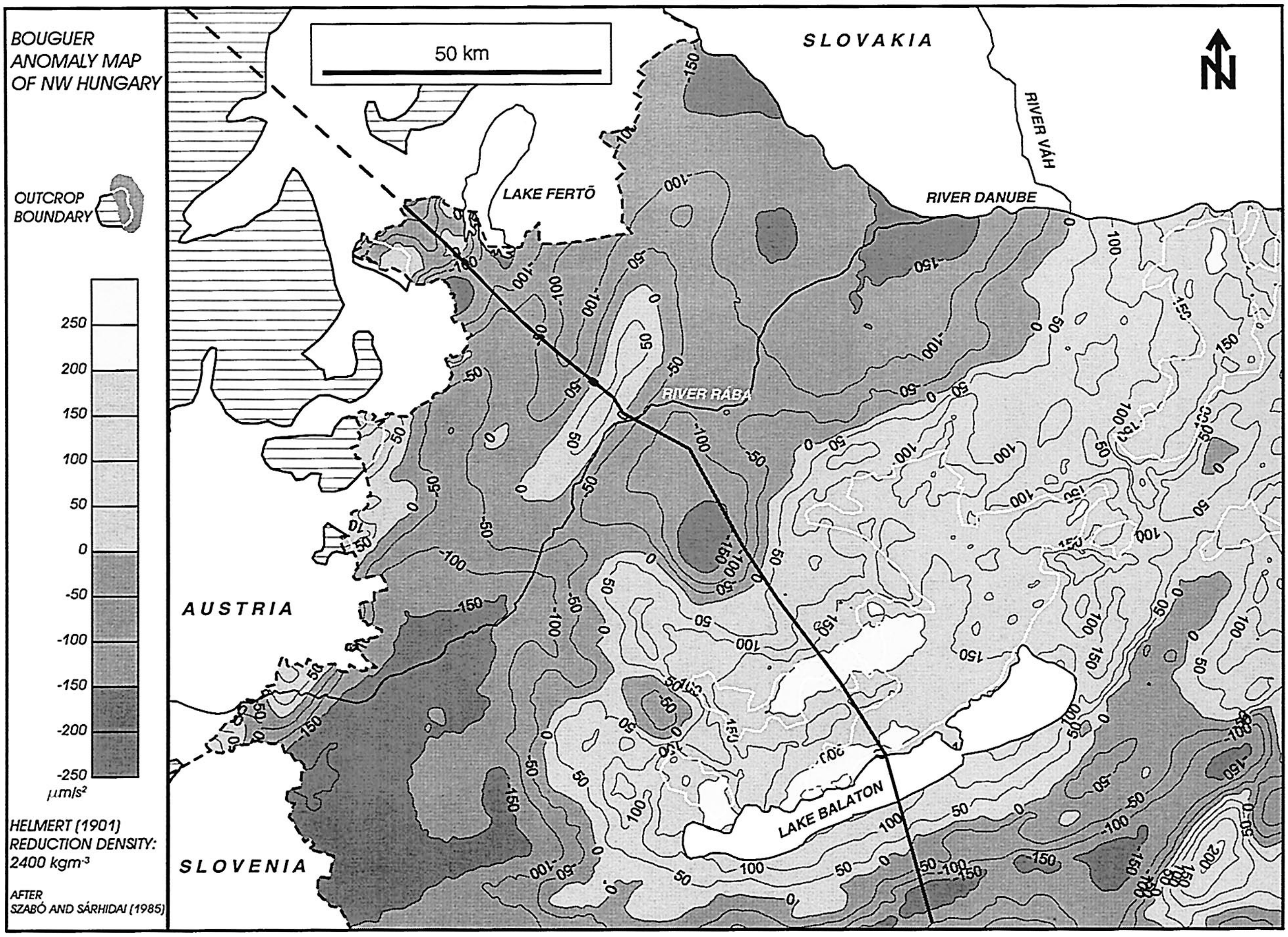

Fig. 8 Bouguer anomaly map of NW Hungary; same map frame as in Figs. 2 and 3

we subdivided the crust, and the boundary between the upper and lower part was set after Bielik (1991), Horváth (1993) and Szafián et al. (1997). The depth of the Mohorovičić discontinuity and the asthenosphere–lithosphere boundary was determined from the crustal and lithospheric thickness maps of Horváth (1993) and the contour maps of the Mohorovičić discontinuity of Meissner et al. (1987) and Posgay et al. (1991). In order to avoid the possible edge effects, we incorporated the topography of these deep-seated density boundaries along the northwest and southeast continuation of the profile (see Fig. 11). Note that the topography of the pre-Tertiary basement is not incorporated beyond 300 km in the section because it does not have any effect on the gravity anomalies of the studied area.

The Neogene sedimentary fill of the Pannonian basin consists of mainly shale, siltstone, sandstone and volcanic rocks. The density-depth relations of shale, siltstone and sandstone are well known on the basis of core samples from hydrocarbon exploration wells (unpublished data). Bielik (1988, 1991) independently suggested similar density values for the same sedimentary sequence. For the calculations the sedimentary sequences were divided into 1-km-thick layers, regardless of synrift or postrift position, each layer having a uniform density. The densities range from 2100 kg m^{-3} to 2670 kg m^{-3} (see Table 2).

We subdivided the Mesozoic Upper Austroalpine units of Tari (1994) in the Bakony Mountains. This is especially important in the shallow parts of the section where slight density differences can cause significant changes in the modelled anomaly pattern. Therefore, we used four different groups of formations, according to well and field data: Hauptdolomite, Dachstein and Kardosrét limestones, Veszprém Marl, and, if no proper distinction could be made, the undifferentiated Mesozoic Upper Austroalpine units (Figs. 9, 10). Note that in Fig. 9 this subdivision of the Upper Austroalpine units is not shown. Each of these groups had different densities (Figs. 9, 10). The density values were chosen after Dudko et al. (1990), Hoffer et al. (1991), Lillie et al. (1994) and Szafián et al. (1997). In some cases the same lithology in different tectonic units (e.g. Paleozoic Middle and Lower Austroalpine units) provided different densities. This represents the increase of the density with depth.

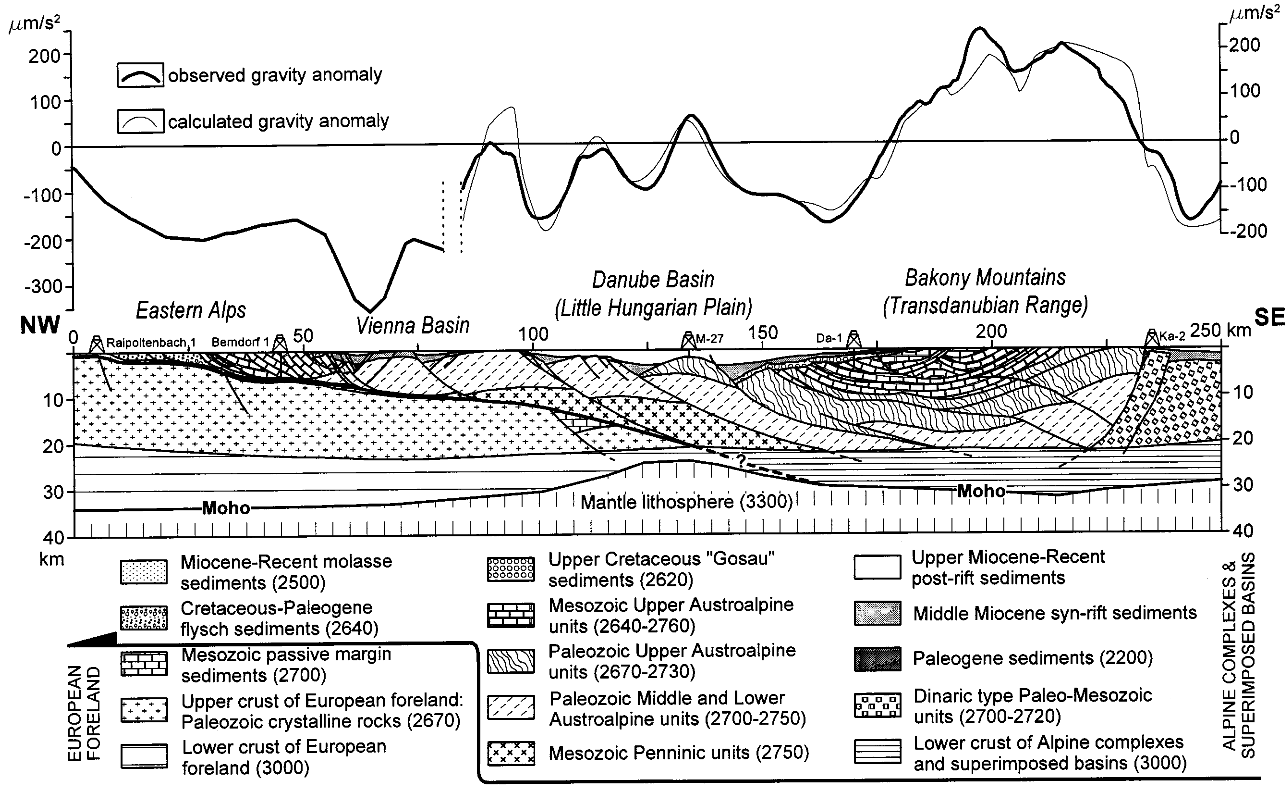

Fig. 9 Gravity model of the crustal transect. For location see Fig. 2. Gravity data are after Szabó and Sárhidai (1985) and Bureau Gravimétrique International (1963). *Numbers in parentheses* indicate densities used in the modelling (in kilograms per cubic metre)

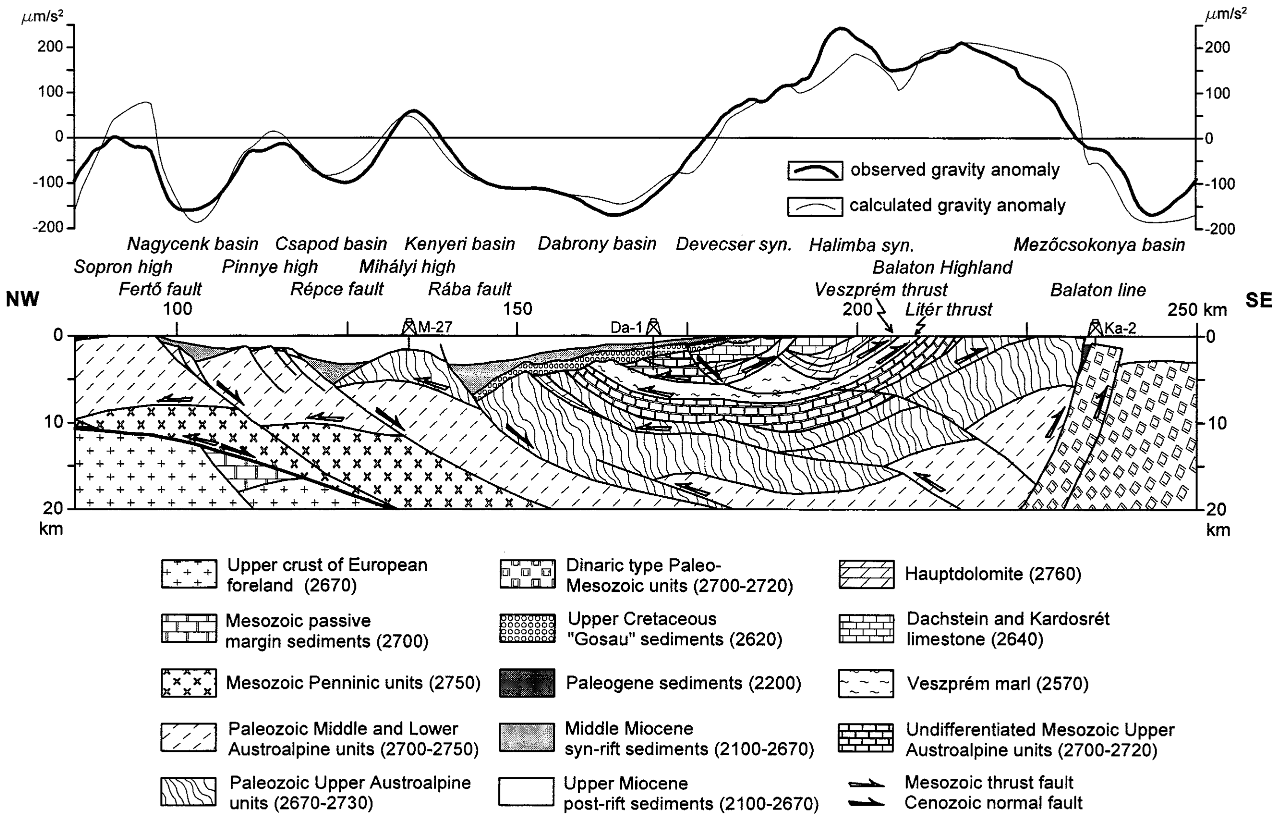

Fig. 10 Detail of gravity modelling shown in Fig. 9. Numbers in parentheses indicate densities used in the modelling (kilograms per cubic metre)

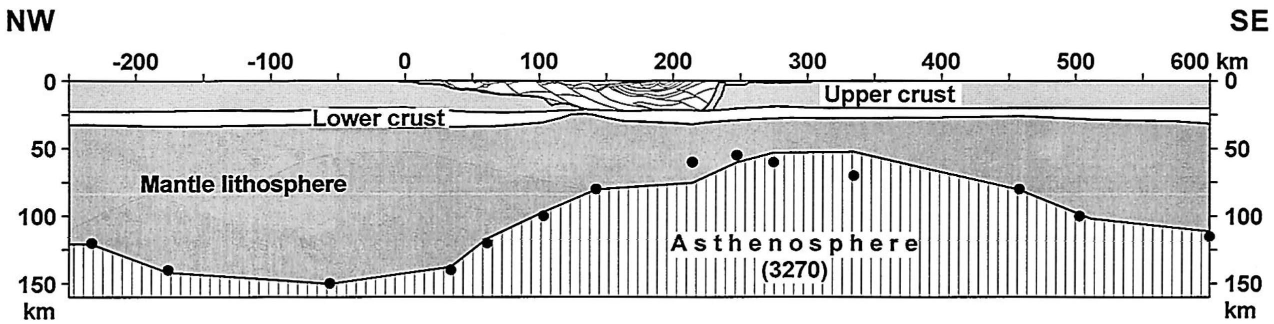

Fig. 11 Lithospheric structure deduced from the gravity modelling. *Dots* show the lithosphere/asthenosphere boundary calculated from delay times of teleseismic P-waves and magnetotelluric soundings. (After Horváth 1993)

Results

The model calculations were carried out using a two-dimensional forward and inverse modelling package for gravity data (Webring 1985). The program fits in a least-squares sense the theoretical gravity response of a density structure model to a profile of observed data using generalized linear inversion to improve both the geometry and density parameters of the model.

The difference between the observed and calculated gravity values along the transect is mostly less than 50 μ ms^{-2} (Figs. 9, 10). The fit is very good especially in the deepest part of the basin (140–160 km). Note that this part of the section was critically important for Dudko et al. (1990) to locate their Rába line (see also Fig. 4).

In the area of the Bakony Mountains the inconsistencies between the observed and the calculated gravity anomalies (Fig. 10) may result from the inaccurate position of certain near-surface (<5 km) tectonic boundaries in our model and, more importantly, from the inaccuracies of the two-dimensional modelling method; however, this does not effect the conclusions drawn on the crustal structure.

Conclusion

Our gravity modelling confirms that there is no need to postulate a major subvertical dislocation zone (Rába line) offsetting even the Mohorovičić discontinuity underneath the Danube basin (Dudko et al. 1990). An alternative structural model can in fact provide the same gravity anomaly pattern. Similarly, gravity data in itself cannot be used to infer the presence of a high-density, Ivrea-type body under the Mihályi high (cf. Balla 1994). This alternative model comes from the interpretation of many industrial and deep seismic sections combined with borehole data. It suggests that the formation of the Danube basin has been primarily controlled by a set of low-angle normal faults which all sole out in the lower crust. This idea is supported by the results of Ratschbacher et al. (1990, 1991), Horváth (1993), Lankreijer et al. (1997) and Lankreijer (1998), who proposed that the rheology of the lower crust in the Pannonian region is significantly different from that of the upper crust and its characteristic deformation is ductile shear. The position of the normal faults was strongly influenced by the Eoalpine (Cretaceous) thrust planes because normal faults usually merge with the earlier compressional detachment planes at mid-crustal depth.

Regarding the whole lithosphere of the northwest Pannonian basin, our results indicate the detached nature of extension within the lithosphere. Whereas the Mohorovičić discontinuity shows a significant updoming under the Danube basin (Figs. 5, 9), the thinnest part of the lithosphere is located approximately 160 km to the south from the axis of the Danube basin (Fig. 11). This supports the idea that the Neogene deformation in the upper crust was decoupled from that of the lithospheric mantle lid along a rheologically weak lower crust (Horváth 1993; Lankreijer et al. 1995). Figure 11 shows that teleseismic P-wave delay time analysis and magnetotelluric measurements also indicated this asymmetry; therefore, our conclusion seems to be verified. This implies that the western Pannonian basin offers a good example for the statement of Reston (1990) that basin extension is not so pure and simple.

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