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# Calculation of a stripped gravity map with a high degree of accuracy: a case study of Liptovská Kotlina Basin (Northern Slovakia)

Eva SZALAIOVÁ, Miroslav BIELIK, Irina MAKARENKO, Olga LEGOSTAEVA, Jozef HÓK, Vitalij STAROSTENKO, Martin ŠUJAN and Ján ŠEFARA

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The paper deals with the construction and calculation of a stripped gravity map with a high degree of accuracy. In the Western Carpathian basins such types of gravity maps represent the corrected Bouguer anomalies by the gravity effects of the Tertiary sedimentary masses. It means that the resultant stripped gravity map reflects the gravity effects of density inhomogeneities, which are located beneath the pre-Tertiary basement. For determination of this map, the modern progressive forward-modelling gravity method was applied. The advantage of this method in comparison with previous approaches is that it is capable of calculating the 3D gravity effects of the geological bodies with real topography. A case study for presentation of a new and precise stripped gravity map, the Liptovská Kotlina Basin, was chosen, because it is one of the best-surveyed basins in the Western Carpathians. This new gravity map represents, for this moment, the most accurate stripped gravity map in the whole Western Carpathians. It allows construction not only of a very precise 3D gravity model of the sedimentary fill but also enables interpretation of the sources of the gravity anomalies revealed in the stripped gravity map. This interpretation is based on all available geophysical and geological constraining data. It is also supported by 2D analysis of the gravity effects of the main tectonic units building the Liptovská Kotlina Basin.

*Eva Szalaiová, Miroslav Bielik, Jozef Hók, Faculty of Natural Sciences, University of Comenius, Mlynská dolina, 842 15 Bratislava, Slovak Republic, e-mails: szalaiova@gmail.com, bielik@fns.uniba.sk, hok@fns.uniba.sk; Miroslav Bielik, Ján Šefara, Geophysical Institute of the Slovak Academy of Sciences, Dúbravská cesta 9, 845 28 Bratislava, Slovak Republic; e-mails: geofmiro@savba.sk, geofsefa@savba.sk; Irina Makarenko, Ola Legostaeva, Vitalij Starostenko, Institute of the Geophysics, National Academy of Sciences, Palladin av., Kiev-142, 036 80 Ukraine; e-mails: irina@igph.kiev.ua, olgal@igph.kiev.ua, vstar@igph.kiev.ua; Martin Šujan, EQUIS, Ltd., 831 02 Bratislava, Slovak Republic, e-mail: mato@equis.sk* *(received: March 27, 2007; accepted: Fabruary 19, 2008).*

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## INTRODUCTION

The calculation of a stripped gravity map is one of the most effective methods for studying pre-Tertiary basement structure (e.g., Bielik, 1988; Królikowski and Petecki, 2002; Makarenko *et al*., 2002; Bielik *et al*., 2004, 2005; Yegorova *et al*., 2004). In general, the stripping approach is well-known globally (e.g., Dirkzwager *et al*., 2000; Rybakov *et al*., 2000; Starostenko *et al*., 2004; Ebbing *et al*., 2006; Tašárová *et al*., 2006; Tassara *et al*., 2006; Zanolla *et al*., 2006; Møller *et al*., 2007). The process is based on subtraction of the 3D gravity effects of well-known geological structures (density-anomalous zones and/or density inhomogeneities) from the Bouguer gravity anomalies. Hammer (1963) calls it a geological filtration. Mostly, the density inhomogeneities are represented by surface geological structures. Sometimes, when sufficient qualitative good geophysical and geological constraining data exists on the geometry and density of deeper density-anomalous zones, Bouguer anomalies can also be corrected by their gravity effects.

In the Western Carpathians, the first complete stripped gravity map was calculated for the Inner Western Carpathians at a scale of 1:200 000 (Šefara *et al*., 1987). One year later a stripped gravity map from the Pannonian Basin region at the scale of 1:1 000 000 was published by Bielik (1988). Despite the quality of these maps being not very high, their applicability to the research of deep-seated structures of the Western Carpathian–Pannonian Basin region was clear. Nevertheless, they showed that for more qualitative interpretation of these structures it would be necessary to calculate more detailed stripped gravity maps with a higher degree of accuracy. The first attempt to determine a stripped gravity map in the western part of the Liptovská Kotlina Basin was performed by Maďar *et al*. (1997). This stripped gravity map was calculated without taking into account the real topography. The gravity effect of the surface density inhomogeneities of the basin was determined only with average planar topography. Moreover, the map was not constructed for the whole basin region.

Therefore, the main aim of this paper is the calculation of a stripped gravity map with a high degree of accuracy. For that purpose the modern progressive forward-modelling gravity method was applied. The method is based on formulas developed and published by Starostenko *et al.* (1997). The significant advantage of this method, in comparison with former approaches, is that it is capable of calculating the 3D gravity effect of an anomalous body with real topography. An another advantage of the applied method is that it efficiently to calculates the effect of a geological body (layer) not only with a constant density, but also with a density that varies in the horizontal and vertical directions. In the vertical direction the density can vary linearly or exponentially (Starostenko *et al.*, 1997). A case study for presentation of such a stripped gravity map, the Liptovská Kotlina Basin was chosen, because it is among the best-surveyed basins in the Western Carpathians. The 3D gravity model of the basin sedimentary fill includes all available geophysical and geological constraining data. The new gravity map of the Liptovská Kotlina Basin represents, for the moment, the most accurate stripped gravity map in the whole Western Carpathians. For more objective interpretation of the observed and calculated gravity anomalies, the gravity effects of the main tectonic units building the Liptov Through were also determined. The gravity effects were calculated along the representative profile I–I´ by means of 2D density modelling. The description of the regional gravity field of the Liptovská Kotlina Basin in the context of the surrounding Nízke Tatry Mts. and Tatra Mts. is also presented.

The Liptovská Kotlina Basin (Fig. 1) is located in the northern part of Slovakia between the Tatra Mts. in the north and the Nízke Tatry Mts. in the south. The depression is elongated in an east-west direction; the length and width are 50 km and 15 km, respectively. A number of mineral and thermal water springs are located in this basin (Liptov region). The growing interest in the use of geothermal water for energy and recreation purposes make this region an attractive one. The sources of thermal water are Mesozoic rocks in the pre-Tertiary basement of the basin, a reason for research into the pre-Tertiary basement structures of this region.

## GEOLOGICAL SETTING

The Western Carpathians form a mountain range with a dominant nappe structure with a significant zonal arrangement reflecting orogenic processes that migrated through time from south to north. From the point of view of the rock types, the tectonic emplacement age of units and the relations thereof, is possible to divide the Western Carpathians into two basic units, namely the Outer Western Carpathians and the Inner Western Carpathians. Tectonism (folding) of the Inner Western Carpathians was completed before the Late Cretaceous (*ca*. 65 Ma ago), while the Outer Western Carpathians were folded in the Tertiary (30–12 Ma). The deposits of the uppermost Cretaceous (the Gossau Cretaceous), the Paleogene (the Podtatranská group) and the Neogene belong to the post-nappe formations of the Inner Western Carpathians. Basins and depressions are distinct morphostructural features of the Inner Western Carpathians. The development of basins and depressions were geodynamic processes that controlled the development of the Carpathian arc at the close of the Paleogene and during the Neogene.

The sedimentary fill of the Liptovská Kotlina Basin (Fig. 1A) comprises Quaternary and Paleogene deposits. The Quaternary deposits are represented predominantly by alluvial, proluvial and deluvial sediments. The south slopes of the Tatra Mts. are covered by thick glacifluvial deposits (Maďar *et al*., 1997).

The Paleogene strata include conglomerates, claystones and sandstones. They belong to the Podtatranská group (Central Carpathian Paleogene) and, as regards their lithology, they are divided into four basic formations (Gross *et al*., 1980). The Borové Formation represents a basal transgressive lithofacies with conglomerates and breccias. The Huty Formation is a succession of monotonous claystones. The Zuberec Formation comprises an alteration of claystones and sandstones. The youngest Biely Potok Formation is not present in the Liptovská Kotlina Basin.

The pre-Tertiary basement (Fig. 1B) consists of three different tectonic units of the Central Western Carpathians. From the bottom to top these are the Tatricum, Fatricum and Hronicum. The Tatricum is an autochthonous unit. It crops out at the northern margin of the Liptovská Kotlina Basin in the Tatra Mts. The Tatricum basement is represented by crystalline rocks including granitoids and gneisses. The Tatric cover unit contains subautochthonous Cretaceous strata and remnants of Triassic carbonates. The Tatricum unit has not yet been recognized in boreholes that reach the pre-Tertiary basement.

The Fatricum is an allochthonous tectonic unit thrust over the Tatricum. The stratigraphic extent of the Fatricum is Middle Triassic to Middle Cretaceous. It predominantly contains various facies of limestones, dolomites, marls and marly limestones. The Fatricum tectonic unit was drilled immediately below Paleogene deposits in boreholes V-1 (Biela, 1978*a*, *b*) and FGL-1 (Remšík *et al*., 1979). Rocks belonging to the Fatricum unit are present below the Hronicum rock sequence in ZGL-1 borehole and most probably in ZGL-3 (Remšík *et al.*, 1990; Král *et al*., 2004).

The Hronicum is the uppermost tectonic unit that overlies the Fatricum. The stratigraphic extent of the Hronicum rock sequences is Late Palaeozoic to Early Cretaceous. The Late Palaeozoic rocks in the Hronicum are represented by a volcano-sedimentary succession of the Ipoltica Group (Vozárová

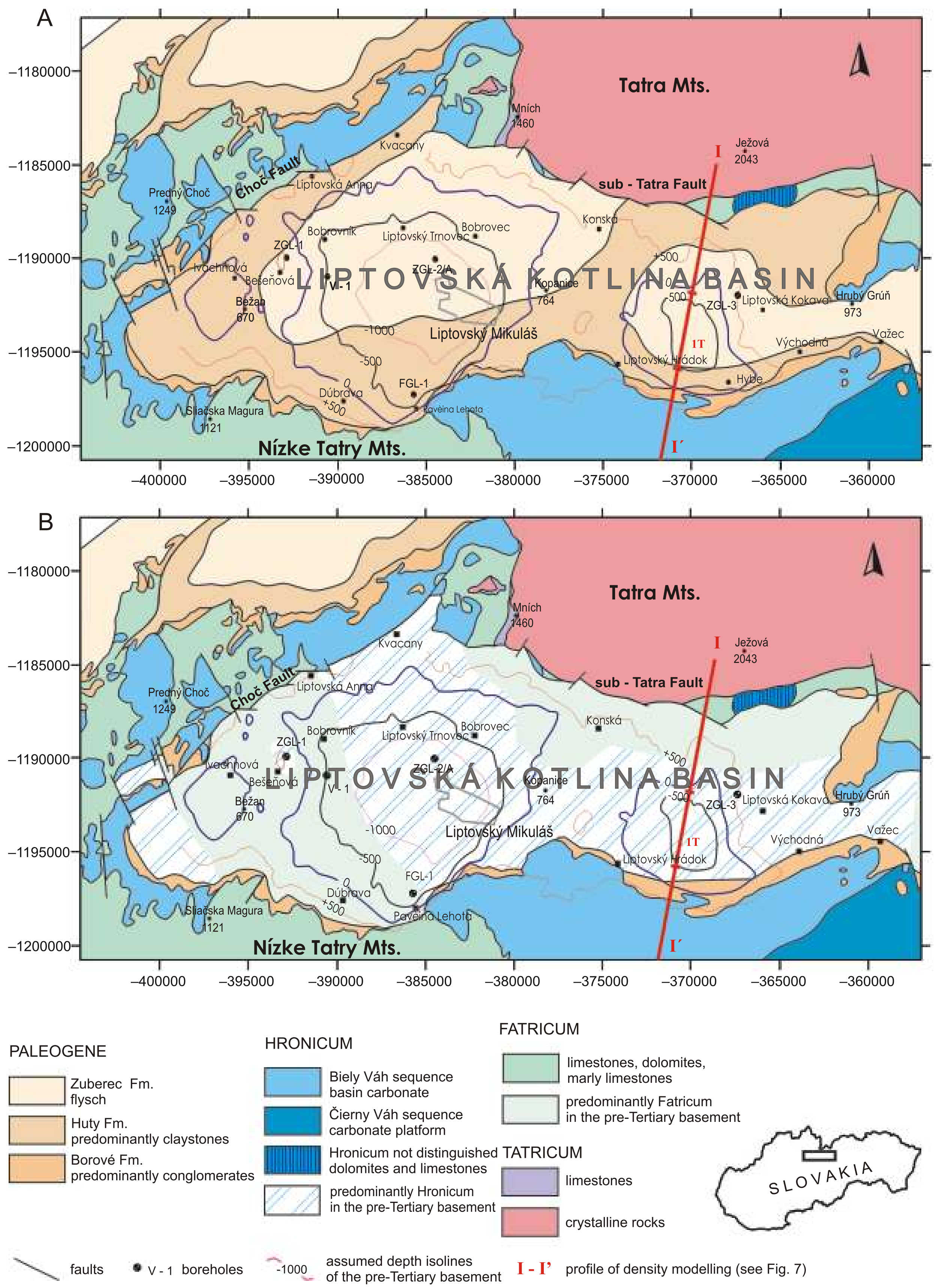


**Fig. 1A — Geological map of the Liptovská Kotlina Basin and its surroundings (modified after Biely *et al*., 1992); B — stripped geological map of the Liptovska Kotlina Basin (compiled by Hók in Král *et al*., 2004, using data from Maheľ, 1964; Gross *et al*., 1980; Biely, 1992; Nemčok *et al*., 1994)**

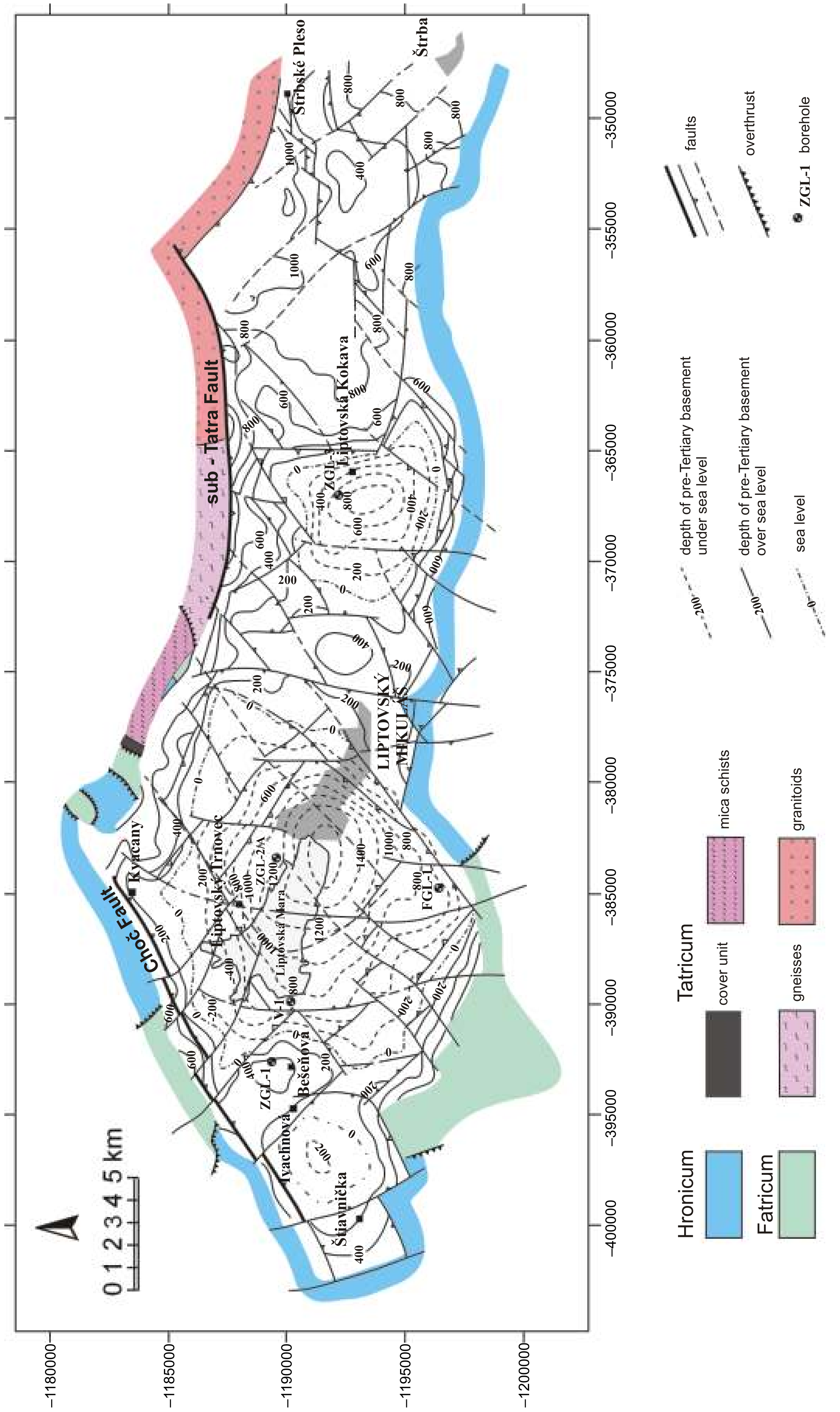


**Fig. 2. Depth of the pre-Tertiary basement of the Liptovská Kotlina Basin (modified after Maďar *et al*., 1997)**

and Vozár, 1981). The Mesozoic strata are divided into two different sequences: the Biely Váh Basin type sequence and the Čierny Váh carbonate platform sequence (Maheľ, 1986). The Biely Váh sequence is more frequently present in the vicinity of the Liptovská Kotlina Basin. The Hronicum tectonic unit was reached in boreholes ZGL-1 (dolomites and limestones — Fendek *et al.*, 1988), ZGL-2/A (dolomites and the Lunz beds — Remšík *et al.*, 1992) and ZGL-3 (dolomites and limestones — Remšík *et al.*, 1990; Král *et al.*, 2004).

The depth of the pre-Tertiary basement varies from about 100 to 1 600 m (Fig. 2). On the map of the pre-Tertiary basement (Maďar *et al.*, 1997) four depressions can be distinguished. From the west to the east these are: the Ivachnová depression, the Liptovská Mara depression, the Liptovská Kokava depression, and the Štrbské Pleso depression. The depressions are separated by elevations (the Bešeňová elevation, the Liptovský Ondrej elevation, the Hrubý Grúň elevation, and the Štrba elevation).

A number of faults have been described in the Liptovská Kotlina Basin. The Choč Fault and the sub-Tatra Fault are the most important faults (Figs. 1 and 2). The Choč Fault separates the Paleogene strata from the Fatricum and Hronicum rock complexes on the western margin of the depression. The orientation of this predominantly normal fault is NE–SW. The sub-Tatra Fault is situated in the northern part and separates the Tatricum unit from the Paleogene deposits (Figs. 1 and 2). The sense of predominant fault displacement is normal, and its orientation is generally E–W. The origin and activity of these faults are associated with the Miocene tectonic evolution of the West Carpathians (e.g. Kováč, 2000).

## 3D DENSITY MODEL

The quality of the resultant 3D stripped gravity map, except of the quality of the applied mathematical method, depends also on the accuracy of the sedimentary filling density model. The most important data for this model are its geometry and density. The basic data for construction of this density model were taken from the wells situated in the Liptovská Kotlina Basin (Figs. 1 and 2): V-1 (Biela, 1978*a*, *b*), FGL-1 (Remšík *et al.*, 1979), ZGL-1 (Fendek *et al.*, 1988), ZGL-3 (Remšík *et al.*, 1990 and Král *et al.*, 2004), ZGL-2/A (Remšík *et al.*, 1992). Note that the density logging of the sedimentary filling of the Liptovská Kotlina Basin has been done to a limited extent only. Therefore, as the additional data related to the thickness of Quaternary and Paleogene sediments were applied the results published by Tomek *et al.* (1989), Szalaiová *et al.* (1991, 1993), Maďar *et al.* (1997) and Král *et al.* (2004).

After Eliáš and Uhmann (1968) and Gross *et al.* (1980) the Paleogene sediment densities change from 2.04 g/cm$^3$ to 2.68 g/cm$^3$. Based on the determination of the densities of the well core samples (Stránska *et al.*, 1986), density 2.53 g/cm$^3$ has been evaluated as average Paleogene sedimentary density. This value is in accordance with the average density of

Table 1

**Densities of the Quaternary and Paleogene deposits applied for the calculation of the gravity effects of different density models**

| Density model | Quaternary deposits | Paleogene deposits | | |
|---|---|---|---|---|
| No. | Density [g/cm$^3$] | Density [g/cm$^3$] | | |
| | Constant | Constant | Linear change | Exponential change |
| 1 | 2.42 | 2.50 | – | – |
| 2 | 2.42 | 2.53 | – | – |
| 3 | 2.42 | 2.56 | – | – |
| 4 | 2.42 | – | 2.42–2.60 | – |
| 5 | 2.42 | – | 2.53–2.60 | – |
| 6 | 2.42 | – | – | 2.42–2.60 |

the Paleogene basin filling, which was also suggested by Maďar *et al.* (1997). The results of the density logging of the sedimentary filling of the Liptovská Kotlina Basin (Král *et al.*, 2004) and the results published by Maďar *et al.* (1997) suggest the average density of 2.42 g/cm$^3$ for the Quaternary sediments (Table 1).

The topography of the basin was taken from the Atlas of Geophysical Maps (Kubeš *et al.*, 2001) and the relief of the pre-Tertiary basement from the results of Maďar *et al.* (1997).

## CALCULATION OF THE STRIPPED GRAVITY MAP

The 3D gravity effect of the Liptovská Kotlina Basin sedimentary fill was calculated by means of a method based on the formulas developed by Starostenko *et al.* (1997). The method enables calculation of the 3D gravity effect of an anomalous density layer (a geological body) with arbitrary upper and lower boundaries. The significant advantage of this method is that it takes into account the gravity effect of the real topographic relief. The sedimentary fill is approximated by a system of vertical prisms. The upper boundary is formed by the basin topography and the lower one by the pre-Tertiary basement relief. Moreover, the applied software package is able to calculate the effect of a layer not only with a constant density, but also with a density that varies in horizontal and vertical directions. In the vertical direction the density can vary linearly or exponentially (Starostenko *et al.*, 1997).

To evaluate the density influence of the Quaternary and Paleogene sedimentary fill on the total gravity effect we calculated it for six different densities (Table 1). By analysis of the density results (Eliáš and Uhmann, 1968; Gross *et al.*, 1980; Stránska *et al.*, 1986; Maďar *et al.*, 1997; Král *et al.*, 2004) the chosen densities represent the interval of real possible average densities for Paleogene deposits. The reference density (2.67 g/cm$^3$) characterizes the average density of the pre-Teriary basement. The analysis of calculated gravity effects of all density models showed that they are very similar. The amplitudes

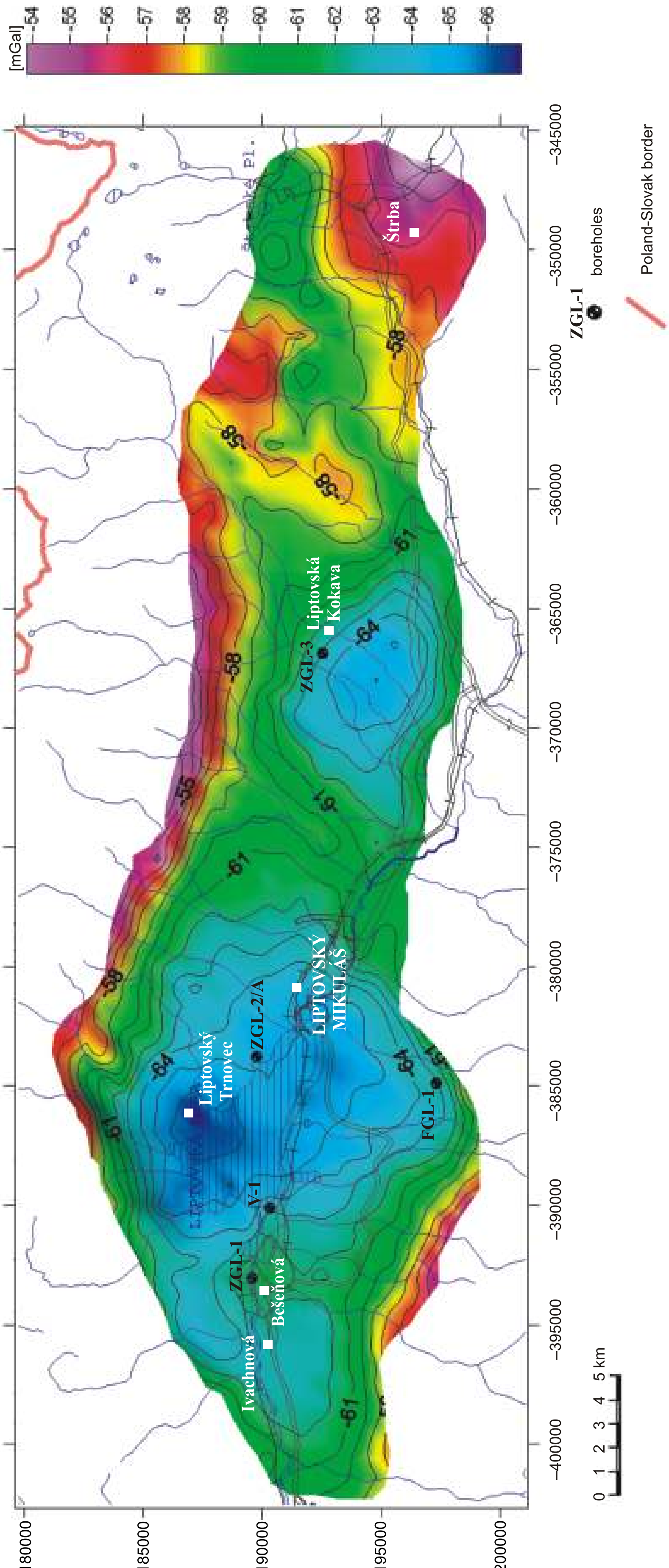


**Fig. 3. Bouguer gravity anomaly map of the Liptovská Kotlina Basin (modified after Kubeš *et al.*, 2001)**

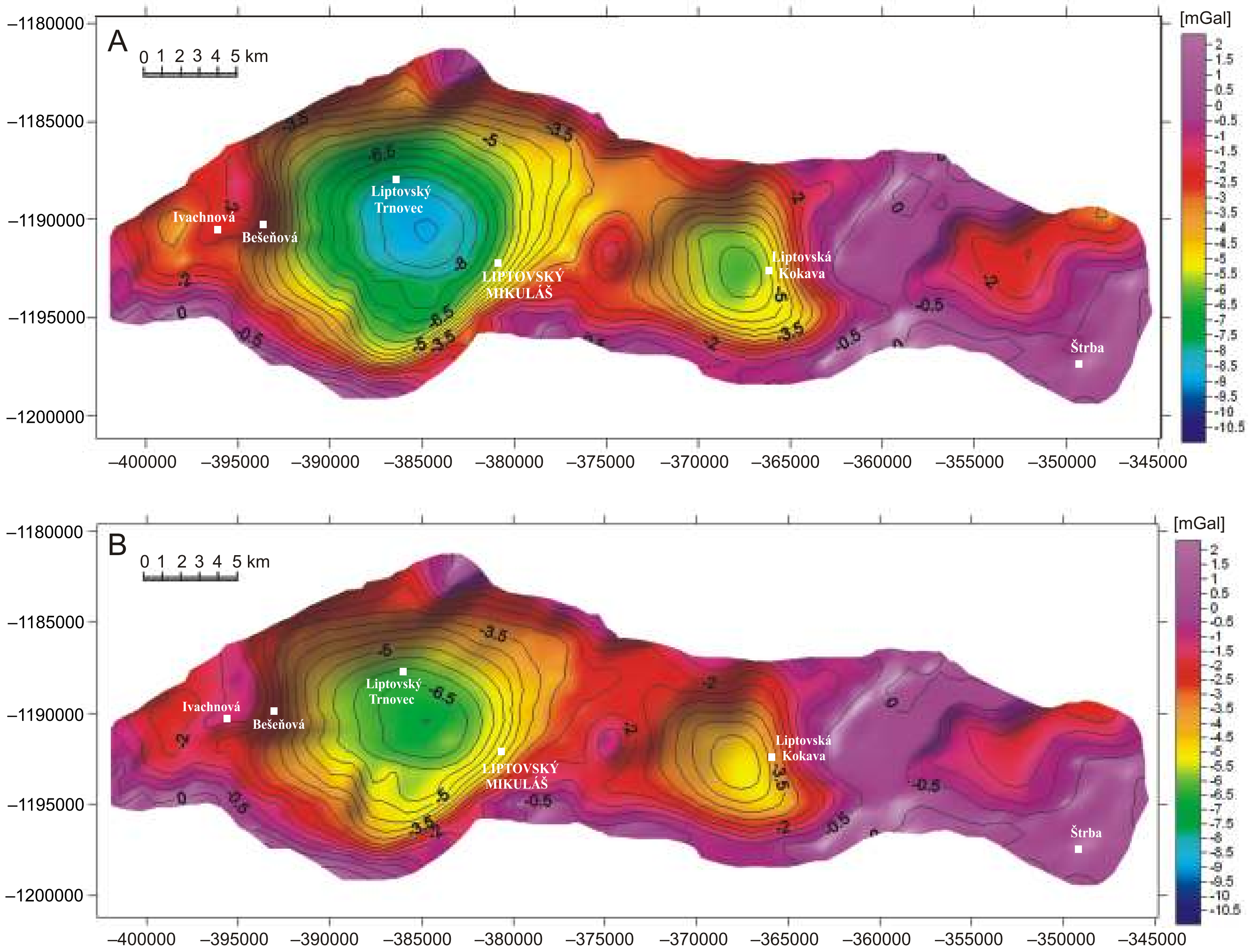


**Fig. 4. Gravity effects of the Quaternary-Paleogene deposits**

**A** — constant density 2.53 g/cm$^3$; **B** — linear density change from 2.53 g/cm$^3$ to 2.60 g/cm$^3$

of the gravity effects vary across a very small interval. The largest differences are only ±3–4 mGal.

The resultant stripped gravity maps of the Liptovská Kotlina Basin are a result of the subtraction of the basin sedimentary fill gravity effects from the Bouguer anomalies (Fig. 3; Kubeš *et al.*, 2001). In this paper two representative stripped gravity maps are presented. They were calculated for the density models No. 2 (Fig. 4A) and No. 5 (Fig. 4B)

## INTERPRETATION OF THE GRAVITY ANOMALIES

On the map of the Bouguer gravity anomalies, which takes into account also the surrounding Tatra Mts. and Nízke Tatry Mts. (Fig. 5), the Liptovská Kotlina Basin represents a significant local gravity low which is, from a regional point of view, a part of the Central Western Carpathian gravity minimum (Tomek *et al.*, 1979; Bielik *et al.*, 2006). The surrounding Nízke Tatry Mts. and Tatra Mts., in which the pre-Tertiary basement outcrops at the surface, are characterized by relative gravity highs. The northern margin of the Liptovská Kotlina Basin is associated with a large horizontal gravity gradient, which can be explained by the very steep slope of the pre-Tertiary basement. The southern margin is characterized by a smaller horizontal gravity gradient due to smaller slope of the basin basement.

In the Liptovská Kotlina Basin gravity low (Fig. 5) two significant local gravity lows can be observed. The first one is located in the Liptovská Mara depression with a maximum amplitude of about –66.5 mGal. The second gravity low reaches a maximum amplitude of –65 mGal, being observed in the Liptovská Kokava depression. Except for these local gravity lows, two other (smaller) local gravity lows can be seen. One is represented by the Ivachnovská depression (–62 mGal) and the second one by the depression, which is located to the south of Štrbské Pleso (–60 mGal). It is interesting to note that the largest thicknesses of the sedimentary fill correlate with the largest local gravity lows (see Figs. 2 and 3). This indicates that the sources of the gravity lows are a superposition of the effects due to the larger thicknesses and lower density of the Quaternary-Paleogene deposits. The re-

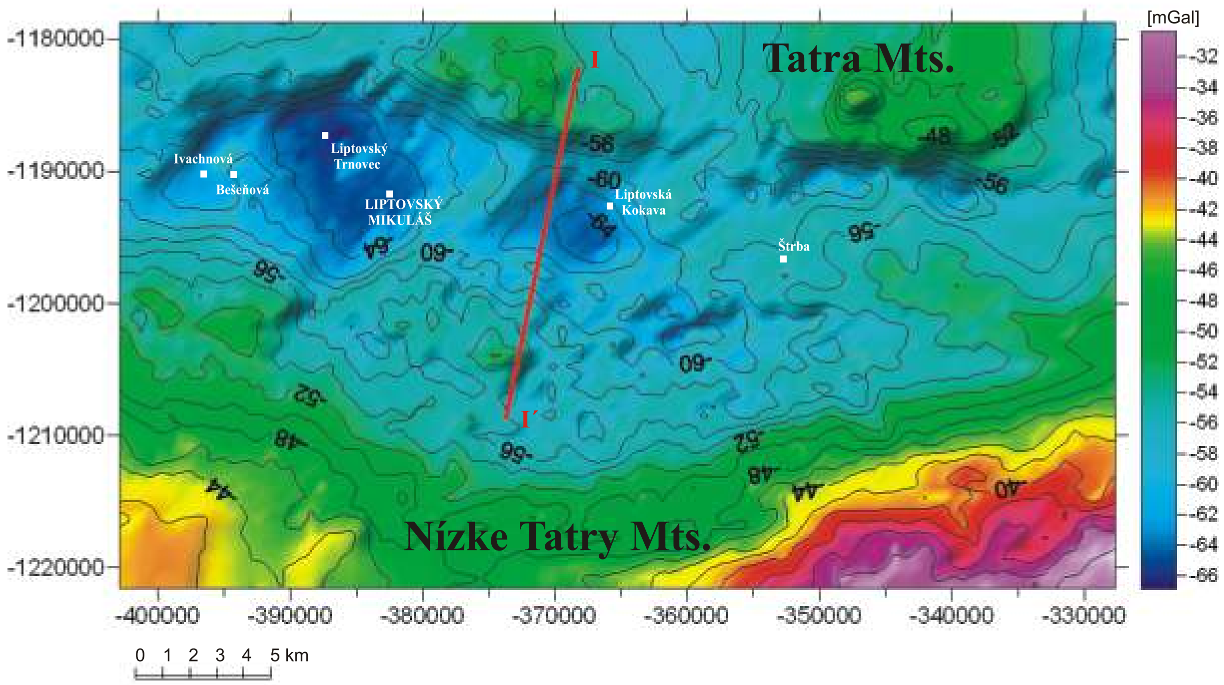


**Fig. 5. Bouguer gravity anomaly of the Liptovská Kotlina Basin with the surrounding Tatra Mts. and Nízke Tatry Mts. (modified after Szalaiová and Šantavý, 1996; Vozár and Šantavý, 2000)**

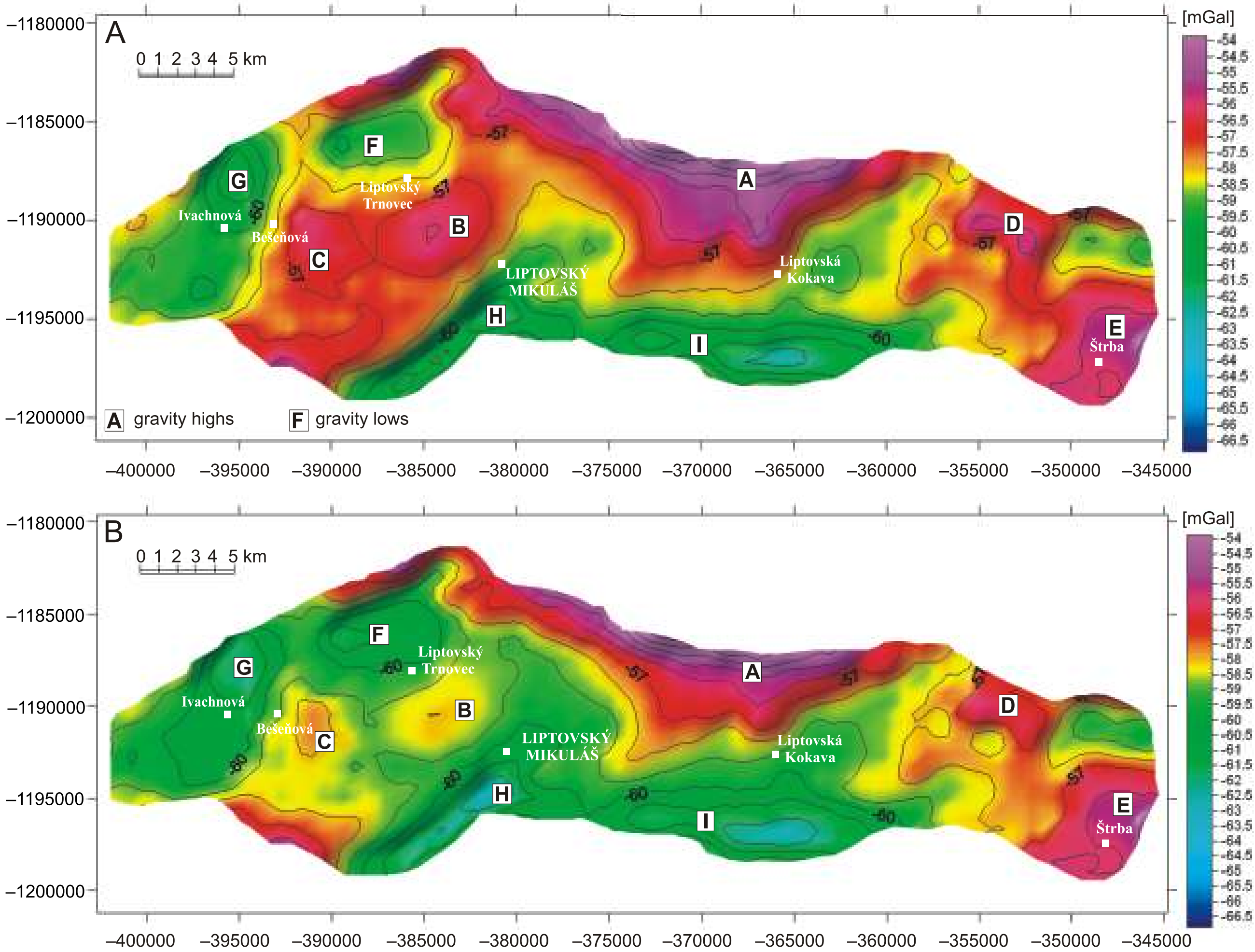


**Fig. 6. Stripped gravity maps in which the Bouguer gravity map was corrected by the gravity effects of the Quaternary-Paleogene deposits**

**A** —constant density; **B** — linear density change from 2.53 g/cm$^3$ to 2.60 g/cm$^3$

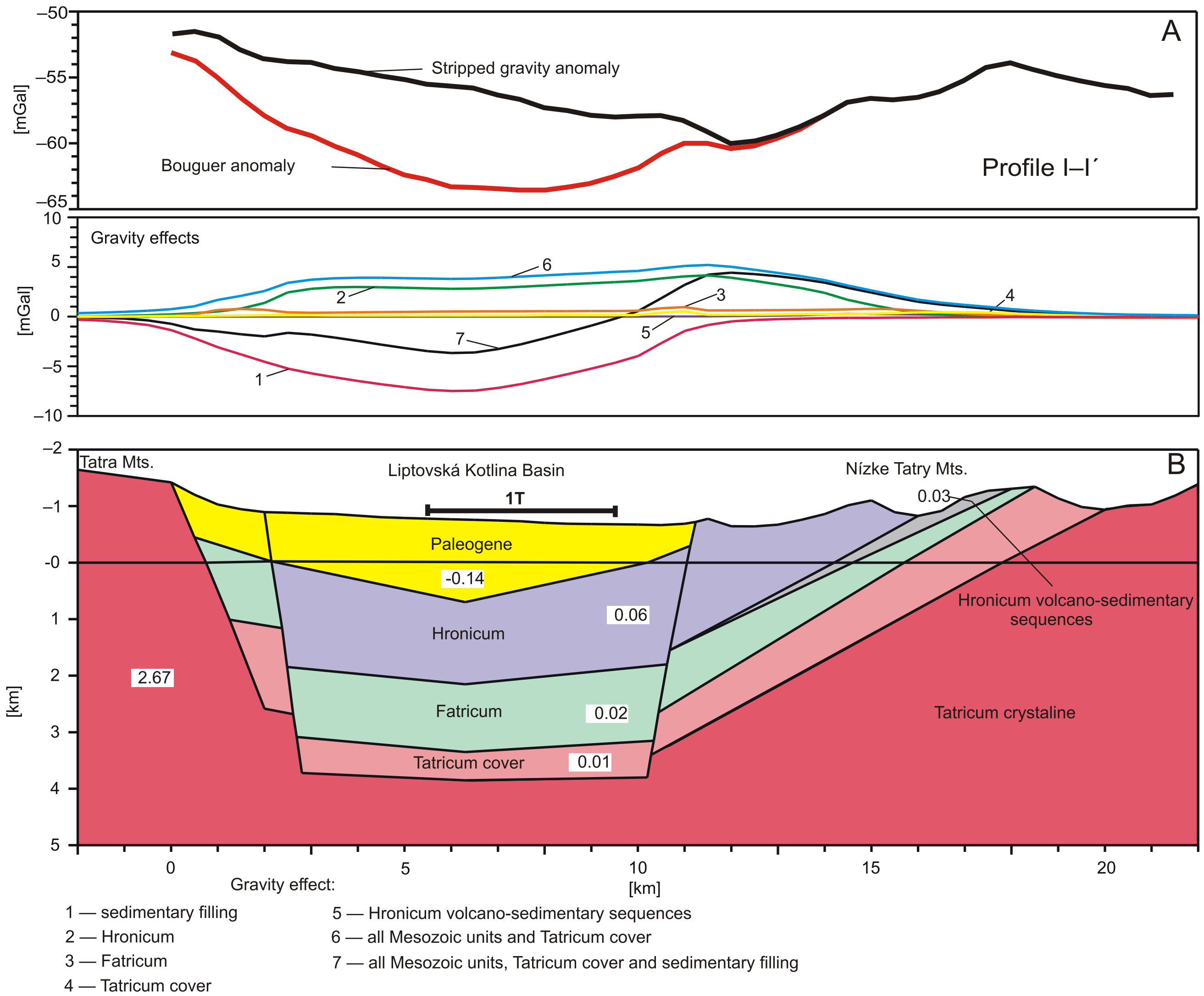


**Fig. 7. 2D density model along the profile I–I´**

**A** — Bouguer gravity anomaly and the stripped gravity anomaly; **B** — individual and common gravity effects of the main tectonic units building the Liptov Trough; density model along the profile I–I´ was compiled by means of seismic interpretation results of the profile 1T/80 (Král *et al*., 2004)

sultant stripped gravity maps (Fig. 6) clearly support this suggestion, because after subtracting the gravity effects of the sedimentary fill from the Bouguer anomalies these local gravity lows almost wholly disappeared.

To make an objective geological-geophysical interpretation of the stripped gravity map we made along the profile I–I´ a 2D quantitative interpretation of the gravity effects of the main tectonic units that build the pre-Tertiary basement (Fig. 7). The *GMSYS* software was used for this 2D density modelling. The location of the profile I–I´ was guided by the course of the seismic reflection profile 1T/80 (Král *et al*., 2004). The seismic interpretation offered very good constraints on thicknesses of the Mesozoic nappes (Hronicum and Fatricum) and of the Tatric cover. Based on the lithological compositions of the Hronicum, Fatricum and Tatric cover units and densities of the rocks which build them (Eliáš and Uhmann, 1968; Gross *et al*., 1980; Stránska *et al*., 1986), their average densities were defined as: the Hronicum $\sigma = 2.73$ g/cm$^3$, the Fatricum $\sigma = 2.69$ g/cm$^3$ and the Tatric cover $\sigma = 2.68$ g/cm$^3$. The gravity effect of the Hronicum is the largest and it varies from 0 to +4.4 mGal. The Fatricum gravity effect is 2–4 times smaller (maximum +1.2 mGal) by comparison with the Hronicum. It can also be seen that the gravity effects of the Tatricum cover unit and of the Hronicum volcano-sedimentary sequences are relatively small. They have maximum gravity values of only +0.5 mGal and +0.4 mGal, respectively. This study (Fig. 7) indicates clearly that the total gravity effect of the Mezozoic nappes and of the Tatricum cover unit has, for reference density $\rho = 2.67$ g/cm$^3$, positive gravity effect (maximum $V_z = +5.3$ mGal), while the sedimentary fill gravity effect is negative (maximum $V_z = -7.5$ mGal). As the negative gravity effect of the basin sedimentary fill is higher than total positive gravity effect of the Hronicum, Fatricum and Tatricum cover, the total gravity effect of all these tectonic units is negative over the Liptovská Kotlina Basin.

On the stripped gravity maps (Fig. 6) several relative gravity highs and lows can be observed. It is worth to note that the amplitudes of all gravity anomalies are small. They vary only in the range of –66 to –54 mGal. The largest and the most intensive relate gravity high (A) with an amplitude from –52 to –56 mGal correlates with the outcrop of the Tatricum crystalline unit in the Tatra Mts. (Figs. 1 and 2). Therefore it is suggested that the source of this anomaly likely comes from the Tatricum crystalline rocks (Fig. 7).

A relative gravity high with a NE–SW axis is observed between Bešeňová and Liptovský Mikuláš. In general, it can be expected that its source is the Mesozoic nappes, because they contribute most to the observed gravity field (Fig. 7). Based on the high-quality stripped gravity map it is predicted that this significant anomaly may be divided into two parts with two different maxima (B) and (C) and sources. Our suggestion is also supported by the results of the gravity effect testing the boreholes V-1 (Biela, 1978*a*, *b*), ZGL-1 (Fendek *et al*., 1988), ZGL-2/A (Remšík *et al*., 1992) and the pre-Tertiary map of the Liptovská Kotlina Basin (Král *et al*., 2004). As the Hronicum rocks were drilled in the borehole ZGL-2/A (Remšík *et al*., 1992) and they have highest density (due to dolomitic lithology) it is suggested that the main source of the maximum (B) is due to this tectonic unit. On the other side, the maximum (C) may come from the rocks of Fatricum, because it is predicted that this tectonic unit is characterized by lighter rocks (the limestones and marly limestones lithology). Moreover, the Fatricum is represented by a large thickness as a consequence of two superposed tectonic slices there [boreholes V-1 (Biela, 1978*a*, *b*); FGL-1 (Remšík *et al*., 1979) and ZGL-1 (Remšík *et al*., 1990; Král *et al*., 2004), see Fig. 2]. It is worth noting, to support our suggestion as regards the anomaly source, that the Hronicum (which could be also taken into account as a source of the anomaly) was drilled only in the borehole ZGL-1 and its thickness is negligible. Note that the NW–SE linear gravity features (sigmoidals) running between both maxima could reflect a tectonic line that separates the Hronicum and Fatricum, which probably are characterized by different thicknesses in the basin basement.

The similarity of the the Štrbské Pleso (D) and Štrba (E) highs, which can be observed on the pictures of the Bouguer gravity map as well as an stripped gravity maps (Figs. 3 and 6) indicates that their origin may be explained by the larger gravity effect of the Hronicum and Fatricum nappes. In the case of the Štrba gravity high, the Hronicum volcano-sedimentary sequences (Biely *et al*., 1992) with their higher density and thickness of the volcano-sedimentary rocks (Eliáš and Uhmann 1968, Gross *et al*., 1980, Stránska *et al*., 1986) probably increase the intensity of this gravity high in comparison with the past gravity high.

The pattern of the gravity field on the stripped gravity maps (Fig. 6) also includes relative gravity lows. These are characterized by almost the same amplitude values of –62 mGal and they can be observed in the western part (anomalies G and F) and in the southern part (anomalies H and I) of the Liptovská Kotlina Basin. Based on the study of the composition of the borehole cores, the densities of drilled rocks and the analysis of the gravity effect of the tectonic units building the Liptov trough it is predicted that the observed gravity lows reflect a tectonic arrangement of the pre-Tertiary basement. The anomalies probably reflect the majority of the Fatricum and Tatricum rocks with lower densities (e.g. marly limestones, sandy limestones, quartzites and sandy shales) and greater thicknesses. Such rocks were drilled in the boreholes ZGL-1, ZGL-3 and FGL-1 (Remšík *et al*., 1979, 1990; Král *et al*., 2004). The existence of these gravity lows on the high-quality stripped gravity map suggests that the Hronicum unit is thinner than the Fatricum and Tatricum units in these parts of the pre-Tertiary basement.

## CONCLUSIONS

The results obtained by means of the calculation of stripped gravity maps with a high degree of accuracy indicate clearly their usefulness for study of the pre-Tertiary basement structure. These high-quality transformed gravity maps are partierlary useful, in those cases where the sedimentary basins and their basement structures do not show very large differences in the gravity field. To distinguish such gravity anomalies, which are characterized by small and near amplitudes (intensities) of the gravity field, only high-quality stripped gravity maps can suffice. They can help, in spite of the natural ambiguity of the gravity (geophysical) interpretation, in prospecting of density-anomalous zones located beneath basins with a thick sedimentary fill. Gravity anomalies so delineated, which reflect sensitive but significant changes of the gravity field pattern, enable recognition of differences in the structure and lithology of the pre-Tertiary basement as well as in the thicknesses of the tectonic units that build this basement. This case study of a calculation of the most accurate stripped gravity map in the Liptovská Kotlina Basin showed clear agreement between the gravity anomalies and the relatively well-known basin structure. Therefore, this very cheap and relatively simple method for stripping of the gravity field, by comparison with expensive geological and geophysical surveys, can be successfully applied not only for other Western Carpathian structures but for basins and depressions elsewhere in the world.

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