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3D gravity interpretation of the pre-Tertiary basement in the intramontane depressions of the Western Carpathians: a case study from the Turiec Basin

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Abstract: New results related to the thickness and density of the sedimentary fill of the Turiec Basin allowed us to construct the first original stripped gravity map for this typical intramontane Neogene depression of the Western Carpathians. The stripped gravity map of the Turiec Basin represents the Bouguer gravity anomalies corrected for the gravity effect of the density contrast of its Quaternary-Tertiary sedimentary basin fill. It means that the map reflects the gravity effects of the density inhomogeneities which are located beneath the sedimentary basin fill. This map is therefore suitable for the interpretation of the structure and composition of the pre-Tertiary basement. Based on the new data analysis, two different density models of the sedimentary fill were constructed. The 3D density modelling was used to calculate the gravity effect of the density models. The stripped gravity maps were produced by subtracting the density model gravity effects from Bouguer anomalies. The regional trend was also removed from the stripped gravity maps. The residual stripped gravity maps were consequently used for geological interpretation of the pre-Tertiary basement of the Turiec Basin. The pre-Tertiary basement of the Turiec Basin can be divided into northern and southern parts due to its gravity characteristics. Furthermore the northern part can be split into two domains: western and eastern. The crystalline basement of the western domain is probably formed by the Hercynian crystalline basement of the Tatric Unit. In the eastern domain the basement could consist mostly of the Mesozoic complexes of the Fatric Unit. The southern part of the pre-Tertiary basement of the Turiec Basin is built predominantly by Mesozoic complexes of the Hronic Unit. It is suggested that the Hronic Unit also forms the bedrock of the volcano-sedimentary complex of the Kremnické vrchy Mts. The resultant stripped gravity maps and the map of total horizontal gravity gradients have also proven to be very useful for the interpretation of faults or fault systems in the study area. Various faults, particularly of NNE-SSW and NW-SE directions were discovered. The analysis of the faults indicates clearly that the contact of the Turiec Basin with the Malá Fatra Mts and the Veľká Fatra Mts is tectonic.

Key words: Western Carpathians, Turiec Basin, applied geophysics, gravity, 3D density modelling, stripped gravity map.

Introduction

Turiec Basin (TB) is one of the most typical intramontane Neogene depressions of the Western Carpathians. It is situated in the northern part of Slovakia, elongated in the NNE–SSW direction. It is about 40 km long and 10 km wide (Kováč et al. 2011; Fig. 1).

This basin, belonging to the region of the Western Carpathians, is well covered by geophysical data. Seismic, gravity, geoelectric, and thermal measurements have been collected there at various scales. Deep seismic profile K-III (Hrdlička et al. 1983) has shown that the TB is a zone with higher effective velocities, where v_p velocities 5.8–6.0 km/s occur at depth of 9 km. At the K-III profile the depth of the Moho discontinuity was set to 35 km with a NNE dip. Regional seismic profiles 4HR/86, 4AHR/86 and 519/87 (Tomek et al. 1987) brought information about the geological structure, structure of the Tertiary sedimentary fill, as well as its relation to the crystalline basement in the TB. The basin is well covered by gravity measurements in a scale of 1:50,000 (Zbořil et al. 1975; Szalaiová & Stránska 1978). The main acquisition of the geoelectrical survey (Zbořil et al. 1985) yielded a definition of a relief of the pre-Tertiary basement with thick accumulations of Tertiary sediments. The geothermal characteristics are also well known in the TB. The basin represents an area of higher temperatures compared to the surrounding region. The results from borehole GHŠ-1, in the southern part of the basin, show a temperature of 35 °C at 500 m depth, 49 °C in 1000 m depth, and 64 °C in 1500 m depth (Fendek et al. 1990).

Geophysical measurements carried out for the TB were summarized by Šefara et al. (1987). The last geophysical measurements were performed and interpreted by Panáček et al. (1991). The results consist of the physical properties of the rocks, additional geoelectrical profiling and vertical electrical sounding, and geological-geophysical interpretation of the geological structure in the TB.

The development of the TB and the evolution of its landscape were reconstructed by means of geological research (structural geology, sedimentology, paleoecology, and geochronological data), as well as by geophysics and geomorphology (e.g. Hók et al. 1998; Kováč et al. 2011).

On the basis of the geophysical constraints, a two dimensional interpretation of the gravity field in the TB by the density modelling method was presented by Bielik et al. (2007, 2009) and Grinč et al. (2010). Krajňák et al. (2012) extended this study by the calculation of the first preliminary stripped gravity map in the TB. This preliminary stripped gravity map did not take into consideration the real topography of the basin. The upper boundary of the density model was approximated only by sea level (0 m). This approximation is inadequate for a high quality interpretation of the gravity field by the stripping gravity method.

From this point of view the main goal of the paper presented here is to apply 3D gravity modelling for the calculation and presentation of new, more precise, stripped gravity maps in the TB. The improvement of the new stripped gravity maps presented here dwells in the construction of more precise density models including the topography of the basin. On the basis of the resultant stripped gravity maps calculated for two different density models, and corrected for the regional gravity anomalies, we also present a geophysical and geological interpretation of the structure and composition of the pre-Tertiary basement of the TB.

Geology

The Turiec Basin is the northernmost intramontane depression of the Central Western Carpathians filled with Paleogene, Neogene and Quaternary deposits (Figs. 1, 2). Its northern margin (Kováč et al. 2011) is formed by the Krivánska Malá Fatra Mts, which are predominantly composed of the Hercynian crystalline basement of the Tatric Unit. The western flank of the basin is part of the Lúčanská Malá Fatra Mts, while the eastern flank borders the Veľká Fatra Mts. Both are composed of Mesozoic complexes of the

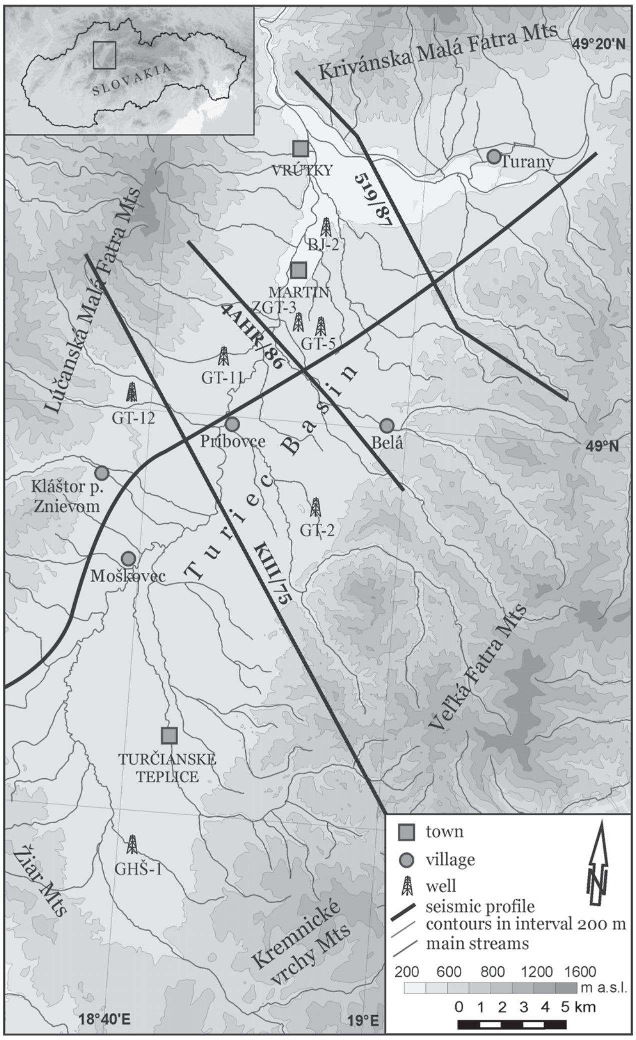

Fig. 1. Geographical position of the TB (modified after Kováč et al. 2011 and Krajňák et al. 2012).

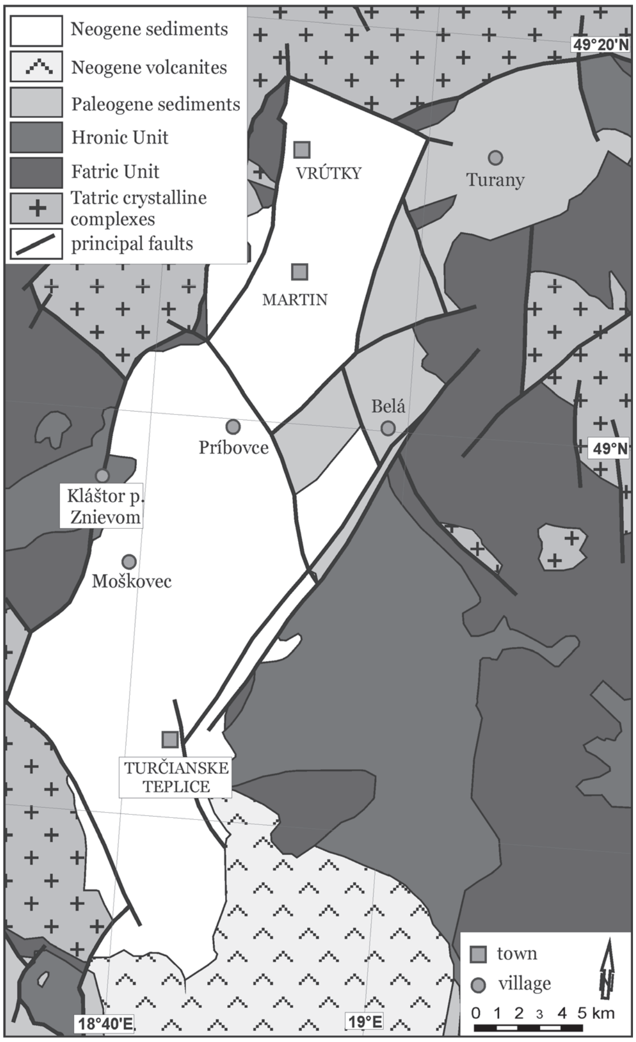

Fig. 2. Schematic geological map of the TB and its surroundings (modified after Bielik et al. 2007; Kováč et al. 2011).

Fatric or Hronic Nappes and the Hercynian crystalline complex of the Tatric Unit. The Tatric crystalline basement of the Žiar Mts and the volcano-sedimentary complex of the Kremnické vrchy Mts restrict the basin to the south (Fig. 2). The TB is a westward dipping halfgraben (Kilényi & Šefara 1989; Kováč et al. 2011). The pre-Neogene basement of this basin consists of the Central Western Carpathian paleo-Alpine tectonic units, which mainly comprise Mesozoic complexes, and also Paleogene post-nappe sedimentary cover in its northern part (Fusán et al. 1987; Kováč et al. 2011).

The Paleogene and Early Miocene deposits crop out on the eastern and north-eastern margin, as well as in the footwall of the Miocene basin fill. They represent a basal formation containing coarse-grained deposits to clays, claystones, sandstones and deposits of turbidity flows lying directly on the Mesozoic basement. The Late Badenian initial rifting, caused by transtensional to extensional tectonic regime, led to subsidence in the southern part of the TB, where the volcano-sedimentary andesite complex of the Turček Formation was deposited. Late Miocene clockwise rotation of the principal compressional axis to a NNE-SSW led to the Pannonian subsidence of the TB and the synrift sedimentation of the principal fill of the TB — the Martin Formation deposited in isolated basin surrounded by uplifted mountains. Pelitic grey clay is a dominant lithological type, along with clay with the presence of coal pigment, thin lignite coal seams, sand and sandstone. The uniform dip of the sedimentary sequence points to the long-term activity of faults near the western margin of the depression (Hók et al. 1998). These played a dominant role during the basin's evolution. In the time from the latest Pannonian to Pontian, the coarse-grained alluvial fans of the Abramová and Blážovce Members were deposited on the margin of the uplifted central part of the Lúčanská Malá Fatra Mts. They were deposited on the pre-Neogene basement and the Middle Miocene pelitic sediments. Toward the basin, the marginal coarse-grained subaereal sediments are interfingering with fine-grained lacustrine deposits. In some places they partly intercalate with clays of the Martin Formation. During the Pontian and Early Pliocene, the change of tectonic regime led to the end of subsidence and the end of deposition followed by the uplift of the whole TB catchment (Kováč et al. 2011). A rapid uplift of the crystal-

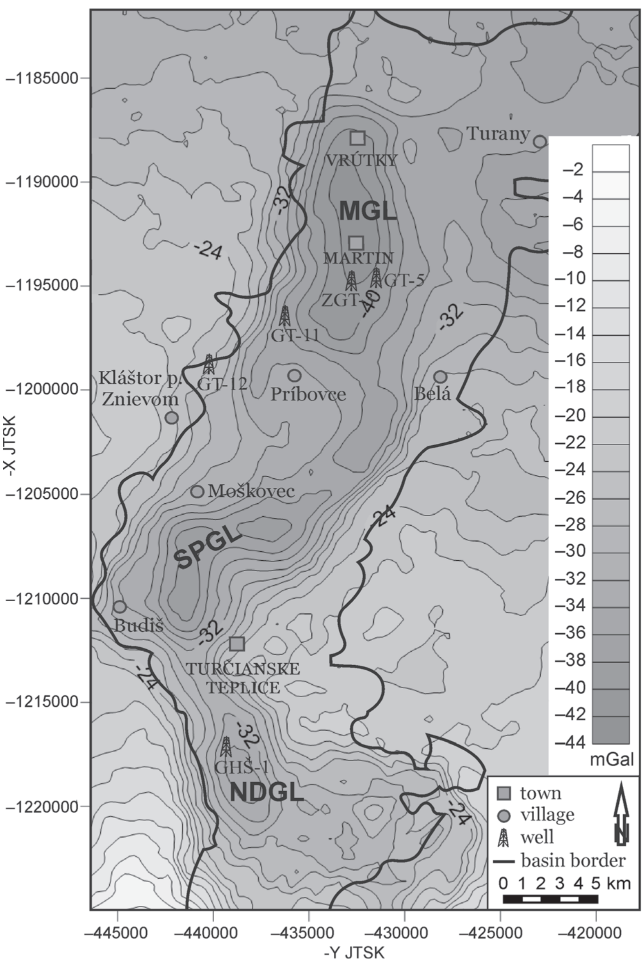

Fig. 3. Complete Bouguer gravity anomaly map calculated by Kučera & Michalík (in Bielik et al. 2007). **MGL** — Martin gravity low, **SPGL** — Slovenské Pravno gravity low, **NDGL** — Nový Dvor gravity low.

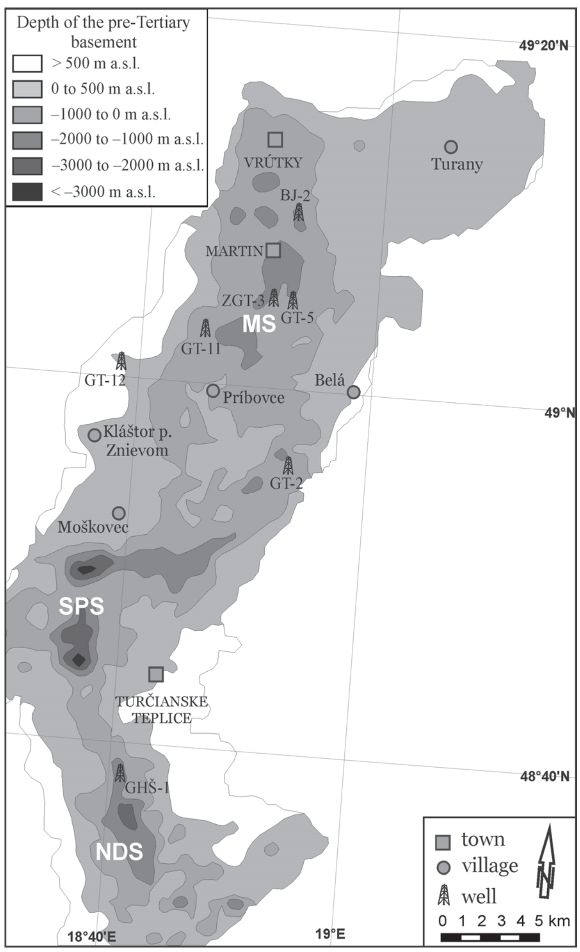

Fig. 4. Map of the pre-Tertiary basement depth calculated by Kučera & Michalík (in Bielik et al. 2009). **MS** — Martin sub-basin, **SPS** — Slovenské Právno sub-basin, **NDS** — Nový Dvor sub-basin.

line basement of the Krivánska Malá Fatra Mts is documented by the Upper Pliocene Bystrička Member and the Pleistocene alluvial fans of the Podstráne Member, containing Tatric material derived only from the mountains.

3D density modelling and stripped gravity map

The 3D gravity (density) modelling method was applied to generate the stripped gravity map from the Bouguer gravity map in the TB. The Bouguer gravity map was compiled from Bouguer gravity anomalies rather than gravity disturbances (c.f. Vajda et al. 2006, 2007), since the geophysical indirect effect (e.g. Vajda et al. 2006; Vajda & Pánisová 2007) is negligible on the regional scale of the TB from the viewpoint of our study and interpretation (c.f. Vajda & Pánisová 2007). Stripping is often applied in geophysical studies, on global or regional scale, to unmask the signal of unknown sources, when the signal of known sources/structures can be computed (e.g. Vajda et al. 2008; Tenzer et al. 2009, 2012a,b). Stripping is particularly useful in geophysical and geological investigations of the basement and the deep-seated structure beneath sedimentary basins (e.g. Bielik 1988; Bielik et al. 2005; Alasonati Tašárová et al. 2009; Bielik et al. 2013). The 3D gravity effect of the sedimentary fill of the TB was computed by the GMT-AUTO software package (Starostenko et al. 1997, 2011; Starostenko & Legostaeva 1998, 2006).

The principle of the method is that the geological structures are divided into horizontally and vertically stratified media with an arbitrary density distribution in each layer. The geological structure is approximated by inhomogeneous, arbitrarily truncated vertical rectangular prisms. An automatization of the input of initial graphic information (maps) by digitization is also very useful in the process of the modelling (Legostaeva 2000). The gravity effect of three dimensional bodies can be determined not only by constant densities, but also by different densities on the upper and lower limits having a linear or exponential vertical transition. After the gravity effect calculation of the TB sedimentary fill the resultant stripped gravity map is calculated by subtraction of this effect from the complete Bouguer anomaly map.

Input data

Input data for the calculation of the stripped gravity map in the TB comprise the map of complete Bouguer gravity

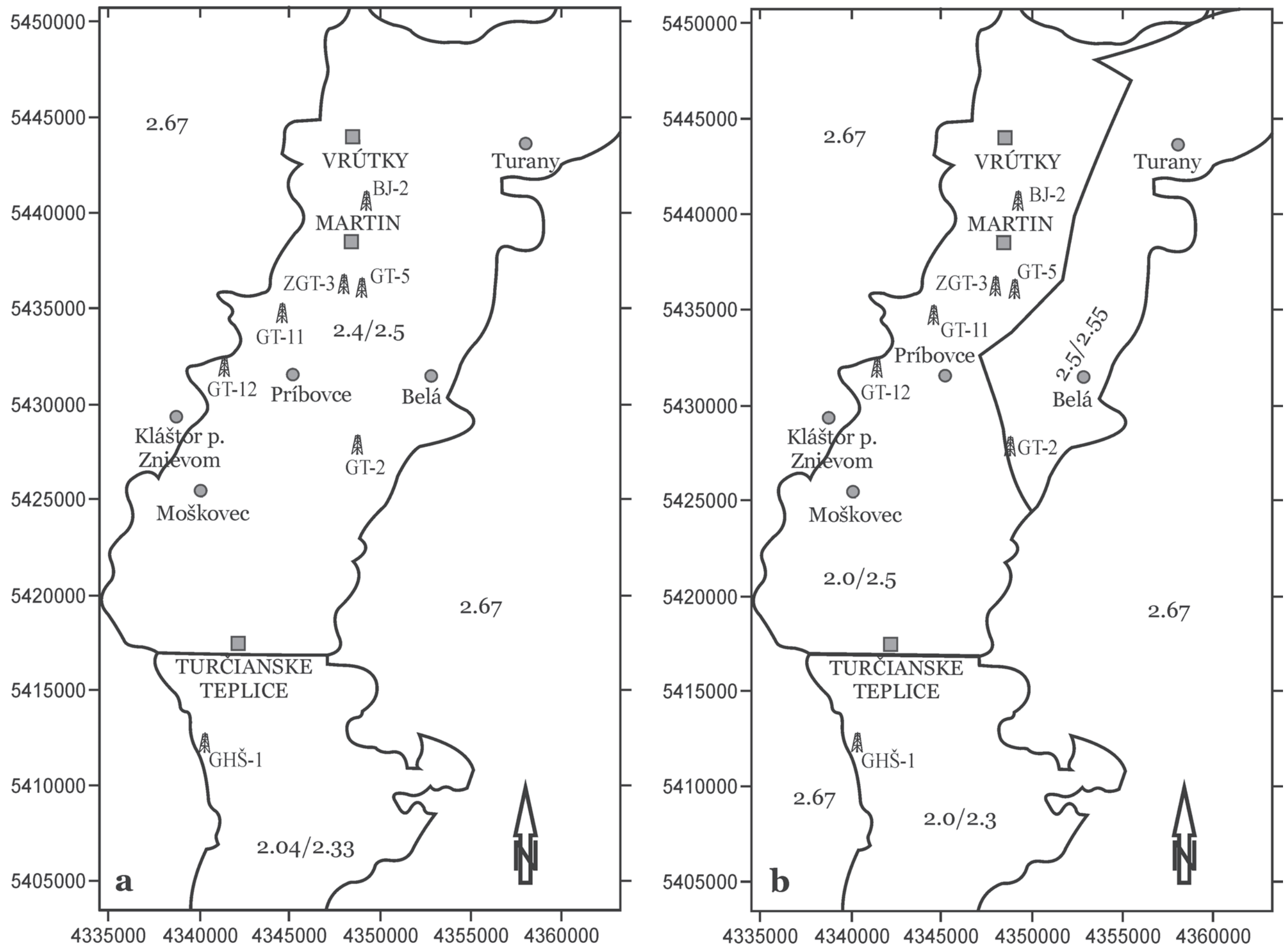

Fig. 5. Alternative two density models of the TB sedimentary fill defined on the basis of the results published in Eliáš & Uhmann (1968), Šefara et al. (1987), Panáček et al. (1991), Bielik et al. (2009), Grinč et al. (2010) and Krajňák et al. (2012).

anomalies (Michalík & Kučera in Bielik et al. 2009), the map of the pre-Tertiary basement depth, and the density model of the sedimentary fill.

The complete Bouguer gravity anomalies are based on gravimetric measurements on a scale of 1:25,000. As the gravity data in the studied area have been acquired and processed by different approaches and in different time periods it was necessary to unify all data by re-calculations of the terrain corrections T1, T2 a T3 in all measured points (Michalík & Kučera in Bielik et al. 2007). The Bouguer gravity anomaly was calculated using the WGS84 ellipsoidal normal gravity formula, height correction by a Taylor series expansion of normal gravity up to 2nd order in geometric flattening and height and Spherical Bouguer gravity slab with radius 166.7 km (Bielik et al. 2006). The Bouguer gravity anomaly, the terrain correction and the Bullard term were calculated for the reduction density of 2.67 g/cm^3 (2670 kg/m^3). The mean error of the gravity differences is less than ±0.5 mGal. The complete Bouguer anomalies of the TB (Fig. 3) are characterized by a local gravity low (amplitude of −42 mGal) with significant gravity gradients on its margins. The gravity low coincides very well with the surface of the TB. The relative amplitude of this gravity low is about −13 mGal. The TB gravity low can be divided into three gravity sub-lows (Grinč et al. 2010; Krajňák et al. 2012): the Martin gravity low (MGL), the Slovenské Pravno gravity low (SPGL) and the Nový Dvor gravity low (NDGL) (Fig. 3). From the regional gravity field point of view it is possible to observe that the negative gravity field gradually increases from the southwest to the northeast.

The second set of input data is represented by the thickness of the Tertiary sediments (Fig. 4). The first map of this type was calculated by Kučera & Michalík (in Bielik et al. 2009). This was solved as a 3D inverse gravimetric problem based on Pohánka's formula, which allows us to calculate the gravitational effect of a polyhedral prism with a linear density transition with depth (Pohánka 1988). Barry's algorithm (1991) was used for the 3D model construction here. In this map three main sub-basins can be distinguished: the Martin Sub-basin (MS), the Slovenské Právno Sub-basin (SPS) and the Nový Dvor Sub-basin (NDS) (Fig. 4). Note that the observed gravity field of the TB (Fig. 3) correlates expressly with this map. Spatially the largest MS correlates with the largest relative gravity sub-low in the complete Bouguer gravity map. The SPS and NDS are the deepest depressions — more than 3000 m below sea level (b.s.l.) in the TB (Fig. 4). In the MS several lows with depths exceeding 2000 m b.s.l. can be

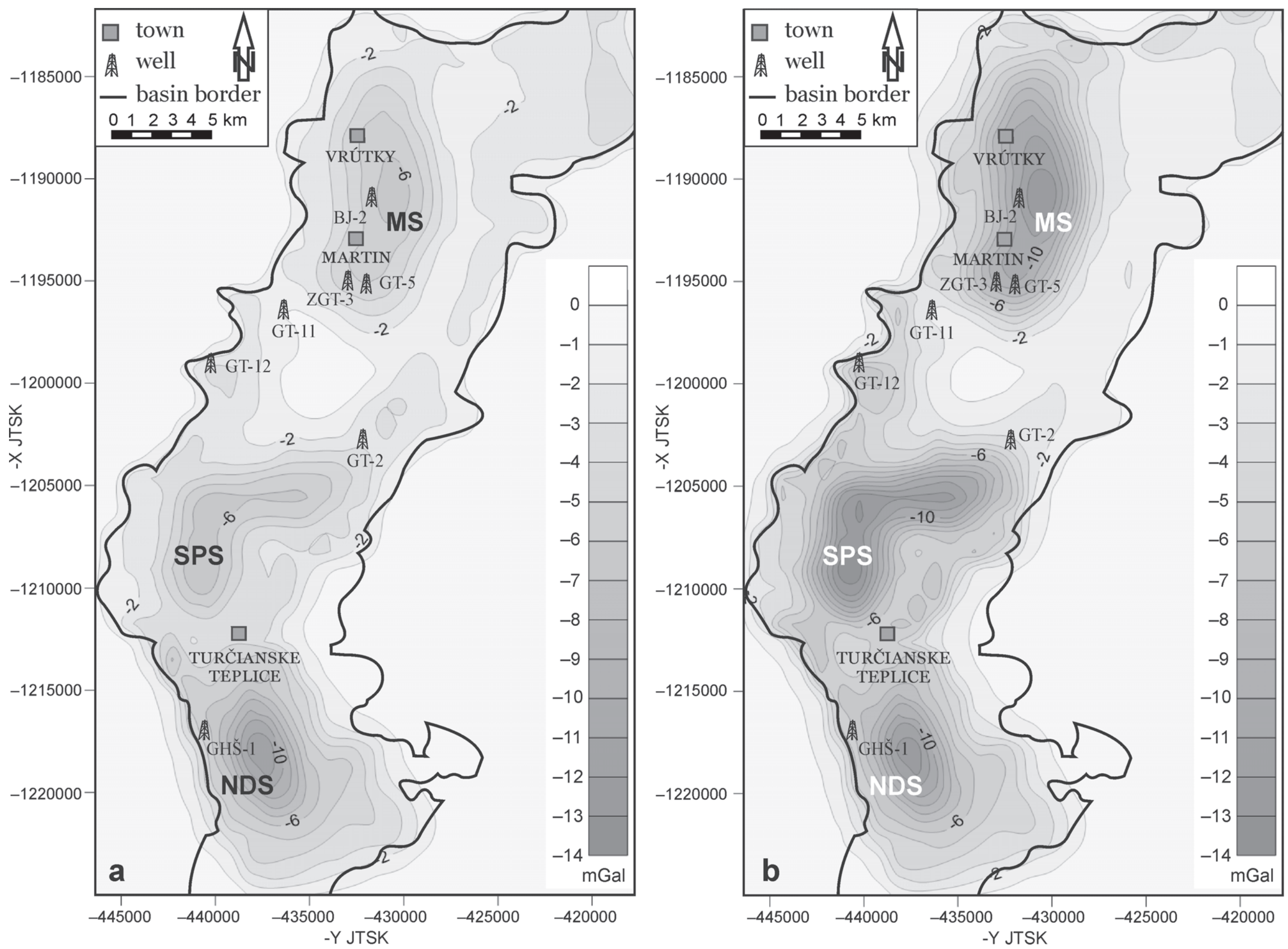

Fig. 6. Gravity effect for the first (**a**) and second (**b**) density model. **MS** — Martin sub-basin, **SPS** — Slovenské Právno sub-basin, **NDS** — Nový Dvor sub-basin.

found. The SPS and NDS are separated from the MS by the central basin elevation clearly visible in the area of Kláštor pod Znievom and Moškovec, which reaches up to 500 m a.s.l. Another remarkable feature of the pre-Tertiary basement depth is located in the vicinity of Turany (north-eastern part of the TB). In this area the relief of the pre-Tertiary basement is formed by a plateau with an altitude around 350 m a.s.l. The boundary between the basin and the surrounding mountain ranges appears at about 500 m a.s.l.

Density models

The study and analysis of the density measurements of the rocks coming from drill cores of the boreholes GT-5, GT-11, GT-12, ZGT-3 and GHŠ-1 (Panáček et al. 1991) and results related to the density values of the sedimentary fill in the TB (Eliáš & Uhmann 1968; Šefara et al. 1987; Bielik et al. 2009; Grinč et al. 2010; Krajňák et al. 2012) show that rock densities vary in a wide interval vertically as well as horizontally. Therefore, the determination of simple average densities for the sedimentary fill in the TB is very complicated. To assess how big is the dependence of the gravity effect of the sedimentary fill on its densities, two different density models were constructed (Fig. 5). In these models the TB was divided into vertical rectangular prisms with a linear increase of density with depth. The average density contrasts applied in the calculations of the gravity effects of the models were relative to a reference density of 2.67 g/cm^3, which represents the average density of pre-Tertiary basement rocks.

In the first model (Fig. 5a) the TB was divided into two prisms, where the southern part consists of Neogene volcanic complexes with an average density of 2.33 g/cm^3 (according to boreholes GHŠ-1 — Panáček et al. 1991). This section differs from the northern part not only by the presence of the volcano-sedimentary complex, but also by the low average density of the overlying the Neogene sedimentary layer (2.04 g/cm^3). The density variation in the northern part (2.40–2.50 g/cm^3) is based on the overall average densities of the Neogene and Paleogene sediments from boreholes GT-5, GT-11, GT-12, ZGT-3 (Panáček et al. 1991). In the second density model (Fig. 5b), the average densities of the basin's southern part are slightly lower (2.00–2.30 g/cm^3) than in the first model (Fig. 5a). The northern part was divided into two parts, because the eastern part is mostly formed by Paleogene sediments. In its western part the defined average densities represent the Neogene and Paleogene extreme values (2.00–2.50 g/cm^3) measured in boreholes GT-5, GT-11, GT-12, and ZGT-3. Average densities of the Paleogene sedi-

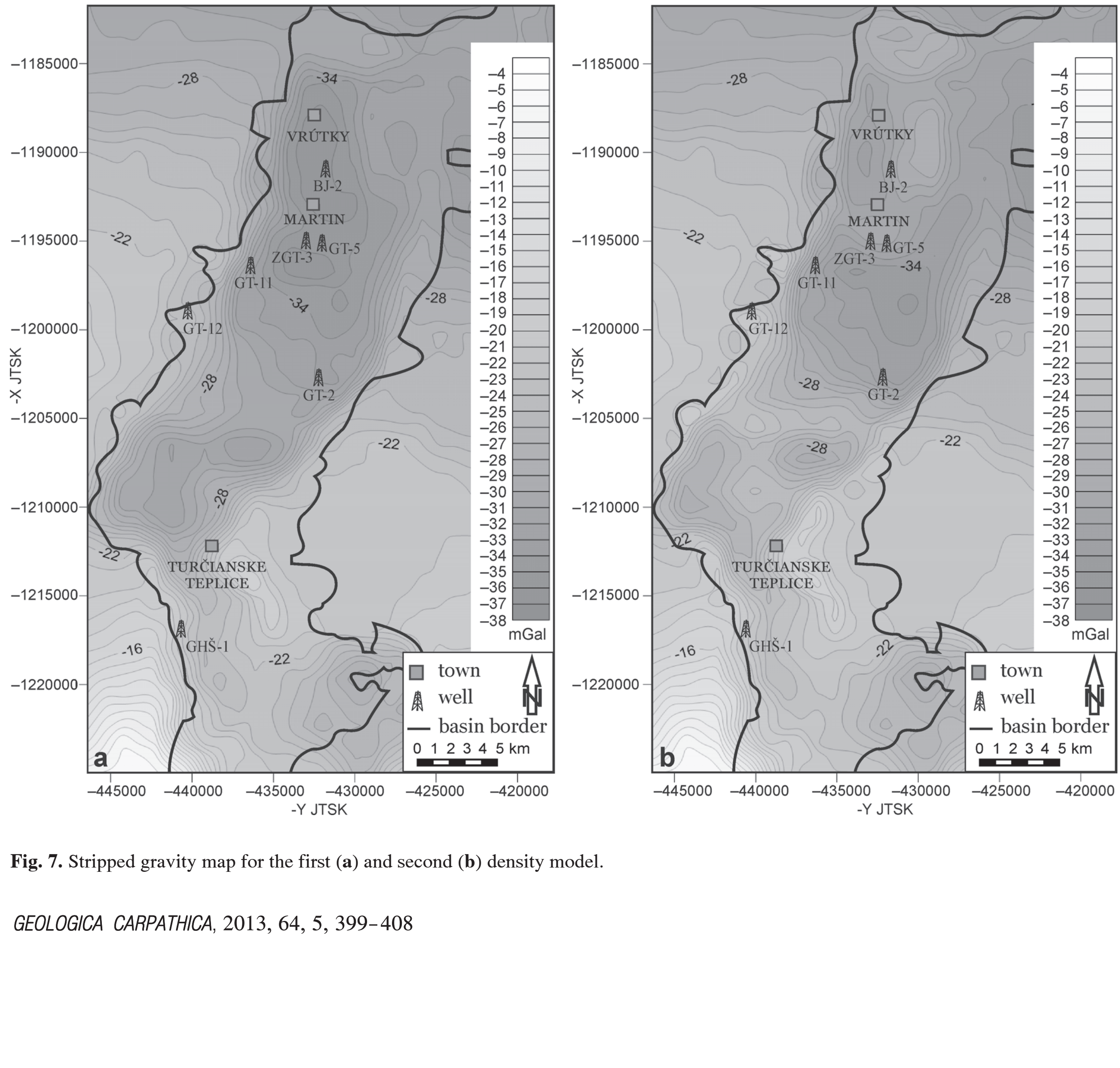

Fig. 7. Stripped gravity map for the first (**a**) and second (**b**) density model.

ments forming the eastern basin part were defined based on the results of Grinč et al. (2010) and Krajňák et al. (2012).

Results

The gravity effects of two different density models were calculated by the GMT-AUTO software package on the basis of the 3D gravity modelling method. The analysis of the gravity effect maps (Fig. 6) showed clearly that the character of the gravity field is very similar for each model. They vary only in the amplitudes of the gravity anomalies. These are smaller for the first model (Fig. 6a), but higher for the second one (Fig. 6b). Note that the gravity effects in the MS and SPS are −6 mGal (−12 mGal) for the first (second) density model. The amplitudes of the gravity effect in the NDS are almost the same (about −11 mGal) in both density models.

The stripped gravity maps were determined for both sedimentary density models (Fig. 7a,b) by subtracting their gravity effects from the complete Bouguer anomalies (Fig. 3). It is possible to see that the character of the individual gravity fields is very similar. Looking at more detail on the stripped gravity maps, we can recognize immediately that their gravity fields are affected significantly by the regional trend. This trend has a decreasing tendency in the direction from SW to NE. This regional trend reflects the gravity effects of the deep-seated crustal inhomogeneities (mostly the Moho gravity effect (Grad et al. 2009; Csicsay 2010)). As the regional gravity trend masks the residual gravity field, which is the fundamental goal of our study here, aiming at interpretation of the pre-Tertiary basement of the sedimentary basin, it is necessary to remove it from the stripped gravity maps. The same approach has also been applied in the interpretation of gravity field in Israel (Bielik et al. 2013). For the elimination of the regional gravity trend we used the map of regional gravity anomalies in the wider area of the TB, which was calculated for a radius of 5000 m (Bielik et al. 2007). The resultant trend-corrected stripped gravity maps for both density models are presented in Fig. 8a,b.

Our interpretation of the pre-Tertiary basement structure of the TB is based on the corrected stripped gravity maps (Fig. 8). But for this interpretation we used other known geological and geophysical constrains, which are represented by drill data (e.g. Gašparik et al. 1974, 1991, 1995; Fendek et al. 1990; Havrila 1997), geophysical (e.g. Zbořil et al. 1975, 1985; Hrdlička et al. 1983; Šefara et al. 1987; Panáček et al.

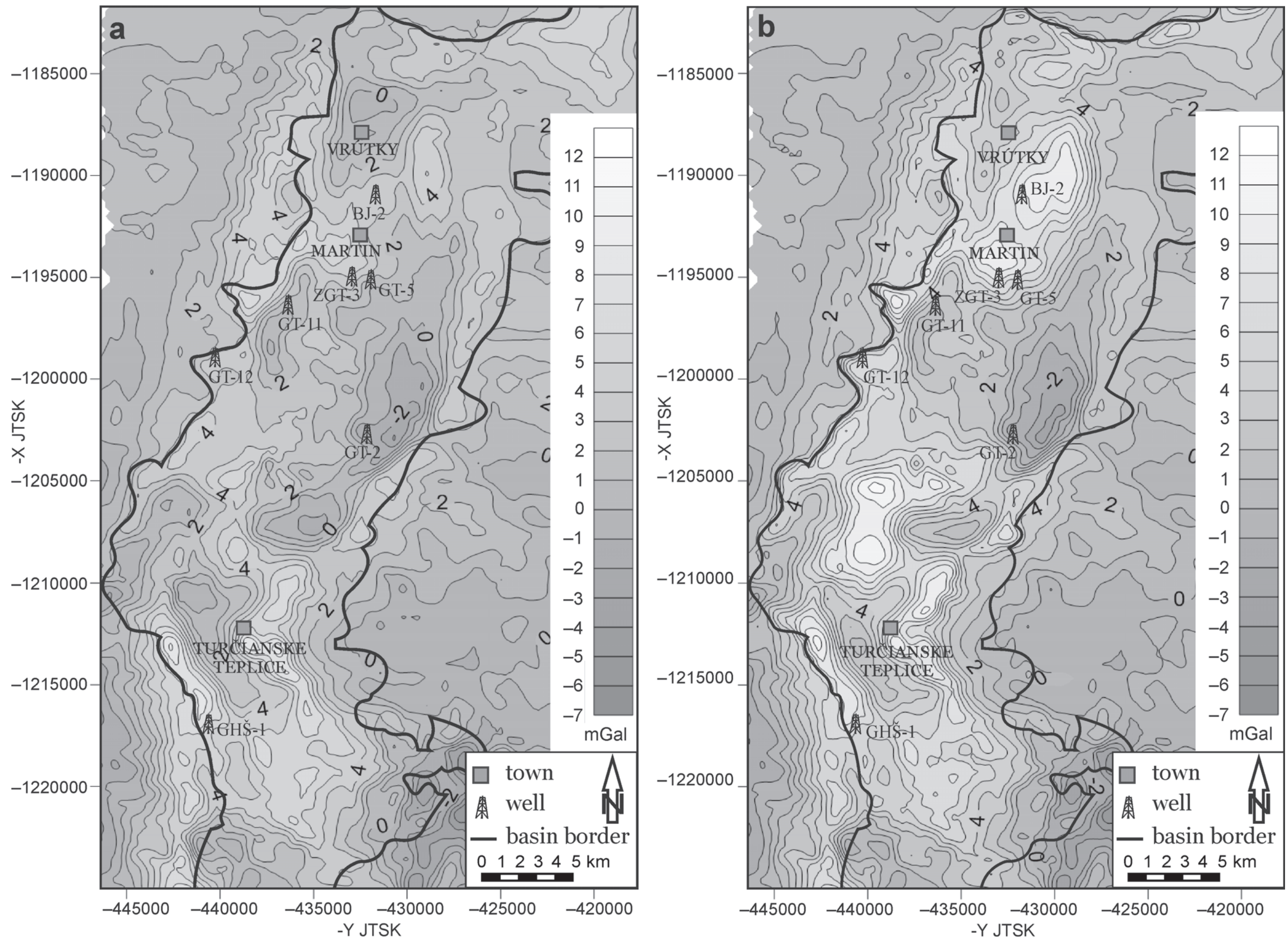

Fig. 8. The resultant stripped gravity map for the first (**a**) and second (**b**) density model corrected by regional gravity anomalies, which were calculated for a radius of 5000 m (Bielik et al. 2007).

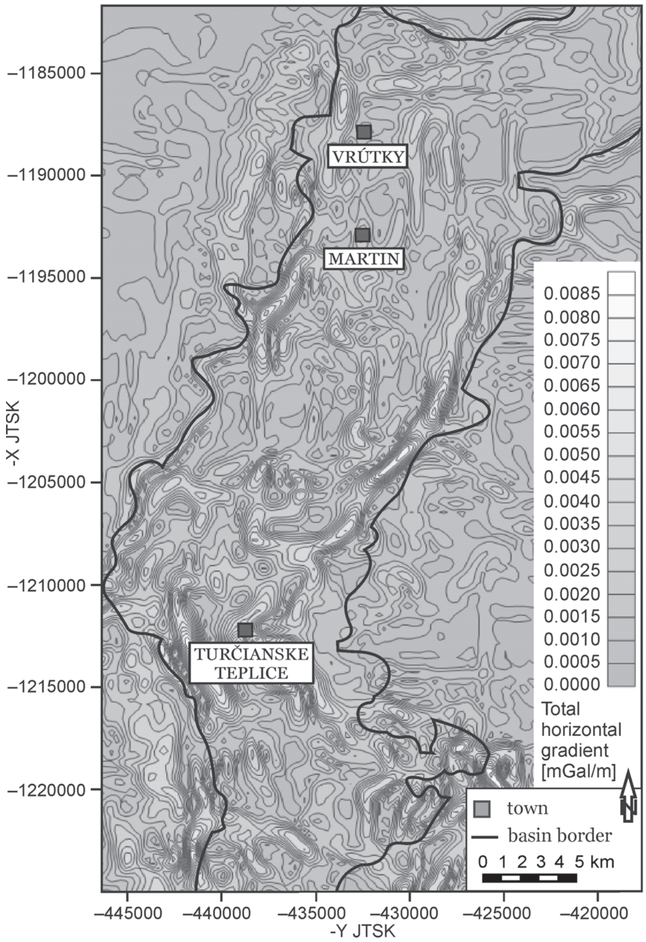

Fig. 9. The total horizontal gradient map.

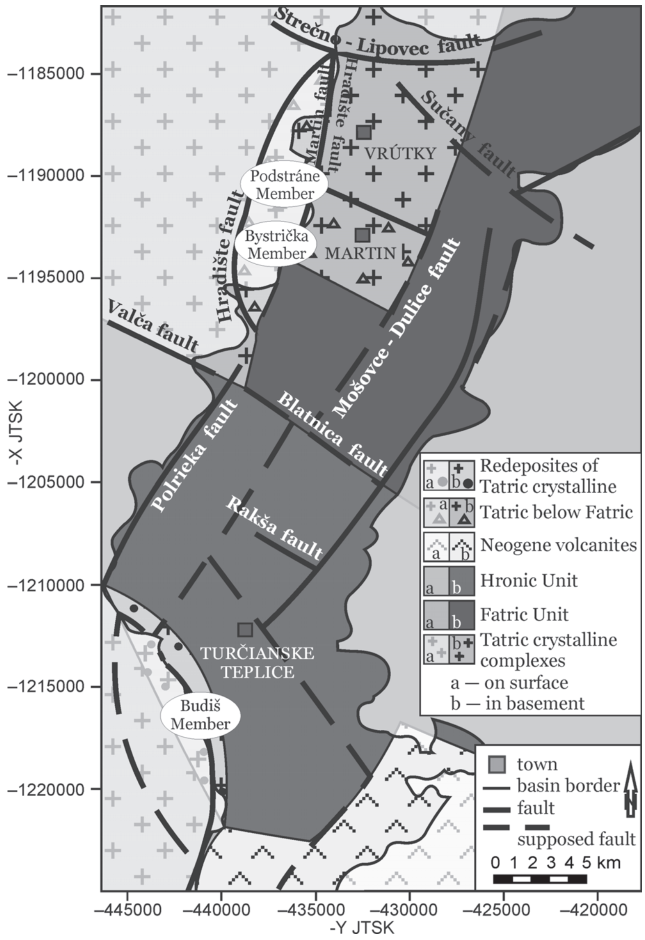

Fig. 10. A sketch of the pre-Tertiary basement structure of the TB.

1991) and geological (e.g. Gašparik et al. 1995; Rakús 1999; Kováč et al. 2011) data, results and knowledge. A sketch of the pre-Tertiary basement structure of the TB is shown in Fig. 10. The TB can be separated into northern and southern parts. The NW-SE gravity gradient in the basin's central part (near Kláštor pod Znievom) is the boundary between them. Taking into account the gravity pattern of the corrected stripped gravity maps, boreholes data (e.g. ZGT-3, GT-5, GT-11, GT-12, BJ-2) and the geology of the surrounding tectonic units of the TB, the northern part of the pre-Tertiary basement was additionally split into two sub-parts (domains). The first is characterized by the Hercynian crystalline basement of the Tatric Unit. In the second the basement consists mostly of the Mesozoic complexes of the Fatric Nappe, the thickness of which decreases eastward. In the first domain we also recognize another interesting part of the pre-Tertiary basement. This area has a prolonged shape in the NE-SW direction, being located to the west of the towns of Martin and Vrútky. This anomalous gravity field zone correlates very well with the Neogene alluvial Podstráne and Bystrička Members (fans). It is believed that this type of anomalous zone also forms the pre-Tertiary basement in a wider region of Martin. The basement here is probably formed by Mesozoic rocks (not of great thickness) and the Tatric crystalline complex underneath.

The southern part of the pre-Tertiary basement of the TB is formed mostly by Mesozoic complexes of the Hronic Nappe. The continuation of the gravity high to the SE from the area of borehole GHŠ-1, where the Kremnické vrchy Mts extend on the surface, indicate that the Hronic Nappe forms the bedrock of this volcano-sedimentary complex. The significant gravity low located in the south-eastern part of the area reflects the center of the Kremnické vrchy Mts. In the area of the surface Neogene alluvial Budiš Member (fan) outcrop (Kováč et al. 2011) we discover an anomalous gravity zone, in which the basement probably consists of the Hronic Nappe of prevailing dolomite composition.

The resultant stripped gravity maps have also proven to be very useful for the interpretation of faults, or fault systems, in the study area. In the image of the gravity field the faults are characterized by the maxima of horizontal gradients. For this reason, we evaluated the map of total horizontal gradients (Fig. 9) using the regularized (smoothed) derivatives in the Fourier domain, selecting the optimum regularization (low-pass filter) parameter by means of the C-norm functions analysis (Pašteka et al. 2009, 2012). In the TB (Figs. 9 and 10) we found the faults and fault systems with prevailing NNE-SSW and NW-SE directions. The analysis of the faults shows clearly that the contact of the TB with the Malá Fatra Mts and the Veľká Fatra Mts is tectonic. The gravity pattern suggests that the Blatnica fault should be the south-westernmost boundary of the area, in which the Paleogene post-nappe sediments are a part of the Tertiary sedimentary basin fill. In the future we would like to verify the interpreted faults in the TB by incorporating also geoelectrical (e.g. Putiška et al. 2012a,b) and radiometric (e.g. Mojzeš et al. 2006; Marko et al. 2010) methods and observations.

Discussion and conclusions

Detailed analysis of densities of rocks forming not only the Tertiary sedimentary fill of the Turiec Basin, but also the pre-Tertiary surrounding tectonic units shows that in general the average densities vary only a little. This applies specifically to the densities of rocks that are part of the Hronic and Fatric Units. The density differences between the Tatric crystalline complexes and the Mesosoic complexes are also inperceptible.

Another element that is very important for the quality of the resultant stripped gravity map is the existing lack of knowledge on the course of the boundary between the Neogene and Paleogene layers in the Turiec Basin. The local gravity low located westward of the village of Belá indicates that the gravity effect of the sedimentary fill here is probably underestimated.

Nevertheless, we think that even if the results of the stripping gravity method are, by definition, not unique, the results presented in the paper are important and valuable at this stage of research in the Turiec Basin. The results show that the applied method is very useful for investigating the structure, composition and tectonics of the basements of Tertiary depressions in the Western Carpathians.

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