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3D density modelling of Gemeric granites of the Western Carpathians

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Abstract: The position of the Gemeric Superunit within the Western Carpathians is unique due to the occurrence of the Lower Palaeozoic basement rocks together with the autochthonous Upper Palaeozoic cover. The Gemeric granites play one of the most important roles in the framework of the tectonic evolution of this mountain range. They can be observed in several small intrusions outcropping in the western and south-eastern parts of the Gemeric Superunit. Moreover, these granites are particularly interesting in terms of their mineralogy, petrology and ages. The comprehensive geological and geophysical research of the Gemeric granites can help us to better understand structures and tectonic evolution of the Western Carpathians. Therefore, a new and original 3D density model of the Gemeric granites was created by using the interactive geophysical program IGMAS. The results show clearly that the Gemeric granites represent the most significant upper crustal anomalous low-density body in the structure of the Gemeric Superunit. Their average thickness varies in the range of 5–8 km. The upper boundary of the Gemeric granites is much more rugged in comparison with the lower boundary. There are areas, where the granite body outcrops and/or is very close to the surface and places in which its upper boundary is deeper (on average 1 km in the north and 4–5 km in the south). While the depth of the lower boundary varies from 5–7 km in the north to 9–10 km in the south. The northern boundary of the Gemeric granites along the tectonic contact with the Rakovec and Klátov Groups (North Gemeric Units) was interpreted as very steep (almost vertical). The results of the 3D modelling show that the whole structure of the Gemeric Unit, not only the Gemeric granite itself, has an Alpine north-vergent nappe structure. Also, the model suggests that the Silicicum–Turnaicum and Meliaticum nappe units have been overthrusted onto the Golčatov Group.

Keywords: applied geophysics, gravity, 3D density modelling, Gemeric granites, Spiš-Gemer Ore Mts., Western Carpathians.

Introduction

The Gemeric granites comprise several small intrusions outcropping in the western and south-eastern parts of the Gemeric Superunit, which is one of the principal Alpine tectonic units of the Central Western Carpathians. They are particularly interesting not only from the point of their geological structure, tectonic position, mineralogical and petrographical composition but also in terms of mineral deposits occurring in the Spiš-Gemer Ore Mts. This was one of the reasons why this mountain belongs to the best geophysically explored regions of Slovakia (e.g., Filo 1968; Plančár et al. 1977; Grzywacz & Margul 1980; Husák & Muška 1984; Mikuška 1984; Grecula et al. 1985; Šefara et al. 1987; Filo & Kubeš 1994; Suk et al. 1996; Vozárová 1996; Mikuška & Marušiak 1999; Vozár & Šantavý 1999; Szalaiová et al. 2001). Some of these works deal with the geophysical interpretation of the geological structure of the Gemeric Unit and the Gemeric granites. These geological structures are well documented by their outcrops and in structural boreholes (e.g., SG-2 in the Prakovce locality, Grecula 1992). They can also be clearly recognized in the seismic and gravimetric images (e.g., Šefara et al. 1987; Tomek 1993; Vozár et al. 1996; Vozár & Šantavý 1999; Bielik et al. 2006). The seismic reflection measurements along the N–S trending Transect G (Fig. 1) played perhaps the greatest significance for the geological and geophysical studies of the Gemeric Superunit. It was situated in the eastern part of the Spiš-Gemer Ore Mts. The explanation of the complicated geological and tectonic structure of the Gemeric Superunit as a dominant mega-tectonic unit of the innermost Western Carpathians has been the goal of the previous seismic reflection measurements.

In the last decades, there was unbelievable progress in development of 3D interpretation of anomalous bodies by means of gravity field (anomaly). At the beginning the calculated effect of the anomalous density body has been solved by

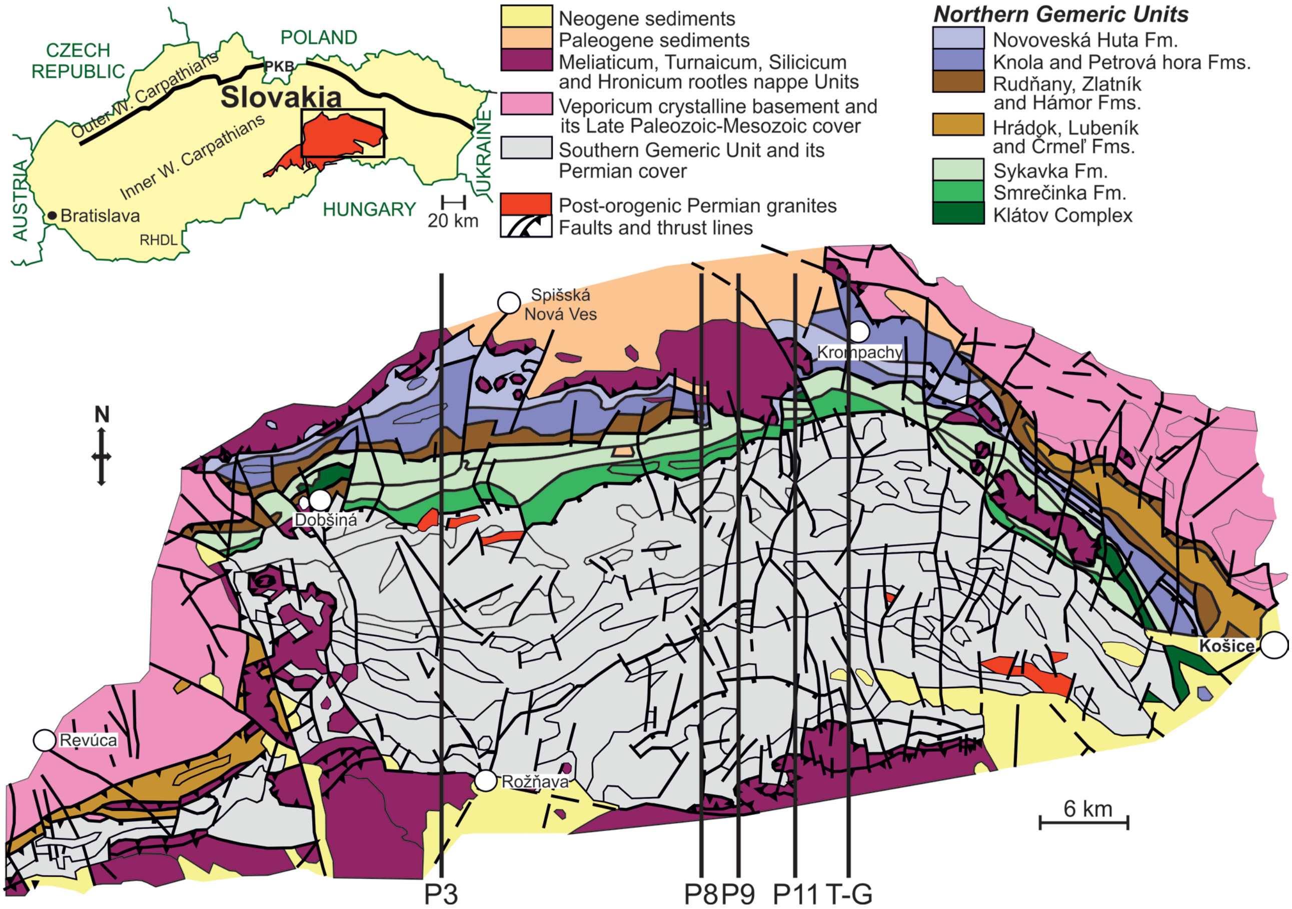

Fig. 1. Geological map of the Gemeric Superunit — a segment of the studied region (modified after Vozárová et al. 2013 and Geological Map of the Slovak Republic at scale 1:500,000; Biely et al. 1996a, b). The course of the approximated Transect G and the interpretative profiles shown in Fig. 6.

replacing the sum of calculated effects of the geometrically simple (regular shaped) bodies. The most widely used approximation consisted of a variable number of rectangular prisms (e.g., Talwani & Ewing 1960; Grant & West 1965; Cordell & Henderson 1968; Smíšek and Plančár 1970; Talwani 1973; Plančár et al. 1977; Starostenko et al. 1997, 2015, 2016; Starostenko & Legostaeva 1998; Grabowska et al. 1998; Bojdys 2006a, b). Currently, the 3D interpretive methods using the so-called polyhedrons (i.e. the bodies bounded by a polygonal surfaces (facets)) are applied frequently (e.g., Bott 1963; Nagy 1966; Okabe 1979; Hansen & Wang 1988 in Blakely 1996; Pohánka 1988, 1998). This category also includes the software IGMAS (Interactive Gravity and Magnetics Application System), which is a tool applied for the interpretation of observed gravity and magnetic fields. The IGMAS program is an indirect modelling approach using trial-and-error forward modelling. It works by means of a numerical simulation of underground structures that are described as closed polyhedrons of constant density/susceptibility, the surface of which is triangulated (Götze 1978; Götze & Lahmeyer 1988; Schmidt & Götze 1998). Now, the current IGMAS software ranks among the best in the world (Schmidt et al. 2011, 2015; Alvers et al. 2014).

The main aim of this work is to apply the interactive IGMAS program for development of the original 3D density model of the Gemeric granites, which gives results consistent with recent geological and geophysical knowledge. The article has been completed in honour and memory of J. Šefara by the team of the authors.

Geological overview

According to the classical definition (e.g., Andrusov 1968; Andrusov et al. 1973), the Gemeric Superunit (Fig. 1) includes the Early Palaeozoic complexes and Late Palaeozoic–Mesozoic envelope sequences. The classical definition changed fundamentally, as it was proved that the Mesozoic carbonate rock complexes, originally thought to be its cover sequence are in an allochthonous position on the nappe units of Silicicum, Turnaicum and Meliaticum, which was verified (Kozur & Mock 1973; Bajaník et al. 1983; Mello et al. 1996). Detailed investigations of the Early and Late Palaeozoic rock complexes led to the subdivision of the formerly defined Gemeric Superunit into two tectonic units: the Northern and Southern Gemeric Units (Bajaník et al. 1983, 1984a, b; Vozárová &

Vozár 1988; Vozár et al. 1996; Vozárová 1996). Both consist mainly of pre-Carboniferous crystalline rock complexes and late- to post-orogenic Variscan formations. In the cover sequence only linking between the Lower Triassic and Permian is evident. The majority of the Mesozoic part in both cover complexes was tectonically truncated.

Sporadically, stratigraphic data in pre-Carboniferous formations were and are the reason of the controversial understanding of the inner structure. According to one group of authors, there is an asymmetric highly Alpine-reworked mega-anticline, lined up by granitoid (see the map of Bajaník et al. 1984a). According to Grecula (1982) the inner structure of the Gemeric Superunit is dominated by a system of Late Variscan nappes, in which granites are also included. However, this interpretation is not in agreement with the results of the deep reflection seismic transect G (Vozár et al. 1993, 1996). It confirmed an Alpine north-vergent nappe structure supported by the mainly Permian age of granitoids (Finger & Broska 1999; Poller et al. 2002; Kohút & Stein 2005) and/or the Jurassic to Cretaceous cooling ages of their tectonic overprinting (Kantor 1957; Kantor & Rybár 1979; Kovách et al. 1979). The seismic interpretation was also supported by that of Hók et al. (1993), data of contact metamorphism (Vozárová et al. 2001) and the Alpine age of reworked mica (Breiter et al. 2015).

The Northern Gemeric Unit consists of Lower Palaeozoic volcanic-sedimentary formations reflecting subduction-collisional processes of the Variscan orogeny, which were connected with polyphase, metamorphic events and development of the Carboniferous–Permian syn- and post-orogenic basins (Bretonic, Sudetic, Asturian movements). They contain pre-Carboniferous high-grade and low-grade metamorphosed complexes of distinct oceanic affinity, which were amalgamated by polyphase processes in the Early and Middle Carboniferous times. This is confirmed by relicting infillings of the Lower Carboniferous remnant-basin with olistoliths of serpentinized ultrabasic rocks, metabasalts, dolerites and amphibolites (Ochtiná and Črmeľ Groups — Vozárová 1996), as well as of a peripheral shallow-marine Westphalian basin (remaining formations of the Dobšiná Group) and the sediments, which already superimposed on the Variscan structure. The post-orogenic transpressional regime was linked with development of continental Permian sequences. The lagoonal-sabkha-type Upper Permian to Lower Triassic formations are connected with the beginning of the Alpine cycle.

The Southern Gemeric Unit is composed, in its major part, of the Lower Palaeozoic volcanogenic flysch (Gelnica Group in the sense of Snopko & Ivanička 1978; Ivanička et al. 1989), probably affected by Late Variscan folding and very low-grade metamorphism. The origin of this complex is connected with an active continental margin (Bajaník & Reichwalder 1979; Vozárová 1993). The Gelnica Group was generally described as a megasequence of deep-water turbidite siliciclastic sediments, associated mainly with the rhyolite-dacite volcanic/volcaniclastic rocks. Acidic to intermediate magmatic arc volcanism (Vozárová & Ivanička 1996; Vozárová et al. 2010) was highly explosive, which resulted in the redeposition of vast amounts of volcaniclastic material into the sedimentary basin by a system of gravity and mass currents. Besides them, thin horizons of metabasaltic volcaniclastics and sparse associated metabasalts occur. Olistoliths of metabasalts were included in the binder of gravity sliding and slumping. Their chemical composition points to mixed tectonic settings of the magmatic source, similar to CAB, VAB, E- and E-MORB (Ivan et al. 1994).

According to microflora, the stratigraphy of the Gelnica Group ranges from the Cambrian to Lower Devonian (Snopková & Snopko 1979). Further biostratigraphical data, based mainly on agglutinated foraminifers of the family *Psammosphaeridae* and *Saccamminidae*, prove the Late Cambrian/Ordovician to Early Silurian ages (Vozárová et al. 1998; Soták et al. 1999). The Late Cambrian-Ordovician *in situ* U–Pb sensitive high-resolution ion microprobe (SHRIMP) concordant average zircon ages, 494±1.6 Ma, 465.8±1.5 Ma and 463.9±1.7 Ma (Vozárová et al. 2010), of magmatic rocks confirm the biostratigraphic data.

The Štós Formation is a further pre-Permian low-grade complex, situated only in the SE part of the Southern Gemeric surface exposures. The contact of the Gelnica Group and Štós Formation rock complexes is tectonic. A shallow north-verging thrust plane is documented by the deep seismic profile (Vozár et al. 1995). Due to the intense Lower/Middle Cretaceous nappe stacking of the Inner Western Carpathians nappe units, the Southern Gemeric complexes are affected by strong Early Cretaceous overprinting (chemical Th–U-total Pb isochrone method (CHIME) monazite data (Urban et al 2006; Vozárová et al. 2014).

The Lower Palaeozoic Southern Gemeric Unit is disconformably covered with an angular unconformity at the base by the Permian continental riftogenic formation (Gočaltovo Group) prograding into Upper Permian–Lower Triassic lagoonal to shallow-marine deposits. This sequence is genetically connected with the beginning of the Alpine geotectonic cycle.

The Northern Gemeric and Southern Gemeric Units were probably juxtaposed during latest Pennsylvanian/Permian transtensional movements, as is documented by detrital zircon assemblages (Vozárová et al. 2013). This does not exclude later separation during the Late Permian-Triassic extension or subsequent Cretaceous juxtaposition during Alpine nappe stacking. The latter is documented by the 131 Ma newly-formed zircon rims around older detrital zircons.

The Gemeric granites (Uher & Broska 1996) are exposed in several massifs which intruded Lower Palaeozoic metapelites-metapsammites as well as acid metavolcanics (rhyolites to dacites and their pyroclastic equivalents) of the Gelnica Group, in the Southern Gemeric Unit. It is assumed that they are the topmost parts of a granite body, of which the main part is located at depth. Known surface exposures of granites are found in the vicinity of Hnilec, Zlatá Idka, Poproč, Betliar. The granite is also outcropping in the transverse elevations of three (Hnilec, Lužice and Turecka Hill) anticlinal bands of the Gelnica Group and in many other smaller outcrops. The greatest outcrop around Poproč has dimensions of 6.5 km to 1.5 km.

These leucocratic biotite and biotite-muscovite granites are accompanied by granite porphyries (Betliar body), and sometimes by greisens and albitites in granitic cupolas with Sn-W-(Li-Nb-Ta) mineralization (Hnilec, Dlhá Valley; Malachovský 1983). According to the first monazite electron-microprobe dating results (Finger & Broska 1999), they are post-orogenic and of Permian age. Uher & Broska (1996), Petrík & Kohút (1997), Broska & Uher (2001) and Broska et al. (2002) assigned these granites to the specialized S-type characteristics, for example, by their high Si, K, Rb, Sn, B, F; and low Zr and REE contents. Their data indicate a high temperature (solidus T−750 °C), dry (1–3 % $H_2 0$), and a variable oxygen fugacity of the magma.

It is not certain today whether the Gemeric granites are formed by Variscan post-orogenic and/or the Early Alpine riftogenic processes. Indeed, their age was proven as Permian (275–251 Ma) by various mineral dating methods (monazite — CHIME, Finger & Broska 1999; zircon — CC-TIMS — cathodeluminescence controlled thermal ionization mass spectrometry, Poller et al. 2002; molybdenite — N-TIMS — negative thermal ionization mass spectrometry, Kohút & Stein 2005; zircon — SHRIMP Radvanec et al. 2009; zircon — LA ICP-MS — laser ablation inductively coupled plasma mass spectrometry, Kubiš & Broska 2010). Their geochemical and mainly isotopic characteristics suggest sources in the mature upper crustal material with a contribution from lower crustal metabasites (Kohút 2012). Generally, granites are emplaced within the crust during extension/relaxation phases of orogeny, albeit the situation in the Gemeric Superunit suggests rather transition between the post-Variscan subduction/collision relaxation and the initial Palaeo-Alpine rifting (Kohút & Stein 2005; Radvanec et al. 2009).

Recent U–Pb zircon SHRIMP/SIMS dating results from the various Variscan Western Carpathians I/S-types of granitic rocks (Kohút et al. 2009, 2010; Broska et al. 2013) imply that they originated between 367–353 Ma, and 340–332 Ma respectively, mirroring subduction and collision stages of the Variscan orogeny. Most probably, they originated in an arc-related environment within the Galatian superterrane (an assemblage of Gondwana derived fragments) in the so-called "Proto-Tatricum" (Broska et al. 2013). Now, these granitoids are incorporated as a part of the crystalline basement into the Alpine tectonic units — Tatric and Veporic Units within the present West-Carpathian mountain chain.

Specialized Permian granites from the Gemeric unit represent another family of granitoids, influenced by high contents of volatiles (F, B, H_2O) and highly increased P, Rb, Li concentrations. A model of their evolution (Breiter et al. 2015) involves differentiation into three levels, postmagmatic retrogression and a strong Alpine reworking. Their minerals record intensive low temperature overprint which caused a strong oxidation of micas and formation of low temperature aluminophosphates (Petrík et al. 2014). Both mentioned interpretations, however, have one common basis, namely the Early Proterozoic development of the Northern and Southern Gemeric Units in the framework of one geotectonic domain, whether already with lateral continuous or vertical connection.

Previous geophysical interpretations of the Gemeric granites

In the Spiš-Gemer Ore Mts., geophysical research and surveys have been carried out roughly from the middle of the last century. Regional gravimetric mapping at the scale 1:25,000 (Kadlec 1965; Šefara 1966; Bárta 1969; Grzywacz & Margul 1976, 1980; Obernauer & Stránska 1983; Mikuška 1984) and detailed at a scale 1:10,000 (Ferenc et al. 1974, 1978; Mikuška & Špaček 1982; Steiner et al. 1983,1987; Grecula et al. 1985; Mikuška et al. 1985; Kucharič et al. 1987, 1988, 1989, 1990, 1993; Kucharič 1991) provided a sufficiently high-quality gravity database that became the basis for defining the gravity field of these mountains.

The first attempts to estimate the geometry and position of the Gemeric granite bodies were made by Šefara & Filo (in Plančár et al. 1977). Their granite-geological model was based on the results of the gravimetry. To define the model they applied the method of vertical prisms, in which each inhomogeneity was replaced by a system of vertical n-side prisms of final heights. The output was a map of the surface granite relief up to a depth of 3000 m (Plančár et al. 1977).

Further research was performed by Grzywacz & Margul (1980) in the eastern part of the Spiš-Gemer Ore Mts. The 2D interpretation showed that the relief of the granite would be more rugged than was expected. The authors of the interpretation used a combination of the vertical steps, with density contrast of -0.15 $g.cm^{-3}$ to the reference density of the Gelnica Group. This anomalous high-density contrast caused the lower boundary of the granite body to be interpreted as too shallow under the surface.

Grecula et al. (1985) performed the interpretation of the Gemeric granites along forty profiles. Separation of the gravity field into regional and residual anomalies and a 2D inverse gravimetric problem have been solved. The gravity effect of the granite bodies has been calculated by Pohanka's unpublished formulas for the 2D prismatic bodies with a polygonal cross-section. The applied density contrast for the granite body against the Gelnica Group was -0.11 $g.cm^{-3}$ (Husák & Muška 1984). The lower boundary of the anomalous granite body was interpreted approximately at a level of 4200 to 5000 m under the surface. The results suggested that the upper boundary of the granite is discontinuous and that the lower boundary in the eastern part of the Gemeric Superunit is about 1000 m more shallow in comparison to the west.

The reflection seismic measurements along the Transect G meant a major benefit for the study of the Gemeric Superunit's geology. Its course (Fig. 2a) was situated based on many terrain geological and geophysical works (e.g., Vozárová 1973; Bajaník et al. 1984b; Fusán et al. 1987; Šefara et al. 1987; Vozárová & Vozár 1988) and realized in 1991–1992 (Vozár

1991). The S–N transect crosses the Northern and Southern Gemeric Units including their cover and nappe formations: Bôrka nappe, Silicicum, Turnaicum and Meliaticum. Further it runs across the Palaeozoicum of the Southern Gemeric Unit — the Štós formation and the Gelnická Group. The northern part, the Transect G crosses the Northern Gemeric Unit — the Rakovec and Klátov Groups and their cover formations (the Dobšina and Krompachy Groups). The measurements were carried out by ELGI of Budapest in 1992. The first interpretation of the reflection seismic measurements (Novotný & Dvořáková 1993) identified the nappe character of the northern part of the transect. Based on these results, Vozárová (1996) improved the geology of the Gemeric Superunit internal structure. A new interpretation of the crustal elements along the Transect G was presented by Vozár & Šantavý (1999). It was based on reprocessing done by ELGI of Budapest in 1996 (Fig. 2b). From the interpretations, it can be clearly seen that the Gemeric Superunit is overthrusted on the units of the Northern and Southern Veporicum and the tectonic basement of the Gemeric Superunit decreases from the north to south. The Gemeric granites were manifested as the low reflection zone. In terms of deep seated structure, it is worth mentioning that the significant reflection zone was found at about 10 seconds. This anomalous zone probably represents the Moho discontinuity (Vozár et al. 1997, 1998a, b).

The next model was estimated by Mikuška & Marušiak (1999). The new element in the process of interpretation was the introduction of new findings on the bottom boundary of the granite body, which resulted from interpretation of the reflection seismic Transect G (Vozár et al. 1998a, b; Vozár & Šantavý 1999). The determined depths of the bottom boundary of the granite body for density contrast −0.11 g.cm^{-3} was about 4 km in the north and 8 km in the south.

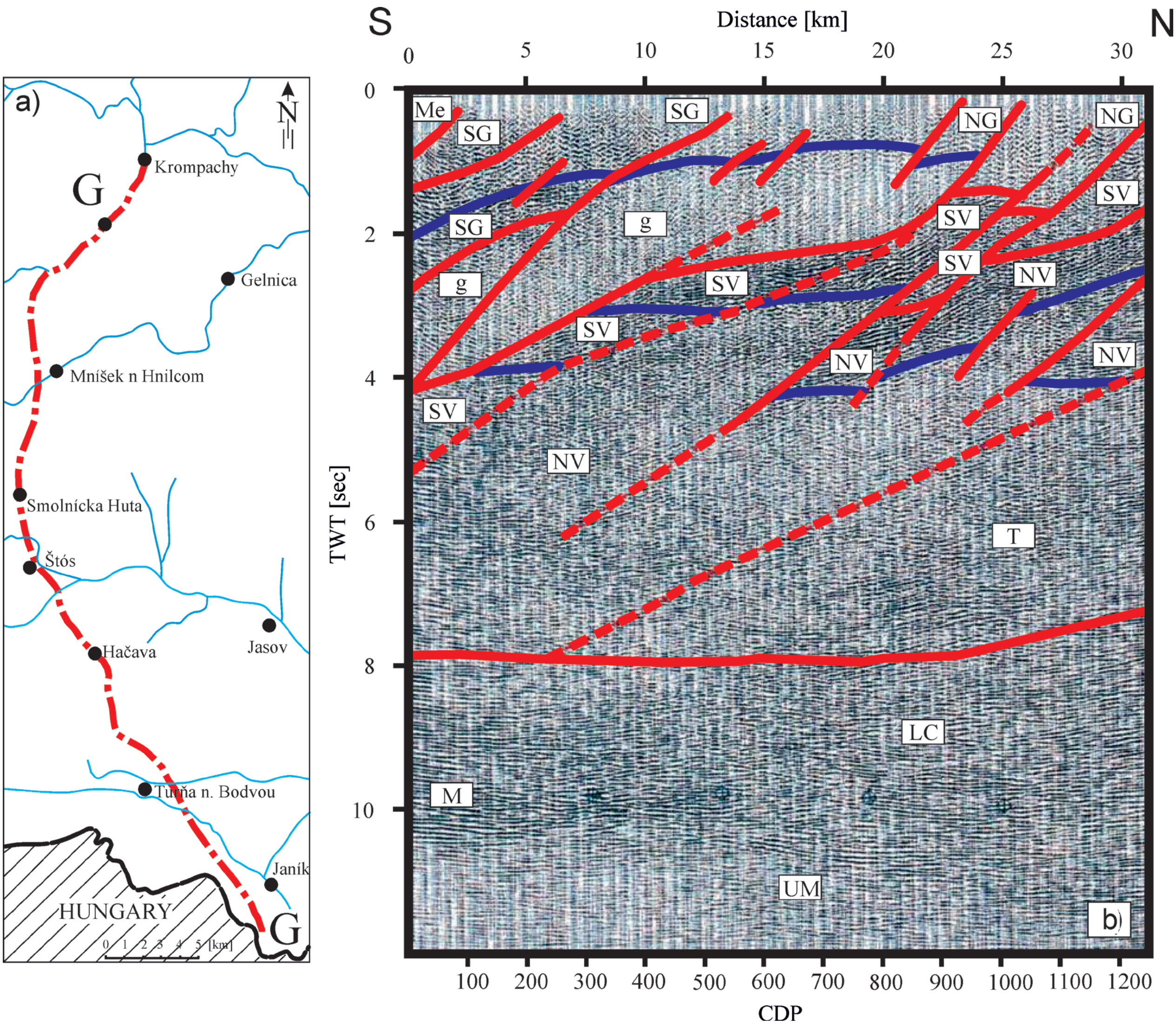

Fig. 2. a — Location of the deep reflection seismic Transect G. **b** — Reprocessing: ELGI Budapešť, 1996; interpretation by Vozár & Šantavý 1999. Legend: T–Tatricum, NV–North Veporicum, SV–South Veporicum, NG–Northern Gemeric Unit, g–granites, Me–Meliaticum including the Bôrka nappe, LC–Lower crust, M–Moho, UM–Upper mantle.

The latest work, concerning the interpretation of the Gemeric granites was carried out by Szalaiová et al. (2001). Their interpretation was done by the program GM-SYS $2^{1/2}$D along the four profiles going across the Gemeric Superunit. The basic interpretative profile was coincident with the seismic reflection Transect G (Fig. 2a). The resultant $2^{1/2}$D density model is shown in the Figure 3a. Outside of the interpretative profiles the values of the upper boundary of the granite body (Fig. 3b) were estimated by interpolation.

Interactive gravity and magnetics application system

Our new and original 3D density model of the Gemeric granites was constructed using the IGMAS software. The interpretation of a potential field (gravity or magnetic) in the IGMAS system is based on determining shapes, positions and physical parameters of the geological structures that cause that particular field in an investigated area (Schmidt 1996; Schmidt & Götze 1998). The problem of data inversion requires the application of additional geological and geophysical information (constrains), which can be obtained, for example, from wells, other geophysical methods, and measurements of physical properties of rocks. The indirect modelling approach includes calculation of the effects of modelled bodies that approximate geological structures, followed by matching the modelled curve with the observed gravity curve. The 3D structure is achieved in IGMAS by including several vertical planes, on which geological bodies are geometrically defined in the form of polygons that are based on all the available data. The planes are always parallel and should be placed perpendicular to the geological structures that they represent. Through triangulation, these cross-sections with defined polygons are connected to create the layer boundaries (triangular facets). They are represented by the shape and form of the modelled geological structures of constant density or susceptibility. The triangulation between the vertical planes is performed automatically. The data structure in IGMAS, which is required for the description of 3D model geometry, must be simple and flexible enough to visualize the results obtained. The construction of the final 3D modelled structures is done by the IGMAS system and does not require any knowledge of the topology of a model and/or the triangulation techniques (Schmidt 1996). All the processes are done visually and interactively. The modelled bodies are adjusted by trial and error method using interactive graphical tools until a good fit is obtained (Tašárová 2004).

Input data

Gravity anomaly maps

In general, a basic map for interpretation of the gravity field is represented by the Bouguer gravity anomaly. The map of the Bouguer gravity anomaly of the Gemeric Superunit was calculated for the reference density of 2.67 $g.cm^{-3}$ by Katona (2007; Fig. 4a). Since the Bouguer gravity anomaly represents a superposition of the gravity effects of all the masses located below the surface it is necessary to separate from it the effects of the masses which are not the subject of the interpretation. In our case, it was therefore necessary to determine the so-called map of the residual gravity anomaly, which should reflect primarily the gravity effect of the anomalous masses located in the upper crust. To achieve this residual gravity anomaly map we corrected the Bouguer gravity anomaly by the regional gravity field, which represents, on the contrary, the effect of deep-seated inhomogeneities (masses located approximately beneath the upper crust). For 3D quantitative gravity interpretation of the Gemeric granites, we used this evaluated residual gravity anomaly, which is shown in the Figure 4b. The regional field was approximated by using the mathematically defined polynomial function of the third degree (estimated by means of the Least Squares method), the main requirement of which was that its character would agree with the regional trend observed on the map of the Bouguer gravity anomaly. In other words, the determined regional gravity trend would approximate the regional increasing of the observed gravity from the Western Carpathian gravity low area towards the Pannonian gravity high. The resultant map of the residual gravity anomaly was also compared with another one that has been calculated, in this region, by the Fourier transformation using a high-frequency Butterworth's filter (Kubeš et al. 2001). The character and amplitude of the gravity fields of both residual gravity maps were very similar.

Analysis of the gravity fields presented by the Bouguer gravity anomaly and residual gravity anomaly maps (Fig. 4a,b) indicate that the individual anomalous areas correlate well with the main tectonic units of the geological structure as well as with their density distribution. In the central part of the Spiš-Gemer Ore Mts., a significant Southern Gemeric gravity low (SGGL with maximum amplitude −28 mGal on the Bouguer gravity anomaly and −9 mGal on the residual gravity anomaly) dominates. The source of this anomaly is a deep granite (granitoid) body, the top parts of which reach the surface and are the sources of local gravity lows. From the northern part, the gravity low is bounded by a distinct Northern Gemeric gravity high (NGGH with maximum amplitude −13 mGal on the Bouguer gravity anomaly and +11 mGal on the residual gravity anomaly). Its position correlates well with the occurrence of the Rakovec and Klátov Groups, in which the relatively heaviest Palaeozoic rocks (basic volcanics and metamorphites) occur. In the south-eastern direction it continues towards the sizable gravity high. The zone turns and it becomes a part of the Košice gravity high (KGH — maximum amplitude +1 mGal on the Bouguer gravity anomaly and +11 on the residual gravity anomaly) reflecting metamorphic rocks of the Veporicum in the Čierna hora Mts. In this part, a positive anomaly occurs induced by the Mesozoic and crystalline rocks. To the south, the SGGL is bounded again by gravity high (maximum amplitude −5 mGal on the Bouguer gravity

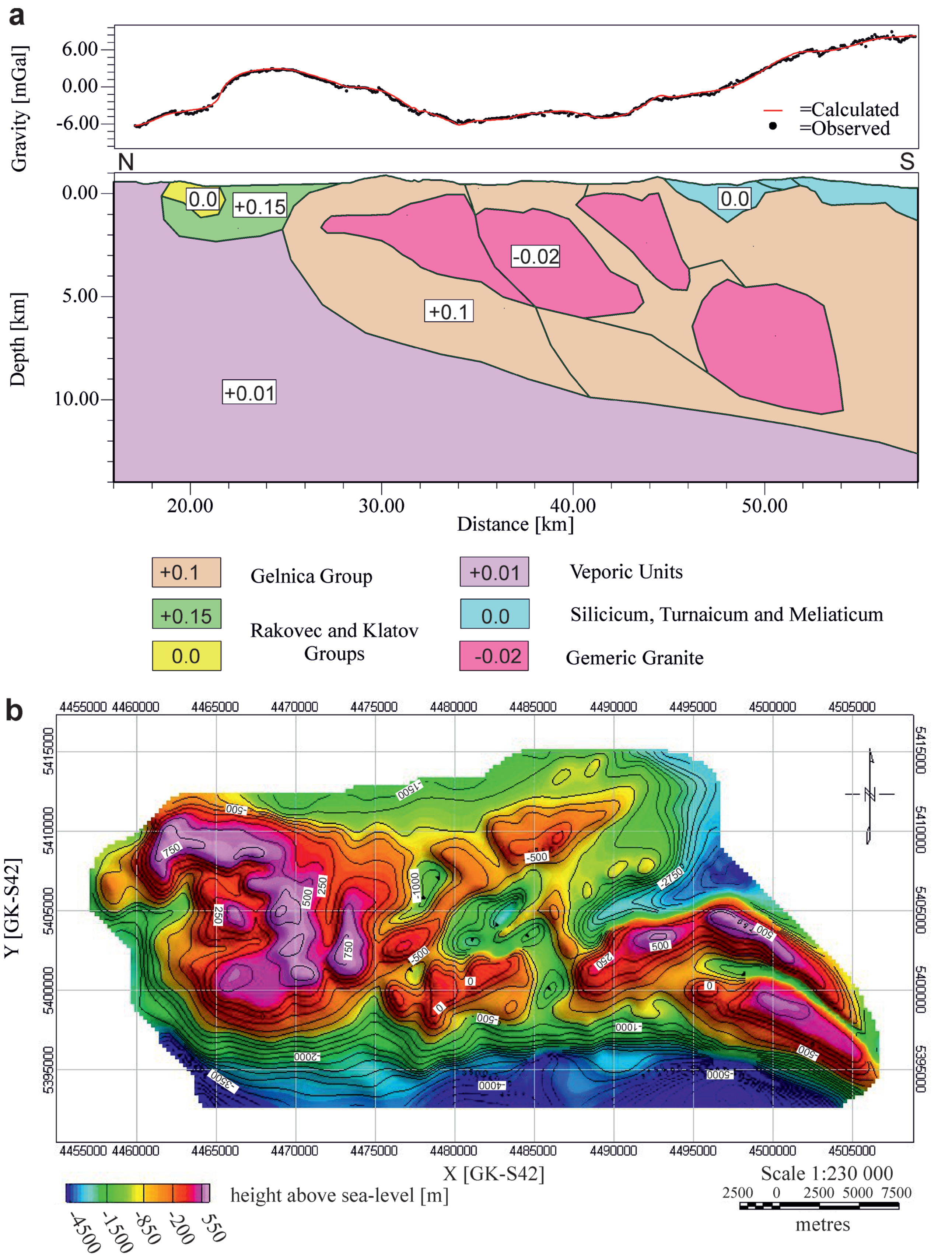

Fig. 3. a — The 2D$^{1/2}$ density model of the Transect G (after Szalaiová et al. 2001). **b** — Scheme of the upper boundary of the Gemeric granite body (after Szalaiová et al. 2001).

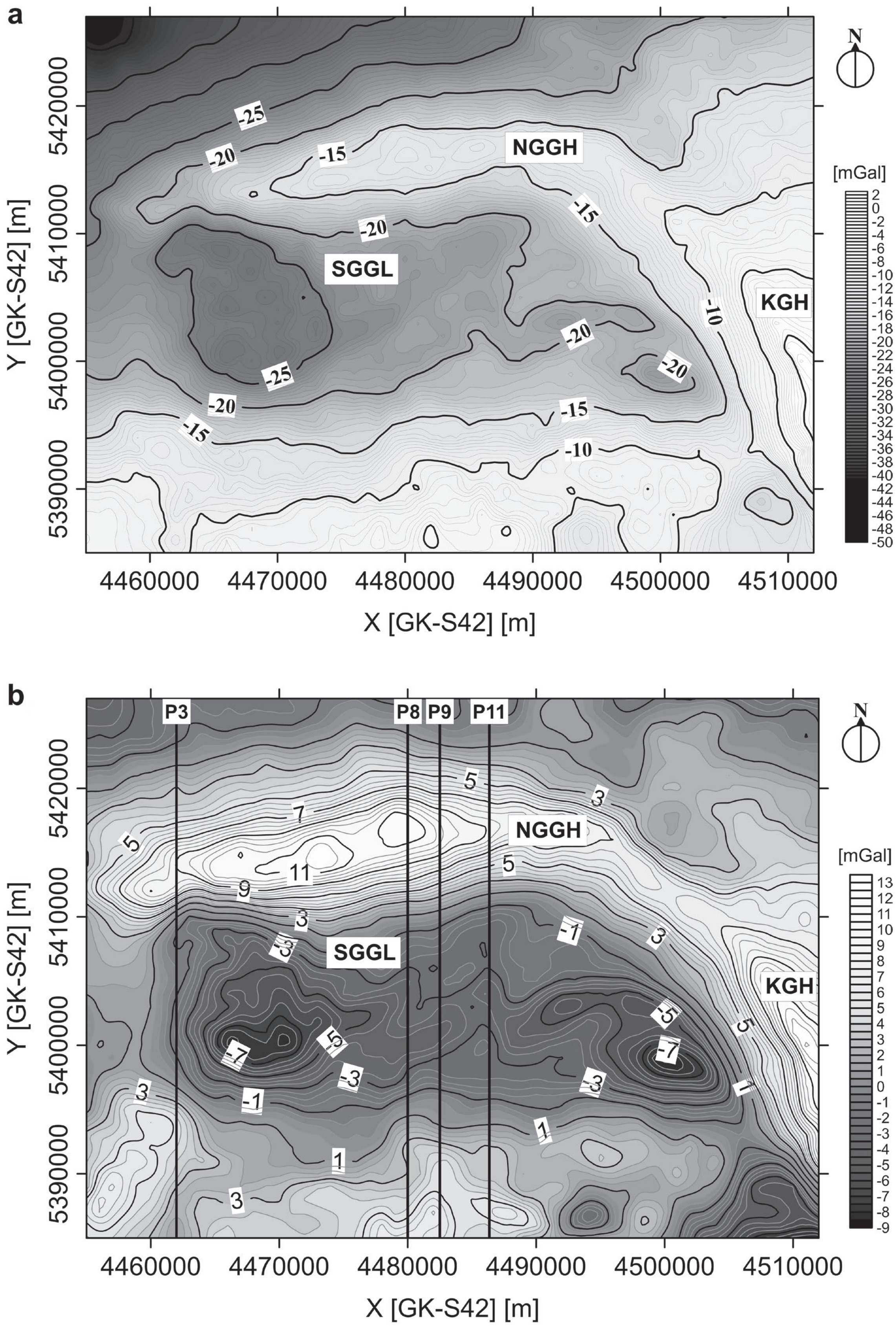

Fig. 4. a — Map of Bouguer gravity anomaly with the reference density 2.67 gcm^{-3} (after Katona 2007). Legend: SGGL – Southern Gemeric gravity low, NGGH – Northern Gemeric gravity high, KGH - Košice gravity high. **b** — Residual gravity map (after Katona 2007). Location of the interpretative profiles shown in Fig. 6.

anomaly and +5 mGal on the residual gravity anomaly), which overlaps with the Slovak Karst.

The character of the gravity anomalies is also accompanied by linear gravity features representing a zone of maximum gravity gradients, which indicate the presence of vertical (inclined) density boundaries located at different depth levels. The zones of maximum gravity gradients have four predominant orientations: N–S, W–E, NW–SE, NE–SW.

Density of the rocks

It is well-known that the quality of the gravity field interpretation also depends on the quality of our knowledge about the density of rocks. The densities applied in our interpretation were obtained by means of analysis of rock samples coming from surface outcrops, mining and drilling works (e.g., Plančár et al. 1977; Husák & Muška 1984; Mikuška & Marušiak 1999; Szalaiová et al. 2001 and references therein). In the 3D model, the following geological units and their average densities were defined:

- Neogene sediments (2.40 gcm^{-3})
- Inner Carpathian Palaeogene (2.61 gcm^{-3})
- Silicicum, Turnaicum and Meliaticum (2.73 gcm^{-3})
- Southern Gemeric Units
  - Golčatov Group (2.68 gcm^{-3})
  - Gelnica Group (2.77 gcm^{-3})
  - Gemeric granite (2.65 g.cm^{-3})
- Northern Gemeric Units
  - Rakovec and Klatov Groups (2.82 g.cm^{-3})
  - Dobšina and Krompachy Groups (2.73 g.cm^{-3})
- Veporic Units (2.68 g.cm^{-3})

Results

The input model of the granites was based on the interpretation of the seismic reflection Transect G (Vozár & Šantavý 1999). The value of this profile is that in the north-south direction it runs perpendicularly across all geological units, which allowed us to define the positions and geometries of the geological units forming the Gemeric Superunit. Within this context, the granite body was modelled. The seismic results allowed us to define also the lower boundary of the granite body, which decreases in depth from north to south. The basic input shapes of the individual bodies and their physical characteristics were taken from the interpretation of gravity field along this profile (Szalaiová et al. 2001). There is no doubt that it is very likely that the granite body consists of several smaller bodies located in different positions. But for effective modelling it is necessary to approximate realistic geological units in a simplified model. The modelled area and boundaries of the geological units on the relief, we obtained by digitalization of the geological map of the Gemeric Superunit with the scale 1:500,000 (Biely et al. 1996a, b).

The initial model in the vicinity of the reference Transect G was created by increasing of the number of parallel profiles on both sides of this transect (its approximated course is identical to the profile with co-ordinates X=4490000) in order to create a resultant model in the 3D space. It can be assumed that in more distant parts from this reference seismic transect the approximation accuracy of the geological structure is going down (the absence of constraints). Finally, 21 north–south profiles were defined (twelve profiles on the left and eight on the right of the reference Transect G). Along each of them the model (the shape of the inhomogeneities) was adjusted by the method of trial and error until a good fit between the calculated effect and the residual gravity anomaly map was obtained.

The results of the 3D density modelling in IGMAS yield a model showing the simplified geological structure of the studied region (Fig. 5) with the main emphasis on the interpreted granite body. The resultant model shows clearly the tectonic position of the granite body in relation to adjacent geological units. Figure 6 shows the geometry and location of the anomalous granite body along the selected four 2D cross-sections (3, 8, 9, 11). We present a better and clearer 3D view of the tectonic position of the Gemeric granites in relation to the Veporic unit basement in Figure 7a.

The Gemeric granites form the most significant low-density anomalous body in the structure of the Gemeric Superunit. Its average thickness varies in the range 5–8 km, with the lower boundary sloping downwards from north to south. In the north, the lower boundary of the Gemeric granites is located at depths of only about 5–7 km, while in the south it is 9–10 km. The upper boundary of the Gemeric granites is much more rugged. There are areas where the granite body is very close to the surface (these places correlate very well with known surface outcrops of the granites, e.g., Hnilec, Betliar, Zlatá Idka) and places where the depth of its upper boundary is deeper (on average 1 km in the north and 4–5 km in the south). A horizontal slice through the density model at 1.0 km depth (Fig. 7b) indicates that the Gemeric granites cannot be represented by a unified body. It can be divided into smaller blocks, each differently offset (Grzywacz & Margul 1980).

The northern boundary of the Gemeric granites along the tectonic contact with the Rakovec and Klátov Groups was interpreted as very steep (in some places up to subvertical). The importance of the presented 3D model goes beyond the scope of the individual Gemeric granite bodies, since it expresses the overall structure of the Gemeric Superunit, its internal structure and its relationship to the underlying Veporic unit. The model also shows that the Silicicum-Turnaicum and Meliaticum nappe units are overthrusted onto the Golčatovo Group. The whole 3D model clearly indicates that not only the Gemeric granite body but also the whole structure of the Gemeric Superunit represents an Alpine north-vergent nappe structure.

Discussion

For the purpose of the transformation of the Bouguer gravity anomalies to the residual and regional gravity anomalies we applied the classical method of approximating regional

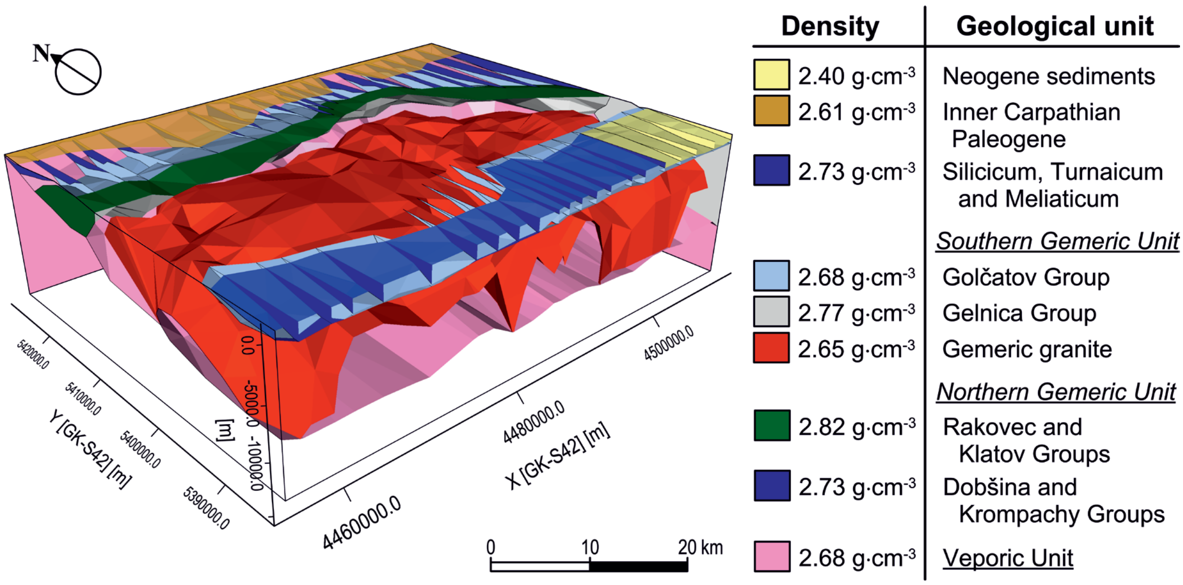

Fig. 5. The resultant 3D density model of the Gemeric granites showing their tectonic position in relation to the surrounding tectonic units.

field by using the mathematically defined polynomial function of the third degree and digital filtering. This approach is supported by the fact that the Gemeric Superunit area is very small. The courses of the Moho and lithosphere-asthenosphere boundary are very smooth and do not change. From this point of view it can be suggested that their regional gravity effects will not influence the results of the interpretation of the Gemeric granites.

In recent years, new data on the deep physical boundaries, such as the boundary between the upper and lower crust, Moho discontinuity and lithosphere–asthenosphere boundary have been obtained (e.g., Zeyen et al. 2002; Dérerová et al. 2006; Grad et al. 2006, 2009; Środa et al. 2006; Alasonati Tašarová et al. 2008, 2009, 2016; Hrubcová et al. 2008; Csicsay 2010; Janik et al. 2011; Grinč et al. 2013). Therefore, if the density modelling of the studied area on a regional scale will be done in the future, then it will be necessary to take into account the above mentioned lithosphere discontinuities, since it can be expected that their influences on the observed gravity field will play an important role.

The post-orogenic Permian Gemeric granites are specialized (tin-bearing), SS-type granites that are interpreted as products of partial melting of a sedimentary protolith due to magmatic underplating during the post-Variscan orogenic collapse and crustal stretching (e.g. Broska & Uher 2001). Despite voluminous Variscan granite magmatism in the Western Carpathian basement complexes, this type of granite is spatially restricted to the Gemeric Unit. On the surface, the Gemeric granites only occur as comparatively small bodies with narrow contact aureoles (see geological map in scale1:50 000, Bajaník et al. 1984a). A question may arise whether or not these are only apophyses of a large subsurface plutonic body as it could be indicated from the resultant 3D density model. Here, it necessary to emphasize that the geophysical modelling in 3D space is very difficult and the 3D model represents a major simplification. Therefore, it may seem that the interpreted model of the Gemeric granites generates a unified massive body at a depth. On the other hand, this does not exclude the assumption that the granites may consist of smaller single bodies. Moreover, the Gemeric granites have the shape of relatively thinner intrusions and apophyses and they are well defined to its surrounding. In a seismic image they are not reflective (Novotný & Dvořáková 1993; Vozár & Šantavý 1999; Vozárová 1996). The Veporic granites in contrast to the Gemeric ones form the large masses of granite bodies (more metamorphosed) with large thickness and are highly reflective (Tomek et al. 1987, 1989).

An alternative model was presented by Lexa et al. (2003), in which the low-density body underlying the Gemeric Palaeozoic metasedimentary formations might represent a pre-Variscan (possibly Cadomian) crystalline basement sheet that originated from the foreland lower plate of the ancient Variscan orogen. This interpretation takes into account the general southern tectonic polarity of the Variscan orogen in the Western Carpathians (Plašienka 1991; Putiš 1992; Vozárová 1996; Plašienka et al. 1997; Bezák et al. 1997; Vozárová et al. 1998; Putiš et al. 2009) with the Gemeric complexes forming the frontal fold-and-thrust belt overriding a Gondwana-derived Cadomian terrane. Later on, during the Alpine orogeny with a distinct opposite — northern vergency, the Gemeric thrust sheet might have incorporated a part of this basement, which is likely composed of felsic rocks like granitoids and migmatites.

Conclusion

For the first time, a new 3D density model of the Gemeric granites in the Gemeric Superunit was created by using the interactive geophysical program IGMAS.

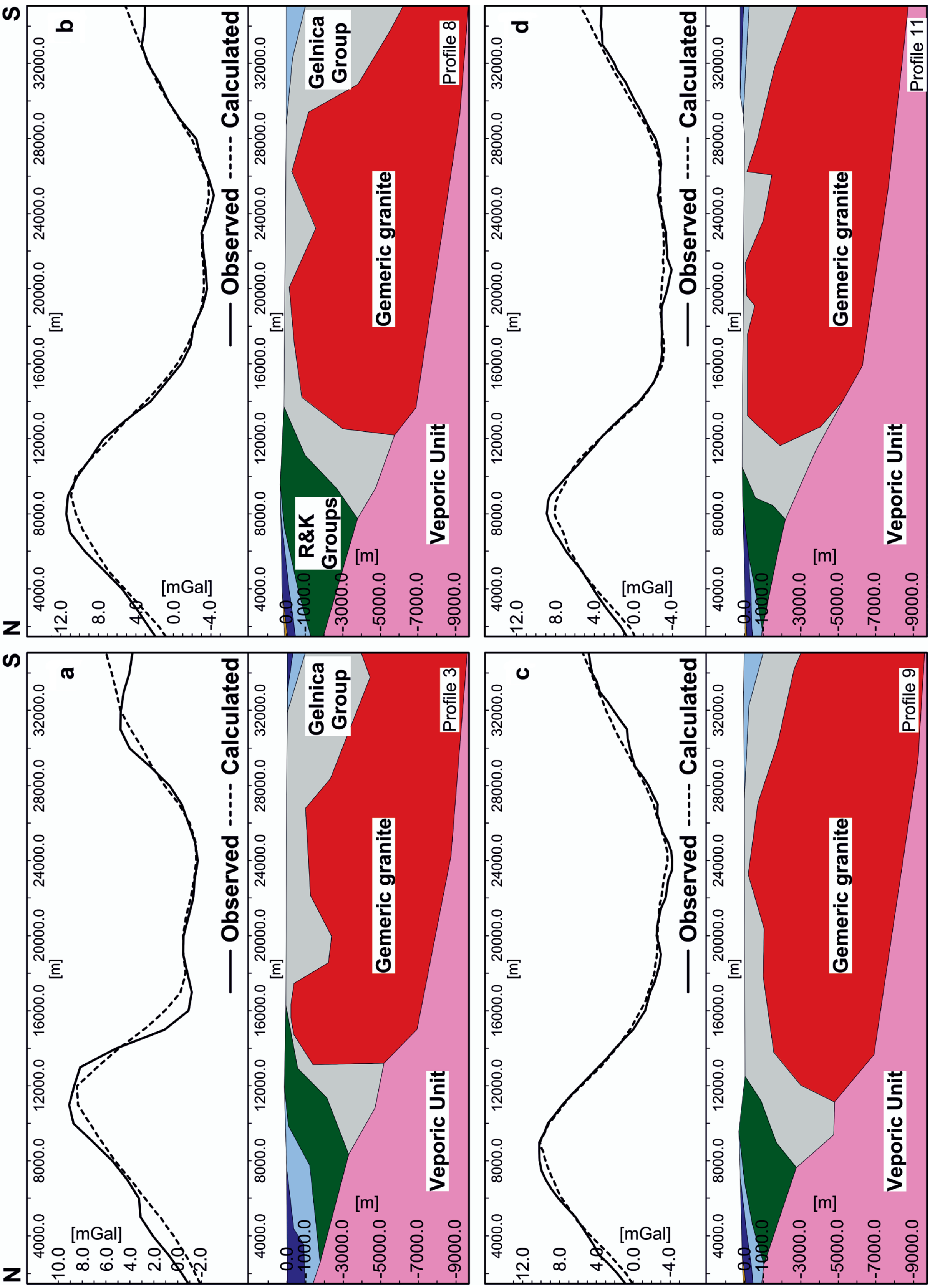

Fig. 6. The geometry and position of the Gemeric granites along the selected four 2D cross-sections: **a** — profile 3; **b** — profile 8; **c** — profile 9; **d** — profile 11.

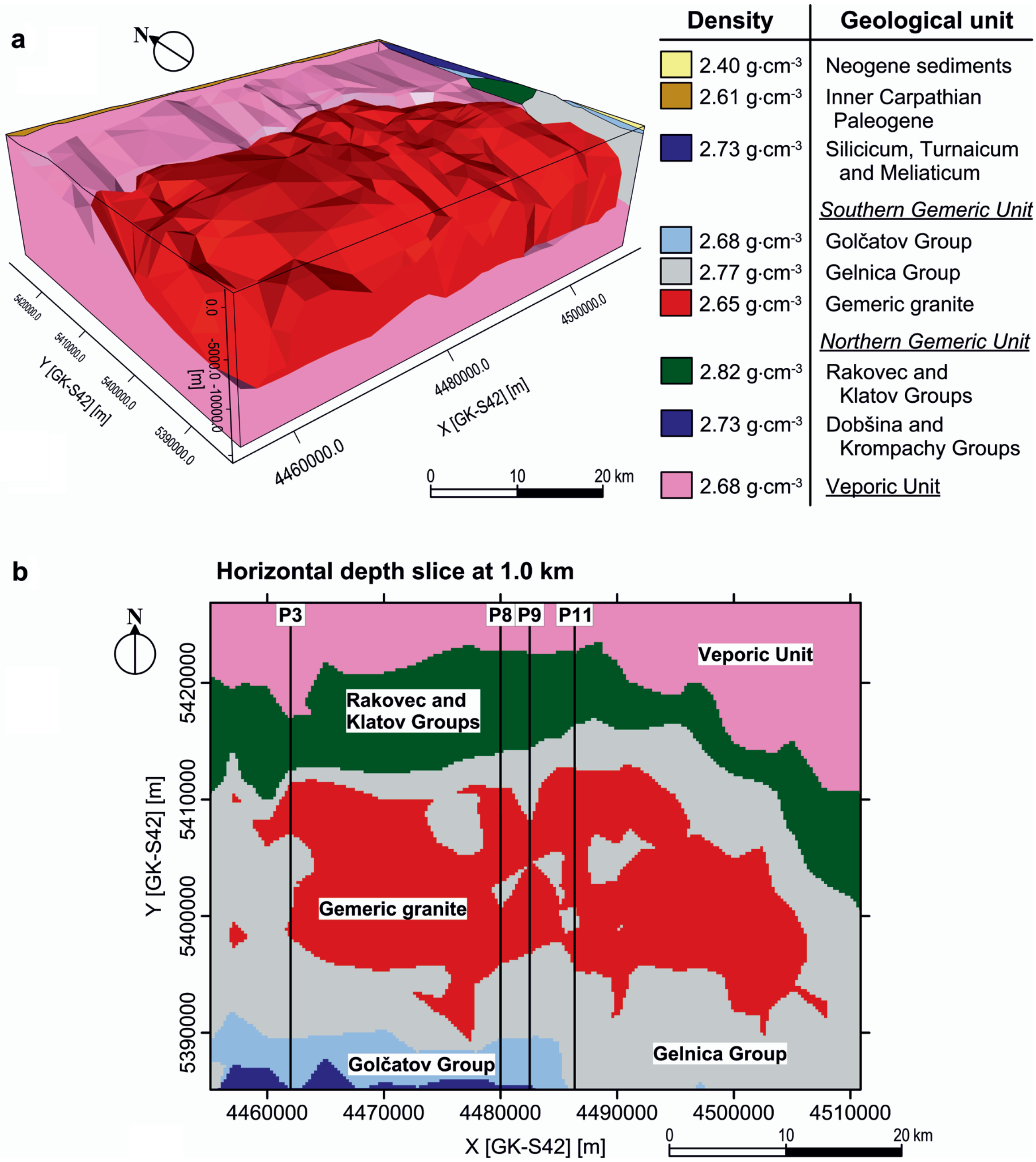

Fig. 7. a — Simplified view of the resultant 3D density model showing the tectonic position of the Gemeric granites to the Veporic unit basement. **b** — A horizontal slice through the 3D density model at 1.0 km depth.

The main results that were obtained are summarized as follows:

- The Gemeric granites represent the most significant upper crustal anomalous low-density body in the Gemeric Superunit.
- Its average thickness varies in the range 5-8 km.
- The upper boundary of the Gemeric granites is much more rugged in comparison with the lower boundary.
- The Gemeric granite body has an Alpine north-vergent nappe structure, with its upper and lower boundaries sloping downwards from north to south.
- The tectonic contact between the Gemeric granites and the Northern Gemeric Units is very steep.

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