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Geophysical and geological interpretation of the Vienna Basin pre-Neogene basement (Slovak part of the Vienna Basin)

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Abstract: The Vienna Basin is situated at the contact of the Bohemian Massif, Western Carpathians, and Eastern Alps. Deep borehole data and an existing magnetotelluric profile were used in density modelling of the pre-Neogene basement in the Slovak part of the Vienna Basin. Density modelling was carried out along a profile oriented in a NW–SE direction, across the expected contacts of the main geological structures. From bottom to top, four structural floors have been defined. Bohemian Massif crystalline basement with the autochthonous Mesozoic sedimentary cover sequence. The accretionary sedimentary wedge of the Flysch Belt above the Bohemian Massif rocks sequences. The Mesozoic sediments considered to be part of the Carpathian Klippen Belt together with Mesozoic cover nappes of Alpine and Carpathian provenance are thrust over the Flysch Belt creating the third structural floor. The Neogene sediments form the highest structural floor overlying tectonic contacts of the Flysch sediments and Klippen Belt as well as the Klippen Belt and the Alpine/Carpathians nappe structures.

Key words: Applied geophysics, gravimetry, magnetotelluric, tectonics, Western Carpathians.

Introduction

The Vienna Basin represents a Neogene structure superimposed on the rock sequences of the Bohemian Massif, Eastern Alps, External and Internal Western Carpathians (Fig. 1; e.g. Arzmüller et al. 2006). The paper presents the results of geological and tectonic interpretation of gravimetric and magnetotelluric data from the Slovak part of the Vienna Basin and provides discussion regarding tectonic affiliation of different Mesozoic complexes.

The Vienna Basin represents one of the areas where the first gravimetric measurements were performed. These measurements have been carried out by the Eötvös torsion balance in the Gbely (Egbell) oil field back in 1915–1916 (Pekár 1928; de Böckh 1934). The result of these measurements was a Torsion-balance map (horizontal gravity map) of the Gbely high. Since then, the Vienna Basin has been in the centre of interest of both geologists and geophysicists.

The Vienna Basin is considered one of the most explored basins. Among the numerous geophysical works, we mention only those, which we have drawn the most information (e.g., Tomek & Budík 1981; Šefara et al. 1987; Speváková 2011 and references herein). The results of Speváková (2011) provided important data on the densities of the Tertiary Basin rocks on the basis of seismic logging data (Novák 1997). These data were first converted into velocities and using a shifted Cornwell polynomial of the fourth degree were transformed to densities.

The geological/geophysical model was constructed along the profile oriented in a NW–SE direction passing the tectonic mega units, in order to clarify their mutual configuration. The profile crosses the boreholes Cunín-10 (Cu-10), Gbely-105 (G-105), Smolinské-26 (Sm-26), Šaštín-9 (Š-9), Šaštín-12 (Š-12), and Lakšárska Nová Ves-7 (LNV-7) within the Vienna Basin, passes through the Malé Karpaty Mts. and borehole Vištuk-2 (V-2) situated in the Danube Basin (Fig. 2). Data from boreholes were published by Němec & Kocák (1976); Biela (1978); Kysela & Kullmanová (1988) and Jiříček (1988) (Fig. 3). The depth of the pre-Neogene basement is displayed on maps (Němec & Kocák 1976; Fusán et al. 1987; Jiříček 1988; Kilényi & Šefara 1989; Wessely 1990, 1992).

The aim of the contribution is to bring new insight on the pre-Neogene basement of the Vienna Basin inferred from the interpretation of geological, gravimetric and magnetotelluric data. Particular attention has been paid to the long-discussed issue of the Alpine or Carpathian tectonic affiliation of the Mesozoic cover nappes in the pre-Neogene basement of the Slovak part of the Vienna Basin (Němec & Kocák 1976;

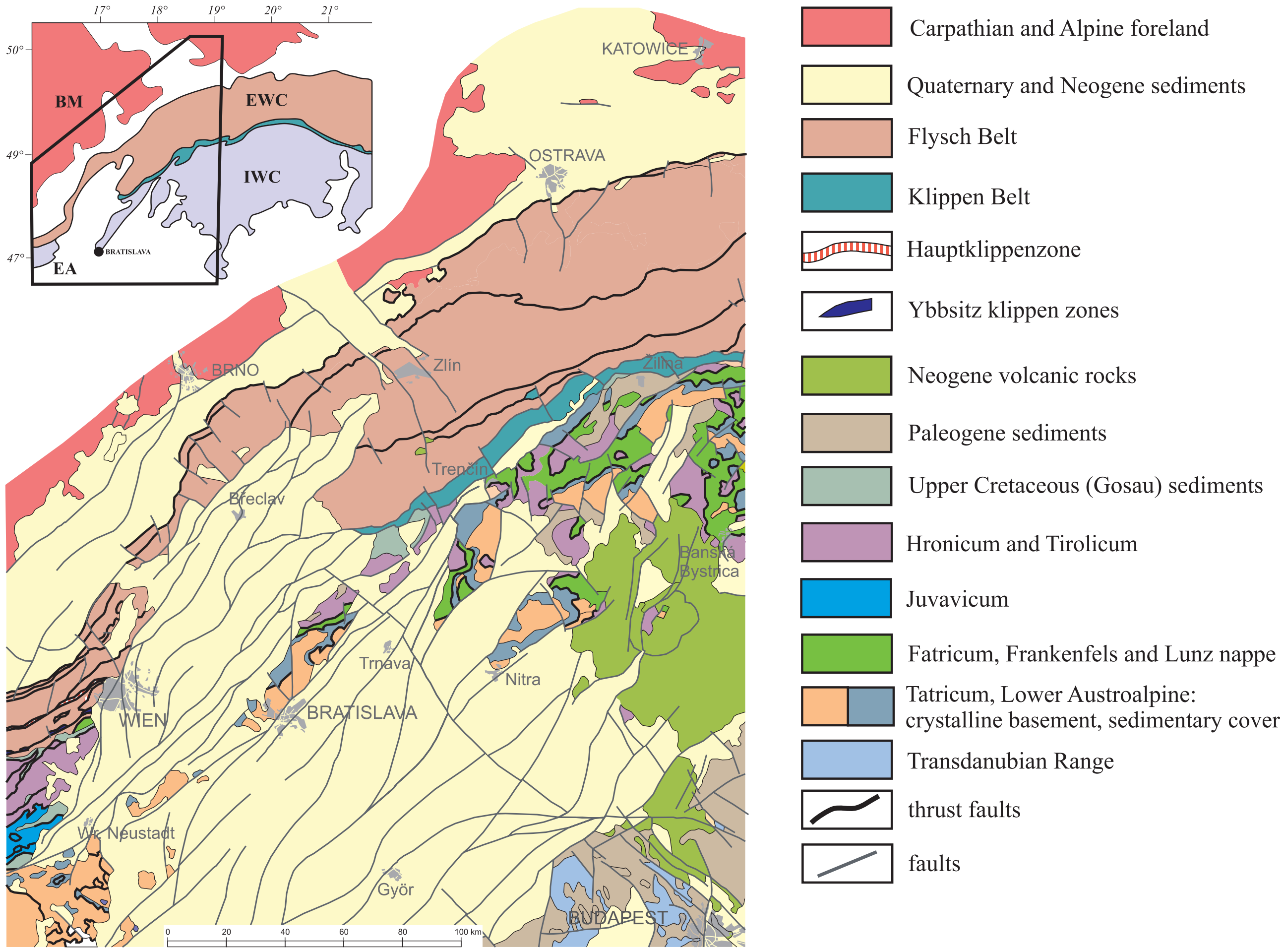

Fig. 1. Simplified tectonic map of the Western Carpathians and adjacent areas (modified after Lexa et al. 2000). BM — Bohemian Massif; EA — Eastern Alps; EWC — External Western Carpathians; IWC — Internal Western Carpathians.

Fusán et al. 1987; Jiříček 1988; Kysela & Kullmanová 1988; Wessely 1992; Wessely et al. 1993).

Geological background

The geological structure of the investigated area (Fig. 1) includes from NW to SE the accretionary prism (Flysch Belt) of the External Western Carpathians thrust onto the Bohemian Massif during the Miocene. The Flysch Belt consists mainly of Upper Cretaceous to Paleogene sediments separated into numerous rootless thrust sheets of the Magura and Krosno (Waschberg–Ždánice–Pouzdřany Unit) nappe systems (Biely et al. 1996). The Bohemian Massif rock complexes are represented mainly by crystalline rocks (Picha et al. 2006). Sediments of the autochthonous Mesozoic cover of the Bohemian Massif crystalline basement were drilled by several deep wells in the area of the Vienna Basin and its marginal parts. Due to the location of the area in question, the nearest deep borehole in the Austrian part of the Vienna Basin is Zistersdorf Üt 2A (Wessely 1988; Eliáš & Wessely 1990). In the southern part of the south-eastern slopes of the Bohemian Massif (NW marginal part of the Vienna Basin) the boreholes Sedlec-1, Bulhary-1, Kobylí-1 or Nové Mlýny-1,2,3 were drilled (Špička et al. 1977; Adámek 1986, 2005). All these boreholes have proved the presence of autochthonous Mesozoic sediments (mainly represented by the Upper Jurassic Mikulov marls) in max. 1500 m layer thickness. The Klippen Belt forms the frontal part of the Internal Western Carpathians composed mainly of Jurassic and Cretaceous sediments which underwent several phases of folding and faulting during the Late Cretaceous to Miocene (Plašienka & Soták 2015; Hók et al. 2016; Plašienka 2018).

The Tatricum, Fatricum and Hronicum tectonic units (Fig. 2) are situated internally (south-eastward) of the Klippen Belt. The Tatricum is a thick-skinned structure and contains the crystalline basement and the Mesozoic cover (autochthonous) sediments with a minor portion of Permian sediments. The Fatricum and Hronicum are cover nappe structures containing mostly Mesozoic sedimentary sequences thrust over the Tatricum. The Hronicum comprises also the late Paleozoic volcano-sedimentary sequence of the Ipoltica Group (Vozárová

& Vozár 1988). Alpine provenance cover nappes are represented by the Bajuvaric, Tirolic and Juvavic nappe systems of the Northern Calcareous Alps (e.g., Janoschek & Matura 1980; Fuchs & Grill 1984; Sauer et al. 1992). The Upper Cretaceous to Paleogene sediments (Gosau Group) overlie the Alpine cover nappes as well as the Hronicum tectonic unit. Besides these, the Paleogene sediments are tectonically incorporated between the Hronic imbricated thrust slices in the Malé Karpaty Mts. (Polák et al. 2011). The Neogene sediments overlie the crystalline, Mesozoic and Paleogene rock sequences with significant angular unconformity.

Borehole data and their interpretations

The most important information was yielded by boreholes (Fig. 3) Lakšárska Nová Ves-7 (LNV-7), Šaštín-12 (Š-12) and Studienka-83 (St-83).

The borehole LNV-7 (Fig. 3) drilled Upper Cretaceous grey, dark grey organodetritic limestone below the Miocene sediments in depth 1564 m. Downwards dolomite (Hauptdolomite), Opponitz limestone and subvertical dipping strata of the Lunz Fm. continue. There is a tectonically disturbed zone below the Lunz Fm., and below this zone up to the final depth (6400 m) the dolomite (?Hauptdolomite) and Opponitz limestone occur, both with abundant intercalations of anhydrite (Němec & Kocák 1976; Biela 1978; Kysela & Kullmanová 1988).

In the borehole Š-12 the pre-Neogene basement occurs at depth 2200 m. From this depth to 4142 m the Upper Triassic (Norian) Hauptdolomite is presented with inclination of bedding between 40° to 80°. Below the Hauptdolomite a limestone/dolomite sequence with abundant anhydrite was drilled (Carnian; most probably the Opponitz Fm.). This sequence is followed by the Lunz Fm., Opponitz limestone and again Lunz Fm., according to graded bedding in overturned position and finally again dolomite (Kysela & Kullmanová 1988).

Borehole St-83 (Studienka-83) is located out of the profile (Fig. 2) south-west of borehole LNV-7. Pre-Neogene basement was reached in the interval 3087–4117 m. From the top to the bottom, the Upper Cretaceous (“Senonian”) carbonate breccia is composed of clasts of the Triassic carbonate with Upper Cretaceous limestone and sandstone also occurring. The clasts indicate a deeper erosion of the nappe or its frontal part with synsedimentary displacements during the Upper Cretaceous (late Cretaceous clasts in the late Cretaceous sediments, Bujnovský et al. 1992). Similar late Cretaceous sediments in the same position were drilled on the frontal part

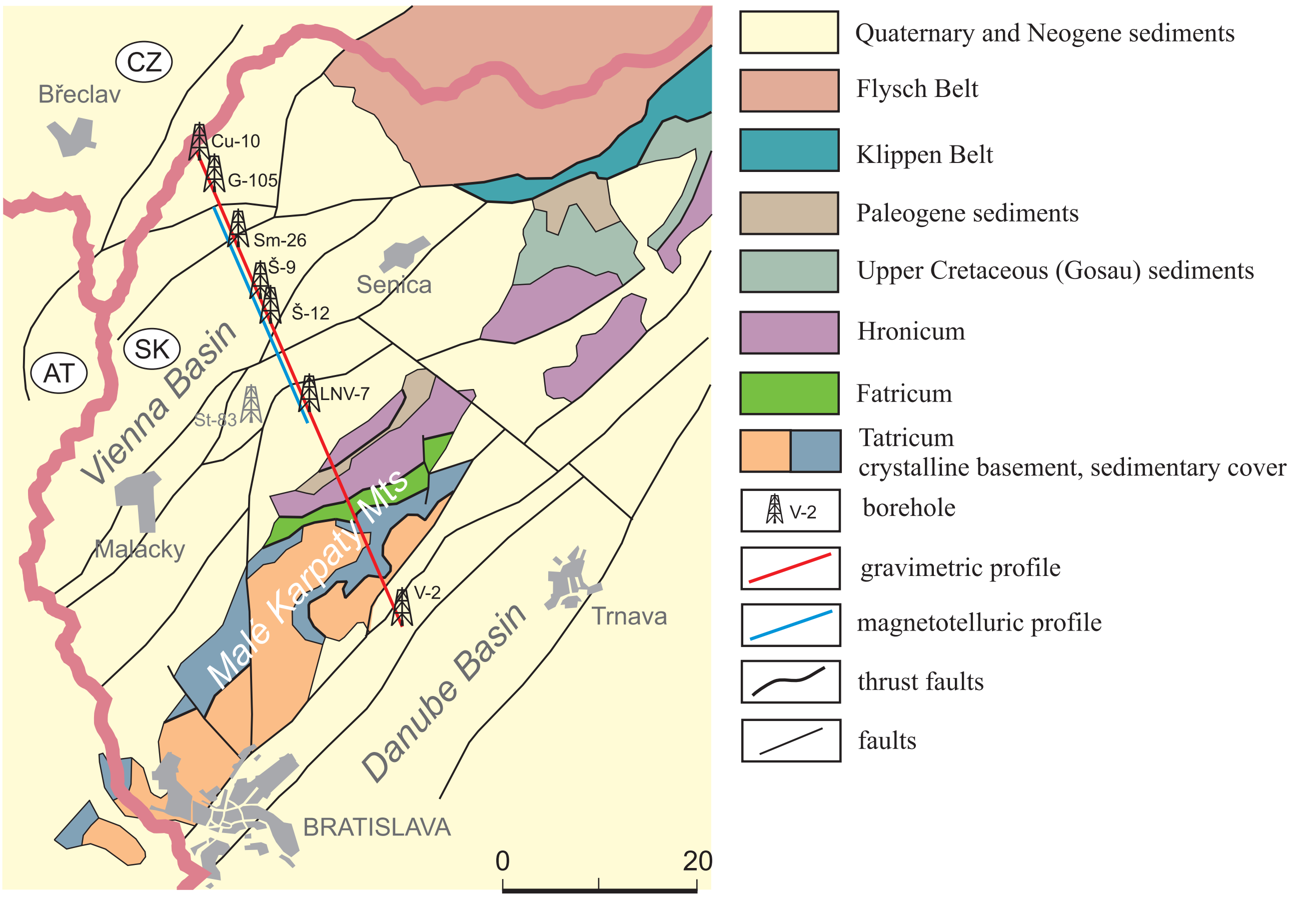

Fig. 2. Simplified tectonic map of the investigated area with position of the gravity and magnetotelluric profiles and boreholes.

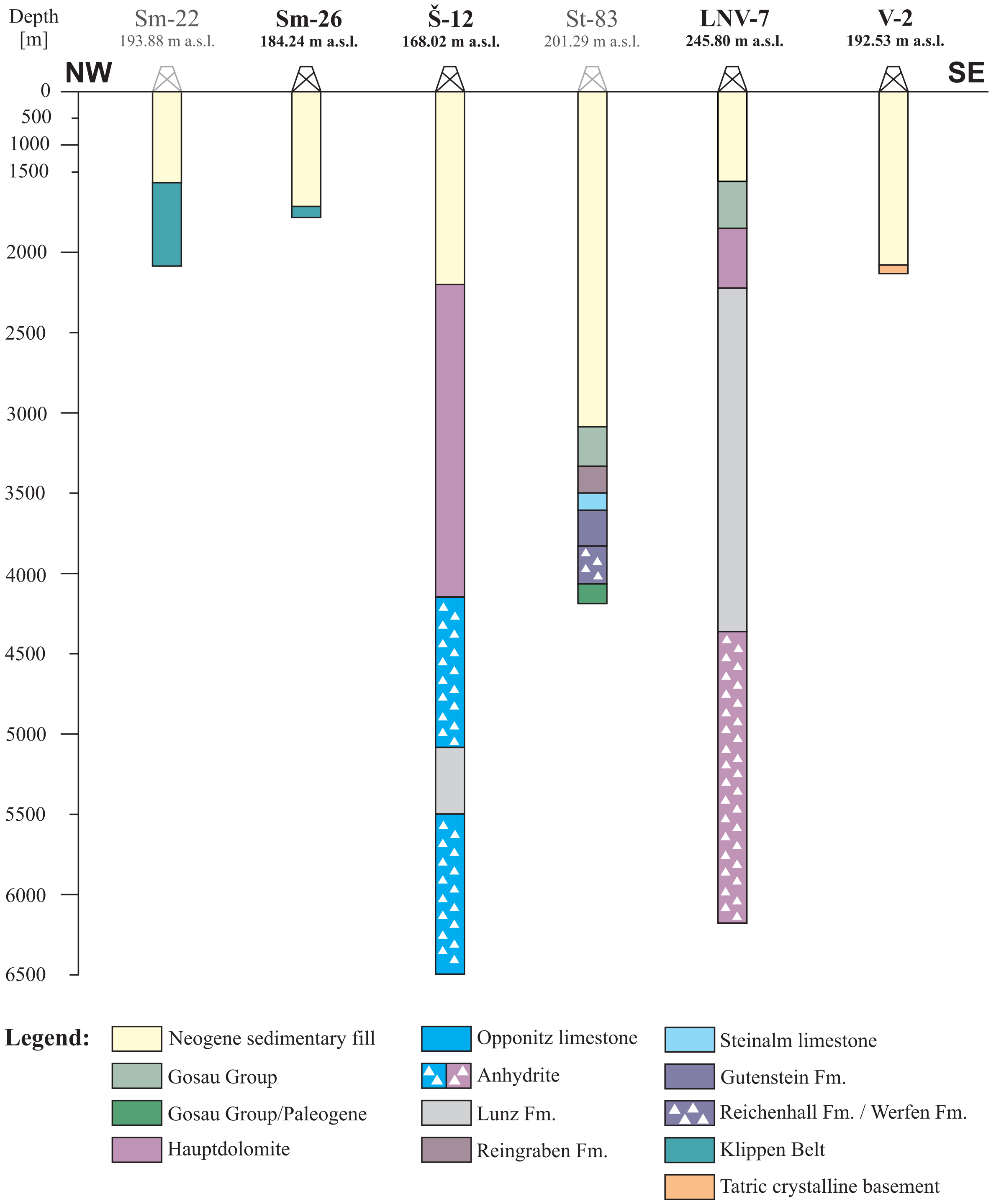

Fig. 3. Boreholes data (adapted from: Němec & Kocák 1976; Biela 1978; Jiříček 1988; Kysela & Kullmanová 1988 and Bujnovský et al. 1992). The off-profile boreholes are grey.

of the Ötscher nappe at Prottes in the Austrian part of the Vienna Basin (cf. Kröll & Wessely 1973; Wessely 1975).

The deeper portion of the sequence below the breccia is represented by the Reingraben shales, Steinalm Limestone, Gutenstein Fm., evaporitic Reichenhall Fm. and finally the Upper Cretaceous to Paleocene dark grey carbonate claystone (Jiříček 1988; Bujnovský et al. 1992). The lithostratigraphic character of the Triassic sediments, especially presence of the Reingraben Fm. and Reichenhall Fm., allows us to correlate them with the Tirolicum nappe system (c.f., borehole Berndorf-1, Wachtel & Wessely 1981).

The Smolinské-26 (Sm-26, Fig. 3) borehole reached below the 1700 m of the Miocene sediments the Cretaceous (mostly Albian–Cenomanian) marlstone, clayey limestone considered to be a part of the Carpathian Klippen Belt (Němec & Kocák 1976; Biela 1978; Jiříček 1988 and Kysela & Kullmanová 1988). Boreholes Gbely-105 (G-105) and Cunín-10 (Cu-10) penetrated the sandy clays, and carbonatic sandstones of the Magura nappe system (Biele Karpaty Unit) below the Neogene sediments.

Geophysical methods

The 2D density model was created in GM-SYS software (GM-SYS User's Guide for version 4.9, 2004). It is an interactive software for calculating the gravity and magnetic field from the geological models. 2D model is composed of closed polygons with representative density. The calculations of the gravitational effects of the geological bodies are based on the formulae of Talwani et al. (1959), with Won & Bevis's algorithm (GM-SYS User's Guide 4.9, 2004).

For elimination of the edge-effect, the GM-SYS software allows us to extend the profile up to the distance of ±30,000 km. The input model was based on the boreholes (Table 1) and surface geological data. The densities used in final models are shown in Fig. 4. The final model was modified by the trial and error method until a reasonable fit was obtained between the measured and calculated gravity data. In this study, the maximum deviation between gravitational effect and observed gravity reaches only ±0.85 mGal.

The magnetotelluric method (Szalaiová et al. 2011) is a passive electromagnetic technique for which the electric and magnetic fields are measured in orthogonal directions on the earth's surface. The field sources are: equivalent current systems in the ionosphere (frequency range — below 1 Hz) and lightning discharges in the earth-ionosphere cavity in the equatorial zone (Audio-frequency Magnetotelluric frequency range from 1 Hz to 10 kHz). The periodicity of the source as well as the resistivity distribution of the subsurface has influence on the depth of information retrieval. The depth of investigation is from a few tens of metres to hundreds of kilometres.

In 2D space the equations for resolving apparent resistivity and phase decouple into two different models of propagation (Szalaiová et al. 2011). In one mode, electric currents are flowing parallel to the strike of structures, and are termed the transverse–electric mode. The other mode describes currents crossing the structure and is called the transverse magnetic mode. For 2D models one can invert two pairs of apparent resistivity and phase curves. When the complexity of the Earth is fully taken into account, 3D special modelling inversion algorithms should be used. At present this approach is time consuming and does not give satisfactory results. In some cases restricted 2D interpretation of 3D data may be valid.

Table 1: Boreholes maximum depth and coordinates.

Name	Locality	TD [m]	Latitude	Longitude	Z [m a.s.l.]
Cu-10	Cunin	950	48°45'44.219'' N	17°3'35.836'' E	158.53
Gb-105	Gbely	1300	48°43'14.424'' N	17°4'59.832'' E	168.80
Sm-22	Smolinské	2100	48°40'51.401'' N	17°7'29.972'' E	198.88
Sm-26	Smolinské	6405	48°40'26.178'' N	17°7'30.387'' E	184.24
Š-9	Šaštín	2200	48°38'58.376'' N	17°8'37.326'' E	178.91
Š-12	Šaštín	6505	48°38'44.909'' N	17°8'47.136'' E	168.02
LNV-7	Lakšárska Nová Ves	6405	48°33'55.698'' N	17°11'39.21'' E	245.80
St-83	Studienka	4186	48°31'31.372'' N	17°5'54.717'' E	201.29
V-2	Vištuk	2335	48°18'53.478'' N	17°22'19.054'' E	192.53

Gravity data

The gravity data were obtained from the Bouguer anomaly map with the grid of 200×200 m (Pašteka et al. 2014, 2017). The topography data were taken from the Topographic Institute (2012). The 2D quantitative interpretation depends on geometry of the modelled polygons that approximate geological bodies and the knowledge of the rock densities.

The surface and subsurface structures of the individual tectonic units was constrained using the geological map, structural data and deep boreholes (lithology, tectonic affiliation and sediment thickness).

The Moho depth (crustal thickness) along the profile is consistent with the Moho depth imaged in the papers of Alasonati Tašárová et al. (2016) and Bielik et al. (2018). The Moho depth varies between 32 km (Vienna Basin) to 29.7 km (Danube Basin).

The lithosphere–asthenosphere boundary (lithospheric thickness) has been taken from Dérerová et al. (2006) and Alasonati Tašárová et al. (2016). The lithosphere–asthenosphere boundary in the study area is more or less horizontal and has a depth of about 105 km.

The sediment densities were constrained using data summarized in the paper of Šamajová & Hók (2018). The natural densities of the tectonic units which form the upper part of the upper crust (Fig. 4) were taken from the map of the tectonic units of the Western Carpathians (Šamajová & Hók 2018). Input average densities of the lower part of the upper crust, lower crust, mantle lithosphere and asthenosphere were determined by analysis of the results of Lillie et al. (1994); Bielik (1995, 1998); Hrubcová et al. (2005, 2010); Alasonati Tašárová et al. (2008, 2009, 2016); Šimonová & Bielik (2016) and Šimonová et al. (2019).

To present final model of the deep and subsurface structures in relevant resolution, the lithosphere–asthenosphere boundary and Moho discontinuity are not shown in the final model. However, their gravitational effects were calculated.

Magnetotelluric data

The magnetotelluric profile (Fig. 2) was located near Šaštín-Stráže, crossing the deep boreholes (Sm-26, Š-12, LNV-7; Table 1) and it was ended by the high-density housing (Lakšáre elevation, Němec & Kocák 1976).

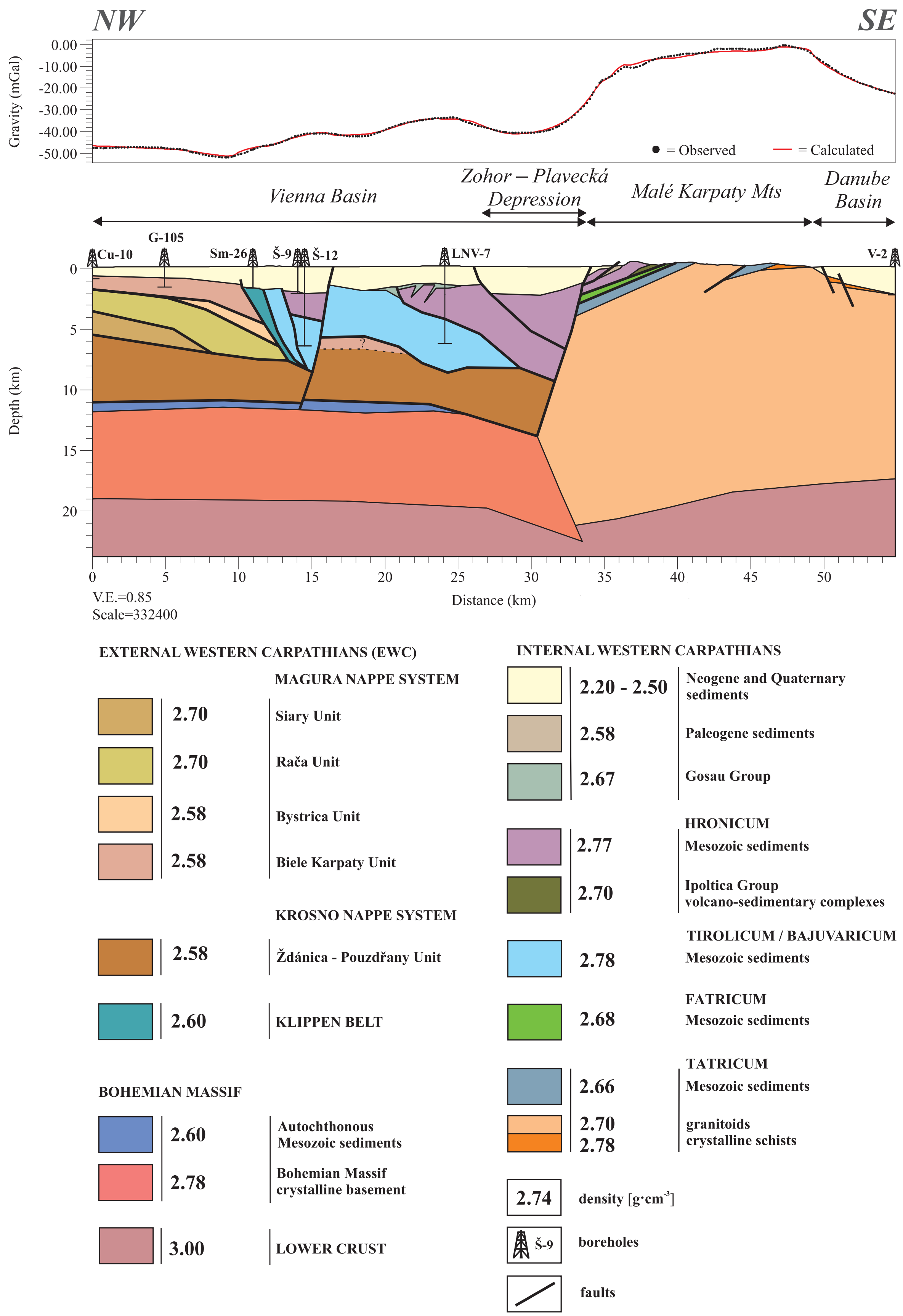

Fig. 4. Geological interpretation of the gravimetric profile.

Data acquisition was made with the use of system 2000.net manufactured by Phoenix Geophysics, Canada. Recording of the electromagnetic field components was carried out in the frequency range 0.0005–10,000 Hz. Electric dipoles E_x were oriented at azimuth 0°. Electric dipoles E_y were perpendicular to E_x. For recording magnetic field components two horizontal and one vertical magnetic coils were used. To eliminate or reduce the effects of artificial electromagnetic noise, magnetic remote reference point was applied and reference processing was made. A remote reference station was located in Poland (Chyrowa remote site), close to Dukla town. Results of the geophysical and geological interpretation with description were made by PBG Ltd. Krakow Branch for NAFTA a.s.

Based on analysis of the distribution of the skew of the impedance tensor (Szalaiová et al. 2011) it was found that for the whole frequency band, the survey area is characterized by the geological structure equivalent to the 1D or 2D geoelectrical model (skew values for the whole area are less than 0.3). Only in the case of the MT site (S1_57), the 1D or 2D hypothesis was not perfectly valid and for the whole range of frequency. As it is the last point of the profile, the measurement does not have much impact on the quality of magnetotelluric interpretation. Higher values of Skew (for noise free data) indicate 3D effect, which was also confirmed by looking at polar diagrams. Therefore, an analysis of polar diagrams was also done to produce more precise information about the dimensionality. The analysis of polar diagrams indicated that the geoelectric environments are almost 1D for frequencies from 10 kHz to about 0.1 kHz. For lower frequencies, a 2D model should generally be taken into account. Tipper values vary between 0.05 and 0.4 remaining within an acceptable range for main range frequency. It is well known that tipper parameter values occurring above 1.0 are incorrect and it is the result of larger noise of the vertical component of the magnetic field, therefore they should not be interpreted in any way. In the presented magnetotelluric measurements higher values for tipper occurred mainly in the interval 1.0–0.1 Hz. It means that the measured curves obtained by processing are very good quality. From this point of view the easiest approach how to show the results in cross-section was the using the Bostick transformation (Szalaiová et al. 2011).

Interpretation of the gravity profile

The resultant lithospheric density model along the interpretative profile is shown in Fig. 4. It is important to note, that the density model was calculated up to the lithosphere–asthenosphere boundary, since our goal is to interpret the structure of the pre-Neogene basement. Since the gravity effects of the Moho discontinuity, and the lithosphere-asthenosphere boundary are almost constant the resultant model displays density inhomogeneities only up to a depth of ~25 km.

The calculated gravity of the resultant model consists of several local anomalies. The Vienna Basin is represented by a gravity low (values vary between −52 mGal and −15 mGal), which is due to the superposition of the gravity effects of the Neogene and Paleogene sediments with low densities. This interpretation is also supported by the field of the stripped gravity map (Tomek & Budík 1981). The Vienna Basin gravity low, which is a part of the westernmost Western Carpathian low (Tomek et al. 1979) is divided by the system of faults into the partial depressions. The faults in the Vienna Basin are interpreted according to Němec & Kocák (1976); Jiříček (1988); Kysela & Kullmanová (1988); Wessely et al. (1993).

The density model suggests that the Magura and Krosno nappe systems, mostly formed by the Upper Cretaceous and Paleogene sediments, are overthrust onto the Bohemian Massif. They emerge on the surface from beneath the Neogene sediments NE of the Vienna Basin. Both nappe systems are formed by "flysch" character deposits in which sandstone and claystone (marl) layers alternate. The density characteristic is different depending on the prevailing grain size. The Krosno nappe system, represented by the Waschberg–Ždánice–Pouzdřany Unit, is mostly composed of fine-grained sediments (clays, marls, marlstones), while the Magura nappe system contains primarily sandstones (Siary and Rača units) with fine-grained sediments occurring only to a lesser extent (Biele Karpaty and Bystrica units). The total thickness of the Flysch Belt wedge sediments in the Vienna Basin reaches about 9–11 km. The thickness of the Magura nappe system on the contact with the Klippen Belt (7–8 km) was estimated on the basis of the results of Picha et al. (2006).

The Carpathian Klippen Belt is interpreted as a shallow structure thrust together with Mesozoic cover nappes over the Flysch Belt sediments. In gravity field all these tectonic units are characterized by small local gravity anomalies with a maximum amplitude of 5 mGal.

Two local anomalies were observed consisting of one local gravity high and low on the profile section from 16 km to 33 km (Fig. 4). The first one is a result of the larger thickness of the Mesozoic sediments of Alpine and Carpathian provenance (see borehole LNV-7). The second one (gravity low with maximum amplitude of −20 mGal) is due to the Zohor–Plavecká depression. Careful investigation of the borehole/subsurface data and correlation of Mesozoic/Triassic lithostratigraphy of Alpine and Carpathian nappes allows us to propose criteria for their discrimination. The key feature is the presence or absence of anhydrite-rich strata (Opponitz Fm. the Reichenhall Fm., Haselgebirge Fm.). Furthermore, the occurrence of an anhydrite-rich Mesozoic sequence affects the density value. The sediments of the Gosau Group are infolded or overthrust by the Triassic carbonate.

The density model clearly indicates fault contacts of the Malé Karpaty Mts. with the Vienna and Danube basins. The contact between the Vienna Basin and Malé Karpaty Mts. is characterized by a large horizontal gradient of about 5.3 mGal/km, while the contact between the Malé Karpaty and Danube Basin is represented by a smaller one (~3.5 mGal/km). The horst structure of the Malé Karpaty Mts. is represented by a significant gravity high with amplitude of ~20 mGal.

The westernmost part of the Danube Basin is accompanied by a gravity low. The Tatricum crystalline basement below the Neogene sediments was penetrated by in borehole Vištuk-2 (V-2). Therefore, this tectonic unit was modelled by granitoids (2.70 g.cm^{-3}) and crystalline schist (2.78 g.cm^{-3}). The deep contact of the Tatricum tectonic unit outcropping in the Malé Karpaty Mts. is slightly shifted over the Bohemian Massif.

The boundary between the upper and lower crust was modelled at depths of about 17.5 and 19 km. The deep contact between the Flysch Belt nappes and the Bohemian Massif is characterized by a small inclination. It is frequently visible in evolutionary models of continental collision maintained in isostatic equilibrium (e.g., Karner & Watts 1983; Stockmal & Beaumont 1987; Lillie 1991; Lillie et al. 1994).

Interpretation of the magnetotelluric profile

Four floors of different resistivity are interpreted on the magnetotelluric profile. The first two floor are controlled by borehole data. The first of these floors belongs to the Neogene sediments.

The second floor with significantly higher resistivity is represented by the Mesozoic sediments (boreholes Sm-26, Š-9, Š-12, LNV-7). The Magura nappe system of the Flysch Belt with a significant portion of the sandstones occupied the NW part of profile (boreholes Cu-10 and G-105).

The third floor is characterized by low resistivity (0.0–0.2 Ohm.m) and density (2.58–2.60 g.cm^{-3}). These resistivity and density values are representative for the Krosno nappe system sediments as well as the autochthonous Mesozoic sediments of the Bohemian Massif (Figs. 4, 5). However, the position and thickness of this floor better correspond to the lithological character of the Krosno nappe system (e.g., Chlupáč et al. 2002). On the other hand, autochthonous Mesozoic sediments were identified beneath the Flysch belt and Neogene sediments as known from wells (Eliáš & Wessely 1990; Adámek 2005), thus their presence cannot be completely excluded. Therefore, the presence of an autochthonous Mesozoic layer on the top of the Bohemian Massif crystalline basement is assumed in a limited thickness below the Krosno nappe system (Fig. 5).

Based on the former magnetotelluric results published by Jankowski et al. (1985, 2008) in the structures below 6 km it could be also considered the presence of the Carpathian Conductivity Anomaly (CCA). On the closest Profile P-78a to our study area, the CCA was estimated in the depth interval 10–20 km (Jankowski et al. 1985). It is characterized by the same low resistivity values (1–4 Ohm.m) we attributed to the ?Paleozoic rocks in our interpretation. This general well known anomaly and its origin is topic for debate for decades (Hvoždara & Vozár 2004; Jankowski et al. 2008). Its presence could also cover the more resistive structures below.

The deepest high resistivity floor is attributed to the crystalline complexes of the Bohemian Massif (Picha et al. 2006). The interpretation is also supported by the seismic interpretation along the Profile 8HR (Tomek & Hall 1993).

Discussion

Gravimetric and magnetotelluric surveys were done to clarify the geological structure of the Slovak part of the Vienna Basin pre-Neogene basement. The thickness of the Neogene sediments was obtained from borehole data. The Neogene sedimentary fill is represented by a low-resistivity anomaly on the magnetotelluric profile. Similar resistivity values for the sedimentary layers were observed in older magnetotelluric and geomagnetic deep sounding works, along the international Deep Seismic Sounding profile No. VI (Červ et al. 2001). The newest and closest geoelectrical study situated just a few kilometres to the west from our analysed profile (Klanica et al. 2018) and the borehole logs confirms these resistivity values. The course of this anomaly is observable in detail in the gravimetric interpretation. The density ranges from 2.20 to 2.50 g.cm^{-3}, depending on the lithification rate of the Neogene sediments. The applied densities have been compared, in detail, with the densities calculated on the basis of seismic logging data converted to velocities and their subsequent transformation to densities. The densities thus determined directly on the wells Šaštín-9 (Š-9), Šaštín-12 (Š-12), and Lakšárska Nová Ves-7 (LNV-7) are in good accordance with our determined densities (e.g., Eliáš & Uhmann 1968; Stránska et al. 1986; Ibrmajer et al. 1989; Šamajová & Hók 2018).

The pre-Neogene basement is reliably visible on the both geophysical interpretations. The pre-Neogene floor of the Vienna Basin consists of Mesozoic and Paleogene sediments. Based on the magnetotelluric interpretation, it is possible to differentiate the position of the Paleogene (low resistivity) and Mesozoic sequences (high resistivity). The gravimetric interpretations allow variation in the density value of these sequences. Tectonic affiliations of the Mesozoic nappe systems mainly in the south-west (Austrian) part is indisputable. A problematic and long-discussed question is the tectonic classification of the Mesozoic sediments in the north-eastern (Slovak) part of the Vienna Basin. The main problem is the lithofacial similarity of the individual lithostratigraphic members of the Bajuvaricum, Tirolicum and Hronicum tectonic units (c.f., Wessely 1992 and Havrila 2011).

According to Fusán et al. (1987), Kysela & Kullmanová (1988) and partially also Němec & Kocák (1976) the Mesozoic sediments of the Slovak part of the Vienna Basin belong to the Hronicum tectonic unit. Continuation of the Northern Calcareous Alps nappes below the Neogene sediments of the Slovak part of Vienna Basin is reported by Jiříček (1988); Hamilton et al. (1990); Wessely (1992) and Wessely et al. (1993).

The Hronicum tectonically overlies the Fatricum and represents the highest nappe system of the Middle group of nappes of the Internal Western Carpathians (*sensu* Hók et al. 2014). The Triassic lithostratigraphy of the Fatricum and

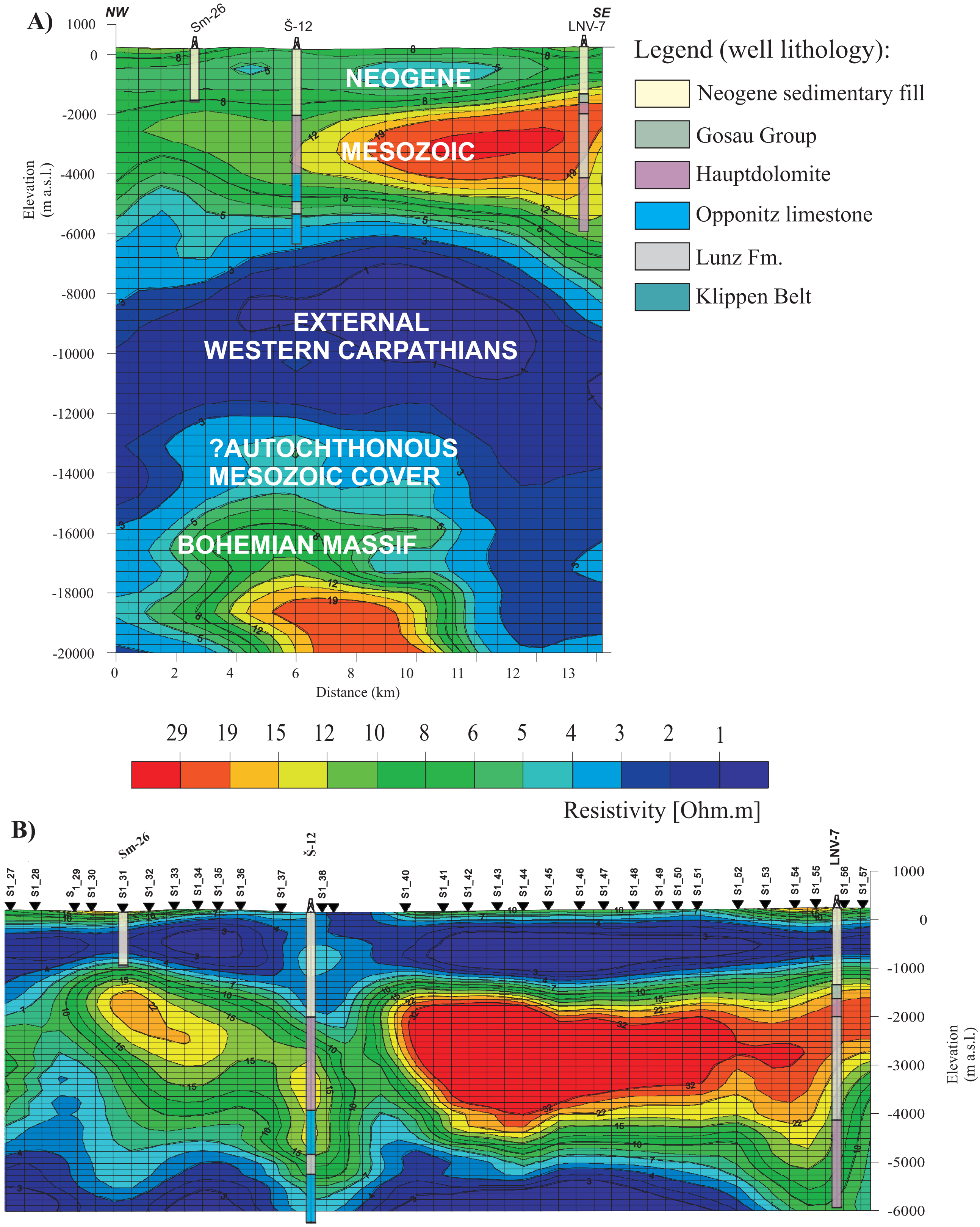

Fig. 5. Magnetotelluric profile between boreholes Lakšárska Nová Ves-7 (LNV-7) and Smolinské-26 (Sm-26). Visualization of the measured data to the depth 20.0 km (**A**), more detailed visualization to the depth 6.0 km (**B**).

Hronicum is considerably different (e.g., Biely et al. 1996). However, the Triassic lithostratigraphy of the Hronicum and the Tirolicum and/or Bajuvaricum is in many aspects similar (Table 1). Correlation of the Bajuvaricum (especially Frankenfels–Lunz nappe system) and Fatricum (Wessely 1992) can be excluded due to different Triassic lithostratigraphy of these tectonic units. The Fatric nappe system does not contain lithostratigraphic members typical for the Bajuvaricum (e.g., Reichenhall Fm., Reifling Fm., Opponitz Fm.). This lithostratigraphy is closer to the Biely Váh and/or Dobrá Voda basinal sequences of the Hronic nappe system in the Internal Western Carpathians (Kováč et al. 2002; Havrila 2011). Moreover, the Carpathian Keuper sequence systematically presented within the Fatricum has only limited occurrences in the Bajuvaric (Frankenfels-Lunz) and/or Hronic nappe systems (e.g., Mandl 2000; Polák et al. 2003; Havrila 2011).

The Tirolic nappes in the pre-Neogene basement of the Vienna Basin were linked to the Malé Karpaty Mts. and correlated with the Veterlín, Havranica and Jablonica nappes of the Hronic nappe system (Jiříček 1988; Hamilton et al. 1990; Wessely 1992; Wessely et al. 1993). The original paleogeographic position of the Tirolicum and western parts of Hronicum was probably in proximity as seen from the lithofacial similarity of Triassic lithostratigraphic members (Table 2).

The decisive argument how to distinguish between the Tirolicum and Hronicum or Alpine versus Carpathian tectonic provenance is the presence or absence of the anhydrite-rich strata of the Opponitz Fm. and Reichenhall Fm. as well as the Reingraben Fm. The Opponitz Fm. is the integral member of the Havranica and Jablonica partial nappes of the Hronicum, but does not contain anhydrite (Began et al. 1984; Salaj et al. 1987; Havrila 2011). In the boreholes of the Závod series (e.g., Jiříček 1988) the Haselgebirge Fm., which probably indicates the presence of Juvavicum, has also been documented. None of these formations occur in the Hronicum even in the whole Western Carpathians (Table 2). Therefore, the anhydrite-rich sediments in the lower sections of boreholes LNV-7 and Š-12 (Fig. 3) are interpreted as part of the Alpine provenance nappe system, while the upper sections belong to the Hronicum (Fig. 6). Similarly, the Triassic interval with the Reingraben shales, Steinalm Limestone, Gutenstein Fm. and evaporitic Reichenhall Fm. in borehole Studienka-83 (Fig. 3) belongs to the Tirolicum (Unterberg nappe in borehole Berndorf-1 section, Wachtel & Wessely 1981). The Upper Cretaceous–Paleocene sediments below the Triassic sequence in borehole Studienka-83 can be correlated with the Gießhübel basin (Bujnovský et al. 1992; Stern & Wagreich 2013) and Bajuvaric nappe system can be expected below.

The upper boundary (12 km; Fig. 5) crystalline basement of the Bohemian Massif is visible on the magnetotelluric interpretation as a high resistivity anomaly (5–19 Ohm.m). On the gravimetric profile, the high density Bohemian Massif was interpreted (in depth 11 km; Fig. 4).

The Bohemian Massif is overlain by autochthonous Mesozoic cover. This structure is undetectable in the magnetotelluric profile. The gravimetric interpretation is supported by well log analyses and by study of the borehole lithology Zistersdorf Üt 2A, Sedlec-1; Bulhary-1; Kobylí-1 or Nové Mlýny-1,2,3 (Špička et al. 1977; Adámek 1986, 2005; Wessely 1988; Eliáš & Wessely 1990) even though the sediments were not reached in the borehole Berndorf-1 (Wachtel & Wessely 1981).

The Flysch Belt, located directly below the Neogene sediments, outcrops only in the northern part of the Vienna Basin. However, we assume that it extends deeper, even below the Northern Calcareous Alps as well as below the Internal Western Carpathians units almost to the NW margin of the Malé Karpaty Mts. (compare Arzmüller et al. 2006).

The mentioned assumptions are based on the knowledge of the surface structure of the Flysch Belt (Potfaj et al. 2014), the borehole data from the Vienna Basin (Adámek 2005; Picha et al. 2006) and surroundings (Lubina-1, see Leško et al. 1982; Klanečnica-1, Teťák 2016) as well as the magnetotelluric data (Fig. 5).

We assume a 3–6 km thick complex formed by "flysch" deposits above the crystalline basement and autochthonous Mesozoic sediments of the Bohemian Massif.

It is represented (upward) by the autochthonous Paleogene sediments and overlaying Krosno and Magura nappe systems. Krosno nappe system represents in particular Waschberg–Ždánice–Pouzdřany Unit. They are

Table 2: Lithostratigraphic columns of the Hronicum and Tirolicum nappe systems (Piller et al. 2004; Buček in Polák et al. 2012). The Opponitz Formation does not contain anhydrite intercalations in the Hronicum. *Göstling Fm., ** Reingraben Fm.

			HRONICUM *Havranica, Jablonica nappe system*	**TIROLICUM** *Unterberg, Göller nappe system*
TRIASSIC	**Norian**	*Sevatian*	Dachstein limestone	Plattenkalk; Dachstein dolomite limestone
		Alaunian	Dachstein limestone	Hauptdolomite; Dachstein dolomite limestone
		Lacian	Hauptdolomite	Hauptdolomite; Dachstein dolomite limestone
	Carnian	*Tuvalian*	Opponitz limestone	Opponitz limestone
		Julian	Lunz Fm.	Lunz Fm.; **
		Cordevolian	*; Wetterstein dolomite; Wetterstein limestone	*; Reifling Formation; Wetterstein limestone / dolomite
	Ladinian	*Longobardian*	Wetterstein dolomite; Wetterstein limestone	Reifling Formation; Wetterstein limestone / dolomite
		Fassanian	Wetterstein limestone; Reifling limestone	Reifling Formation; Wetterstein limestone / dolomite
	Anisian	*Illyrian*	Steinalm limestone	Reifling Formation; Wetterstein limestone / dolomite
		Pelsonian	Gutenstein limestone	Gutenstein / Steinalm Formation
		Bythinian	Gutenstein limestone	Gutenstein / Steinalm Formation
		Aegean	Gutenstein dolomite	Reichenhall Fm.
	Olenekian		Šuňava Fm.	Werfener Schichten
	Induan		Benkovo Fm.	Werfener Schichten

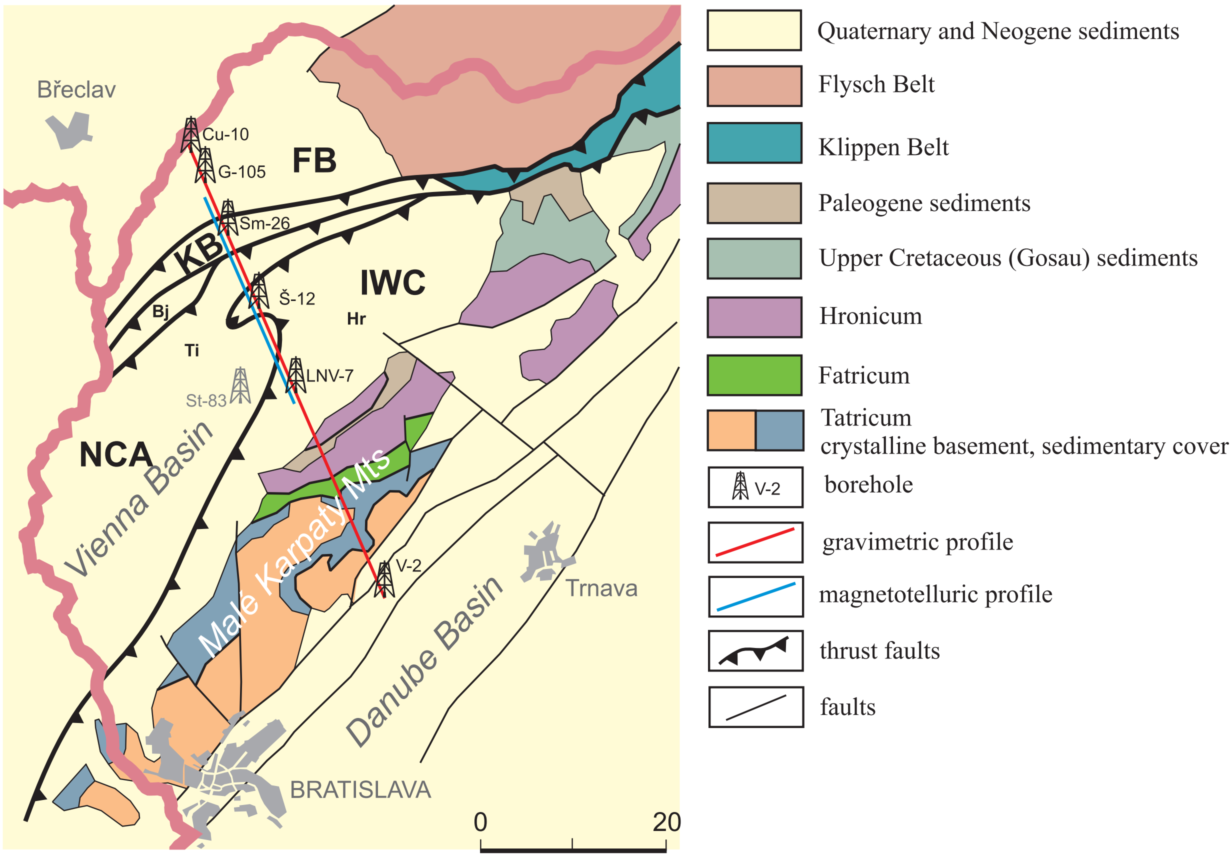

Fig. 6. Simplified geological map with the position of the Alpine and Carpathians nappe systems. FB — Flysch Belt; KB — Klippen Belt; NCA — North Calcareous Alps; Bj — Bajuvaric nappe system; Ti — Tirolic nappe system; IWC — Internal Western Carpathians; Hr — Hronic nappe system.

partly autochthonous deposits of the margin of the Bohemian Massif, and partly thrust-sheets or duplexes of the Waschberg–Ždánice–Pouzdřany Unit and other external units. We do not expect that the Silesian Unit or the Fore-Magura Unit reach so far west. The Waschberg–Ždánice–Pouzdřany Unit is formed predominantly by Upper Cretaceous (Campanian–Maastrichtian) to Lower Miocene (Egerian to Karpatian) marls and mudstones. The organic-rich rocks of the Menilitic Fm. of the Waschberg–Ždánice–Pouzdřany Unit or the autochthonous Paleogene sediments are an important source rocks of hydrocarbons in the Vienna Basin (Picha et al. 2006). Based on the mentioned prevailing lithology, the density of this complex is 2.58 g.cm^{-3}.

The sediments of the Magura nappe system are thrust over the Krosno nappe system. Prevailing Upper Cretaceous to Paleogene flysch deposits analogous to underlying units are found here, although their stratigraphy and lithology are fundamentally different. The lowest and most external Siary Unit (northern Rača Unit) is formed by typical thick sandstone complexes of the Soláň and Zlín Fms. Sandstone rich lithology is overlying the Rača Unit with sandstones of the Luhačovice and Zlín Fms. (Picha et al. 2006). Based on the predominant sandstone lithology, we determine the density of the Siary and Rača units at 2.70 g.cm^{-3}.

The marls are typical for the Bystrica Unit of the Magura nappe system. The Bystrica Unit does not outcrop on the surface. If this unit occurs in the Vienna Basin, it will most likely occupy deeper parts close to the Klippen Belt.

The Biele Karpaty Unit reaches much larger dimensions (Potfaj 1993). The Biele Karpaty Unit is represented by the Bošáca Nappe predominantly containing marls and mudstones. The stratigraphically and tectonically higher sandstone-rich Javorina Nappe either does not occur here or only in a limited extent with a reduced proportion of sandstone due to the distal position of Javorina type sandstones. The density of the Siary and Rača units is 2.58 g.cm^{-3}.

We do not expect the occurrence of Magura nappe system sediments internally from the Klippen Belt. If they were to be present, then only to a limited extent and represented by the Biele Karpaty Unit with lower density.

Conclusion

Geophysical and geological modelling and interpretations along the gravimetric and magnetotelluric profiles brought new results on the structures of the pre-Neogene basement of the Slovak part of the Vienna Basin (Fig. 1). The gravimetric profile was constructed in the NW–SE direction along the expected tectonic contacts and deep boreholes. Part of the gravimetric profile is parallel to the magnetotelluric profile (Fig. 2). The data from deep boreholes, especially from Lakšárska Nová Ves-7 (LNV-7) and Šaštín-12 (Š-12), have been reviewed from the point of view of the current lithostratigraphic knowledge of the Mesozoic rock sequences (Fig. 3). The obtained results can be summarized as follows:

- Four floors with different geological structure can be defined (Figs. 4, 5)
- The deepest floor is formed by the crystalline basement of the Bohemian Massif and its autochthonous Mesozoic cover (Figs. 4, 5).
- The floor above the Bohemian Massif is represented by the accretionary prism of the Flysch Belt formed by (upward) the Krosno (Waschberg–Ždánice–Pouzdřany Unit) and Magura nappe systems thrust over the rock sequences of the Bohemian Massif (Figs. 4, 5).
- The third floor is controlled by borehole data. It contains the Mesozoic sequences of the Klippen Belt and cover nappes of the Alpine and Carpathian tectonic provenance.
- The decisive argument for determining the tectonic identity of the cover nappes is the presence or absence of anhydrite-rich strata documented in boreholes (Opponitz Fm., Reingraben Fm., Reichenhal Fm.) that do not occur in the Hronicum tectonic unit (Fig. 3).
- The Hronicum tectonic unit is thrust over the Tirolic and Bajuvaric nappe systems (Fig. 6).
- The Neogene sediments of the Vienna Basin infill represent the highest floor of geological structure in the interpreted/modelled profiles (Figs. 4, 5).

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