Geological structure of the Dobrá Voda seismoactive area (western Slovakia)

Jozef Hók[1], Juraj Littva[1,2], Martin Šujan[3], Lenka Šamajová[1], Michal Šujan[1] & František Šipka[3]

[1] Department of Geology and Paleontology, Faculty of Natural Sciences, Comenius University in Bratislava, Mlynská dolina, Ilkovičova 6, 842 15 Bratislava, Slovak Republic; jozef.hok@uniba.sk; juraj.littva@ssj.sk
[2] State Nature Conservancy of the Slovak Republic, Slovak Caves Administration, Hodžova 11, 031 01 Liptovský Mikuláš, Slovak Republic
[3] EQUIS Ltd., Račianska 57, 831 02 Bratislava, Slovak Republic

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Abstract: The Dobrá Voda seismoactive area is the most significant seismic source zone in terms of seismic hazard of Slovakia. It is situated at the contact of the Bohemian Massif, Western Carpathians, and Eastern Alps. On the surface, the Dobrá Voda seismoactive area is built from the Triassic carbonate rocks overlain by Cainozoic sediments. The deeper basement consists of crystalline rocks. The whole structure is disrupted predominantly by normal faults oriented in NW–SE and NE–SW directions. Majority of the earthquakes hypocentres is concentrated in the crystalline basement. The Dobrá Voda seismoactive area represents crust portion located above the zone of assumed persisting convergence between the Bohemian Massif and Internal Western Carpathians crystalline basement. The apical parts of this segment are in tensional to transtensional tectonic regime. The seismic activity in the Dobrá Voda seismoactive area was previously linked to the transpression segment of the Vienna Basin Transfer Fault, extending from the Alps through the Mur–Mürz Valley, the Vienna Basin, and continuing into the External Western Carpathians. The Vienna Basin Transfer Fault could not be identified via new research in the Dobrá Voda seismoactive area.

Key words: Western Carpathians, neotectonics, Vienna Basin Transfer fault

1. INTRODUCTION

The Dobrá Voda seismoactive area (*sensu* Fojtíková et al., 2010), situated at the contact of the Bohemian Massif, Western Carpathians, and Eastern Alps (Fig. 1), is an integral part of the Dobrá Voda seismic source zone, representing the most significant zone in terms of seismic hazard of Slovakia (Hók et al., 2016[a]). Within this zone, 271 earthquakes with M_W from 2.0 up to 5.7 were documented (SLOVEC, 2011). Most hypocentral depths in DVSA are located between 4–7 km. According to focal mechanism solutions, the documented seismic activity is predominantly associated with the sinistral strike-slip faulting with weak normal or reverse components (Fojtíková et al., 2010).

A diverse array of rock complexes crops out in the broader vicinity of DVSA (Fig. 2). Among them, the tectonic units of the External Western Carpathians, Internal Western Carpathians (sensu Hók et al., 2014), and the Neogene sediments are presented and represent the essential portion of the Danube and Vienna Basins infill. The Magura Unit of the Flysch Belt accretionary wedge and the Oravicum (Pieniny Klippen Belt) belong to the External Western Carpathians. Thick-skinned Tatricum Unit, and cover nappes of the Fatricum and Hronicum units, along with the Upper Cretaceous and Palaeogene (Gosau Group) sediments are parts of the Internal Western Carpathians.

Several important rock complexes in the vicinity of DVSA are not observable on the surface. The Mesozoic sediments of the Eastern Alps provenance were identified within the pre-Cainozoic basement of Vienna Basin (e.g., Biela, 1978; Fusán et al., 1987; Wessely, 1992). Rock complexes of the Bohemian Massif are present in footwall of the Western Carpathians, as well as the Eastern Alps tectonic units (e.g., Kysela & Kullmanová, 1988; Wessely, 1993; Picha et al., 2006). According to seismic profile interpretations (Kadlečík et al., 1980; Vozár & Šantavý, 1999), the marginal parts of Bohemian Massif can be traced along the north-western margin of Malé Karpaty and Brezovské Karpaty Mts., and further to the northeast between the Čachtické Karpaty and Považský Inovec Mts. (Fig. 2). Structures of different tectonic regimes are registered throughout the broader vicinity of DVSA. Age of the youngest Alpine northward thrusting can be estimated as the post-Senonian (Hók et al., 2016[b]; Pelech et al., 2017). After termination of thrusting, predominantly normal faults oriented in the NE–SW direction had essential importance, restricting the Neogene depressions against the horst structures of pre-Cainozoic basement. Age of the main activity of these faults is the Middle-Late Miocene (Kováč, 2000). Geological mapping and structural research was conducted in the study area, with purpose to clarify the geological structure of DVSA and its relation to the seismic activity.

2. METHOD USED

New research activities were focused mainly on the central part of DVSA (Dobrá Voda Depression). The standard methods and techniques of the geological mapping were used at a scale of 1:10,000. The main portion of investigation was devoted to the internal structure of the Hronicum Unit, mutual contact between the Mesozoic and Miocene sediments, kinematic character, and age of surface visible (mappable) faults with the special emphasis on the Quaternary faults. Density modelling along the profile passing through DVSA was realized with the purpose to better understand configuration of geological structures in deeper basement. The results of new research are presented in this contribution, allowing for improved insight into the geological structure of this area.

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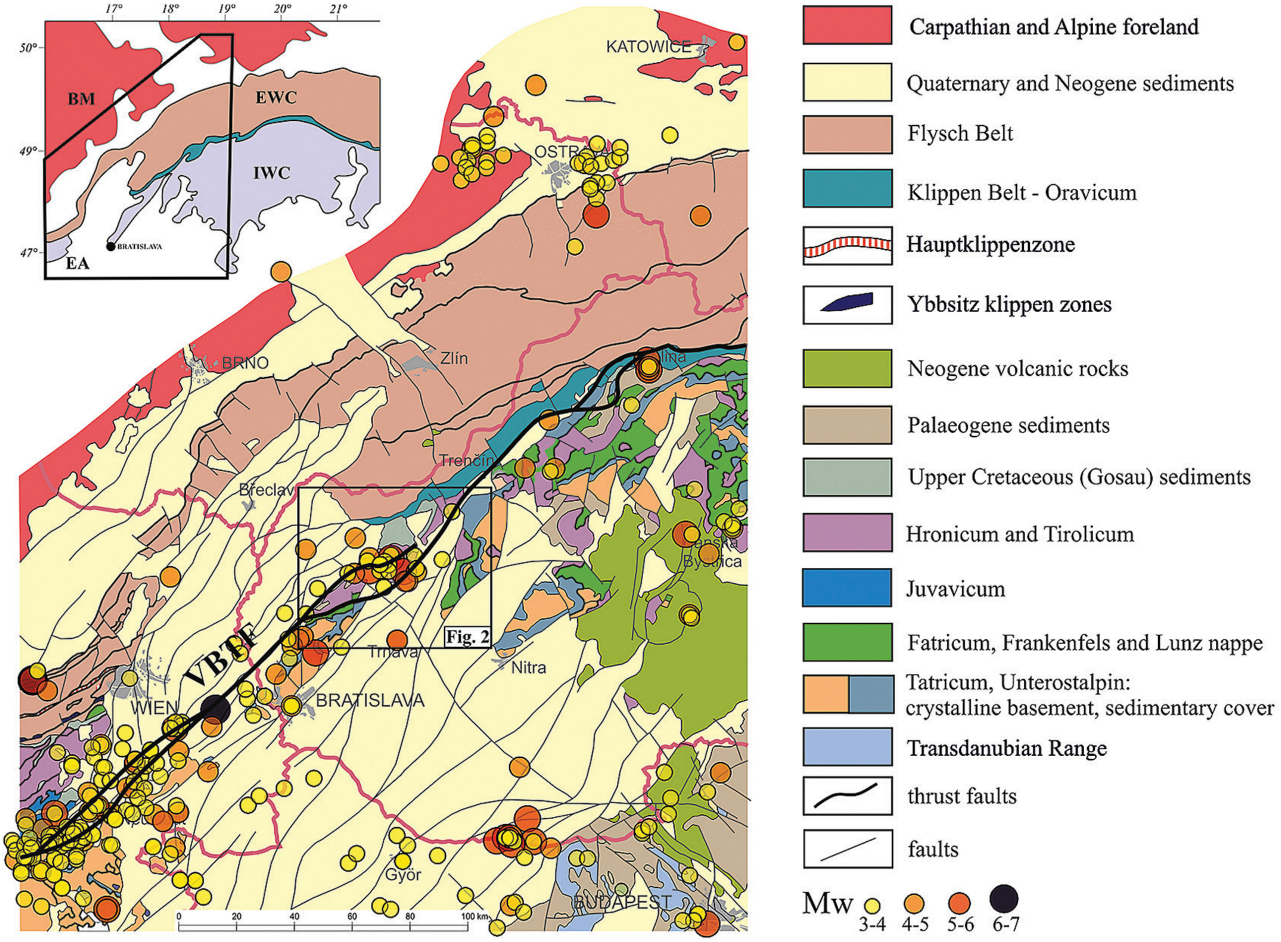

Fig. 1. Simplified geological map of the Western Carpathians and adjacent areas (simplified after Lexa et al., 2000). Earthquake epicentre locations are adapted from SLOVEC (2011). BM – Bohemian Massif; EA – Eastern Alps; EWC – External Western Carpathians; IWC – Internal Western Carpathians; VBTF – Vienna Basin Transform Fault (cf. Decker et al., 2005).

Density modelling along the PF-1 profile (Figs. 2, 5) passing through DVSA structure and DV-1 (Michalík et al., 1992) Šp-1, and Tra-5 (Biela, 1978) boreholes used gravity data obtained from the Bouguer anomaly map with a spatial resolution of 200 m (Pašteka et al., 2014). Densities for individual rock types or individual rock sequences were determined according to Eliáš & Uhmann (1968), Fusán et al. (1987), Michalík et al. (1992), and Šimonová & Bielik (2016). The GM-SYS software (GM-SYS User's Guide for version 4.9, 2004) was used to quantitative interpretation of the Bouguer anomaly along the PF-1 profile (Fig. 5).

3. RESULTS

The Dobrá Voda Depression represents the central portion of DVSA with the most abundant occurrence of the earthquakes epicenters (Fig. 1). Surface pre-Cainozoic rocks of DVSA comprise only the Hronicum Unit arranged into two thrust sheets with different facial provenience of their sediments (Fig. 3). The lowermost partial structure contains sediments derived from the basinal part of the Hronicum palaeographic area in the Triassic period (the Dobrá Voda Nappe *sensu* Havrila, 2011). The Upper partial structure of the Hronicum typically contains shallow water or carbonate platform facies of the Wetterstein Limestone and Wetterstein Dolomite (the Považie Nappe *sensu* Havrila, 2011). The same structural position of the Hronicum partial nappes was also documented in DV-5 borehole (Kováč et al., 1991[a]) situated about 4 km southeast of Dobrá Voda village (Fig. 3). The Dobrá Voda nappe is internally imbricated into tectonic slices dipping to the northwest with presence of the Reifling Limestone and the Lunz Formation. DV-1 borehole (Fig. 3) penetrated these slices (Michalík et al., 1992), and their existence most probably led to interpretation of the reverse fault overthrusting the Miocene sediment on the northern margin of the Dobrá Voda Depression (Marko et al., 1991; Michalík et al., 1992).

In the past, there were problems with the stratigraphic affiliation and tectonic position of the carbonate conglomerates in the Dobrá Voda Depression. These were originally dated to the Early Miocene (Buday et al., 1962, 1963), later (Began et al., 1984; Salaj et al., 1987; Michalík et al., 1992; Geological map of Slovakia, 2013) to the Late Cretaceous (Gosau Group). Finally Kováč et al. (1991[a], 1991[b]) demonstrated that mentioned sediments stratigraphically belong to the Early Miocene (Eggenburgian-Karpatian). Moreover, the tectonic position of the Upper

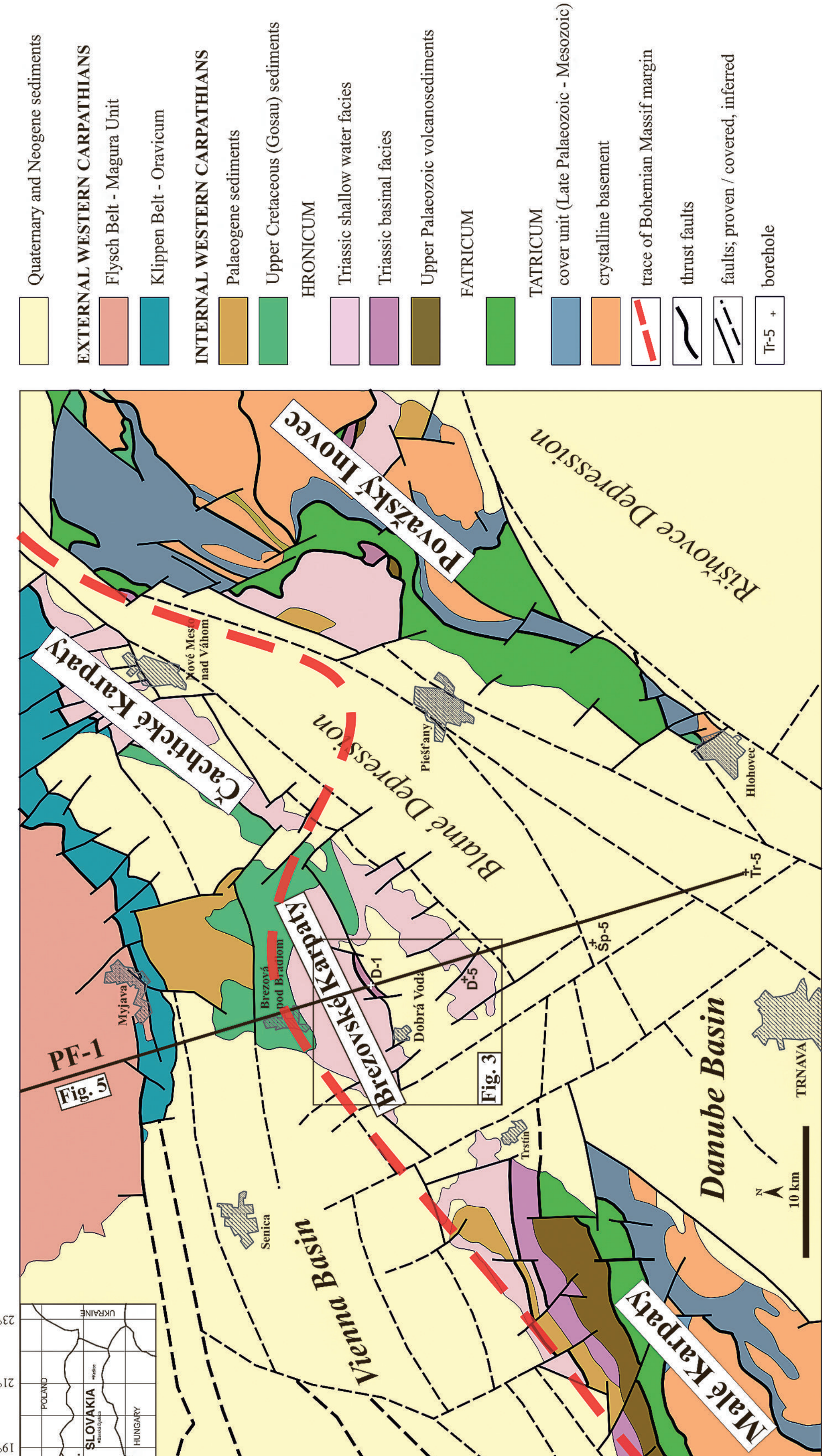

Fig. 2. Simplified geological map of the broader vicinity of the Dobrá Voda seismoactive area (simplified after: Began et al.,1984; Maglay et al., 2005; Ivanička et al., 2007; Polák et al., 2011; Fordinál et al.,2012; Potfaj & Teťák (Eds.) et al., 2014 and own research).

Cretaceous/Lower Miocene sediments was interpreted (with exception Buday et al., 1962, 1963) to be in tectonic footwall of the Mesozoic sediments in the south-verging Dobrá Voda Fault Zone (Marko et al., 1991). The results of geological mapping reveal that the Early Miocene sediments either overlay different tectonic slices, or they are tectonically separated from the Mesozoic sediments by the normal faults (Figs. 3, 4B). Most of mapped faults are oriented generally in NE–SW and NW–SE directions, and show normal kinematics with negligible oblique component. The faults with proven Quaternary tectonic activity also exhibit normal sense of movement (Fig. 4A). From this point of view, the interpretation of the "push up" transpression/positive flower structure of the Mesozoic sediments, which is squeezed between two right-stepping sinistral faults, named the Dobrá Voda Fault zone by Marko et al. (1991 *see* Fig. 3), later interpreted as a segment of the Vienna Basin Transfer Fault by Hinsch & Decker (2011 *see* Fig. 2), did not take into account real geologic/tectonic situation. The Quaternary sedimentary record of the Dobrá Voda Depression consists mostly of alluvial deposits, with presence of colluvium close to its margin, and locally thin loess cover.

Results of density modelling, combined with current knowledge of surface geology, tectonics, and seismological data, point to several important details and implications regarding the structure and seismicity of DVSA. The Oravicum (Pieniny Klippen Belt) represents rootless structure thrust over the External Western Carpathians sediments (Flysch Belt). The uppermost part of PF-1 profile shows normal faults kinematics with the extensional to transtensional tectonic regime. Majority of the earthquake hypocenters is concentrated into the crystalline basement of the Tatricum Unit (Fig. 5).

4. DISCUSSION

Earthquake epicenters in DVSA are linked with seismicity arranged along relatively narrow zone stretching from Mur Valley of the Eastern Alps to DVSA (Fig. 1). Seismicity was hypothesized to be associated with a fault zone currently called the Vienna Basin Transform Fault (Decker et al., 2005) or Vienna Basin Transfer Fault (Hausmann et al., 2010; Hinsch & Decker, 2011). In the past, this fault had several different names and

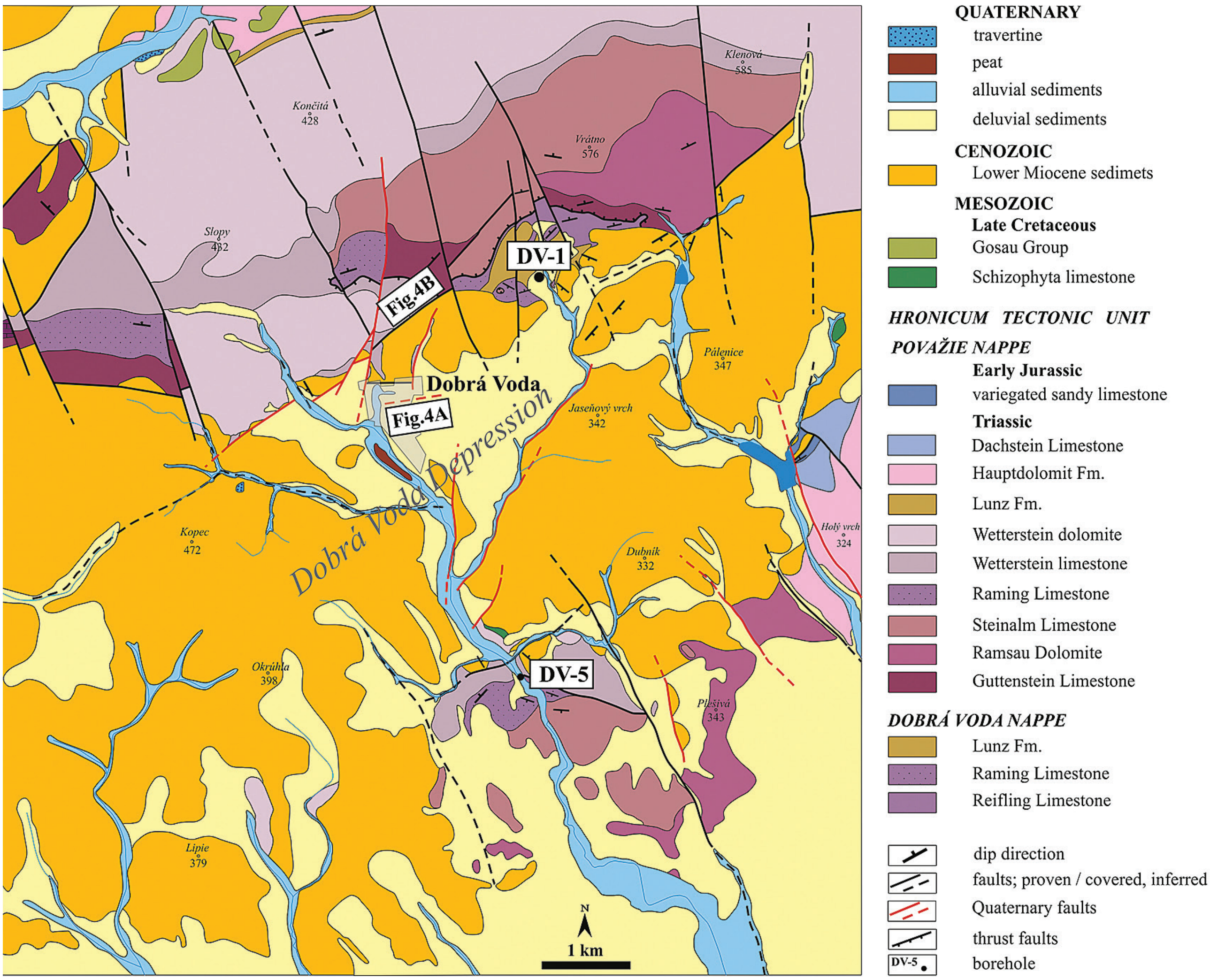

Fig. 3. Simplified geological map of the Dobrá Voda Depression and surroundings (Hók & Littva, 2018, original).

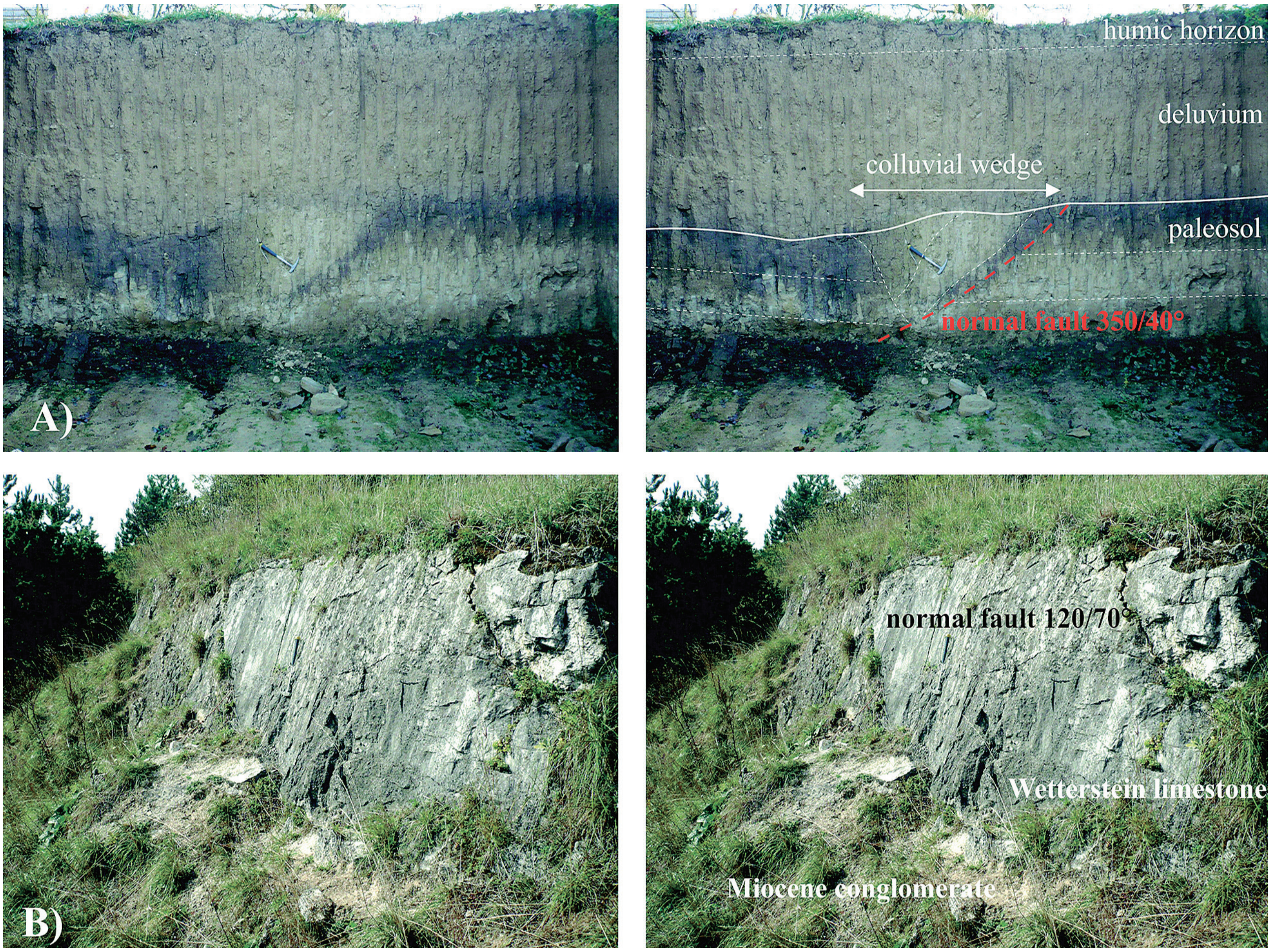

Fig. 4. **A) Covered normal fault oriented in the ENE–WSW direction disturbing the Quaternary palaeosol horizon. B) Normal fault separating the Mesozoic Wetterstein Formation and Lower Miocene conglomerate (see Fig. 3 for localization).**

localizations, e.g., Verona - Semering - Váh zone (Schenková et al., 1995), Mur - Mürz - Leitha - Little Carpathian fault system/zone (Reinecker & Lenhardt, 1999), Mur - Mürz - Žilina (Bada et al., 2007; Špaček et al., 2015; Tokarski et al., 2016). According to Hinsch & Decker (2011), Vienna Basin Transfer Fault (VBTF) is 450 km long, extending from the Central Alps through the Mur - Mürz Valley, the Vienna Basin across the Malé Karpaty Mts., and continues along Váh River valley into the External Western Carpathians (Fig. 1). The existence of this extremely long fault or fault zone does not correspond to the data from the geological map (*see* [online] Geological map of Slovakia, 2013). Also the presence of VBTF in DVSA vicinity is questionable, where VBTF coincides with the Cretaceous thrust plane of the Hronicum nappe in the northeastern portion of the Malé Karpaty Mts. (e.g., Hinsch & Decker, 2003; Decker et al., 2005; Beidinger & Decker, 2011, 2016) or with the normal faults bordering the Miocene Depressions against the Malé Karpaty Mts. horst structure (e.g., Bada et al., 2007). The new research in DVSA proved that the reverse faults or back thrust faults are not present neither at the north margin of Dobrá Voda Depression (Figs. 3, 5), nor the northern margin of the Brezovské Karpaty Mts. (Potfaj & Teťák (Eds.) et al., 2014). Hence, the interpretation of the DVSA as a push up structure (Dobrá Voda Fault Zone) declared by Marko et al. (1991 *see* Fig. 3) and later by Hinsch & Decker (2011 *see* Fig. 2) is also disputable. The focal mechanisms of the earthquakes refer to strike-slip tectonic regime (Fojtíková et al., 2010). The nodal planes of focal mechanisms have different orientations than the faults observed on the surface i.e. earthquakes are connected with faults of different orientations and kinematics (Fojtíková et al., 2010; Jechumtálová & Bulant, 2014) than the faults observed on the surface. This fact is probably related to a different stress regime in basement level and near-surface superficial nappes. The earthquake epicentres concentration in DVSA is most probably linked with the persistent convergence, shape and rheology of the Bohemian Massif margin at the deep contact with Internal Western Carpathians (Figs. 2, 5) in a similar way as it is in the Eastern Alps (*see* Reinecker & Lenhardt, 1999).

5. CONCLUSIONS

The Dobrá Voda Seismoactive area (DVSA) is one of the most seismically active region within the Slovakia's territory (Fig. 1). DVSA is situated at the contact of the Western Carpathians, Eastern Alps, and Bohemian Massif (Figs. 1, 2). The structure of DVSA comprises the rock sequences of Hronicum Unit imbricated into tectonic slices during the Cretaceous, and covered by the Lower Miocene and Quaternary sediments (Fig. 3). The Fatricum superficial nappe and Tatricum thick skinned tectonic unit are underlying the Hronicum. The whole surface structure of DVSA is disrupted by normal faults generally oriented in the NW-SE and NE-SW directions (Figs. 3, 4B) The faults with proven Quaternary tectonic activity document normal sense of movement (Fig. 4A). According to 2D density model, DVSA represents uplifted crustal segment located above the zone of assumed persisting convergence between the Bohemian Massif and crystalline basement of Internal Western Carpathians. The apical parts of this segment are in tensional to transtensional tectonic regime (Fig. 5). Interpretation of the transpression/positive flower structure of the Mesozoic sediments overthrusting the Lower Miocene deposits (Marko et al., 1991; Hinsch & Decker, 2011) should no longer be accepted. Majority of the earthquakes hypocenters are concentrated into the Tatricum crystalline basement (Fig. 5). The earthquake focal mechanism solutions indicate predominantly sinistral strike-slip regime of faults (Fojtíková et al., 2010) in contrast to the normal sense of movement of documented surface faults. The orientation of faults observed on the surface and the nodal planes of the earthquake focal mechanisms significantly differs. Differences between surface fault orientations and their sense of movements with those obtained from focal mechanisms solutions are explained as function their various depth. The increased seismicity in DVSA is considered to be caused by the spur shape of the Bohemian massif margin (Fig. 2) and its persistent convergence with the Western Carpathians.

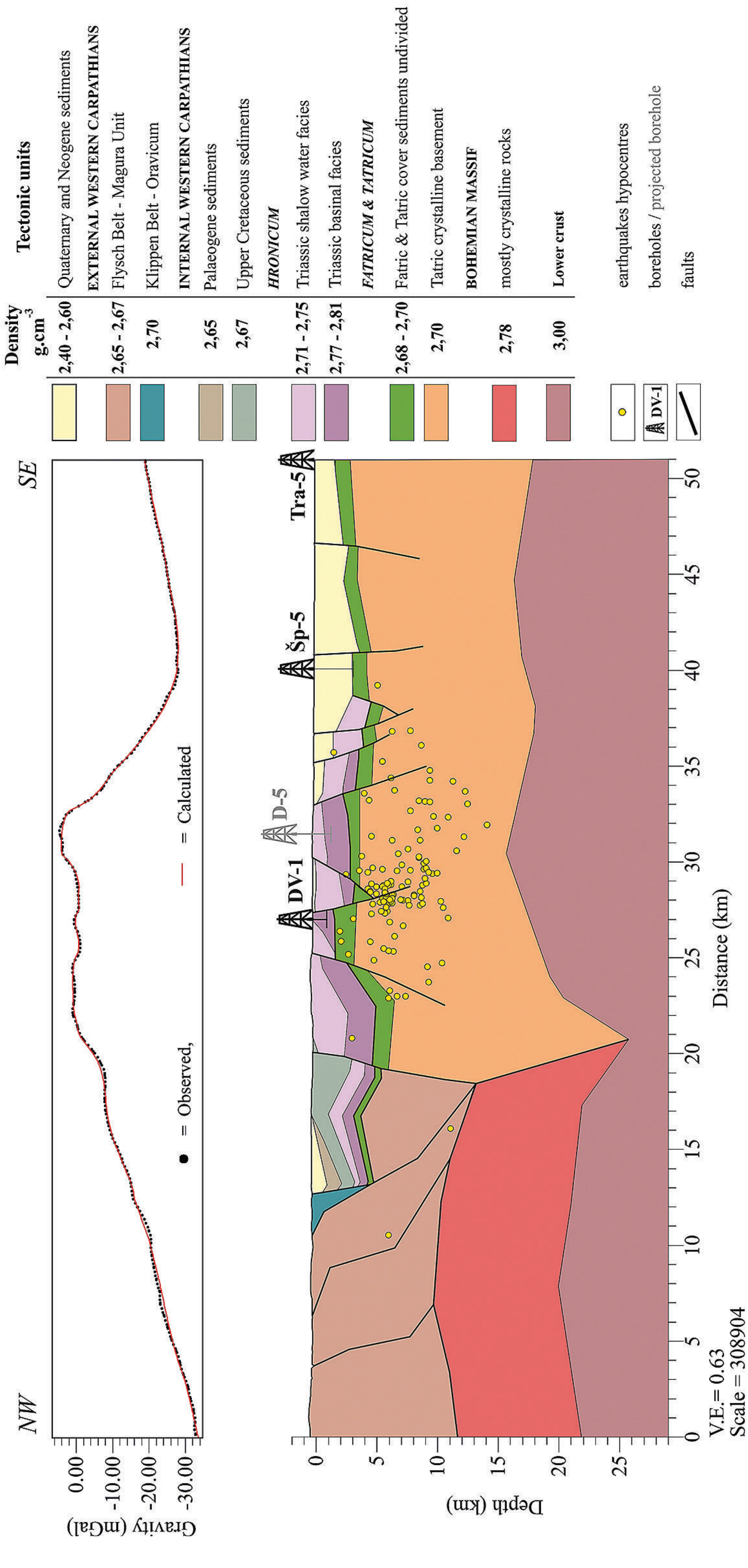

Fig. 5. Geological and tectonic interpretation of the 2D density model along the PF-1 profile (earthquake hypocentre locations are adapted from SLOVEC, 2011).

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