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2. Geological Model of the Danube Basin; Transboundary Correlation of Geological and Geophysical Data

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Abstract. The presented paper comprises the first successful attempt towards compiling the full 3D horizontal and cellular model of the Danube Basin created in the frame of the international TRANSENERGY project. In this article we are presenting only one of the five pilot areas of the TRANSENERGY project – the Danube Basin.

The 3D model is built on a large amount of geological (mapping, stratigraphic, wells) and geophysical (seismic, geomagnetic, gravitational) data, completed by structural and geodynamic studies in all participating countries (Slovenia, Austria, Hungary and Slovakia). After gathering and processing all available data a unified stratigraphical framework was compiled for all participating countries, followed by defining the main structural features and finally creating the model.

Our 3D model contains 8 horizons (Quaternary, Upper and Lower Pannonian, Sarmatian, Badenian, Neogene volcanites, Lower Miocene and Paleogene and the Pre-aienozoic basement) subdivided into 37 formations. The structural pattern of the area was simplified after several consultations into a scheme of 7 approximately SW-NE and 4 roughly NW-SE to W-E faults.

The 3D model is also the first attempt to visualize the Neogene volcanic bodies buried below younger sediments, including hypothetical Gabčíkovo volcano.

Keywords: Danube Basin, international cooperation, cross-border geology, 3D geological model, structural model, buried volcanoes

2.1. Introduction

The aim of the TRANSENERGY project was to support the harmonized geothermal water and geothermal energy utilization in the western part of the Pannonian Basin and its adjacent basins (e.g. Vienna Basin), which are situated in the transboundary zone of Austria, Hungary, Slovak Republic and Slovenia. The so called supraregional model includes the entire project area of the NW Pannonian Basin and the adjacent areas, encompasses the main geothermal reservoirs and manages the complete area in a uniform system approach. The supraregional model area was further divided into several subregions of enhanced hydrogeothermal utilization potential, designated as pilot areas, usually forming geological or hydrogeological units which have been identified and investigated in a more detailed way. In the Supra regional area five pilot areas were chosen, where local models had been developed. They focused on the local transboundary problems, and the detailed geological characteristics of the areas. The areas were the following: Vienna Basin, Danube Basin, Komárno-Štúrovo area, Lutzmannsburg-Zsira area and the Bad Radkersburg-Hódos area (Fig. 2.1).

As a starting step we collected all available seismic (160 sections) and well data (1672 wells). After this step it was necessary to define the technical framework for the project (file exchange formats, scale of maps etc.). Finally the WGS1984 UTM Zone 33N as the common coordinate system and Transverse Mercator as the common projection were chosen.

The next step was the harmonization of stratigraphic data, e.g. the time-consuming process of correlation of different formations. These formations describe sometimes the same lithologic and temporal geological units of a partner country with different synonyms, but more often the different names can cover slightly different rock lithologies as well. The most problematic question was the harmonization of the Post-Oligocene formations of the Paratethys. The most valuable sources for this task were the Geological Map of Western Carpathians and adjacent areas (Lexa et al. eds., 2000), the DANREG project maps and explanatory notes (Császár et al., 2000) and the T-JAM project (Fodor et al., 2011). The complete harmonized stratigraphical chart is published in Maros et al. (2012).

The 3D geological models for each one of the pilot areas were made separately: the Vienna Basin in Austria, the Danube Basin in Slovakia, the Komárno-Štúrovo and Lutzmannsburg-Zsira areas in Hungary and the Bad Radkersburg-Hódos area in Slovenia.

The final products scales of the Supra regional and Pilot areas models are the following:

- Supra regional area 1:500 000, Surface geology 1: 200 000
- Pilot areas:
  - Danube Basin 1:200,000;
  - Vienna Basin 1:200,000;
  - Lutzmannsburg-Zsira 1:100,000;
  - Bad Radkersburg-Hódos 1:200,000;
  - Komárno-Štúrovo 1:200,000.

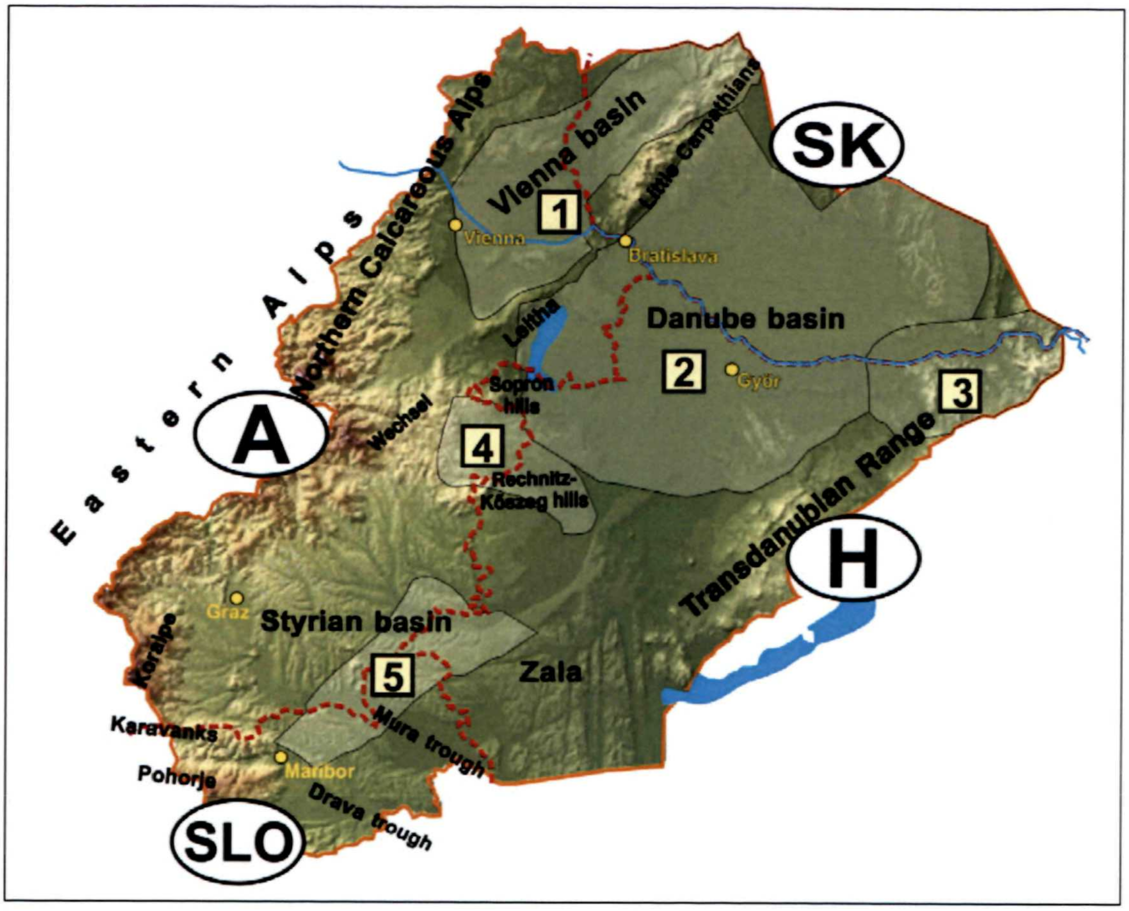


Fig. 2.1 Localization of the supraregional (orange line) and the pilot areas: 1 - Vienna Basin; 2 - Danube Basin; 3 - Komárno-Štúrovo area; 4 - Lutzmannsburg-Zsira area; 5 - Bad Radkersburg-Hódos area (modified after Maros et al., 2012)

2.2. Methodology

The primary aim of the geological model of the Danube Basin pilot area was to create a 3D geological framework accurate enough for hydraulic modelling, however we realized, that such a model itself would be valuable for further research. The model is based on seismic and borehole data, partially on other sources (published results, maps). The Danube Basin pilot area is located in three countries (Slovakia, Hungary and Austria) and was modelled in the frame of geological horizon models of the TRANSENERGY territory (Maros et al., 2012). The pilot area covers 1,2340 km^2, has a slightly elongated shape with length ca. 140 km in SW-NE and width ca. 110 km in NW-SE direction.

The steps of creating the model we can be summarized as follows:

1. *Creation of the common framework for all participants:* since the TRANSENERGY Supra area covers parts of four states, the work on the model started with unifying the different local stratigraphic charts for all four states (Slovakia, Hungary, Austria and Slovenia). In this phase we also needed to agree on horizons to be modelled, coordinate system and projection, scale of outputs, exchange formats to be used etc.

2. *Data compilation and processing*: collecting the existing seismic and well data (Tab. 2.1, Figs. 2.2 and 2.3), as well as other published works. In this phase we had consulted concepts as well as details with experts due to the optimization (simplification in fact) of the later fault model and stratigraphy.

3. *Pre-modelling data processing*:
   - calculation of time-to-depth for the seismic profiles;
   - redefinition of the borehole data according to the unified stratigraphic legend;
   - converting and entering the data into the 3D modelling software.

4. *Creation of the 3D model in main steps*:
   - creation of non-faulted horizons;
   - creation of the fault model;
   - combining non-faulted surfaces with fault model into a faulted 3D model;
   - input and refining lithological and stratigraphic content of 3D "space" between horizons (zones).

5. *Creation of outputs*: visual (maps, sections) as well as text outputs, presentations.

During the work we used common text and tabular editing tools (MS Office, OpenOffice), vector and bitmap-based graphical software (Corel, Inkscape, GIMP), MapInfo and partly also ArcGIS for map and GIS based tasks. The 3D modelling itself was realized with software Petrel 2008.

Table 2.1 Overview of input data

	Number of wells	Deepest well [m]	Medium depth of wells [m]	Number of seismic profiles
Slovakia	146	3,303	1,139	19
Hungary	189	4,517	1,084	63
Austria	74	1,860	243	–

2.3. Overview of the geological history of the Danube Basin

The Neogene Danube Basin is the largest subunit of the Western Carpathian basin system. In the Slovakian territory it corresponds to the Danube Lowland and in the area of Hungary it is called Little Hungarian Plain. It`s western margin is bordered by the Eastern Alps with Leitha Mts., and northernmore by the Western Carpathian Malé Karpaty Mts. In the North, the basin is laterally finger-like protruding among the Malé Karpaty, Považský Inovec and Tribeč Mts.

Structural evolution of the basin comprises several temporal phases, depending closely on the evolution of the mountain chain. The major part of the basin started its evolution in the Badenian time. Structurally, this was an episode of the finalizing phase of the pull-apart type depocentres collapse, gradually changing into extensional grabens of the basin rifting. The extension started along NNE-SSW trending normal faults which could be rejuvenated displacements along previously reverse faults in the basement and a very complex reverse–strike slip–normal fault deformation history has to be supposed along Rába and Hurbanovo tectonic zones. The later (Sarmatian and Pannonian) history is characterized like a back-arc basin, with the depocentres functioning as extensional grabens and half-grabens. The wide rifting at the Sarmatian/Pannonian boundary was followed by deep thermal postrift subsidence phase (Royden et al., 1983, Kováč, 2000).

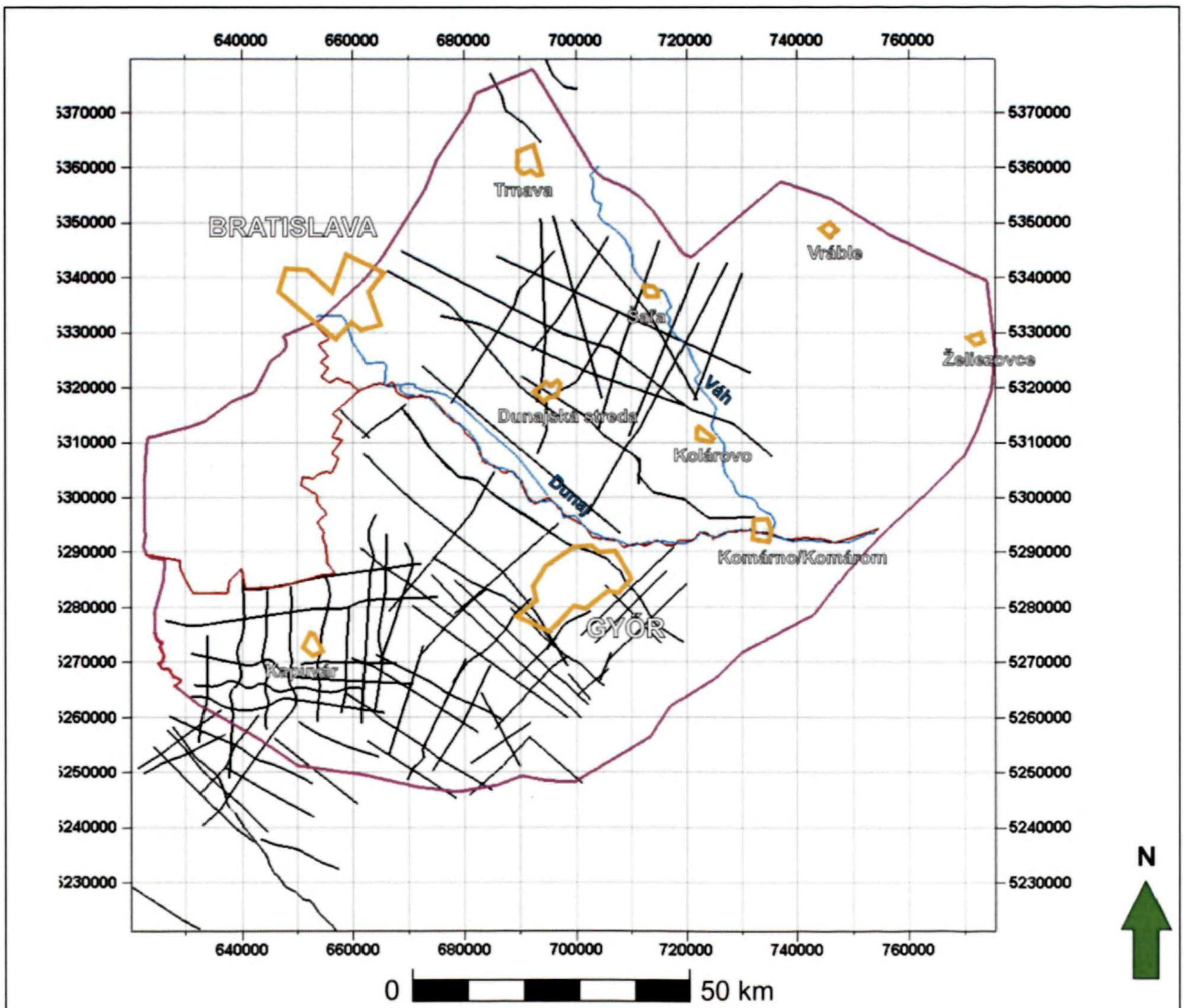


Fig. 2.2 Localization of seismic profiles

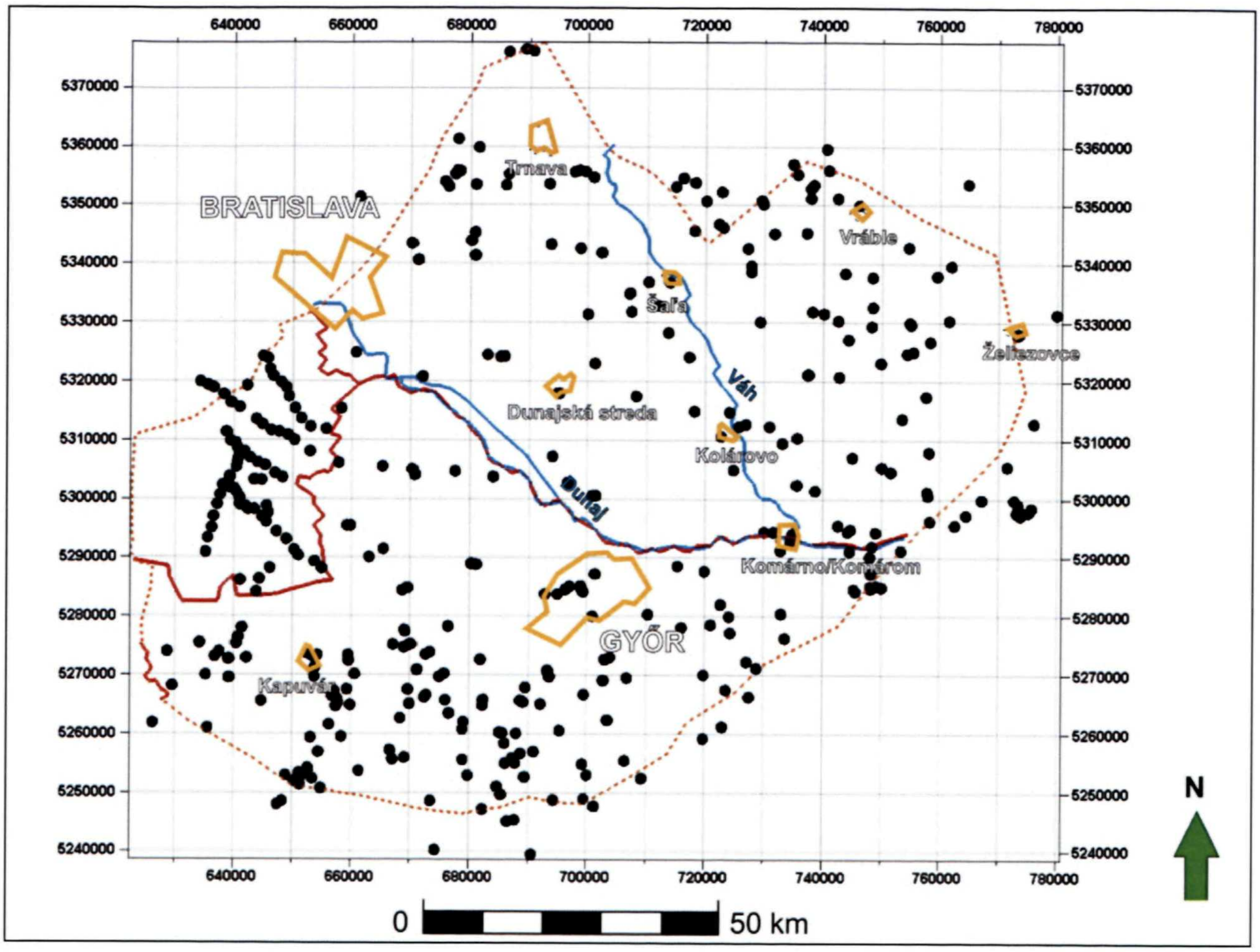


Fig. 2.3 Localization of wells

2.4. Results and discussion

2.4.1. Stratigraphy

Because of the geological structure of the pilot area the final model comprises zones (formations) in 8 horizons which we defined as base surfaces at chosen stratigraphic boundaries of the core column (e.g. Pre-Badenian surface). These zones (Table 2.2) are not the strict equivalents of the formations of the stratigraphic charts of the participating countries, but are purpose-created for the needs of the project by correlating and unifying the similar complexes of each country (for example the Late Pannonian zone "MPl" is equivalent of Zagyva and Nagyalföld Fms. in Hungary, the Volkovce and Beladice Fms. in Slovakia and the Rohrbach Fm. in Austria).

The topmost surface of our model - the Earth's surface in fact - was created using the SRTM (Shuttle Radar Topography Mission) project's global digital elevation model, spearheaded by the U.S. National Geospatial-Intelligence Agency (NGA) and the U.S. National Aeronautics and Space Administration (NASA). Altough the SRTM model in some cases showed a few metres differences especially near the major rivers against other local data, it is the most useful model with sufficient accuracy for our purposes which covers the whole area.

Horizon: Pre-Cainozoic basement

The Pre-Cainozoic basement of the basin at the western and northern boundary is built up of several units of the Central Eastern Alps and Central Western Carpathians, while in the south-eastern part of the basement units of the Transdanubian Central Range are also present, belonging to the ALCAPA unit. In the Slovakian part the basement is built up of Hercynian crystalline rock complexes and mainly Late Paleozoic and Mesozoic cover sequences of the Tatric and Veporic units as well as of superficial nappe systems of Fatricum and Hronicum composed mainly of Mesozoic (dominantly Triassic – Jurassic) sedimentary sequences. The Tatric and Veporic units continue into Hungarian and Austrian territories as their equivalents in the Lower Austroalpine nappe systems. The Transdanubian Central Range forming the basement in the southern part of the area is built up of a sequence of Paleozoic rocks (dominantly clastic rocks also with carbonates), massive Triassic and Jurassic strata dominantly formed in platform or open-sea environment. Cretaceous sediments of terrestrial or shallow-water environment are terminating the Mesozoic part of this succession.

Table 2.2 Summary of the stratigraphical and lithological content of horizons and zones of the model

Surface	Horizon	Zone (Formation)
▼*SRTM (surface)*	–	–
▼ *Base Q*	Quaternary	undivided
Top U. Pann. ▲	Late Pannonian basin fill	MPl - fluvial-lacustrine-continental sediments *(Late Pannonian - Pliocene)*
▼*Base U. Pann.*		Md - lacustrine sediments *(Late Pannonian)*
Top E. Pann. ▲	Early Pannonian basin fill	Mplf - shallow-water clay/silt *(Late Miocene - Pannonian)*
		Mpc - near-shore psephite/psamite *(Late Miocene - Pannonian)*
		Mptb - turbidite *(Late Miocene - Pannonian)*
▼*Base E. Pann.*		Mpcm - calcareous and clayey marl *(Late Miocene - Pannonian)*
Top Sarm. ▲	Sarmatian basin fill	Msrt - rhyolitic/andesitic volcanoclastics *(Sarmatian)*
▼*Base Sarm.*		Msmf - shallow-marine and brackish clay/marl *(Sarmatian)*
Top Bad. ▲	Badenian basin fill	Mbmf - shallow-marine and open basin claymarl *(Badenian)*
		Mbc - shoreline coarse/grained clastics/marl *(Badenian)*
▼ *Base Bad.*		Mbls - shallow-marine fossil-bearing limestone *(Badenian)*
Top Neovolc. ▲	Neogene volcanites	Mbzt - subvolcanic dacite, dacitic volcanoclastics *(Badenian)*
		Mbptr - trachyte, trachytic agglomerate *(Badenian - Pannonian)*
▼ *Base Neovolc.*		Mba - subvolcanic and effusive andesite *(Badenian)*
Top Mi1/Pg. ▲	Early Miocene and Paleogene	Mkb - open-marine silt/clay *(Karpatian-Badenian)*
		Olb - intertidal/lacustrine sandstone/silt/clay *(Oligocene)*
		Olf - fluvial/lacustrine clay/marl/sandstone *(Oligocene)*
		Olmf - open marine/restricted basin clay/marl *(Early Oligocene)*
		E2-3ml - open and shallow marine silty and clayey marl *(Middle - Late Eocene)*
		E2ls - shallow marine limestone, calcareous marl *(Middle Eocene)*
▼ *Base Mi1/Pg*		PcE2ml - shallow marine marl *(Paleocene/Early Eocene)*
Top Pre-Cen. ▲	Pre-Cainozoic basement	K2ml - pelagic limestone/marl *(Senonian - Early Paleocene)*
		K2ls - platform limestone *(Senonian)*
		J - Jurassic in general *(mainly limestones)*
		T3ls - platform limestone *(Late Triassic - Early Jurassic)*
		T3p - platform carbonates *(Carnian - Rhaetian)*
		T3d - platform carbonates *(Norian - Rhaetian)*
		Tkbls - basinal marl/limestone *(Carnian)*
		Tpd - platform dolomite *(Ladinian - Carnian)*
		Tacb - shallow marine bituminous limestone *(Anisian)*
		T1cb - continental/near-shore siliciclastics *(Early Triassic)*
		Pt - continental siliciclastics *(Middle - Late Permian)*
		C_Tgr - granitoid rocks of the Tatric and Veporic megaunits *(Carboniferous)*
		OC_Tr - low-grade metamorphic rocks of the Transdanubic megaunit *(Ordovician - Carboniferous)*
		Pz_Vcr - medium-grade metamorphic rocks of the Veporic megaunit *(Early Paleozoic ?)*
		PzF/PzS - medium-grade metamorphic rocks of the Tatric and Austroalpine megaunit *(Early Paleozoic ?)*

The Pre-Cainozoic basement rocks are correlated only on the base of lithology and sedimentology. The Senonian part of the rock-pile represents a kind of post-orogenic basins formation, covering the principal nappe boundaries. The correlation of older rocks is much more complicated, because of differences in the Late Cretaceous regional tectonic behaviour, and also of the significant Tertiary faulting. In fact they are parts of a complicated Alpine thrust/fault system, comprising several nappe systems and para-autochthonous Mesozoic and Late Paleozoic rock units, as well as their magmatic and metamorphic "cores". Since only a small part of all wells reached the basement - especially in the deeper central parts and troughs - during the modelling of the Pre-Cainozoic surface (Fig. 2.4) we respected the works of Hrušecký (1999), Pěničková at el. (1984), Fusán et al. (1987) and Császár et al. (2000). In the horizon of Pre-Cainozoic basement rocks we distinguished the following facies types:

- **K2ml:** pelagic limestone/marl *(Senonian - Early Paleocene)* - Jákó and Polány Marl Fm.
- **K2ls:** platform limestone *(Senonian)* - Ugod Limestone Fm.
- **J:** Jurassic in general *(mainly limestones)*

- **T3ls:** platform limestone *(Late Triassic - Early Jurassic)* - Dachstein, Kardosrét and Norovice Fms.
- **T3p:** platform carbonates *(Carnian - Rhaetian)* - Dachstein Limestone and Dolomite, Hauptdolomit Fms.
- **T3d:** platform carbonates *(Norian - Rhaetian)* - Hauptdolomit Fm., Ederics Limestone and Sédvölgy Dolomite Fm.
- **Tkbls:** basinal marl/limestone *(Carnian)* – Sándor-hegy, Veszprém, Lunz, Oponice and Partnach Fms.
- **Tpd:** platform dolomite *(Ladinian - Carnian)* – Budaörs, Ramsau Dolomite Fms., Podhradie, Vysoká and Wetterstein Limestone Fms.
- **Tacb:** shallow marine bituminous limestone *(Anisian)* - Gutenstein, Steinalm, Tagyon, Megyehegy, Iszkahegy and Aszófő Fms.
- **T1cb:** continental/near-shore siliciclastics *(Early Triassic)* - Csopak, Köveskál, Hidegkút, Arács, Alcsút-doboz, Lužná, Benkovský potok and Šuňava Fms.

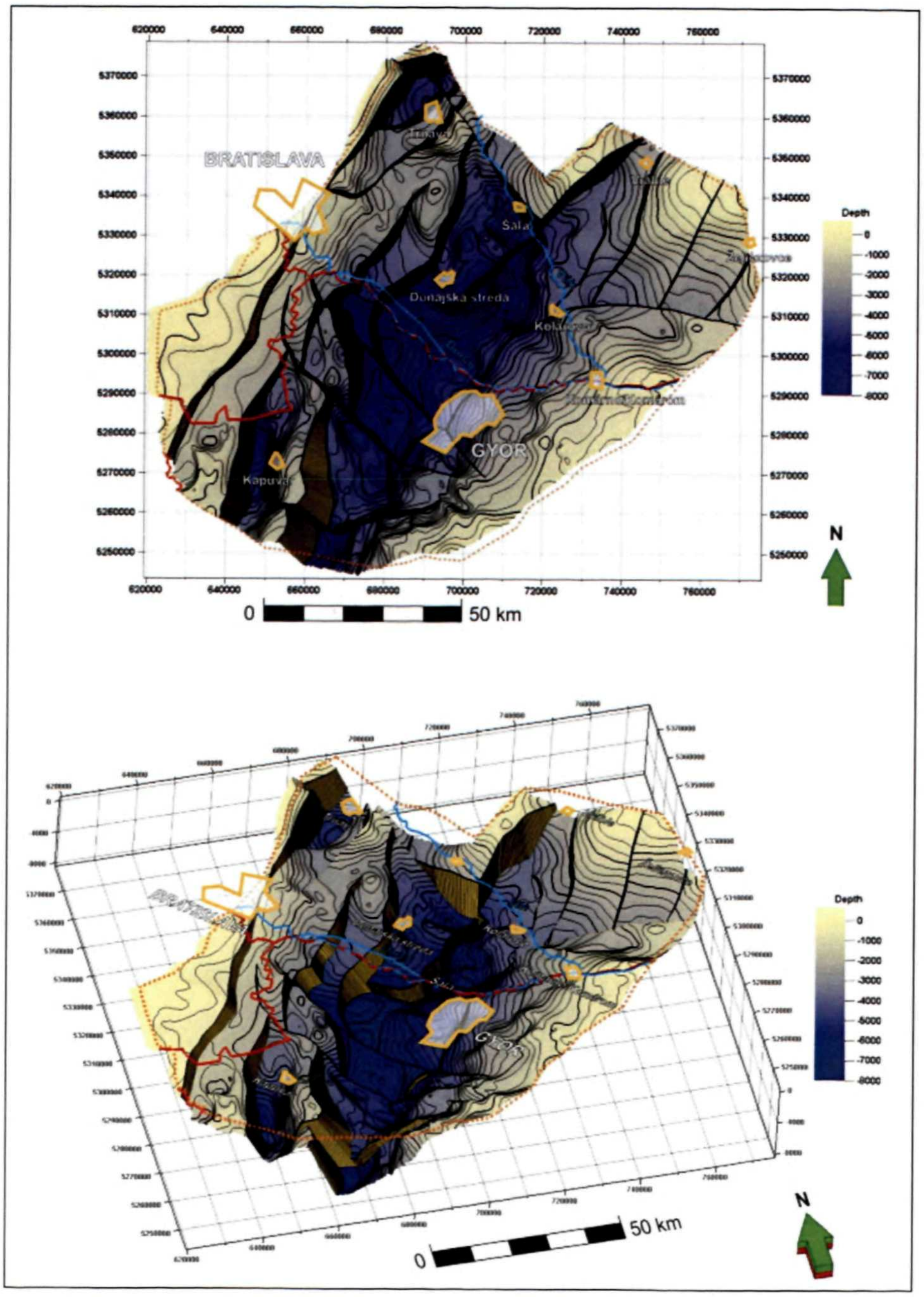
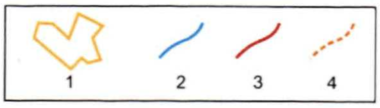


Fig. 2.4 The modelled top surface of Pre-Tertiary basement in 2D (above) and 3D (below, from SSW)



Legend to Figs 2.4.- 2.10.
1 - major cities; 2 - rivers; 3 - state borders; 4 - project boundaries

(Note for Figs. 2.4-2.10: since the slightly rotated 3D view shifts the relative position of objects on the surface - cities, rivers, borders - for the correct position please see the 2D view of each pair of Figures)

- **Pt:** continental siliciclastics *(Middle - Late Permian)* - Balatonfelvidék and Devín Fms.
- **C_Tgr:** granitoid rocks *(Carboniferous)* - Tatric and Veporic megaunits
- **OC_Tr:** low-grade metamorphic rocks *(Ordovician – Carboniferous)* - Transdanubic megaunit: Balatonfőkajár, Lovas, Alsóörs, Szabadbattyán, Polgárdi, Kékkút, Úrhida, Nemeskolta and Mihályi Fms.
- **Pz_Vcr:** medium-grade metamorphic rocks *(Early Paleozoic?)* - Veporic megaunit
- **PzF/PzS:** medium-grade metamorphic rocks *(Early Paleozoic?)* - Tatric and Austroalpine megaunit.

Horizon: Paleogene - Early Miocene

This horizon represents a very early stage of the Danube Basin evolution, and/or some relics of the preexisting structurally different phases. Since the Paleogene and Early Miocene deposition represent the same sedimentary cycle in the studied area, we grouped these horizons together.

There are two genetically different occurrences of this horizon: the Paleogene of the Hungarian Paleogene Basin (here the Buda-type Paleogene) and separately the Central Carpathian Paleogene in the Blatné Depression (NW part of the area). The Tertiary rocks of the Buda-type Paleogene in the area are known only from the Transdanubian unit on the southern rim of the area. This type of succession is characterized by shallow-water to terrestrial sedimentation and is represented by shallow-water limestones, sandstones, marls and clays as well as coal occurrences. Paleogene rocks in the Blatné Depression occur only in smaller amounts without outcrop in the studied area and are represented mainly by flysch-type clastics (Hričovské Podhradie and Domaniža Fms.) or carbonates (Dedkov vrch and Jablonové Fms.), therefore they were joined together for their very limited occurrence.

Early Miocene deposits occur in the NE part of the area (Blatné Depression, Slovakia) as well as in the SW (Transdanubian area, mainly in Hungary). In the Blatné Depression the Eggenburgian marine depositional area was paleogeographically connected to those in the northern part of the Vienna Basin. It belongs to the Čausa Fm. In the Ottnangian the depositional environment started to be brackish, and only a small remnant of these deposits assigned to the Bánovce Fm. is preserved. The Karpatian marine deposits of the Lakšárska Nová Ves Fm. and alluvial-deltaic Jablonica Fm. are present in the northern part of the Blatné Depression and in the Dobrá Voda Depression. Early Miocene deposits in the Transdanubian part represent a stratigraphical continuation from the underlying Buda-type Paleogene and are built up of fluvial – lacustrine or brackish-water gravels, sands and clays sometimes with coal layers (Somlóvásárhely and Tekeres Fms.). The distribution of Paleogene and Lower Miocene formations is presented in Fig. 2.5.

The facies types can be recognized and correlated as follows:

- **Mkb:** open-marine silt/clay *(Karpatian-Badenian)* - Tekeres Schlier and Somlóvásárhely Fms., Čausa, Jablonica, Bánovce and Lakšárska Nová Ves Fms.
- **Olb:** intertidal/lacustrine sandstone/silt/clay *(Oligocene)* - Törökbálint, Mány and Lučenec Fms.
- **Olf:** fluvial/lacustrine clay/marl/sandstone *(Oligocene)* - Csatka Fm.
- **Olmf:** open marine/restricted basin clay/marl *(Early Oligocene)* - Kiscell, Tard and Hrabník Fms.
- **E2-3ml:** open and shallow marine silty and clayey marl *(Middle - Late Eocene)* - Padrag Marl Fm. together with Szentmihályi Andesite Fm.
- **E2ls:** shallow marine limestone, calcareous marl *(Middle Eocene)* - Szőc Limestone Fm.
- **PcE2ml:** shallow marine marl *(Paleocene/Early Eocene)* - Csolnok, Csernye and Priepasné Fms.

Horizon: Neogene volcanites

We included into this horizon all Neogene volcanic products regardless of to which stratigraphic, genetic or petrographic group they belong. Although the existence of several buried Neogene volcanic bodies in the area is well known, our model is the historically first attempt to create an approximate spatial image of these volcanic centres. In our model we distinguished five volcanic bodies: the Pásztori, Rusovce, Kráľová and Šurany bodies proven by boreholes and the anticipated Gabčíkovo volcano. Unfortunately almost all these volcanic bodies are deeply buried, so there is only a limited number of borehole data available. Since similar volcanic bodies known from the surface always comprises products several volcanic phases, dykes and vein systems they are also problematic for seismic interpretation, usually we were able to contour these bodies only very roughly (Fig. 2.6). The degree of knowledge about these bodies is variable.

From the petrographical point of view the volcanic bodies Rusovce, Kráľová and Šurany represent mainly products of Early Badenian (sometimes even Karpatian?) to Sarmatian intermediary andesitic-dacitic volcanism similar to the slightly younger Central Slovakian Neogene volcanites. All three volcanic bodies were penetrated by at least one well and show more or less clear magnetic anomaly (Seiberl et al., 1998), what was an important help for contouring the bodies.

Table 2.3 Summary of known well and seismic data of the neovolcanic bodies in the Danube Basin area

Volcanic centre	Country	Wells	Seismic sections
Pásztori	Hungary	Pá-1, 2, 4; Tét-5, 6	VPA-10, 21, 23, 92; VPE-27, 29
Rusovce	Slovakia	HGB-1	–
Kráľová	Slovakia	Kr-1	MXS-2, 3, 6 (?), 7A; 552/77
Šurany	Slovakia	Š-1	–
Gabčíkovo	Hungary / Slovakia	Msz-1 (?)	XK-1/85; VPE-39 (?) *(Hungary)* 551/81-82 *(Slovakia)*

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The Pásztori volcanic body also shows very clear magnetic anomaly and it is specific from the petrographic point of view, since it - or at least its topmost parts - is built of alkalic rocks (trachytes) and is probably genetically related to nearby alkali basalts (Harangi, 2001). The shape of the Pásztori volcanic body due to the complicated seismic record is not known, we in general respected the idea of Mattick et al. (1996) of a buried, probably subaqual volcano situated on the hanging wall of a remarkable SE-dipping normal fault, where the products of the multi-phase volcanic activity are interlayering with the sedimentary fill on the continously subsiding basement.

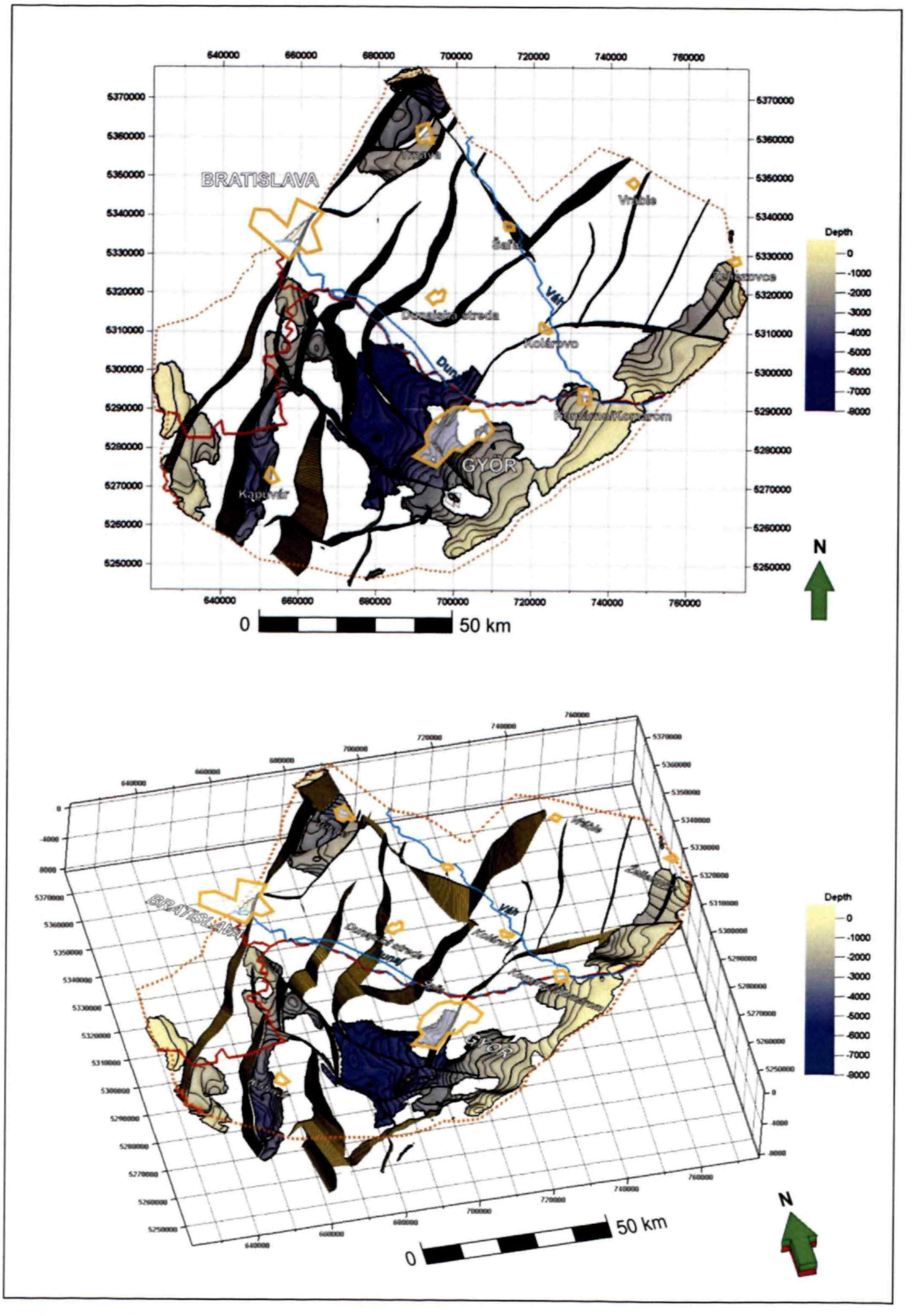

Fig. 2.5 The modelled top surface of the Paleogene - Early Miocene horizon 2D (above) and 3D (below, from SSW)

The most problematic among these volcanic complexes is the biggest one assumed in the wider vicinity of Gabčíkovo village. It is the deepest part of the Danube Basin with estimated depths up to 8 km (Kilényi et al., 1991) so the subsidence of the basin floor in these area was so extreme, that all wells terminated in the Pannonian - thus all complexes below are practically hypothetic, we have no (and obviously never will have) rock samples from these complexes. However, based on the nearest borehole data from the well Msz-1 (village Mosonszolnok, Hungary) situated already on SW-NE elongated morphologic elevation we suppose similar

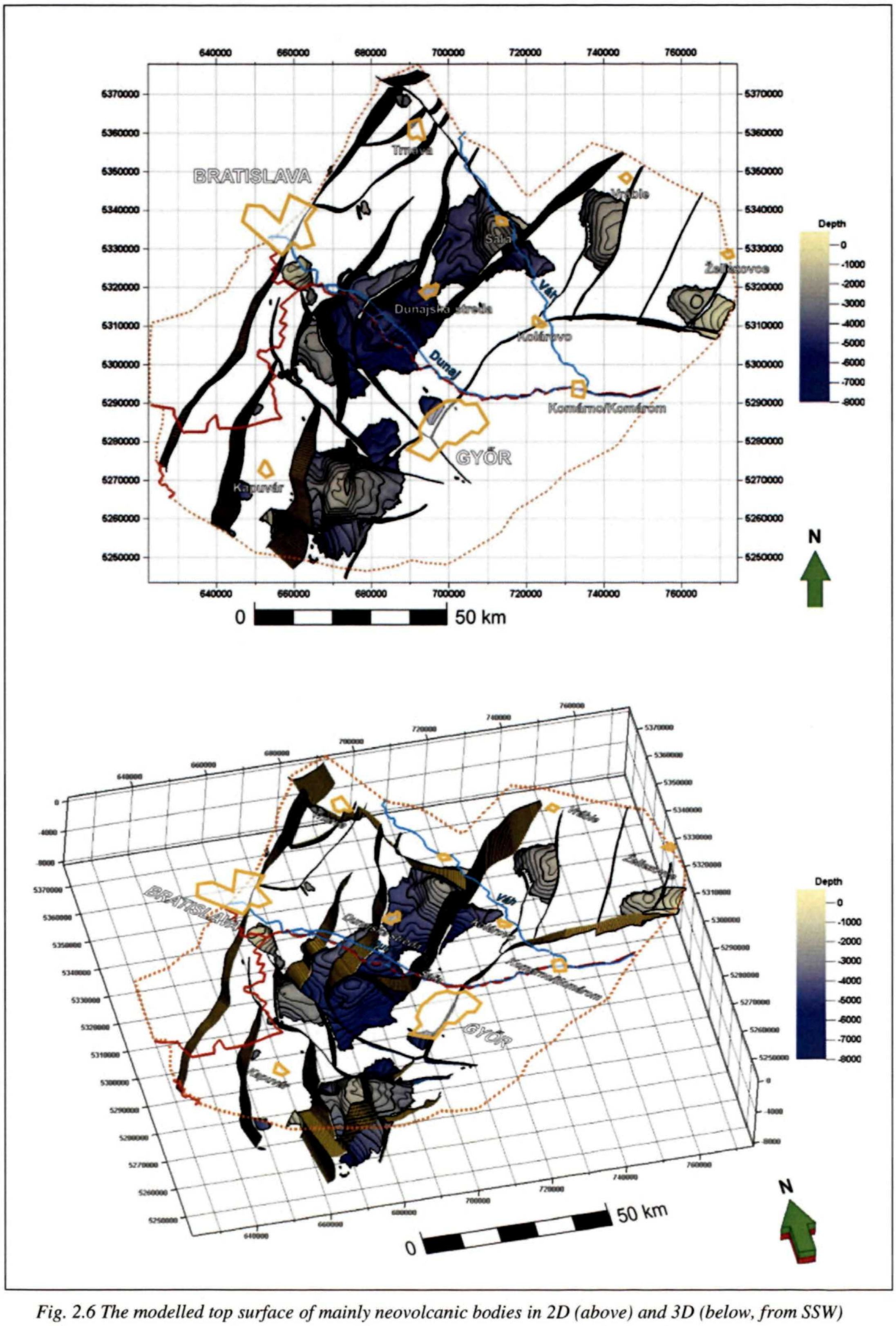

Fig. 2.6 The modelled top surface of mainly neovolcanic bodies in 2D (above) and 3D (below, from SSW)

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andesitic composition as the most of similar bodies (Šurany, Kráľová etc. - except Pásztori). The existence of the deeply buried Gabčíkovo stratovolcano is not a new idea, it was mentioned first time by Vass et al. (1988) and discussed mainly by geophysicists. Volcanoclastics in general, despite of their composition do not show significant magnetic anomalies, thus the very strong and also spatially huge magnetic anomaly near Gabčíkovo (Seiberl et al., 1998) is according to Fiľo et al. (2000), Kubeš et al. (2001) and Bezák et al. (2004) probably caused by two different sources: 1. a deeper source most probably amphibolites of the Tatric (?) crystalline (ca. 5-6 km depth); 2. an overlying huge andesitic complex (top at ca. 3.2 km depth). Since we assume total depth estimates of Kilényi et al. (l.c.) of about 8 km to be more realistic, our model calculated the depth of the basement below supposed volcanic body between 7.8-6.5 km. We also suppose only a relatively thin layer of Early Badenian (or maybe older) basal clastics below this volcanic body, thus we can estimate the height of the body from ca. 7.5-6.5 km up to 4.3-4.4 km in the topmost part of the body - a generally ca. 2-2.5 km high volcanic body. The reasons, why we modelled this horizon below the Badenian sediments even if these volcanites can be sometimes of younger age, are: a) below the volcanites there is - if any - usually only a thin cover of Lower Badenian (or Lower Miocene ?) b) the base surfaces of the volcanites are too deeply buried and very problematic to detect in the seismic profiles through the whole column of structurally very complicated volcanic complex.

The horizon of Neogene volcanites contains lithological types:

- **Msrt:** rhyolitic/andesitic volcanoclastics (Sarmatian-Pannonian);
- **Mbzt**: dacite-volcanoclastics, subvolcanic dacite, andesite (Badenian);
- **Mba**: subvolcanic andesite, andesite volcanoclastics, andesite dyke (Badenian).

The Badenian formations (Mba, Mbzt) roughly correspond to Magasbörzsöny - Dobogókő and Šurany (or Burda) Fms. while the Sarmatian - Pannonian part (Msrt) is representing the Pásztori volcanic body.

Horizon: Badenian basin fill

The lower part of the Early Badenian is missing all over the area due to Early Badenian tectonic movements and erosion. Badenian successions start with the upper part of the Early Badenian with abrasional basal breccia and conglomerate. The Early Badenian transgression came from the S-SW. In this time two main sedimentary basins formed by Early Badenian tectonic movements existed in the SW part of the area: the Csapod Trough in its western part and the Győr Basin in the East divided by the Mihályi Ridge (Hungary), the transgressional event formed in both basal clastic formations (Pusztamiske Fm.). Independently in the NE part of the area (Želiezovce Depression, Slovakia), the Early Badenian basal clastics represented by polymict conglomerates of the Bajtava Fm. transgressively cover the older Štúrovo Paleogene units, and/or the Pre-Tertiary sedimentary and metamorphic rocks. They are associated with algal limestone and sandstone (Leitha Fm., "Leithakalk"), basinwards passing into fine calcareous sandstone and siltstone. Deep-basin (shallow bathyal) facies are represented by fine siliciclastic sediments: sandy silt, silty clay marl with sandstone intercalations (Tekeres Formation), and sandy-silty clayey marl classified into the Baden Fm.

During the Middle and Late Badenian times, the depositional area subsided and widened, covering almost the whole modelled area. The Middle Badenian deposits in their NE and NW parts of the basin (Špačince Fm.) in Slovakia contain organogeneous algal limestone and sandstone. In the Slovakian part of the basin, the depositional log continues with the Late Badenian Madunice and Pozba Fms., comparable with the Szilágyi Clay/Marl Fm. The spatial distribution of the Badenian sediments is illustrated in Fig. 2.7.

The horizon of Badenian sedimentary fill contains facies types:

- **Mbmf:** shallow-marine and open basin clay marl *(Badenian)* - Szilágy, Baden, Tekeres Schlier, Báhoň, Pozba and Bajtava Fms.
- **Mbc:** shoreline coarse/grained clastics/marl *(Badenian)* - Pusztamiske, Jakubov and Špačince Fms.
- **Mbls:** shallow-marine fossil-bearing limestone *(Badenian)* - Lajta and Studienka Fms.

Horizon: Sarmatian basin fill

With the onset of the Sarmatian a significant change occurred, which was triggered by the restriction of the open sea connections of the Central Paratethys. Biogenic calcareous sediments of shoreline facies (Tinnye Formation) and fine-siliciclastic sediments (grey, greenish-grey clay marl, sand, silty clay marl) of shallow-marine facies (Kozárd Fm.) were deposited. The Late Sarmatian carbonate successions indicate a considerably productive carbonate factory of subtropical climate.

In the northern part, the Sarmatian transgression manifested in the deposition of a brackish shallow-water succession (Vráble Fm.), which unconformably overlies various Badenian formations and Pre-Neogene formaions in the marginal part of the basin. The Sarmatian basin fill is built of mostly brackish marine clay and marl with abundant sandy intercalations, containing mostly shallow marine molluscan and foraminiferal fauna. Spatial distribution of Sarmatian sediments is shown on Fig. 2.8.

After correlation we joined all Sarmatian sediments into one facies type:

- **Msmf:** shallow-marine and brackish clay/marl *(Sarmatian)* - Kozárd, Tinnye and Vráble Fms.

The contemporaneous volcanic complexes represented by acid tuffite, andesitic sand and also lava flows were included in the not age-specific horizon of Neogene volcanites (Msrt).

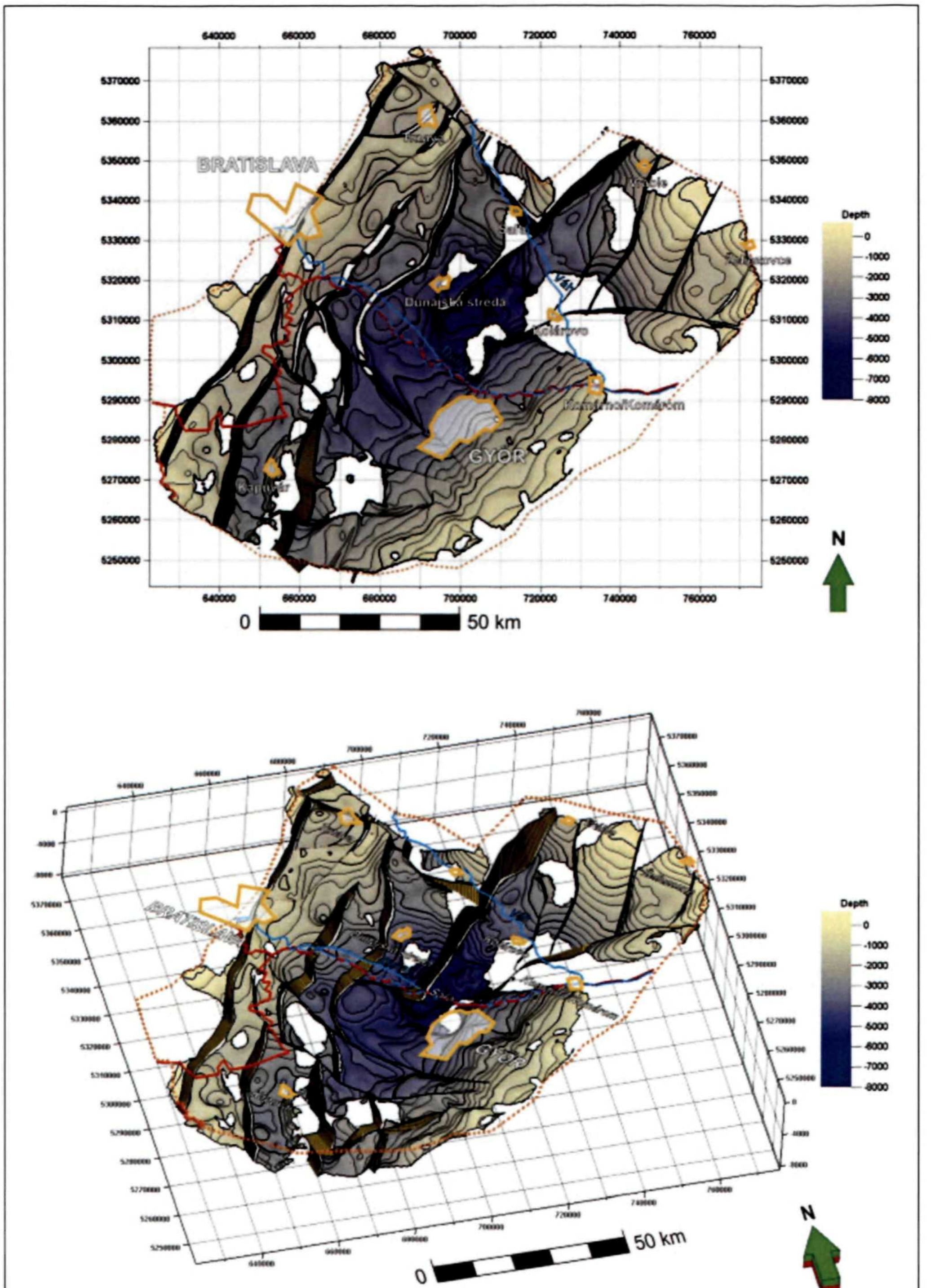

Fig. 2.7 The modelled top surface of Badenian sediments in 2D (above) and 3D (below, from SSW)

Horizon: Early Pannonian basin fill

The Pannonian (Late Miocene and Pliocene) geohistory of the project area is characterized by the presence of the Lake Pannon, isolated from a large open sea Paratethys about 12 Ma ago. The lake reached its largest extent between 10-9.5 Ma, than it was gradually infilled by sediments carried from the surrounding Alps and Carpathians from the NW. The Vienna Basin was the first major sub-basin to be infilled, where the open lacustrine sedimentation was replaced by the deposition of deltaic, and later alluvial units 9.5-10 Ma ago. Then the shelf-slope system started to prograde across the large, deep Danube Basin. The lower part of the Pannonian basin fill - in fact only this part belongs to the previous "Pannonian s. s." in the Slovakian/Austrian realm – contains clayey-silty deposits of subaqueous slopes, shallow water clay and marl, fine-grained sand, silt; variegated clay and limestone.

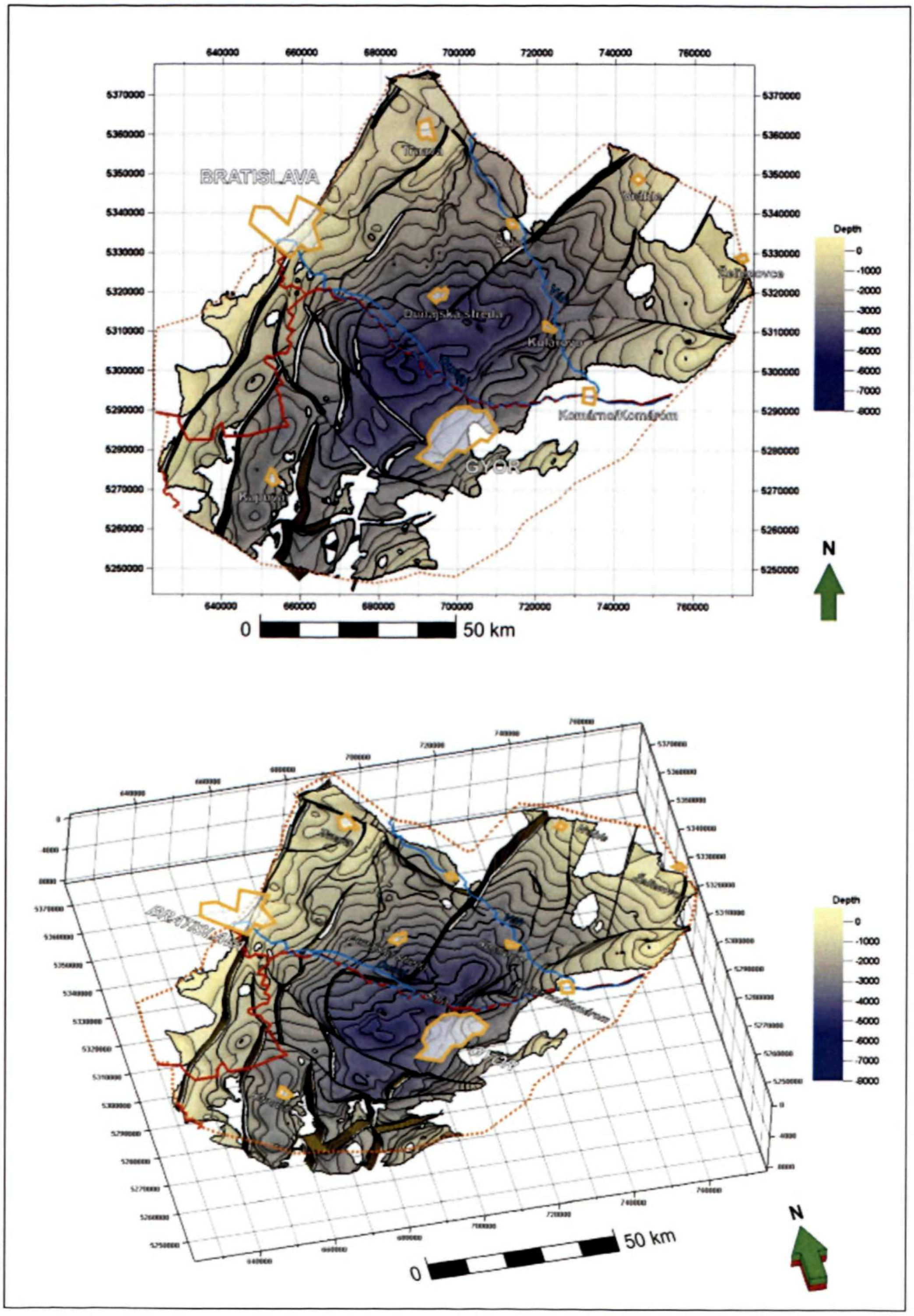

Fig. 2.8 The modelled top surface of Sarmatian in 2D (above) and 3D (below, from SSW)

In our model we defined the Lower Pannonian horizon as the Ivánka Fm. in Slovakia which is correlated with numerous dominantly marly beds in Hungary (Peremarton, Endrőd, Zsámbék, Szolnok, Algyő, Békés, Csákvár Marl Fm., partly also the lower part of Tihany, Újfalu formations). All these formations formed from shallow water to lacustrine environment, the Ivánka Fm. also contains prograding deltaic lobes.

- **Mplf:** shallow-water clay/silt *(Late Miocene - Pannonian)* - Algyő–Szák–Csákvár Clay Marl, Csór Silt, Zsámbék Marl and Ivanka Fms.
- **Mpc:** near-shore psephite/psamite *(Late Miocene - Pannonian)* - Kisbér–Zámor–Kálla–Diás Gravel, Békés Conglomerate, Piešťany Mb. of the Ivánka Fm.
- **Mptb:** turbidite *(Late Miocene - Pannonian)* – Szolnok sandstone Fm.

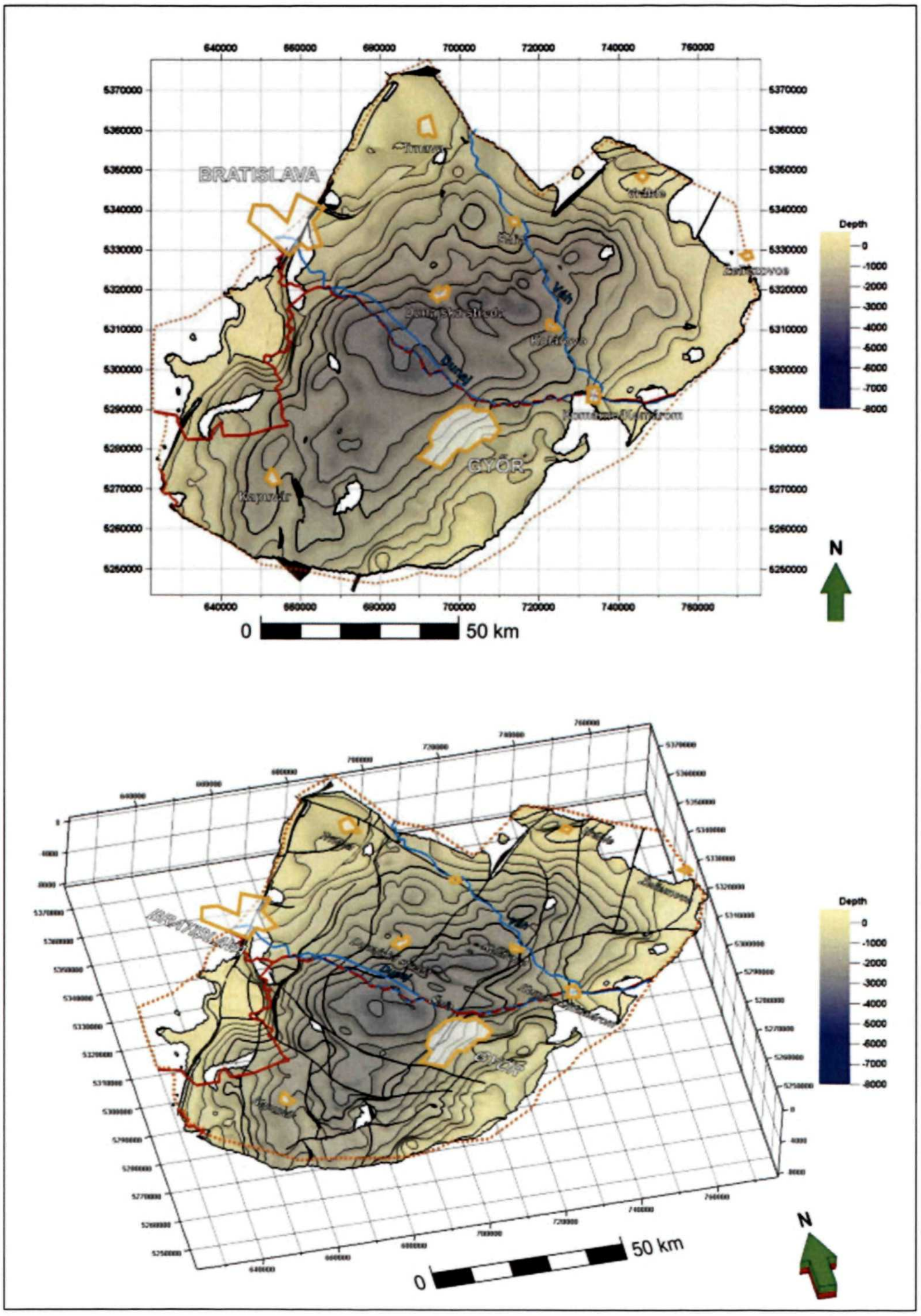

Fig. 2.9 The modelled top surface of Early Pannonian in 2D (above) and 3D (below, from SSW)

- **Mpcm:** calcareous and clayey marl *(Late Miocene - Pannonian)* - Endrőd and Bzenec Fms.

Horizon: Late Pannonian basin fill

We joined the Late Pannonian (Pontian) and Pliocene (Dacian and Romanian) sediments due to their lithological similarities and unclear definition of the boundary between them into one horizon. In the central parts of the Danube Basin their thickness exceeds sometimes 2,500 m. They developed in continuing and further shallowing lacustrine environment changing upward into deltaic and fluvial facies.

The Late Pannonian horizon is present almost in the whole territory, except around the Leitha Mts. on the west, the NW foothills of the Transdanubian Range and partly also in the E part of the area on the foothills of the Central Slovakian Neogene Volcanic Field. The criteria for defining the boundary between the Late Pannonian and Quaternary are not solved yet, in the presented scale.

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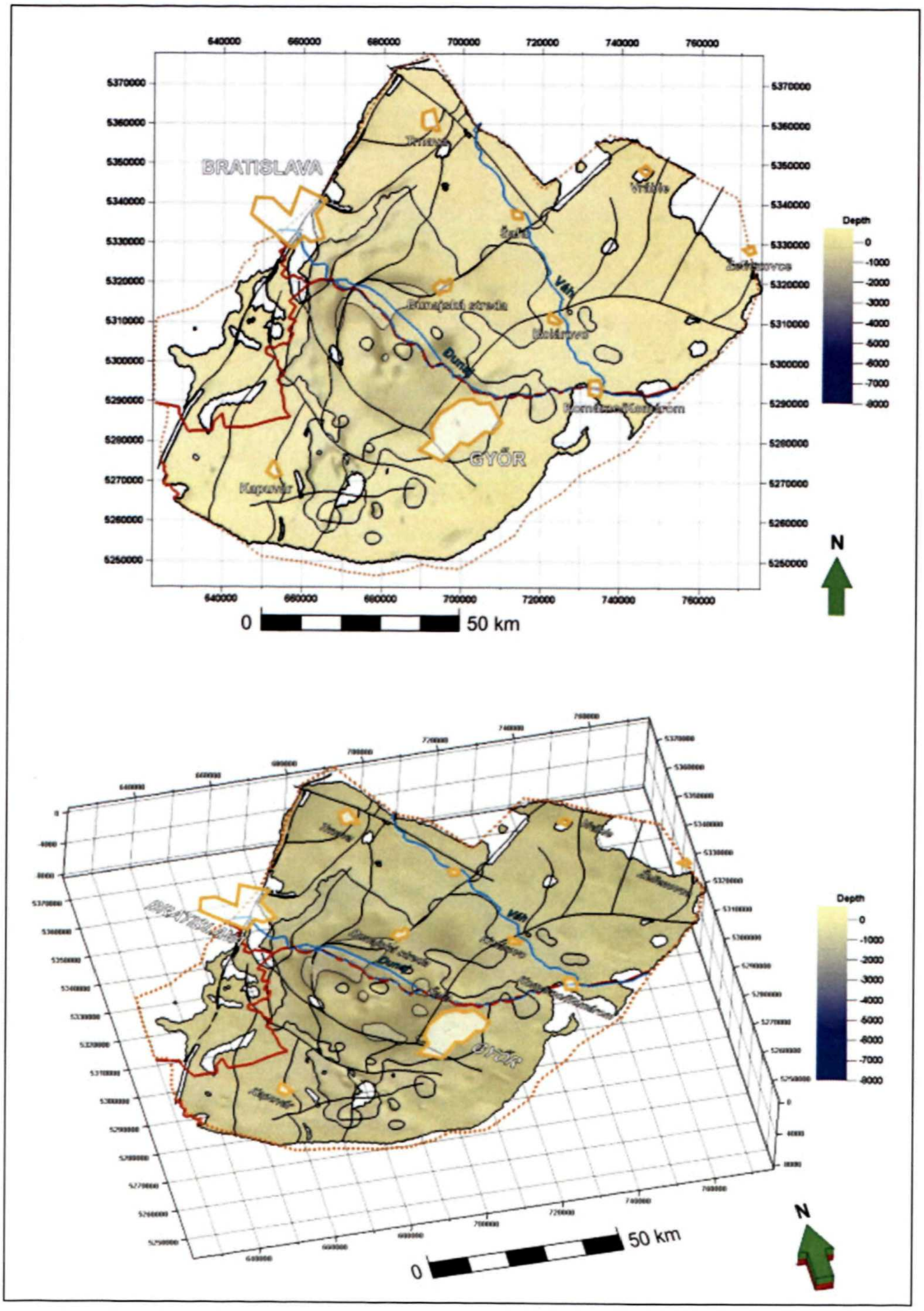

Fig. 2.10 The modelled top surface of Late Pannonian in 2D (above) and 3D (below, from SSW)

In general, the horizon is built mainly of alluvial and lacustrine deposits, which we grouped into two zones:

- **MPl:** a more variegated complex of fluvial – lacustrine and continental clastics, usually in higher stratigraphic position, roughly corresponding with the *Pliocene (Dacian-Romanian)* - Kolárovo, Nagyalföld, Hanság, and Variegated Marl formations.
- **Md**: a more homogenous lacustrine complex (Md), stratigraphically lower *Late Pannonian/Dacian/Pontian* - Volkovce, Torony, Újfalu, Zagyva and Rohrbach Clay formations.

Horizon: Quaternary

The Quaternary horizon was modelled mostly on the basis of the compiled results of the DANREG project (Császár ed., 1998, Scharek et al., 2000).

However, we have got borehole as well as seismic data on the base surface of the Quaternary, showing significant differences in the interpretation of the depth of this surface. The method of joining Slovakian, Hungarian and Austrian datasets of different quality, age of compilation and thus stratigraphic interpretation did not work, so we used the mentioned DANREG outputs, where the same task was once already solved by an international team of experts. Because of the differences in the interpretations and terminology, and also of often small thickness of the deposits, we were not able to divide this horizon into zones.

2.4.2. Structural pattern

The recent structure of the Danube Basin is a product of the Middle Miocene to Pannonian tectonic history, mainly. Due to the huge thickness of basin fill (exceeding 8 km in the central parts) there are many different views of the probable structural patterns. The main fault direction in the area is SW-NE (see Figs. 2.11. and 2.12.) combined with numerous and usually not well detectable faults of roughly perpendicular direction (S-N or SE-NW).

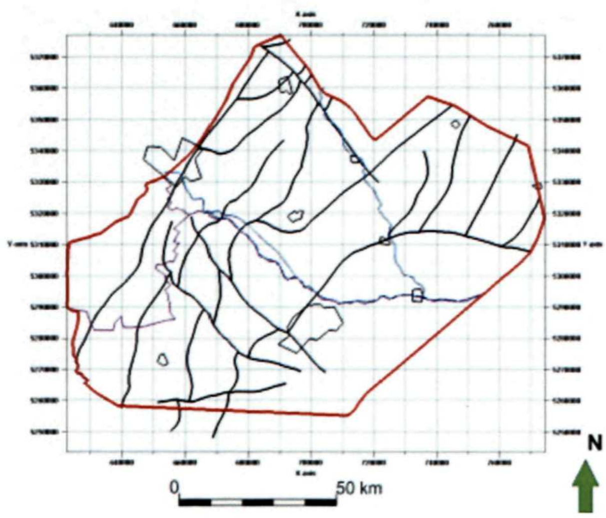

Fig. 2.11 2D fault map

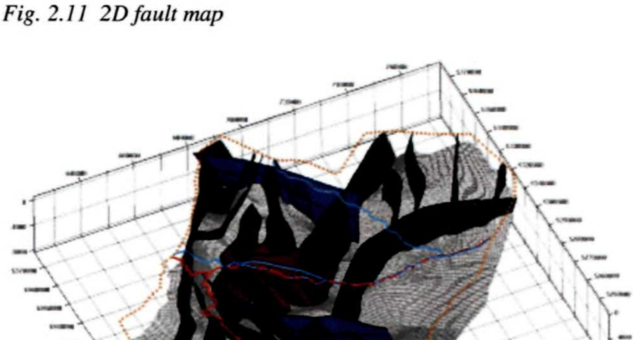

Fig. 2.12 Faults of the area in the 3D model on the basal Pre-Tertiary surface

The basement is dissected by them to a set of elevations and depressions (Fig. 2.13): in Slovakia there are four main depressions defined by NE-SW faults (from N to S): Blatné, Rišňovce, Komjatice and Želiezovce depressions. Except the northernmost and the oldest Blatné Depression, the other depressions are directing into the Central, so-called Gabčíkovo Depression near the Slovakian-Hungarian border, whose depth exceeds 8,500 m. This depression is continuing further to the SW into the Kenyeri - Győr Trough. On the NW side of the Mihályi Ridge an other fault-defined depression, the Csapod Trough of smaller depth is located.

Among these depressions expressively elevated areas - ridges - are located. Since some of them reach the surface - mostly outside the studied area in the mountains Malé Karpaty, Považský Inovec, Tríbeč, Mid-Hungarian Range and Leitha Mts. - another ones stay buried as the Mihályi (-Úľany?) ridge and the Levice and Komárno elevations.

The fault pattern used in the model is strongly simplified for the purposes of further use in the hydrogeological model. The fault model is based on the seismic record, in the areas with poor coverage by seismic profiles we considered also different available sources (Hrušecký, 1999; Pěničková at el., 1984; Fusán et al., 1987; Tari 1994, Dudko et al., 2000, Császár et al., 2000, Maros et al., 2012) as well as personal consultations with experts (our thanks belong especially to M. Kováč and M. Pereszlényi).

Since the model was created on seismic and well data of different quality and density, while some modelled faults well correspond to known fault lines, many of them are hypothetical, created for reasons of steep basement morphology, or on the other hand, some smaller faults are neglected or joined together into one fault zone for the optimization of the model. At the beginning of the project the team of geologists working on modelling agreed to deal with only those faults which have a vertical dislocation at least 500 meters. However, in many cases we could not follow this, because of the fading out or forking of the fault planes, or simply because geologically important lines (for example the Rába line) had less vertical dislocation.

The faults finally included in the model can be divided into two main groups according to their directions: NE-SW faults and faults roughly perpendicular to them of NW-SE or W-E directions. Since the majority of seismic profiles is oriented roughly in the NW-SE direction, faults perpendicular to that direction are much better traceable than faults parallel to them. Thus, we should expect much more faults in NE-SW directions but we were not able to incorporate them into our model.

Faults of NE-SW direction incorporated into the model, as they are shown in Fig. 2.13:

A. Normal fault on the SE slopes of the Malé Karpaty Mts. continuing into Austrian territory in the area of lake Neusiedl and Leitha Mts., created by joining of main and some smaller faults together, active to recent;

B. Two curved normal faults on the S and SE side of the Blatné Depression; simplified from more faults (e.g. the Považie fault system), terminated at the end of Sarmatian;

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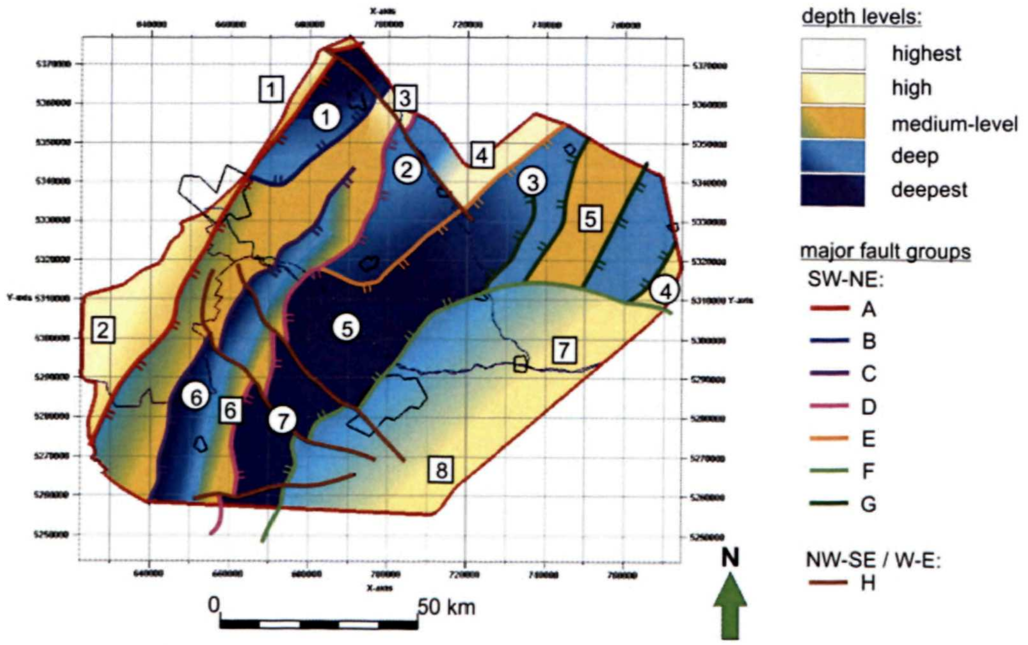

Fig. 2.13 Structural scheme of the modelled area: main elevated areas *(numbers in rectangles): 1 - Malé Karpaty Mts.; 2 - Leitha Mts.; 3 - Považský Inovec Mts.; 4 - Tribeč Mts.; 5 - Levice High Block; 6 - Mihályi (-Úľany?) Ridge; 7 - Komárno High Block; 8 - Transdanubian High Block;* main depressions *(numbers in circles): 1 - Blatné Depression; 2 - Rišňovce Depression; 3 - Komjatice Depression; 4 - Želiezovce Depression; 5 - Gabčíkovo Depression; 6 - Csapod Trough; 7 - Kenyeri-Győr Basin; for faults: see text*

C. Normal fault NW of the Csapod Trough – hypothetical, dipping to the SE, terminated mainly at the end of Sarmatian, some parts in the Pannonian;

D. Ripňany - Galanta fault - very steep normal fault on SE side of the Považský Inovec Mts. dipping to the SE, active to recent;

E. Mojmírovce fault - very steep normal fault dipping to the SE delimiting the elevation of the Tríbeč Mts., active to recent;

F. Rába - Hurbanovo - this south-dipping tectonic surface is one of the geologically most important ones in the area, which was originally a Mesozoic overthrust plane of the Transdanubicum onto the Austroalpine and Tatric-Veporic units, but during the early Middle Miocene was rejuvenated and functioned as an extensional listric plane in opposite direction; in the model we modelled this fault as a complicated curved normal- to reverse fault cut by NW-SE strike-slip faults, terminated at the Pannonian;

G. normal faults in the E part of the area to the NW (Šurany fault) and SE of the Levice High Block;

We were able to define only four major faults in NW-SE direction (H. in Fig. 2.13):

- the problematic Ludina line in the northernmost part of the area cutting the NE-SW directed Malé Karpaty, Blatné Depression, Inovec and probably even Mojmírovce faults. The character of the fault is unclear, we modelled it as a steep normal fault dipping to the SW, in the N part with a dextral strike-slip component;

- two parallel NW-SE and one rather W-E directed normal faults with dextral strike-slip component dipping to the NE or N, respectively; all three appear in the Transdanubic block, the two NW-SE faults cut the Kenyeri-Győr Trough, Mihályi Ridge and Csapod Trough, the third and southernmost W-E fault after cutting the Mihályi Ridge continues off the studied area.

These faults are dividing the area into higher or deeper level blocks, whose relative positions are summarized in Fig. 2.13.

One of the most important outputs of the modelling were cross sections demonstrating the resume of the geological structure of the area (Fig. 2.14).

2.5. Conclusions

The whole TRANSENERGY project area - called the supra area - was subdivided into five partial basins called pilot areas, where the State Geological Institute of Dionýz Štúr was entrusted with the work on the Danube Basin pilot area. For the purposes of the project we created a 3D geological model of the area as an input for hydrogeological model, but its partial results have their specific importance and can be evaluated independently.

The 3D model was built from all available data (409 wells and 82 seismic sections) known from the area regarding many published works about the structure of the basin. For the purposes of the model a unified and simplified stratigraphical scheme was compiled derived from the Slovak, Hungarian as well as Austrian local stratigraphic charts, which can be considered an important result. However similar attempt already was made in the framework of the project DANREG, our harmonized stratigraphic scheme is based more on lithology and genetic features and can be considered more universal.

The 3D geological model itself is the historically first attempt of its kind to visualize the whole Danube Basin in 3D and in the future can serve as a base for further, more

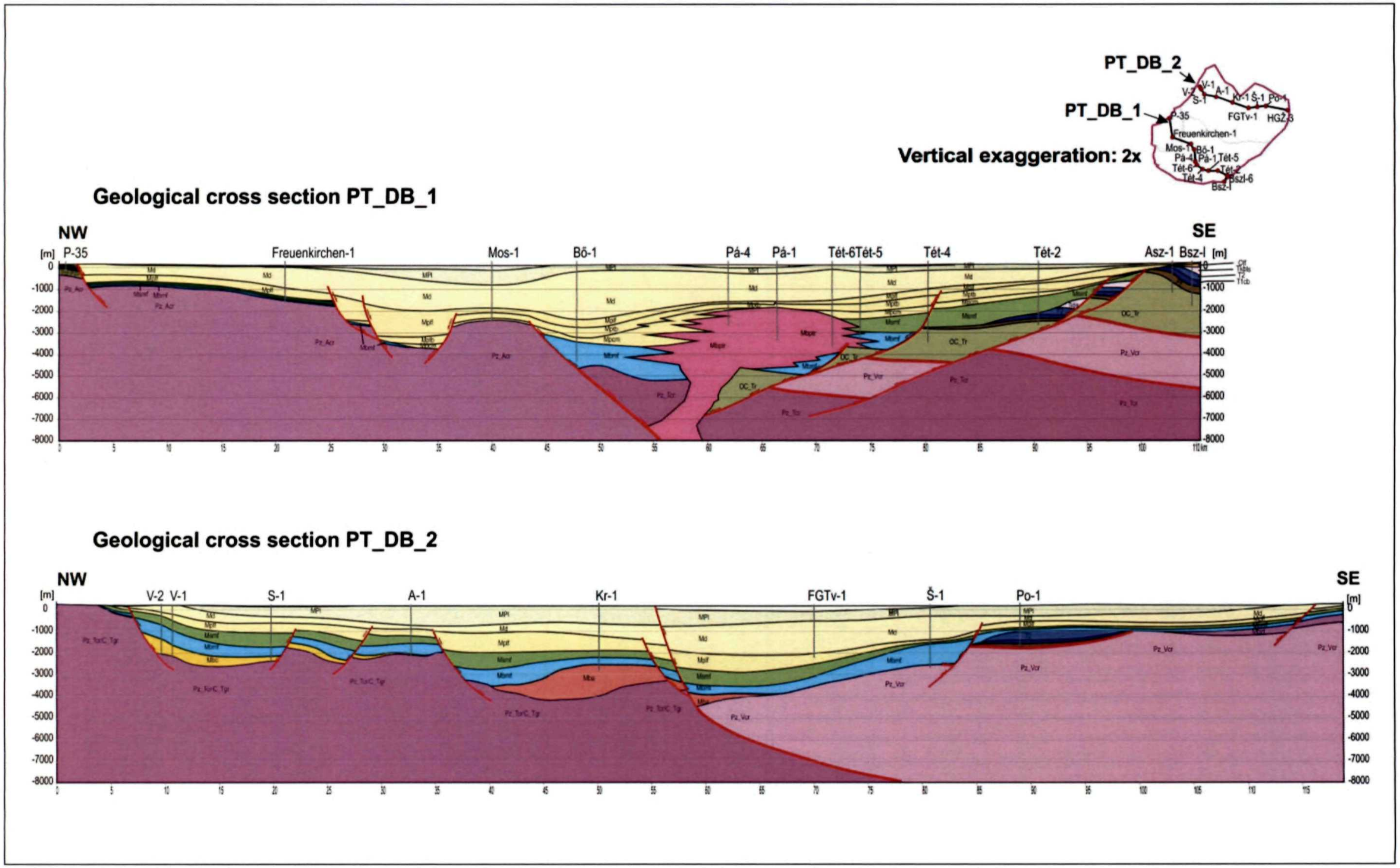

Fig. 2.14 Cross sections created based on the 3D geological model

Q	*Pleistocene - Holocene*: sediments in general
MPl	*Late Miocene - Pliocene*: fluvial-lacustrine-continental sand, silt, clay marl; mottled clay; lignite; gravel
Md	*Late Miocene (Late Pannonian):* lacustrine, sediments of delta plain: clay marl, silt, fine-grained sand; calcareous clay, variegated clay, lignite,dolomite; freshwater limestones, boglime and travertine
Mplf	*Late Miocene - Pannonian:*clay silt deposite on underwater slope, shallow-water clay marl, fine-grained sand, silt; variegated clay, limestone
Mptb	*Late Miocene - Pannonian:* turbidite
Mpcm	*Late Miocene - Pannonian:* lacustrine calcareous marl – clay marl; sandstone
Msmf	*Sarmatian*: shalow-marine – brackish-water, mollusc-bearing clay - clay marl; sand-sandstone, calcareous
Mbmf	*Badenian*: shallow-marine and open basin foraminiferal mollusc-bearing clay marl, clay
Mbptr	*Miocene, Badenian - Pannonian:* trachyte agglomerate, tuff
Mba	*Badenian*: subvolcanic andesite, andesite pyroclastics, andesite dyke
Olf	*Oligocene*: fluvial-lacustrine-paludal clay, clay marl, sand-sandstone, gravel, conglomerate
Tkbls	*Late Triassic - Carnian*: basinal marl and limestone, bituminous limestone, dolomite
T2	*Middle Triassic* sediments in general
T1cb	*Early Triassic*: siliciclastic and carbonate formations
Pt	*Middle-Late Permian*: continental siliciclastic formation
PzF-PzS	*Paleozoic*: medium-grade polymetamorphic formations with Alpine overprint (gneiss, mica schist, phyllite, pegmatite, leucophyllite, quartzite, quartz schist)
OC_Tr	*Early Paleozoic?:* Veporic unit - gneiss, schist, phyllite, marble
Pz_Vcr	*Ordovician - Carboniferous:* Low-grade metamorphic formations (slate, calc-phyllite, quartz phyllite, quartz metasandstone, metaconglomerate, basic metatuffite, limestone)
Pz_Tcr	*Early Paleozoic?*: Tatric unit - gneiss, schist, phyllite, marble, amphibolite
Pz_Tcr/ C_Tgr	*Early Paleozoic?, Carboniferous:* Tatric unit - gneiss, shist, phyllite, marble, amphibolite, biotitic and two-mica granite, granodiorite and tonalite, leucocratic granite, diorite
Pz_Acr	*Early Paleozoic?:*Austroalpine units - gneiss, schist, phyllite, marble, amphibolite
	geological boundary
	nappe overthrust plane
	normal fault
Po-1	borehole

Legend to Fig. 2.14

precise models. Based on the formerly compiled unified stratigraphic chart we agreed on the horizons to be modelled, however during the work two additional horizons were created (Paleogene - Early Miocene and Neogene volcanites). The final model contains horizons defined by their age - except the Neogene volcanites (bottom to top):

- Pre-Cainozoic basement surface (divided into 15 zones);
- Paleogene - Early Miocene (divided into 7 zones);
- Neogene volcanites - not age-specific horizon (divided into 3 zones);
- Badenian sedimentary fill - without volcanites (divided into 3 zones);
- Sarmatian - without volcanites (containing only one zone);
- Early Pannonian - comprising "Pannonian s.s." (divided into 4 zones);
- Late Pannonian - comprising Pontian and Pliocene (divided into 2 zones);
- Quaternary (undivided).

The structural pattern of the area was simplified after several consultations into a scheme of 7 approximately SW-NE and 4 roughly NW-SE to W-E faults.

The model is also the first attempt to visualize the Neogene volcanic bodies buried below younger sediments. In addition to well and seismic data the geophysical - mostly geomagnetic - anomalies were considered for their contouring. We defined five buried volcanic bodies in the area: Šurany, Kráľová, Rusovce, Pásztori and Gabčíkovo. The most problematic among them is the Gabčíkovo volcano, whose existence was contemplated formerly by different authors. The main argument for defining this volcanic body was the huge magnetic anomaly measured in the area and showing very similar image as other bodies proven by wells.

The final 3D geological model and the "by-products" of the modelling (e.g. stratigraphic scheme) were used - according to their primary aim - as an input to thermal and hydrogeological modelling of the same area in the next working phase of the project. Some of the products of the model can be, however, useful also separately (cross-sections, base-maps etc.) and the model itself, we hope, will serve as a base for more accurate models in the future.

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