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# Summary report of geological models

**Title** Summary report of Geological models

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**Project** TRANSENERGY –Transboundary Geothermal Energy Resources of Slovenia, Austria, Hungary and Slovakia

**Work package** WP5 Cross-border geoscientific models
5.2.1. 3D geological model

## CONTENT

# 1 Introduction

The aim of the Transenergy project is to support the harmonized thermal water and thermal 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.

This report describes the results of the geological models, which serve as a frame for the hydrogeological and geothermal models. Although the problems of transboundary thermal water utilization can be locally confined, they are rather connected to distant hydrogeological processes. Therefore the modelling activity had to be done at two different scales.

The so called **Supra regional** model includes the entire project area and manages the complete area in a uniform system approach.

Five **Regional or Pilot areas** were chosen, where local models had been developed. They focus on the local transboundary problems, and the detailed geological characteristics of the areas. These areas are the following (Figure 1).

- Vienna Basin
- Danube Basin
- Komarno-Sturovo area
- Lutzmansburg-Zsira area
- Bad Radkensburg-Hodos area

# 2 Project area definition

The same aspects were considered to outline the different area boundaries, both at the supra-regional and local scales. The most important consideration of the outlining was to define natural model boundaries. Assigning the contours of the model areas the following aspects were taken into consideration:

- Geological framework of the areas,
- Important tectonic structures
- Recharge areas, connecting the thermal water system (the recharge areas do not include the entire mountain regions, only the regions where the main thermal water bearing layers outcrop at the surface),
- Rivers as main discharges,
- Contours of groundwater bodies,
- Groundwater divides

The final borders of the model areas consist of the mixture of different boundary types mentioned above.

The supra-regional model area encompasses the main geothermal reservoirs of the NW Pannonian Basin and the adjacent areas where the different natural and human processes have effects on the geothermal systems. Within the project area several sub-regions of enhanced hydrogeothermal utilization potential (pilot areas) have been identified and investigated in a more detailed way.

The pilot areas usually form geological or hydrogeological units. The Vienna Basin is a deep sedimentary basin surrounded by mountains, the outer border of the Eastern Alps and

Central West Charpatians. It joins to the Danube Basin at the SSE edge. The Danube Basin is a deep sedimentary basin too. The border of the model area was appointed along the pinch out, truncation and thinning of sedimentary formations. Due to the location of its recharge area, it locally overlaps to the Komarno-Sturovo model area. This latter one was outlined along regional fault systems which often coincide with the border line of groundwater bodies. The Bad-Radkersburg-Hodos model area is mainly bordered by tectonic structures too, forming a tectonic halftrench. The Lutzmansburg-Zsira model area is not connected to a specific geologic or hydrogeologic unit. The western border of the area forms the margin of the Neogen basin. The other parts are appointed along artifical borders, taking into account that the area includes the important Hungarian spa „Bük”.

The vertical boundary of the geological models has been defined at the depth of 8000 m below see level. The Supra regional and Pilot areas are shown on Fig. 1.

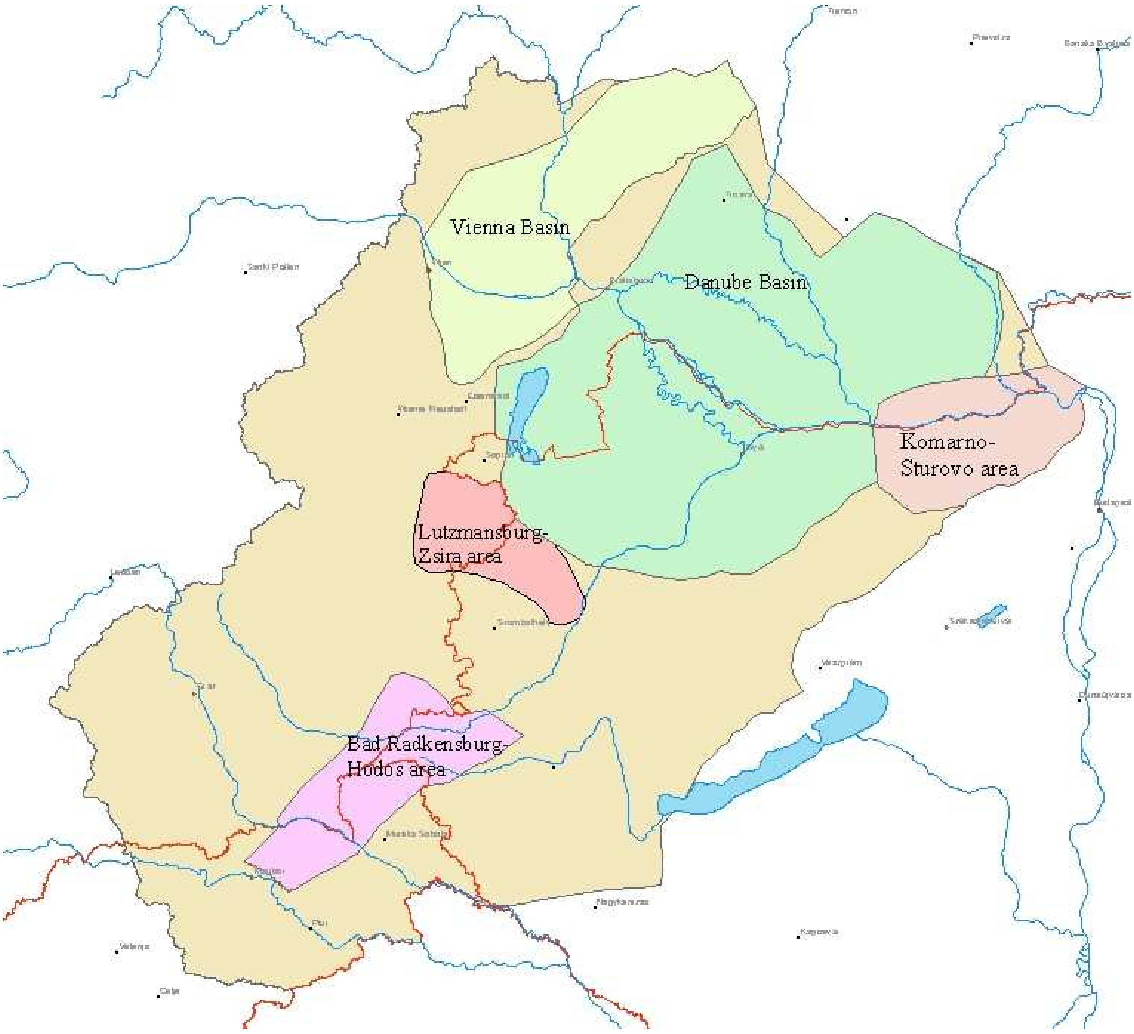

Fig. 1. The supra-regional and the pilot model areas

Figure 2 shows the generally used geographical names and morphological conditions of the whole project territory. It is characteristically a lowland and basin area, the recharge mountainous regions have only marginal positions. Two capitals of the partner countries lie on the supra area, Vienna and Bratislava, but numerous populated citys are in it i.e. Győr, Graz, Maribor.

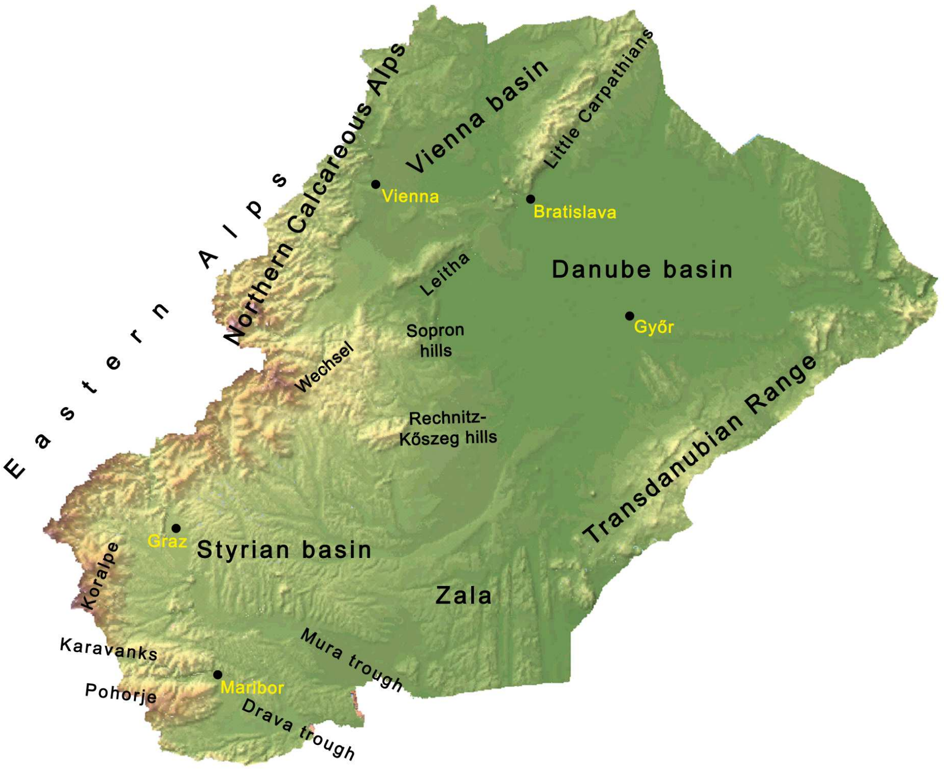

Fig. 2. Often used geographical terms in the project area

# 3 Geological modelling in general

In the following, we demonstrate the main features and steps of creating the geological models at different scales.

## 3.1 Scales and workflow

The final products scales of the Supra regional and Regional area models are the following:

| | |
|---|---|
| Supra regional area | 1:500 000, Surface geology 1: 200 000 |
| Danube basin | 1:200 000, |
| Vienna Basin | 1:200 000, |
| Lutzmasburg-Zsira | 1:100 000, |
| Bad Radkensburg-Hodos | 1:200 000, |
| Komarno-Sturovo | 1:200 000. |

The applied workflow can be seen on Figure 3. The greyish columns represent work months. The workflow could be devided into 3 parts: 1) Evaluation and systematization of geological data, 2) Correlation among data systems, 3) Geological modelling. Note the double headed arrows that figure the necessary iterative processes which were the most time-consuming working steps.

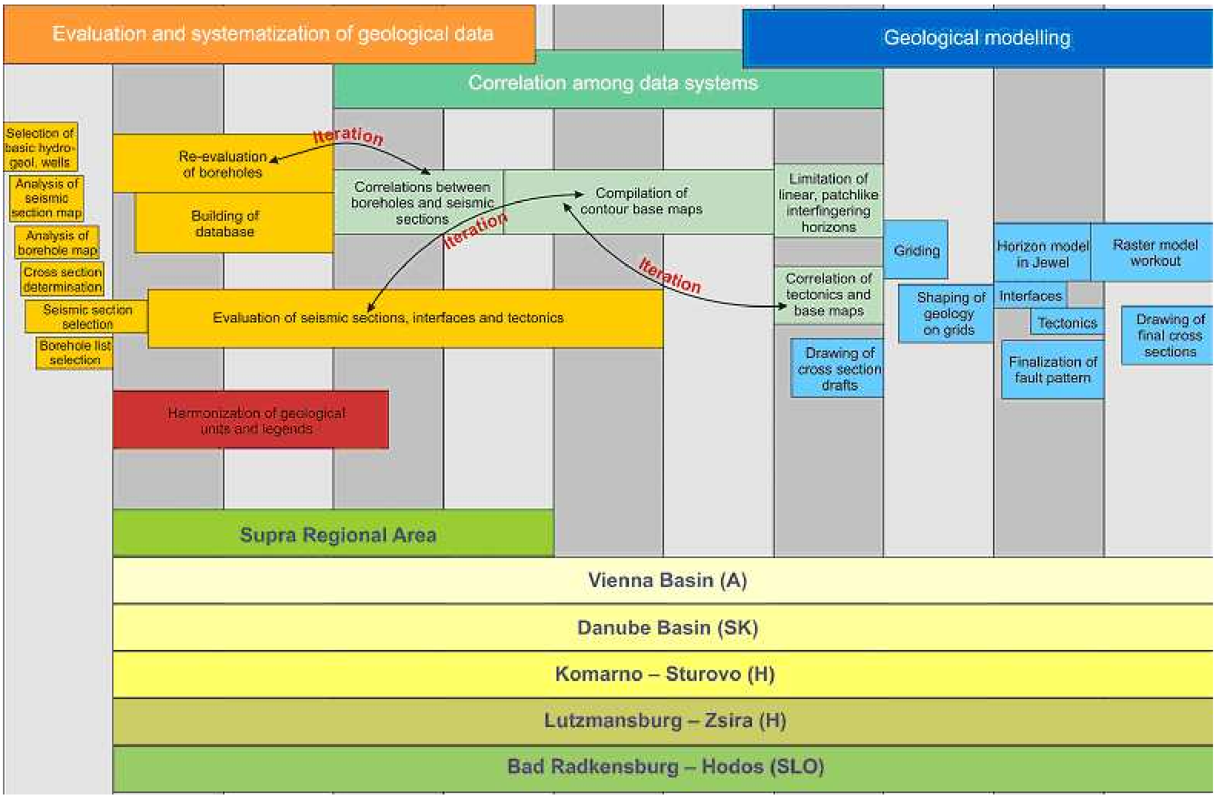

Fig. 3. Workflow chart of geological modelling. The greyish columns are work months.

The country codes after Pilot area models show, that each Pilot area model was dedicated to responsibility of different partner countries.

## 3.2 Correlation of the formations

One of the first data harmonization steps had to be the correlation of different formations. These formations describe sometimes the same lithologic and time frame of the geological buildup of a partner country with different synonymes, but more often the different names can cover slightly different rock columns as well. The most problematic question was the harmonization of the Post-Oligocene formations of the Paratethys.

As a start-up three available regional correlation charts were used, the Correlation chart of the Geological Map of Western Carpathians and adjacent areas (Lexa et al. eds. 2000), the Danreg project maps and explanatory notes (Császár et al 1998) and T-JAM project (Fodor et al. 2011).

The result of the harmonisation and correlation charts for the Paleogene, Neogene and separately for the Pannonian age are demonstrated in chapter 4.

## 3.3 Harmonized legend and surface geological map

The catalogue of commonly used names concerning the regions and formations that do not fall within the competence of the correlation committees had to be elaborated. The unified legend and indexes were created following the philosophy of the OneGeology project.

To develop the harmonized legend, the scale of the maps and sections (Chapter 3.1.), andthe agreement with a common symbol system was essential.

During the meetings it gradually became clear, that different scales with different details, symbols, sizes of the units on the surface map cause additional problems. So a final decision was born, that the scale of the Supra area geological map will be exceptionally 1:200 000.

The composition of the legend started with the Hungarian part. Here a surface geological map at a scale of 1:200 000 was available, which had a given type of symbols (first the age, after a number growing from the youngest to the oldest deposits).

In the Slovenian part, the original maps had the scale of 1:100 000 from the ‘80s; the symbols were numbers. Hungary and Slovenia had a joint project (T-JAM), where a correlated surface geological map was compiled of the two countries on the scale of 1:100 000. It covered only the eastern part of the Slovenian Supra area territory, but we solved the problems remained at the Hungarian-Slovenian border on the surface map. So it was an easy task to reach the same result at a scale of 1:200 000. The western part of Slovenia’s map was compiled by the Slovenian geologists using the symbols of the created harmonized legend system,.

The Slovakian part did not have too many problems either. Slovakia has a series of 1:200 000 surface geological maps; only the legend elements had to be correlated with the symbols of the other countries. There were no problems on the surface map in the border region, because the Danube and the Ipel rivers separate Hungary and Slovakia and their formations. Here, we had to correlate the tectonic units (e.g. Tatricum, Fatricum, Hronicum etc.) of the Alpine and Carpathian region.

In the Austrian territory we had an unexpected problem to solve. Austria had digital surface geological maps of 1:200 000 covering the major part of the Austrian Supra area territory, except for the Steiermark sheet, which had too “good resolution” in digital form, at a scale of 1:50.000. In addition a good map was available in scale of 1:200 000, but it existed only in printed form. It was decided that instead of generalization of the 1:50 000 map, we digitalised the printed map, and afterwards we made harmonization with the other Austrian parts, changed the old symbols (numbers) to the new ones, and made the harmonization at the borders.

As a result the surface geological map at a scale of 1:200 000 with a harmonized legend was compiled, which is a considerable result of the whole project. The newly created symbol shows the age first, followed by the facies or genetics of the formation, the lithology, and the tectonic unit (age is in every symbol, the others appear only when more variations have to be distinguished within a given age).

The harmonized legend is applied for all model horizons (e.g. Pre-Sarmatian, Pre-Badenian etc.) and for the geological sections, too. Here, inevitably new formations appeared which were incorporated into the legend.

Another source of legend symbols was the database of boreholes. In those cases, where it was not possible to resolve all appropriate formations, we had to create sum-up legend units and symbols.

Time by time iterations and cross-checkings were made between the surface map, the horizont-maps, boreholes and the sections. At the end we have near 200 (exactly 197) legend units, grouped by ages: Quaternary+Plio-Quaternary – 19, Pliocene+Late Miocene, Pliocene – 3, Miocene – 48, Oligocene+Oligocene-Pliocene – 8, Eocene+Eocene, Oligocene – 12, Palaeocenec+Palaeocene, Eocene+Paleogene – 10, Cretaceous – 27, Jurassic, Creatceous+Jurassic, Eocene – 10, Jurassic – 6, Triassic – 16, Mesozoicz +Palaeozoic, Mesozoic– 9, Permian+Permian, Triassic – 7, Cambrian-Ordovician-Silurian-Devonian-Carboniferous 14, Palaeozoic – 8.

The harmonized legend is shown in the following Table 1.

| | Transenergy symbol | Lithology | Detailed age | HU-200 map symbol | Hungarian Unit-name | Slovak symbol | Slovakian Unit-name | Slove-nian symbol | Slovenian Unit-name | HU-A symbol | Austrian symbol | Austrian Unit-name |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | **Qs** | Soil (in boreholes) | Holocene | | | | | | | | | |
| 2 | **Qa** | Anthropogeneous deposit (banks, mine dump, slurry) | Holocene | Qh1 | | | | | | 10 | 1 | |
| 3 | **Qh** | Holocene sediments in general | Holocene | | | | | | | | | |
| 4 | **Qhf** | Fluvial sediment (clay, silt, sand, gravel) | Holocene | Qh2, Qh3, Qh4 | | 1.2 | Fluvial | 3,7,8,9 | | 20 | 2,3,4,13,14,21 | |
| 5 | **Qhpd** | Proluvial-deluvial sediment (sandy silt, silt) | Holocene | | | | | 100 | | | | |
| 6 | **Ql** | Lacustrine sediment (clay, silt, fine-grained sand) | Holocene | Qh6, Qh7 | | — | | | | 30 | 6 | |
| 7 | **Qb** | Paludal sediment (clay, silt, sand, calcareous mud) | Holocene | Qh8, Qh9 | | — | | 4,5,6 | | 40 | 5 | |
| 8 | **Qes** | Drift sand | Holocene | Qh10, Qph1 | | 10 | Eolian sand of dunes | | | 50 | | |
| 9 | **Qph** | Pleistocene–Holocene sediments in general | Pleistocene–Holocene | | | | | | | | | |
| 10 | **Qsp** | Slope sediment (clay, silt, sand, gravel, rock debris) | Pleistocene–Holocene | Qph2, Qph3, Qph4 | | | | 4 | | 60 | 7,10 | |
| 11 | **Qsl** | Slide sediment (clay, silt, sand, gravel, rock debris) | Pleistocene–Holocene | Qph5 | | | | | | 70 | 9 | |
| 12 | **Qfe** | Fluvial-eolic sand | Pleistocene | Qp1 | | 7 | Fluvial to fluvial-eolian sand | 10 | | 80 | 11,12,16 | |
| 13 | **Qpf** | Fluvial clay, silt, sand, gravel | Pleistocene | Qp2, Qp3, Qp4, Qp8, Qp11 | | 6,6a,b,c, 13,13a,b,c, 16 | Fluvial sediments | 13 | | 100 | 29,30,31,32,36,38,40,42,44,46, 48,49,51-61,63,64, 66,68,483, 490,492,515,522 | |
| 14 | **Qel** | Loess | Pleistocene | Qp5, Qp6 | | 9 | Eolian loess | 11.12 | | 90 | 15,22,28 | |

|  | Transenergy symbol | Lithology | Detailed age | HU-200 map symbol | Hungarian Unit-name | Slovak symbol | Slovakian Unit-name | Slove-nian symbol | Slovenian Unit-name | HU-A symbol | Austrian symbol | Austrian Unit-name |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 15 | **Qpp** | Proluvial clay, silt, sand, gravel, rock debris | Pleistocene | Qp13 |  | 3,8,8a,14,14a,17,17a,b | Proluvial sediments |  |  | 120 | 18 |  |
| 16 | **Qmo** | Glacigene sediment (moraine, breccia, terrace) | Pleistocene |  |  |  |  |  |  | 125 | 34,502,503 |  |
| 17 | **Qp** | Pleistocene sediments in general | Pleistocene |  |  |  |  |  |  |  |  |  |
| 18 | **Qls** | Travertine | (Pontian)–Pliocene–Pleistocene | Qp12, PlQp1 |  | 18, 30 | Travertine |  |  |  |  |  |
| 19 | **PlQfc** | Fluvial up to alluvial – limnic argillaceous, strongly weathered sandy gravel, sand and sandy clay | Pliocene–Pleistocene | — | Tengelic Fm | 19 | Fluvial to alluvial gravel and sand | 13 |  |  |  |  |
| 20 | **Pl** | Pliocene sediments in general | Pliocene |  |  |  |  |  |  |  |  |  |
| 21 | **MPl_f** | Fluvial–lacustrine–continental sand, silt, clay marl, mottled clay; lignite; gravel | Late Miocene – Pliocene | MPl2 | Zagyva Fm, Nagyalföld Fm. | 27, 27a, 28, 38 | Volkovce and Kolárovo Fm., Gbely Fm. | 151 | Ptuj-Grad Fm | 130 | 72,73,74,76,77 | Rohrbach Formation |
| 22 | **MPl_1** | Alteration of clay, sand and gravel deposited on deltaic and alluvial plains | Late Miocene – Pliocene |  | Újfalu Sandstone, only upper part (Szentes Mb), Somló–Tihany Fms., Zagyva Fm., Nagyalföld Fm. |  | Beladice Fm., Volkovce Fm., Kolárovo Fm., Gbely Fm. |  | Mura Fm., Ptuj-Grad Fm. |  |  |  |
| 23 | **MPl_2** | Thick sand sheets of delta front origin, with overlying clay, sand and gravel deposited on deltaic and alluvial plains | Late Miocene – Pliocene |  | Újfalu Sandstone lower and upper part (Mindszent and Szentes Mb), Zagyva Fm., Nagyalföld Fm. |  | Čáry Fm., Beladice Fm., Volkovce Fm., Kolárovo Fm., Gbely Fm. |  | Mura Fm., Ptuj-Grad Fm. |  |  |  |

| | Transenergy symbol | Lithology | Detailed age | HU-200 map symbol | Hungarian Unit-name | Slovak symbol | Slovakian Unit-name | Slove-nian symbol | Slovenian Unit-name | HU-A symbol | Austrian symbol | Austrian Unit-name |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 24 | **MPl_3** | Lignite, silt, clay and carbonaceous clay deposited in shallow basins or deltaic and alluvial plains | Late Miocene – Pliocene | | Torony Lignite, Somló–Tihany Fms., Zagyva Fm. | | Beladice Fm., Volkovce Fm., Kolárovo Fm., Gbely Fm. | | Mura Fm., Ptuj-Grad Fm. | | | |
| 25 | **MPl_4** | Basalt tuffs with intercalations of clay, sand and gravel | Late Miocene – Pliocene | | Tapolca Basalt Fm. | | Podrečany Basalt Fm. | | Ptuj-Grad Fm. | | | |
| 26 | **MpPl** | Fluvial–lacustrine–continental–deltaic sand, silt, clay marl | Late Miocene – Pliocene | | Dunántúl Group | | | | | | | |
| 27 | **Mβ** | Extrusive basalt, lava flows, basalt-pyroclastics, subvolcanic basalt; hot spring sediment: post-volcanic geyserite (calcareous tufa, laminated, siliceous limestone); lacustrine laminated alginite, diatomite, bentonite | Late Miocene – Pliocene | MPl3, MPl4, Pl | Tapolca Basalt; geyserite; Pula Alginite | 97c | Podrečany Basalt Fm. | 152 | Ptuj-Grad Fm | 140 | 70,91 | |
| 28 | **Mlls** | Lacustrine limestone, calcareous marl, calcareous mud | Late Miocene, Pannonian | M2 | Nagyvázsony–Kapolcs Limestone | — | | | | | | |
| 29 | **Md** | Lacustrine, sediment of delta plain: clay marl, silt, fine-grained sand; carbonaceous clay, variegated clay, lignite, dolomite; freshwater limestones, boglime and travertine (SK) | Late Miocene (Late Pannonian) | M3, M4 | Tihany Fm, Torony Lignite, Újfalu Sandstone Upper part (Szentes Mb), Somló Fm | 39, 39a,41 | Beladice Fm.,Čáry Fm. | 17.18 | Mura Fm | 160 | 78,79,80,81,87,90 | |
| 30 | **Mdr** | Mouth bar, shoreface | Late Miocene, Pannonian | — | Lower part of Újfalu Sandstone (Mindszent Mb) | 41 | Čáry Fm. | | | 170 | 82,83,88,89,128,615 | |

|  | Transenergy symbol | Lithology | Detailed age | HU-200 map symbol | Hungarian Unit-name | Slovak symbol | Slovakian Unit-name | Slove-nian symbol | Slovenian Unit-name | HU-A symbol | Austrian symbol | Austrian Unit-name |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 31 | **Mplf-Md** | Shallow marine clay, clay marl to lacustrine clay marl, sand, silt | Late Miocene, Pannonian | M3, M4, M5 | Algyő Clay Marl – Somló-Tihany-Torony Lignite |  |  |  |  |  |  |  |
| 32 | **Mplf** | Clay silt deposite on underwater slope, shallow-water clay marl, fine-grained sand, silt; variegated clay, limestone | Late Miocene, Pannonian | M5 | Algyő–Szák–Csákvár Clay Marl, Csór Silt, Zsámbék Marl | 43 | Ivanka Fm | 19 | Lendava Fm, Sodinci Mb | 180 | 84,85,86 |  |
| 33 | **Mpc** | Lacustrine, abrasion shore quartz sand, gravel, pea gravel, siliceous sandstone; slope debris | Late Miocene, Pannonian | M6 | Kisbér–Zámor–Kálla–Diás Gravel, Békés Conglomerate | 43a | Ivanka Fm, Piestany Mb |  |  |  |  |  |
| 34 | **Mpla** | Lagoonal sediments: clay marl, silt, carbonaceous clay | Late Miocene, Pannonian | M7 | Taliándörögd Marl |  |  |  |  |  |  |  |
| 35 | **Mptb** | Turbidite | Late Miocene, Pannonian | — | Szolnok Sandstone |  |  | 20 | Lendava Fm, Jeruzalem Mb |  |  |  |
| 36 | **Mpcm** | Lacustrine calcareous marl – clay marl; sandstone | Late Miocene, Pannonian | — (M12) | Endrőd Marl | 42 | Bzenec Fm. | 21 | Špilje Fm, Miklavž Mb |  |  |  |
| 37 | **Mp_1** | Littoral, deltaic and fluvial coarse deposits (mainly sand and gravel) | Late Miocene, Pannonian |  |  |  | Gbely Fm., Čáry Fm. |  |  |  |  | Hollabrunn-Mistelbach Fm., Paldau Fm. |
| 38 | **Mp_2** | Lacustrine silty clayey marl and littoral-deltaic-fluvial coarse deposits | Late Miocene, Pannonian |  | Szák–Csákvár Fm., Zsámbék Marl, Csór Silt, Kisbér–Zámor–Kálla–Diás Gravel |  | Bzenec Fm., Čáry Fm., Gbely Fm., Beladice Fm. |  | Mura Fm. |  |  | Feldbach Fm., Paldau Fm., Hollabrunn-Mistelbach Fm. |
| 39 | **Mp_3** | Lacustrine silty clayey marl (with sporadic occurrences of a turbiditic unit thinner than 100 m) | Late Miocene, Pannonian |  | Endrőd Fm., Szolnok Fm., Algyő Fm., Szák Fm. |  | Bzenec Fm., Ivanka Fm. |  | Špilje Fm., Lendava Fm. |  |  | Pannon undifferentiated |

|  | Transenergy symbol | Lithology | Detailed age | HU-200 map symbol | Hungarian Unit-name | Slovak symbol | Slovakian Unit-name | Slove-nian symbol | Slovenian Unit-name | HU-A symbol | Austrian symbol | Austrian Unit-name |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 40 | **Mp_4** | Lacustrine silty clayey marl and sandy turbidites (thickness of the turbiditic unit: 100-500 m) | Late Miocene, Pannonian |  | Endrőd Fm., Szolnok Fm., Algyő Fm. |  | Bzenec Fm., Ivanka Fm. |  | Špilje Fm., Lendava Fm. |  |  | Pannon undifferentiated |
| 41 | **Mp_5** | Lacustrine silty clayey marl and sandy turbidites (thickness of the turbiditic unit: >500 m) | Late Miocene, Pannonian |  | Endrőd Fm., Szolnok Fm., Algyő Fm. |  | Bzenec Fm., Ivanka Fm. |  | Špilje Fm., Lendava Fm. |  |  | Pannon undifferentiated |
| 42 | **Mp_6** | Lignite with shallow-water silt and clay | Late Miocene, Pannonian |  |  |  |  |  |  |  |  |  |
| 43 | **Mp** | Lacustrine to fluvial: clay, silt, sand, gravel | Late Miocene, Pannonian |  | Peremarton Group |  |  | 22 | Špilje Fm, Osek Mb |  |  | Pannon undifferentiated |
| 44 | **MPl** | Fluvial–lacustrine–continental–deltaic clay, clay marl, silt, sand, gravel | Late Miocene, Pannonian – Pliocene |  | Peremarton–Dunántúl Group together |  |  |  |  |  |  |  |
| 45 | **Mbptr** | Trachite bearing agglomerate, tuff | Miocene, Badenian – Pannonian |  | Pásztori Trachite Fm |  |  |  |  |  |  |  |
| 46 | **Mbst** | Kaolinic clay, continental red clay, bauxitic clay | Karpatian–Badenian–Late Miocene | M16 | Cserszegtomaj-Vöröstó Fm, Ősi Varigated Clay | — |  |  |  |  |  |  |
| 47 | **Msls** | Brackish-water – shoreline, mollusc-bearing limestone, sand, gravel | Sarmatian | M19 | Tinnye Fm | — |  | 23 | Špilje Fm, Selnica Mb | 240 | 94,95,96 | Leithakalk |
| 48 | **Msfp** | Tuffaceous claystones and siltstones with sandstones and lignites | Sarmatian | M17 | Sajóvölgy–Gyulafirátót Fm | 126b | Orovnica coal-bearing Fm. |  |  |  |  |  |

|  | Transenergy symbol | Lithology | Detailed age | HU-200 map symbol | Hungarian Unit-name | Slovak symbol | Slovakian Unit-name | Slove-nian symbol | Slovenian Unit-name | HU-A symbol | Austrian symbol | Austrian Unit-name |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 49 | **Msrt** | Pyroclastics: biotitic rhyolite tuff and agglomerate, tuffite; Grey, biotitic vesicular rhyolite tuff, with dacite and andesite bearing volcanoclastics of ignimbritic or tuff agglomerate type | Sarmatian | — (M20) | Galgavölgy Rhyolite Tuff | 121a,b,c, 122c,125a,134a,b, c,d,135a,b,c, 136,137b, 140a,b,c | Baďany Fm., Priesil Fm., Zbrojníky Fm. |  |  |  |  |  |
| 50 | **Msmf-ls** | Shallow-marine–brackish-water, clay marl; sand–sandstone; brackish-water–shoreline limestone, sand, gravel | Sarmatian | M21, M19 | Kozárd, Tinnye Fm |  |  |  |  |  |  |  |
| 51 | **Msmf** | Shallow-marine – brackish-water, mollusc-bearing clay – clay marl; sand–sandstone, calcareous marl | Sarmatian | M21 | Kozárd Fm | 53,54,55, 55a,57,57a | Vráble Fm.[D](53);Holíč Fm., Skalica Fm. [V](54–55,57) |  | upper part of Špilje Fm and Ptujska Gora - Kog formation | 260 | 92,93 |  |
| 52 | **Ms** | Miocene Sarmatian sediments in general | Sarmatian |  |  |  |  |  |  |  |  |  |
| 53 | **Mbsc** | Sandstone, sand, sandy marl, silty marl, clayey marl, conglomerate, gravel, breccia, algal limestone, dolomite, coal | Middle Badenian – Sarmatian |  |  |  |  | 26-1, 26-2 (old 271) | Ptujska Gora - Kog formation |  |  |  |
| 54 | **Mbmf** | Shallow-marine and open basin foraminiferal, mollusc-bearing clay marl, clay | Badenian | M27, M34 | Szilágy Clay Marl, Baden Fm, Tekeres Schlier | 61,62,71, 72 | D:Báhoň,Pozba Fm.(61), Bajtava Fm.(71) V:Studienka Fm.(62), Lanžhot Fm.(72), Madunice Fm | 24 | lower part of Špilje Fm and Ptujska Gora - Kog formation Špilje Fm, Šentilj Mb | 270 | 98,99 |  |
| 55 | **Mba** | Subvolcanic andesite, andesite-pyroclastics; andesite dyke | Badenian | M29 | Magasbörzsöny – Dobogókő Andesite | 304a, 304b | Burda Fm. - andesitic lavas |  |  | 280 | 106 |  |

|  | Transenergy symbol | Lithology | Detailed age | HU-200 map symbol | Hungarian Unit-name | Slovak symbol | Slovakian Unit-name | Slove-nian symbol | Slovenian Unit-name | HU-A symbol | Austrian symbol | Austrian Unit-name |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 56 | **Mbzt** | Dacite-pyroclastics; subvolcanic dacite, andesite | Badenian | M30 | Nagyvölgy – Holdvilágárok Dacite Tuff | 305, 306a, 306b, 306c, 307a, 307b, 308, 309a, 309b, 310, 311 | Burda Fm. - effusives, epiclastics |  |  |  |  |  |
| 57 | **Mbf** | Brackish-water brown coal-bearing clay marl, marl, calcareous marl | Badenian | —<br>(M31) | Hidas Fm |  |  |  |  |  |  |  |
| 58 | **Mbvs** | Štiavnica stratovolcano: Tuffitic sandstones with siltstones and conglomerates | Badenian |  |  | 151a, 151b, 151c | Demandice Fm. |  |  |  |  |  |
| 59 | **Mblsml** | Alternation of shallow-marine, red-algae-bearing limestone and clay marl | Badenian |  | Lajta Limestone – Szilágy Clay Marl or Baden Fm together |  |  |  |  |  |  |  |
| 60 | **Mbls-mf** | Alternation of shallow-marine, mollusc- and red-algae-bearing limestone and conglomerate; foraminiferal, mollusc-bearing clay marl, clay | Badenian | M32; M27, M34 | Szilágy Clay Marl, Baden Fm, Tekeres Schlier; Lajta Limestone together |  |  |  |  |  |  |  |
| 61 | **Mbls** | Shallow-marine, mollusc- and red-algae-bearing limestone with patch reefs; conglomerate | Badenian | M32 | Lajta Limestone | 62a | Studienka Fm. | 25 | Špilje Fm, Hrastovec-Kresnica Mb | 300 | 104 | Leithakalk |

|  | Transenergy symbol | Lithology | Detailed age | HU-200 map symbol | Hungarian Unit-name | Slovak symbol | Slovakian Unit-name | Slove-nian symbol | Slovenian Unit-name | HU-A symbol | Austrian symbol | Austrian Unit-name |
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| 62 | **Mbc-mf** | Shoreline gravel-conglomerate, sandstone; calcareous siltstone, marl; shallow-marine and open basin foraminiferal, mollusc-bearing clay marl, clay | Badenian | M33; M27, M34 | Pusztamiske Fm; Szilágy Clay Marl, Baden Fm, Tekeres Schlier |  |  |  |  |  |  |  |
| 63 | **Mbc-ls** | Shoreline gravel, sandstone; siltstone; shallow-marine limestone | Badenian | M33 | Pusztamiske Fm; Lajta Limestone |  |  |  |  |  |  |  |
| 64 | **Mbc** | Shoreline gravel and conglomerate, sandstone; calcareous siltstone, marl | Badenian | M33 | Pusztamiske Fm | 67a, 67b, 68, 68a, 68b | Špačince Fm.<br>Jakubov Fm. | 27+28 | Haloze Fm, Naraplje-Cirknica Mb | 310 | 100,101,103,105,129 |  |
| 65 | **Mbtu** | Tuff (Ranca tuff bed) | Early Badenian |  |  |  |  | 29 | Haloze Fm, Stoperce-Kungota Mb |  |  |  |
| 66 | **Mbbr** | Breccia | Badenian |  |  |  |  |  |  |  |  |  |
| 67 | **Mb** | Miocene Badenian sediments in general | Badenian |  |  |  |  |  |  |  |  |  |
| 68 | **M2** | Middle Miocene sediments in general | Middle Miocene |  |  |  |  |  |  |  |  |  |
| 69 | **Mkb-Mbc-ls-mf** | Open-marine silt, clay marl; shoreline conglomerate, sandstone; shallow-marine limestone; shallow-marine and open basin clay marl, clay | Karpatian–Badenian | —<br>(M39, M33, M32, M27-M34) | Tekeres–Garáb Schlier, Pusztamiske Fm, Lajta Limestone; Szilágy, Baden, Tekeres Fm |  |  |  |  |  |  |  |
| 70 | **Mkb-Mbls-mf** | Open-marine silt, clay marl; shallow-marine limestone; shallow-marine and open basin clay marl, clay | Karpatian–Badenian | —<br>(M39, M32, M27-M34) | Tekeres–Garáb Schlier, Lajta Limestone; Szilágy, Baden, Tekeres Fm |  |  |  |  |  |  |  |

|  | Transenergy symbol | Lithology | Detailed age | HU-200 map symbol | Hungarian Unit-name | Slovak symbol | Slovakian Unit-name | Slovenian symbol | Slovenian Unit-name | HU-A symbol | Austrian symbol | Austrian Unit-name |
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| 71 | **Mkb-Mbmf** | Open-marine silt, clay marl; shallow-marine and open basin clay marl, clay | Karpatian–Badenian | — (M39, M27-M34) | Tekeres–Garáb Schlier, Szilágy, Baden, Tekeres Fm |  |  |  |  |  |  |  |
| 72 | **Mkb** | Open-marine silt, sandy clay, clay marl | Karpatian–Badenian | — (M39) | Tekeres Schlier (karpatian, from Slovenien), Garáb Schlier | 75, 76, 76a, 76b | Závod Fm., Lakšáry Fm. | 30 | Haloze Fm, Stoperce-Kungota and Plešivec-Urban Mb |  |  |  |
| 73 | **Mkb_t** | Terrestrial breccia, red clay, debris | Karpatian–Badenian |  |  |  |  |  |  |  |  | Eggenberger Brekzie |
| 74 | **Mkb_czt** | Alternation of open-marine silt, sandy clay, clay marl and biotitic, pumiceous dacite tuff | Karpatian–Badenian |  | Tekeres Schlier–Tar Dacite Tuff together |  |  |  |  |  |  |  |
| 75 | **Mkzt** | Pyroclastics: biotitic, pumiceous dacite tuff | Karpatian–Badenian | M40 | Tar Dacite Tuff |  |  |  |  |  |  |  |
| 76 | **M1c** | Shoreline sand–sandstone, gravel–conglomerate; shallow-marine sand–sandstone with patch reefs, gypsum-bearing clay | Karpatian | M44 | Egyházasgerge Fm, Fót Fm, Budafa Fm |  |  |  |  | 340 | 109,136 | Korneuburg Formation |
| 77 | **M1fc** | Fluvial – brackish-water gravel–conglomerate, sand, marl | Ottnangian–Karpatian (Badenian) | M45 | Ligeterdő Gravel |  |  |  |  | 350 | 108,110,112,113,114 | Sinnersdorf Formation, Rust Formation |
| 78 | **M1cgs** | Conglomerate, sand, schlier | (Ottnangian–) Karpatian |  |  |  |  |  |  |  |  | Arnfelser Konglomerat, Leutschacher Sand, Gamlitzer Schlier |
| 79 | **M1bc-fc** | Fluvial–paludal–brackish-water brown coal; sand–sandstone; carbonaceous clay, | Ottnangian–Karpatian (Badenian) | M45-M46 | Brennberg Brown Coal – Ligeterdő Gravel together |  |  |  |  |  |  |  |

|  | Transenergy symbol | Lithology | Detailed age | HU-200 map symbol | Hungarian Unit-name | Slovak symbol | Slovakian Unit-name | Slove-nian symbol | Slovenian Unit-name | HU-A symbol | Austrian symbol | Austrian Unit-name |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
|  |  | gravel–conglomerate, sand, marl |  |  |  |  |  |  |  |  |  |  |
| 80 | **M1bc** | Fluvial–paludal–brackish-water brown coal; sand–sandstone; carbonaceous clay | Ottnangian–Karpatian | M46 | Brennberg Brown Coal | 81 | Salgótarján Fm., Bánovce Fm., Planinka Fm. |  |  | 360 | 107,115 | Kohlefürende Süßwasserschichten |
| 81 | **M1ml** | Open-marine silt, sandy clay, clay marl | Ottnangian–Karpatian |  |  |  |  |  |  |  |  | Gamlitzer Schlier |
| 82 | **Mort** | Pyroclastics: biotitic, pumiceous rhyolite-rhyodacite ignimbrite (Ottnangian) | Ottnangian | —<br>(M48) | Gyulakeszi Rhyolite Tuff |  |  |  |  |  |  |  |
| 83 | **Meb_t** | Terrestrial clay, sand, gravel, lignite | Eggenburgian–Badenian |  | Somlóvásárhely Fm, Perbál Fm |  |  |  |  |  |  |  |
| 84 | **M1a** | Amphibole andesite, subvolcanic bodies and dykes | Eggenburgian–Ottnangian |  | Mecsek Andesite |  |  |  |  |  |  |  |
| 85 | **M1m** | Intertidal–subtidal sand, loose sandstone; gravel, sand, clay | Eggenburgian | M51 | Budafok Fm | 84, 84a, 84c | Lužice Fm. |  |  | 380 | 116,117,118,119,120,121,122, 149,152 | Luschitzer Serie |
| 86 | **M1gr** | Granodiorite, transition to dacite | Early Miocene |  |  |  |  | (old 381) | Peripannonian pluton Fm |  |  |  |
| 87 | **M1** | Lower Miocene sediments in general | Early Miocene |  |  |  |  |  |  |  |  |  |
| 88 | **M** | Miocene sediments in general | Miocene |  |  |  |  |  |  |  |  |  |
| 89 | **Ol-Pl** | From Oligocene to Pliocene sediments | Oligocene–Pliocene |  |  |  |  |  |  |  |  |  |
| 90 | **Olb** | Intertidal, brackish-water – lacustrine sand–sandstone; calcareous silt, clay, variegated clay, conglomerate, | Oligocene | Ol2 | Törökbálint Sandstone – Mány Fm | 411e | Lučenec Fm | 31 | Govce Fm | 390 | STMK (131) |  |

|  | Transenergy symbol | Lithology | Detailed age | HU-200 map symbol | Hungarian Unit-name | Slovak symbol | Slovakian Unit-name | Slove-nian symbol | Slovenian Unit-name | HU-A symbol | Austrian symbol | Austrian Unit-name |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
|  |  | coal |  |  |  |  |  |  |  |  |  |  |
| 91 | **Olf-Olb** | Fluvial–lacustrine–paludal clay, sand, variegated clay, gravel; intertidal, brackish-water–lacustrine sand, silt, clay, conglomerate, coal | Oligocene | Ol3, Ol2 | Csatka Fm; Törökbálint–Mány Fm |  |  |  |  |  |  |  |
| 92 | **Olf** | Fluvial–lacustrine–paludal clay, clay marl, sand–sandstone, gravel–conglomerate | Oligocene | Ol3 | Csatka Fm |  |  | 32.35 | Pletovarje Fm | 400 | STMK (127–130,132, 133,134,137) |  |
| 93 | **Olαtu** | Andesitic tuff, tuffite; marlstone | Early Oligocene (Rupelian) |  |  |  |  | 401 | Smrekovec Fm |  |  |  |
| 94 | **Olmf-Olb** | Open-marine silt, clay marl; intertidal, brackish-water–lacustrine sand; silt, clay, coal | Oligocene | Ol4, Ol7 | Kiscell–Tard Clay; Törökbálint–Mány Fm |  |  |  |  |  |  |  |
| 95 | **Olmf** | Open-marine clayey, clay marly silt, clay marl; restricted sea basin: clayey silt, tuffite, sandstone | Early Oligocene | Ol4, Ol7 | Kiscell Clay, Tard Clay | 425 | Hrabník Fm. |  |  | 410 | 170,171,172 |  |
| 96 | **Olc** | Shoreline coarse-grained sandstone; fine-grained sandstone, conglomerate, fireclay; calcareous conglomerate, variegated clay; calcareous sandstone | Early Oligocene | Ol5, Ol8 | Hárshegy Sandstone, Iharkút Fm |  | Číž Fm.- Blh Mb., Ćíž Fm.-Skálnik Mb. |  |  |  |  |  |

|  | Transenergy symbol | Lithology | Detailed age | HU-200 map symbol | Hungarian Unit-name | Slovak symbol | Slovakian Unit-name | Slove-nian symbol | Slovenian Unit-name | HU-A symbol | Austrian symbol | Austrian Unit-name |
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| 97 | **Olbx** | Continental, re-deposited bauxite; clay, red clay, debris | Early Oligocene | — (Ol9) | Óbarok Bauxite |  |  |  |  | 430 | STMK (135,136, 138–141) |  |
| 98 | **Ol** | Oligocene sediments in general | Oligocene |  |  |  |  |  |  |  |  |  |
| 99 | **EOl_ml** | Shallow bathial marl, calcareous marl | Late Eocene – Early Oligocene |  |  |  |  |  |  |  |  |  |
| 100 | **E3ls** | Subtidal sediments: limestone and calcareous marl containing large foraminiferans and red algae | Late Eocene | E2 | Szépvölgy Limestone |  |  |  |  | 440 | 124,173,174,183 |  |
| 101 | **E2-3cl** | Terrestrial clay, silt, sandstone, gravel–conglomerate, coal | Middle–Late Eocene | E4 | Kosd Fm, Szentlőrinc Fm |  |  |  |  |  |  |  |
| 102 | **E3** | Upper Eocene sediments in general | Late Eocene |  |  |  |  |  |  |  |  |  |
| 103 | **E2-3a** | Biotite-amphibole andesite lava, piroclasts, subvolcanic bodies, intrusive quartzdiorite | Middle–Late Eocene |  | Szentmihályi Andesite |  |  |  |  |  |  |  |
| 104 | **E2-3mla** | Alternation of open-marine silty marl, glauconitic sandstone; shallow-marine clay marl, marl and biotite-amphibole andesite lava, piroclasts | Middle–Late Eocene |  | Padrag Marl – Szentmihályi Andesite together |  |  |  |  |  |  |  |
| 105 | **E2-3ml** | Open-marine silty marl; tuff, bentonite, tuffite, glauconitic sandstone; shallow-marine clay marl, marl, fresh-water calcareous marl, fluvial sand, | Middle–Late Eocene | E5, E6 | Padrag Marl, Tokod Fm, Lencsehegy Fm | 431,431a | Lubina Fm, Jablonka Fm. | 43 | Socka beds | 450 | 176 |  |

|  | Transenergy symbol | Lithology | Detailed age | HU-200 map symbol | Hungarian Unit-name | Slovak symbol | Slovakian Unit-name | Slove-nian symbol | Slovenian Unit-name | HU-A symbol | Austrian symbol | Austrian Unit-name |
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|  |  | calcareous sandstone |  |  |  |  |  |  |  |  |  |  |
| 106 | **E2ls** | Shallow-marine limestone and calcareous marl containing large foraminiferans and red algae | Middle Eocene | E7 | Szőc Limestone |  |  | 45 | Alveolina-nummulites limestone | 460 | 177 |  |
| 107 | **Ebc** | Paralic, paludal brown coal, carbonaceous clay, bauxitic clay; sand, gravel, travertine, calcareous marl | Middle Eocene | E10 | Dorog Fm, Darvastó Fm, Lencsehegy Fm |  | Obid Mb. (neformalny nazov, Vass) |  |  |  |  |  |
| 108 | **E2** | Middle Eocene sediments in general | Middle Eocene |  |  |  |  |  |  |  |  |  |
| 109 | **Ebx** | Continental bauxite, bauxitic clay, kaolinic clay | Early–Middle Eocene | E11 | Gánt Bauxite |  |  |  |  |  |  |  |
| 110 | **E** | Eocene sediments in general | Eocene |  |  |  |  |  |  |  |  |  |
| 111 | **Pc-E3ls** | Reefal, organogenic and organodetritic limestones, Operculina-limestones, dolomitic breccias, carbonatic sandstones | Paleocene (Montian) to Late Eocene |  | — | 426, 429, 429a, 430, 432 | Domaniža, Hričovské Podhradie , Jablonov, Dedkov vrch Fm. |  |  |  |  |  |
| 112 | **PcE2ml** | Shallow-marine clay marl, marl; mollusc-bearing marl, calcareous marl, silt, sandstone | Paleocene – Middle Eocene | E8, E9 | Csolnok Clay Marl, Csernye Fm (E2) | 433 | Priepasné Fm.(Pc-E2) |  |  | 470 | — |  |
| 113 | **PcE1_W** | Western Carpathian Flysch Belt: flysch with dominant grey calcareous shelly claystones | Paleocene – Early Eocene |  |  | 478 | Svodnica Fm. |  |  |  |  |  |

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| 114 | **Pg_R** | Raca Nappe – flysch sediments | Palaeocene–Eocene |  |  |  |  |  |  |  | 80, 81 | Raca nappe |
| 115 | **PcMo_W** | Waschbergzone – marl, clay, sand, sandstone | Paleocene–Ottnangian |  |  |  |  |  |  | 1000 | 178 | Waschbergzone (Känozoikum) |
| 116 | **Pg_GfZ** | Greifenstein nappe (Zistersdorf slice) – flysch sediments | Paleogene? |  |  |  |  |  |  |  |  | Greifenstein nappe Zistersdorf slice |
| 117 | **Pg_GfG** | Greifenstein nappe (Göstling slice) – flysch sediments | Paleogene? |  |  |  |  |  |  |  | 94 | Greifenstein nappe Göstling slice |
| 118 | **Pg_Gf** | Greifenstein nappe – flysch sediments | Paleogene? |  |  |  |  |  |  |  | 90, 91, | Greifenstein nappe |
| 119 | **Pg_K** | Kahlenberg nappe – flysch sediments | Paleogene? |  |  |  |  |  |  |  | 100, 101 | Kahlenberg nappe |
| 120 | **Pg_L** | Laab nappe – flysch sediments | Paleogene? |  |  |  |  |  |  |  | 120, 121 | Laab nappe |
| 121 | **KPg_G** | Marlstone, turbitite, sandstone, limestone, coal | Upper Cretaceous – Paleogene |  |  | 435-440, 434, 441b | Brezová Group (435-440), undivided Gosau-type sediments (434, 441b) | 501 | Gosau Fm | 1300 | 351 | Gosau-Gruppe |
| 122 | **K2ml** | Pelagic limestone and marl | Senonian – Early Paleocene | K2, K4 | Jákó–Polány Marl |  |  | 49 | Sabotin beds | 500 | 355 |  |
| 123 | **K2ml-ls** | Pelagic limestone and marl and platform limestone | Late Cretaceous | K2, K3, K4 |  |  |  |  |  |  |  |  |
| 124 | **K2v** | Alcali basic and ultrabasic dykes | Late Cretaceous |  |  |  |  |  |  |  |  |  |
| 125 | **K2tb** | Gosau-type dominantly marly, often turbiditic clastic complex | Senonian |  |  |  |  |  |  |  |  |  |
| 126 | **K2_Ffl** | Flysch Belt – flysch complex: sandstones, shales | Senonian |  |  | 481b,c, 477 | Lopeník Fm. (481b,c), unclear tect. pos. (477) |  |  |  |  |  |
| 127 | **K2_Pfl** | Pieniny Klippen Belt – flysch | Senonian |  |  | 482a | Jarmuta Fm. |  |  |  |  |  |

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|  |  | complex |  |  |  |  |  |  |  |  |  |  |
| 128 | **K2ls** | Platform limestone | Senonian | K3 | Ugod Limestone |  |  | 57.54 | Lipica Fm, Sežana Fm | 510 | STMK (394) |  |
| 129 | **K2t** | Continental siliciclastic and swamp facies | Senonian | K5 | Halimba Bauxite, Csehbánya Fm, Ajka Brown Coal |  |  |  |  | 520 | 352,353,358,367,369 | Kainacher Gosau und Äquivalente |
| 130 | **K2Mo_W** | Washberg Zone – claystone, marlstone, sand, sandstone | Turonian–Ottnangian |  |  |  |  |  |  |  | 70, 71 | Washberg Zone |
| 131 | **K2_bd** | Subvolcanic díke: picrite, microgabbro, basalt, carbonatic dyke rocks | Late Cretaceous | K6 | Budakeszi Pikrit Fm |  |  |  |  |  |  |  |
| 132 | **K2_Au** | Autochtonous – marine clastic sediments | Late Cretaceous |  |  |  |  |  |  |  | 60 | Autochtonous |
| 133 | **K2** | Upper Cretaceous in general | Late Cretaceous |  |  |  |  |  |  |  |  |  |
| 134 | **K_Tfl** | Tatricum – Middle-Upper Cretaceous clastic complex (flysch) | Albian–Senonian |  |  | 696,697, 698 | Hranty, Rázov, Poruba Fm. |  |  |  |  |  |
| 135 | **Kml-ls** | Pelagic marl – open marine limestone | Aptian – Albian |  | Vértessomló Marl – Tata Limestone |  |  |  |  |  |  |  |
| 136 | **Kml** | Pelagic marl | Albian–Cenomanian | K7 | Vértessomló, Pénzeskút Marl |  |  |  |  |  |  |  |
| 137 | **Kss** | Marlstone, sandstone, turbitite, breccia | Early Cretaceous – Cenomanian |  |  |  |  |  |  |  |  | Lower Cretaceous undifferentiated |
| 138 | **Kpls-K1f** | Platform limestone | Albian | K8 | Környe–Zirc Limestone |  |  |  |  |  |  |  |
| 139 | **Kpls** | Platform limestone | Albian | K8 | Környe–Zirc Limestone |  |  |  |  |  |  |  |
| 140 | **K1f-Kpls** | Lacustrine and lagoonal formations – platform limestone | Albian | K8-K9 | Tés Clay Marl – Környe Limestone |  |  |  |  |  |  |  |

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| 141 | **K1f** | Continental, lacustrine, and lagoonal formations | Albian | K9 | Tés Clay Marl |  |  |  |  |  |  |  |
| 142 | **K1t** | Flyschoid formations (marl, sandstone, conglomerate) | Early Cretaceous | K12 | Lábatlan Sandstone, Bersek Marl |  |  |  |  | 570 | 372 |  |
| 143 | **K1Tls** | Tatricum – Biodetritic, sandy etc. limestones | Early Createcous |  |  | 699, 699a | Solivar Fm., undivided |  |  |  |  |  |
| 144 | **K1bml** | Bathial silty marl, siltstone, calcareous marl | Barremian–Aptian | — | Sümeg Marl |  |  |  |  |  |  |  |
| 145 | **K1Tlim** | Tatricum – Intrusive and extrusive bodies of basic eruptives, hyaloclastites, limburgites and their volcanoclastics | Early Cretaceous |  |  | 700 | Limburgites – Tatricum |  |  |  |  |  |
| 146 | **K1ls** | Shallow marine limestone | Valanginian – Albian | K10 | Borzavár--Tata Limestone |  |  |  |  |  |  |  |
| 147 | **K1ml** | Fatricum – Northern Veporicum: dark grey marl, sandy and organodetritic limestones, breccias, cherty limestones | Berriasian – Albian |  |  | 626, 628 | Poruba Fm. (626)<br>Padlá Voda, Hlboča and Bohatá Fm. (628) |  |  |  |  |  |
| 148 | **K1** | Lower Cretaceous in general | Early Cretaceous |  |  |  |  |  |  |  |  |  |
| 149 | **K** | Cretaceous in general | Cretaceous |  |  |  |  |  |  |  |  |  |
| 150 | **JK_W** | Sand-sandstone, claystone, marl, cherty limestone (A: Molasse, Waschberzone) | Late Jurassic – Cretaceous (Oxfordian–Maastrichtian) |  |  |  |  |  |  | 1050 | 179,180,181,182 | Mucronaten Schichten, Palava, Klement, Ernstbrunn, Klentnitz(Klentnice) Fm |

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| 151 | **JK_I** | Very low grade metasediments | Late Jurassic?–Cretaceous? |  | Ikervár Unit |  |  |  |  |  |  |  |
| 152 | **JE_H** | Mottled clay marl (Buntmergelserie), limestone, marlstone (Klippen) (A-Helvetikum) | Middle Jurassic – Middle Eocene |  |  |  |  |  |  | 1100 | 247.249 | Buntmergelserie, "Klippen" |
| 153 | **JE_R** | Rhenodanubic flysch zone – sandstone, claystone, marlstone, calcareous marl, siltstone | Jurassic – Middle Eocene |  |  |  |  |  |  | 1200 | 253,254,255,258,259,260, 265-278 | Greifenstein, Altlengbach Fm, Wolfpassing, Sulz, Sievering, Kahlenberg, Laab, Kaumberg Fm, Zementmergel-serie, calcareous Flysch, Gaultflysch, Pikrit, Quarzit, Serpentinit |
| 154 | **JK_P** | Pieniny Klippen Belt – Jurassic limestones, cherty and marly limestones and Cretaceous flysch complex | Jurassic–Cretaceous |  |  |  |  |  |  |  | 170,171,P5,P6 | Pieniny Klippen Belt (Hrbka, Pieniny, Koňhora, Tissalo, radiolarites, Czorsztyn, Allgäu and Gresten Fm. And Jarmuta Fm.) |

|  | Transenergy symbol | Lithology | Detailed age | HU-200 map symbol | Hungarian Unit-name | Slovak symbol | Slovakian Unit-name | Slove-nian symbol | Slovenian Unit-name | HU-A symbol | Austrian symbol | Austrian Unit-name |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 155 | **JK_Pls** | Pieniny Klippen Belt: dominantly limestones, cherty and marly limestones | Jurassic – Early Cretaceous |  |  | 486, 491b, 491c, 492a, 492b, 495a | Hrbka, Pieniny, Koňhora, Tissalo, radiolarites, Czorsztyn, Allgäu and Gresten Fm. |  |  |  |  |  |
| 156 | **JK_Tls** | Tatricum: cherty, nodular, marly limestones, silicites, | Jurassic – Early Cretaceous |  |  | 701, 702, 705, 709, 712, 716, 717 | Crinoidal and brecciated limestones, Trlená Fm., dark shales, Lučivná Fm., Adnet Limestone |  |  |  |  |  |
| 157 | **JK_Vls** | Northern Veporicum – Fatricum: cherty, nodular and marly limestones | Jurassic – Early Cretaceous |  |  | 630, 632,633a, 633b, 635 | Mráznica, Osnica Fm., Adnet, Hierlatz, Allgäu, Kopienec, Ždiar, Jasenina, Fatra and Prístodolok Fm., „ammonitico rosso“ |  |  |  |  |  |
| 158 | **JK1_Pe** | Low-grade metamorphic formations (phyllite, calc-phyllite, quarz phyllite, quartzite, metasandstone, metaconglomerate, greenschist, basic metatuff, metatuffite) (Penninic unit) | Jurassic – Early Cretaceous | JK1, JK2, J8 | Kőszeg Quartz Phyllite, Velem Calc-phyllite, Felsőcsatár Greenschist, Vashegy Serpentinite |  |  |  |  | 580 | 279-285,287-289 | Penninic unit / Rechnitzer Einheit |
| 159 | **J-K1bml** | Jurassic pelagic limestone – Early Cretaceous bathial marl | Jurassic – Early Cretaceous | J13-K | Mogyorósdomb Limestone – Sümeg Marl |  |  |  |  |  |  |  |

| | Transenergy symbol | Lithology | Detailed age | HU-200 map symbol | Hungarian Unit-name | Slovak symbol | Slovakian Unit-name | Slove-nian symbol | Slovenian Unit-name | HU-A symbol | Austrian symbol | Austrian Unit-name |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 160 | **J** | Pelagic limestone, cherty limestone, argillaceous limestone, nodular limestone, crinoidal–brachiopodal limestone, marl, radiolarite | Jurassic – Early Cretaceous | J1, J5, J7, J9, J11, J13 | Pisznice–Isztimér–Tűzköves-árok–Hierlatz–Eplény–Tölgyhát–Pálihálás Limestone, Kisgerecse Marl, Úrkút Manganese Ore, Lókút Radiolarite, Mogyorósdomb Limestone, Sümeg Marl | | | | | 590 | 375,378,382,384,388,392,394 | Schwellenfazies, Kalksburg Formation |
| 161 | **J3** | Upper Jurassic undifferentiated | Late Jurassic | | | | | | | 1500 | 495 | |
| 162 | **J3_Aubs** | Autochtonous Malmian basinal sediments | Late Jurassic | | | | | | | 50 | | Autochtonous Malmian basinal sediments |
| 163 | **J_Tls** | Grey limestone, shale, slope breccia and sandstone (Northern Tatric, e.g. Vahic slope) | Early–Late Jurassic (Liassic – Malmian) | | | 704, 708, 711, 713, 714 | Somár, Marianka, Korenec, Slepý and Prepadlé Fm. | | | | | |
| 164 | **JPg_Sch** | Helvetic unit | | | | | | | | 110.11 | | Schottenhofzone with Klippen |
| 165 | **J_Hls** | Hronicum: grey to reddish limestones, marly, organodetritic or muddy limestones, marlstones | Jurassic | | | 599 | grey to reddish limestones, marly, organodetritic or muddy limestones – undivided | | | | | |
| 166 | **T3ls** | Platform (shallow-marine), cyclic (thick-bedded, partly alga-laminated) limestone | Late Triassic – Early Jurassic | T2, J10 | Dachstein–Kardosrét Limestone | 600 | Hronicum: Dachstein and Norovice Fm. | | | 610 | 395,399,400,403 | Oberrhät-Riffkalk |

|  | Transenergy symbol | Lithology | Detailed age | HU-200 map symbol | Hungarian Unit-name | Slovak symbol | Slovakian Unit-name | Slovenian symbol | Slovenian Unit-name | HU-A symbol | Austrian symbol | Austrian Unit-name |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 167 | **T3bls** | Basinal limestone, dolomite, cherty limestone, cherty dolomite, marl, clay marl, calcareous marlestone | Norian–Rhaetian and Earlymost Jurassic | T3, T4 | Kössen, Rezi Dolomite, Feketehegy Fm | 496, 637, 719, 720, | Pieniny Klippen Belt, Tatricum, Fatricum–N-Veporicum: Carpathian Keuper, Kössen Fm |  |  | 620 | 396,397,405,406,407 | Kössen Kormation |
| 168 | **T3p** | Platform carbonate (dolomite, limestone) together | Carnian-Rhaetian |  | Dachstein Limestone, Main Dolomite (’Hauptdolomit’), Ederics Limestone, Sédvölgy Dolomite |  |  |  |  |  |  |  |
| 169 | **T3d** | Platform (shallow-marine) (thick-bedded, partly alga-laminated dolomite, biogenic limestone | Carnian–Norian | T5, T6 | Main Dolomite (’Hauptdolomit’), Ederics Limestone, Sédvölgy Dolomite | 602, 639 | Fatricum–N-Veporicum, Hronicum: Main Dolomite | 77 | Main Dolomite (’Hauptdolomit’) | 630 | 404 | Dachstein Formation, Haupdolomit Formation |
| 170 | **Tkbls** | Basinal marl and limestone, bituminous limestone, dolomite | Carnian | T7, T8 | Sándorhegy Fm, Veszprém Marl | 603, 605, 610, 640 | Fatricum–N-Veporicum, Hronicum: Lunz Mb., Vyšný Slavkov Mb., Oponice Limestone, Partnach Beds |  |  | 640 | 408,409,410 | Lunz Formation, Raibl Formation |
| 171 | **T3** | Upper Triassic sediments in general | Late Triassic |  |  |  |  |  |  |  |  |  |
| 172 | **Tpd** | Platform dolomites | Ladinian–Carnian | T15 | Budaörs Dolomite | 606, 607, 608,613, 642, 643, 721, 721a | Tatricum, Fatricum–N-Veporicum, Hronicum: Ramsau Dolomite, Podhradie Fm., Vysoká Fm., Wetterstein Fm. | 86.84 | Schlern Fm | 650 | 413,414,415,417,149 | Wetterstein Formation |

|  | **Transenergy symbol** | **Lithology** | **Detailed age** | **HU-200 map symbol** | **Hungarian Unit-name** | **Slovak symbol** | **Slovakian Unit-name** | **Slove-nian symbol** | **Slovenian Unit-name** | **HU-A symbol** | **Austrian symbol** | **Austrian Unit-name** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 173 | **T23_SKcb** | South Karavanka unit – Formations of platform and basin facies | Middle–Late Triassic |  |  |  |  |  |  |  |  | South Karavanka unit |
| 174 | **Tcb** | Formations of platform and basin facies (Middle Transdanubian Tectonic Unit, Transdanubian Unit) | Middle–Late Triassic | — |  | — | — |  |  |  |  |  |
| 175 | **T2ls** | Pelagic, basin limestone, nodular or cherty limestone with tuffaceous and siliciclastic intercalations | Anisian–Ladinian | T16 | Füred Limestone, Buchenstein Fm, Felsőörs Fm | 609, 611, 612 | Hronicum: Reifling, Zámostie, Gader, Raming and Schreyeralm Limestones | 90.88 | Wengen Fm | 670 | 420,421,422,423,670 | Reifling Formation |
| 176 | **T2cb** | Platform and basinal carbonates, silisiclastic intercalatons | Middle Triassic |  | Transdanubian Range unit |  |  |  |  |  |  |  |
| 177 | **Tacb** | Shallow marine, platform, cyclic, partly bituminous limestone and dolomite;  bitumenic marly limestone | Anisian | T25, T27,T28 | Tagyon Limestone, Megyehegy Dolomite, Iszkahegy Limestone, Aszófő Dolomite | 614, 617, 617a, 722 | Tatricum, Hronicum: Gutenstein Fm., grey dolomites, Steinalm Fm. | 91 | Anisian dolomite Fm | 680 | 425,428,429 | Gutenstein Formation |
| 178 | **T2** | Middle Triassic sediments in general |  |  |  |  |  |  |  |  |  |  |
| 179 | **T1cb** | Siliciclastic and carbonate formations | Early Triassic | — | Csopak Fm, Köveskál Fm, Hidegkút Fm, Arács Fm, Alcsútdoboz Fm | 619, 645c, 723 | Tatricum, Fatricum–N-Veporicum, Hronicum: Lúžna Fm., Benkovský potok and Šuňava Fm. | 92 | Werfen Fm | 690 | 430,431,432,434 | Werfen Formation |
| 180 | **T_L** | Siliciclastic and carbonate formations | Triassic |  |  |  |  |  |  |  |  | Ljutomer Unit |
| 181 | **T** | Triassic sediments in general |  |  |  |  |  |  |  |  |  |  |

|  | Transenergy symbol | Lithology | Detailed age | HU-200 map symbol | Hungarian Unit-name | Slovak symbol | Slovakian Unit-name | Slove-nian symbol | Slovenian Unit-name | HU-A symbol | Austrian symbol | Austrian Unit-name |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 182 | **Mz_UA** | Uppermost Austroalpine nappes – siliciclastic and carbonate formations | Triassic–Cretaceous |  |  |  |  |  |  |  |  | Uppermost Austroalpine nappes |
| 183 | **Mz_UH** | Unterberg, Havranica, Reisalpe, Göller, Veternic, Jablonica, Choc nappes – siliciclastic and carbonate formations | Triassic–Cretaceous |  |  |  |  |  |  |  |  | Reisalpe, Unterberg, Göller, Veternic, Havranica, Jablonica, Choc nappes |
| 184 | **Mz_F** | Frankenfels, Lunz, Vysoka nappes – siliciclastic and carbonate formations | Triassic–Cretaceous (locally Permian) |  |  |  |  |  |  |  |  | Frankenfels, Lunz, Vysoka nappes |
| 185 | **Mz_AT** | Austroalpine, Tatric units – very low-grade to low-grade siliciclastic and carbonate formations | Triassic–Cretaceous |  |  |  |  |  |  |  |  | Austroalpine, Tatric units |
| 186 | **Mz_V** | Veporic unit – low-grade siliciclastic and carbonate formations | Triassic–Cretaceous |  |  |  |  |  |  |  |  | Veporic unit |
| 187 | **Mzls** | Triassic – Jurassic – Cretaceous limestone of Transdanubian Range |  | TJK |  |  |  |  |  |  |  |  |
| 188 | **Mzcb** | Mesozoic carbonates |  |  |  |  |  |  | Mesozoic carbonates |  |  |  |
| 189 | **Mz** | Mesozoic in general |  |  |  |  |  |  |  |  |  |  |
| 190 | **Pz-Mz** | Upper Paleozoic and Mesozoic formations in general | Late Paleozoic and Mesozoic | — |  |  |  | 105 |  | 700 | 294-301, 303,304,307,426,427,433,439 | Zentralalpines Permo-Mesozoikum |

|  | Transenergy symbol | Lithology | Detailed age | HU-200 map symbol | Hungarian Unit-name | Slovak symbol | Slovakian Unit-name | Slove-nian symbol | Slovenian Unit-name | HU-A symbol | Austrian symbol | Austrian Unit-name |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 191 | **PT_SK** | Southern Karavanka unit – Permian and Triassic clastic and carbonate formations |  |  |  |  |  |  |  |  |  | Southern Karavanka unit |
| 192 | **PT_NK** | Northern Karavanka unit – Permian and Triassic clastic and carbonate formations |  |  |  |  |  |  |  |  |  | Northern Karavanka unit |
| 193 | **Pt** | Continental silicilcastic formation | Middle–Late Permian | — | Balatonfelvidék Sandstone | 724b | Devín Fm. | 94 | Val Gardena fm |  |  | Haselgebirge, Prebichl-Formation |
| 194 | **Pmcb** | Shallow marine silicilcastic and carbonate formations | Permian | — | Tabajd Anhydrite, Dinnyés Dolomite |  |  | 98.1 | Rattendorf Group |  |  |  |
| 195 | **P1** | Limestone | Early Permian |  |  |  |  | 33, 97 | Dolzanova soteska fm |  |  |  |
| 196 | **P** | Permian sediments in general in Transdanubian Unit | Permian |  | Permian sediments in general |  |  |  |  |  |  |  |
| 197 | **P_SK** | Southern Karavanka unit – Permian sediments in general | Permian |  |  |  |  |  |  |  |  | South Karavanka unit |
| 198 | **CT1_H** | Hronic unit – sandstone, shale | Carboniferous – Lower Triassic |  |  |  |  |  |  |  |  | Choc nappe (Hronic unit) |
| 199 | **CP_lvs** | Cyclical volcanosedimentary complex: clastic and basaltic rocks | Late Carboniferous – Permian |  |  | 624a, 624b, 624c, 625a | Hronicum: Ipoltica Group (Malužiná and Nižná Boca Fm.) |  |  |  |  |  |
| 200 | **C_Tgr** | Biotitic and two-mica granite, granodiorite and tonalite, leucocratic granite, diorite | Carboniferous |  |  | 735a, 737, 738, 740, 742, 743, 745 | Tatric Crystalline – hercynian intrusive rocks |  |  |  |  |  |

|  | Transenergy symbol | Lithology | Detailed age | HU-200 map symbol | Hungarian Unit-name | Slovak symbol | Slovakian Unit-name | Slove-nian symbol | Slovenian Unit-name | HU-A symbol | Austrian symbol | Austrian Unit-name |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 201 | **Dmb** | Marble, calcareous slate (Graz Paleozoikum and Equivalents) | Devonian | — | Bük Fm |  |  |  |  | 730 | 612 | Graz Paleozoikum and Equivalents |
| 202 | **SD_SaR** | Sausal unit – Radochen beds | Paleozoic? |  |  |  |  |  |  |  |  |  |
| 203 | **SD_Sa** | Sausal unit in general | Paleozoic |  |  |  |  |  |  |  |  |  |
| 204 | **SD_mb** | Metabasit | Paleozoic |  |  |  |  |  |  |  |  |  |
| 205 | **SD_Bl** | Blumau unit – Phyllite and carbonate rocks | Paleozoic |  |  |  |  |  |  |  |  |  |
| 206 | **SD_Ar** | Arnwies group (Graz Palaeozoic ) | Paleozoic |  |  |  |  |  |  |  |  |  |
| 207 | **SD_G** | Graz paleozoic in general | Silurian–Devonian |  |  |  |  |  |  | 1700 | 468,469 | Graz Paleozoikum and Equivalents |
| 208 | **OC_G** | Greywakezone in general | Ordovician–Carboniferous (-Jurassic) |  |  |  |  |  |  | 1600 | 442,443,444,447,449,451,455,457,458,459 | Grauwackenzone |
| 209 | **OC_Tr** | Low-grade metamorphic formations (slate, calc-phyllite, quarz phyllite, quartzite, metasandstone, metaconglomerate, basic metatuffite, limestone) | Ordovician–Carboniferous |  | Balatonfőkajár, Lovas, Alsóörs, Szabadbattyán, Polgárdi, Kékkút Úrhida Fm-s, Nemeskolta Fm, Mihályi Fm |  |  |  |  |  |  |  |
| 210 | **OSsh** | Slates with lenses of diabase and interlayering of marmorized limestone | Ordovician–Silurian |  |  |  |  | 103.104 | Magdalensberg fm |  |  |  |
| 211 | **CaOph** | Clorite-amphibole and biotite chlorite schists and phylite | Cambrian–Ordovician |  |  |  |  | 106.107 | Kobansko and Phyillite Fm |  |  |  |
| 212 | **Pz_s** | Serpentinite | Paleozoic |  |  |  |  | 105 | Pohorje Fm, serpentinite |  |  |  |
| 213 | **Pz_Vcr** | Veporic unit – gneiss, schist, phyllite, marble, | Early Paleozoic? |  |  |  | Veporic unit |  |  |  |  |  |

|  | **Transenergy symbol** | **Lithology** | **Detailed age** | **HU-200 map symbol** | **Hungarian Unit-name** | **Slovak symbol** | **Slovakian Unit-name** | **Slove-nian symbol** | **Slovenian Unit-name** | **HU-A symbol** | **Austrian symbol** | **Austrian Unit-name** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
|  |  | amphibolite |  |  |  |  |  |  |  |  |  |  |
| 214 | **Pz_Tcr** | Tatric unit – gneiss, schist, phyllite, marble, amphibolite | Early Paleozoic? |  |  |  | Tatric unit |  |  |  |  |  |
| 215 | **Pz_Acr** | Austroalpine units – gneiss, schist, phyllite, marble, amphibolite | Early Paleozoic? |  |  |  |  |  |  |  |  | Austroalpine units |
| 216 | **Pz_met** | Paleozoic metamorphis units in general | Paleozoic |  |  |  |  |  | Paleozoic metamorphic rocks |  |  |  |
| 217 | **PzS** | Medium-grade polymetamorphic formations with Alpine overprint (gneiss, mica schist, phyllite, pegmatite, leucophyllite, quartzite, quartz schist) | Paleozoic | Pz1, Pz2, Pz3, Pz4 | Óbrennberg–Vöröshíd Mica Schist, Sopronbánfalva Gneiss, Füzesárok White Schist |  |  | od 106 do 114 | Pohorje Fm | 740 | 309,311,312,315-325,333,338,342,346,347,348, 475,476 | Austroalpines Kristallin i.A. |
| 218 | **PzF** | Medium- and high-grade polymetamorphic formations (amphibolite, gneiss, mica schist) | Paleozoic | Pz5, Pz6 | Fertőrákos Crystalline Schist Group, Gödölyebérc Amphibolite | 747, 748, 748a, 749, 756, 758 | Tatric Crystalline – metamorphic rocks |  |  | 750 | 326-331 | Austroalpines Kristallin, Wechsel-Einheit |
| 219 | **Pz** | Paleozoic in geneal | Paleozoic |  |  |  |  |  |  |  |  |  |

## 3.4 Definition geological time horizons corresponding to hydrostratigraphical units – the buildup of the geological model

The hydrostratigraphic units are composite units which encompass different geological formations with the same hydrogeological properties.

One of the aims of the project was to delineate these main hydrostratigraphic units connected to different geological formations of certain age and lithology. The compiled model maps show the interface of these hydrostraigraphic units. In general, we compiled the lower interface, called base map. The base map shows formations appearing just below a given age horizon and the topographic surface of these formations above see level for the distribution area of the formations. For instance, the Pre-Badenian horizon map contents the surface grid and geological formation patches of pre-badenian age below the badenian rock's distribution area. So, building the model upward from the lowermost model map, the model space is filled up with all ages and formations without gaps.

The supra-regional geological model is a so called "flying carpet" model, which means that instead of a voxel model, surfaces encompass the surface space grid and geological database informations (Encl. 1.1.−1.17). Model building and verification is further discussed in chapter 3.8. The main difference between the supra area and the pilot areas models is that only the pilot models contain modelled tectonic surfaces, and these model grids were edited more accurately based on the evaluations of 2D seismic section series and gravitational, magnetotelluric modelling.

The most important hydrostratigraphical units of the supra-regional area and the pilot areas respectively are the following:

### Supra-regional area:

| ***Supra regional area hydrostratigraphical units*** | ***Supra regional area geological model maps*** |
|---|---|
| Holocen-Pleistocen alluvial systems along the main rivers, Quaternary formations in the deep basins | Quaternary covered geological map (Encl.1.1.) |
| Upper Pannonian sediments | Base of the Quaternary formations (Pre-Quaternary) (Encl. 1.2., 1.3.) |
| Lower Pannonian sediments | Base of the Upper Pannonian formations (delta front sand) (Encl. 1.4., 1.5.) |
| Sarmatian sediments | Base of the Lower Pannonian formations (Pre-Pannonian) (Encl. 1.6., 1.7.) |
| Badennian sediments | Base of the Sarmatian formations (Pre-Sarmatian) (Enc. 1.8., 1.9.) |
| pre-Badennian sediments | Base of the Badenian formations (Pre-Badenian) (Encl. 1.10., 1.11.) |
| Paleogene formations | Base of the Pre-Lower Miocene formations (pre-Neogene) (Encl. 1.12., 1.13) |
| Post Triassic Formations | Base of the Cenozoic formations (pre-Cenozoic) (Encl. 1.14., 1.15) |
| Triassic karstified limestone and dolomite complex | Base of Senonian formations (pre-Senoniain) (Encl. 1.16., 1.17.) |

## Danube Basin:

| ***Danube Basin hydrostratigraphical units*** | ***Danube Basin geological model maps*** |
|---|---|
| Quaternary formations | Surface geological map (Encl. 2.0.) |
| Upper Pannonian formations (delta front sand) | Base of Quaternary (Encl. 2.1.) |
| Lower Pannonian formations (delta slope sediments) | Base of Upper Pannonian (Encl. 2.2.) |
| Sarmatian formations | Base of Lower Pannonian (Encl. 2.3.) |
| Badenian formations | Base of Sarmatian (Encl. 2.4.) |
| Oligocene formations | Base of Badenian (Encl.2.5.) |
| Cenozoic formations | |
| Cretaceous formations | Base of Cenozoic (Encl. 2.7.) |
| Triassic karstified limestone and dolomite complex | |

## Vienna Basin:

| ***Vienna Basin hydrostratigraphical units*** | ***Vienna Basin geological model maps*** |
|---|---|
| Quarternary and Pannonian sediments | Surface geological map (Encl.1.1.) |
| Sarmatian sediments | Base of Upper Pannonian (Encl. 3.1.) and Base of Lower Pannonian (Encl. 3.2.) |
| Badenian sediments | Base of Sarmatian (Encl. 3.3.) |
| Aderklaa Conglomerate | Base of Aderklaa Formation (Encl. 3.5.) |
| Carpathian sediments | Base of Badenian (Encl. 3.4.) |
| Eggenburgian and Ottnangian sediments | Base of Karpatian (Encl. 3. 6.) |
| Flyschzone | Base of Eggenburgian and Ottnangian sediments (Encl. 3.7.) |
| Gosau units | Base KPg_G - Giesshuebel Gosau model horizon (Encl. 3.11a.) |
| | Base KPg_G - Brezová-Myjava, Gruenbach Gosau model horizon (Encl. 3.11b.) |
| Juvavic nappes and Carpathian Analogoues (Triassic karstified limestone and dolomite complex) | Base Mz_UA - Juvavic Units model horizon (Encl. 3.10.) |
| Tirolic nappes and Carpathian Analogoues (Triassic karstified limestone and dolomite complex) | Base Mz_UH - Tirolic Units model horizon (Encl. 3.12.) |
| Bajuvaric nappes | Base Mz_F - Bajuvaric Units model horizon (Encl. 3.13.) |
| Crystalline and metamorphic basement of Central Alpine & Tatridic units | Base Mz_AT - Mesozoic Cover of Austroalpine Crystalline model horizon (Encl. 3.8.) |
| Greywacke Zone | Base OC_Gw - Greywacke Zone model horizon (Encl. 3.9.) |
| Autochthonous basement of the Bohemian Massif (Paleozoic – Tertiary) | Top Bohemian Massif model horizon (Encl. 3.14.) |

## Lutzmansburg-Zsira:

| ***Lutzmansburg-Zsira hydrostratigraphical units*** | ***Lutzmansburg-Zsira geological model maps*** |
|---|---|
| Quaternary formations | Surface geological map (Encl. 4.1.) |
| Upper Pannonian formations (delta front sand) | Base of Quaternary (Encl. 4.2., 4.3.) |
| Lower Pannonian formations (delta slope sediments) | Base of Upper Pannonian (Encl. 4.4., 4.5.) |
| Sarmatian formations | Base of Lower Pannonian (Encl. 4.6., 4.7.) |
| Badenian formations | Base of Sarmatian (Encl. 4.8., 4.9.) |
| Devonian formations | Base of Badenian (Encl. 4.10., 4.11)<br>Base of Cenozoic (Encl. 4.12., 4.13.) |
| Formations of the crystalline basement | Basement-Devonian formations (Encl. 4.14., 4.15) |

**Bad Radkersburg-Hodos:**

| *Bad Radkersburg-Hodos hydrostratigraphical units* | *Bad Radkersburg-Hodos geological model maps* |
|---|---|
| Quaternary formations | Surface geological map (Encl.1.1.) |
| Upper Pannonian formations (delta front sand) | Base of Quaternary (Encl. 5.1.) |
| Lower Pannonian formations (delta slope sediments) | Base of Upper Pannonian (Encl. 5.3.) |
| Sarmatian formations | Base of Pannonian (Encl. 5.5.) |
| Badenian formations | Base of Sarmatian (Encl. 5.6.) |
| Cretaceous formations | Base of Badenian (Encl. 5.7.) |
| Triassic karstified limestone and dolomite complex | Base of Lower Miocene sediments (Encl. 5.8.) |
| Formations of the crystalline basement | Pre-Tertiary Encl..5.9.) |

**Komarno-Sturovo:**

| *Komarno-Sturovo hydrostratigraphical units* | *Komarno-Sturovo geological model maps* |
|---|---|
| Quaternary formations | Surface geological map (Encl.1.1.) |
| Upper Pannonian formations (delta front sand) | Base of Quaternary (Encl. 6.1., 6.2.) |
| Lower Pannonian formations (delta slope sediments) | Base of Upper Pannonian (Encl. 6.3., 6.4.) |
| Sarmatian formations | Base of Lower Pannonian (Enncl. 6.5., 6.6.) |
| Badenian formations | Base of Sarmatian (Encl. 6.7., 6.8.) |
| Oligocene formations | Base of Badenian (Encl. 6.9., 6.10.) |
| | Base of Neogene (Encl. 6.11, 6.12) |
| Cretaceous formations | Base of Oligocene (Encl. 6.13., 6.14.) |
| | Base of Cenozoic (Encl. 6.15., 6.16.) |
| Triassic karstified limestone and dolomite complex | Base of Cretaceous (Encl. 6.17., 6.18.) |
| Crystalline and metamorphic basement | |

## 3.5 Borehole re-evaluations

The project area includes several hydrocarbon fields and well-known thermal water resources. In the neighborhood of such objects, numerous exploration wells have been drilled (Figure 4). Data from these boreholes were obvious to use in our study, however, the availability of data was limited by confidentiality issues. The density of boreholes was much lower farther from the targets of fluid exploration, especially in the deepest regions of the sub-basins. Despite of that, we attempted to select a relatively evenly distributed set of boreholes as input data for the geological modelling, which had to be complemented with thermal wells providing relevant hydrogeological data.

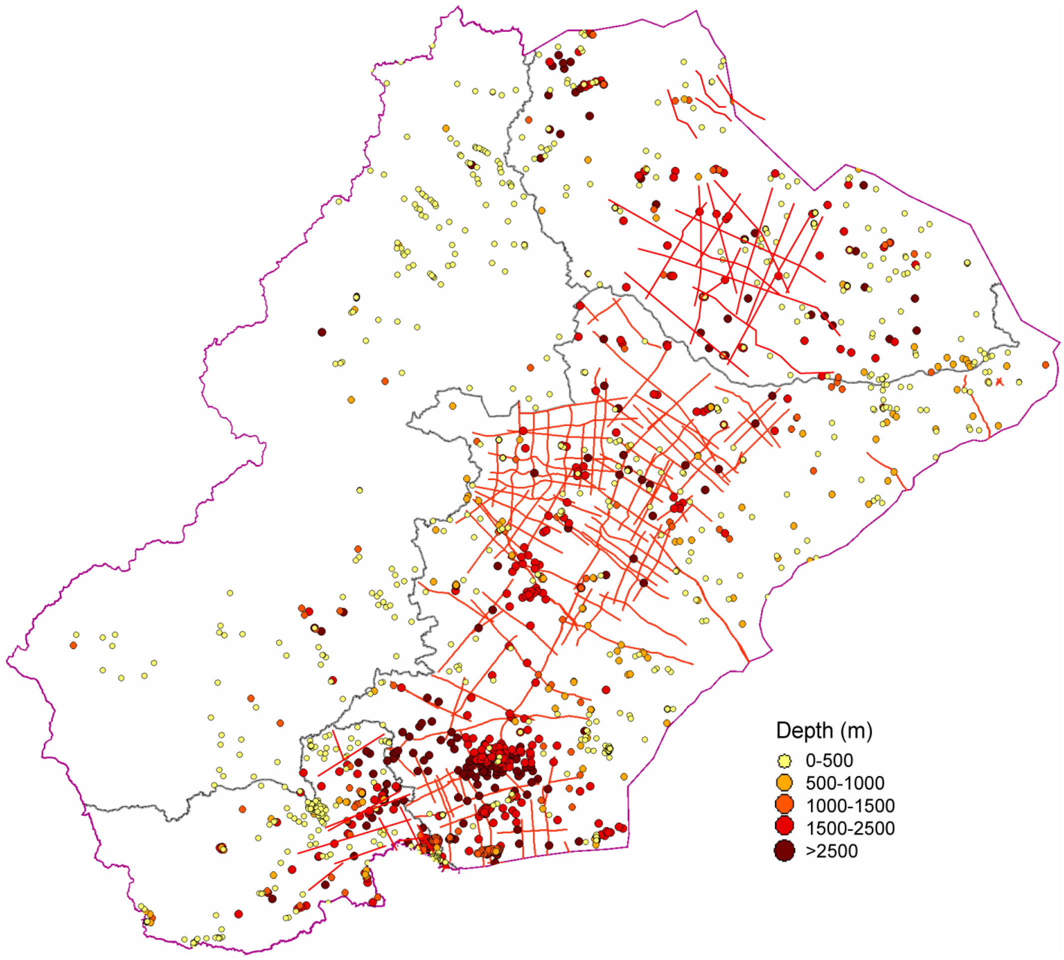


Fig. 4. Overview map showing the spatial distribution of the wells (1672) and seismic profiles used in the project

Finally, 1672 boreholes throughout the project area have been selected for evaluation (Figure 4). In the Austrian, Slovakian and Slovenian areas, the depth values of the main model horizons ("base maps") were obtained for each well using original borehole documentations and existing databases. In the Hungarian area (including 742 wells), experts have defined the depth of all formation boundaries crossed by the boreholes on the basis of documentations and wireline logs, so a full re-evaluation of the successions was carried out. Some of the Hungarian wells had been partially or fully involved in other recent re-evaluation projects (e.g. the edition of Pre-Cenozoic basement map in 2008-2010 or T-JAM in 2010-2011); formation boundaries already defined in these projects have not been modified. However, the majority of the selected boreholes became subject of re-evaluation in the frame of Transenergy.

The used borehole documentations included primarily the lithological description of cores and drilling chips. In some cases, paleontological data also had a key role in setting the boundaries between chronostratigraphic units. Wireline log interpretation was very important for defining several horizons, e.g. the boundaries between the Pannonian formations. The bulk of the Pannonian succession is built up by alternating mud, silt and sand, although each formation has been deposited in a different type of palaeoenvironment, resulting in different sedimentological and hydrogeological features. These differences are not reflected in the lithology, but are very pronounced on well-logs. For example, the uppermost unit of Lower Pannonian generally comprises silt and mud deposited on a prograding slope, where only thin, isolated sand ribbons were formed. Therefore the "Upper/Lower Pannonian" boundary is clearly marked by the appearance of thick, fining-upward sandy intervals (delta front sand bodies) on the logs above the previously described slope, making this time horizon of the model easy to define. As the well-log interpretation focused mainly on the sedimentology of clastic sediments, SP (spontaneous potential), R (resistivity) and GR (natural gamma-ray) have been used, all of them strongly connected to the grain-size variations (Figure 5).

The position of all main geological time horizons in the boreholes could have been obtained as a simplification of the re-evaluated succession. In the Transenergy database, the formation names have been also converted to the indexes of the harmonized legend (see Chapter 3.3). Figure 6 shows an example for a re-evaluated succession and the possible steps of its simplification.

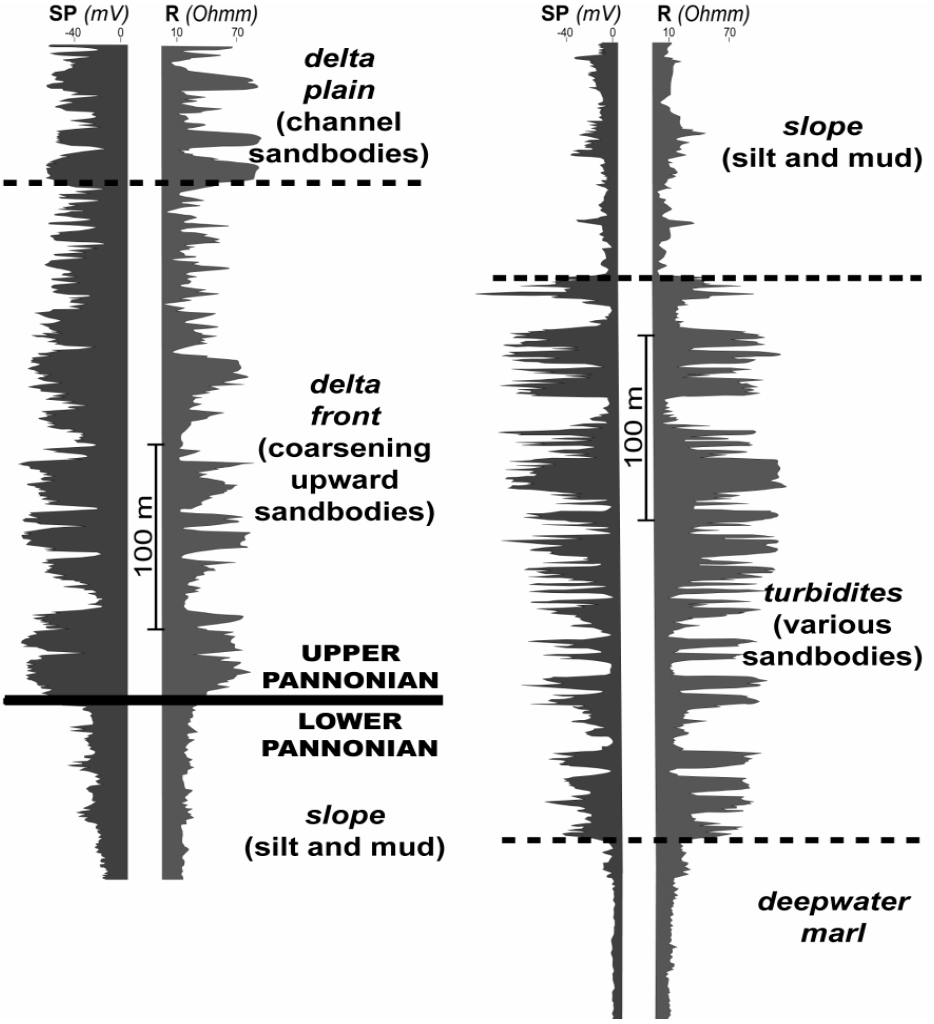
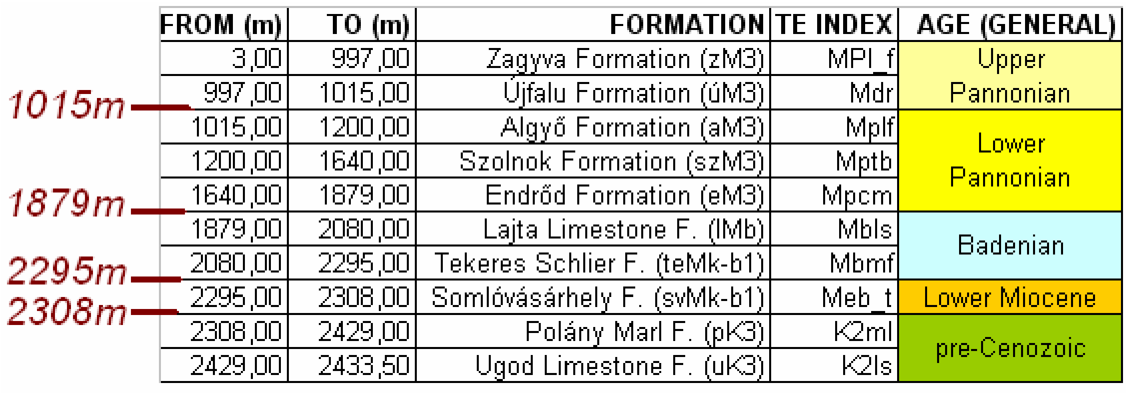


Fig. 5. Reconstruction of a series of Pannonian clastic sedimentary facies on wireline logs



| FROM (m) | TO (m) | FORMATION | TE INDEX | AGE (GENERAL) |
|---|---|---|---|---|
| 3,00 | 997,00 | Zagyva Formation (zM3) | MPl_f | Upper Pannonian |
| 997,00 | 1015,00 | Újfalu Formation (úM3) | Mdr | |
| 1015,00 | 1200,00 | Algyő Formation (aM3) | Mplf | Lower Pannonian |
| 1200,00 | 1640,00 | Szolnok Formation (szM3) | Mptb | |
| 1640,00 | 1879,00 | Endrőd Formation (eM3) | Mpcm | |
| 1879,00 | 2080,00 | Lajta Limestone F. (lMb) | Mbls | Badenian |
| 2080,00 | 2295,00 | Tekeres Schlier F. (teMk-b1) | Mbmf | |
| 2295,00 | 2308,00 | Somlóvásárhely F. (svMk-b1) | Meb_t | Lower Miocene |
| 2308,00 | 2429,00 | Polány Marl F. (pK3) | K2ml | pre-Cenozoic |
| 2429,00 | 2433,50 | Ugod Limestone F. (uK3) | K2ls | |

Fig.6. Re-evaluated borehole succession on different levels of details

## 3.6 Interpretations of seismic sections

The boreholes can provide only point-based information about the position of the time horizons, and the spatial distribution of these points is more or less uneven (Figure 4). Therefore adding any method which can continously image geological horizons along cross-sections can significantly improve the reliability of the model surfaces. For the subsurface mapping of large areas with targeted horizons in several kilometers depth, seismic profiles are commonly used.

Across the project area, 160 2D seismic profiles were available for the project (Figure 4): 132 from Hungary (107 in electronic, 25 in raster format), 17 from Slovakia (in raster format) and 11 from Slovenia (in raster format). The total length of this seismic network was ca. 3000 km. The images of the profiles in electronic format (SEG-Y files) have been visualized and interpreted in KINGDOM 8.5 sotfware. This software makes it possible to track the identified horizons and fault surfaces along the profiles, to correlate them at the intersections and to export their interpreted positions. In the exported datasets, the horizons are sampled with X, Y, Z coordinates in intervals of 100-200 m along each profile. Along those profiles which have been provided only in raster format, horizons have been drawn manually (always verifying them at the intersections with other profiles), than they have been digitized for providing the same type of dataset (series of X, Y, Z coordinates).

It is very important to note that the vertical dimension on a seismic profile is the two-way travel time of the seismic wave; hence it is necessary to know the relation between the two-way travel time and depth. Because of the complex geological buildup, a single function can not describe adequately the time-depth relation for the whole area. Using a single velocity value for each formation would result in different time-depth functions for different locations due to the varying thickness of the formations, but this method was not convenient in our case, because the lithologies of the known formations are not uniform, and their boundaries are not known properly (note that locating them is the goal of the study).

The analysis of some checkshot data (time-depth pairs measured directly in wells) proved that typical time-depth functions can be defined for given parts of the study area. After choosing several wells as sources of characteristic checkshot data, the depth values for the area between these wells has been calculated as differently weighted averages of the values given by the characteristic functions. As a first step, the weight factors used for this calculation were assessed for the positions of 158 wells, based on the depth of stratigraphic levels identifiable both on the seismic profiles and in well-logs (the use of these levels as control points is shown on Figure 7. Than grids were obtained by kriging from these 158 data; the grids provided weight factors, and (indirectly) time-depth relations for the entire area. Using the obtained weight factors in the previously described way, it became possible to calculate the depth of the interpreted surfaces quasi-continuously. The error margin of the depth conversion is some tens of meters in the clastic basin fill, and some hundreds of meters if other lithologies (carbonates, volcanic or metamorphic rocks) are also present above the mapped surface.

For interpreting the stratigraphic horizons continuously on the seismic profiles, we have used the stratigraphic columns of wells located along them as starting points. As a given seismic reflection represents coevally deposited strata (it is a 'time-line'), reflection tracking can provide continuous time horizons for the whole seismic network. The only mapped time horizon for which this method is not appropriate is the Upper/Lower Pannonian boundary. Despite of its name, this horizon is not a chronostratigraphic boundary, but a facies change developing in a time-transgressive way across the Pannonian Basin. However, the appearance of this horizon on seismic profiles is very charecteristic in the areas with relatively thick Pannonian succession. The uppermost part of the Lower Pannonian succession is built up by a prograding slope, appearing as a series of clinoforms on the profiles. The topsets of these clinoforms (representing delta front and delta plain deposits) already belong to the Upper Pannonian, hence the boundary can be exactly drawn by connecting the slope-topset breaks (the ancient shelf breaks) across the subsequent clinoforms (Figure 8).

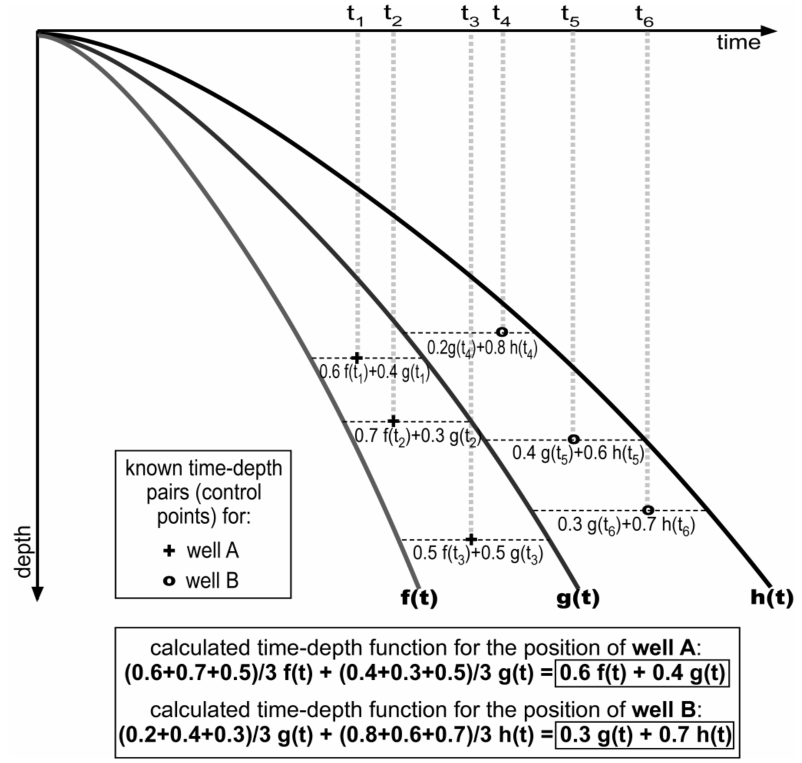


Fig. 7. Example showing the method of calculating the appropriate time-depth function for the position of two wells (A and B), each having three control points with known two-way travel time and depth. Time-depth functions of three 'typical' wells from areas with different subsidence history are labeled as f(t), g(t) and h(t).

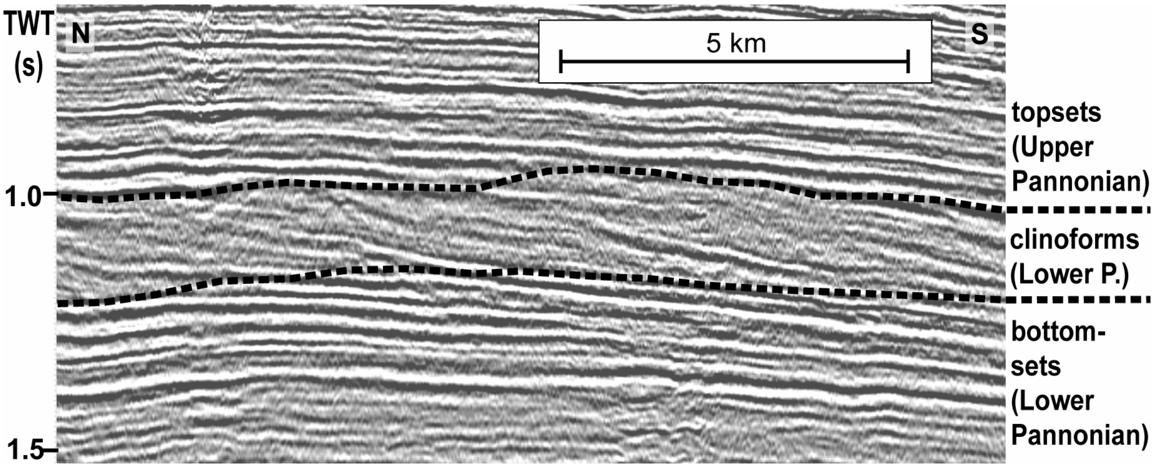


Fig.8. Typical clinoform pattern indicating the Upper/Lower Pannonian boundary on a seismic profile

The contribution of seismic interpretation to the edition of time horizons and 3D models proved to be especially important in the deep basement troughs, where there are no boreholes reaching the pre-Neogene or even the pre-Pannonian basement; only the seismic profiles could relieve the real thickness of the basin fill in such cases (Figure 9). It should be also noted that good quality seismic images show the position of major faults and thrust planes (Figure 10). These elements are seldom penetrated by enough wells for setting their position in 3D. However, fault planes obtained from the interpretation of a dense seismic network can be used as an input for 3D geological modelling, as it was acquired in case of some pilot areas of Transenergy.

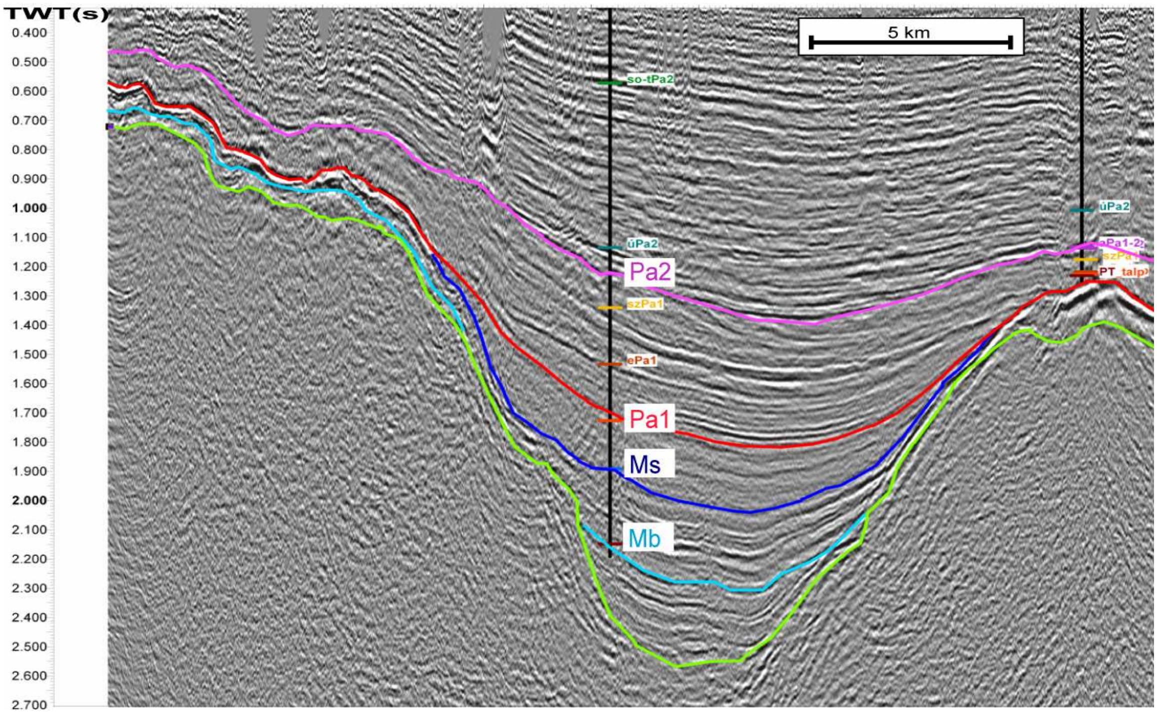


Fig.9. Seismic profile across SW Danube Basin, allowing the assessment of the depth of geological horizons in a major basement trough with a single well on the margin (Pa2: base Upper Pannonian, Pa1: base Lower Pannonian, Ms: base Sarmatian, Mb: base Badenian, PT: pre-Cenozoic basement)

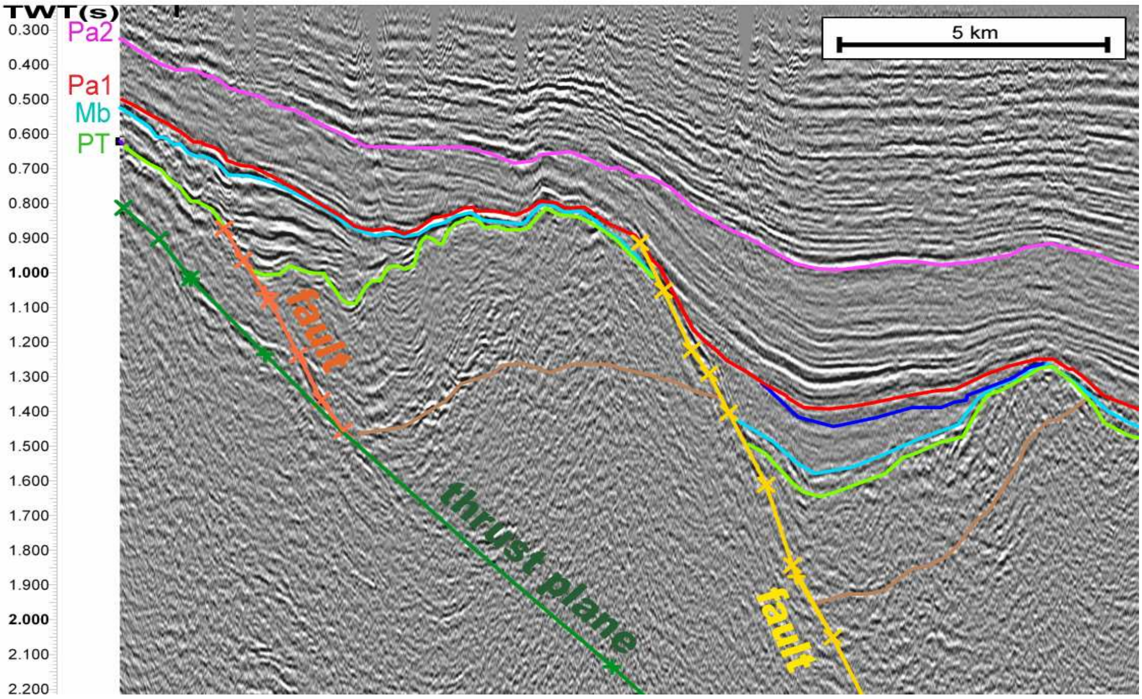


Fig.10. Faults and thrust planes on a seismic profile from the Lutzmannsburg-Zsira pilot area (Pa2: base Upper Pannonian, Pa1: base Lower Pannonian, Mb: base Badenian, PT: pre-Cenozoic basement)

## 3.7 Gravitational and magnetotelluric interpretations

To support the geological models of the pilot areas, the gravitational and magnetotelluric interpretation of the entire Hungarian project area (i.e. the Hungarian part of the supra-regional area) was prepared, which was calibrated by interpreted seismic sections and calculations of velocity-depth relations. First a map of geophysical surveys was edited (Figure 11) (i.e. map showing locations of various existing geophysical measurements, datasets). The used data for the present investigations are shown on Figure 12. Than gravitational and magnetotelluric datasets were interpreted at a regional scale, complemented by seismic data. By comparing gravitational, seismic and geological datasets (statistical analyses, iterative modelling) those areas were outlined, where geophysical methods were suitable to follow the basement morphology. The gravitational model was optimized for selected areas, and gravitation-based depth calculations were performed (Figure 13). To supplement tectonic information, a boundary of gravity sources map was edited, which shows the horizontal gradient maxima (Figure 14). Furthermore, the locations of geoelectric inhomogenities within the basement were also determined.

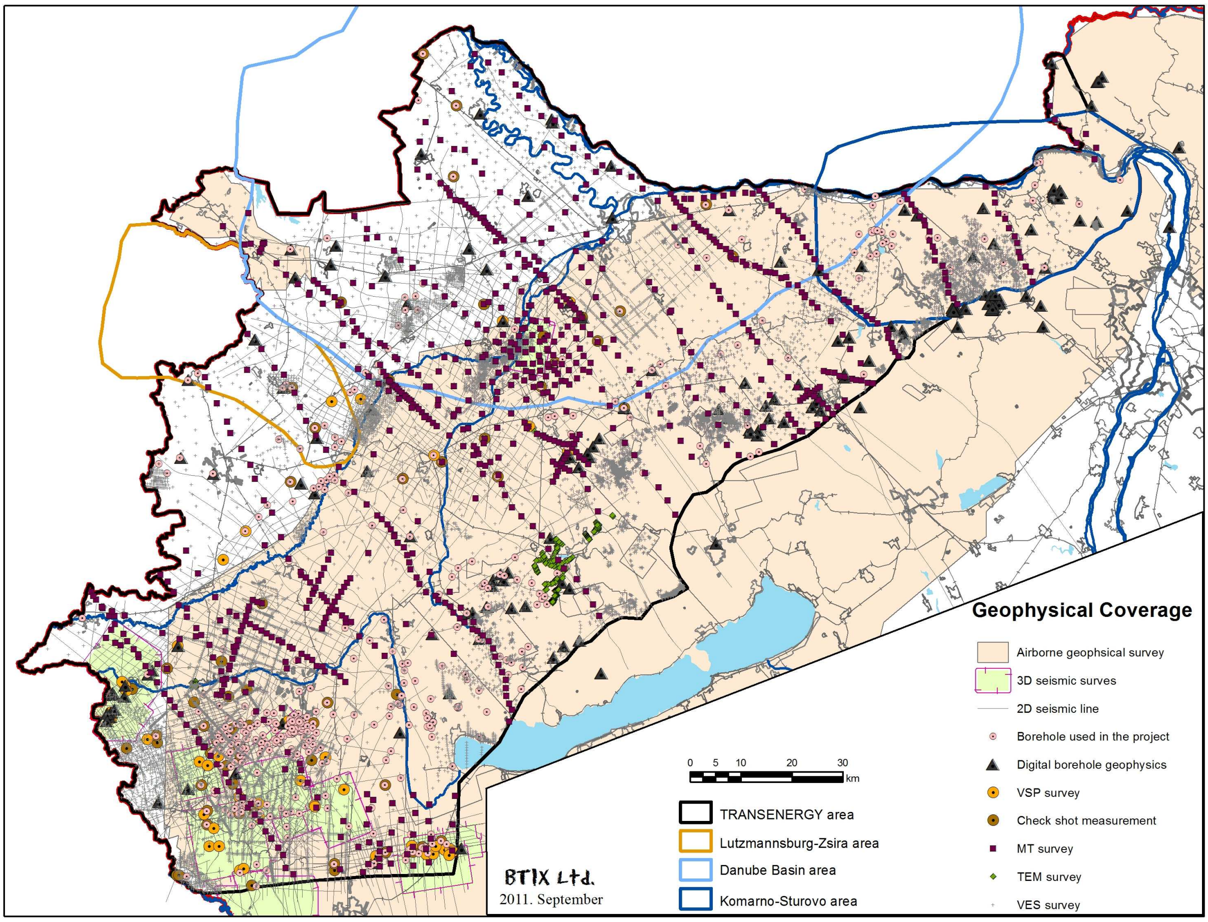


Fig. 11. Geophysical coverage map for Hungarian part of the Supra area

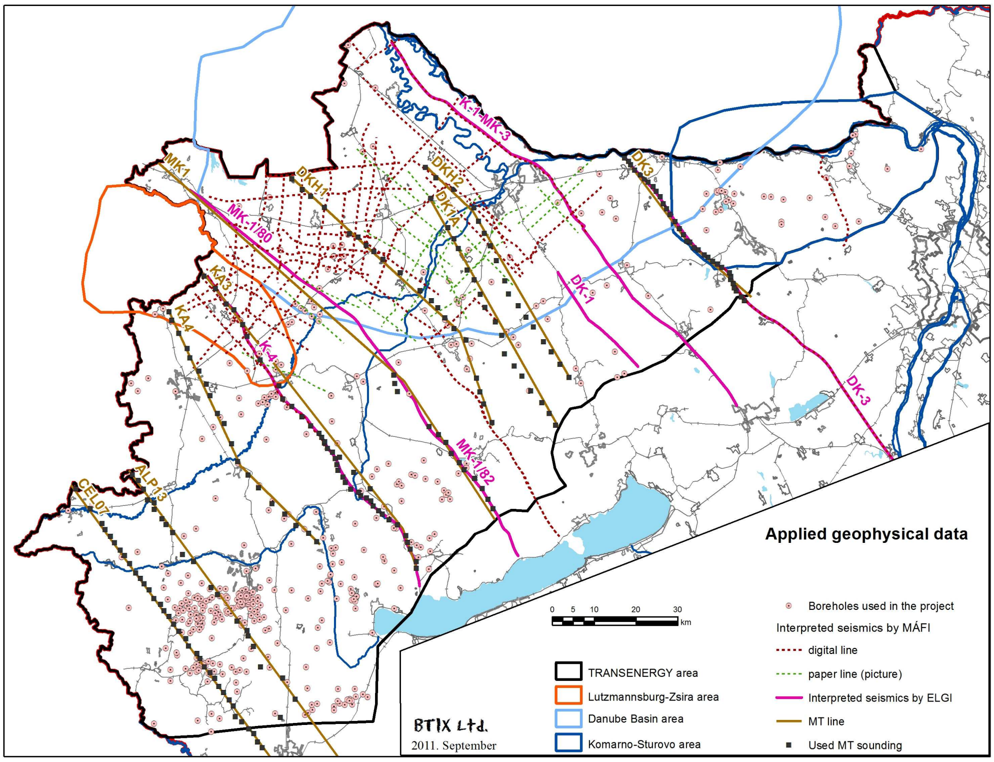


Fig.12. Applied geophysical map for Hungarian part of the Supra area

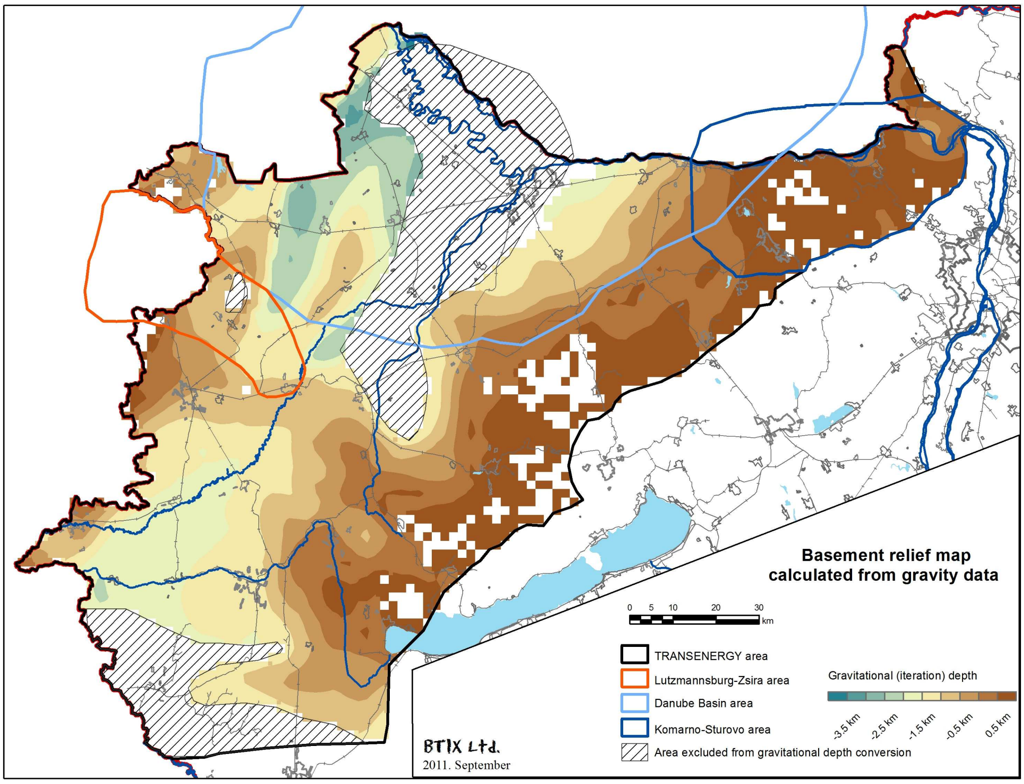


Fig. 13. Gravitational basement relief map for Hungarian part of the Supra area

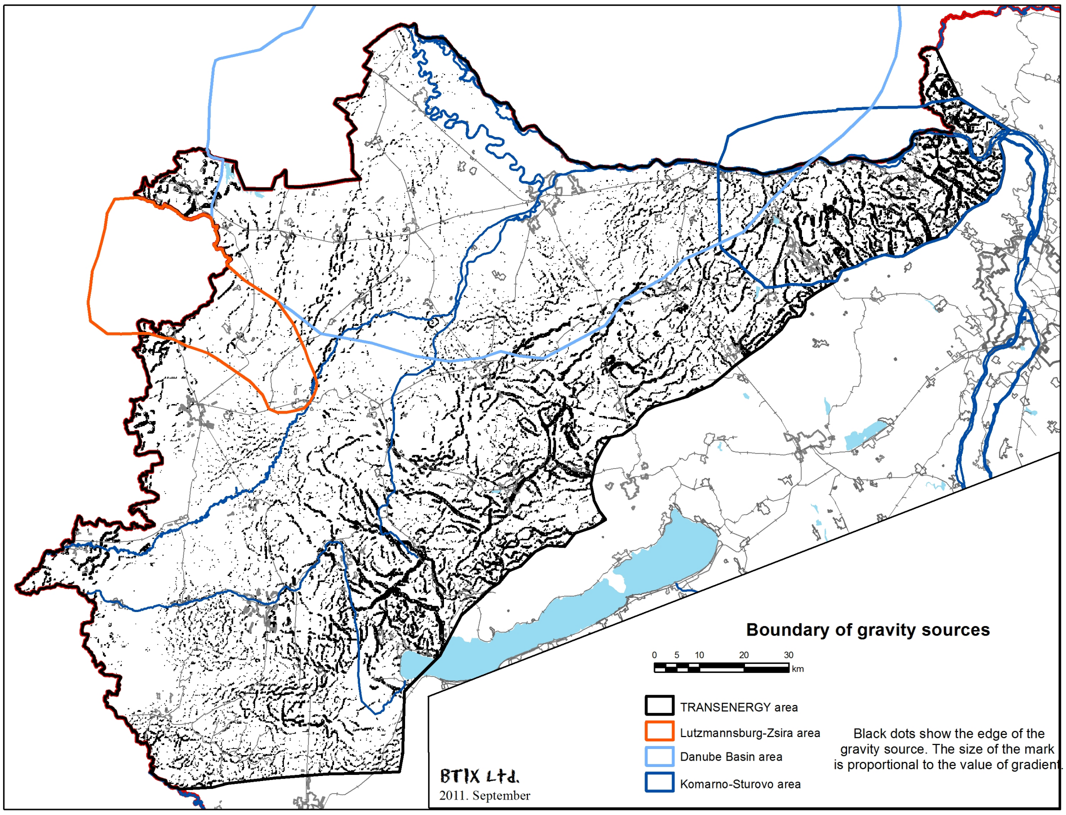


Fig.14. Boundary of gravity sources map for Hungarian part of the Supra area

A Bouger anomaly map with 1 x 1 km grid and 2 200 kg/m$^3$ correctional density was edited from gravitational data measured at 1.6 point / km$^2$ average density. Depth data can be calculated from gravitational data using inversion method. Parameters of the calculations were tested along sections using various models and borehole data in an iterative way looking for the best fitting. In the 5 km surroundings of the sections, the gravitation-based depth calculations were adjusted to the basement surface, pre-determined by borehole data.

The magnetotelluric measurements made it possible to outline the major inhomogenities (i.e. zones of good conductivity) in the basement (specific resistivity smaller than 10 Ohmm, shown by blue colors on the map). The reason for decreased resistivity cannot be specified from the raw data. There are two possible explanations: presence of hot salty brines and/or graphite. A part of the outlined conductivity zones have a limited vertical extension down to a depth of 10-15 km from the basement surface. These zones are extremely important from a point of view of geothermal utilization as they can provide space for fluid migration. Larger zones with increased conductivity - which can extend as deep as the lower crust - provide important information for the tectonic interpretation of the area. A map series was edited about the spatial distribution of the conductive zones in the crust at depths of -7,5 km, -10 km, -15 km and -20 km (Figures 15-18).

During the completion of the seismic datasets and their correlation with the above mentioned geophysical datasets, the horizons of the pre-cenozoic (pre-Tertiary) basement interpreted on the basis of regional seismic sections measured by ELGI were also considered. This independent method of interpretation provided a good tool for cross-checking, which showed a good correspondence, except for one section.

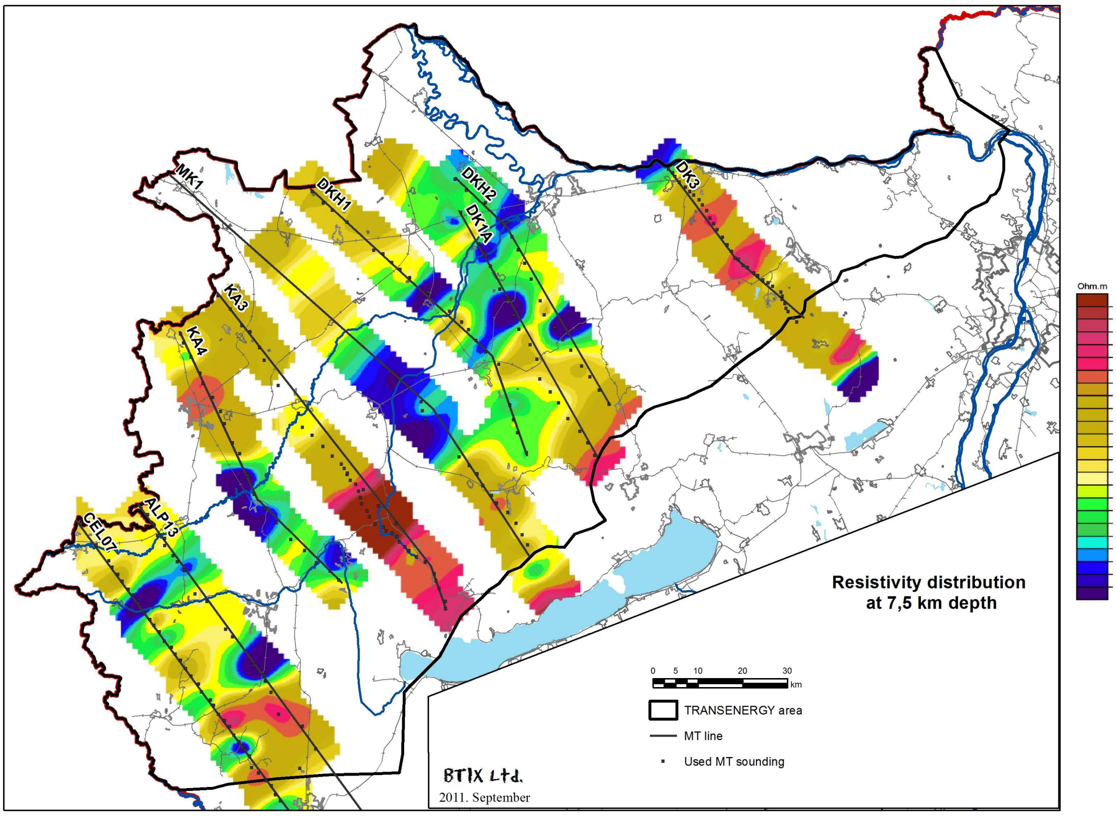


Fig. 15. Resistivity distribution map at depth of 7.5 km bsl for Hungarian part of the Supra area

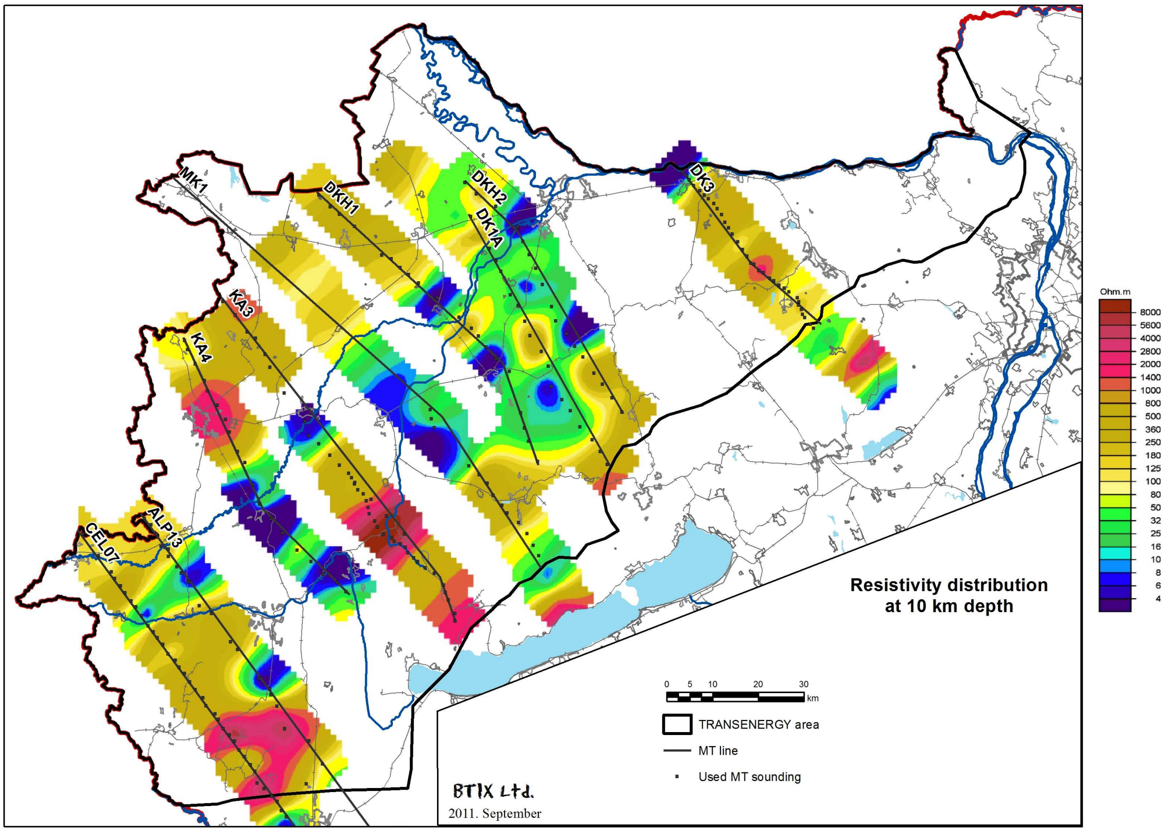


Fig. 16. Resistivity distribution map at depth of 10 km bsl for Hungarian part of the Supra area

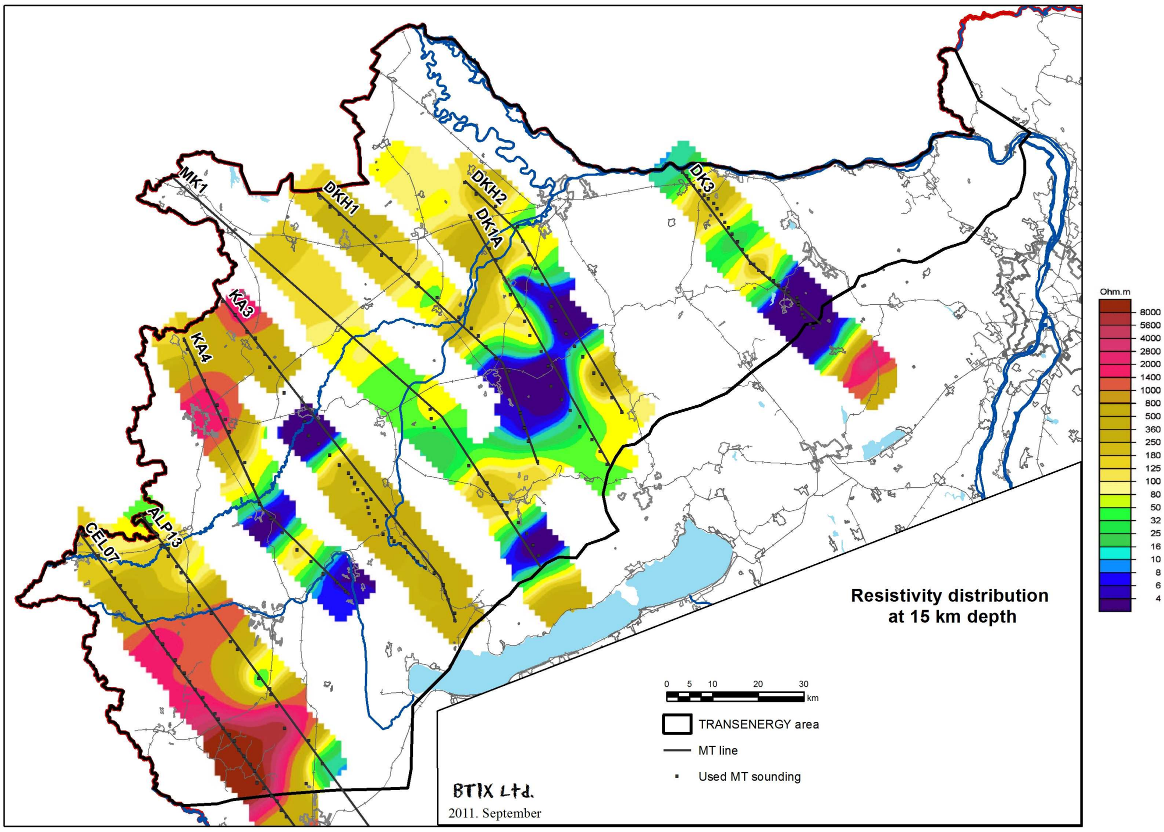


Fig. 17. Resistivity distribution map at depth of 15 km bsl for Hungarian part of the Supra area

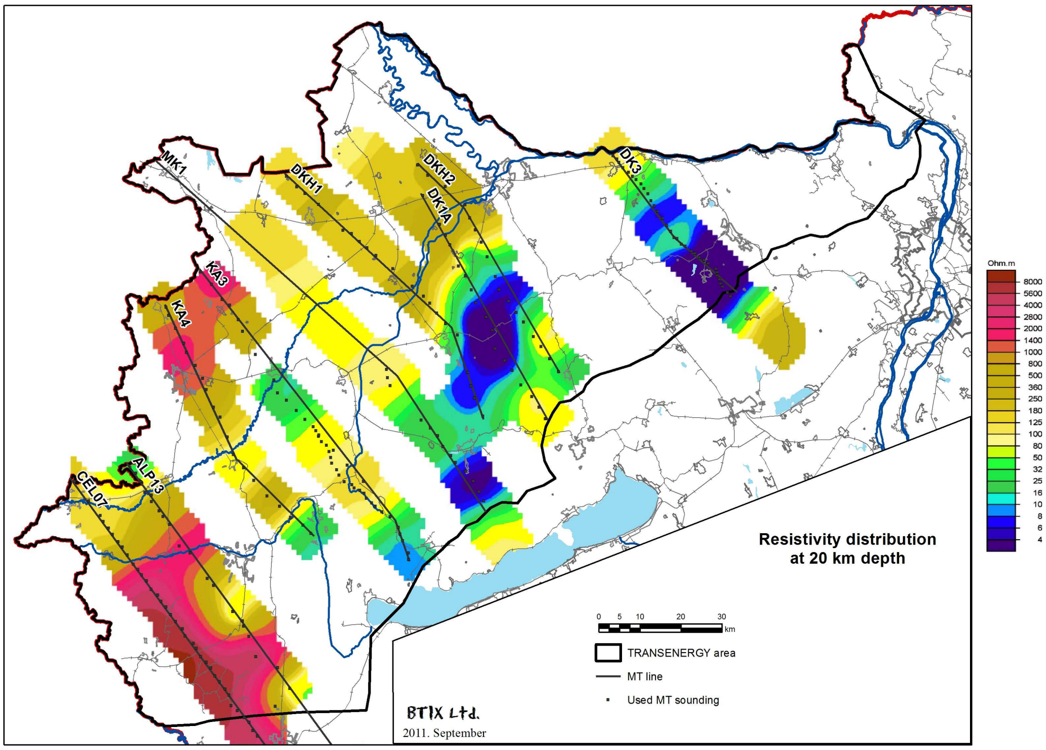


Fig. 18 Resistivity distribution map at depth of 20 km bsl for Hungarian part of the Supra area

## 3.8 Creation of the Supraregional geological model in ArcGIS and Jewel

The modeling of the Supraregional area was carried out primarily in ArcGIS (ESRI ArcGIS Desktop 9.2 and 10 versions, 3D Analyst, Spatial Analyst, as well as Surfer 10. The coordinate system of the model is WGS1984 UTM Zone 33N, its area is N 5405000, S 5122000, E 487500, W 801500. The projection is Transverse Mercator. All data is created in or transformed into this system. The coordinate transformation was carried out by ArcGIS and Global Mapper 10 software. In case the data transformations were carried out by third party actors, the results were verified and the inconsistencies were corrected. For the surface the SRTM (Shuttle Radar Topography Mission) elevation model was used. The final cell size is 500 x 500 m, however during edition, 100 x 100 m grid was used temporarily

During edition, the largest problem was the heterogenity of available data from the partner countries. Input datasets included final grids, existing maps with isolines, geological and geophysical data, as well as geological maps. All these different of data had to be harmonized, especially along state borders.

In the model, the lower interface (so called base map) of the previously defined geological horizons was edited. The deepest horizon is the pre-cenozoic (pre-tertiary), which is shown on the entire model area, all horizons above it are displayed only within the boundary of occurrence of the geological formations of the given geological age.

As a first step of modeling, an expert outlined the distribution area of the formations of a given horizon. This was based on borehole data and surface outcrops. Then after the combination of various data, the isolines of the given horizon were edited, which were interpolated by az ArcGIS 3D Analyst.

ArcGIS is suitable to edit individual horizons, however it cannot handle the multiple editing of several surfaces, e.g. considering their sequence. During the validation, several checking methods were used by Spatial Analyst. E.g. where a geological horizon is known to overlie the other one, do the two modeled surfaces have a correct relationship, e.g. the older surface does not cut into, or overlie the younger surface. This mistake was generally caused by the lack of data related to one of the horizons, therefore interpolation created untrue data. Another typical mistake was, when an „empty space” was generated in the model, i.e. some strata were missing between two horizons. This could have been corrected with the combination of different geological maps and horizon grids. As there was no automatic method for the correction of the above mistakes, in each case an individual decision had to be made considering the geological buildup of the given area. Furthermore, each modification affected the other horizons as well, therefore iteration process took a long time and required a lot of efforts.

To identify the spatial distribution of model horizons between the pre-cenozoic and the base of Lower Pannonian and Upper Pannonian (these were the key horizons for the hydrogeological models) another method was used to avoid the above lengthy iteration. The position of these “intermediate” horizons was identified on seismic sections using KINGDOM seismic interpretation software. Along the seismic sections the depth of each horizon was determined at each 200 m, and their thickness was calculated related to these points. These point-related thickness data were then interpolated using kriging methods in Surfer 9 software, which made possible to edit thickness maps. Afterwards the available space between the pre-cenozoic surface and the pannonian surfaces was determined for each model cell using ArcGIS, and in this available space the above edited thicknesses were proportionally distributed. Based on the thicknesses, the bottom horizons were edited, which surely overlie each other in the right sequence and do not cut into each other.

The heterogeneity of data and all above described techniques caused that not all borehole data matched necessarily the given edited (interpolated) horizon. Verification of the consistency between the well data and the created model-horizons was carried out by the JewelSuite 11 geological modelling software.

The verification process started with the import of different types of data in the modelling software. To import the data it was usually necessary to transform the different file-formats into proper form. The file-format transforming applications were developed by the modelling team.

After the import of the main data-sets, the definition of well-tops from borehole data was carried out. The well-tops in the model were in accordance with the main subsurface horizons.The main task at this phase was to match each horizon with the well data. In JewelSuite, a built-in application can be used for this task. The well matching application was executed on the subsurface horizon-models which had 500x500 m grid resolution.

The final model was verified for each horizon using kriging with isometric exponential function. The primary aim was to generate grids, which are correlated with the wells. Since the distance between two wells is often smaller than the resolution of the grid (500x500), the well matching was inevitable imperfect. Despite of this the mean of the differences between a well log data and the nearest grid point on the proper surface model was always near zero (+/-12 m), and the Standard Deviance was always smaller than 12 m (Table 2).

Some modelled horizons using JewelSuite are shown on Figures 19-20.

Table 2. The punctuality of the subsurface horizon-models after matching them with the well database

| Object | Property Name | Mean [tvss*] | StdDev [m] | Min [m] | Max [m] | Number of grid points |
|---|---|---|---|---|---|---|
| Pre-Quaternary | WM-residual | 0.63 | 3.47 | -174 | 141 | 121938 |
| Pre-Upper Pannonian | WM-residual | 2.59 | 2.06 | -138 | 153 | 101069 |
| Pre-Pannonian | WM-residual | 4.91 | 6.46 | -329 | 148 | 114619 |
| Pre-Sarmatian | WM-residual | 11.6 | 11.8 | -399 | 349 | 100302 |
| Pre-Badenian | WM-residual | -0.43 | 2.39 | -143 | 150 | 123399 |
| Pre-Neogene | WM-residual | 4.11 | 0.47 | -20.5 | 26.4 | 55155 |
| Pre-Cenozoic | WM-residual | -12.1 | 3.18 | -463 | 170 | 157902 |

* true vertical sub-sea depth

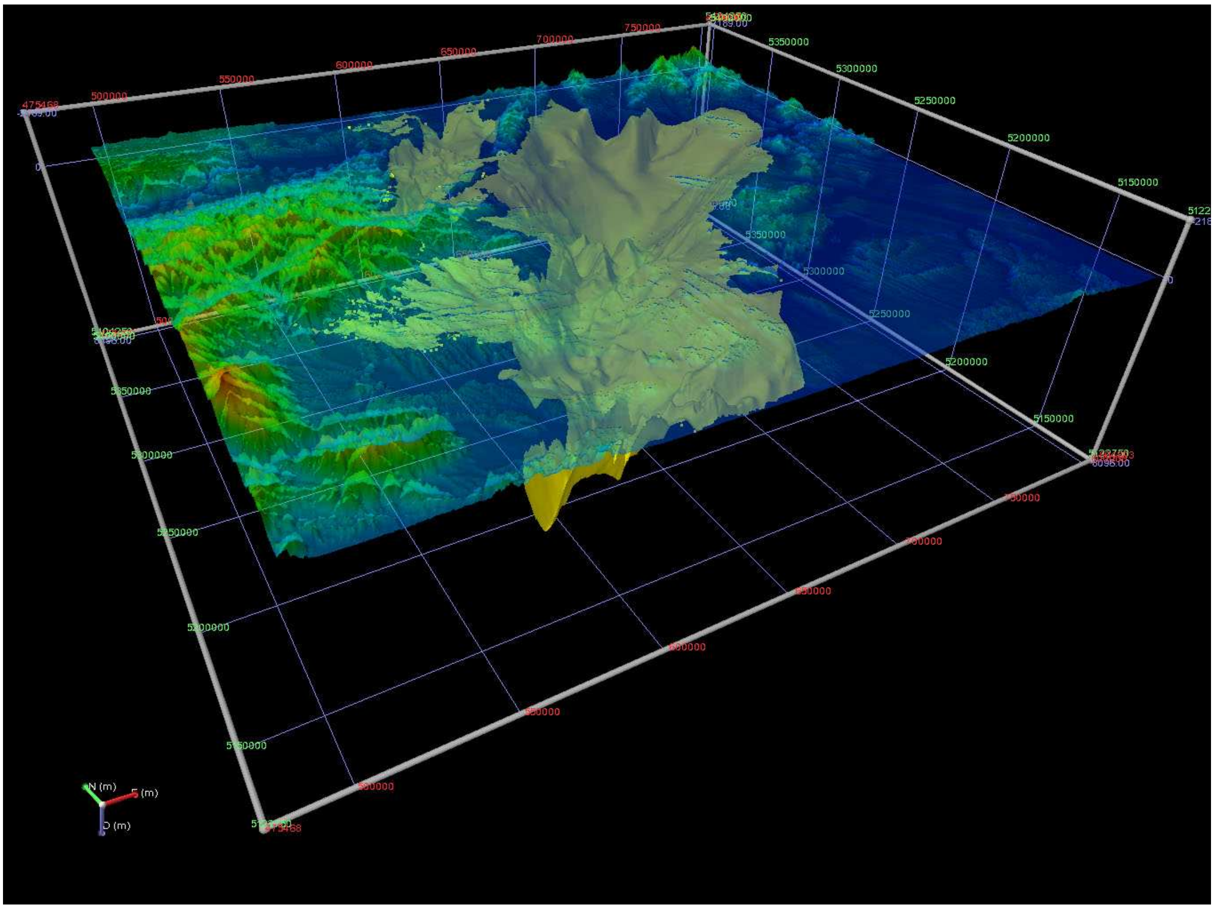
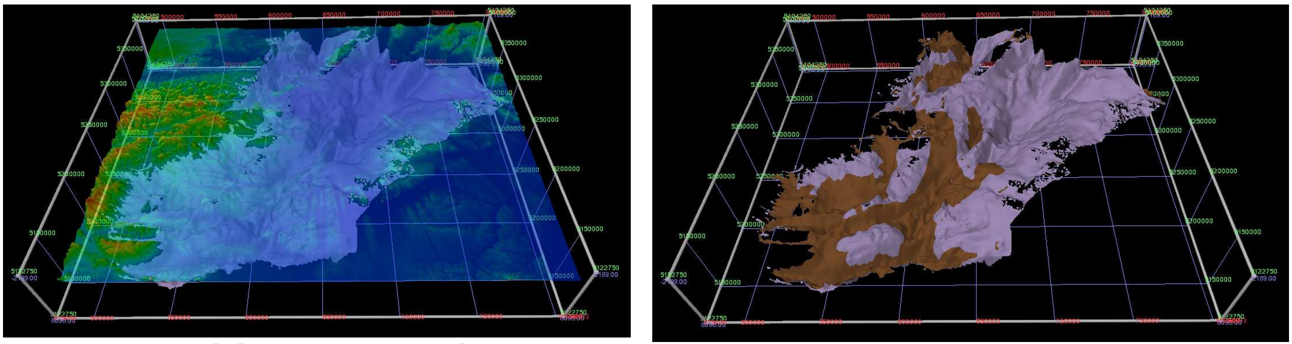
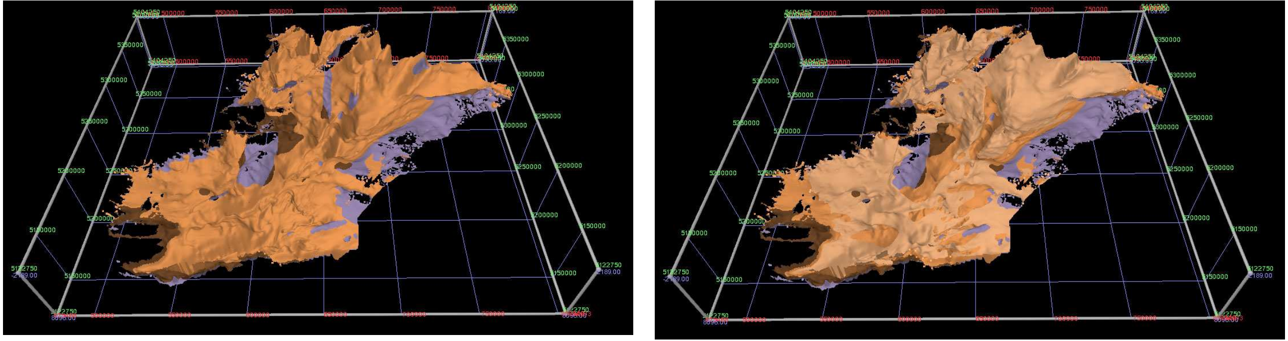


Fig. 19. The SRTM model (transparent) and the Pre-Pannonian subsurface horizon from the SW (10x height exaggeration).



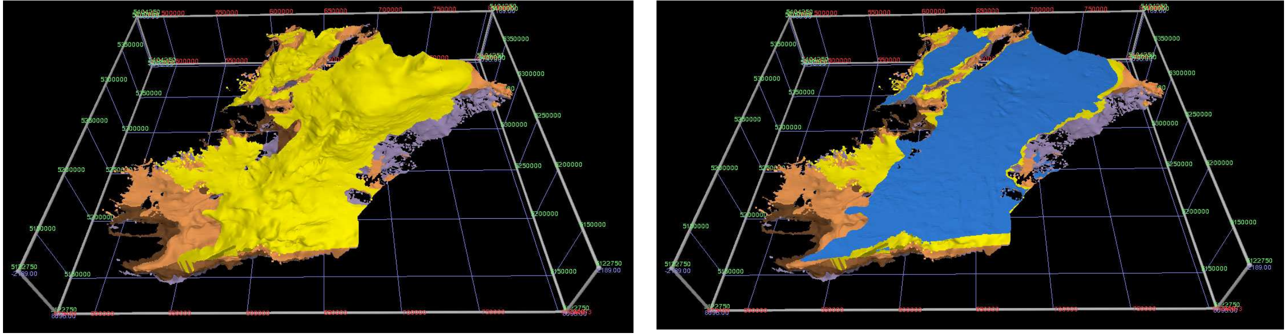
SRTM and the Pre-Cenozoic horizon

Pre-Cenozoic and the Pre-Neogene horizons



Pre-Badenian horizon above the Pre-Neogene

Pre-Sarmatian horizon on the top



Pre-Pannonian horizon on the top

Pre-Upper Pannonian horizon on the top

Fig. 20. The SRTM model and different subsurface horizons from the South (5x height exaggeration).

# 4 Geological modell of the Supra area

## 4.1 Summary of the geological buildup

Although the terminology slightly differs in the published data from the different countries and areas, the studied area belongs mostly to the ALCAPA major tectonic unit (East Alpine-Central Western Carpathian-North Pannonian lithospheric segment: Ratschbacher et al. 1991a,b; Csontos & Vörös 2004).

The project area is bordered by the Transdanubian Central Range unit on the east and southeast. The northwestern boundary is contoured by the northwestern margin of the Vienna Basin (Waschberg Zone), than it crosses through the northern Danube Basin boundary to the southeast, and is closed along the Transdanubian Central Range towards the southwest. On the west, the basement is containing Palaeo- and Mesozoic crystalline and sedimentary sequences belonging to the Lower to Upper Austroalpine nappe units, the Penninic unit, the

Graz Palaeozoic unit, and the Rhenodanubic (Magura) units. In the north, the basement rocks belong to the Central Western Carpathians nappe system. On the southeast the geological units of the basement are built by the Transdanubian Range unit and subsequently the inner and outer Dinaric related units. From the structural point of view, the framework shows characteristically nappes, thrust sheets, strike slip structures and normal fault systems. These units show a complicated structure, and in several areas a number of Alpine and older metamorphic phases can be detected; other areas are non-metamorphic.

The geological buildup of the project territory is very complex. Several subdivisions are possible for reviewing the different structural units. A possible method is to describe them by ages, or by main orogenic events of the pre-Alpine, Alpine cycle (pre-Alpine continental crust, eo-Alpine rift, oceanic sedimentary basins, collisional nappe stacking, flysch and flexural basins, gravitational collapse). Since the present project is a rather applied geological, one we chose a combined method. According to this, we firstly describe the units of the precenozoic basement (4.1.1.), than the flexural basins with the events of continental extrusion (4.1.2.), and finally we introduce the different syn-rift and postrift basins of orogenic collapse (4.1.3.). In this chapter (4.1.) a general Alpine evolutional framework of the units and basins is presented. The detailed formation descriptions of the different rock formations can be found in chapter 4.2.

The plate tectonic frame can be delineated as follows. The post-Variscan metamorphic crustal bodies and their molasse cover sediments were spreaded apart during the opening of Neotethys and Meliata-Maliac Oceans (Late Triassic) than by the differently designated Alpine Tethys oceanic basins (Piemont-Liguria, Vardar - Late Jurassic) linked to the opening of the initial Atlantic Ocean. In the Jurassic marine sedimentary successions deposited partly on these continental cores, or on the new oceanic crust. The collisional closure and subduction started in the early and mid-Cretaceous. As a consequence, an orogenic wedge was born which sustained the shortening. In front of the forming nappe stacks, flysch sequences deposited in the Valais, Rhenodanubian and Magura Oceans in the Late Cretaceous and Paleogene. In the Late Cretaceous times, a phase of gravitational collaps occurred and as a consequence, Gosau and connected sedimentary sequences deposited on the tilted blocks of the down-slipped nappes. During the Paleogene, flexural basins formed on the bending continental crust. Large scale strike slip faults with hundreds of kilometres of lateral displacements overprinting the nappe systems caused the present spatial distribution of the crustal fragments and the formation of pull-apart basins, which was accompanied by a series of volcanic-subvolcanic intrusions. This continental escape was also forced by the subductional roll-back process beneath the East Carpathian in the Neogene, when the bending subductional slab drew onto itself the escaping-rotating crustal unit of ALCAPA. Due to these extensional forces, the gravitational collapse of the territory happened along normal down-slip on the nappe surfaces, diagonal normal fault systems and subsequent strike slips. Due to this synrift process, metamorphic core complexes and tectonic windows were exhumed. Deep basins originated with various heteropic sedimentary rocks in the margins, on the rapidly sinking basin floor and tilting basement highs. This general extension stress field was punctuated by convergent, compressional inversion events, local block rotations from time to time. Subduction–related andesitic volcanism took place, followed by basaltic volcanic activity. In the postrift thermal subsidence phase firstly marine than turbiditic and gradually fluviatile sedimentary delta complexes filled up the basins. In the Quaternary, terrestrial alluvial clastic sedimentation took place.

### 4.1.1 Pre-Cenozoic basement

Based on the subdivision of Schmid et al. (2008) (Figure 21) we use 3 main divisions or tectonic Megaunits:

1. Bohemian Massive, stabile Europe
2. Oceanic accretionary nappe system (mainly green coloured),
3. Adria derived prowedge ALCAPA nappe system (mainly pink coloured),
4. Adria derived retrowedge Southern Alps and Dinarides (mainly brown coloured).

Within them we separate Main Units and Units and instead of Schmid further palinspastic based subdivision we use the traditional unit names. The recent relative position of the different units are shown on two published cross sections (Figures 22, 23) of Schmid et al. (2008) and Plašienka in Froitzheim et al. (2008).

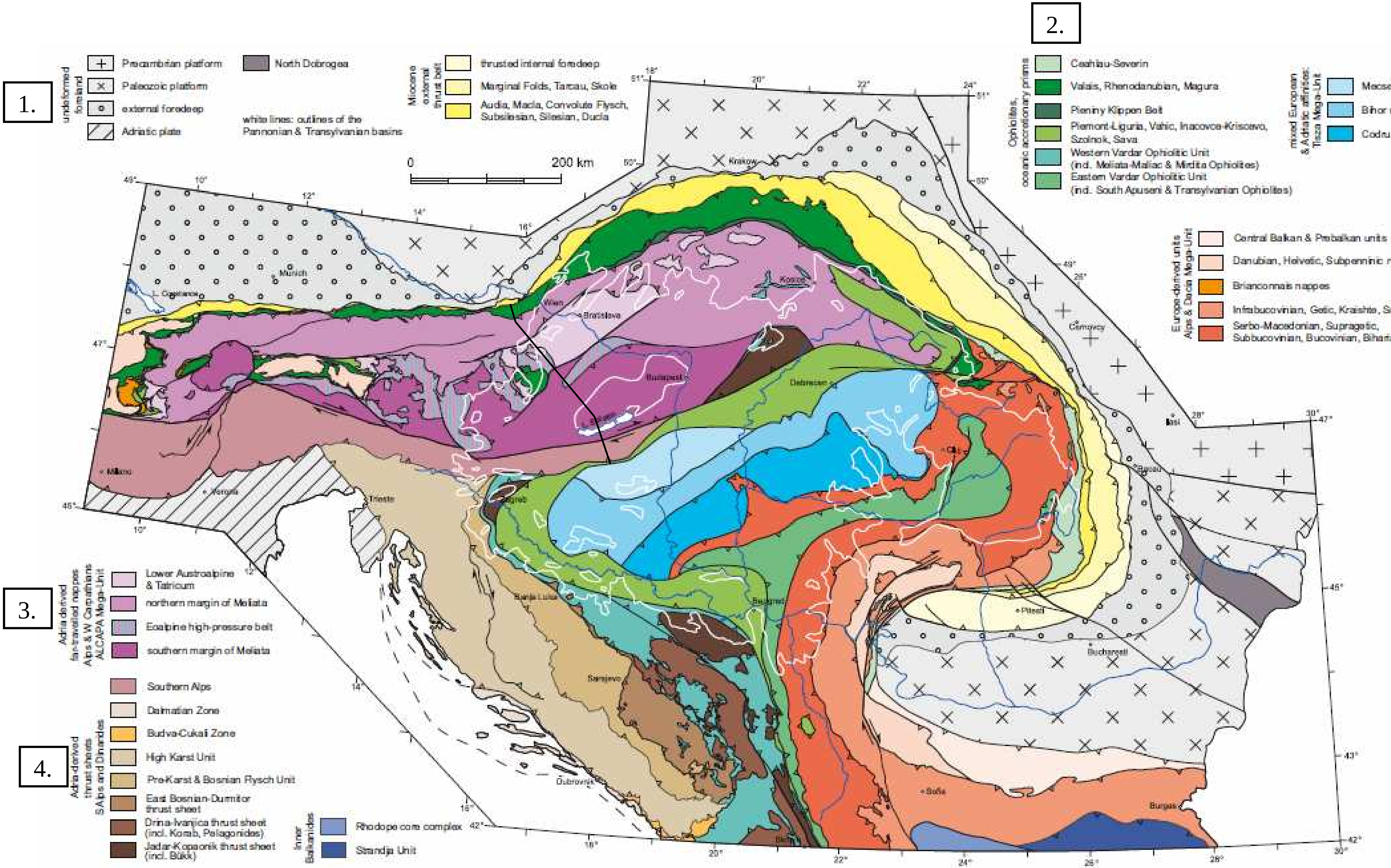
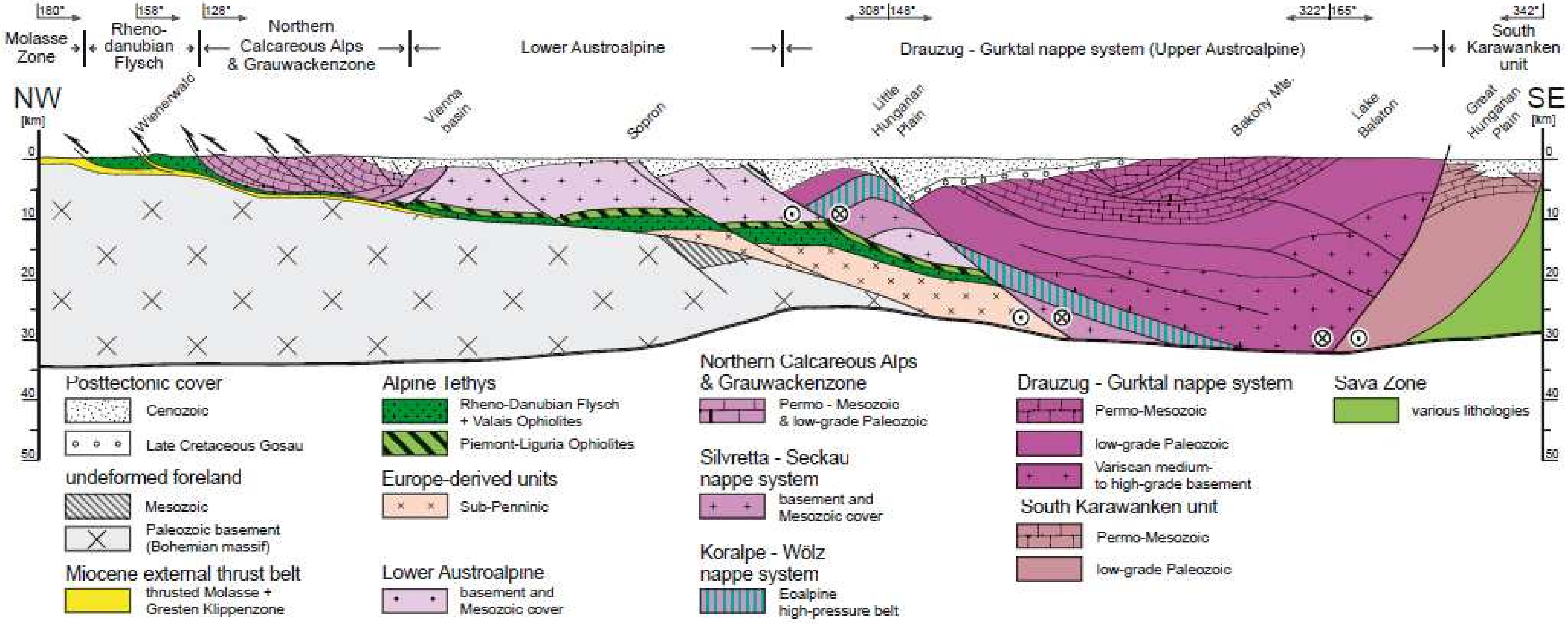


Fig. 21. Major tectonic units of the Alps, Carpathians and Dinarides (Schmid et al. 2008).



Construction using data from: Wessely (1987); Tari (1994, 1996); Szafián et al. (1999). Moho-depth after Horvath et al. (2006).

Fig. 22. Cross section from Eastern Alps to Transdanubian Range (Schmid et al. 2008.). Location of section is shown on Fig. 21

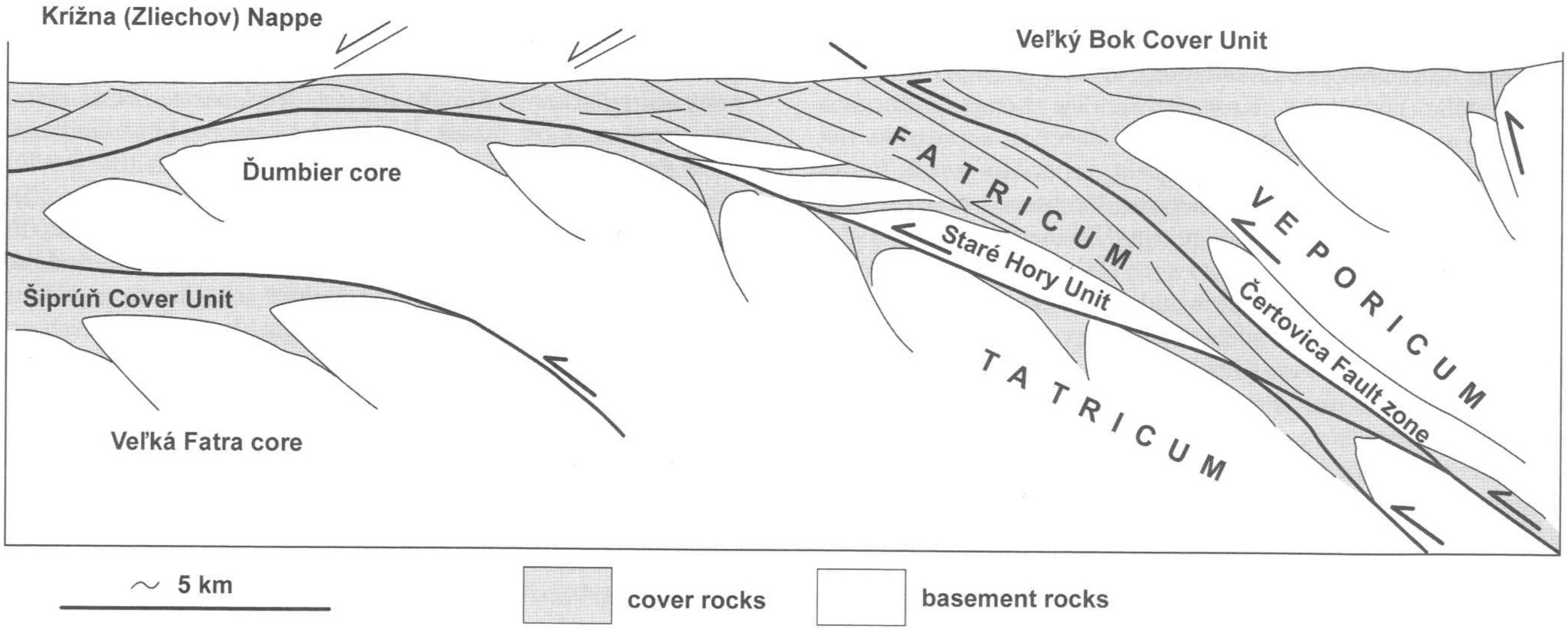


Fig. 23. Schematic cross section showing the relationships between Western Carpathian nappes (Plašienka 1999). Location of section is shown on Fig. 21

## 1. Stabile Europe

### *1.1. Bohemian Massive mesosoic cover*

## 2. Oceanic accretionary nappe system

### *2.1. Waschberg- Ždánice zone*

The Waschberg zone is a part of the Outer Carpathian Flysch Belt (Moldavides). Its northeastern continuation is the Ždánice Unit is Slovakia. Subordinately Upper Jurassic thrusted imbricates, Senonian to Eocene marine sediments and dominantly Oligocene deep water sediments represent this nappe system.

### *2.2. Rhenodanubian – Magura flysch*

We correlate and describe these two units together (Schnabel 1992). These units build up the Inner Carpathian Flysch Belt. Their sediments were deposited in the flysch oceanic basins in front of the nappe systems in the Alpine and Western Carpathian segment and represent the siliciclastic sedimentary complex of the northern Penninic realm. The Renodanubian flysch accreted in the Eocene, the Magura flysch accreted in the Late Oligocene times to the accretion wedge in the Alpine and Tatric-Veporic-Gemeric area respectively. They can be divided into different subunits in our territory, as Biele Karpaty and Rača nappes (Plašienka in Froitzheim et al. 2008).

### *2.3. Pieniny Klippen Belt*

This is a tectonically strongly deformed and condensed, complex unit. It follows the boundary between external and central Carpathian zones. It’s lateral and vertical position largely coincides with the Peri-Pieniny-Lineament at least till 5 km in depth (Birkenmajer 1986), which is thought to separate the subducted margin of the Europen platform and the Carpathian orogenic nappe stack as a suture zone (Froitzheim et al. 2008). The outcropping formations are non-metamorphic (Triassic)Jurassic limestones, cherty and marly limestones and Cretaceous–Paleogene flysch complexes. They originated from the Vahic Ocean (Plašienka 1995, 2003) which was the eastern continuation of Piemont-Liguria Ocean, and is completely subducted from Senonian times.

### *2.4. Penninicum or Kőszeg–Rechnitz window*

These basicly oceanic crust and covering metasediments are exposed now in a tectonic window. It is the deepest positioned tectonic unit; the Austroalpine nappes are overthrusted on it. It contains greenshist facies alpine metamorphic rocks, called the Rechnitz Series. Similar "Bündenschiefer" and greenschist sequences are exposed in the Tauern Window. The Unit is strongly folded, consists of several internal nappes (Ratschbacher et al. 1990; Dudko & Younes 1990; Neubauer et al. 1992). The protolites are Jurassic oceanic crust formations and pelagic sediments which were rich in marly pelites (Dunkl & Koller 2001). It was exhumed during the Middle Miocene crustal extension (Tari & Bally 1990, Dunkl & Demény 1997).

## 3. Adria derived prowedge ALCAPA nappe system

The ALCAPA term is used as defined by Csontos & Vörös (2004). These are the traditional basement units. They overthrusted onto each other predominantly in nappes of southeastern vergency during the early and mid-Cretaceous collisional processes.

In the sense of Schmid et al.(2008) the whole ALCAPA nappe system can be grouped into an Adria derived far travelled nappe system, which comprises the Austroalpine nappes, Tatricum, Veporicum and the Transdanubian range, too. Although the Supra area represents only smaller part of the whole Alpine orogene system, we follow the division of Schmid, but we divide the basement Superunits into more traditional Units, as follows.

### *3.1. Austroalpine and Western Carpathian nappes*

These elements are often referred as being derived from Adria (or "Apulia" in the sense of Schmid et al. 2004) amalgamated in the variscan orogeny or even earlier. In the Alps this implies that their initial paleogeographical position was to the south of the Alpine Tethys (Piemont-Liguria Ocean). Nowadays, these elements represent far-travelled thin crustal slices found above the Penninic (or Vahic in case of the West Carpathians) suture zone. There are units of crystalline rocks and of paleozoic-mezozoic cover on them. In general, the crystalline sequences are polimethamorphic of medium grade amphibolite facies. They were metamorhised during the variscan orogeny and after they suffered an alpine overprint.

#### Lower Austroalpine Unit

The Lower Austroalpine units are defined as part of the Austroalpine units, which formed in the northern margin of Apulia, towards the Piemont-Ligurian ocean. When the Penninic Ocean closed this nappes were involved in subduction related deformation and greenshist facies metamorphism (Froitzheim et al. 2008). The crystalline islands of the Sopron Mts. are clearly the continuation of the Semmering-Wechsel-system (Wechsel and Grobgneiss complex) to the southwest and are belonging to the Lower Austroalpine nappe complex. The Leitha Mts. form the northeasternmost spur of the Central Alpine chain and are lithologically quite similar to the Lower Austroalpine unit of the Semmering-Wechsel area. The Central Alpine crystalline basement outcrops at the surface also in the Sopron Mts. in the southern continuation of the Rust Range.

#### Tatricum Unit

It shows similarities to the Lower Austroalpine unit, and is regarded to be a Carpathian continuation of the Central Alpine units in Slovak territory. In the Supra area three "core mountains" (Malé Karpaty Považký Inovec, Tribeč) are represented on the surface and in the basement of Tertiary basins. In the Malé Karpaty Mts., the Tatric unit system is represented by high grade crystalline rocks and cover sequences (Late Permian to Cretaceous). The Hainburg hills consists of a core of granodiorite and are regarded to be a part of the Tatricum of Carpthian Malé Karpaty Mts.

#### Fatricum, Križna nappe

In the basement of the Supra area it is a tectonically clipped thin nappe of detached sedimentary cover and basement rocks, which overlay the Tatricum. It is present in the areas of Tríbec, Považský Inovec and Malé Karpaty Mts. and is known in the pre-Tertiary basement of the Vienna basin. Two types of subunits can be recognised. The first type is represented by basement crystalline rocks and pre-Alpine Permian–Lower Triassic cover duplexes (e.g. Plašienka 2003), the second type is represented by detached Middle Triassic–Mid-Cretaceous sedimentary rocks (Križna, Andrusov 1968), which are overthrusted on the Tatricum.

#### Hronicum, Choč nappe

The Križna nappe is tectonically overlain by the Hronic nappes, which outcrop in the northern part of Malé Karpaty Mountains. Some Upper Austroalpine nappes (upper Bajuvaric, Tirolic units) have similarities to the Hronicum (Plašienka in Froitzheim et al. 2008). It is a detached nappe system and has no connections to its original basement. It consists of non-metamorphosed eo-Alpine sedimentary series, deposited on the northern passive margin of the Meliata-Maliac Ocean (Schmid et al. 2008) and is overlain by sediments of the post-tectonic Gosau formation system.

*Veporicum Unit*

It is a methamorphic core complex, which is overthrusted onto the Tatricum, Fatricum and Hronicum units, and emerged from deeper crustal position in the Eoalpian times (Tomek 1993, Plašienka in Froitzheim et al. 2008). It represents the basement of the northern margin of Meliata-Maliac Ocean (Schmid et al. 2008). In the Supra area it occurs only in the basement between the Mojmírovce fault and the Hurbanovo–Diósjenő Fault.

*Upper Austroalpine Unit*

They represent a complex nappe stack formed by the Eoalpine tectonomethamorphic events. During the Tertiary Alpine events the nappe stack stayed in an upper plate position. In Hungary a unic nappe complex is considered to be a part of this stack and named a little bit confusingly as Upper Austroalpine nappe (Rába Metamorphic Complex, Fülöp 1990). In Austria and Slovenia it consists of a series of nappes: Drauzug-Gurktal, Ötztal-Bundschuh, Bajuvaric, Tirolic, Juvavic, Greywacke, Koralpe-Wölz-Pohorje, Silvretta-Seckau nappe systems (Froitzheim et al. 2008). It comprises the following units.

*Koralpe-Wöltz–Pohorje Unit*

This basement crystalline series of different metamorphic grade (Froitzheim et al. 2008, Lelkes-Felvári et al. 2002.) lacks Permo-Mesozoic cover sediments. It crops out in the Koralpe and Pohorje Mts. The southern part of this unit contains eclogites of Cretaceous age. The metasedimentary formations show Permo-Triassic amphibolite-, possibly Cretaceous eclogite- and subsequent amphibolite-facies overprints. This unit has a Cenozoic tectonic contact to the NE with the Transdanubian Range unit, near the Hungarian border it forms a tectonic window. The formations of this unit show similarities to the Lower an Upper Austroalpine system. The greenshist grade metamorphic formations can be correlated with the Upper Austroalpine, the eclogite- and amphibolite-facies metamorphic formations with the Lower Austroalpine nappes (Fodor et al. 2011). The formations of this unit are affected by milonitisation.

*Graz paleozoic and Rába Complex*

The Graz paleozoic is an exposed basement unit of the Upper Austroalpine system. It crops out north and west of Graz and then sinks below the Neogene sediments of the Styrian basin. It forms a complex pile of nappes with different lithostratigraphic and metamorphic styles (Bełka & Narkiewicz 2008). Three major nappes can be recognised (Kreutzer et al. 2000). All nappes contain thick Devonian sequences which evolves from the Silurian and more condensed Carboniferous layers of two facies groups (McCann et al. 2008).

The Rába Complex is known from boreholes beneath the Danube basin, mainly in Hungary, partly in Slovakia. Near Szentgotthárd it is connected to the Graz Paleozoic, but the style of contact is unclear. It consists of various metasediment and metavolcanite formations of Variscan and weak Alpine metamorphism (Árkai et al. 1987).

*Ikervár Unit*

This is a small nappe fragment in the basement of the Danube basin, which is known only from a few borehols. It contains metasediments which age is supposed to be Jurassic-Cretaceous based on tentatively determined fossils (Haas et al. 2010).

*Bajuvaric, Tirolic and Juvavic Units*

The Northern Calcareous Alps are composed of these three nappe systems from bottom to top. All three nappes consist of Permian to Paleocene sediments, however in the Mezozoic sequences there are significant differences. They were mobilized under different Eoalpine and

Alpine tectonic conditions.The Juvavic nappe was transported over the Tirolic nappe. However, the Tirolic nappe underwent lowermost greenshist metamorphism, while the Northern Calcareous Alps remaind in the diagenesis phase (Kralik et al 1987). They occur in the basement of the Vienna basin and on the surface in the Northern Calcareous Alps.

*Greywacke zone Unit*

It is part of the Upper Austroalpine units and underlies the Tirolic nappe system, representing a complex nappe system itself. It is a stack of four different nappes (Neubauer et al. 1994). They incorporate hercynian crystalline metamorphic rocks of greenshist and amphibolite facies (downward increasing metamorphic grade in the different nappes) Paleozoic metasediments, Permian clastic sediments and possibly Jurassic metavolcanics.

*Transdanubian Range Unit*

This thick, Paleozoic-Mezozoic mainly sedimentary sequence represents the Southern margin of Meliata-Maliac Ocean (Schmid et al. 2008). Its northwestern border is a Neogene strike slip and normal fault system, which is partly a Cretaceous nappe sheet (Tari 1994, Haas et al. 2010). It is the highest positioned Austroalpine nappe. Its southern border is the Periadriatic-Balaton line system, acting as a strike slip zone in the Paleogene (Kázmér & Kovács 1985, Balla 1988). Its recent position evolved by complex Paleogene extrusion and Neogene extensional collapse due to subduction related roll-back extension forces and rotations. In the Supra area, the Periadriatic-Balaton line can be correlated in Slovenia with the Ljutomer belt consisting of Triassic formations. In the SW-ern part of the unit, there are metamorphites under the Paleozoic-Mezozoic system: greenshist facies Kobansko and Koralpe-Wölz nappe system which crops out in Pohorje.

*Gosau in the Transdanubian Range Unit*

Regional uplift led to subaerial exposure and strong erosion especially on the limbs of the mega-synform. As a consequence of denudation of the younger Mesozoic rock sequences, Upper Triassic platform carbonates were exposed and karstified. By the Santonian a large sedimentary basin came into being in the western side of the synform. In the northern part of the depressions fluviatile and lacustrine sediments were deposited. Coevally, in some sub-basins on the southeast lakes and freshwater swamps came into being. As a result of the ongoing transgression brackish-water and subsequently marine basins evolved, while on the elevated ridges were colonized by rudist reefs. These platforms drowned in the middle Campanian. and a pelagic basin came into being.

## 4. Adria derived retrowedge Southern Alps an Dinarides

*Mid-Hungarian Unit*

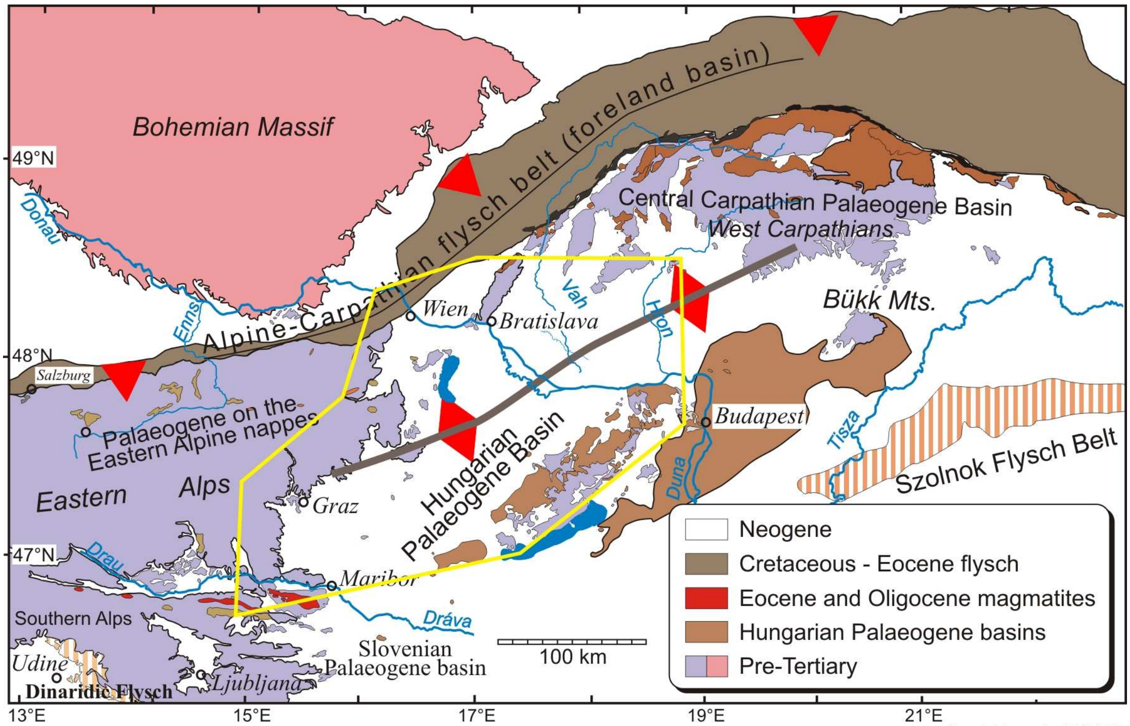
This unit is located at the southernmost border of the Supra area. It’s tectonical position is between the Periadriatic-Balaton line and the Mid-Hungarian Line (Zagreb–Zemplén Line). This Southern Alps related unit has a very complex buildup and represents strongly sheared and deformed strike slip duplexes of various origin. This is mirrored in the various synonyms used for this unit [Mid-Hungarian unit (Haas et al. 2010), Zagorje–Mid-Transdanubian unit (Pamić and Tomljenović 1998), Sava Composite unit (Haas et al. 2000)]. The relation to the Southern Alps is derived from correlation to Carnic Alps, Southern Karavanks, Sava folds. This tectonic mega-melange is thought to be a junction complex of the Southern Alps, Dinarids and Tisza unit which incorporates Cretaceous nappes, Paleogene strike slips, Neogene transpression and tension structures.

The project area contains the South Karavanks subunit, which consists of Permian to Triassic siliciclastics, ramp facies, marine and platform carbonates.

## 4.1.2 Paleogene basins

As a consequence of the compressional stress-field resulting from the Late Cretaceous–Paleocene Alpine collision, three major basins of different tectonic structure and evolution history were formed in the TransEnergy project area during the Paleogene (Figure 24). In the Alpine and Western Carpathian regions, in the foreland of the nappe fronts behind the Alpine-Carpathian subduction zone, the sedimentation continued in a deep foreland basin (Alpine-Carpathian Flysch Belt), which was formed during the Alpine tectogenetic cycle and was filled with several 1000 m thick detrital sediments, during the Paleocene. Simultaneously, a WSW-ENE striking series of narrow basins of great depth (Gosau Basins – Austria and Western Central Carpathian Palaeogene Basin – Slovakia) developed due to the dynamic, rapid uplift in the inner part of the Eastern Alps, in the foreland of the Late Cretaceous nappe fronts. Inverse faults and folds with large amplitude developed in the southern margin of the Austroalpine nappe system with a vergency opposite to that of the nappes belonging to the subduction front which formed a flexural basin (Tari et al. 1993) between the Northern and the Southern Alps (Hungarian and Slovenian Paleogene Basin). This basin is situated in the southern backarc of the Alpine-Carpathian system isolated from the northern foreland.

The correlated geological formations of the different Paleogene basins for the Supra area are shown on Figure 25.



after Kázmér (2003)

Fig. 24. Paleogene basins in the Carpathian Basin behind the Alpine-Carpathian subduction zone. Yellow line: boundary of the TransEnergy area (after Kázmér et al. 2003)

## The Flysch basins (PILLER et al. 2004)

The deposits of the Paleogene flysch zone occur in the Eastern Alps, the Western Outer Alps, in the Vienna Basin and partly in Slovakia in the studied area. The formation of the detrital deposits of the Late Cretaceous flysch zone in the frontal part of the Penninic nappe system continued in the Early and Middle Paleogene (Paleocene, Eocene). The only place where the sedimentation lasted with short pauses until the Ottnangian is the Austrian Washberg Zone (Washbergzone = PcMo_W). The sedimentation of the flysch zone is characterized by deep water marine, cyclic turbidites, rhythmic coarse sand, conglomerate and sand, as well as fine grained aleurite with marl intercalations (flysch deposits), deep water fans and channel deposits containing conglomerate bodies and shallow marine olistoliths. The rock formations of the different facies areas can differ considerably along the narrow, long chain of basins and its margins.

The flysch formations are named differently in the different facies areas and in the different nappe units in the professional literature of Austria (Laab Fm = Pg_L, Sievering Fm in Kahlenberg Nappe = Pg_K, Greifenstein Sandstone Fm = Pg_G, in Göstling slice = Pg_GfG, in Zisterdorf slice = Pg_GfZ, Raca Nappe in Austria and Slovakia = Pg_R). In Slovakia the Paleogene flysch formations of the Western Outer Carpathians are represented by the Svodnica (PcE1_W), Priepasné (PcE2ml) and Jablonka (E2-3ml) Formations from the Paleocene, and by the Lubina Formation (E2-3ml) from the Lutetian, which contains slope conglomerates as well as coral-algae bearing limestone olistoliths.

## The Gosau Basins (PAVLISHINA et al. 2004, BEZÁK, 2008)

In the TransEnergy area the deposits of the Gosau Basins appear in the inner Paleogene basins of the Calcareous Alps and around the Vienna Basin in Austria, in the basement of the Paleogene formations in Slovenia and in the inner, southern part of the Western Carpathians in Slovakia.

In Austria and Slovenia proximal and distal coarse detrital slope fan deposits, channel conglomerate bodies and shelf olistoliths are interbedded in the deep water clay marl and sandy clay marl flysch sequence of the Gosau Basins. At the same time, shallow marine limestone, coral reef and fore-reef sediments are also present in the succession (Obere Gosau Subgroupe: Giesshübl Fm, Kambühel Fm = KPg_G).

In Slovakia calcarenite, conglomerate and breccia of shelf and shelf margin environments, as well as reef deposits (Hricovske Podharie Fm = Pc-E3ls) are typical of the Early and Middle Paleocene sedimentation of the Gosau Basin. In the shallow marine environments coral and algae reef-bearing limestone and limestone with marl intercalations (Dedkov Fm = Pc-E3ls), in the coastal, land environments dolomite breccia, well stratified carbonate breccia, conglomerate, dolomitic, organic-rich sandstone and sandy limestone, then Operculina limestone (Jablonové Fm = Pc-E3ls) were formed during the Late Paleocene–Early Eocene. In the Gosau-type succession deep water flysch-like sediments (Domaniza Fm = Pc-E3ls) were deposited in the Middle Lutetian.

In the terrestrial facies of the Gosau-type sequences in Slovakia, bauxite was formed from the Cretaceous possibly up to the Paleocene, while in the shallow marine environments coral reefs developed (Cretaceous terrestrial sediments in Slovakia, Brezová Group, Kambühel Fm = KPg_G), which is of the same age as the bauxitic sediments in the Hungarian and Slovenian Paleogene Basin.

### The Inner Carpathian Paleogene Basin (GYALOG 1996, GYALOG & BUDAI 2004, CIMERMAN F et al. 2006)

The Slovenian and Hungarian Paleogene Basin, which was uniform during the Paleogene, was sheared along the Periadriatic Lineament during the rift phase of the Pannonian Basin, which was characterized by large-scale strike-slips. Sheared, tectonically isolated basin fragments (e.g. Zala Basin and smaller basins along the Mid-Hungarian Lineament) can be found in the strike-slip zone. The deposits and the evolution history of the two basins show a uniform picture.

The sedimentation in the Paleogene Basin started at the very end of the Early Eocene–at the very beginning of the Middle Eocene. The Paleocene–Early Eocene red clayey, bauxitic formations (Gánt Bauxite Fm = Ebx) overlie Gosau-type deposits in Slovenia, and the blocky, sometimes karstic eroded surface of the Mesozoic in Hungary. At the beginning paralic coal-bearing layers and sandy, clayey lagoon sediments (Dorog Fm, Darvastó Fm, Obid Mb = Ebc) deposited in the coastal, shallow marine environments of the NNW-ward deepening basin. Due to the Lutetian transgression, the coal-bearing strata are covered with shallow, then deep water sandy clay marl and clay marl layers (Csernye Fm, Csolnok Fm = PcE2ml) in the basin areas, with heteropic shallow marine milioline, nummulitic-discocyclina limestone and limestone with marl intercalations (Szőc Limestone = E2ls) on the carbonate ramp. At the same time, in the deeper marine environments glauconitic clay marl deposited, in which siliciclastic layers of a SW prograding delta (Padrag Marl Fm, Tokod Fm = E2-3ml) were deposited at the end of the Bartonian. A similar environmental distribution takes place in Slovenia, where the alveolina-nummulitic ramp carbonates (Alveolina, Nummulites limestone = E2ls) characterize the whole Lutetian–Middle Bartonian period, then with an erosional gap deep water Priabonian flysch-type marl, clay marl, sandy clay marl layers (Socka Beds or Dobrna Fm = E2-3ml) followed. In the SW part of the Paleogene Basin, andesite lava and pyroclastic layers are interbedded in the clay marl (Szentmihály Andesite Fm = E2-3a). At the margin of the rapidly sinking basin, foraminiferal, red algae-bearing carbonate deposition (Szépvölgy Fm = Esls) started again at the very end of the Bartonian–beginning of the Priabonian, the olistostromes of which appear also in the deep basin sediments. The Eocene succession of the Hungarian Paleogene Basin was eroded by the Early Oligocene denudation.

Following the Early Oligocene uplift and erosional period in the Hungarian Paleogene Basin, the geometry of the basin turned over and the deep marine facies were situated in the SE, while the land and shallow marine environments existed in the NW during the Oligocene. During the Early Oligocene, erosion took place in the W-ern part of the basin, and gravel, conglomerate and sandstone layers were accumulated by longshore currents (Hárshegy Fm, Cíz Fm – Blh Mb, Skálnik Mb = Olc) in the E-ern part of the studied area, interfingering with clayey sediments that were deposited in open marine, anoxic isolated basins (Kiscell Clay Fm, Hrabník Fm = Olmf) to the ESE. In the Late Oligocene, fluvial (Csatka Gravel Fm = Olf) deposits were formed in the NW, while in the SE coastal coarse detrital, as well as lagoonal, brackish and transitional clayey, sandy strata (Mány Fm, Törökbálint Fm; Lucenec Fm – Kovacov Sand = Olb) were deposited.

The first major difference between the two main units of the Inner Carpathian Paleogene Basin appeared during the Oligocene. The Early Oligocene formations of the Slovenian Paleogene Basin are represented by andesite tuff, tuffite and marl layers in isolated tectonic units. The siliciclastic sedimentation started with sandy marl, sandstone sequences (Pletovarje Fm = Olf) at the beginning of the Late Oligocene and continued with quartz sandstone, glauconitic sandstone and conglomerate layers (Govce Fm = Olb) up to the Early Miocene.

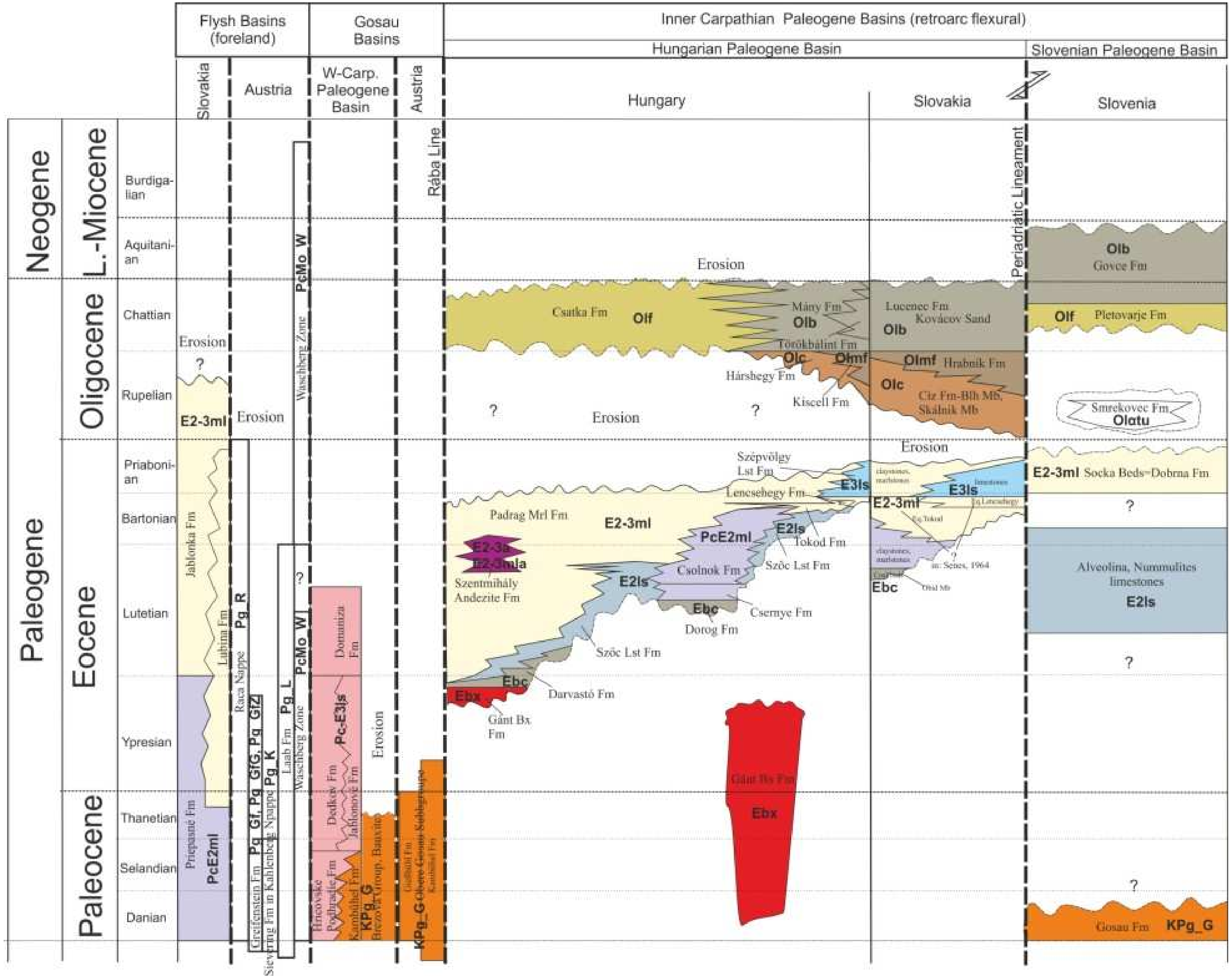


Fig. 25. Correlated geological formations of the different Paleogene basins for the Supra area

### 4.1.3 Neogene basins

In the followings, the synrift and postrift neogene basins will be described. The correlated geological formations of the different Neogene basins for the Supra area are shown on Figure 26.

#### 4.1.3.1 Early and Middle Miocene

**Vienna Basin**

The basement of the Neogene-aged pull-apart Vienna Basin is formed of Alpine–Carpathian nappes, and is filled with a more than 5000-m-thick Neogene succession.

During the Early Miocene, marine sedimentation was restricted to the north, and extended to the south only in the Middle and Late Miocene.

The initial phase of Miocene sedimentation is in connection with the Eggenburgian transgression and the tectonic opening of depocenters in the northern part of the Vienna Basin. Deposition started with fluvial sediments which were followed by the onset of a marine succession (conglomerates, sands). Laterally, towards the south and the east these pass into marine deposits (Luzice Formation/Lusitzer Serie).

As a result of an extensional tectonic regime, in the course of the Karpatian, a pull-apart basin began to open. Due to rapid subsidence and sea-level rise, off-shore pelitic sediments were deposited (Laksáry Formation, Závod Formation). Due to the existence of a topographic barrier in the central Vienna Basin (i.e. the Spannberg Ridge), sedimentation of the southern part of the basin was quite different: terrestrial and brackish-littoral facies can be found. In the Korneuburg (Sub)-Basin marly silts and fine to medium-grained sands (Korneuburg Formation) deposited during the Karpatian.

In the area of the Eisenstadt–Sopron (Sub-)Basin the oldest Miocene deposits are Lower Miocene fluvial–lacustrine sediments which are genetically related to the fluvial system of the southern Vienna Basin (Rasser, Harzhauser coord. 2008). Ottnangian coal-bearing beds can be found in the vicinity of Sopron (Brennberg Formation) overlain by Ottnangian–Karpatian–lower Badenian, mostly fluvial deposits (Ligeterdő Gravel = Auwaldschotter).

The Karpatian–Badenian boundary is characterised by a regressive event, which was followed by a renewed transgression. During this time, predominantly off-shore pelites deposited (Lanžhot Formation). Locally corallinacean limestones were formed.

The major sea-level fall during the early Badenian manifested in the formation of deltaic, fluvial and lagoonal sediments and littoral sands and sandy clays which are overlain by neritic off-shore calcareous clays (Jakubov Formation).

The upper Badenian marine succession of basinal facies comprise marls and sandy silts with marine fauna (Studienka Formation). It overlies the older Badenian marine succession. In marginal facies sands and conglomerates, breccias, calcareous clays and organodetritic limestones can be found (Leithakalk).

The Badenian–Sarmatian boundary is characterised by a major sea-level fall resulting in erosion along the margins. The renewed transgression in the early Sarmatian is represented by silts, calcareous clays and acidic tuffs (Holič Formation, Skalica Formation). The basin facies is developed in brackish-marine environment.

## Kisalföld–Danube Basin

The Miocene sedimentation commenced during the Eggenburgian transgression, when the sea invaded the northern margin of the Western Carpathians and penetrated into the northwestern part of the basin, being connected with the northern Vienna Basin. During this time littoral gravel and sand were predominant; subsequently these were covered by offshore sandy clay (Rasser, Harzhauser coord. 2008).

During the Ottnangian and Karpatian, terrestrial–fluvial–limnic successions were formed along the western margin of the Danube Basin. Ottnangian and Karpatian marine successions are known in the northern part of the basin (Dobrá Voda and Blatná depressions)

In the Kisalföld area continental–fluvial sedimentation took place at the beginning of the Early Miocene (Eggenburgian–Karpatian: Somlóvásárhely Formation). Fluvial-limnic successions made up of pebble, sand, marl, variegated clay, locally with thin coal seams can be traced in boreholes drilled in the Kisalföld. Eastward to the western foot of the Gerecse Mts. rhyolite tuff interbeddings (Gyulakeszi Rhyolite Tuff) are known in this succession.

The subsidence of the Danube Basin started at the end of the Early and the beginning of Middle Miocene. The main part of the syn-rift phase acted during the Middle Miocene and the post-rift, or thermal phase during Late Miocene and Pliocene.

The depocenter of the Kisalföld was invaded by the sea from the SW; transgression led to accumulation of off-shore, deep-marine siliciclastic sediments (sandy silt, silt, silty clay marl) in the Celldömölk–Vaszar–Tét–Vinár depression (Tekeres Formation — Karpatian/lower Badenian).

In the early Badenian, transgression (corresponding to the Bur5/Lan1 sequence boundary of Hardenbol et al. (1998) came from the S–SW via the “Trans-Dinaride Trench Corridor” within an almost unchanged palaeogeographic framework, however, in a larger area. Due to early Badenian tectonic movements two main sedimentary basins existed in the area of the Kisalföld: the Csapod Trough in its western part (it formed due to early Badenian tectonic movements), and the Győr Basin in the East. These two marine depressions were divided by the Mihályi Ridge. The lower part of the lower Badenian is missing all over the area due to early Badenian tectonic movements and erosion. Badenian successions start with the upper part of the lower Badenian with abrasional basal breccia and conglomerate, locally with calcareous matrix (Pusztamiske Formation). In marginal, shallow marine facies it is overlain by corallinacean limestone (“Leithakalk”, Lajta Formation). Nearshore facies are characterized by grey, greenish-grey sand-sandstone (Pusztamiske Formation). Offshore deep-basin (shallow bathyal) facies are represented by fine siliciclastic sediments: sandy silt, silty clay marl with sandstone intercalations (Tekeres Formation), and sandy-silty claymarl, which, in spite of being an “atypical Baden Clay” (formerly known as “Tortonian Schlier”), has been classified into the Baden Formation. In several borehole sections thick siliciclastic successions can be observed, which, based on biostratigraphic investigations, can be divided into lower and upper Badenian (the deposition of upper Badenian siliciclastic sediments (Szilágy Clay Marl Formation) is due to the renewed flooding in the late Badenian). Lithologically, the top of the lower Badenian can locally be marked by the appearance of gypsum and dolomite laminae, which can presumably be correlated with the sea level drop at about 14.2 Ma. In shallow marine environments deposition of the „Leithakalk”continued. Tuff intercalations (Tar Dacite Tuff) can be observed mostly in the Tekeres Schlier.

Along the eastern margin of the Danube Basin transgressive conglomerates, sandstones and volcaniclastics are overlain by neritic calcareous clays, siltstones and subordinately sandstones (Bajtava Formation).

In the northwestern part of the Danube Basin calcareous clays and siltstones can be found (Middle Badenian — Špačince Formation). The deposition of delta-front sands (Madunice Formation) in the Blatné sub-basin is due to shallowing in the late Middle Badenian and in the late Badenian in this area.

The upper Badenian succession comprises calcareous clays, siltstones and sandstones with volcanoclastics, as well as biogenic limestones in the margins (Pozba Formation) unconformably overlying the Špačince Formation.

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 (mollusc-bearing limestone, and oolithic limestone, Cerithium limestone) of shoreline facies (Tinnye Formation) and fine-siliciclastic sediments (grey, greenish-grey clay marl, sand, silty clay marl) of shallow-marine facies (Kozárd Formation) were deposited. The upper Sarmatian carbonate successions indicate a considerably productive carbonate factory of subtropical climate (Persian-Gulf-type ooids), reflecting hypersaline or hypercalcareous conditions, thus the previous brackish-water hypothesis is under debate.

In the northern part, the Sarmatian transgression manifested in the deposition of a brackish shallow-water succession (Vráble Formation), which unconformably overlies various Badenian formations and pre-Neogene formations in the marginal part of the basin. It comprises clay, clay marl, calcareous marl, siltstones and sand. In nearshore areas conglomerates, sandstones, limestones can be found, locally with lignites and tuffs.

A 600–700 m-thick rock body representing the product of a volcanic activity from the Badenian up to the Pannonian, and built up of the alternation of trachyte-bearing agglomerate, tuff and marl of unclear structure and genetics can be found in boreholes (Pásztori Trachyte Formation).

### Styrian Basin

In the western Styrian Basin fault-controlled limnic-fluvial deposits developed during the Early Miocene (Ottnangian-Karpatian), in which thick lignite-bearing successions were formed [Coal-bearing fresh-water beds (Kohleführende Süsswasserschichten]. Simultaneously the eastern part of the basin was covered by the Paratethys.

During the Karpatian the Middle Styrian and Leibnitz swells established beside the already existing South Burgenland Swell (Gross et al. 2007a). Due to subsidence (resulted by tectonic activity) and transgression a several hundred-metre thick off-shore succession (Gamlitzer Schlier) was deposited. Through the Trans-Tethyan-Trench-Corridor the Styrian Basin was in connection with the Mediterranean via Slovenia (Rögl 1998). Marine facies developed at the transition to the western Styrian Basin (Arnfelser Konglomerat, Leutschacher Sand).

There are limnic-deltaic deposits and fine-clastic sediments which probably can also be dated as Karpatian. Fluvial fan sediments (Sinnersdorf Formation) are predominant in the Bay of Friedberg-Pinkafeld and they probably pass into the Fürstenfeld Subbasin (Goldbrunner 1988). Karpatian extensional movements were accompanied by acidic to intermediate volcanism until the end of the early Badenian (Handler et al. 2006). The tectonic movements at the end of the Karpatian resulted in erosion and unconformities.

Terrestrial breccia, conglomerate, red clay and debris (Eggenberger Breccia) dated to the Karpatian–Badenian can be mainly found in the vicinity of Graz.

In the early Badenian, the area had a marine connection via Slovenia. In spite of a low-grade subsidence, marine deposits have a large areal extent. Volcanic activity continued. In the central part of the East Styrian Basin pelitic sedimentation was predominant. In some parts of the basin (Fürstenfeld) fan-deltas developed with thick conglomerates. Corallinacean algae patch-reefs were formed around basement highs (Weisenegg Formation*). Carbonates interfinger with shallow-marine siliciclastic or coarse-clastic deltaic formations. In the West Styrian Basin lagoonal deposits are predominant. The global sea level fall at the Badenian–Sarmatian boundary resulted in erosion and progradation of fluvial and deltaic systems.

During the Sarmatian, sedimentation took place in brackish (Papp 1956), or according to other opinions (Piller, Harzhauser 2005), hypersaline environment. Fault-controlled subsidence increased; marls were deposited in large areas, whereas in the coastal areas and on the topographic highs bryozoan-serpulid biostromes formed (Grafenberg Formation*). At the top of the Lower Sarmatian erosion took place (Carinthischer Schotter*). The Upper Sarmatian is characterised by oscillating sea level: silts, sands, ooliths, marly limestones (Gleisdorf Formation*) were deposited in shallow, high-energetic environment under normal/hypersaline conditions (Gross et al. 2007b)

Units marked with an asterisk (*) are not included in the legend and in the lithostratigraphic chart.

## Zala Basin

### *Lower Miocene*

In the western foreland of the Transdanubian Range the Lower Miocene is represented by the coarse-grained fluvial, and fine-grained lacustrine (locally paludal) sediments of the Somlóvásárhely Formation of Eggenburgian-Ottnangian and Karpatian age; it can be distinguished from older continental successions (the Oligocene Csatka Formation) only with difficulties, and its areal delineation is also problematic. Its maximum thickness is less than 200 m.

The Lower Miocene continental deposits of the western part of the Zala area (Ligeterdő Formation/Auwaldschotter) pass up to the Karpatian. Their material is derived from rocks of the Eastern Alps; debris were transported into the western Hungarian sedimentary basins by rivers. The formation overlies the Mesozoic basement. In the Szombathely–II borehole there is a tectonic contact between the Ligeterdő Formation and the Mesozoic basement. It is overlain by the Badenian formations. In the study area the thickness of the Ligeterdő Formation is of some tens of metres. The age of the formation was formerly infered as Ottnangian and Karpatian, but based on data from Austria (Pascher 1991), its age should be revised to the Early Badenian.

Some boreholes penetrated volcanics, such as the Mecsek Andesite Formation and the Gyulakeszi Rhyolite Tuff (‘lower rhyolite tuff’). The latter occurs in connection with the Lower Miocene continental successions.

The thickness of the Karpatian–Lower Badenian successions is uncertain, since most of the boreholes have not transected it. The maximum thickness in the Őrség–Lovászi deep zone (L-II) is 2000 m. Sedimentation took place in the Őrség-Lovászi-Budafa-Oltárc area, which was an inlet with marine connections towards the W.

The denudation terrain was predominantly made up of Mesozoic carbonates and pelitic sediments (in the western part of the Őrség, moreover of Palaeozoic rocks along the Balaton Line); disintegration of these rocks took place within relatively short distances. This may be the reason why not far from the one-time shorelines, exclusively pelitic sediments can be found. The sedimentary basin did not occupy a large area, the thick pelitic sedimentary succession does not refer to a deep basin, but it indicates that sedimentation kept pace with the sinking of the basin floor.

The Karpatian coarse-grained facies (Budafa Formation) is predominant only along a narrow strip at the marginal zone; the internal part of the sedimentary basin is predominated by thick pelitic successions (Tekeres Schlier). Sedimentation of the eroded material derived from the margins kept pace with the rapid sinking; therefore sedimentation took place in a shallow-marine environment all the time. Facies characteristics were determined by the restriction of the sub-basins from the sea, the decrease of salinity due to the rivers carrying freshwater into the depressions, and the degree of subsidence and filling up.

Due to the same lithologic characteristics, Karpatian sediments can hardly be distinguished from Badenian ones. Karpatian rocks are predominated by brackish-water fauna, showing a gradual transition into the Badenian, in which it is still not diverse. A significant change happened within the Badenian, with the appearance of a rich marine fauna; simultaneously, this horizon represents the boundary of the sedimentary cycle.

*Middle Miocene*

Tectonic movements led to regression at the end of the Karpatian and, in the basinal areas, in the lower Badenian. This resulted in the formation of coal-bearing marsh facies and clastic deposits. The regression was terminated by a new compression phase.

This process was followed by a remarkably intense transgression in the Őrség-Lovászi-Budafa-Oltárc area. The entire area of South Transdanubia may have been a shallow archipelago.

In the Őrség-Lovászi-Budafa-Oltárc area there is a transition from the Karpatian into Badenian succession. Eastward, in the area located between the Rába Line and the Salomvár-Hottó-Nagytilaj line, Badenian sediments overlie the eroded surface of the Mesozoic rocks with a considerable hiatus. Badenian sediments overlie the eroded surface of Palaeozoic, Mesozoic and Eocene formations unconformably in the area between the Salomvár-Hottó-Nagytilaj Line and the Balaton line. S of the Balaton Line, Badenian sediments are found above Karpatian, in smaller areas above Mesozoic, Palaeozoic formations and Early Palaeozoic metamorphites.

Since Badenian transgression invaded the area from the W–SW, the northeastern uplifted part of the region and the higher parts of the ranges within the basin were not affected by it.

In the early Badenian the nearshore areas (especially in the forelands of the Transdanubian Range) were characterised by a marine coarse-clastic to sand–sandstone succession (Pusztamiske Formation) reaching a thickness of more than 100 m. There is a lateral transition from this unit into the biogenic (corallinacean algae–foraminifer–mollusc-bearing) limestone (Lajta Formation — “lower Leithakalk”), which discordantly overlies older rocks or interfingers with the fine-siliciclastic sediments.

In restricted or semi-restricted bays, inlets, coal-bearing successions were formed during the Badenian (Hidas Formation). Their thickness and areal extent is small.

In the area of the Transdanubian Range, locally reworked red clay, kaolinic clay and bauxitic clay occur; their deposition ranges from the Karpatian up to the Pannonian (Cserszegtomaj–Vöröstó–Ősi Formations).

In the northwestern basinal area (Őrség-Lovászi-Budafa-Oltárc) sedimentation was continuous. The dark-grey and brownish-grey marls and silty marls (Szilágy–Baden–Tekeres Formations) differ from older ones only due to the tuff interbeddings (tuff strips — Tar Dacite Tuff, Tekeres–Tar Formations together), and in the appearance of the abundant Badenian faunal elements. During the Badenian this part of the basin remained a rapidly sinking inlet in which sedimentation kept pace with subsidence. Sedimentation was predominated by pelitic deposits.

At the end of the Badenian a barrier formed again, which isolated the area from the open sea, and an epicontinental sea of decreasing salinity evolved by the Sarmatian. This regressive process is indicated by the increasing number of sandstone beds.

Sarmatian basically has a regressive character, but due to the different movements of the basin floor, locally it shows transgressive features. It is characterized by brackish-water formations.

In the northwestern part of the basin and in the adjacent eastern margin, there is a continuous transition from the Badenian, and, compared to the latter, it shows regressive characteristics. In the centre of the basin it is predominated by sandy beds. At this time, due to the former uplifting (i.e. upwarping of the Budafa–Lovászi area), the deepest part of the basin was located in the Szentgyörgyvölgy, Kerkáskápolna, Őriszentpéter, Kotormány region, where coarse-grained sandstone was formed, locally with small-sized pebbles. These features do not indicate the proximity of the shore, but sediment transport from the margins, and gravitational re-deposition on the slopes. This material accumulated in the deepest parts. Southwards, clastic sediments become finer; in the Lovászi and Budafa area pelites and silts are predominant (Kozárd Formation).

In the marginal areas, the thicknesses of the Sarmatian beds decrease and become more marly, and characterized by a pinching out against the Badenian tectonic highs. In the basin and in the marginal areas, the Sarmatian is conformably overlain by the lower Pannonian. Coarse-clastic, biogenic limestone facies of the Sarmatian (Tinnye Formation) can be found in areas, which were in the highest position during the Badenian, and were affected by transgression only at the end of the Badenian.

By the end of the Badenian connection towards the open sea became narrower and salinity of the sea decreased. Connections towards the Mediterranean ceased; brackish-water sediments were deposited. The thickness of the Sarmatian ranges between 100 m and 200 m in the basin, whereas on the elevated highs their thickness does not exceed some tens of metres.

Sarmatian terrestrial–fluvial (delta) deposits (Gyulafirátót Formation) in the Zala Basin are subordinate. These sediments interfinger with the marine brackish-water formations, and are locally characterised by tuff interbeddings (Galgavölgy Rhyolite Tuff).

## Mura-Dráva Basin

A granodiorite (transition to dacite) rock body of uncertain Early Miocene age (Peripannonian Pluton Formation (Trajanova et al., 2008, Fodor et al., 2008)) can be traced in the Slovenian area. The sedimentary infill of the "core complex" stage lasted from the Late Ottnangian to the Karpatian as a part of the first synrift phase (Jelen & Rifelj 2005c). The initial infill onto the Pre-Cenozoic basement was due to significant subsidence of the area mostly along ENE trending fault systems: the Donat transtensional fault system and the Raba Extensional corridor (Jelen & Rifelj 2003, 2004, 2005a, b) are represented by the sediments of the Haloze Formation ranging from the Karpatian to Lower Badenian. In the Karpatian, sandstone, conglomerate, muddy breccia and conglomerate, oyster banks represent the lowest part of the Haloze Formation in the Maribor sub-basin. Southward, in the Haloze – Ljutomer – Budafa sub-basin sandy and silty marl, alternation of sandy marl, silty marl and sandstone build up the Karpatian and Lower Badenian deposits of the Formation. Tuffs dated to the Early Badenian age are also part of this lithostratigraphic unit, as well as questionnable assignation of conglomerate and conglomerate with lithothamnian nodules. Alteration of sandstone, sand, sandy marl and conglomerate represent the uppermost part of the Haloze Formation and also belong to the Lower Badenian succession.

Field observations indicated that the Mura–Zala Basin was a turbiditic basin since the beginning (in the Karpatian) until the Early Pontian (Jelen & Rifelj 2001, 2003). Deposits are present in the westernmost part of the Maribor sub-basin and probably in the western part of the Haloze – Ljutomer – Budafa sub-basin. In the central part of the Mura–Zala Basin, on the Murska Sobota block the deposits of the Haloze Formation are missing either due to subsequent erosion, or partly due to absence of the deposition. Eastward, they are found in boreholes in the East-Mura – Őrség sub-basin. The thickness of the deposits may reach 1300 m in the Maribor sub-basin, and approximately the same thickness is reported to the east, in the Hungarian cross sections.

During the Badenian, sedimentary infill of the wide rift stage took place as a second part of the first synrift phase. Tectonic uplift and synchronous eustatic sea level drop at the Karpatian/Badenian boundary resulted in the erosional unconformity in the shallow parts, and fans of coarse grained deposits in the deeper parts of the sub-basins. In the deepest parts of the basins a “starving basin” condition evolved. The sudden tectonic uplift and eustatic sea level drop was followed by a very rapid subsidence accompanied by an Early Badenian transgression (Jelen & Rifelj, 2001, 2004, 2005a, b). For this reason the Lower Badenian sedimentary rocks onlap also onto the Pre-Tertiary (Pre-Paleogene) basement of the relatively uplifted tectonic blocks. Deep water conditions evolved over transgressive biostromes of the algal limestones and fans. Mud rich turbidites and hemipelagic mud began to fill up the lowest parts of the basins due to intense subsidence and sea level rise.

An extensional collapse provoked the postrift subsidence of the tectonic blocks including the highest areas. The extensional collapse and the almost synchronous onset of compression in the Alps (Massari et al. 1986) initiated a change in the sedimentation to sand rich turbidites. These sand rich turbidites are proximally prevailing, while in the distal parts the change is marked by a progradation in the Upper Badenian.

In the shallow areas of the sub-basins there is an unconformity near the Badenian/Sarmatian boundary. Subsequently, in the deeper parts of the sub-basins the correlative normal sequence boundary moves towards the sand richer turbidite fans.

The Sarmatian is represented by heterolitic siliciclastic sediments and carbonates deposited during the transgressive system tract of the Early Sarmatian in the shallow parts of the Mura-Zala Basin, while turbiditic sedimentation persisted in the deeper parts of the sub-basins, still as a part of the sedimentary infill of the first post-rift phase. A weak kinematic inversion took place during the Late Sarmatian in the Mura-Zala Basin.

The Maribor sub-basin, the western part of the Radgona – Vas sub-basin and the western part of the Haloze – Ljutomer – Budafa sub-basin were filled up by the end of Sarmatian, and acted as a by-pass zone for the sediments since the Pannonian transgression.

The described (Badenian and) Sarmatian deposits, together with the Badenian ones as a sedimentary infill of the wide rift and the first post rift phase were defined as Špilje Formation by Jelen & Rifelj (2005d).

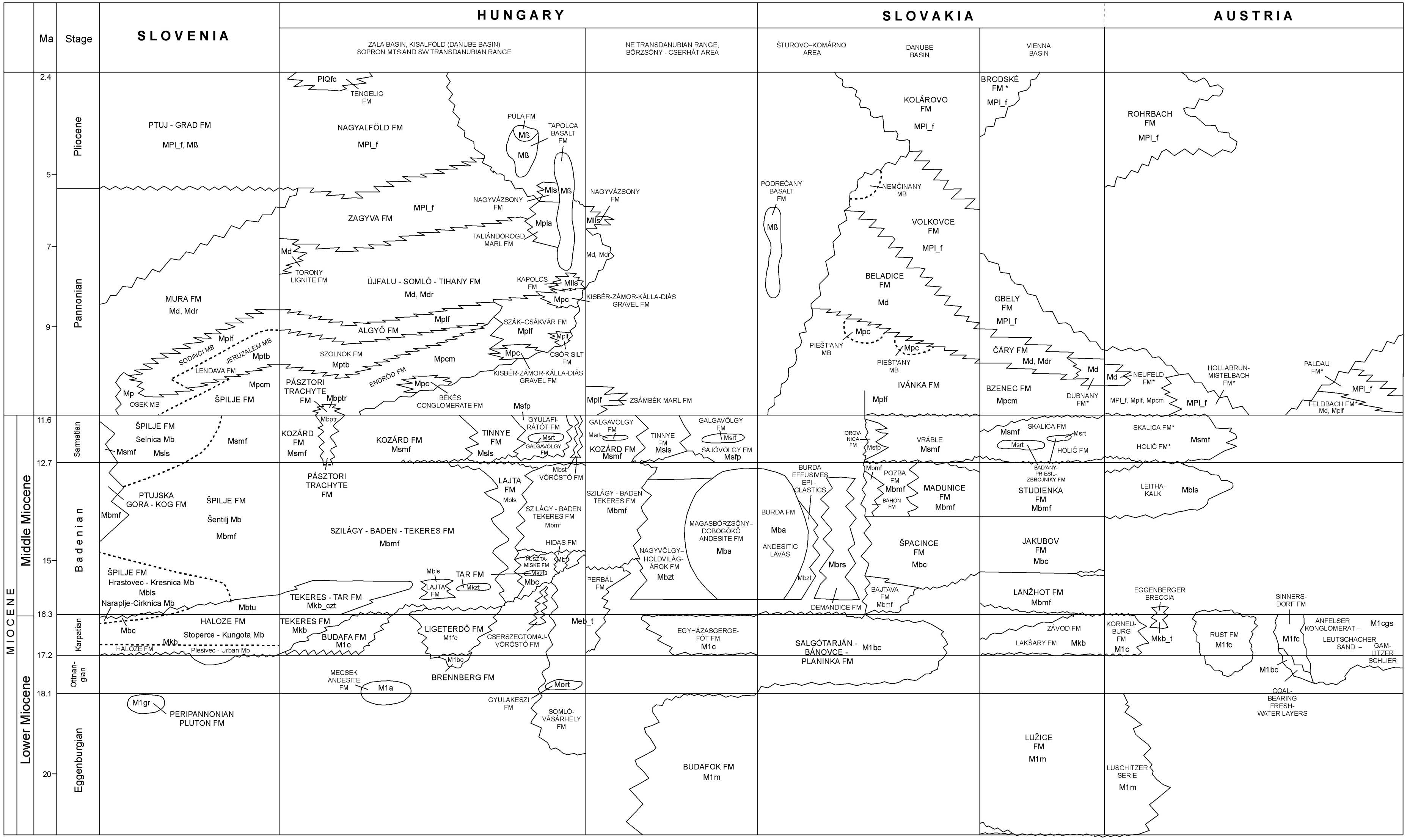


Fig. 26. Correlated geological formations of the different Neogene basins for the Supra area

#### 4.1.3.2 Pannonian

The Pannonian (Late Miocene and Pliocene) geohistory of the project area is characterized by the presence of Lake Pannon, a large, probably endorheic lake (Kázmér 1990, Magyar et al. 1999, Uhrin 2011) in the Pannonian Basin. This water body got isolated from Paratethys, a large open sea 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 (Figure 27). Because the depth of the lake reached several hundred meters, a sedimentary shelf-slope system (cf. Posamentier & Allen 1999, Olariu & Steel 2009) could evolve in the basin.

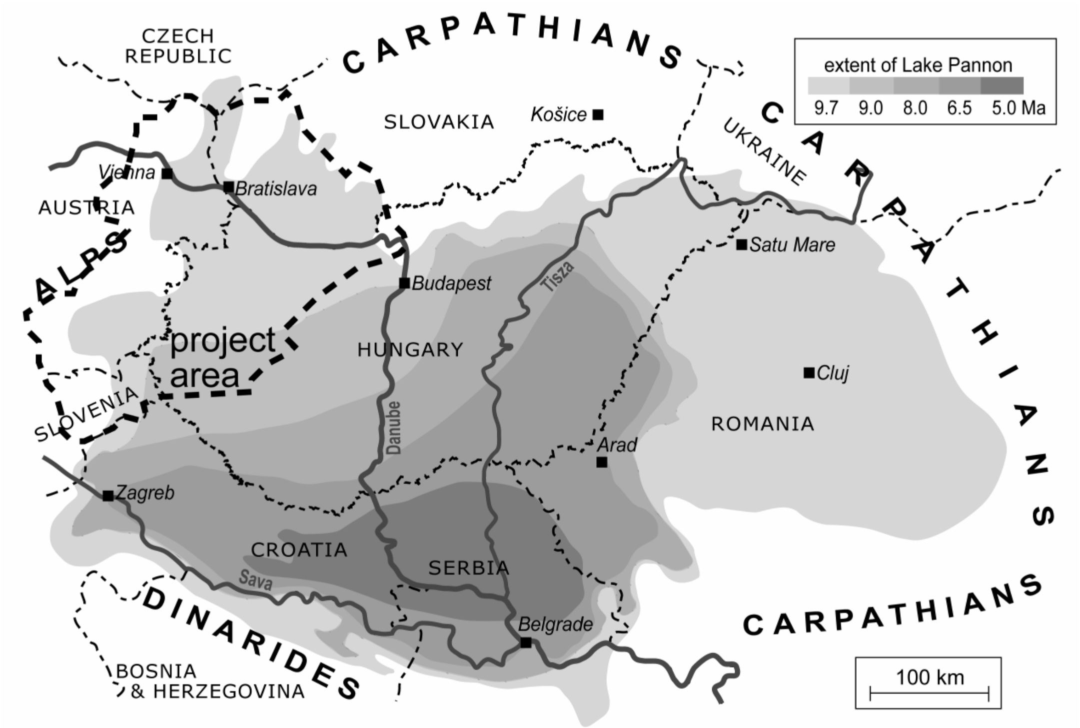


Fig. 27. Steps of the infill of Lake Pannon (after Magyar et al. 1999, Magyar 2009) Dotted area refers to the area of the Transenergy project

In our study area, the shelf-slope system prograded chiefly from northwest to southeast; the main units of the Pannonian succession represent the steps of this progradation (Fig. 27). However, the lake generally transgressed in the earliest Pannonian time, hence the deposition of coarse sediments took place only in a narrow belt along the shorelines at first. Fluvial deltas were formed along the feet of mountain ranges (Paldau Fm. and Hollabrunn-Mistelbach Fm. in Austria), while chiefly abrasional conglomerates were deposited along some shorelines elsewhere (Kisbér, Zámor and Diás Fms.), especially along the margins of exposed basement highs (Békés Fm.). However, the most prevalent deposits of this time were the pelagic marls of the 'starving' basin (Endrőd, Ivanka and Špilje Fms.)

As the largest amount of sediment was carried into the lake from northwest, the Vienna Basin was the first major sub-basin to be infilled. Open lacustrine sedimentation was replaced by the deposition of deltaic, (Čáry Fm.) and later alluvial (Gbely Fm.) units before 9.5–10 Ma. Than the shelf-slope system started to prograde across the large, deep Danube Basin and coevally, eastwards along the narrow, west-east trending Mura trough. As the slope approached a given location, turbidites (few m to several 10 m thick sandbodies intercalating with deepwater mud) started to deposit (Szolnok Fm. in Hungary, Jeruzalem Mb. of Lendava Fm. in Slovenia). On the slope itself, mainly silt was deposited (Algyő Fm. in Hungary, Sodinci Mb. of Lendava Fm. in Slovenia, upper part of Ivanka Fm. in Slovakia), as coarser sediments were carried further basinwards to be deposited as turbidites. Turbidity currents did not reach the relatively shallow regions, especially the margins of the lake, where it is difficult to distinguish fine-grained deepwater and slope deposits (therefore they are referred together as Szák Fm. in Hungary, while such units belong to Ivanka Fm. in Slovakia)

Historically, the previously described part of the succession was considered 'Lower Pannonian', while the term 'Upper Pannonian' was introduced for the overlying strata, deposited in deltaic or terrestrial environments. Although the time-transgressive nature of Pannonian formation have been revealed from the 1980s (Pogácsás 1984, Mattick et al. 1985), these terms are still widely used. Due to the hydrostratigraphic importance of the 'Lower/Upper Pannonian' boundary, it is also used in the Transenergy models.

The earliest 'Upper Pannonian' strata were formed by delta fronts built on the sedimentary shelf (unofficial 'Mindszent Mb.' of Újfalu Fm, in Hungary). In the central regions of the basin, the prograding delta fronts deposited several kilometers wide and several 10 meters thick sheets of sand with relatively good connectivity. That clearly explains why this unit is traditionally referred as 'thermal water level' in Hungary. After the crossing (or several crossings, due to lake-level fluctuations) of the delta front at any location, a deltaic plain (Beladice, Somló and Tihany Fms.; unoffiicial ’Szentes Mb.’ of Újfalu Fm.; lower part of Mura Fm.), and than an alluvial plain (Volkovce and Zagyva Fms.; upper part of Mura Fm.) was formed, both built up by a large amount of floodplain silt and mud with isolated channel sandbodies. In regions that were not reached directly by the major sources of sediment input, marshlands developed, represented by significant lignite seams (Torony Fm.) today.

In the Early Pliocene, features of the fluvial systems have been probably changed. The ancient rivers started to deposit thick beds of gravel in areas relatively close to the margins and also in the Danube Basin, while an increasing amount of variegated clay formed in some of the central areas. The sediments of these younger river systems belong to Ptuj-Grad, Nagyalföld, Kolárovo, Brodské and Rohrbach Fms.

Compared to the short time-span for their deposition, Pannonian strata can reach very big thickness, e. g. 4–5 km in large areas of Danube Basin. That can be only explained by rapid basement subsidence and very high sediment influx keeping up with it. Although the 'syn-rift' subsidence of Pannonian Basin is thought to be replaced by 'post-rift' (thermal) phase in earliest Pannonian (Royden et al. 1983, Horváth 1995), subsidence rates rather increased as a result, of the vertically non-uniform stretching of the litosphere (i.e. basin inversion cf. Horváth et al. 2012). Of course, the succession becomes much thinner towards basement highs and basin margins. However, basin inversion started during the Pliocene in the major part of the Pannonian Basin (Horváth 1995), and even during the Latest Miocene in its southwestern part. Due to the differentiated subsidence of the sub-basins, continuous sedimentation from 'Lower Pannonian' to Quaternary is restricted to the central part of Danube Basin on the Transenergy area, while tilted, eroded Pannonian strata are common to be exposed along the margins.

The crustal thinning related to the formation of Pannonian Basin also induced basaltic volcanism in several parts of the area (Tapolca Basalt Fm., Podrečany Basalt Fm.). The basalts and their tuffs comonly interfinger the coevally deposited sediments.

### 4.1.4 Structural evolution of the territory

**The Alps** (Froitzheim et al 2008)

It could be subdivided into four main structural belts: Helvetic, Penninic, Austro-Alpine, South-Alpine. The nappe structure of the orogene is bi-vergent. It means that the Helvetic, Penninic, Austro-Alpine belts are forming a so called pro-wedge what is consisted of north directed thrust and fold systems (Helvetic is the lowest, Penninic is in the middle, Austro-Alpine is in the highest position), and in contrary the South-Alpine belt - which is situated to the south of the Periadriatic lineament - is forming a so called retro-wedge (according to the generally southward subduction) what is consisted of south directed thrust and fold systems. Another main difference is that the Helvetic, Penninic, Austro-Alpine units are partly metamorphosed in the Cretaceous and Tertiary times, but the South-Alpine zone is almost unmetamorphosed.

| | | |
|---|---|---|
| Late Carboniferous – Early Permian | | Orogenic collapse of the Variscan orogen, extension, origination of graben structures and intramontane basins |
| Early Triassic | | Thermal subsidence, normal fault systems |
| Early Middle-Triassic – Late Triassic | | Rifting and opening of Meliata-Maliac Ocean |
| Early Jurassic | | Rifting |
| Late Early-Jurassic – Middle-Jurassic | | Ocean floor spreading of Piemont-Ligurian Ocean cutting across the Triasssic shelf; east and westward diping normal faults and detachments; sinistral transtension in Eastern Alps |
| Middle Jurassic | | Compressional event in the Juvavic and Tirolic. Ofiolites obduction; questionable continental collision, or intra-oceanic subduction, or regional sinistral strike-slip motion between Juvavic–Tirolic and Austroalpine units |
| Valanginian- | Austroalpine | Eo-Alpine shortening; SE-E dipping subduction; Noric, Tirolic, Juvavic detached and formed orogenic wedge |
| Albian- | | Bajuvaric, Greywacke zone join to the wedge; beginning of the subduction of the Penninic ocean beneath the Austroalpine. Between the downgoing slab and Upper Austroalpine units, the Lower Austroalpine units represents continental crust slices subducted in different times. |
| Turonian- | | Eclogitic Austroalpine units exhumed |
| Santonian-Eocene | | On the upper plate Drauzug-Gurktal, Ötztal-Bundschuh, Graz paleozoic transpressional normal faults, Gosau basin formations; emerging and erosion (bauxite formation) in the Northern Calcareous Alps |

| | | |
|---|---|---|
| Cretaceous (?), Paleocene-Early Eocene | South Alpine | South-directing nappe origination and folding what is postdated by Adamello intrusion |
| Late-Cretaceous | Penninic | Oceanic subduction in the SE Piemont-Ligurian Ocean |
| Tertiary | | Consumption of oceanic realms; continental collision; crustal shortening; extensional faulting and strike slips |
| 47-40 Ma | Eastern Alps | Eastward propagating closure of the remaining parts of the Penninic Ocean |
| 47-17 Ma | | Thrusting of Penninic and Austroalpine units over European continental margin |
| 35-28 Ma | | Syn-intrusive shear along Periadriatic zone, tonalite, granodiorite, granite intrusions |
| 25-9 Ma | | E-W extension and eastward extrusion of crustal fragments of Austroalpine; origination of tectonic windows, pull apart basins (Vienna basin), extrusion and gravitational collapse vs roll back extension: opening of Pannonian basin, Styrian basin |
| 9-5.3 Ma | | E-W compressional event |
| recent | | Eastward motion in the Eastern Alps, N-S convergence and inversion in the Pannonian basin |
| Paleocene-Early Eocene | Southern Alps | Thrusting |
| Chattian-Tortonian | | After tonalite thrusting |

**Western Carpathians** (Plašienka in Froitzheim et al 2008)

The border between the Alps and Western Carpathians could be positioned under the basin fill of the Vienna basin and the Pannonian basin. The Western Carpathians consists of three main units, the External, Central and Internal Western Carpathians. The External Western Carpathians is represented by the Carpathian Flysch belt in our territory. It is the Tertiary accretionary complex of two nappe complexes, the Moldavide and Magura nappe stacks. The last is the direct continuation of the Rhenodanubian Flysch. It is characterised by southward subduction of the Magura flysch ocean (North Penninic).

The boundary between the External and Internal Western Carpathians is the Pieniny Clippen belt.

The Central Western Carpathians consist of pre-Tertiary units, discordant Cenozoic sediments and volcanic complexes. Its main units are the Tatra-Fatra belt which is the continuation of the Austroalpine units. They are built up of pre-Alpine basement and Mesozoic cover systems, detached cover nappes of Fatric and Hronic units.

The Vepor belt corresponds to the Middle Austroalpine stack of mainly basement nappes.

The Internal Western Carpathians is thought to be part of the so called Pelso Megaunit. The Central and Internal Western Carpathians represent the Mesozoic collisional pro- and retro-wedge systems.

| | |
|---|---|
| Late Carboniferous – Permian | Orogenic collapse of the Variscan orogen, extension, origination of graben structures and intramontane basins, rift related volcanism and plutonism |
| Triassic | Thermal subsidence, rifting (Late Anisian) of the Meliata Ocean, normal fault systems |
| Early – Middle Jurassic | Rifting and thermal subsidence |
| Late Jurassic | Closure of the Meliata Ocean |
| Early Cretaceous | Gemericum overthrusted Veporicum |
| Mid-Cretaceous | Northward progradation of nappe stacking, Veporicum overthrusted Tatrikum, Fatricum, Hronicum detachment and overthrust |
| Senonian | Extensional collapse of the southern zones, Vepric exhumation |
| Early Paleogene | Shortening, sinistral transpression |
| Eocene-Oligocene | Extensional collapse of the northern zones, basin formation |
| Early Miocene | renewed crustal shortening |
| Middle Miocene | Calc-alkaline volcanism |
| Late Miocene-Pliocene | uplift of the “core mountains” |

Transdanubian Range and the Pannonian basin (Fodor et al 2011 and Fodor 2010)

This part of the project territory belongs to the Pelso unit sensu Haas et al 2010 with the South Alpine thrust and strike-slip belt of the Sava unit. These terranes came into juxtaposition during the Late Cretaceous-Early Paleogene large-scale displacements. The Transdanubian Range is an upper plate positioned nappe of the Upper Austroalpine nappe stack and shows non-metamorphosed texture in the Alpian deformation realms.

The Pannonian basin s.l. (including the Danube basin, Styrian basin) is described here, however it is formed above the previously mentioned Alpian and Carpathian units as well.

| | |
|---|---|
| Early Paleozoic | Marine sedimentary basins |
| Early-Mid Carboniferous | Variscan orogeny, slight metamorphosis, folding |
| Late Carboniferous | Deposition of molasse sediments in intramontane basins, supposed extensional collapse |
| Early Triassic | Shallow marine ramp developed on the Tethyan shelf |
| Middle Anisian | Rifting, extension, volcanic activity |

| | |
|---|---|
| Early Jurassic- Earliest Cretaceous | Rifting, extension, normal fault systems, subsidence, pelagic sedimentation and submarine highs |
| Aptian/Albian boundary-Coniacian | Closure of the South-Penninic ocean, compression, nappe position above the Koralpe-Phorje-Wölz units, mega-syncline structure, uplift, erosion |
| Senonian | Gosau basin formation and sedimentation, both compressional and extensional origin is possible |
| Palaeocene – Early Eocene | Uplift and intense erosion |
| Middle Oligocene-Early Miocene | Dextral strike slip movements, strike slip duplexes |
| Ottnangian-Sarmatian | 40-50° CCW rotation, synrift extension, transtension; Slightly diping detachments and normal faults, tilted blocks and ridges, connected sinistral strike slips |
| Late Sarmatian | Dextral strike slips |
| Pannonian | Post-rift thermal subsidence |
| Late Pannonian-Quaternary | Compressional basin inversion, blind thrusts, folded anticlines |

### 4.1.5 The most important structures of the territory

The most important tectonic structures of the project area can be devided into two basic — a little bit artificial but from the point of view of the project aims relevant — groups:

the curved, ragged planar thrust planes, nappe horizons of the mainly MesozoicEarly Paleogene orogenic crustal shortening (later they can act as detachment planes too)

the curved, steeply diping or subvertical fault planes, predominantly post thrusting, connecting to the basin formation

The elements of the first group can be recognized on the geological map of the pre-Tertiary basement (Encl. 1.14.) They generally remain within the basement, the dip is subhorizontal. The average azimut plunges predominantly southeastward, in the South-Alpine regions northwestward.

The second group touches partly the Paleogene and mainly the Neogene formations and probably plays a more remarkable role in the heat and hydraulic conductivity, so we show them separately on Figure 28 projected on the top of the pre-Tertiary basement. Because of the lack of the correlatable tectonic informations, these zones are shown as a simplified sketch (Figure 28), separately from the horizon maps. Since the different rejuvenation phases could result different slip styles, we did not figure them on the sketch, please refer to the text as follows. Due to similar reasons we did not cut off the lines by each other.

Most of the fault zones have a long life slip history and it is difficult to classify them to single deformation phases, instead, most faults suffered reactivation and belong to several phases with different fault kinematics. Despite of this, we can form subgroups, based on the time interval of the most remarkable phases of their deformation history.

Cretaceous–Quaternary (green)

Pieniny Clippen Belt fault zone: Cretaceous thrusts and nappe planes, $Ol_3$-M deep crustal flower structure, dextral, recent times sinistral strike slip

Hurbanovo-Diósjenő fault zone: probably a Cretaceous nappe boundary, with nothwestern transport direction; late Cretaceous probably reactivated low-angle normal fault; in the latest Cretaceous and Tertiary strike-slip; in the Miocene north-facing normal fault; recent times extensional, low angle fault zone

Oligocene–Quaternary (brown)

Periadriatic-Balaton fault zone: $Ol_3$-M dextral strike slip duplex zone with anastomosing fault branches and volcanic activity

Mid-Hungarian tectonic zone: $Ol_3$-M dextral strike slip duplex zone with anastomosing fault branches, probably coeval thrusts show transpressional strike slip

MMLLD (Mur-Mürz-Leitha-Láb-Dobrá Voda (Lassee)) zone: $Ol_3$-M sinistral strike slip duplex zone with anastomosing fault branches; Miocene orogene collapse detachment fault

SEMP (Salzach-Ennstal-Mariazell-Puchberg) zone: sinistral strike slip: $Ol_3$-M sinistral strike slip duplex zone with anastomosing fault branches

Steinberg fault: $Ol_3$-M sinistral strike slip duplex zone with anastomosing fault branches; Miocene orogene collapse detachment fault

Radgona-Vas: $Ol_3$-M strike slip

Ptuj-Ljutomer: $Ol_3$-M strike slip

Neogene (red)

Ikva-Répce-Rohonc(-Radgona-Vas): Ottnangian–Sarmatian gravitational detachment and normal fault, between the fault planes there are tilted blocks and ridges, the exact continuation to Radgona-Vas cannot be proved

Rába (-Radgona-Vas, -Baján): Ottnangian–Sarmatian gravitational detachment and normal fault combined with sinistral strike slip, the exact continuation cannot be proved, between the fault planes there are tilted blocks and ridges

Čertovica: Ottnangian–Sarmatian gravitational detachment and normal fault

Baján: Ottnangian–Sarmatian gravitational detachment and normal fault, between the fault planes there are tilted blocks and ridges

Leopoldsdorf: Ottnangian–Sarmatian gravitational detachment and normal fault

Middle Miocene (yellow)

Nagytilaj: mainly Sarmatian dextral strike slips with connecting thrusts

Sümeg: mainly Sarmatian dextral strike slips with connecting thrusts

Padrag: mainly Sarmatian dextral strike slips with connecting thrusts

Telegdi Roth: mainly Sarmatian dextral strike slips with connecting thrusts

Late Miocene–Quaternary

Ormož-Lovászi-Budafa antiform: above blind thrusts originated from inverted synrift faults

Rechnitz-Sümeg high: WNW-ESE basement high, questionable origination

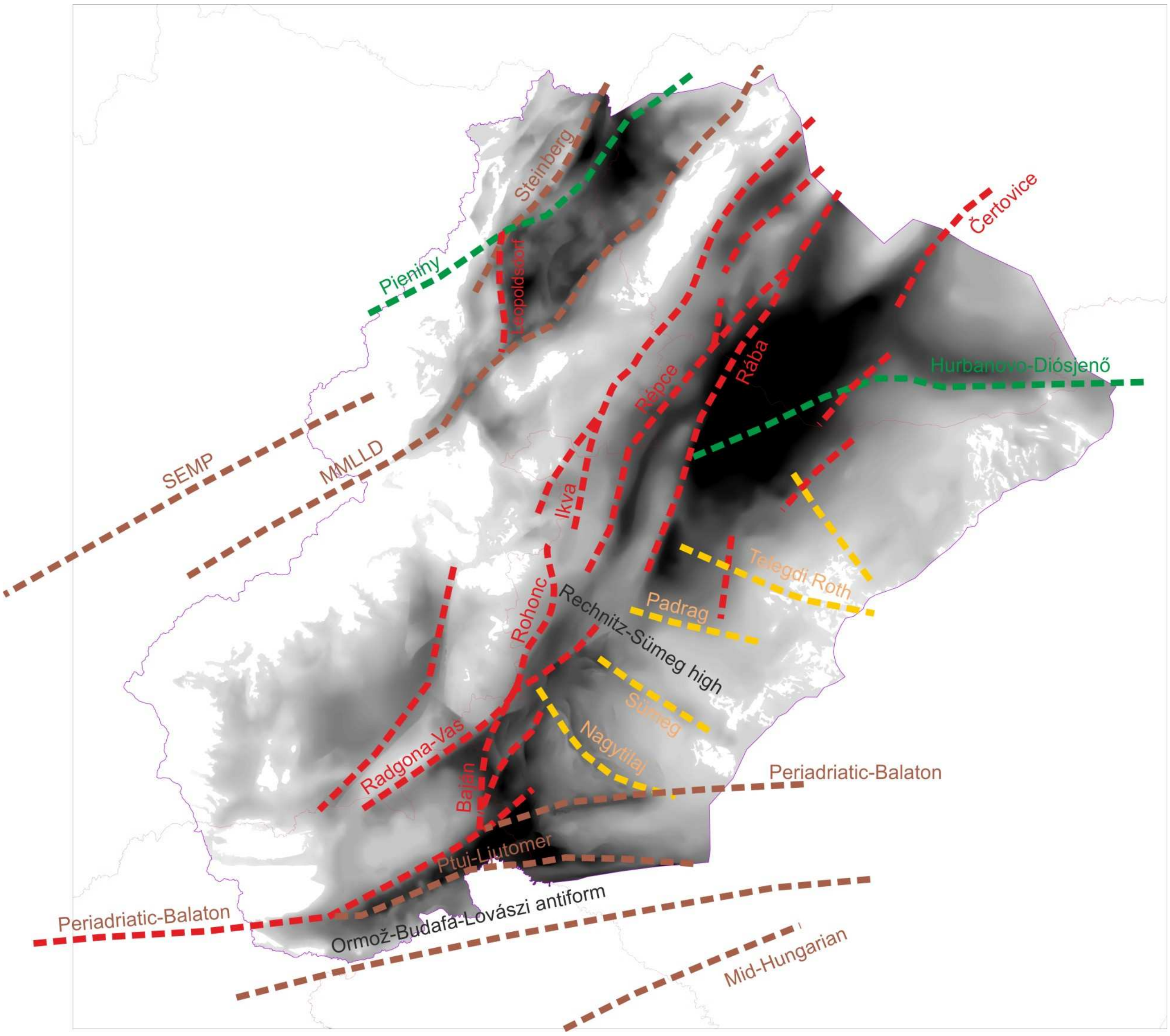


Fig 28. Tectonic sketch of the Supra area territory post-Cretaceous structures deformation history: green: K–Q; brown: Ol–Q; red: Neogene; yellow: Middle Miocene

### 4.1.6 Geological cross-sections of the supra-regional area

Two regional geological cross-sections have been edited for the supra-regional area (Figure 29, Encl.1.18.)

The cross section lines's (Figure 29) selection were based on the followings:

- Boreholes of regional importance and hydrogeological features,
- Seismic sections along the section lines,
- Compiled pilot area sections along the section lines,
- More or less perpendicular direction to the local and regional structural systems.

The sections themselves (Encl. 1.18.) are based on:

- The modeled horizon grids of the Supra area geological model,
- The modeled horizon geology of the Supra area geological model,
- The re-evaluated borehole database of the project,

- The unified legend of the geological model (in the Neogene basin fill some simplification was done, ie. Pa1: Lower-Pannonian, Pa2: Upper-Pannonian, Q: Quaternary sediments)
- General knowledge of the geological buildup of the territory.

The sections generally show the various Alpine structural deformations of the territory. One of the main features is the Southeastward dipping, Northwestward dipping nappe and thrust fault system, along which the Alpine nappe stack system was built. Within the Vienna basin some planes of opposite direction can be detected. These are eroded planes of overturned nappe fronts, the structural sense of the movement is just the same. The nappe system formation was accompanied by folding too (ie. Transdanubian thrusts and synclines). The thrust planes served as downslip horizons later, during the postorogene gravitational collapse. This feature is signed by the double arrows. This planes are the main boundary faults of the Neogene synrift phase basins. During the Paleogene and Neogene considerable strike slip faults were activated too, which moved different rock bodies next to each other of different thickness, or different origin. The normal faults connected to the postrift thermal subsidence touched mainly the Neogene sediments and the fault tips are often terminated within the basins, or above the deep detachment faults (revers then normal faults).

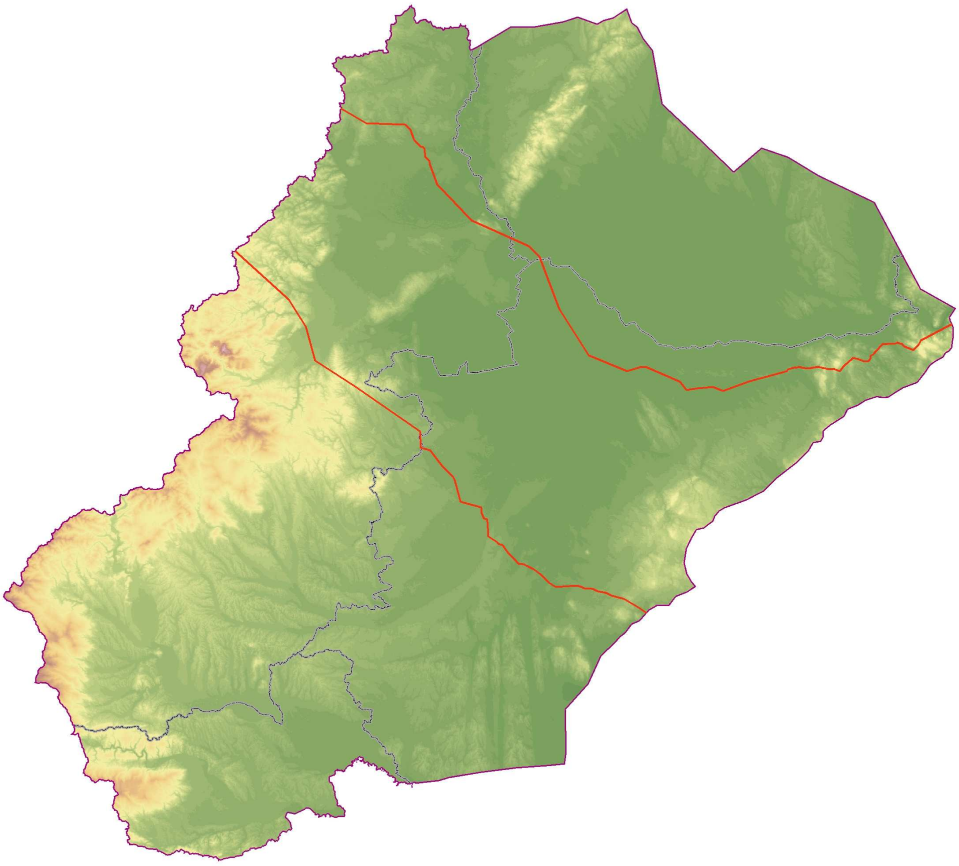


Fig. 29**.** Location of the geological cross sections of the supra-regional area

## 4.2 Descriptions of the elements of the harmonised legend

The descriptions are divided by the occurance of a given element on the horizon maps of the Supra geological model (Encl. 1.1−1.17.). If an element occures on more than one sheet, it is described on the older one, unless the geological content of an element is modified through the different horizon sheets.

The Pre-Senonian and Pre-Cenozoic horizon maps are closed up together because they contain almost the same basement formations.

### 4.2.1 Formations on Pre-Senonian (Encl.1.16) and Pre-Cenozoic (Encl. 1.14) horizon map

**1. STABILE EUROPE – BOHEMIAN MASSIVE UNITS**

*Autochthonous Upper Cretaceous* K2_Au

1. Synonyms, correlated formations: Ameis-Poysdorf Formation
2. Lithology: marls, sandstones
3. Facies: siliciclastic, carbonatic
4. Paleoenvironment: shallow marine to marine slope
5. Thickness:300 - 500 m
6. Average sandiness rate:
7. Porosity type: fissure, intergranular
8. Estimated porosity: low to medium (5%)
9. Tendencies mainly in time: shallow marine/neritic
10. Tendencies mainly in space: NW-SW: continental margin - marine basin
11. Tectonic situation: passive continental margin of stable Europe (Bohemian Massiv)

*Autochthonous Malmian* J3_Aubs

1. Synonyms, correlated formations: Mikulov Formation
2. Lithology: marls, calcareous sandstones
3. Facies: carbonatic-siliciclastic
4. Paleoenvironment: basinal marine, marine slope
5. Thickness:500 - 1500 m
6. Average sandiness rate:
7. Porosity type: fissure,
8. Estimated porosity: low (4%)
9. Tendencies mainly in time: terrestric-siliciclastic to shallow marine/neritic
10. Tendencies mainly in space: NW-SW: continental margin - marine basin
11. Tectonic situation: passive continental margin of stable Europe (Bohemian Massiv)

**2. OCEANIC ACCRETION NAPPE SYSTEM**

*Waschberg unit* PcMo_W

1. Synonyms, correlated formations: Palava-, Bruderndorf beds, etc.
2. Lithology: pelites, marls, sandstones, conglomerates
3. Facies: siliciclastic, subordinate: carbonatic
4. Paleoenvironment: shallow marine to basinal marine
5. Thickness: 500 - 1000 m
6. Average sandiness rate:
7. Porosity type: fissure
8. Estimated porosity: low (4%)

9. Tendencies mainly in time: shallow marine/neritic to pelagic-siliciclastic
10. Tendencies mainly in space: NW-SE: shallow marine/neritic to pelagic-siliciclastic
11. Tectonic situation: foreland basin with continental margin and active margin of advancing Alpine nappes

*Klippen of Waschberg unit* PcMo_W

1. Synonyms, correlated formations: Klentnitz-, Ernstbrunn-, Klement Formation
2. Lithology: marls, carbonates, sandstones
3. Facies:shallow marine carbonatic to siliciclastic
4. Paleoenvironment: terrestric-siliciclastic to shallow marine, subordinate: basinal marine
5. Thickness: 50 - 200 m
6. Average sandiness rate:
7. Porosity type: karstic, fissure
8. Estimated porosity: low to medium (4 - 9%)
9. Tendencies mainly in time: terrestric-siliciclastic to shallow marine/neritic, partly pelagic (Klentnitz Fm.)
10. Tendencies mainly in space: NW-SE: terrestric-siliciclastic to shallow marine/neritic
11. Tectonic situation: fragments of passive continental margin of stable Europe (Bohemian Massiv) incorporated in Waschberg nappe

*Schottenhof unit* JPg_Sch

1. Synonyms, correlated formations: Buntmergelserie
2. Lithology: pelites, marls, sandstones
3. Facies: siliciclastic/carbonatic
4. Paleoenvironment: basinal marine siliciclastic/carbonatic
5. Thickness: 600 - 1000 m
6. Average sandiness rate:
7. Porosity type: fissure
8. Estimated porosity: low (1%)
9. Tendencies mainly in time: pelagic
10. Tendencies mainly in space: N -S: European continental margin - marine basin
11. Tectonic situation: allochthonous Helvetic basement unit, incorporated in Alpine nappe-system

*Pieninic Klippen-Belt* JK_P

1. Synonyms, correlated formations:
2. Lithology: sandstones, cherts, pelites, carbonates, ophiolites
3. Facies: siliciclastic, subordinate carbonatic, rarely: volcanic
4. Paleoenvironment: basinal marine with various clastic input
5. Thickness: 50 – 400 m
6. Average sandiness rate:
7. Porosity type: fissure
8. Estimated porosity: low (4%)
9. Tendencies mainly in time: pelagic siliciclastic
10. Tendencies mainly in space: strongly tectonized unit
11. Tectonic situation: trench/melange zone with various elements of Alpine nappes, marking a suture zone or a major nappe-system boundary

*Greifenstein nappe* Pg_Gf

1. Synonyms, correlated formations: Göstling slice, Zistersdorf slice, Raca nappe
2. Lithology: sandstones, slates, marls
3. Facies: siliciclastic, subordinate: carbonatic
4. Paleoenvironment: basinal marine
5. Thickness: > 2000 m
6. Average sandiness rate:
7. Porosity type: fissure
8. Estimated porosity: low (4%)
9. Tendencies mainly in time: pelagic-siliciclastic
10. Tendencies mainly in space: penninic trough
11. Tectonic situation: Penninic sl. unit, lowermost flysch-nappe of north-penninic provenance

*Kahlenberg nappe* Pg_K

1. Synonyms, correlated formations:
2. Lithology: sandstones, marls, calcareous sandstones
3. Facies: siliciclastic, subordinate: carbonatic
4. Paleoenvironment: basinal marine
5. Thickness: > 1000 m
6. Average sandiness rate:
7. Porosity type: fissure
8. Estimated porosity: low (4%)
9. Tendencies mainly in time: pelagic-siliciclastic
10. Tendencies mainly in space: penninic trough
11. Tectonic situation: Penninic sl. unit, flysch-nappe of north-penninic provenance superimposed on Greifenstein nappe

*Laab nappe* Pg_L

1. Synonyms, correlated formations:
2. Lithology: sandstones, marls, calcareous sandstones
3. Facies: siliciclastic
4. Paleoenvironment: basinal marine
5. Thickness: > 1000 m
6. Average sandiness rate:
7. Porosity type: fissure
8. Estimated porosity: low (4%)
9. Tendencies mainly in time: pelagic-siliciclastic
10. Tendencies mainly in space: penninic trough
11. Tectonic situation: Penninic sl. unit, flysch-nappe of north-penninic provenance superimposed on Greifenstein nappe

*Rechnitz unit* JK1_Pe

1. Synonyms, correlated formations:
2. Lithology: phyllites, greenschists, ophiolites, quarzites
3. Facies: siliciclastic, volcanic-subvolcanic-intrusive, carbonatic
4. Paleoenvironment: shallow marine-siliciclastic/carbonatic to basinal marine siliciclastic/carbonatic, subvolcanic-intrusive

5. Thickness: > 2000 m
6. Average sandiness rate:
7. Porosity type: fissure
8. Estimated porosity: low (2,5%)
9. Tendencies mainly in time: unknown
10. Tendencies mainly in space: upper penninic basement unit
11. Tectonic situation: Penninic str. unit, allochthonous basement unit, exhumed in Miocene times

## 3. ADRIA DERIVED PROWEDGE ALCAPA NAPPE SYSTEM

*Medium-grade polymetamorphic formations (Alpine overprint)*

*In Lower Austroalpine unit* PzS

1. Synonimes, correlated formations: Óbrennberg–Vöröshíd Mica Schist, Sopron-bánfalva Gneiss, Füzesárok White Schist
2. Lithology: gneiss, mica schist, phyllite, pegmatite, leucophyllite, quartzite, quartz schist
3. Facies: medium-grade polymetamorphic
4. Paleoenvironment: not interpreted
5. Thickness: ?
6. Average sandiness rate: 0%
7. Porosity type: fissure
8. Estimated porosity: low
9. Tendencies mainly in time: paleozoic, Variscan
10. Tendencies mainly in space: Sopron Mts
11. Tectonic situation: nappe

*Medium- and high-grade polymetamorphic formations* PzF

1. Synonimes, correlated formations: Fertőrákos Crystalline Schist Group, Gödölyebérc Amphibolite
2. Lithology: amphibolite, gneiss, mica schist
3. Facies: medium- and high-grade polymetamorphic
4. Paleoenvironment: not interpreted
5. Thickness: ?
6. Average sandiness rate: 0%
7. Porosity type: fissure
8. Estimated porosity: low
9. Tendencies mainly in time: paleozoic, Variscan
10. Tendencies mainly in space:
11. Tectonic situation: nappe

*Mesozoic Cover of Austroalpine Crystalline* Mz_AT

1. Synonyms, correlated formations: Semmering unit
2. Lithology: carbonates, quarzites, phyllites, conglomerates, lignites, evaporites
3. Facies: carbonatic, siliciclastic, evaporitic
4. Paleoenvironment: shallow marine, deltaic – fluviatil, supratidal
5. Thickness:200 - 700 m
6. Average sandiness rate:
7. Porosity type: karstic, fissure
8. Estimated porosity: low to medium (6%)

9. Tendencies mainly in time: terrestric-siliciclastic to shallow marine/neritic to shallow marin-continental
10. Tendencies mainly in space: nappe system
11. Tectonic situation: cover nappes of Austroalpine basement unit in parautochthonous position

### *Graz Paleozoic* Dmb

1. Synonyms, correlated formations: Rannach Fm., Schöckelkalk Fm. etc.
2. Lithology: carbonates, phyllites, greenschists, quarzites
3. Facies: carbonatic, siliciclastic, volcanic
4. Paleoenvironment: marine shelf, marine slope, basinal marine,deltaic – fluviatil
5. Thickness: 300 - 1700 m
6. Average sandiness rate:
7. Porosity type: karstic, fissure
8. Estimated porosity: low to medium (5 -15%)
9. Tendencies mainly in time: terrestric-siliciclastic/volcanic to shallow marine/neritic to pelagic carbonatic
10. Tendencies mainly in space: nappe system
11. Tectonic situation: Upper Austroalpine basement unit in allochthonous position

### *Paleozoic phyllitoids (Graz Paleozoic)* DS_Sa

A small area of outcroping low grade metamorphic rocks located at Sotina, next to the border with Austria are presented as phyllitoids that could correlate with the Graz Paleozoic or with the Magdalensberg Fm as well. On the basement map they are presented as Graz Paleozoic, which is extensively developed in the Austrian part of the project area.

1. Synonyms, correlated formations in partner countries: Sausal unit in general in Austria, which is not a direct equivalent of the phyllitoids occurring in Slovenia.
2. Lithology (colour, texture, grainsize): Mainly, subordinately, rarely: Outcrops of low grade metamorphic slates occur on the surface in a small area in the vicinity of Sotina, in the Goričko region. The characteristic rocks are sericite phyllite, with transitions to carbonate phyllite and chlorite slates, as well as rare marble and graphitic quartzite.
3. Facies: Lowermost greenschist facies
4. Paleoenvironment: Not known
5. Thickness: from 0 and estimated up to 700 m
6. Average sandiness rate: –
7. Porosity type: fissure
8. Estimated porosity: impermeable to low
9. Tendencies mainly in time: not known
10. Tendencies mainly in space: not known
11. Tectonic situation: Extensional allochton above the exhumed units of Pohorje Fm.

### *Blumau Phyllite-Carbonate-Formation* SD_Bl

1. Synonyms, correlated formations:
2. Lithology: carbonates, phyllites
3. Facies: carbonatic - siliciclastic
4. Paleoenvironment: shallow marine/neritic, carbonatic/siliciclastic
5. Thickness: > 200 m

6. Average sandiness rate:
7. Porosity type: karstic, fissure
8. Estimated porosity: low to medium (5 -15%)
9. Tendencies mainly in time: shallow marine
10. Tendencies mainly in space: subsurface basement nappe
11. Tectonic situation: Upper Austroalpine basement unit in allochthonous position

*Wollsdorf Metabasite-Formation* SD_mb

1. Synonyms, correlated formations:
2. Lithology: phyllites, carbonates, metabasites
3. Facies: siliciclastic - volcanic
4. Paleoenvironment: terrestric-volcanic, shallow marine
5. Thickness: > 250 m
6. Average sandiness rate:
7. Porosity type: fissure
8. Estimated porosity: low (3,5%)
9. Tendencies mainly in time: terrestric-volcanic to shallow marine
10. Tendencies mainly in space: subsurface basement nappe
11. Tectonic situation: Upper Austroalpine basement unit in allochthonous position

*Sausal unit* SD_Sa

1. Synonyms, correlated formations:
2. Lithology: phyllites, greenschists, metabasites, carbonates
3. Facies: siliciclastic, volcanic, carboatic
4. Paleoenvironment: terrestric-siliciclastic, terrestric-volcanic, shallow marine
5. Thickness: > 800 m
6. Average sandiness rate:
7. Porosity type: fissure
8. Estimated porosity: low (2%)
9. Tendencies mainly in time: terrestric-siliciclastic/volcanic to shallow marine/neritic
10. Tendencies mainly in space: basement nappe
11. Tectonic situation: Upper Austroalpine basement unit in allochthonous position

*Radochen unit* SD_SaR

1. Synonyms, correlated formations:
2. Lithology: slates, sandstones, carbonates
3. Facies: siliciclastic, subordinate carbonatic
4. Paleoenvironment: terrestric-siliciclastic, shallow marine
5. Thickness: > 700 m
6. Average sandiness rate:
7. Porosity type: fissure
8. Estimated porosity: low (5%)
9. Tendencies mainly in time: terrestric-siliciclastic to shallow marine
10. Tendencies mainly in space: subsurface basement nappe
11. Tectonic situation: Upper Austroalpine basement unit overlaying Sausal unit

*Austroalpine Cristalline* Pz_Acr

1. Synonyms, correlated formations:
2. Lithology: schists, gneiss, phyllites, amphibolites, marbles, pegmatites, eclogites, serpentinites, quarzites
3. Facies: low to high grade metamorphic rocks
4. Paleoenvironment:
5. Thickness: > 5000 m
6. Average sandiness rate:
7. Porosity type: fissure
8. Estimated porosity: low (2%)
9. Tendencies mainly in time:
10. Tendencies mainly in space:
11. Tectonic situation: lower and upper austroalpine basement complexes

*Gosau unit* KPg_G

1. Synonyms, correlated formations: Brezová Group in Slovakia, some small isolated patches are found within tectonic zone on surface along the western prolongation of the Raba fault close to Kobansko area and on Kobansko as well, near the SLO - A border.
2. Lithology: sandstones, slates, pelites, conglomerates, lignites, carbonates
3. Facies: siliciclastic/turbiditic, subordinate: carbonatic, rarely: limnic
4. Paleoenvironment: marine slope to basinal marine, subordinate: shallow marine to deltaic, rarely: brackisch to freshwater
5. Thickness: 500 - 2000 m
6. Average sandiness rate:
7. Porosity type: fissure
8. Estimated porosity: low (2,5%)
9. Tendencies mainly in time: terrestric-siliciclastic to shallow marine/neritic to pelagic carbonatic to pelagic siliciclastic
10. Tendencies mainly in space: heterogeneous
11. Tectonic situation: Northern Calcareous Alps incl. Greywacke unit and Gosau unit, local tectonic basins on nappe system of NCA

*Bajuvaric unit* Mz_F

1. Synonyms, correlated formations: Frankenfels-, Lunz nappe
2. Lithology: carbonates, sandstones, slates, conglomerates, evaporites, lignites, cherts
3. Facies: terrestrial to pelagic basinal
4. Paleoenvironment: terrestic/evaporitic to pelagic carbonatic to pelagic siliciclastic
5. Thickness: > 4000 m
6. Average sandiness rate:
7. Porosity type: karstic, fissure, intergranular
8. Estimated porosity: low to medium (6 - 20%)
9. Tendencies mainly in time: from continental (Permian) via shallow marine (Triassic) to pelagic (Jurassic-Lower Cretacous)
10. Tendencies mainly in space: nappe system
11. Tectonic situation: Northern Calcareous Alps incl. Greywacke unit and Gosau unit, lowermost nappe system of NCA

*Tirolic unit* Mz_UH

1. Synonyms, correlated formations: Reisalpe-, Unterberg-, Göller nappe
2. Lithology: carbonates, sandstones, slates, conglomerates, evaporites, lignites, cherts
3. Facies: terrestrial to pelagic basinal
4. Paleoenvironment: terrestic/evaporitic to pelagic carbonatic to pelagic siliciclastic
5. Thickness: > 5000 m
6. Average sandiness rate:
7. Porosity type: karstic, fissure, intergranular
8. Estimated porosity: low to medium (6 - 20%)
9. Tendencies mainly in time: from continental (Permian) via shallow marine (Triassic) to pelagic (Jurassic-Lower Cretacous)
10. Tendencies mainly in space: nappe system
11. Tectonic situation: Northern Calcareous Alps incl. Greywacke unit and Gosau unit, nappe system of NCA with largest extension, underlaid by Greywacke unit and tectonic underlaid Bajuvaric unit, superimposed by Juvavic unit

*Juvavic unit* Mz_UA

1. Synonyms, correlated formations: Upper nappes of NCA, Schneeberg nappe
2. Lithology: carbonates, sandstones, slates, evaporites, cherts
3. Facies: shallow marine to basinal
4. Paleoenvironment: fromshallow marine to pelagic marine
5. Thickness: > 3000 m
6. Average sandiness rate:
7. Porosity type: karstic, fissure, intergranular
8. Estimated porosity: medium (6 – 20 %)
9. Tendencies mainly in time: from shallow marine (partly slope and pelagic rise) (Triassic) to pelagic (Jurassic)
10. Tendencies mainly in space: nappe system
11. Tectonic situation: Northern Calcareous Alps incl. Greywacke unit and Gosau unit, highest nappe system of NCA

*Greywacke unit* OC_Gw

1. Synonyms, correlated formations: Noricum
2. Lithology: sandstone, slate, carbonate, porhyroid, gneiss, conglomerate, volcaniclastic
3. Facies: siliciclastic, volcanic, carbonatic
4. Paleoenvironment: continental margin, intramontane basin
5. Thickness:500 - 3000 m
6. Average sandiness rate:
7. Porosity type: fissure, intergranular
8. Estimated porosity: low to none (3%)
9. Tendencies mainly in time: terrestric-siliciclastic/volcanitic to shallow marine/neritic to pelagic carbonatic to shallow marine/neritic to terrestric-siliciclastic
10. Tendencies mainly in space: nappe system
11. Tectonic situation: Northern Calcareous Alps incl. Greywacke unit and Gosau unit, base nappe of Tirolic unit of NCA

*Bük Fm* Dmb

1. Synonimes, correlated formations: Graz Paleozoikum and Equivalents
2. Lithology: marble, calcareous slate
3. Facies: low-grade metamorphic
4. Paleoenvironment: not interpreted
5. Thickness: more 100m
6. Average sandiness rate:
7. Porosity type: fissure, karstic
8. Estimated porosity: low
9. Tendencies mainly in time: no data
10. Tendencies mainly in space: in the basement of Danube Basin
11. Tectonic situation: tectonic window

*Jákó–Polány Marl* K2ml

1. Synonimes, correlated formations: Inoceramus marl, Gryphaea marl
2. Lithology: grey marl, silty marl, clayey limestone
3. Facies: sublitoral to basin facies
4. Paleoenvironment: pelagic basin
5. Thickness: max 900 m
6. Average sandiness rate: only in the uppermost part (Ganna Mb)
7. Porosity type: karstic/fissure
8. Estimated porosity: low
9. Tendencies mainly in time: the uppermost layers are slightly sandy; limestone breccia member in the middle part
10. Tendencies mainly in space: heteropic connection with Ugod Limestone
11. Tectonic situation: Transdanubian Range Unit, senonian sedimentary cycle after Pre-Gosau orgeny

*Ugod Limestone* K2ls

1. Synonimes, correlated formations: Hippurites limestone
2. Lithology: light-grey thick-bedded limestone
3. Facies: carbonate platform
4. Paleoenvironment: shallow marine high
5. Thickness: 100-300 m
6. Average sandiness rate:
7. Porosity type: karstic
8. Estimated porosity: great
9. Tendencies mainly in time:
10. Tendencies mainly in space: Transdanubian Range Unit, heteropic connection with Polány Marl
11. Tectonic situation: senonian sedimentary cycle after Pre-Gosau orgeny

*Halimba Bauxite, Csehbánya Fm, Ajka Brown Coal* K2t

1. Synonimes, correlated formations:–
2. Lithology: bauxite; cyclic alternation of sand/sandstone, siltstone, clay with coal seams
3. Facies: terrestrial, fluvial, lacustrine
4. Paleoenvironment: karstified surface, alluvial plain, delta, swamp
5. Thickness: 50-200 m

6. Average sandiness rate: 30-40%
7. Porosity type: intergranular
8. Estimated porosity: medium
9. Tendencies mainly in time: bauxite is overlain by the other two heteropic formations
10. Tendencies mainly in space: heteropic connection with each other
11. Tectonic situation: Transdanubian Range Unit, senonian sedimentary cycle after Pre-Gosau orgeny

*Vértessomló Siltstone – Tata Limestone* Kml-ls

1. Synonimes, correlated formations: Aptian crinoidal limestone
2. Lithology: grey siltstone, crinoidal limestone
3. Facies: sublittoral facies
4. Paleoenvironment: pelagic basin
5. Thickness: max 400 m
6. Average sandiness rate: sandstone intercalations occur in both formations
7. Porosity type: karstic/fissure/intergranular
8. Estimated porosity: medium
9. Tendencies mainly in time: siltstones are above, limestones are below
10. Tendencies mainly in space: siltstones are in heteropic connection with Környe Limestone
11. Tectonic situation: Transdanubian Range Unit, depositional cycle after the Austrian phase, disconformably overlying pre-Aptian rocks

*Vértessomló Siltstone – Pénzeskút Marl* Kml-ls

1. Synonimes, correlated formations: Turrilites marl
2. Lithology: grey siltstone, glauconitic marl
3. Facies: basin facies
4. Paleoenvironment: pelagic basin
5. Thickness: max 700 m
6. Average sandiness rate: sandstone intercalations occur in upper part
7. Porosity type: fissure/intergranular
8. Estimated porosity: low
9. Tendencies mainly in time: siltstones are below, marls are above
10. Tendencies mainly in space: siltstones are in heteropic connection with Környe Limestone
11. Tectonic situation: Transdanubian Range Unit, deepening upward depositional cycle after the Austrian phase

*Környe–Zirc Limestone* Kpls

1. Synonimes, correlated formations: Urgonian limestone, Pachyodonta limestone
2. Lithology: thick-bedded limestone
3. Facies: platform and slope facies
4. Paleoenvironment: sublitoral platform
5. Thickness: max 450 m
6. Average sandiness rate: –
7. Porosity type: karstic
8. Estimated porosity: medium to great
9. Tendencies mainly in time: –

10. Tendencies mainly in space: Környe Limestone is heteropic with Vértessomló Siltstone
11. Tectonic situation: Transdanubian Range Unit, highstand deposits within depositional cycle after the Austrian phase

*Alsópere Bauxite, Tés Clay Marl* K1f

1. Synonimes, correlated formations: Munieria clay
2. Lithology: bauxite, variegated clay, calymarl
3. Facies: fluvio-lacustrine to backish
4. Paleoenvironment: karstified surface, swamp, lagoon
5. Thickness: max 230 m
6. Average sandiness rate: sandstone intercalations are rare
7. Porosity type: intergranular
8. Estimated porosity: no/low
9. Tendencies mainly in time: basal and uppermost part consist limestone
10. Tendencies mainly in space: Tés Clay Marl is heteropic with Környe Limestone
11. Tectonic situation: Transdanubian Range Unit, lowstand deposits at the base of depositional cycle after the Austrian phase

*Lábatlan Sandstone, Bersek Marl* K1t

1. Synonimes, correlated formations: Aptychus marl, Rossfeld Sandstone
2. Lithology: marl with sandstone intercalations (below) and sandstones with conglomerate in the uppermost part
3. Facies: turbidite
4. Paleoenvironment: bathyal submarine slope (channel) and basin
5. Thickness: max 500 m
6. Average sandiness rate: sandstones give 80% of the succession
7. Porosity type: intergranular
8. Estimated porosity: low
9. Tendencies mainly in time: coarsening upward sequence, marl below, sandstone and conglomerate above
10. Tendencies mainly in space:
11. Tectonic situation: Transdanubian Range Unit, flysh deposition in connection with early obduction of a branch of the Neotethys

*Sümeg Marl* K1bml

1. Synonimes, correlated formations: –
2. Lithology: silty marl, siltstone, calcareous marl
3. Facies: basin
4. Paleoenvironment: shallow bathyal pelagic basin
5. Thickness: max 270 m
6. Average sandiness rate:
7. Porosity type: intergranular
8. Estimated porosity: no/low
9. Tendencies mainly in time: calcareous marl below, siltstone above
10. Tendencies mainly in space:
11. Tectonic situation: Transdanubian Range Unit, oceanic stage of the Neotethys

*Jurassic – Early Cretaceous marine succession* J

1. Synonimes, correlated formations: Hierlatz Limestone, Adnet Limestone, ammonitico rosso, maiolica, biancone
2. Lithology: limestone, cherty limestone, clayey limestone, radiolarite, manganese
3. Facies: basin
4. Paleoenvironment: submarine high and bathyal pelagic basin
5. Thickness: 20–500 m
6. Average sandiness rate:
7. Porosity type: karstic
8. Estimated porosity: low
9. Tendencies mainly in time: limestones below and above, radiolarites middle
10. Tendencies mainly in space: thin and condensed successions on the paleohighs and thick continuous successions in the basin areas
11. Tectonic situation: Transdanubian Range Unit, oceanic stage of the Neotethys

*Dachstein–Kardosrét Limestone* T3ls

1. Synonimes, correlated formations:
2. Lithology: thick-bedded, Lofer cyclic limestone
3. Facies: platform
4. Paleoenvironment: shallow marine tidal flat
5. Thickness: max 1500 m
6. Average sandiness rate:
7. Porosity type: karstic
8. Estimated porosity: great
9. Tendencies mainly in time: dolomite-limestone alternation at the lower part
10. Tendencies mainly in space: thickness of Dachstein Limestone increase from SW to NE, Kardosrét Lmst restricts to the Bakony Mts
11. Tectonic situation: Transdanubian Range Unit, passive continental margin of the Neotethys

*Rezi Dolomite, Kössen Marl, Feketehegy Fm* T3bls

1. Synonimes, correlated formations:
2. Lithology: well-bedded, laminated bituminous dolomites and limestones, marl, clay marl
3. Facies: basin
4. Paleoenvironment: restricted extensional hemipelagic basin
5. Thickness: max 700 m
6. Average sandiness rate:
7. Porosity type: karstic
8. Estimated porosity: no/low
9. Tendencies mainly in time: dolomites and limestones below, marls above
10. Tendencies mainly in space: Kössen+Rezi Fm in the SW (S Bakony, Zala Basin), Feketehegy Fm in the NE (Pilis)
11. Tectonic situation: Transdanubian Range Unit, extensional Late Triassic basin

*Ederics Limestone, Sédvölgy Dolomite, Main Dolomite* T3d

1. Synonimes, correlated formations: Hauptdolomit
2. Lithology: well-bedded dolomites and poorly bedded limestones
3. Facies: carbonate platform

4. Paleoenvironment: lagoon and reef of shallow marine tidal flat
5. Thickness: 2000 m
6. Average sandiness rate:
7. Porosity type: karstic
8. Estimated porosity: great
9. Tendencies mainly in time:
10. Tendencies mainly in space: Ederics Limestone restricts to the SW (Keszthely Mts), dolomites are widespread
11. Tectonic situation: Transdanubian Range Unit, passive continental margin of the Neotethys

*Veszprém Marl, Sándorhegy Fm* Tkbls

1. Synonimes, correlated formations: Raibl Fm, Lunz Fm, Opponitz Fm
2. Lithology: marl, clay marl, calcareous marl, limestone
3. Facies: basin
4. Paleoenvironment: shallowing upward intraplatform basin
5. Thickness: max 1000 m
6. Average sandiness rate:
7. Porosity type: karstic
8. Estimated porosity: low
9. Tendencies mainly in time: marls are overlain by bituminous laminites and nodular liemstones
10. Tendencies mainly in space: Carnian basin deposits are in heteropic contact with Carnian platforms (Ederics and Sédvölgy Fm)
11. Tectonic situation: Transdanubian Range Unit, passive continental margin of the Neotethys

*Budaörs Dolomite* Tpd

1. Synonimes, correlated formations: Diplopora dolomite, Ramsau Dolomite, Wetterstein Dolomite
2. Lithology: well-bedded dolomites
3. Facies: carbonate platform
4. Paleoenvironment: lagoon of shallow marine platform
5. Thickness: max 1000 m
6. Average sandiness rate:
7. Porosity type: karstic
8. Estimated porosity: large
9. Tendencies mainly in time:
10. Tendencies mainly in space: Transdanubian Range Unit, Budaors platform is heteropic with Ladinian–lowermost Carnian basin succession
11. Tectonic situation: passive continental margin of the Neotethys

*Felsőörs Limestone, Buchenstein Fm, Füred Limestone* T2ls

1. Synonimes, correlated formations: Reifling Lmst
2. Lithology: laminated or nodular limestones, cherty limestones, tuffs, tuffites
3. Facies: basin
4. Paleoenvironment: hemipelagic to pelagic, deepening upward intraplatform basin
5. Thickness: max 1000 m
6. Average sandiness rate:

7. Porosity type: karstic
8. Estimated porosity: medium
9. Tendencies mainly in time: volcanites devide limestone succession into two parts
10. Tendencies mainly in space: Felsőörs Fm is partly heteropic with Middle Anisian platform (Tagyon Fm), Buchenstein and Füred Fms are heteropic with Budaörs platform
11. Tectonic situation: Transdanubian Range Unit, passive continental margin of the Neotethys with initiating rifting

*Aszófő Dol., Iszkahegy Lmst, Megyehegy Dol.,Tagyon Fm* Tacb

1. Synonimes, correlated formations: Reichenhall Beds, Gutenstein Fm, Steinalm Fm
2. Lithology: vuggy dolomite, laminated and/or thick-bedded bituminous limestone and dolomite, Lofer-cyclic limestone
3. Facies: carbonate ramp and platform
4. Paleoenvironment: shallow marine carbonate ramp and isolated platform
5. Thickness: max 700 m
6. Average sandiness rate:
7. Porosity type: karstic
8. Estimated porosity: medium/large
9. Tendencies mainly in time: ramp facies below, platform facies above
10. Tendencies mainly in space: Tagyon Fm is partly heteropic with Felsőörs Fm (Middle Anisian basin)
11. Tectonic situation: Transdanubian Range Unit, passive continental margin of the Neotethys with extensional tectonic movements during the Middle Anisian rifting

*Alcsútdoboz Fm, Arács Fm, Köveskál Fm,* T1cb
*Hidegkút Fm, Csopak Fm,*

1. Synonimes, correlated formations: Werfen Fm in Austria and Slovenia, in Slovakia occurs in Tatricum, Fatricum–N-Veporicum, Hronicum: Lúžna Fm., Benkovský potok and Šuňava Fm.
2. Lithology: marl, siltstone, limestone, (dolomite, sandstone)
3. Facies: mixed siliciclastic–carbonate ramp
4. Paleoenvironment: inner and outer shelf, sand-bar
5. Thickness: max 600 m
6. Average sandiness rate: 10%
7. Porosity type: karstic
8. Estimated porosity: low/medium
9. Tendencies mainly in time: dolomite and limestone below, siltstone middle, marls above
10. Tendencies mainly in space: Köveskál (SW) Arács and Alcsútdoboz Fm (NE) are heteropic with each other
11. Tectonic situation: Transdanubian Range Unit, passive continental margin of the Neotethys

*Balatonfelvidék Sandstone* Pt

1. Synonimes, correlated formations: Val Gardena (Grödener) Sandstone
2. Lithology: sandstone, pebbly sandstone, siltstone
3. Facies: cyclic terrestrial siliciclastics
4. Paleoenvironment: alluvial plain

5. Thickness: 50–800 m
6. Average sandiness rate:
7. Porosity type: fissure
8. Estimated porosity: medium
9. Tendencies mainly in time: platform dolomites and limestones below, marls and tuffitic limestones of basin facies above
10. Tendencies mainly in space: thickness decrease from SW to NE
11. Tectonic situation: Transdanubian Range Unit, rifting phase of the Neotethys

*Tabajd Anhydrite, Dinnyés Dolomite* Pt

1. Synonimes, correlated formations: Bellerophon Fm
2. Lithology: siltstone–anhydrite, dolomite
3. Facies: sabkha, lagoon
4. Paleoenvironment: coastal plain, shallow-marine lagoon
5. Thickness: max 700 m
6. Average sandiness rate: –
7. Porosity type: karstic/fissure
8. Estimated porosity: medium/large
9. Tendencies mainly in time: evaporates below, dolomites above
10. Tendencies mainly in space: thickness increase from SW to NE
11. Tectonic situation: Transdanubian Range Unit, rifting phase of the Neotethys

*Low-grade metamorphic formations in Transdanubian Range* OC_Tr

1. Synonimes, correlated formations: Balatonfőkajár, Lovas, Alsóörs, Szabadbattyán, Polgárdi, Kékkút, Úrhida, Nemeskolta, Mihályi Fm-s, Carboniferous Formation in Slovenia
2. Lithology: slate, calc-phyllite, quartz phyllite, quartzite, meta-sandstone, meta-conglomerate, alcaline meta-tuffite, limestone
3. Facies: low-grade metamorphic
4. Paleoenvironment: not interpreted
5. Thickness: ?
6. Average sandiness rate: 5%
7. Porosity type: fissure, intergranular
8. Estimated porosity: low
9. Tendencies mainly in time: paleozoic, diverse units, separates each other
10. Tendencies mainly in space: SE and NW limb of Transdanubian Range
11. Tectonic situation: Transdanubian Range Unit, uppermost Austroalpine nappe

*South Karavanke unit, Permian* P_SK

1. Synonyms, correlated formations in partner countries: This complex unit comprises several formations, therefore no synonyms are given. Here, only Val Gardeana Fm. is equivalent of Balatonfelvidék Sandstone in Hungary, Devín Fm. in Slovakia and Haselgebirge, Prebichl-Formation in Austria.
2. Lithology: Lower part consists of grey quartz conglomerates, subordinately quartz sandstones. Above, quartz sandstones follow, transiting to slaty mudstones interlayered with quartz sandstones and some reef limestones (brecciated, conglomeratic). In continuation, red, grey and greenish sediments of Val Gardena Fm were deposited, mainly siltstones and subordinately conglomerates and sandstones. Transgresively carbonate rocks of Upper Permian cover clastic rocks.

3. Facies: fresh water, rarely: marine carbonate
4. Paleoenvironment: Lower part shows retrogradational, transgressive series of sedimentary rocks. The Val Gardena Fm. Is interpreted as a product of river sedimentation environment, incuding also shallow lake (playa) environments. The Val Gardena Fm. ended with retrogardation and marine transgression with carbonate sedimentation.
5. Thickness: not known, estimated to more than 1500 m
6. Average sandiness rate: –
7. Porosity type: mostly fracture, subordinately intergranular
8. Estimated porosity: low
9. Tendencies mainly in time: not known
10. Tendencies mainly in space: The Permian clastic rocks occur as tectonic lenses within South Karavanke unit in the southern part of the Slovenian project area teritory. Smaller outcrops are found only in the westernmost corner merged with Triassic rocks, while in the southernmost part of the South Karavanke unit their presence is interpreted. In the area northeast of Maribor, the borehole Šom-1 reached Permian clastic rocks within small erosional remain of thrust imbricates.
11. Tectonic situation: Not known

### *South Karavanke unit, Permo-Triassic* PT_SK

Permian and Triassic clastic and carbonate formations are comprised in this unit. Their occurrence is documented in the south-westernmost end of the Slovenian part of the project area within the Labot fault zone and in the southernmost part within the Donat fault zone. Small lens occur also in the border region between Slovenia and Hungary under Tertiary sediments. Characteristics of the Permian sequences are presented previously. Lower Triassic rocks will be presented under the Triassic (T1+T2) siliciclastic and carbonate formations - T_L.

### *South Karavanke unit* T23_SKcb

Formations of platform and basin facies (Anisian dolomite *Tacb*, Wengen *T2ls* and Schlern *Tpd* Formations)

1. Synonyms, correlated formations in partner countries:
   in Hungary: Tagyon Limestone, Megyehegy Dolomite, Iszkahegy Limestone, Aszófő Dolomite;
   in Slovakia: Tatricum, Hronicum: Gutenstein Fm., grey dolomites, Steinalm Fm.- Hronicum: Reifling, Zámostie, Gader, Raming and Schreyeralm Limestones,
   in Austria: Gutenstein Formation- Reifling Formation.
2. Lithology: Anisian dolomites, pelagic, basin limestone, nodular or cherty limestone with tuffaceous and siliciclastic intercalations, in Ladinian Wetterstein Fm. has been deposited as limestone and dolomite; Carnian shales with limestone intercalations; Upper Triassic beds are developed as limestones, and partly dolomites.
3. Facies: Mainly: Anisian intra- to supratidal environment, Ladinian fore-reef, reef and lagoonal environment, Carnian to Rhaetian platform and basin facies
4. Paleoenvironment: Carbonate platform shallow water and reef, locally closed lagoonal sedimentation
5. Thickness: not known
6. Average sandiness rate:
7. Porosity type: fracture, intercrystalline, vague, karstic porosity
8. Estimated porosity: medium to high

9. Tendencies mainly in time: not known
10. Tendencies mainly in space: not known
11. Tectonic situation: This unit is interpreted as wide belt in the southernmost part of the Slovenian part of the project area, belonging to Southern Karavanke unit.

*North Karavanke unit* PT_NK

This unit comprises Permian and Triassic clastic and carbonate formations. Permian Fm. are described in the previous section, therefore North Karavanke carbonate rocks will be shortly presented under the Main Dolomite (’Hauptdolomit’) T3d (T3d_surf) formation. Their occurrence is documented only as a thin wedged slice within the Labot fault zone at the south-westernmost end of the Slovenian part of the project area. They have only structural meaning in the project context.

North Karavanke Mountains are built up of Upper Permian to Lower Triassic terrigenous quartz sandstones and conglomerates with gradual upwards transition into marls and then into oolitic dolomites and platform fossiliferous limestones. Within, the Anisian dolomites formed in the intra- to supratidal environment.

*Hronic unit* Mz_UH

1. Synonyms, correlated formations in partner countries: No
2. Synonymes, correlated formations in partner countries: Tirolic unit
3. Lithology (colour, texture, grainsize): carbonates, breccias, shales
4. Facies: from continental base to carbonate and shale
5. Paleoenvironment: minor continental at the base, than carbonate platform and it`s surrounding breccias and intraplatform basins fills
6. Thickness: more than 5000 m
7. Average sandiness rate: no
8. Porosity type: fissure, karstic
9. Estimated porosity: no/low to medium. The highest is in the Hauptdolomite
10. Tendencies mainly in time: Several depositional cycles with a variability of sea depth and the clastic content.
11. Tendencies mainly in space: deepening NW-wards?
12. Tectonic situation: Western Carpathian unit, nappe system

*Hronicum: Ipoltica Group (Malužiná and Nižná Boca Fm.)* CP_Ivs

1. Synonymes, correlated formations in partner countries:
2. Lithology (colour, texture, grainsize): Cyclical volcano-sedimentary complex: clastic and basaltic rocks
3. Facies: volcanic to volcano-sedimentary
4. Paleoenvironment: continental
5. Thickness: more than 300 m
6. Average sandiness rate: no
7. Porosity type: fissure
8. Estimated porosity: medium
9. Tendencies mainly in time: basaltic volcanics intercalated by volcanoclastics, covered by alluvial volcanoclastic facies
10. Tendencies mainly in space: without a continuation to Austria, nor Hungary
11. Tectonic situation: Western Carpathian unit, continental rift volcanism

*Fatric unit* Mz_F

1. Synonymes, correlated formations in partner countries: Bajuvaric unit
2. Lithology (colour, texture, grainsize): quartzites, carbonates, shales
3. Facies: from continental base to carbonate and shale
4. Paleoenvironment: mainly marine
5. Thickness: up to 3000 m
6. Average sandiness rate:
7. Porosity type: grain, fissure, karstic
8. Estimated porosity: low to medium
9. Tendencies mainly in time: several shallowing upward depositional cycles, generally deepening upward
10. Tendencies mainly in space: shallowing NWwards
11. Tectonic situation: Western Carpathian unit, nappe system

*Tatric cover unit* J_Tls

1. Synonymes, correlated formations in partner countries:
2. Lithology (colour, texture, grainsize): from variegated shales, conglomerates and quartzites to shales and carbonates, breccias
3. Facies: from continental base to shale and carbonate and again to breccias
4. Paleoenvironment: from continental base to shale and carbonateup to large amount of breccias
5. Thickness: more than 1000 m
6. Average sandiness rate:
7. Porosity type: fissure, karstic
8. Estimated porosity: low to medium
9. Tendencies mainly in time: several depositional cycles, last period strongly influenced by rifting tectonics (breccias)
10. Tendencies mainly in space: heterogeneous
11. Tectonic situation: Western Carpathian unit, postrift, mainly synrift

*Tatric metamorphic unit (Early Paleozoic?)* Pz_Tcr

1. Synonymes, correlated formations in partner countries: Austroalpine Crystalline units
2. Lithology (colour, texture, grainsize): Tatric unit – gneiss, schist, phyllite, marble, amphibolite
3. Facies: high to low metamorphic
4. Paleoenvironment: aeral periplutonic
5. Thickness: variable, tectonic slices
6. Average sandiness rate: no
7. Porosity type: fissure
8. Estimated porosity: low
9. Tendencies mainly in time: no
10. Tendencies mainly in space: no
11. Tectonic situation: Western Carpathian unit, paraautochtonous position

*Tatric Crystalline – hercynian intrusive rocks* C_Tgr

1. Synonymes, correlated formations in partner countries: Austroalpine Crystalline units

2. Lithology (colour, texture, grainsize): Biotitic and two-mica granite, granodiorite and tonalite, leucocratic granite, diorite
3. Facies: plutonic
4. Paleoenvironment: deep seated
5. Thickness: tectonically cut
6. Average sandiness rate: no
7. Porosity type: fissure
8. Estimated porosity: low
9. Tendencies mainly in time: the acidity growing upwards?
10. Tendencies mainly in space: Male Karpaty Mts. – two main bodies – the souther more acid, the northern more basic
11. Tectonic situation: Western Carpathian unit, paraautochtonous position

*Veporic unit (Early Paleozoic)* Pz_Vcr

1. Synonymes, correlated formations in partner countries: Austroalpine Crystalline units
2. Lithology (colour, texture, grainsize): gneiss, schist, phyllite, marble, amphibolite
3. Facies: high to low metamorphic
4. Paleoenvironment: aeral periplutonic
5. Thickness: variable, tectonic slices
6. Average sandiness rate: no
7. Porosity type: fissure,
8. Estimated porosity: no
9. Tendencies mainly in time: no
10. Tendencies mainly in space: no
11. Tectonic situation: Western Carpathian unit, paraautochtonous position

*Pohorje Formation* Pz_Acr

Occurs on the pre-Cenozoic horizon map as surface formation in the area of Pohorje and Kobansko Mountains, and buried under Tertiary sediments representing Murska Sobota High and most of the western Maribor subbasin and Radgona-Vas half-graben.

1. Synonyms, correlated formations in partner countries: The eastern prolongation of the Pohorje Fm. in Hungary is represented by Óbrennberg–Vöröshíd Mica Schist, Sopronbánfalva Gneiss, and Füzesárok White Schist. The latter do not occur in the Slovenian part of the project area. Northward, the Pohorje Fm. continues to Austria, represented by the so called Austroalpine kristallin in which all greenschist formations are merged to the gneiss-micaschist level of higher metamorphic grade.
2. Lithology (colour, texture, grainsize):
   Mainly: Main lithology is represented by grey gneiss and grey to brownish micaschist with frequent layers and lenses of amphibolite. The rocks are medium grained, though coarse grained varieties are present in deeper parts of the Pohorje massif. Structures express dynamic conditions of formations, i.e. lineation and foliation. Textures exhibit degradational recrystallization.
   Subordinately: pegmatite, quartzite and marble, augen gneiss and eclogite.
   Rarely: serpentinite
3. Facies:
   Mainly: medium to high grade metamorphic facies
   Subordinately: retrogression to upper greenschist facies,

Rarely: ultra-high pressure metamorphism in the easternmost part of the Pohorje Mountains; contact metamorphic epidote and hornblende hornfelses facies and skarn around Pohorje Mts. batholith

4. Paleoenvironment:
   Mainly: shelf related clastic sedimentation, mostly in a confined basin
   Subordinately: transition to ocean floor, but without ophiolites
   Rarely: near shore (meta-conglomerates)
5. Thickness: not known, but speculated several thousand meters
6. Average sandiness rate: -
7. Porosity type: fracture
8. Estimated porosity: low to medium within the strike-slip zones.
9. Tendencies mainly in time: Polyphase metamorphosed core complex, progressive metamorphism already of Variscan age, HP to UHP Cretaceous subduction related metamorphism, followed by late Cretaceous to Paleogene retrogressive metamorphism. Slight contact metamorphism in the area connected to the Pohorje Mountains granodiorite intrusion.
10. Tendencies mainly in space: The Pohorje Formation is represented by medium to high grade polymetamorphic formations of the Pohorje Mountains and Kobansko massifs and Murska Sobota high, buried under Tertiary sedimentary sequences. The outcropping part of this formation occurs in the western part of the project area in the Pohorje and Kobansko Mountains, which are detached from the Karavanke range with the Labot fault west of the project area. Ljutomer transitional zone borders Pohorje Fm. to the south, while to the north; it is cut by Rába Line and continues under tertiary sediments to the Austrian territory.

    In the central part of the Pohorje Mountains, granodiorite batholith with transition to subvolcanic dacite intruded the formation in Lower Miocene. Contact aureole with metamorphic rocks is just some tens of meters thick. It is more pronounced in the western Pohorje Mountains area in contact with low grade Magdalensberg slaty rocks and is represented by hornfelses and skarns (tactites).

    The upper part of the Pohorje Fm. rocks is most often mylonitized and locally phyllonitized, yielding strong foliation with subhorizontal to gentle dip in the central part of the project area and moderate dip in the marginal (southern, northern and eastern) parts of the Murska Sobota high. According to the seismic profiles marginal parts of the Murska Sobota high show gentle folding and intense faulting due to proximity of the main east-west trending reactivated tectonic zones (the Radgona-Vas and the Ljutomer tectonic half-grabens) where dense fracture porosity was formed.

    The Murska Sobota high reaches the highest thickness in the central part of the massif. It is bounded by northern (Radgona-Vas subbasin) and southern strike-slip grabens (Ptuj-Ljutomer subbasin) forming Radgona-Vas and Ptuj-Ljutomer fault zones. Transversely sigmoidal depressions formed, i.e. the western Maribor subbasin and the eastern Mura-Őrség subbasin (named sensu Jelen and Rifelj, 2010). The eastern continuation of the Pohorje formation (the Koralpe-Pohorje-Wölz unit) was deeply sank along a strong detachment fault and buried under several thousand meters of Mesozoic to Cenozoic sedimentary sequences in the Pannonian basin.
11. Tectonic situation: The Pohorje Formation represents the south easternmost part of the Upper Austroalpine nappe pile (UAA) and belongs to the Koralpe-Pohorje-Wöltz mega-unit in the project area. Its formation is interpreted in six main tectonic phases. The most pronounced structures were formed during the Cretaceous collisional deformation (D1), which lead to the nappe formation of the pre-Cenozoic

basement. The Pohorje and Kozjak (comprising Kobansko) massifs and probably also the Murska Sobota high were tectonically exhumed along several low-angle detachment faults (Jelen et al. 2006) in Late Cretaceous (D2 deformational phase). So-called extensional allochtons developed above the exhumed units, to which the Graz Paleozoic and also the Transdanubian Range Unit belong. At the same time in Slovenian territory restricted basins evolved, which were filled with Gosau type sediments. Subsequent late Oligocene strike-slip and thrusting of the D3 phase dismembered the basement in a convergent regime. In the Early Miocene rifting (D4 phase) Pohorje and Kozjak blocks and Murska Sobota high were detached from the Austroalpine hinterland. Granodiorite intruded into the Pohorje metamorphic sequence. The whole area was synchronously ccw rotated and subsided toward the east in the Late Miocene D6 structural phase. The Late Sarmatian strike-slip deformation (D5), which should have resulted in a core complex formation (after Jelen, 2006) cannot be clearly proven in this part of the project area. The latest deformation D7 comprises uppermost Miocene to Quaternary structural inversion in a compressional regime, which is still active. The transpressional Murska Sobota block was rotated in the ccw sense and tilted toward the north, causing slight asymmetric closure of the northern Radgona-Vas tectono-erosional half graben.

### *Kobansko and Phyllite formation* CaOph

This unit represents two unified formations, Kobansko and Phyllite formation, which are merged by the phyllonite to mylonite layer beneath main thrust units on the basement map.

1. Synonyms, correlated formations in partner countries: No synonyms.
2. Lithology:
   Mainly: Chlorite-amphibole (dark green, fine to medium grained) and biotite chlorite schists (greyish green, fine to medium grained) and quartz sericite phyllite (greenish grey, fine grained)
   Subordinately: Phyllite includes lenses of recrystallized iron dolomite and
   Rarely: metakeratophyre and its tuff and recrystallized limestone
3. Facies: upper greenschist (Kobansko Fm.) to middle greenschist metamorphic facies (Phyllite Fm.)
4. Paleoenvironment: active continental margin with accompanying (shoshonitic) volcanic activity
5. Thickness: 0 to about 800 m, all three merged sequences can well exceed 1000 m in places. West of the project area in the western Pohorje their thickness is estimated to about 1000 m, regardless phyllonite to mylonite level.
6. Average sandiness rate: -
7. Porosity type: fracture
8. Estimated porosity: low to medium within the thrust and strike-slip zones.
9. Tendencies mainly in time: Polyphase metamorphosed complex, progressive metamorphism probably of Cretaceous age, though not well constrained yet. Retrogressive metamorphism took place mostly during upper Cretaceous thrusting and uplift within thrust zones, where phyllonite and mylonites were formed.
10. Tendencies mainly in space: This complex thrust unit occurs at northern part of the Murska Sobota high. It consists of the deepest Strojna overthrust, which consists of greenschists and chlorite-amphibole schists and the Dravograd overthrust of phyllite above. Below both thrust sheets phyllonites were developed locally, while mylonites are found just in the upper parts of the Pohorje Fm. No borehole cut the entire thickness of the unit; therefore its real thickness is unknown. According to data

interpretation it reaches the highest thickness adjacent to relatively small lenses of carbonate rocks at the northernmost end of the basement emerging from underneath the Badenian Fm. The thrust sheets thin out in the south-southeast direction.

11. Tectonic situation: The chlorite-amphibole and biotite chlorite schists represent lower thrust sheet of the described unit, occurring immediately above the phyllonite to mylonite layer. They belong to Strojna overthrust. The rocks were probably formed in a pull-apart basin from primary basalt and andesite and corresponding tuffs (Hinterlechner-Ravnik & Moine, 1977). Quartz sericite phyllite is locally thrust onto the Strojna thrust, but locally directly onto the Pohorje Fm. and represent Dravograd thrust sheet. Strojna and Dravograd thrusts are together part of the Krško nappe (Gurktaller Decke), forming its imbricated internal structure.

### *Magdalensberg Formation* OSsh

In the Slovenian part of the project area, this formation comprises lower part of the *OC_Tr*, namely the entire Silurian slaty formation.

1. Synonyms, correlated formations in partner countries: Balatonfőkajár, Lovas, Alsóörs, Szabadbattyán, Polgárdi, Kékkút Úrhida Fm-s, Nemeskolta Fm, Mihályi Fm in Hungary, comprising also Carboniferous rocks; Magdalensberg Fm. in Austria, but is not shown separately on the basement map there.
2. Lithology: The Magdalensberg series consists of two parts. The lower part is characterized by sandy clayey marine sedimentation yielding slates and with acid tuffs and tuffites together with lenses of marmorized limestone. In the upper part finer material was deposited, consisting of greenish and violet slates with lenses of limestone and ferrous dolomite, indicating basin deepening. The rocks are intruded by diabase sills and extrusives accompanied by corresponding tuffs. Diabases are spilitized.
3. Facies: Lowermost greenschist facies
4. Paleoenvironment: Mainly: Oceanic realm of the Paleotethys, probably at culmination of continental rifting (Loeschke & Heinisch, 1994). The geochemical composition of spilites indicates their intraplate origin in the extensional zones of the crust.
5. Thickness: 0 and up to about 1000 m
6. Average sandiness rate: –
7. Porosity type: Fracture porosity
8. Estimated porosity: Impermeable to low porosity
9. Tendencies mainly in time: The Magdalensberg Fm shows finning upward in a general sense. The lower part is older, presumably of Silurian age and slightly siltier. The upper part shows strong influence of basic volcanism and contains diabase sills. This part of the formation is presumably of Devonian age.
10. Tendencies mainly in space: The lower part of the Magdalensberg Fm shows characteristics of terrestrial origin (silty material), while the upper part is mostly pyroclastic and volcanic. From Austria, where the formation reaches the widest spread, it extends to Slovenian territory. Here it occupies just a small area in the westernmost part of the project area and is thinning out toward the south and southeast. The easternmost occurrence is detected near the village Šomat in the Šom-1 borehole northeast of Maribor. It indicates the same characteristics as the phenomenon west of the Labot fault near Ravne na Koroškem.
11. Tectonic situation: The Magdalensberg Fm represents synrift pull-apart basin, where diabase indicates initial rift volcanism. It belongs to Remschnig nappe, which is

partly thrust onto phyllites of the Kobansko and Phyllite formation (SD_Sa) or directly to the Pohorje Fm in the westernmost part of the project area. The few K-Ar radiometric data indicate Cretaceous age of its weak metamorphism.

*Upper Paleozoic and Mesozoic formations in general* Pz-Mz

Under this name several formations are encountered, which due to lack of data were not possible to differentiate. Separate formations are represented under the Paleozoic and Triassic formations.

*Triassic ($T_1$+$T_2$) siliciclastic and carbonate formations* T_L

These formations represent eastward continuation of the complex structure of Lower to Middle Triassic sequences from the west, detached along the Labot fault. They are interpreted to be spread within the Ljutomer transitional tectonic zone at the southern part of the Slovenian project area. Here, Werfen Fm T1cb, Anisian dolomite Fm Tacb and Wengen Fm T2ls are comprised, described in appurtenant formations.

## 4. ADRIA DERIVED RETROWEDGE SOUTHERN ALPS, DINARIDES NAPPE SYSTEM

*Táska, Som, Igal; Sávoly, Murakeresztúr, Újudvar* T23_SKcb

1. Synonimes, correlated formations:
2. Lithology: limestone, dolomite, marl, tuff, radiolarite
3. Facies: platform, basin
4. Paleoenvironment: shallow marine shelf, intraplatform basin
5. Thickness: ?
6. Average sandiness rate:
7. Porosity type: karstic
8. Estimated porosity: medium/large
9. Tendencies mainly in time: platform dolomites and limestones below, marls and tuffitic limestones of basin facies above
10. Tendencies mainly in space:
11. Tectonic situation: Mid-Hungarian Unit, passive continental margin of the Neotethys

*Újfalu, Tab* P_SK

1. Synonimes, correlated formations: Trogkofel Fm, Bellerophon Fm
2. Lithology: marl with limestone, sandstone, dolomite
3. Facies: siliciclastic–carbonate ramp
4. Paleoenvironment: shallow marine shelf
5. Thickness: ?
6. Average sandiness rate: 5%
7. Porosity type: karstic/fissure
8. Estimated porosity: low/medium
9. Tendencies mainly in time: marls with limestone intercalations below, sandstone middle, dolomite above
10. Tendencies mainly in space:
11. Tectonic situation: Mid-Hungarian Unit, rifting phase of the Neotethys

## 5. VOLCANIC, SUBVOLCANIC, PLUTONIC BODIES

### *Young basanites and tuffites* Mb_surf

1. Synonyms, correlated formations:
2. Lithology: volcaniclastics, basalts
3. Facies: young volcanic buildups
4. Paleoenvironment:
5. Thickness: 100 - 200 m
6. Average sandiness rate:
7. Porosity type: fissure, intergranular
8. Estimated porosity: low to medium (5 - 8%)
9. Tendencies mainly in time:
10. Tendencies mainly in space:
11. Tectonic situation: Within plate basalts of Pliocene age

### *Miocene vulcanites* Mbzt_surf

1. Synonyms, correlated formations: Gleichenberg-, Weitendorf vulcanites
2. Lithology: trachytes, trachyandesites, dacite, shoshonite
3. Facies: volcanic
4. Paleoenvironment: volcanic buildups in evolving Styrian basin
5. Thickness: 500 - 2500 m
6. Average sandiness rate:
7. Porosity type: fissure
8. Estimated porosity: low (3%)
9. Tendencies mainly in time: initial volcanism in Karpatian, lasting until Badenian
10. Tendencies mainly in space:
11. Tectonic situation: Within plate basalts of Miocen age

### *Peripannonian pluton Fm* M1gr

This unit comprises Lower Miocene granodiorite with transition to subvolcanic dacite intruded in the Pohorje Formation. It occurs on surface in the Pohorje massif.

1. Synonyms, correlated formations in partner countries: No
2. Lithology:
   Mainly granodiorite and dacite
   Subordinately tonalite, lamprophyre and riodacite
   Rarely gabbroic rock cizlakite, aplite-pegmatite
3. Facies: magmatic
4. Paleoenvironment: Intraplate rift related intrusion connected to the extensional processes of the Pannonian basin formation.
5. Thickness: not known
6. Average sandiness rate:
7. Porosity type: fracture
8. Estimated porosity: impermeable to low
9. Tendencies mainly in time: not known
10. Tendencies mainly in space: not known
11. Tectonic situation: The granodiorite intrusion represents igneous body intruded into the metamorphic rocks of the Pohorje and Magdalensberg Formations and small

Mesozoic cover, representing Pohorje Mountains tectonic massif. The whole area was tilted and ccw rotated along the Labot fault.

### 4.2.2 Formations on Pre-Lower Miocene horizon map (Tertiary) (Encl. 1.12.)

*Mány and Törökbálint Formation* Olb

1. Synonims: "Törökbálint Sandstone" Correlated formations in partner countries: Pletovarje Fm, Govce Fm – SL, Lucenec Fm, Kovácov Sand – SK
2. Lithology: coarse and fine grained sandstone
3. Facies: shallow sublittoral–littoral and brackish–lagoonal
4. Paleoenvironment: shallow marine, near-shore
5. Thickness: 200-500 m
6. Average sandiness rate:
7. Porosity type: intergranular
8. Estimated porosity: medium
9. Tendencies mainly in time: the lower part is fine grained sandstone and clay (Solymár Member), the top part has some calcareous, fine grained sandy silt intercalations (Kovácov Member)
10. Tendencies mainly in space: heteropic facies with the terrestrical Csatka Fm
11. Tectonic situation: transgression on the NW-ern part of the paleogene flexural basin

*Csatka Formations* Olf

1. Synonims: Correlated formations in partner countries: Pletovarje Fm, Govce Fm – SL, Lucenec Fm, Kovácov Sand – SK
2. Lithology: clay, clay marl, sand–sandstone, gravel–conglomerate
3. Facies: fluvial–lacustrine–paludal
4. Paleoenvironment: terrestrical
5. Thickness: 10 to more than 500 m
6. Average sandiness rate:
7. Porosity type: intergranular
8. Estimated porosity: medium/high
9. Tendencies mainly in time: -
10. Tendencies mainly in space: heteropic with Mány Fm
11. Tectonic situation: transgression on the NW-ern part of the paleogene flexural basin

*Szépvölgy Formation* E3ls

1. Synonims: "Upper Eocene limestone sequence", "Nagysáp formation" Correlated formations in partner countries: -
2. Lithology: light grey limestone and calcareous marl with Nummulites, discocyclinids, Lithothamnium frequently occurring in mass
3. Facies: platform and sublittoral facies
4. Paleoenvironment: shallow marine carbonate ramp
5. Thickness: 10-250 m
6. Average sandiness rate: -
7. Porosity type: karstic and fissure
8. Estimated porosity: medium to large
9. Tendencies mainly in time: marl is above
10. Tendencies mainly in space: limestones are in heteropic connection Buda Marl

11. Tectonic situation: new Late Eocene cycle carbonate in the paleogene flexural basin

*Padrag, Tokod and Lencsehegy Formations* E2-3ml

1. Synonims, Correlated formations in partner countries: Socka Beds – SL; Lubina Fm, Jablonka Fm – SK
2. Lithology: Grey, greenish grey silty marl, with tuffaceous and bentonite strips, tuffite intercalations, sandstone sections.
3. Facies: from shallow pelagic to bathyal, and prograding deltaic, prodeltaic and alluvial fan
4. Paleoenvironment: basin-slope and basin, and shallow marine siliciclastic ramp
5. Thickness: 100-300 m
6. Average sandiness rate:
7. Porosity type: no on the lower part, intergranular on the upper part
8. Estimated porosity: no/low
9. Tendencies mainly in time: the lower part is glauconitic calcareous marl, the upper part includes some turbiditic sediments at places and sandy or glauconitic sandy layers
10. Tendencies mainly in space: sediments are thicken and clayey toward the basin, there is sand intercalation toward the basin margin
11. Tectonic situation: deep basin in flexural syncline

*Szőc Formation* E2ls

1. Synonims: “Nummulitic limestone”, Correlated formations in partner countries: Alveolina, Nummulites limestone – SL
2. Lithology: Light grey, yellowish grey limestone, frequently with a large nodular texture, and often with large foraminifers in a rock-forming quantity (Nummulites, Alveolina, Assilina, Discocyclina).
3. Facies: shallow marine platform and sublittoral facies
4. Paleoenvironment: near-shore shallow water
5. Thickness: 10-300 m
6. Average sandiness rate:
7. Porosity type: fissured, karstic
8. Estimated porosity: locally strongly fractured
9. Tendencies mainly in time: basal part consist breccia and uppermost part consist marl
10. Tendencies mainly in space: there is interfingering basin sediments (marl, marly limestone – Csolnok Fm)
11. Tectonic situation: margin of the flexural basin

*Pletovarje Formation* Olf

1. Synonimes, correlated formations in partner countries: In Hungary, this formation corresponds to the Csatka Fm. In Austria no similar deposits are known as there is whole Mura – Zala basin in between.
2. Litology: Mainly: sandy marl, Rarely: sandstone
3. Facies: Not interpreted
4. Paleoenvironment: lacustrine
5. Thickness: not known
6. Average sandiness rate: 30 %
7. Porosity type: intergranular

8. Estimated porosity: medium to low
9. Tendencies mainly in time: not known
10. Tendencies mainly in space: The Oligocene Pletovarje Formation is present along the southernmost margin of the supra area. It is developed only on the southern side of the Ljutomer Belt.
11. Tectonic situation: Initial extension ?

*Govce Formation* Olb

1. Synonimes, correlated formations in partner countries:
2. This formation doesn't have adequate counterpart in Hungary, but the time equivalent may be the Törökbálint Sandstone of the Mány Formation.
3. Litology: Mainly: sand and sandstone; Subordinately: calcareous silt, clay, variegated clay, conglomerate, coal glauconitic sandstone
4. Facies: not interpreted
5. Paleoenvironment: mainly: intertidal, brackish, subordinately: lacustrine
6. Thickness: not known
7. Average sandiness rate:50 %
8. Porosity type: intergranular
9. Estimated porosity: medium
10. Tendencies mainly in time: not known
11. Tendencies mainly in space: at the southernmost tip of the supra area at the Slovene/Croatian border
12. Tectonic situation: Initial extension

### 4.2.3 Formations on Pre-Badenian horizon map (Encl. 1.10.)

*Kiscell Formation* Olmf

1. Synonims, Correlated formations in partner countries: Hrabník Fm – SK
2. Lithology: light grey, argillaceous, calcareous silt, clay marl
3. Facies: open marine
4. Paleoenvironment: shallow bathyal basin
5. Thickness: 30-1000 m
6. Average sandiness rate: fine grain intercalations and fluxoturbidites
7. Porosity type: intergranular
8. Estimated porosity: low
9. Tendencies mainly in time: fine-grained sand intercalations at its lower part, rarely with pebbly fluxoturbidites at its upper part
10. Tendencies mainly in space: heteropic with Hárshegy Sandstone Fm
11. Tectonic situation: uplifted NW-ern, and subsidenced SE-rn part of the Paleogene Basin in the tectonic development of the paleogene flexural basin

*Hárshegy Sandstone Formation* Olc

1. Synonims: "Iharkút Formation", Correlated formations in partner countries: Cíz Fm – SK
2. Lithology: dominantly of coarse-grained sandstone, locally fine-grained sandstone, with intercalations of conglomerate and fire-clay, possibly coal seams (Esztergom Coal Member)
3. Facies: marine, littoral or shallow sublittoral

4. Paleoenvironment: near-shore, shoreline
5. Thickness: 20-200 m
6. Average sandiness rate: -
7. Porosity type: fissure and intergranular
8. Estimated porosity: medium
9. Tendencies mainly in time: top part includes some kaolinitic sandstone
10. Tendencies mainly in space: heteropic interfingering with Kiscell Clay Fm to the east
11. Tectonic situation: uplifted NW-ern, and subsidenced SE-rn part of the Paleogene Basin in the tectonic development of the paleogene flexural basin

*Transition of the Csatka Formation and Mány and Törökbálint Formations* Olf – Olb
see before

*Szentmihály Andesite Formation* E2-3a

1. Synonims, Correlated formations in partner countries:
2. Lithology: Biotite-amphibole andesite lava, piroclasts, subvolcanic bodies, intrusive quartzdiorite
3. Facies: subvolcanic
4. Paleoenvironment: submarine and terrestrial
5. Thickness: 1000 <
6. Average sandiness rate:
7. Porosity type: fissure
8. Estimated porosity:
9. Tendencies mainly in time:
10. Tendencies mainly in space:
11. Tectonic situation: behind of the subduction zone

*Gánt Bauxite Formation* Ebx

1. Synonims: -
2. Lithology: Red, pinky red, fine grain bauxite, bauxitic clay, kaoline clay, bauxite with extraclast and intraclast lenses, Correlated formations in partner countries: Brezová Group – SK
3. Facies: terrestrial, fluvial, lacustrine
4. Paleoenvironment: karstified surface
5. Thickness: 1-50 m
6. Average sandiness rate: -
7. Porosity type: intergranular
8. Estimated porosity: low
9. Tendencies mainly in time: bauxite is overlain by Middle Eocene shallow marine or lagoon facies
10. Tendencies mainly in space: restricted lenses or karstified holes
11. Tectonic situation: deposited on the erosion surface of flexural basin forebulge

*Fluviatile to limnic sediments* M1bc

1. Synonyms, correlated formations: Eibiswalder Beds, Köflach-Voitsberg Formation
2. Lithology: sand, clay, gravel, lingites, conglomerates, breccias, tuffes
3. Facies: siliciclastic, organic
4. Paleoenvironment: terrestric/limnic-siliciclastic, brackisch

5. Thickness: 200 - 2300 m
6. Average sandiness rate: 40%
7. Porosity type: intergranular
8. Estimated porosity: medium (17%)
9. Tendencies mainly in time: terrestric-siliciclastic to limnic-brackisch, four cycles
10. Tendencies mainly in space: coarse to fine from margin to basin
11. Tectonic situation: initial Synrift phase of basin formation (Styrian Basin), marginal facies

*Aderklaa Formation* M1bc-M1fc

1. Synonyms, correlated formations: Rothneusiedl conglomerate
2. Lithology: silty marls, sand/sandstones
3. Facies: siliciclastic
4. Paleoenvironment: limnic
5. Thickness: 500 - 1000 m
6. Average sandiness rate: 25%
7. Porosity type: intergranular
8. Estimated porosity: medium (15%)
9. Tendencies mainly in time: limnic-terrestric
10. Tendencies mainly in space: S-N: fluviatil to limnic to deltaic to marine
11. Tectonic situation: continuation of expansion of Proto-Vienna Basin to the south; on top erosive phase

*Delta sands, shoreline sands* M1c

1. Synonyms, correlated formations: Lab-, Sastin Member
2. Lithology: sands, pelites
3. Facies: siliciclastic
4. Paleoenvironment: deltaic, freshwater to brackisch, subordinate: shallow marine
5. Thickness: 100 - 400 m
6. Average sandiness rate: 50%
7. Porosity type: intergranular
8. Estimated porosity: medium (17%)
9. Tendencies mainly in time: limnic to limnic/brackish, regressive phase, freshwater to limnic
10. Tendencies mainly in space: oscillating
11. Tectonic situation: transition zone from the marine north to the limnic/terrestric south of Vienna Basin

*Leutschach sands* M1cgs

1. Synonyms, correlated formations:
2. Lithology: sands, gravel, lignites
3. Facies: siliciclastic, rarely: organic
4. Paleoenvironment: deltaic, freshwater to brackisch,
5. Thickness: < 150 m
6. Average sandiness rate: 50%
7. Porosity type: intergranular
8. Estimated porosity: medium (17%)
9. Tendencies mainly in time: terrestric-coarse siliciclastic to fine siliciclastic
10. Tendencies mainly in space:

11. Tectonic situation: initial Synrift phase of Styrian basin formation , transition zone from terrestric to marine

*Sinnersdorf Formation* M1fc

1. Synonyms, correlated formations:
2. Lithology: gravel/conglomerates, sild, sands (matrix), boulders, lignites
3. Facies: siliciclastic, rarely: organic
4. Paleoenvironment: fluviatile, rarely: limnic
5. Thickness: 220 - 600 m
6. Average sandiness rate: 20%
7. Porosity type: intergranular
8. Estimated porosity: medium (15%)
9. Tendencies mainly in time: terrestric-coarse siliciclastic to fine siliciclastic
10. Tendencies mainly in space: coarse to fine from margin to basins, conglomerates in new depocenters
11. Tectonic situation: marginal sediments of new developed subbasins/tectonic grabens (e.g. Middle-Burgenland) of the Styrian Basin/Pannonian-Basin-System

*Luzice Formation* M1m

1. Synonyms, correlated formations:
2. Lithology: clayey marls, rarely: sandstones
3. Facies: siliciclastic
4. Paleoenvironment: shallow marine to open marine, rarely: brackish
5. Thickness: > 650 m
6. Average sandiness rate: 5%
7. Porosity type: intergranular
8. Estimated porosity: low (8%)
9. Tendencies mainly in time: from basal coarse clastics to marine -fine siliciclastic
10. Tendencies mainly in space: towards the margin (S) transition to deltaic
11. Tectonic situation: initial subsidence in piggy-back phase of Vienna Basin, sedimentation in regions with high subsidence

*Laa Formation, Styrian Schlier* M1ml

1. Synonyms, correlated formations:
2. Lithology: marls, clays, sands, rarely: tuffs
3. Facies: siliciclastic
4. Paleoenvironment: marine
5. Thickness: 300 - 1000 m
6. Average sandiness rate: 10%
7. Porosity type: intergranular
8. Estimated porosity: low (8%)
9. Tendencies mainly in time: marine -fine siliciclastic
10. Tendencies mainly in space: towards the margin transition to deltaic
11. Tectonic situation: sediments of regions with high subsidence followed by tectonic movements with discordances

## *Haloze Formation* M1ml

1. Synonimes, correlated formations in partner countries: The Haloze Fm. in Slovenia is a time equivalent of the Lower part of the Tekeres Fm. in Hungary. The tuff beds in the Haloze Fm. (Mbtu) may be equivalent of the Tar dacite tuff. It is most probably in connection with the Gleichenberg volcanics in Austria. In Austria, the Haloze Fm. (in time) corresponds to several formations: The Gamlitzer Schlier, Arnfelser Konglomerat, Leutschacher Sand, Sinnersdorf Formation, Rust Formation fit into this frame.
2. Litology: Mainly: Light grey conglomerate and muddy breccia with subrounded pebbles up to 1 m, sandstone, light grey to sandy and silty marl (no data regarding the prevailing lithology). Subordinately: oyster banks, greenish grey dacitic and andesitic tuff.
3. Facies:
4. Paleoenvironment: Mainly: shallow marine and terrestrial, Subordinately: open marine
5. Thickness: 0 – 1000 m
6. Average sandiness rate: 30 %
7. Porosity type: intergranular
8. Estimated porosity: low to medium
9. Tectonic situation: Corecomplex – extension
10. Tendencies mainly in time: Basin formation in the core complex extensional phase resulted in a relatively fast sedimentation of mostly coarse to medium grained sediments with muddy matrix, sandstone and marl. Deposition took place mostly from the Northeast in the subbasins along the wide tectonic zones. Initial volcanism is characterised by modest tuff beds in the middle part of the formation.
11. Tendencies mainly in space: Prebadenian (Lower Miocene) deposits of the Haloze formation are present in the NW along the Radgona – Vas Subbasin between Southburgenland Swell and the Murska Sobota High, in the Maribor Sub-basin between Pohorje massif and Murska Sobota High, and in Mureck Basin between Southburgenland Swell and Pohorje Massif. In the NE Prebadenian deposits are present in the East Mura – Orseg Subbasin east of the Bajan fault, and in the South, these sediments are present also in the Haloze – Ljutomer – Budafa Sub-basin along the SE margin of the Murska Sobota High and along the SE margin of Pohorje Massif.The nearshore deposits are present along the Murska Sobota High as it is fringed by the Sub-basins. The formation is drastically thinned along the Bajan fault and along the faults along the Southburgenland Swell. In the eastern block of the Bajan fault the Haloze formation gives way to the Ligeterdő gravel (M1fc).

## *Budafok Formation* M1m

1. Synonyms: “Large Pecten Beds”. Correlated formations in partner countries: Slovakia. Lužice Formation, Austria: Luschitzer Serie
2. Lithology: yellow and grey sand of variable grain size, with unconsolidated sandstone and intercalations of sandy clay with pebbles. Has a rich fauna of Pecten, Ostrea, Anomia etc. in some beds. 8 to 100 m.
3. Facies: Littoral and sublittoral
4. Palaeoenvironment: intertidal plain
5. Thickness: 80 to 100 m.
6. Average sandiness rate: more than 70 %
7. Porosity type: intergranular

8. Estimated porosity: 10–12 %
9. Tendencies mainly in time:
10. Tendencies mainly in space:
11. Tectonic situation:

*Ligeterdő Gravel Formation* M1fc

1. Synonyms: “Auwaldschotter”. Correlated formations in partner countries: Austria: Sinnersdorf Formation, Rust Formation
2. Lithology: grey, yellowish-grey poorly sorted gravel, conglomerate, sand, marl
3. Facies: fluvial–brackish-water
4. Palaeoenvironment:
5. Thickness: 400 to 500 m.
6. Average sandiness rate: 50 %
7. Porosity type: intergranular
8. Estimated porosity: 10 %
9. Tendencies mainly in time: Starting from the base the first two members (Alsóligeterdő Gravel Member and Felsőligeterdő Gravel Member) are fluvial sandstones or conglomerates with pebbles derived from the crystalline basement. Felsőligeterdő Gravel Member also contains carbonate pebbles. The third member is brackish sand and marl, which includes thin beds of coal with Congeria (Magasbérc Sandstone Member). The fourth member of this Formation is coarse grained gravel and conglomerate (Felsőtödl Gravel Member). The lower two members are Ottnangian, the upper two are assigned to the Carpathian. According to Austrian data it goes up to the lower Badenian.
10. Tendencies mainly in space: east-/south-eastward fining tendency
11. Tectonic situation: initial phase of rifting

*Egyházasgerge Formation, Fót Formation, Budafa Formation* M1c

1. 1. Synonyms: “Pecten-Chlamys-bearing sandstone” — Egyházasgerge Fm. “Lower Mediterranean coarse-grained sediments”, “calcareous sandstone of Leitha facies”, Congeria-bearing succession — Budafa Fm. Correlated formations in partner countries: Austria: Korneuburg Formation
2. Lithology: grey, yellowish-grey sand–sandstone, calcarenite, gravel–conglomerate, patch reefs, gypsum-bearing clay
3. Facies: shallow-marine (subordinately delta)
4. Palaeoenvironment: shore-line, abrasional shore, plain shore
5. Thickness: Egyházasgerge and Fót Formations: some tens of metres up to 600 m
6. Average sandiness rate: more than 50 %
7. Porosity type: intergranular
8. Estimated porosity: 5–8 %
9. Tendencies mainly in time: cyclic, upward-fining successions
10. Tendencies mainly in space: Budafa Fm occurs in the southern and south-western part of the Transdanubian area, Egyházasgerge and Fót Formations occur in the north-eastern part of the SupraArea
11. Tectonic situation: synrift

*Závod Fm., Lakšáry Fm.* Mkb

1. Synonymes, correlated formations in partner countries: Tekeres Schlier, Garáb Schlier
2. Lithology (colour, texture, grainsize): Open-marine silt, sandy clay, clay marl
3. Facies: basinal,
4. Paleoenvironment: open marine
5. Thickness: up to 2000 m
6. Average sandiness rate: 5%
7. Porosity type: no
8. Estimated porosity: no
9. Tendencies mainly in time: shallowing-upward trend, increasing portion of sandy layers upward
10. Tendencies mainly in space: continuous conection in the NE Vienna Basin toward the NW Danube Basin, in the higher part with a delta of Jablonica Conglomerates between the basins
11. Tectonic situation: transtension and pull apart opening of the Vienna Basin

### 4.2.4 Formations on Pre-Sarmatian horizon map (Badenian) (Encl. 1.8.)

*Delta sands, shoreline sands, conglomerates* Mbc

1. Synonyms, correlated formations:
2. Lithology: sand (sandstones), siltstones, gravel (conglomerates), rarely: breccias
3. Facies: siliciclastic
4. Paleoenvironment: deltaic-marine, subordinate: fluviatile to marine shorefacies
5. Thickness: 50 - 500 m
6. Average sandiness rate: 60%
7. Porosity type: intergranular
8. Estimated porosity: medium to high (20%)
9. Tendencies mainly in time: deltasands with transgressive-regressive cycles and intercalations of mud (mudstones)
10. Tendencies mainly in space: laterally interfingering to basinal facies
11. Tectonic situation: onset of pull-apart phase of Vienna Basin formation, large deltasediment input from W

*Marl, silt, sand, gravel* Mbc-Mbmf

1. Synonyms, correlated formations:
2. Lithology: marl (marlstones), sand (sandstones), gravel (conglomerates), limestones, rarely: breccias, coal seams
3. Facies: siliciclastic, subordinate: carbonatic, rarely: organic
4. Paleoenvironment: deltaic-marine, subordinate: fluviatile to marine shorefacies, rarely: paralic
5. Thickness: 300 - 1200 m
6. Average sandiness rate: 25%
7. Porosity type: intergranular
8. Estimated porosity: medium (15%)
9. Tendencies mainly in time: fining upward

10. Tendencies mainly in space: N-S: from paralic/fluviatile to deltaic/shorefacies to basinal with lateral clastic input (Styrian Basin)
11. Tectonic situation: Postrift (wide rift) phase of subsidence in Styrian Basin

*Leitha Limestone-Formation* Mbls

1. Synonyms, correlated formations:
2. Lithology: Leitha limestone (Corallinaceen limestone), subordinate: calcareous sandstones, sand (sandstones), rarely: conglomerates
3. Facies: carbonatic, subordinate:: siliciclastic
4. Paleoenvironment: shorefacies to shallow marine, subordinate: fluviatile to marine shorefacies
5. Thickness: 10 - 60 m
6. Average sandiness rate:
7. Porosity type: karstic, intergranular
8. Estimated porosity: medium to high (24%)
9. Tendencies mainly in time: on margins frequently coarse to fine clastics on base grading into massiv limestones, on basinal highs intercalations of calcareous sandstones in deltafacies
10. Tendencies mainly in space: basinwards grading into detrital limestones
11. Tectonic situation:reefal buildups on margins, islands and basinal highs (Styrian Basin and Vienna Basin)

*Leitha Limestone-Formation* Mbls-Mbmf

1. Synonyms, correlated formations:
2. Lithology: Leitha limestone (Corallinaceen limestone), subordinate: calcareous sandstones, sand (sandstones), rarely: conglomerates
3. Facies: carbonatic, subordinate:: siliciclastic
4. Paleoenvironment: shorefacies to shallow marine, subordinate: fluviatile to marine shorefacies
5. Thickness: 10 - 60 m
6. Average sandiness rate:
7. Porosity type: karstic, intergranular
8. Estimated porosity: medium to high (24%)
9. Tendencies mainly in time: on margins frequently coarse to fine clastics on base grading into massiv limestones, on basinal highs intercalations of calcareous sandstones in deltafacies
10. Tendencies mainly in space: basinwards grading into detrital limestones
11. Tectonic situation: reefal buildups Leitha mountains

*Baden clay* Mbmf

1. Synonyms, correlated formations:
2. Lithology: clayey marls (marlstones), clay (claystones), silt (siltstones)
3. Facies: siliciclastic, subordinate: carbonatic
4. Paleoenvironment: shallow marine basinal
5. Thickness: 700 - 1000 m
6. Average sandiness rate: 5%
7. Porosity type: intergranular, fissure
8. Estimated porosity: low (8%)

9. Tendencies mainly in time: Regressive phase on base with conglomerates, Badenian transgression, basinal facies with few fineclastic intercalations, regressive phase on top
10. Tendencies mainly in space: basinal facies in central Vienna basin (Marchfeld depression) and in stillwater regions in the southern basin
11. Tectonic situation: Onset of pull-apart phase of Vienna Basin formation, main subsidence bound on large fault system

*Weissenegg-Formation (partim)* Mkb-Mbmf

1. Synonyms, correlated formations:
2. Lithology: pelites, marls, argillites, rarely: gravel (conglomerates)
3. Facies: siliciclastic, subordinate: carbonatic
4. Paleoenvironment: shallow marine basinal, partly turbiditic, subordinate: shorefacies
5. Thickness: 200 - 600 m
6. Average sandiness rate: 10%
7. Porosity type: intergranular
8. Estimated porosity: low (8%)
9. Tendencies mainly in time: basinal facies grading into to shorefacies of the margins and local highs, transgressive-regressive cycles
10. Tendencies mainly in space: basinal facies in Gnas sub-basin of Styrian Basin
11. Tectonic situation: postrift (wide rift) phase of subsidence in Styrian Basin

*Lower part of the Špilje formation (Šentilj Mb. and Hrastovec-Kresnica Mb. (Mbls)) interfingering with Ptujska Gora - Kog formation (Mbsc)*

Mkb-Mbmf

1. Synonimes, correlated formations in partner countries: The lower part of the Špilje Formation is an approximate time equivalent of the upper part of the joined Tekeres and Szilagy Formations in Hungary. In Austria, this member corresponds to the “Mbc” unit, not defined as a formation in the legend, consisting of delta sands, shoreline sands and conglomerates
2. Litology:
   Mainly: alternation of silty marl, clayey marl and sandstone (Šentilj Member)
   Subordinately: alternation of sandstone, sand, sandy marl, silty marl, clayey marl, conglomerate, gravel, breccia, algal limestone, dolomite and coal (Ptujska gora – Kog Formation)
   Rarely: discrete occurences of algal limestone (Hrastovec – Kresnica Member)
3. Facies: Not interpreted
4. Paleoenvironment: Mainly: shallow marine, Subordinately: open marine in the sub-basins
5. Thickness: 0 – 850 m
6. Average sandiness rate: 30 %. Less permeable sediments are expected in the basins, so mainly in the easternmost part of Slovenian territory, while in the shallow depositional environment where the formation thickness is less than 300 m, more sand is expected in alteration with marl. Also the Ptujska gora – Kog Formation in the southern part of the Supra area is entirely shallow water and fluvial and therefore more permeable.
7. Porosity type: intergranular
8. Estimated porosity: low to medium
9. Tectonic situation: Post rift and first compressional phase.

10. Tendencies mainly in time: A transgression in the lower Badenian caused large flooded areas where shallow marine depositional environment prevailed. The transgression induced sedimentation of the hemipelagic mud in the basins, and deposition of the limestone and sand in flooded areas. Simultaneously also the subsidence of the basins still generated new accommodation space. In the distal basins sedimentation rate dropped (starved basins) while in the proximal ones mud-rich turbidites took place.
11. Tendencies mainly in space:It is present in the NE part of the Slovenian territory except on the Murska Sobota High and in the anticline at the southern margin of the Supra area south of the Murska Sobota High. In the Murska Sobota High and in the western part of the area the basins were partly filled up with sediments by the Lower Badenian, so this area is characterised by predoiminantly shallow water sands, limestone occurences and marls. To the east, the basins were still evolving hosting predominantly less permeable fine grained sedimentation. In the south, the Ptujska gora – Kog formation is also characterized by shallow water permeable deposits.

*Badenian Breccia* Mbbr

1. Synonyms: – Correlated formations in partner countries: –
2. Lithology: polymict basal breccia made up of metamorphic and carbonate clasts, coarse-grained sand and silt, clay marl, with sandstone beds
3. Facies: –
4. Palaeoenvironment:
5. Thickness: from 30–40 m up to more than 300 m (360 m in borehole Raj–1)
6. Average sandiness rate: not characteristic
7. Porosity type: intergranular, fissure
8. Estimated porosity: 3–10 %
9. Tendencies mainly in time: –
10. Tendencies mainly in space: –
11. Tectonic situation: synrift

*Lajta Limestone Formation* Mbls

1. Synonyms: “Leithakalk”. Correlated formations in partner countries: Studienka Formation: Slovakia; Špilje Formation (Hrastovec-Kresnica Member): Slovenia
2. Lithology: grey, greyish-white, greyish-yellow biogenic (corallinacean algae–foraminifer–mollusc-bearing) limestone, calcarenite, calcareous molluscan sandstone, pebbly limestone and calcareous marl. Occasionally glauconitic contamination can be seen
3. Facies: marine
4. Palaeoenvironment: shallow-marine, reef
5. Thickness: generally less than 100 m
6. Average sandiness rate: low
7. Porosity type: intergranular, fissure, karstic
8. Estimated porosity: 3–10 %
9. Tendencies mainly in time: on the basis of stratigraphic position the formation is divided into two members in the study area, i.e. “lower Leithakalk” (Lower Badenian) and “upper Leithakalk” (Upper Badenian)
10. Tendencies mainly in space:
11. Tectonic situation:

*Pusztamiske Formation* Mbc

1. Synonyms: "Lower Tortonian clastic succession". Correlated formations in partner countries: Špačince Formation, Jakubov Formation: Slovakia; Haloze Formation (Naraplje-Cirknica Member): Slovenia
2. Lithology: grey, yellowish-grey gravel and conglomerate at the bottom; it is overlain by calcareous, occasionally glauconitic sand, loose sandstone, with calcareous siltstone and marl intercalations, occasionally with volcanic tuff, tuffite in some places.
3. Facies: marine
4. Palaeoenvironment: abrasional shore, near-shore to shallow marine
5. Thickness: 100 to 250 m
6. Average sandiness rate: 30%
7. Porosity type: intergranular
8. Estimated porosity: 5–6 %
9. Tendencies mainly in time:
10. Tendencies mainly in space: gravel and conglomerate are characteristic along the abrasional shores in the western forelands of the Transdanubian Range. Grain sizes decrease towards the West (towards the open sea), where it interfingers with pelitic basinal sediments.
11. Tectonic situation: synrift

*Tekeres Schlier Formation – Garáb Schlier Formation and Szilágy Clay Marl–Baden Formation– Tekeres Schlier together* Mkb–Mbmf

1. Synonyms: "Styrian Hauptschlier" — Tekeres Fm. "Helvetian Schlier" — Garáb Fm. "Turritella–Corbula beds" — Szilágy Clay Marl Formation
   Correlated formations in partner countries: For Tekeres Schlier–Garáb Schlier Formations: Závod Formation, Lakšáry Formation: Slovakia; Haloze Formation (Stoperce-Kungota Member and Plešivec-Urban Member): Slovenia
   For Szilágy–Baden–Tekeres Formations: Báhon – Pozba Fms, Bajtava Fm (D): Slovakia, Studienka, Lanžhot and Madunice Fms (V): Slovakia, Lower part of Špilje Fm and Ptujska Gora-Kog Fm; Špilje Fm Sentilj Mb — Slovenia
2. Lithology: grey, greenish-grey fine-grained sandy silt, sandy clay and clay marl, unconsolidated silty sandstone, calcareous marl and calcareous sandstone. Occasionally tuffite stringers appear.
3. Facies: marine
4. Palaeoenvironment: near-shore to off-shore open-sea
5. Thickness: up to 800 m
6. Average sandiness rate: 10 %
7. Porosity type: intergranular
8. Estimated porosity: 5 %
9. Tendencies mainly in time: cyclically alternating sand–silt–clay
10. Tendencies mainly in space:
11. Tectonic situation: synrift-postrift

*Szilágy Clay Marl–Baden Formation–Tekeres Schlier together* Mkb–Mbls–Mbmf

1. Synonyms: “Styrian Hauptschlier” — Tekeres Fm. “Turritella–Corbula beds” — Szilágy Clay Marl Formation
   Correlated formations in partner countries: Báhon – Pozba Fms, Bajtava Fm (D): Slovakia, Studienka, Lanžhot and Madunice Fms (V): Slovakia, Lower part of Špilje Fm and Ptujska Gora-Kog Fm; Špilje Fm Sentilj Mb — Slovenia
2. Lithology: grey, greenish-grey fine-grained sandy silt, sandy clay and clay marl, unconsolidated silty sandstone, calcareous marl and calcareous sandstone.
3. Facies: marine
4. Palaeoenvironment: near-shore to off-shore, open-basin
5. Thickness: up to 800 m
6. Average sandiness rate: 8–10 %
7. Porosity type: intergranular, karstic (fissure)
8. Estimated porosity: 5 %
9. Tendencies mainly in time: cyclically alternating sand–silt–clay
10. Tendencies mainly in space:
11. Tectonic situation: synrift-postrift

*Tekeres Schlier Formation – Garáb Schlier Formation and Lajta Limestone and Szilágy Clay Marl–Baden Formation– Tekeres Schlier undivided* Mkb–Mbls–Mbmf

1. Synonyms and Correlated formations: see above
2. Lithology: grey, greenish-grey fine-grained sandy silt, sandy clay and clay marl, unconsolidated silty sandstone, calcareous marl and calcareous sandstone with algal limestone interbeddings.
3. Facies: marine
4. Palaeoenvironment: near-shore to off-shore open-sea
5. Thickness: 200 to 800 m
6. Average sandiness rate: 8–10 %
7. Porosity type: intergranular, karstic (fissure)
8. Estimated porosity: 5 %
9. Tendencies mainly in time: cyclically alternating sand–silt–clay
10. Tendencies mainly in space: during maximum transgression it unconformably overlies the Paleo-Mesozoic basement
11. Tectonic situation: synrift-postrift

*Tekeres Schlier Formation – Garáb Schlier Formation and Pusztamiske Formation and Lajta Limestone and Szilágy Clay Marl–Baden Formation– Tekeres Schlier undivided*

Mkb–Mbc–Mbls–Mbmf

1. Synonyms: see above
2. Lithology: grey, greenish-grey fine-grained sandy silt, sandy clay and clay marl, unconsolidated silty sandstone, calcareous marl and calcareous sandstone with algal limestone interbeddings.
3. Facies: marine
4. Palaeoenvironment: near-shore to off-shore open-sea
5. Thickness: 200 to 800 m
6. Average sandiness rate: 8–10 %
7. Porosity type: intergranular, karstic (fissure)
8. Estimated porosity: 5 %
9. Tendencies mainly in time: cyclically alternating sand–silt–clay

10. Tendencies mainly in space:
11. Tectonic situation: synrift-postrift

*Hidas Formation* Mbf

1. Synonyms: –, Correlated formations in partner countries: –
2. Lithology: brown coal-bearing clay, marl, calcareous marl
3. Facies: brackish-water
4. Palaeoenvironment: semi-restricted or resticted basins in the area of the Transdanubian Range
5. Thickness: some tens of metres
6. Average sandiness rate: low
7. Porosity type:
8. Estimated porosity: less than 10 %,
9. Tendencies mainly in time:
10. Tendencies mainly in space:
11. Tectonic situation:

*Cserszegtomaj Formation – Vöröstó Formation – Ősi Variegated Clay Formation* Mbst

1. Synonyms: "Cserszegtomaj Kaoline" — Cserszegtomaj Formation, "Miocene bauxite" — Vöröstó Formation; Correlated formations in partner countries:–
2. Lithology: Cserszegtomaj Formation: yellowish-white, pale yellow or ocherous halloysite and kaolinite-bearing deposits

   Vöröstó Formation: reworked red clay of bauxite origin , and bauxitic clay of terrestrial facies, occasionally with Fe-rich bauxite pebbles. Maximum thickness: 30 to 35 m.

   Ősi Formation: grey, greenish-grey, ocherous and yellowish-red, disintegrated variegated clay, clay marl, silty clay with nodular and shiny slump surfaces; light grey or yellowish-white mottled calcareous marl and limestone with carbonaceous clay intercalations.
3. Facies: continental
4. Palaeoenvironment: Cserszegtomaj Fm and Vöröstó Fm: karstifying terrain under warm and humid climate in the south-western part of the Transdanubian Range; Ősi Fm: basin margin, shallow lakes
5. Thickness: some tens of metres
6. Average sandiness rate: less than 10%
7. Porosity type: intergranular
8. Estimated porosity: less than 5 %
9. Tendencies mainly in time:
10. Tendencies mainly in space:
11. Tectonic situation:

*Bajtava Fm., Báhoň Fm., Madunice Fm., Pozba Fm., Studienka Fm., Lanžhot Fm., Špačince Fm., Jakubov Fm.* Mbmf

1. Synonymes, correlated formations in partner countries: Szilágy Clay Marl, Tekeres Schlier, Pusztamiske Fm., Baden Fm.
2. Lithology (colour, texture, grainsize): Shallow-marine and open basin foraminiferal, mollusc-bearing clay marl, clay
3. Facies: open marine to shallow marine, locally with deltaic sand (Madunice, Gajary)

4. Paleoenvironment: open marine to shallow marine, locally with deltaic sand (Madunice, Gajary)
5. Thickness: very variable, up to 3000 m (Blatné depression)
6. Average sandiness rate: 10-20%
7. Porosity type: intergranular
8. Estimated porosity: low, in deltaic sand high
9. Tendencies mainly in time: at least 2 depositional cycles, coarsening upward
10. Tendencies mainly in space: huge conglomerate bodies in Middle Badenian on both the W and E sides of the Male Karpaty Mts., deltaic body in the Gajary area (Vienna Basin)
11. Tectonic situation: transtensional rifting in the Vienna Basin and extensional rifting in the Danube Basin.

### 4.2.5 Formations on Pre-Lower Pannonian horizon map (Sarmatian) (Encl.1.6.)

*Kozárd Formation* Msmf

1. Synonyms: “Cerithium-bearing beds”, “Ervilia beds”; Correlated formations in partner countries: upper part of Špilje Formation and Ptujska Gora-Kog Formation: Slovenia; Vráble Formation: Danube Basin, Slovakia; Holič Formation and Skalica Formation: Vienna Basin, Slovakia, Austria
2. Lithology: grey, greenish-grey clay and clay marl, occasionally of sand, un-consolidated sandstone, calcareous marl and calcareous sandstone. Diatomite, alginite, bentonite bearing rocks (“Ervilia beds”, “Sarmatian clay marl”) are frequent in the lagoon facies.
   Rocks are rich in mollusc remains (Abra, Cardium, Cerithium sp etc.)
3. Facies: marine–brackish water
4. Palaeoenvironment: shallow-marine to near shore, locally lagoon facies
5. Thickness: 100 to 150 m
6. Average sandiness rate: 17–20 %
7. Porosity type: the less tightly packed sandy lithotypes have intergranular porosity
8. Estimated porosity: 5 %
9. Tendencies mainly in time: no characteristic vertical tendencies.
10. Tendencies mainly in space:
11. Tectonic situation:

*Tinnye Formation* Msls

1. Synonyms: Sarmatian coarse-grained limestone; Correlated formations in partner countries: Slovenia: Špilje Formation Selnica Member
2. Lithology: yellowish-grey, whitish-yellow biogenic limestone. Occasionally it is ooidic. It includes mollusc-bearing calcareous sandstone, calcareous molluscan sand and basal gravel. Synsedimentary fracturing/lithoclases are characteristic
3. Facies: marine, brackish water
4. Palaeoenvironment: shoreline
5. Thickness: 50 to 120 m
6. Average sandiness rate: less than 5 %
7. Porosity type: intergranular, fissure and karstic
8. Estimated porosity: 3–10 % max. 25 %

9. Tendencies mainly in time: The lowest beds directly overlying the basement also contain basal gravel
10. Tendencies mainly in space: In the Sopron Mts three members can de distinguished: the abrasion conglomerate with calcareous cement, found at the base (Fertőrákos Conglomerate Member), the overlying limestone and calcareous sand of shore facies (Cárhalma Limestone Member) and the gravel, conglomerate, limestone of delta facies (Dudlesz Gravel Member).
11. tectonic situation

*Sarmatian deltasands* Msls

1. Synonyms, correlated formations:
2. Lithology: sand (sandstones), gravel (conglomerates)
3. Facies: siliciclastic, subordinate: carbonatic
4. Paleoenvironment: deltaic, brackisch, sandbars, subordinate: estuarine/limnic to fluviatil
5. Thickness: 400 - 1000 m
6. Average sandiness rate: 35%
7. Porosity type: intergranular
8. Estimated porosity: medium to high (27%)
9. Tendencies mainly in time: deltasands with transgressive-regressive cycles and intercalations of mud (mudstones) (esp. Middle- and Upper Sarmatian); on top regressive phase and erosion on transition to Pannonian
10. Tendencies mainly in space: main clastic input from West/Nordwest and Southeast with prograding and retrograding fans (Vienna Basin)
11. Tectonic situation: continuation of clastic input (delta) from west, enhenced input from south (Vienna Basin)

*Sarmatian shoreline facies* Msls-Msmf

1. Synonyms, correlated formations:
2. Lithology: detrital Leitha limestone, subordinate: fossiliferous calcareous sandstones, sand (sandstones)
3. Facies: carbonatic, subordinate: siliciclastic
4. Paleoenvironment: shorefacies, partly hypersaline
5. Thickness: 10 - 40 m
6. Average sandiness rate: 25%
7. Porosity type: intergranular
8. Estimated porosity: medium (24%)
9. Tendencies mainly in time: mainly Middle- and Upper Sarmatian, transgressiv-regressive cycles; on top regressive phase and erosion on transition to Pannonian
10. Tendencies mainly in space: widening agains Pannonian realm
11. Tectonic situation: sediments mainly around Leitha mountains and on western basin margin

*Holic-, Scalica-, Gleisdorf-Formation* Msmf

1. Synonyms, correlated formations:
2. Lithology: clayey marls (marlstones), subordinate: clay (claystones), silt (siltstones), sand (sandstones), rarely: gravel (conglomerates)
3. Facies: siliciclastic, subordinate: carbonatic
4. Paleoenvironment: shallow marine, basinal

5. Thickness: 300 - 850 m
6. Average sandiness rate: 15%
7. Porosity type: intergranular
8. Estimated porosity: low to medium (10%)
9. Tendencies mainly in time: basinal facies with few fineclastic intercalations, coarsening- and fining upwards cycles, oscillating sealevel; in Styrian Basin regressive phase with intercalation of terrestric conglomerates at the end of lower Sarmatian; on top of Sarmatian regressive phase with sea level drop
10. Tendencies mainly in space: more restricted basinal areas due to increasing clastic input, retreat of the Sarmatian sea from the Western Styrian Basin
11. Tectonic situation: Vienna Basin: no major changes of distribution of sedimentation areas in respect to Badenian, continuation of pull-apart subsidence

*Upper part of the Špilje Formation – Selnica Mb (Msls), Osek Mb. (Mp), and upper part of the Ptujska gora – Kog Fm (Mbsc)*

Msmf

1. Synonimes, correlated formations in partner countries: In Hungary this entity corresponds to the Kozard and Enrőd Formations. In Austria, this formation can be correlated with the Gleisdorf Formation (in time).
2. Litology: alternation of sand, sandstone, sandy and silty marlstone. Subordinately: silt, siltstone, marly clay, silty clay, conglomerate and breccia, Rarely: sandy algal and oolitic limestone, dolomite, coal
3. Facies: not interpreted
4. Paleoenvironment: Mainly: shallow marine, fluvial and terrestrial, Subordinately: open marine
5. Thickness: < 300 m, in the easternmost part of Slovenia up to 600 m
6. Average sandiness rate: 50 %
7. Porosity type: intergranular porosity in clastites, and intergranular and intragranular - fracture porosity in limestones.
8. Estimated porosity: medium
9. Tendencies mainly in time: In the lower Sarmatian the sea level drop caused erosion on the shallow parts and sandy turbidites in the remaining basins. By the end of Sarmatian the western part of the Mura-Zala basin was already filled up with sediments.
10. Tendencies mainly in space: This joined formation is present in the Haloze – Ljutomer Budafa Sub-basin along the Ljutomer Belt in the southern part of the supra area, in the Radgona - Vas Sub-basin and in the East Mura – Őrség Sub-basin NE of the Murska Sobota High.

    In the western part of the Slovenian territory, mainly permeable shallow water deposits are present, while in the east, towards the Bajan fault, marly deposits prevail, especially in the upper part.

    In the Shallow areas in the NW part of the Slovenian territory involved in the modelling, mostly tidal sands are interchanged with the shallow water marls and occasional gravels, while in the NE parts in the basins, turbiditic sedimentation took place.
11. Tectonic situation: Post rift and first compression phase.

*Vráble Fm., Holíč Fm., Skalica Fm.* Msmf

1. Synonymes, correlated formations in partner countries: Kozárd Fm
2. Lithology (colour, texture, grainsize): mollusc-bearing clay – clay marl; sand–sandstone, calcareous marl
3. Facies: shallow-marine
4. Paleoenvironment: brackish-water sea
5. Thickness: Vráble Fm. up to 500 m, Holíč Fm. up to 350 m, Skalica Fm. up to 600 m
6. Average sandiness rate: 20-30%
7. Porosity type: intergranular
8. Estimated porosity: medium
9. Tendencies mainly in time: two cycles, deepening/fining upward
10. Tendencies mainly in space: filling depocentres and shallow basin
11. Tectonic situation: late rifting phase of the Danube and the Vienna basins development

### 4.2.6 Formations on Pre-Upper Pannonian horizon map (Lower Pannonian facies) (Encl. 1.4.)

Due to the time-transgressive nature of the Late Miocene (Pannonian) to Pliocene formations, maps showing the formation located directly under the pre-Quaternary or the pre-Upper Pannonian surface would not carry significant information about the properties of Pannonian strata. (The top of Lower Pannonian is defined as the top of the fine-grained slope or shallow lacustrine deposits, while the end of Upper Pannonian was characterized by sedimentation on a fluvial plain almost basinwide.) Therefore we have chosen to show the boundaries between several types of facies series, based on the composition of the whole Upper Pannonian and Lower Pannonian succession, respectively. This way, the maps reflect the spatial variances of Pannonian sedimentation even if the uppermost formation of a given unit is the same or similar across the area. In the following, the composition and the general properties of the mapped facies assemblages are introduced.

*Littoral, deltaic and fluvial coarse deposits (mainly sand and gravel)* Mp_1

1. Synonimes, correlated formations:
   Čáry Fm.: Slovakia - deltaic
   Paldau Fm.: SE Austria - deltaic and fluvial
   Gbely Fm.: Slovakia - fluvial
   Hollabrunn-Mistelbach Fm.: NE Austria - fluvial
2. Lithology (colour, texture, grainsize): mainly yellow or brown sand, sandstone, sandy gravel, gravel, conglomerate; subordinately silt and clay
3. Facies: littoral (shoreface), deltaic and fluvial (braided rivers)
4. Paleoenvironment: In these areas (very close to the sediment sources at the feet of mountain ranges) Early Pannonian already began with the deposition of coarse shoreface and/or deltaic, then (following the basinward progradation of deltas) fluvial sediments. Finer-grained littoral sediments occur only as intercalations between the deltaic levels, due to minor transgressions. The fluvial deposits were chiefly formed by braided rivers.
5. Thickness: 50–200 m
6. Average sandiness rate: 90%
7. Porosity type: intergranular
8. Estimated porosity: 15%

9. Tendencies mainly in time: not significant
10. Tendencies mainly in space: the coarsest-grained deltas and fluvial channels can be found mainly in the vicinity of the main sediment sources
11. Tectonic situation: onset of the post-rift subsidence of Pannonian Basin

### *Lacustrine silty clayey marl and littoral-deltaic-fluvial coarse deposits* Mp_2

1. Synonimes, correlated formations:
   Bzenec Fm..: Slovakia - lacustrine
   Feldbach Fm.: SE Austria - lacustrine
   Szák–Csákvár Fm., Zsámbék Marl, Csór Silt: Hungary - lacustrine
   Čáry Fm.. Beladice Fm.: Slovakia - deltaic
   Kisbér–Zámor–Kálla–Diás Gravel: Hungary - littoral and deltaic
   Paldau Fm.: SE Austria - deltaic and fluvial
   Mura Fm.: Slovenia - deltaic and fluvial
   Hollabrunn-Mistelbach Fm.: NE Austria - fluvial
   Gbely Fm.: Slovakia - fluvial
2. Lithology (colour, texture, grainsize): marl, clayey marl, clay and silt followed by mainly yellow or brown sand, sandstone, sandy gravel, gravel, conglomerate; subordinately silt, clay marl, mud
3. Facies: sublittoral, littoral (shoreface), deltaic and fluvial (braided rivers)
4. Paleoenvironment: Areas in this zone are characterized by relatively short open-lacustrine (sublittoral) sedimentation, which is followed by the onset of coarse-grained shoreface and/or deltaic, in some zones also fluvial sedimentation even before the main transgressive event of Lake Pannon (ca. 9.8 Ma). The fluvial deposits were chiefly formed by braided rivers.
5. Thickness: 100–400 m
6. Average sandiness rate: average: 70% (lower, thinner part: 20%, upper, thicker part: 90%)
7. Porosity type: intergranular
8. Estimated porosity: average: 12% (lower, thinner part: 6%, upper, thicker part: 15%)
9. Tendencies mainly in time: the lower (sublittoral) part of the unit is composed of chiefly pelitic sediments, therefore the grainsize and porosity of the upper part exceeds the average of the unit
10. Tendencies mainly in space: the coarsest-grained deltas and fluvial channels can be found mainly in the vicinity of the main sediment sources
11. Tectonic situation: onset of the post-rift subsidence of Pannonian Basin

### *Lacustrine silty clayey marl (with sporadic occurrences of a turbiditic unit thinner than 100 m)*

### Mp_3

1. Synonimes, correlated formations:
   Endrőd Fm., Algyő Fm., Szák Fm.: Hungary - lacustrine
   Bzenec Fm,, Ivánka Fm.: Slovakia - lacustrine
   Špilje Fm., Lendava Fm. (Sodinci Mb.): Slovenia - lacustrine
   *Subordinately, sporadically also occur:*
   *Szolnok Fm. - Hungary, lacustrine turbidites*
   *Lendava F., Jeruzalem Mb. - Slovenia, lacustrine turbidites*
2. Lithology (colour, texture, grainsize): almost always grey silt, marl, calcareous marl, clayey marl or clay (turbidites: alternation of fine-grained sand/sandstone, silt and clay)

3. Facies: deep lacustrine, slope, sublittoral and lagoonal
4. Paleoenvironment: Parts of Lake Pannon not reached by deltas before the main transgressive event (ca. 9.8 Ma), allowing the formation of a persistent deep lacustrine or sublittoral environment, in which there were no significant turbidity currents
5. Thickness: 5–300 m
6. Average sandiness rate: 5%
7. Porosity type: intergranular
8. Estimated porosity: 5%
9. Tendencies mainly in time: not significant; in some regions, slight coarsening upwards
10. Tendencies mainly in space: relatively thin turbiditic intercalations can be found in the areas closer to the deep basins (generally these are the areas with higher overall thickness of Lower Pannonian)
11. Tectonic situation: post-rift subsidence of Pannonian Basin

*Lacustrine silty clayey marl and sandy turbidites (thickness of the turbiditic unit: 100-500 m)*

### Mp_4

1. Synonimes, correlated formations:
   Endrőd Fm., Algyő Fm.: Hungary - lacustrine
   Bzenec Fm,, Iványka Fm.: Slovakia - lacustrine
   Špilje Fm., Lendava Fm. (Sodinci Mb.): Slovenia - lacustrine
   Lendava F., Jeruzalem Mb.: Slovenia - lacustrine turbidites
   Lendava Fm. Sodinci Mb.: Slovenia - lacustrine
   Szolnok Fm. - Hungary, lacustrine turbidites
2. Lithology (colour, texture, grainsize):
   chiefly grey silt, marl, calcareous marl, clayey marl or clay
   alternation of fine-grained sand/sandstone, silt and clay (in the turbiditic interval)
3. Facies: deep lacustrine, slope and sublittoral
4. Paleoenvironment: Parts of Lake Pannon reached by deltas later than the main transgressive event (ca. 9.8 Ma), allowing the formation persistent deep lacustrine basins. These basins were regularly reached by turbidity currents originating from the deltas and slopes located marginwards. The uppermost level of Lower Pannonian is built up by the prograding slope itself.
5. Thickness: 300–1000 m
6. Average sandiness rate: average: 30% (turbidites: 50%, other intervals: 5%)
7. Porosity type: intergranular
8. Estimated porosity: average: 7% (turbidites: 9–10%, other parts: 5%)
9. Tendencies mainly in time: turbidites are located in the middle and/or lower part of the Lower Pannonian succession
10. Tendencies mainly in space: turbiditic sandbodies become more thick and frequent towards basin centres and along the axis of basement troughs
11. Tectonic situation: post-rift subsidence of Pannonian Basin

*Lacustrine silty clayey marl and sandy turbidites (thickness of the turbiditic unit: >500 m)*

### Mp_5

1. Synonimes, correlated formations:
   Endrőd Fm., Algyő Fm.: Hungary - lacustrine
   Bzenec Fm,, Iványka Fm.: Slovakia - lacustrine
   Špilje Fm., Lendava Fm. (Sodinci Mb.): Slovenia - lacustrine

Lendava F., Jeruzalem Mb.: Slovenia - lacustrine turbidites
Lendava Fm. Sodinci Mb.: Slovenia - lacustrine
Szolnok Fm. - Hungary, lacustrine turbidites

2. Lithology (colour, texture, grainsize):
   grey silt, marl, calcareous marl, clayey marl or clay
   alternation of fine-grained sand/sandstone, silt and clay (in the turbiditic interval)
3. Facies: deep lacustrine, slope and sublittoral
4. Paleoenvironment: Parts of Lake Pannon reached by deltas later than the main transgressive event (ca. 9.8 Ma), allowing the formation persistent deep lacustrine basins. The zones of this unit were frequently reached by turbidity currents carrying outstandingly high amount of sediment. The uppermost level of Lower Pannonian is built up by the prograding slope itself.
5. Thickness: 800–2000 m
6. Average sandiness rate: average: 35% (turbidites: 55%, other intervals: 5%)
7. Porosity type: intergranular
8. Estimated porosity: average: 8% (turbidites: 10–11%, other parts: 5%)
9. Tendencies mainly in time: turbidites are located in the middle and/or lower part of the Lower Pannonian succession
10. Tendencies mainly in space: turbiditic sandbodies become more thick and frequent towards basin centres and along the axis of basement troughs
11. Tectonic situation: post-rift subsidence of Pannonian Basin

### *Lignite with shallow-water silt and clay*

### Mp_6

1. Synonimes, correlated formations:
   Dubnany Fm. - Slovakia
   Neufeld Fm. - Austria
2. Lithology (colour, texture, grainsize): chiefly grey silt, marl, calcareous marl, clayey marl or clay; alternation of fine-grained sand/sandstone, silt and clay in the turbiditic interval
3. Facies: relatively anoxic in a deltaic or alluvial plain environment
4. Paleoenvironment: Zones belonging to this unit are near the basin margins; therefore they were not covered by the deep water of Lake Pannon. However, neither the sediment sources were close to these locations, therefore in spite of the coarse-grained Lower Pannonian delta lobes, a deltaic plain with swamps and marshlands formed, which were ideal for the accumulation of coal seams.
5. Thickness: 10–150 m
6. Average sandiness rate: average: 35% (turbidites: 55%, other intervals: 5%)
7. Porosity type: intergranular
8. Estimated porosity: average: 8% (turbidites: 10–11%, other parts: 5%)
9. Tendencies mainly in time: turbidites are located in the middle and/or lower part of the Lower Pannonian succession
10. Tendencies mainly in space: turbiditic sandbodies become more thick and frequent towards basin centres and along the axis of basement troughs
11. Tectonic situation: post-rift subsidence of Pannonian Basin

### 4.2.7 Formations on Pre-Quaternary horizon map (Upper Pannonian facies) (Encl. 1.2.)

Facies assemblages have been outlined also in the Upper Pannonian, which contains almost uniformly fluvial deposits in its topmost part (underlying the base of Quaternary). The detailed composition and features of the four facies series distinguished are the following:

*Alteration of clay, sand and gravel deposited on deltaic and alluvial plains*

MPl_1

1. Synonimes, correlated formations:
   Mura Fm.: Slovenia - deltaic and fluvial
   Ptuj–Grad Fm.: Slovenia - fluvial
   Újfalu Fm., 'Szentes Mb.': Hungary - deltaic
   Somló–Tihany Fm.: Hungary - deltaic
   Zagyva and Nagyalföld Fm.: Hungary - fluvial
   Beladice Fm.: Slovakia - deltaic
   Gbely–Volkovce–Kolárovo Fm.: Slovakia - fluvial
   Brodské Fm.: Slovakia - fluvial
   Rohrbach Fm.: Austria - fluvial
2. Lithology (colour, texture, grainsize): sand, sandstone, silt, clay marl, clay; subordinately gravel
3. Facies: deltaic and alluvial plain
4. Paleoenvironment: Following the infill of the deep basins of Lake Pannon, a widespread deltaic than alluvial plain was formed. This unit comprises the sediments of those areas where the formation of the deltaic and alluvial plains was not preceded by typical delta fronts (mouth bars), due to the relatively low rate of basement subsidence.
5. Thickness: 200–500 m
6. Average sandiness rate: 50%
7. Porosity type: intergranular
8. Estimated porosity: 10%
9. Tendencies mainly in time: the uppermost part of the unit consists of gravel beds of variable thickness in the Mura Basin and in the Danube Basin.
10. Tendencies mainly in space: sandbodies are generally thicker and coarser towards the centre of any sub-basin
11. Tectonic situation: post-rift subsidence of Pannonian Basin (for the Pliocene, subsidence and sedimentation becomes spatially limited due to the inversion)

*Thick sand sheets of delta front origin, with overlying clay, sand and gravel deposited on deltaic and alluvial plains*

MPl_2

1. Synonimes, correlated formations:
   Mura Fm.: Slovenia - deltaic and fluvial
   Ptuj–Grad Fm.: Slovenia - fluvial
   Újfalu Fm., 'Szentes Mb.': Hungary - delta front
   Újfalu Fm., 'Szentes Mb.': Hungary - deltaic
   Somló–Tihany Fm.: Hungary - deltaic
   Zagyva and Nagyalföld Fm.: Hungary - fluvial
   Beladice Fm.: Slovakia - deltaic

Gbely–Volkovce–Kolárovo Fm.: Slovakia - fluvial
Brodské Fm.: Slovakia - fluvial
Rohrbach Fm.: Austria - fluvial

2. Lithology (colour, texture, grainsize): sand, sandstone, silt, clay marl, clay; subordinately gravel
3. Facies: delta front, delta plain and alluvial plain
4. Paleoenvironment: Similar to the previous unit (MPl_1), but with the occurrence of mouth bars in the beginning of Late Pannonian
5. Thickness: 10–100 m
6. Average sandiness rate: average: 55% (lower ca. one-quarter: 70%, above: 50%)
7. Porosity type: intergranular
8. Estimated porosity: average: 11% (delta front: 12–14%, other parts: 10%)
9. Tendencies mainly in time: delta front deposits (which contain the largest sandbodies with the best connectivity in the Pannonian) compose the lowermost part (roughly one-quarter) of the whole unit
10. Tendencies mainly in space: the largest delta front sandbodies can be expected in the deepest parts of the sub-basins (with the highest overall thickness of Upper Pannonian)
11. Tectonic situation: post-rift subsidence of Pannonian Basin (for the Pliocene, subsidence and sedimentation becomes spatially limited due to the inversion)

*Lignite, silt, clay and carbonaceous clay deposited in shallow basins or deltaic and alluvial plains*

## MPl_3

1. Synonimes, correlated formations:
   Torony Lignite Fm.: Hungary - deltaic
   Somló–Tihany Fm.: Hungary - deltaic
   Zagyva Fm.: Hungary - fluvial
   Beladice Fm.: Slovakia - deltaic
   Gbely–Volkovce–Kolárovo Fm.: Slovakia - fluvial
   Mura Fm.: Slovenia - deltaic and fluvial
   Ptuj–Grad Fm.: Slovenia - fluvial
2. Lithology (colour, texture, grainsize): grey, bluish grey and variegated silt, fine-grained sand, clay, carbonaceous clay, lignite (in seams)
3. Facies: deltaic and alluvial plain
4. Paleoenvironment: areas of deltaic (and possibly alluvial) plain not reached by the major sediment sources, making the sediments finer than usual and allowing the accumulation of coal (as plant remnants were not carried further to the basin)
5. Thickness: 30–250 m
6. Average sandiness rate: 15%
7. Porosity type: intergranular
8. Estimated porosity: 10%
9. Tendencies mainly in time: not significant
10. Tendencies mainly in space: not significant
11. Tectonic situation: post-rift subsidence of Pannonian Basin (for the Pliocene, subsidence and sedimentation becomes spatially limited due to the inversion)

*Basalt tuffs with intercalations of clay, sand and gravel* MPl_4

1. Synonimes, correlated formations:
   Podrečany Fm.: Slovakia
   Tapolca Basalt Fm.: Hungary
   Pula Alginite Fm.: Hungary
   Ptuj–Grad Fm.: Slovenia
2. Lithology (colour, texture, grainsize): basalt, basalt tuff, locally alginite
3. Facies: basaltic volcanoes + tuff rings, several maar lakes
4. Paleoenvironment: basaltic volcanoes, mainly on land
5. Thickness: 50–250 m
6. Average sandiness rate: 0%
7. Porosity type: intergranular, fissure
8. Estimated porosity: 2%
9. Tendencies mainly in time: different volcanic centres were active in different times
10. Tendencies mainly in space: -
11. Tectonic situation: post-rift subsidence, crustal thinning in Pannonian Basin

*Csolnok Claymarl and Csernye Formations* PcE2ml

1. Synonimes: “Coralline and molluscan marl”(Csernye Fm), “Operculina Marl”, ”Nummulina Marl” (Csolnok Fm) – H , Correlated formations in partner countries: Priepasné Fm – SK
2. Lithology: grey marl, calcareous marl, silt, with fossils of gastropods, bivalves and corals appearing in mass and frequently exhibiting a lumachelle-like enrichment (Csernye Fm). Grey clay marl and marl, with many large and medium sized foraminifers (Operculina, Nummulites, Discocyclina, Aktinocyclina, Assilina exponens) frequently occurring in mass (Csolnok Fm)
3. Facies: shallow-marine to deep neritic facies
4. Paleoenvironment: sea self, selfmargin, shallow basin
5. Thickness: 10-50 and 10-100 m
6. Average sandiness rate:
7. Porosity type: intergranular
8. Estimated porosity: medium in Csernye Fm, medium sand content in the middle and upper part of the Csolnok Formation
9. Tendencies mainly in time: upward of the sequence interbedded the differently thick siliciclastic Tokod Sandstone Formation in the NE Taransdanubial Central Range, other areas the formation is overlain by deep marine Padrag Marl Formation
10. Tendencies mainly in space: heteropic with the Padrag Marl to the deep basin and the Szőc Limestone (nummulitic limestone) to the shallow water carbonate ramp
11. Tectonic situation: in syncline of the retroarc flexural basin

*Dorog and Darvastó Formations* Ebc

1. Synonimes: “Late Lutetian coal seam sequence” and “Lower Lutetian coal sequence”, Correlated formations in partner countries: Obid Mb – SK
2. Lithology: coal, carbonaceous clay, variegated clay, grey clay, bauxitic clay, sand, gravel, limnic limestone and clay marl (Dorog Fm), and grey clay marl, marl, at the base, locally variegated (bright red, or yellow), clay, upwards coal, molluscan and miliolina calcareous marl and limestone lenses, sand, gravel, conglomerate, and locally dolomite detritus (Darvastó Fm).

3. Facies: fluvial, lacustrine, paludial, and paralic sediment (Dorog Fm) and shallow marine lagoon and off-shore bar origin (Darvastó Fm)
4. Paleoenvironment: seashore and fluvial
5. Thickness: 1-25 m (Darvastó Fm), 0-300 m (Dorog Fm)
6. Average sandiness rate:
7. Porosity type: intergranular and fissure
8. Estimated porosity: medium on the base of formations and medium in the coal seams
9. Tendencies mainly in time: formations overlying by deposition of the Middle Eocene transgressive systems (marl, limestone)
10. Tendencies mainly in space: heteropic connection with each other
11. Tectonic situation: syncline deep in retroarc flexural basin.

### 4.2.8 Formations on Surface Geological map (Quaternary) (Encl.1.1.)

*Fluvial* Qhf

1. Synonymes, correlated formations in partner countries:
2. Lithology (colour, texture, grainsize): Fluvial sediment (clay, silt, sand, gravel)
3. Facies: fluvial
4. Paleoenvironment: fluvial
5. Thickness: 0-15 m
6. Average sandiness rate: 0-100%
7. Porosity type: intergranular
8. Estimated porosity: high
9. Tendencies mainly in time: generally fining upward
10. Tendencies mainly in space: depends on main rivers and tributary deposits, going downstream fining
11. Tectonic situation: postrift or slight uplift trends in whole the area

*Aeolian sand of dunes* Qes

1. Synonymes, correlated formations in partner countries:
2. Lithology (colour, texture, grainsize): Drift sand
3. Facies: aeolian
4. Paleoenvironment: continental eolian semi-desert
5. Thickness: 0-12 m in the Vienna Basin
6. Average sandiness rate: 100%
7. Porosity type: intergranular
8. Estimated porosity: high
9. Tendencies mainly in time: stable, locally with soil interbeds
10. Tendencies mainly in space: general wind direction from W –NW, most appearance in the Vienna Basin, smaller dunes in the promontory of the Danube river in the Danube Basin
11. Tectonic situation: postrift or slight uplift trends in whole the area

*Aeolian sand of dunes* Qfe

1. Synonymes, correlated formations in partner countries:
2. Lithology (colour, texture, grainsize): Fluvial-aeolic sand
3. Facies: aeolian
4. Paleoenvironment: continental glacial, interglacial mostly arid

5. Thickness: 0-60 m in the Vienna Basin
6. Average sandiness rate: 100%
7. Porosity type: intergranular
8. Estimated porosity: high
9. Tendencies mainly in time: stable, locally with soil interbeds
10. Tendencies mainly in space: general wind direction from W –NW, most appearance in the Vienna Basin, smaller dunes in the promontory of the Danube river in the Danube Basin
11. Tectonic situation: postrift or slight uplift trends in whole the area

*Fluvial sediments* Qpf

1. Synonymes, correlated formations in partner countries
2. Lithology (colour, texture, grainsize): Fluvial clay, silt, sand, gravel
3. Facies: fluvial
4. Paleoenvironment: continental glacial and interglacial
5. Thickness: 0-400 m in Gabčíkovo depression
6. Average sandiness rate: (estimated sand content %)
7. Porosity type: intergranular
8. Estimated porosity: high
9. Tendencies mainly in time: generally fining-upwards
10. Tendencies mainly in space: several intramontane deltas of the Danube, Váh and hron rivers, the largest is in the Gabcikovo depression (Danube)
11. Tectonic situation: postrift, but locally late rifting

*Aeolian loess* Qel

1. Synonymes, correlated formations in partner countries:
2. Lithology (colour, texture, grainsize): Loess
3. Facies: aeolian, partly deluvial and aluvial
4. Paleoenvironment: continental glacial and interglacial
5. Thickness: 0-80 m
6. Average sandiness rate: silt
7. Porosity type: intergranular
8. Estimated porosity: high
9. Tendencies mainly in time: increasing thickness in the late Pleistocene
10. Tendencies mainly in space: due to the wind direction mostly from NW, the thicker accumulations occur at the E-SE promontories of the mountain chains
11. Tectonic situation: postrift

*Proluvial sediments* Qpp

1. Synonymes, correlated formations in partner countries:
2. Lithology (colour, texture, grainsize): Proluvial clay, silt, sand, gravel, rock debris
3. Facies: alluvial fans
4. Paleoenvironment: continental piedmont
5. Thickness: 0-150 m
6. Average sandiness rate: 80%
7. Porosity type: intergranular
8. Estimated porosity: high
9. Tendencies mainly in time: growing mostly during interglacial periods, or in the case of active uplift of the mountains

10. Tendencies mainly in space: distributed along the mountain slopes toward the basins
11. Tectonic situation: postrift, partly local synrift

*Fluvial to alluvial gravel and sand* PlQfc

1. Synonymes, correlated formations in partner countries: Tengelic Fm.
2. Lithology (colour, texture, grainsize): argillaceous, strongly weathered sandy gravel, sand and sandy clay
3. Facies: fluvial up to alluvial-limnic
4. Paleoenvironment: fresh-water
5. Thickness: few meters
6. Average sandiness rate: up to 40 %
7. Porosity type: intergranular
8. Estimated porosity: medium
9. Tendencies mainly in time: no
10. Tendencies mainly in space: residual patches
11. Tectonic situation: postrift

# 5 Geological models of the Pilot areas

The geological models of the pilot areas were basicly deducted from the relevant parts of the supra-regional models. However, as the scale of the pilot area models were more detailed (generally 1:200 000), it made it possible to provide a more accurate picture on the geological buildup. Where the geology of the area made it necessary, additional geological horizons (compared to those ones which were edited for the supra-regional area) were constructed. Only those formations are described at the additional orizons, which do not form part of the unified geological legend (chapter 4.2.). A major step forward is that tectonics has been incorporated into the pilot area geological models. The pilot models contain modelled tectonic surfaces, and these model grids were edited more accurately based on the evaluations of 2D seismic section series and various geophysical datasets. Another important difference is that the pilot area geological models were prepared by different 3D geological modelling softwares (Jewel, GoCAD, Petrel), therefore they are more advanced, compared to the “flying carpet” model of the supra-regional area and provide more rich input information for the pilot area hydrogeological and geothermal models.

## 5.1 Danube basin

### 5.1.1 Geological frame and history

The Danube Basin is geographically represented by the Danube Lowland in Slovakia and by the Little Hungarian Plain in Hungary. On the west it is bordered by the Eastern Alps, Leitha Mts. and Male Karpaty Mts. On the north the basin has finger like extensions which penetrate among the core mountains of Male Karpaty, Povazsky Inovec and Tribec. On the northeast it is bounded by the Middle Slovakian Neovolcanics and the Burda volcanics. On the southeast, there are emerging units of the Transdanubian Central Range.

The Danube Basin has several depocentrs of various age. On the north there are depressions among the core mountains, from the west to the east: Blatne, Risnovce, Komjatice and Zeliezovce depressions. The southern part of the basin in Hungary is divided by the Mihályi ridge to the depocentres situated west of it (along the Répce fault) and to the easterly situated one (along the Rába line). The deepest central part of the basin is called Gabcikovo depression, where the thickness of the deposits reaches more than 8500 m.

The Pre-Tertiary 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 southeastern 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 crystalline 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 seqences. The Tatric and Veporic units continue into Hungarian and Austrian territories as their equvalents 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, massive Triassic and Jurassic strata dominantly forming in platform or open-sea environment. Cretaceous sediments of terrestric or shallow-water environment are terminating the Mesozoic part of this succession.

Tertiary rocks of the so-called 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 terrestric sedimentation and is represented by shallow-water limestones, sandstones, marls and clays as well as coal or bauxite occurrences.

Lower Miocene deposits occur in two separate areas: in the NE part of the area in Slovakia and in the Transdanubian area at the SW, mainly in Hungary.

The oldest Neogene deposits in the Slovakian part of the Danube Basin are of Eggenburgian age. They are known from the Blatne, Dobra Voda and Vadovce depressions on the northwest. The Eggenburgian marine depositional area was paleogeographically connected to those, in the northern part of the Vienna Basin. They belong to the Causa Formation. In the Ottnangian the depositional environment started to be brackish, and in the Blatne depression a small remnant of these deposits of the Banovce Formation are preserved. The Karpatian marine deposits of the Laksary Formation and alluvial-deltaic Jablonica Formation are present in the northern part of the Blatne depression and in the Dobra Voda depression.

Lower 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.

Due to the Miocene tectonic evolution of the area (escape of the Alcapa block, subduction and back-arc basin extensions) the Badenian is the first horizon with similar sedimentary developement in the whole area. Since our model contains a single horizon for the whole Badenian, we discuss the different Badenian sub-phases together.

The Early Badenian developed separately in the NE and the SW parts of the basin: the mostly deep-marine deposits of the Bajtava Formation are known from the Želiezovce depression, while similar deposits of the Tekeres Schlier Fm. cover the Transdanubian Range as far as to the important Hurbanovo – Diósjenő line. The Middle Badenian open marine Špačince (Slovakia), or Pusztamiske (Hungary) Formation deposits cover practically the entire area of the Danube Basin. The Late Badenian Bahon and Szilágy Formations are represented by shallow marine deposits, covering whole the area of the basin.

In the central part of the basin large stratovolcanic bodies of Early Badenian age belonging to the Šurany (or Burda) Formation can be observed, being covered by younger sediments. Other smaller occurrences are known in the vicinity of Bratislava and in the Csapod Trench in Hungary, but the amount of data did not allow to incorporate these bodies into the model.

The Sarmatian deposits of the Vráble, Tinnye and Kozárd Formation were formed in a shallow brackish sea and are facially variable in the area of the entire basin.

The division and correlation of the Pannonian sediments and their boundary with the Quaternary is probably the biggest stratigraphic problem of the area. In our model we defined the Lower Pannonian horizon as the Ivanka Formation in Slovakia which is correlated with numerous dominantly marly beds in Hungary (Peremarton, Endrőd, Zsámbék, Csákvár Marl Fm.). All these formations formed from shallow water to lacustrine environment, the Ivanka Fm. also contains prograding deltaic lobes. We joined the Upper Pannonian and Pliocene 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 2500 m. They developed in continuing and further shallowing lacustrine environment changing upward into deltaic and fluvial facies. The are built up of clays, marls, sands and are ranged into the Beladice, Volkovce, Kolárovo, Zagyva, Újfalu Formations. In the younger parts of the Upper Pannonian also basaltic intra-plate volcanism is known (Tapolca and Podrečany Basalt Fm. and Pula Alginite Fm.)

The Quaternary deposits have an erosive base and accumulated in depressions. However in the Gabcikovo depression the deposition was continuous from the older sediments. Fluvial deposits are dominant, but an important amount of loess is typical for the basin areas as well.

### 5.1.2 Additional horizons

The geological model of the Danube Basin pilot area was constructed for the six main horizons (base of Quaternary, Upper Pannonian, Lower Pannonian, Sarmatian, Badenian and Cenozoic, Encl.2.1.− 2.7) defined for each pilot area, as well as for the supra area. During the work of the modelling we decided to create an extra horizon for Badenian volcanites in the Slovak part of the pilot area (Encl.2.6).

In the vicinity of the Kralova dam on the river Váh a huge body of a buried stratovolcano (called the Kralova Volcano) was revealed, which was documented by gravimetry, magnetometry as well as with one borehole. Since the body is built mainly up of andesitic lava and pyroclastic rocks, its porosity, chemical composition and probably also thermal characteristics are different from the underlying basement rocks, as well as from the overlying Badenian, Sarmatian and Lower Pannonian mainly sandy rocks.

Between the horizons base of Badenian (or Badenian volcanites, respectively) and the surface of the pre-Tertiary basement, the whole Tertiary and Lower Miocene formations have only limited extent and are of local importance in the modelled area, so they were united as zone Tertiary + Lower Miocene.

### 5.1.3 Descriptions of additional horizon’s formations

We added only one extra horizon to the model: the horizon of Badenian neovolcanites in the area of the buried Kralova stratovolcano (Slovakia). This huge volcanic body is visible in seismic profiles and numerous other geophysical profiles, but unfortunately only one borehole penetrated the volcano itself (well Králová-1).

The rock material is ranged into the Šurany Andesite Fm. and is equivalent with the other Badenian volcanic complexes, e.g. the Burda, Dobogókő and Magasbörzsöny formations. The formation is built u pof mainly andesitic lavas and subvolcanic rocks, its charasteristics are the same as the Burda Fm. (Mba).

*Šurany Andesite Fm.*

1. Synonyms, correlated formations in partner countries: Burda Fm., Dobogókő-Magasbörzsöny Fm.
2. Lithology (colour, texture, grainsize): andesitic lava flows with andesitic volcanoclastics
3. Facies: stratovolcanic
4. Paleoenvironment: subaerial volcanism on pre-Tertiary basement rocks
5. Thickness: from 0 to an estimated 2000 m
6. Average sandiness rate: -
7. Porosity type: fissure
8. Estimated porosity: low
9. Tendencies mainly in time: later phase of volcanic activity of Karpatian – lower Badenian age

10. Tendencies mainly in space: maybe connected to the buried Šurany stratovolcano on the SE by distal volcanoclastic flows
11. Tectonic situation: Back-arc rifting associated with transcurrent fault activity
12.

### 5.1.4 Geophysical evaluations: gravity, seismics, magnetotellury

In the Slovakian part gravity observations started from 1959 in the Blatne depression, which were related to hydrocarbon explorations. Most of the area was measured in the 60-ies. Later seismic and well measurements controlled the observed structures with variable success. Some other parts of the basin and the Male Karpaty Mts. were measured later (1988, 1996), focusing on the Middle Miocene and postrift Late Miocene phase of the basin fill. In the Danube Basin several magnetic field measurements were done, too. In 1989 a magnetic field anomaly map was compiled. Seismic measurements were performed in several periods. In the basin, and the surrounding mountains, there are two major refraction seismic lines, oriented from NW to SE. The reflection seismics data were obtained in 3 periods. In the first period, a ca. 7000 km$^2$ area of the basin was covered, but the quality is very low. Measurements of the second period proceeded much more useful data in the western and central parts of the basin (length 550 km). The third period comprised some reprocessing of the older data and a realization of about 330 km new lines in the central part of the basin. This period was covered by Maxus Energy Corporation for hydrocarbon purposes. Results of the geophysical measurements were used during the compilation of the model horizons.

Geophysical measurements and their results of the Hungarian part of the Danube Basin pilot area are discussed in chapters 3.6 and 3.7

### 5.1.5 Tectonics

The recent structure of the Danube Basin is a product mainly of the Middle Miocene to Pannonian tectonic history. Due to the huge amount of basin fill (exceeding 8 km in the central parts) there are many different views of the probable structural patterns. We tried to find a compromise for a structural model by simplification, i.e. joining smaller faults into a larger one (that was the case in the depressions between the Malé Karpaty, Považský Inovec, and the Považský Inovec and Tríbeč Mts. in Slovakia). We needed to ignore and smooth some smaller faults to achieve a picture, which on the other hand would adequately respect the main tectonic features. At the beginning of the project the team of geologists working on modeling 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 a geologically important line (for example the Rába line) had less vertical dislocation.

The basement of the area is built up of mainly by Austroalpine (Austria, Hungary) or Tatric and Veporic (Slovakia) crystalline complexes and their cover sequences, which are well correlated. The ovrelying superficial Western Carpathian nappe systems: the Fatric and Hronic units are present only in the NE rim of the area, so they have only small influence to the basement structure in general. The third huge tectonic unit of the basement is the Trandanubicum located SE of the Rába and in its continuation S of the Hurbanovo-Diósjenő line. 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 functionned as an extensional listric plane in opposite direction. All other faults of the area are younger.

The main fault direction in the area is SW-NE combined with numerous and usually not well detectable faults of roughly perpendicular direction (S-N or SE-NW) (Figure 30). The basement is dissected by them to a set of elevations and depressions: in Slovakia there are four main depressions defined by NE-SW faults (from N to S): Blatne, Rišňovce, Komjatice and Želiezovce depressions. Except the northernmost and oldest Blatné depression, the other depressions are directing into the Central, so-called Gabčíkovo depression near the Slovakian-Hungarian border, whose depth exceeds 8500 m. This depression is continuing further to the SW into the Csapod Trough. On the NW side of the Mihályi Ridge an other fault-defined depression of smaller depths is located.

Based on seismic profiles only a few faults cut the Lower – Upper Miocene boundary as it is defined in our model. Fault activity in the Blatné depression is terminated already in the Sarmatian.

However in general the NE-SW faults are defining the tectonic structure of the basement, the situation in the central (Gabčíkovo) depression is more complicated, partly due to the lack of reliable data. This depression is too deep for reaching lower horizons by wells and thus also the interpretation of seismic profiles is problematic. In this part we joined Hungarian and Slovakian faults, however the real structure is surely complicated by a set of perpendicular faults.

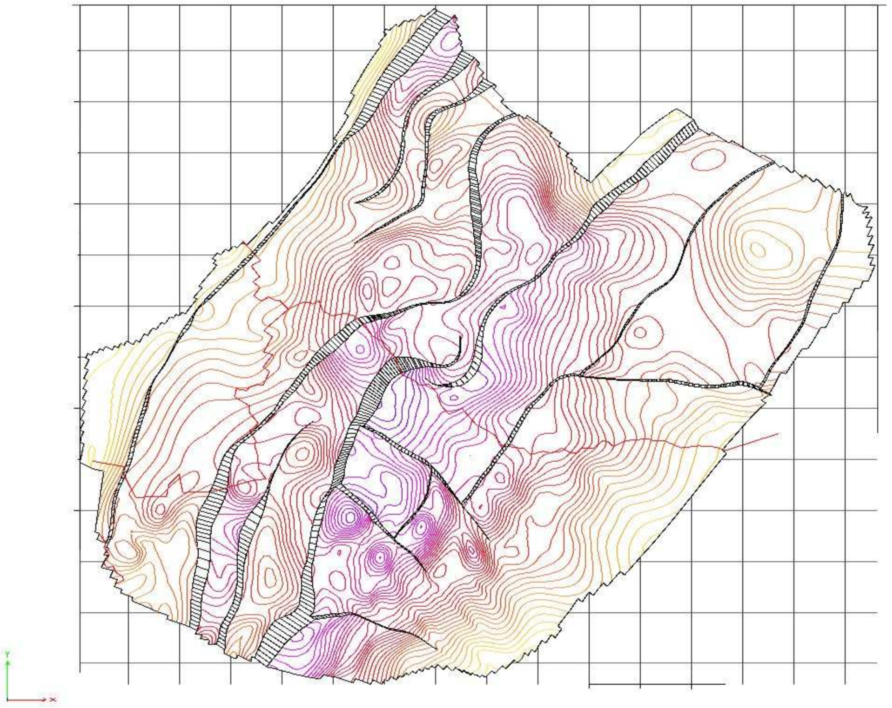


Fig. 30 Simplified fault pattern of the Danube Basin pilot area in the 3D model

### 5.1.6 Cross sections

Based on the 3D geological model we constructed 3 cross sections (Figure 31). These sections illustrate the fault-dominated Neogene evolution of the Danube Basin.

The oldest partial structure of the area is the Blatné Depression, which started to open already in the late Lower Miocene and continued opening through the whole Badenian. On the other side, Paleogene and Lower Miocene cover units can be found independently also in the southern part of the area on the Transdanubian unit. These Paleogene – Lower Miocene occurrences are not in contact, and represent different facies and genesis.

In the Lower Badenian transgressions were approaching from the NE as well as from the SW located Styrian Basin and from south through the Transdanubicum. However the SE part of the area was not affected by these Badenian transgressions. The Badenian transgressions covered most of the area, the thickest depocentres in this time are in the Csapod Through and the Blatné Depression. The Middle Miocene strata are present almost in the whole area – except the mentioned SE part. The Králova Stratovolcano existed in a sub-aerial environment in this area and was gradually flooded by younger transgression events.

The Sarmatian is present in the whole area and shows relatively stable thicknesses, however in the Sarmatian and Lower Pannonian a new subsidence phase is initiated, situated mainly in the central depression. Due to this process the thickness of the Upper Pannonian sediments in this part is extremely huge, exceeding in some cases 2500 m.

Since the process is continuing, Quaternary thicknesses are also the greatest in this central part, exceeding 600 m.

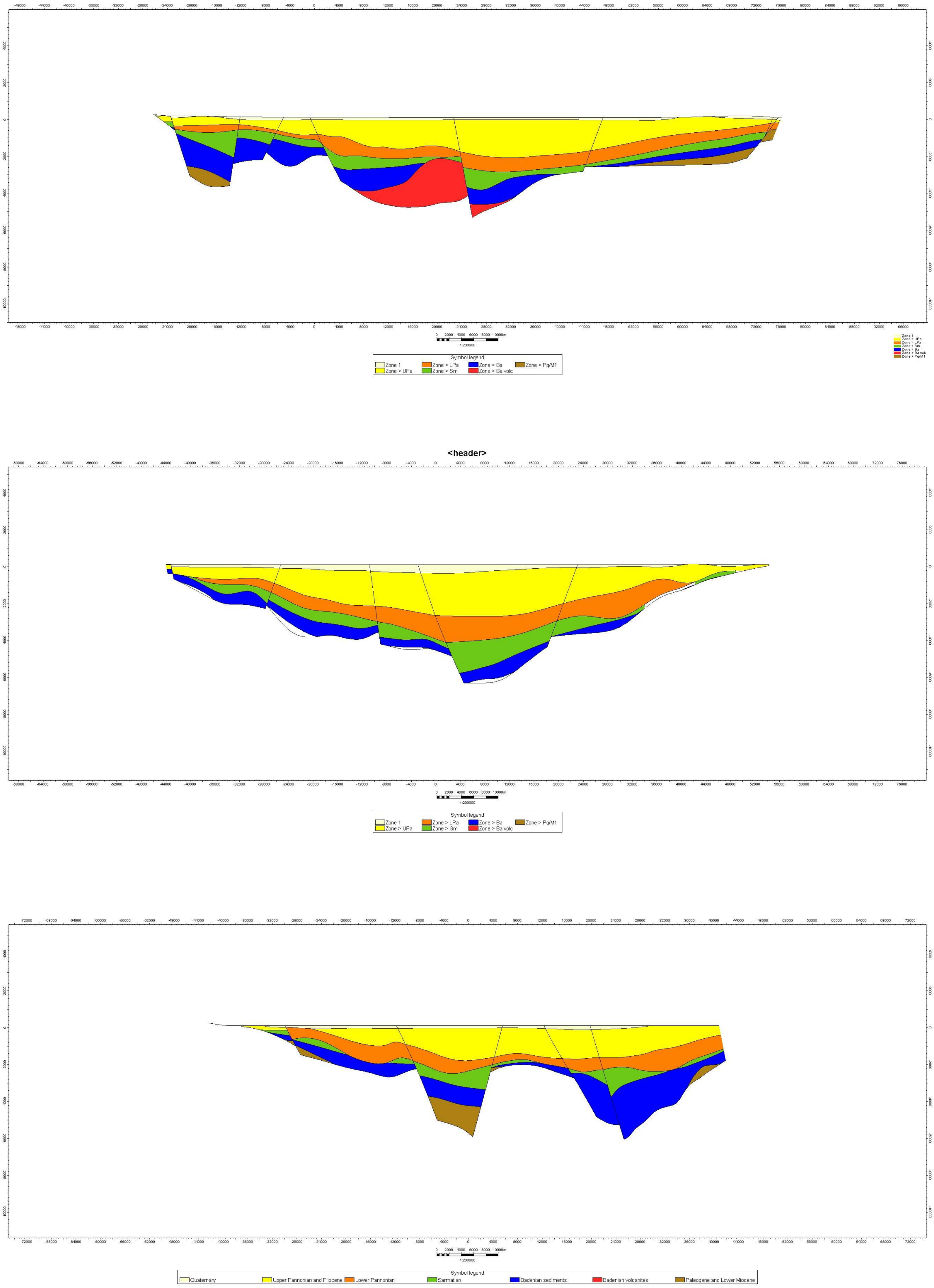


Fig. 31 Geological cross sections of the Danube Basin pilot area

### 5.1.7 Modelling

Before the modelling itself, we needed to prepare our data: well and seismic data as well as bitmaps or other input types.

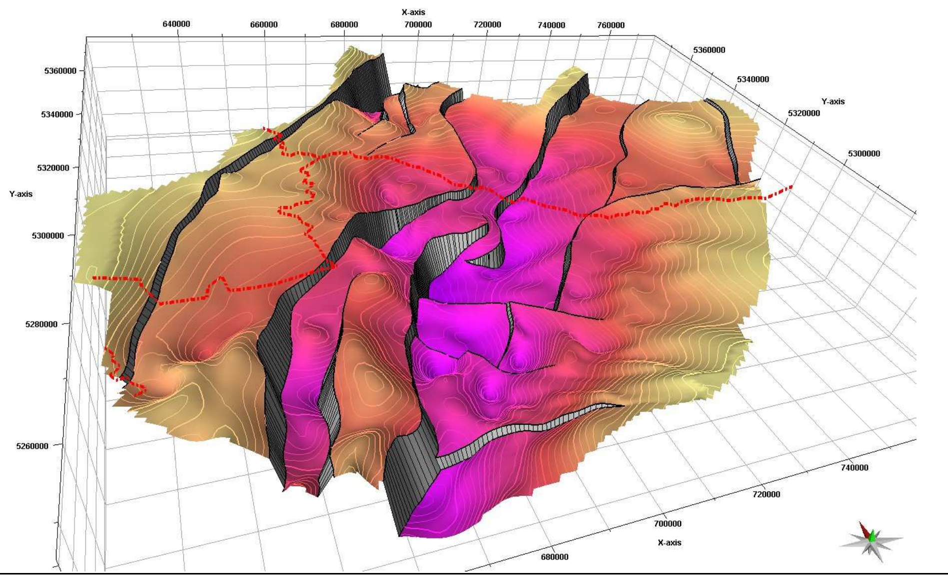
- The preparation of the numerical data-sets for the modelling was provided by common table and graphic editors (MS Excel, Access, GIMP etc.).
- The map-based inputs were created in GIS applications: mainly in MapInfo™, in less extent in ArcGIS™. This phase included georeferencing and digitizing of published maps, creating converting existing maps in different coordinate-systems onto UTM 33N, creating thematic maps (boreholes, seismic profiles).

The 3D geological modelling itself was provided by software package Petrel™. The modelling process included:

- Getting the different types of data in the model
- Editing the main data-sets: creating well-tops from borehole data, digitizing of the seismic profiles and calculating time-data onto depth (for the Slovakian part only), creating simple (non-faulted) horizons
- Defining the fault pattern for the model, creating a faulted grid
- Creating faulted horizons and zones.

For the surface we used the elevation model created by the SRTM Project (The Shuttle Radar Topography Mission). While the base horizon of the Quaternary was mainly compiled from earlier published data, the deeper horizons were constructed from well data and seismic profiles.

The recent fault pattern of the area is a product of numerous tectonic phases of different paleostress and direction characteristics which took place in various geologic periods – so the situation is extremely complicated. In the model we simplified this complexity to achieve an optimal picture, which roughly respects the main structural elements of the fault pattern. An example of the model is shown on Figure 32.

| Views of the 3D model of the pre-Tertiary basement | |
|---|---|
|  | from SW |

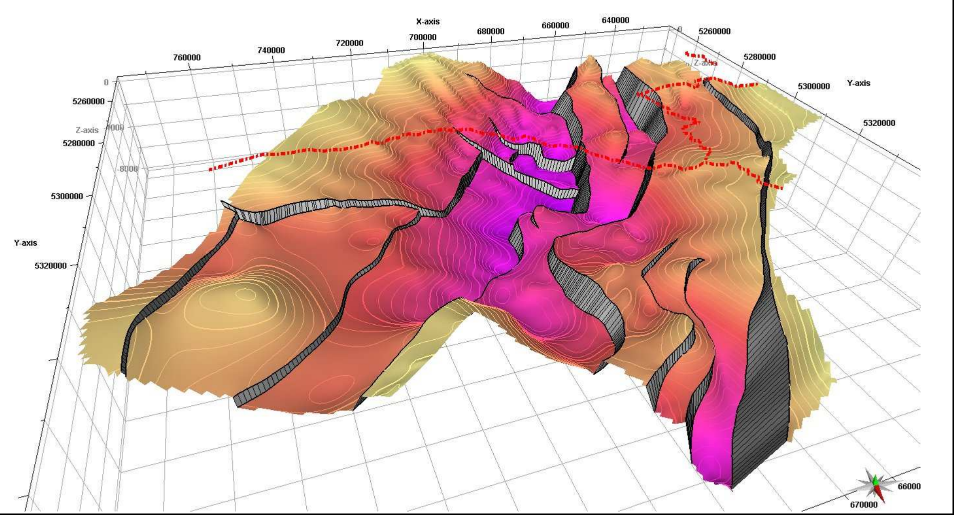
| | |
|---|---|
|  | from NE |

Fig. 32 Pre-Tertiary basement model of the Danube Basin pilot area

## 5.2 Vienna basin

### 5.2.1 Geological frame and history

Located at the transition zone between the Eastern Alps and the Western Carpathians, the Vienna Basin is a well-studied classical pull-apart basin showing the shape of a spindle (Wessely 2006). Its general strike direction is oriented SW – NE, which is related to Paleozoic metamorphic bedrocks of the Bohemian Massif (Variscian orogeny) acting as an indenter for the Alpine thrusting (Brix & Schultz 1993).

In the area of the Vienna Basin sediments of several stages of deposition are building a succession partly in autochthonous position and partly transported as thrust sheets. The tectogenetic evolution of the Vienna Basin area began with a first phase of subsidence during middle Jurassic time which led to the genesis of a synsedimentary rift basin (Pre-Vienna Basin) and was followed by a more or less stable period of sedimentation from late Jurassic to late Cretaceous (autochthonous Mesozoic sediments). This passive margin basin setting ended with the gradually evolving thrust belt in the south forming a molasse fordeep basin in the north which was partly overthrusted by the Alpine/Carpathian nappes. Evidence for that is provided by exploration wells showing Oligocene molasse sediments below the Alpine nappes at depth of up to 6000 m. Tensional forces during ongoing thrusting in the early Miocene led to the development of a piggyback basin on top of the Alpine/Carpathian nappes (Proto-Vienna Basin). Therefore we find today corresponding sediments in the molasse foredeep and in the northern part of the actual Vienna Basin. The last and still ongoing evolutional stage of the Vienna Basin is governed by ceased thrusting and subsidence again since early Miocene age due to pull-apart mechanisms (Neo-Vienna Basin).

As a consequence of this, the Vienna Basin has to be separated into three different main floors: An autochthonous floor consisting of neogene sediments on top, followed by allochthonous Austroalpine and Penninic nappes, which in turn have been thrusted onto a basal autochthonous floor consisting of tertiary and mesozoic sediments as well as its crystalline basement belonging to the Variscian Bohemian Massif.

The “Neo-Vienna Basin” is split into several high-plateaus and depressions, which are separated by a system of normal- and strike-slip faults (e.g. Vienna Basin Transform Fault-

System, Leopoldsdorf- and Steinberg Fault-System). At the main depocenter (Zistersdorf Depression) neogene basin fillings reach thicknesses of up to 5000 meters.

The southern Vienna Basin is characterized by a central, tectonically active rift system (Wiener Neustadt Depression, Mitterndorf Depression), which is flanked by high-plateaus at the western (Moedling Block) and eastern margin of the basin. Heading northwards, the central rift system passes into a major depocenter (Schwechat Depression) showing neogene basing fillings of up to 4000 meters. Separated by the Leopoldsdorf Fault System, the Schwechat depression opposites the thermal water bearing so called “Oberlaa High” structure, which is related to Neogene basin depths of less than 500 meters below surface.

### 5.2.2 Additional horizons

The decision on the build-up of the model was made in agreement of both partners contributing to the pilot area Vienna Basin (SGUDS and GBA)). Prominent stratigraphic, respectively tectonic units were chosen to be modeled with special respect to layers of geothermal/hydrodynamic interest (Figure 33).

The Eggenburgian/Ottnangian horizon mainly consists of delta sands and represents a possible reservoir on the Slovakian side. This layer does not play an important role on the Austrian side of the pilot area as it appears only as a small deposit. Vice versa, the Aderklaa Conglomerates are a promising reservoir on the Austrian side but hardly extends across the border.

To include the layer of the Mesozoic carbonates on top of the Austroalpine crystalline basement was important especially for the border region, as they bear thermal waters circulating between the two involved countries. In order to achieve a good geothermal model, the geometric model had to be set up with special respect to varying petrophysical and structural parameters (main tectonic layers as well as highly permeable-, porous-, dense layers, layers with high heat capacity etc.).

As a result, the main stratigraphic layers (Upper and Lower Pannonian, Sarmatian, Badenian, Karpatian) were modeled, adding the Aderklaa Conglomerates (At) and the Eggenburgian + Ottnangian (Sk). Main tectonic units represent the Tirolic-, Juvavic-, Bajuvaric Units, the Greywacke Zone (mainly on Austrian side), the Central Alpine Mesozoic Carbonates and the Bohemian Massive, adding the Giesshuebel-, Gruenbach- and Brezová-Myjava area Gosau because of their differing petrophysical parameters. The modelled horizons are shown in Enclosures 3.1−3.14.

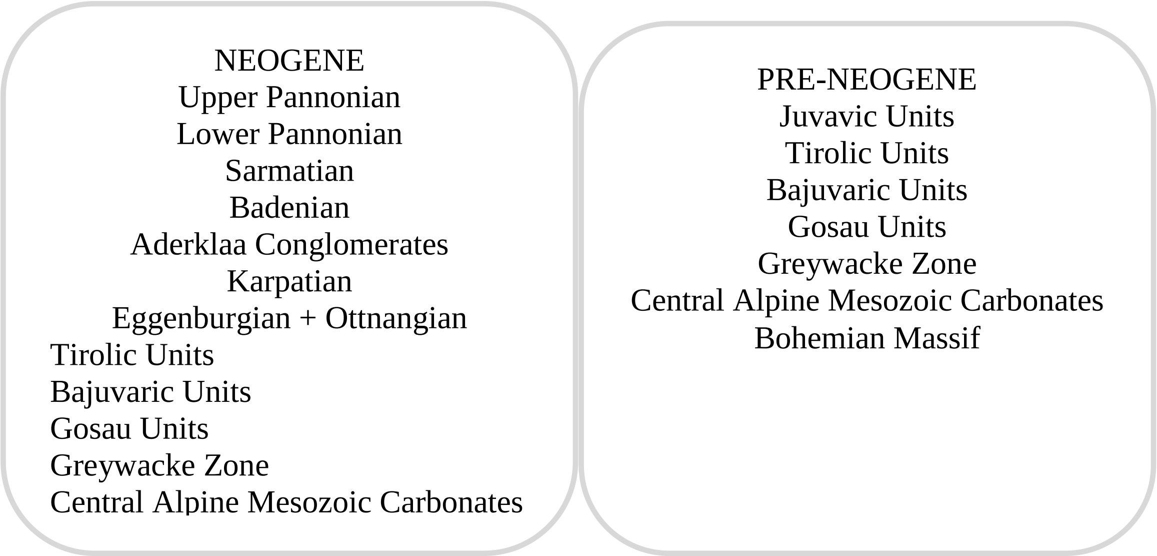


Fig. 33. Sketch of modeled layers in the Vienna Basin pilot area.

The geological model of the Vienna Basin pilot area consists of the following sixteen horizons (underlined horizons were not modeled at the supra-regional area model):

*Neogene sedimentary units:*

- Base of Upper and Lower Pannonian
- Base of Sarmatian
- Base of Badenian (top of Aderklaa Conglomerates)
- Base of Aderklaa Conglomerates (Badenian)
- Base of Carpathian
- Eggenburgian plus Ottnangian;

*Pre-Neogene units:*

- Base of the Tirolic-, Juvavic-, Bajuvaric- Units (Austroalpine nappes)
- Base of Giesshuebel-, Gruenbach- and Brezová-Myjava area Gosau
- Base of Greywacke Zone
- Base of Central Alpine Mesozoic Carbonates
- Top of the Bohemian Massive (representing the deepest unit of the model)

### 5.2.3 Descriptions of additional horizon’s formations

The detailed description of all formations is found in chapter 4.2 of this report.

*Neogene Sediments*

The layer of Aderklaa Conglomerates (part of the Badenian sedimentation) was modeled since it represents one of the most promising geothermal reservoirs in the Austrian part of the Vienna Basin. It does fulfill the requirements for a usage in a geothermal sense: high porosity (up to about 20%) and permeability, adequate depths in order to provide sufficiently high temperature levels and moderate salinity (Wessely 2006). Enhanced subsidence during the deposition is decisive for the great thickness of up to 360 meters and thus significant hydrogeothermal potential.

Other important hydrogeothermal reservoirs are represented by Carpathian conglomerates as well as Eggenburgian and Ottnangian delta sediments. In the chapter 4.3 of this report, the descriptions of Carpathian formations are represented by the Laa Formations and sands of the Šaštín Member; the Eggenburgian and Ottnangian by the Lužice Formation.

As far as the basin is understood up to date, these units are the most promising geothermal reservoirs within the Neogene sedimentation. The geometric and numeric modeling work focuses on these sands and conglomerates; stratigraphical younger sediments without significant potential were not modeled in more detail.

*Pre-Neogene Basement*

The three Gosau Group sedimentary successions (Gruenbach, Giesshuebel and Brezová-Myjava area) were modeled individually. They do not bear geothermal potential but are important to consider for the numeric simulations as these partly up to 2.5 km thick sedimentary deposits differ significantly from the surrounding units in terms of porosity and thermal parameters. With porosities of about 5 % and low permeability, they are acting as important seals in the oil- and gas industry and also act as hydraulic barriers.

In the eastern part of the pilot area, the Mesozoic cover of the Austroalpine Crystalline units can be seen as another interesting formation from a hydrogeothermal point of view. This horizon preliminary consists of karstified carbonates and is object of complex water-circulating systems. A prominent manifestation of these active hydrothermal systems is represented by the thermal spring “Bad Deutsch Altenburg” (AT): Long travelled waters, whose recharge systems are understood to be in the outcropping carbonates in the area of Somár Mountain (SK) mix with young and colder waters from the area of the Hundsheimer Mountains (AT). This flow-system as well as its geometry and the petrophysical properties of the bearing reservoir are aimed to be investigated by integrating them into the later following numerical simulations, which base on the achieved geometrical 3D model.

The Tirolic Units (also karstic carbonates) are the main aquifers within the Vienna Basin system and a huge controlling factor regarding flow dynamics. Waters migrate from the outcropping Calcareous Alps south-west of the basin through the deeply buried carbonates until they rise at the Leopoldsdorf fault system and arise at various places throughout the Vienna Basin (Oberlaa, Baden, Bad Voeslau, etc.). In the central part of the Vienna Basin, which is included at the pilot area, the Tirolic Units comprehend a large reservoir of mostly stagnant or slowly migrating thermal water showing maximum temperature, which are significantly above 100 °C.

### 5.2.4 Geophysical evaluations: gravity, seismics, magnetotellury

The achieved geometrical model of the Vienna Basin pilot area solely bases on published geological data in terms of (i) maps, (ii) cross-sections and borehole data. Relevant results of geophysical surveys until the early 1990s have already been implemented into the processed basement maps, (e.g. Wessely & Kroell 1993). As the Geological Survey of Austria, who has been the responsible partner for the elaboration of the geometrical 3D model, does not have the competence of processing seismic data, and younger surveys are focused on local scale hydrocarbon traps, it has been decided not to use unpublished processed and interpreted seismic data for elaborating the geometrical 3D model.

Other geophysical data, such like gravity or magnetotellury are available from elder surveys from the 1960s to the 1990s and are comprehensively incorporated in the Vienna Basin structural maps (Wessely & Kroell 1993). A detailed interpretation of available geophysical data for deep crustal structures at the Vienna Basin, for instance in order to model background heatflow densities, is far beyond the scope of Transenergy.

### 5.2.5 Tectonics

In general, five main fault systems were taken into account in order to structure the geological model (Figure 34). In this context only faults with a minimum offset of 500 meters were modeled and surfaces were displaced along them.

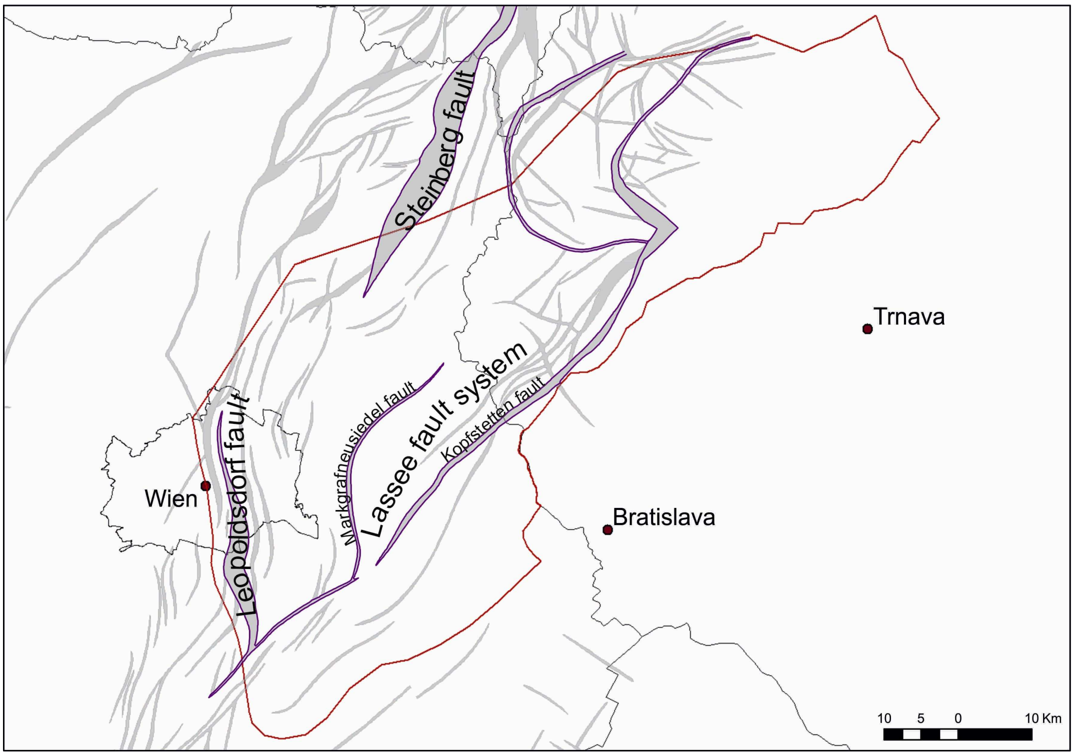


Fig. 34 The faults of the Vienna Basin in grey, the main fault systems framed with purple lines: the Leopoldsdorf-, the Steinberg-, the Lassee-, the Laksary and Hodonin-Gbely fault system.

The most prominent fault on the Austrian side of the pilot area is the Steinberg Fault (Figure 35) with a vertical displacement of up to 5000 meters. It is one of the most prominent faults on which the inner alpine Vienna Basin subsided over long periods of time. In the area of Pyrawarth, iron-rich wells are related to this fault, as well as sulfur-rich wells at the area of St. Ulrich north of Zistersdorf (Griss 1951). The fault itself was drilled several times due to exploration of oil and gas entrapments, making clear that it is a heavily fractured fault zone acting as a hydraulic barrier and thus influencing the water circulation decisively.

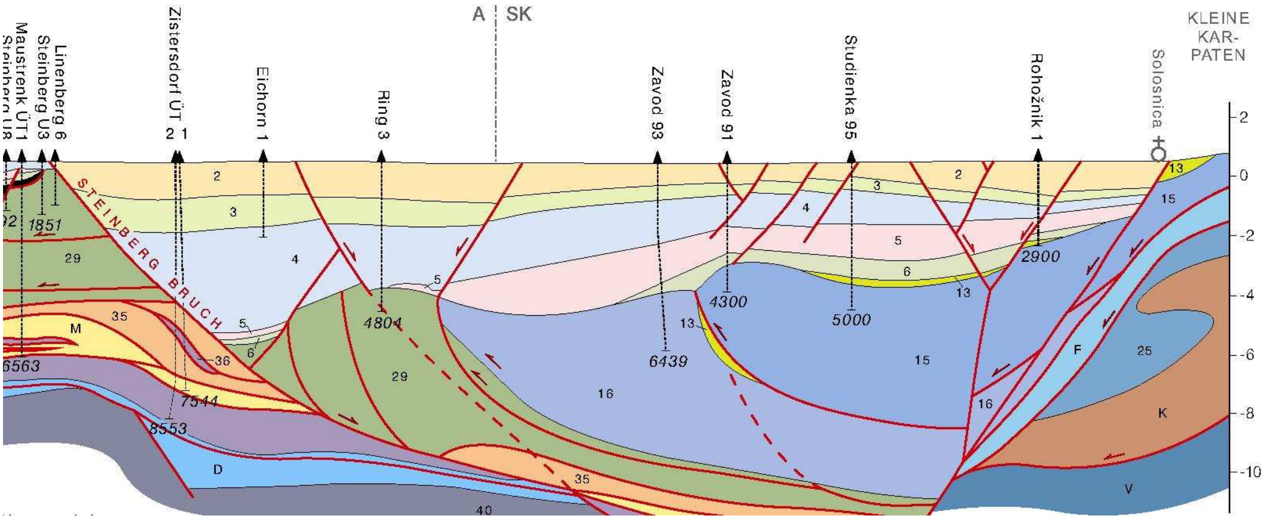


Fig. 35 A west-east oriented cross section with the prominent Steinbergbruch, displacing the basement by several kilometers (by Wessely 2006).

A similar situation is shown at the Leopoldsdorf Fault (-system), a normal fault with an offset of up to 4000 meters. This fault separates the marginal high zones of the southern- (Hochscholle) from the deep parts (depressions) of the central Vienna Basin (Tiefscholle) and represents a main controlling factor for groundwater flow within the basin. It acts as a hydraulic barrier, where deeply circulating waters (travelling mainly from the south-west) are rising. Spas like in Oberlaa, Baden and Bad Vöslau owe their thermal waters to this system and remain an important economic factor in this region.

These two major fault systems (Steinberg and Leopoldsdorf) are the determining factors for tectonic segmentation of the pre-Quartarnary basement on the western edge of the basin (Plachy 1981).

The Lassee depression with the prominent faults Markgrafneusiedel and Kopfstetten represent a very young feature of the tectonic history in the Vienna Basin. The Middle to Upper Miocene negative flower structure of the Lassee – Kopfstetten strike-slip fault shows post sedimentary activity from the Upper Pannonian onwards and produce an offset of up to several hundreds of meters. (Hoelzel 2009)

In the Slovakian part of the basin the faulting is very complicated, so we unified several faults into a general displacement zone.

In the eastern part, mostly the prolongation of the Kopfstetten strike-slip to normal fault system bound the young late Miocene SW-NE trending Zohor-Plavecky Mikulas graben from the SE.

The NE situated Laksary elevation is cut by the circuit Laksary normal fault with a vertical displacement of up to 1500 meters.

The most westerly situated curveted fault system is modeled like one vertical displacement zone with Hodonin-Gbely system in its northern part.

### 5.2.6 Cross sections

Two cross sections were created out of the geological 3D model (Figure 36), one on the Slovakian and one on the Austrian side of the project area. Bold red lines indicate faults; bold black lines indicate main tectonic surfaces.

Section A is located in Austria and stretches from the Hainburg area with outcropping Mesozoic carbonates and Central Alpine Crystalline units of the Hundsheimer Mountains to the oil field of Matzen, operated by OMV. The section was positioned so that it cuts through all modeled horizons except for the Gosau of the Brezová-Myjava area (restricted to SK terrain) and for the Eggenburgian/Ottnangian (main deposits on SK territory). The region around the Hundsheimer Mountains comprising the thermal water spring in Bad Deutsch Altenburg is an interesting case for the mixture of several trans-boundary water-circulation systems. The remarkable fault on the eastern part of the section is the Kopfstetten fault (Lassee Fault System), displacing the Neogene sediments as well as the underlying units several hundreds of meters.

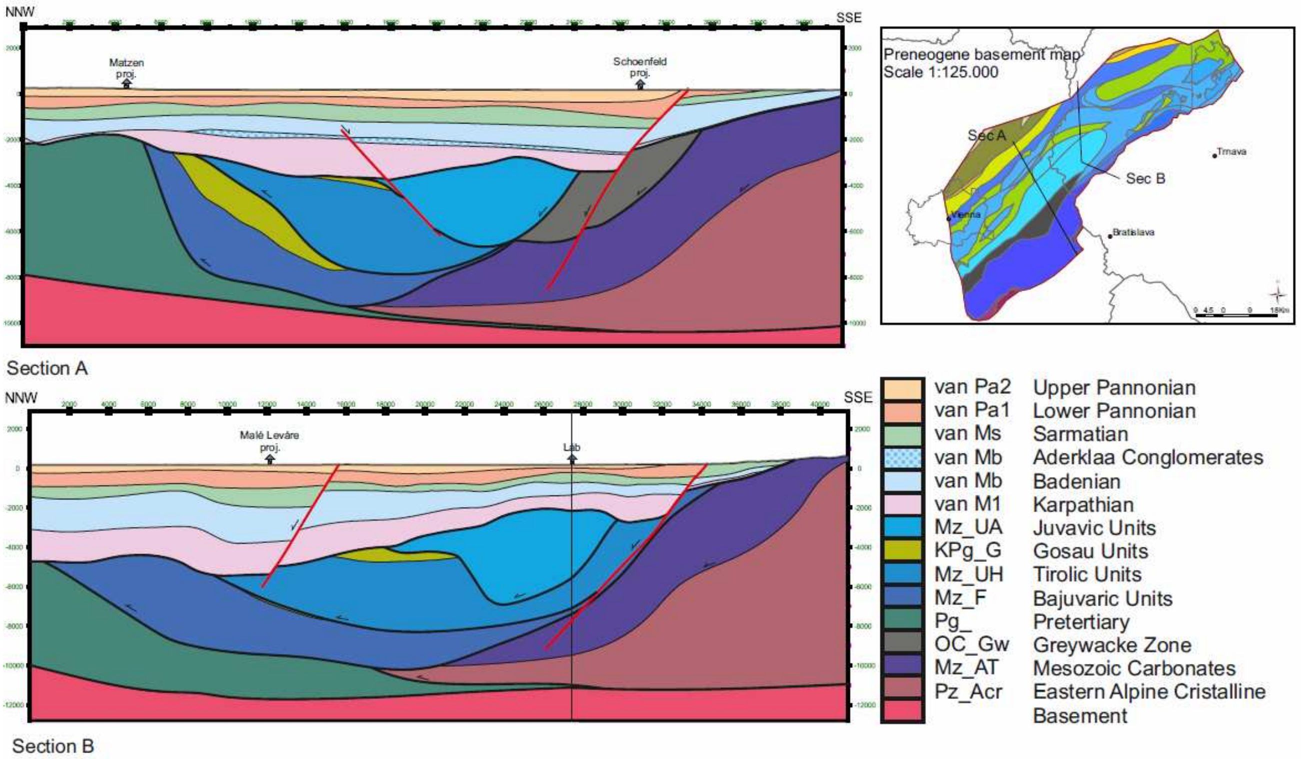


Fig. 36. Cross sections of the Vienna Basin pilot area

Section B is located in the Slovak part of the pilot area and stretches from the outcropping Mesozoic carbonates north-west of the Somár Mountain to the city of Láb from where it prolongs to the city of Sekule, where one of the deepest parts of the Vienna Basin is found. Similar to section A, all modeled surfaces are visualized, except the Gosau of the Brezová-Myjava area, the Eggenburgian/Ottnangian (both more to the north-east) and the Aderklaa conglomerates, which hardly prolong to the Slovakian territory. The geometry of the Mesozoic carbonates, here acting as the main recharge area for the spring in Bad Deutsch Altenburg, is also displayed in this section. In this area, the Kopfstetten fault displaces Neogene sediments as well as the Tirolic units and represents the northern apophysis of this fault.

### 5.2.7 Modelling

As the Vienna Basins Neogene sediments are fairly well known from numerous drillings due to the extensive oil- and gas production, outline for the respective depth of formations and the stratigraphic correlations are present. Parts of the pre-Neogene basement are known from hundreds of drillings but also from seismic surveys, though the deeply buried parts are in fact hardly known. We rely on interpreted and published data like the basement map by Wessely & Kroell (1993) and few cross sections.

The software package GOCAD$^{\text{TM}}$ was used to create the geological 3D models. In combination, the programs ArcGIS (for preparing most of the data and the later visualization of the output) and GOCAD$^{\text{TM}}$ (for the modeling work) provide all necessary tools to create a geological 3D model, but also to later export for further numerical simulations and visualization (Figure 377).

Prepare data in ArcGIS
Digital elevation model
Location of cross sections
Drilling data
Geological surface & subsurface maps

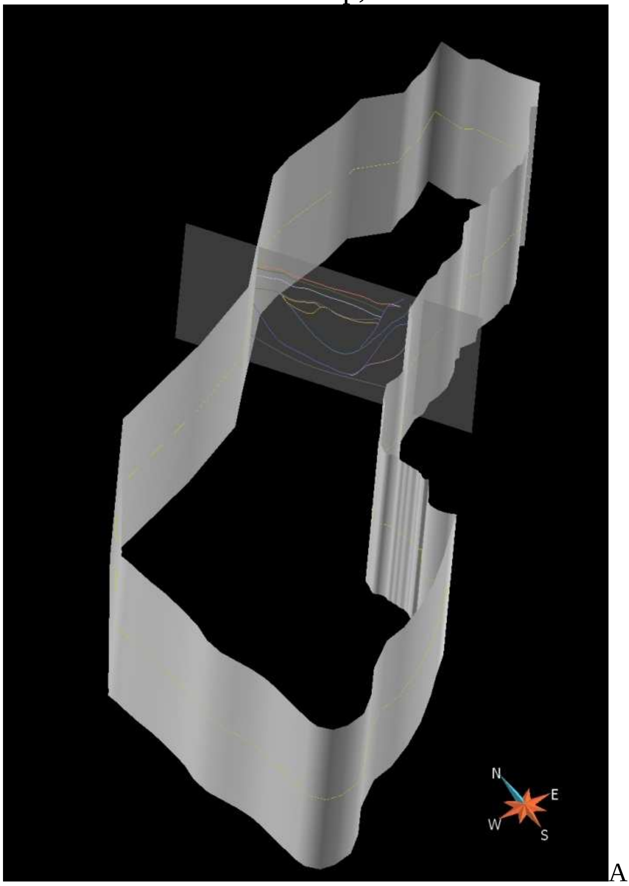
Import and process data in GOCAD $^{\text{TM}}$
Georeference & digitize cross sections
Interpolate horizons individually, cut and displace along faults
Create volumetric information (point clouds, grids)
Export depth maps & cross sections for visualization
Export volumes for further numerical simulations

Fig. 37 Sketch of the general modeling workflow

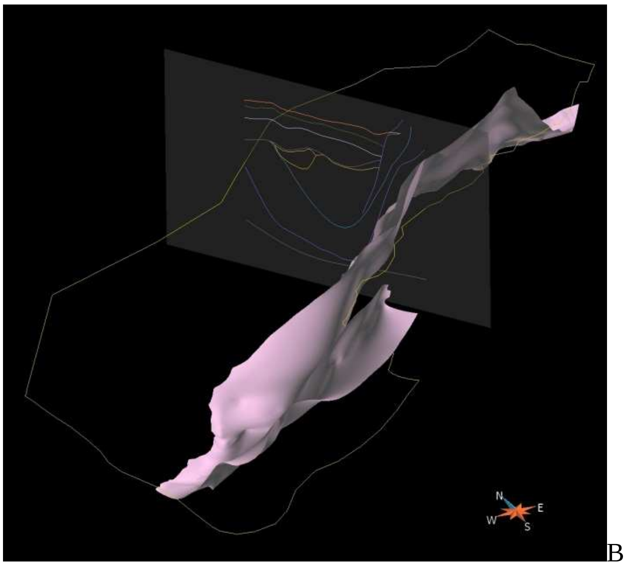
The main inputs for the 3D model were interpreted cross sections (seven in number) created by G. Wessely, (2006), J. Kysela (1983) and B. Leško & Potfaj (1978). They are more or less equally distributed throughout the basin and contain drilling information with seismic data. Well data (about a hundred) were used to define the respective base of the formations in areas where no interpreted cross sections were available, but were also used for georeferencing of the cross sections. All horizons were adjusted to the surface of the pre-Neogene Basement resulting from the published contour lines of the Vienna Basin´s pre-Neogene Basement map (Wessely & Kroell 1993) as it is the best available information regarding this prominent surface. This basement map covers most of the pilot area, except for a relatively small part in the north-eastern part of the Vienna Basin. It also provides the outlines and thus the extent of the pre-Neogene formations under the sedimentary basin fill respectively on the surface. Outlines of the Neogene sediments were used to define the borders and extents of these units. Only faults with a displacement of greater than 500 meters were modeled. Relating to the basement map, the extent of these faults was defined and prolonged to the depth by the interpolated cross sections. All modeled surfaces of the Neogene formations were cut and displaced along faults.

In the Slovakian part of the Vienna Basin, isopach maps (Seifert 1989) of the Neogene sediments in combination with the sparsely existing drilling data were used to model the existing horizons. Two cross sections (from the “General Geological Map of the Slovak Republic 1:200:000, Bratislava 2008”) picturing the basin fill as well as the basement (Kysela 1983 and Lesko & Potfaj 1978) were additionally used for the interpolation. The coherency of the input data for the Slovakian part was not as good as on the Austrian side, thus adjustments of the data had to be done. Drilling information was given the highest priority, afterwards the cross sections and least the interpolated isopach maps.

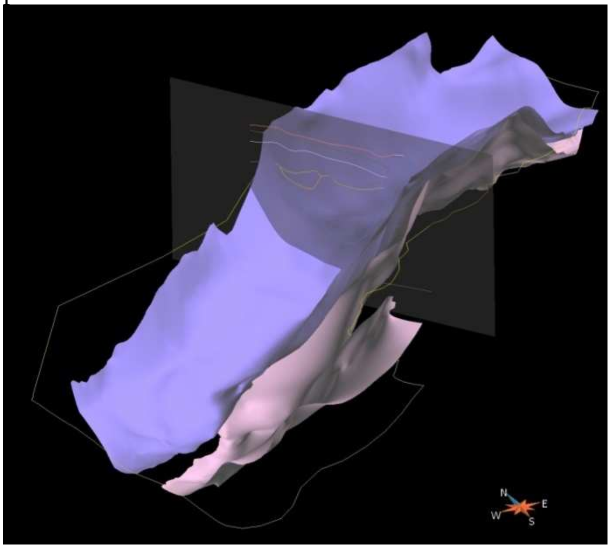
To visualize the surfaces in context, screenshots of the GOCADTM model of the Vienna Basin pilot area were made (vertical exaggeration by factor two). Figure 38 A-J show a series, where first a cross section cutting the model from north-west to south-east is shown and further the model is build-up, each with one surface added.



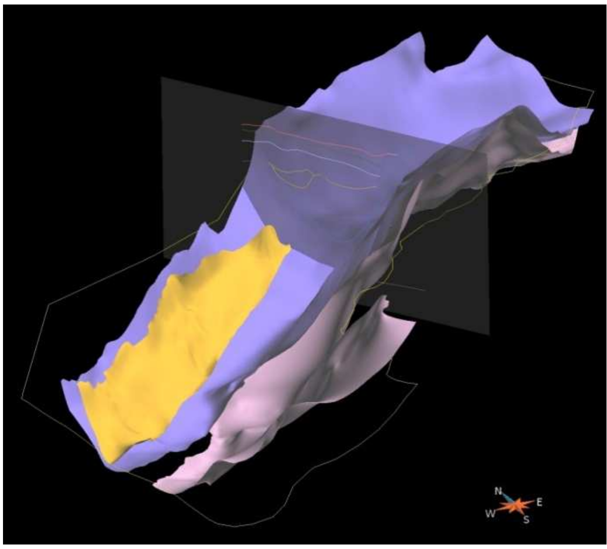
A: North-west – south-east oriented cross section through the pilot area



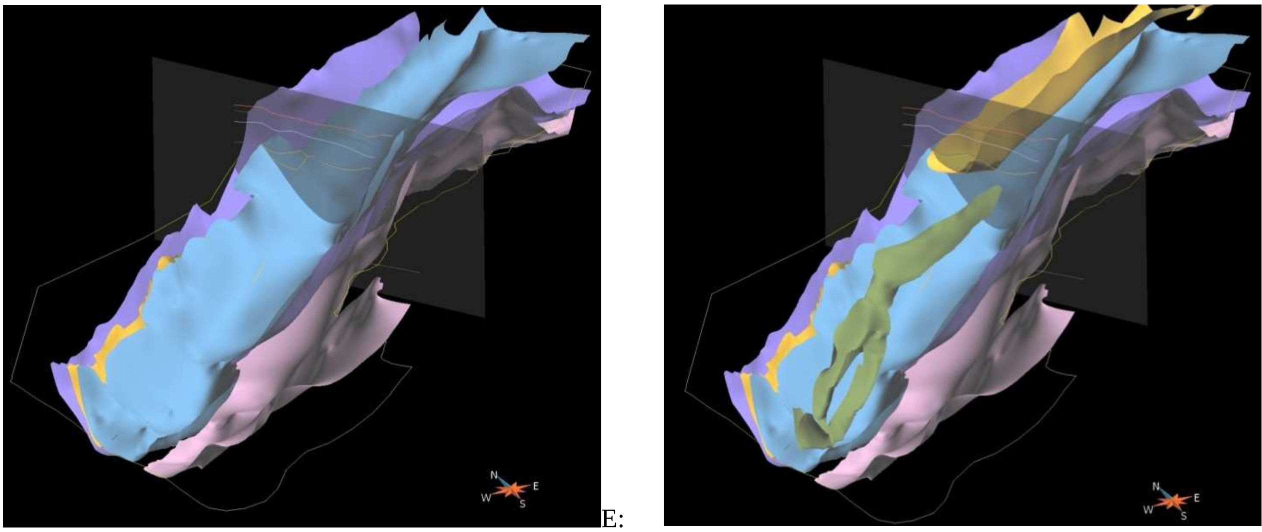
B: Shows the cross section with the horizon of the base Mesozoic Carbonates on the eastern part of the pilot area



C: Adding the base of the Bajuvaric Units (left)



D: Yellow: base of the Giesshuebel Gosau

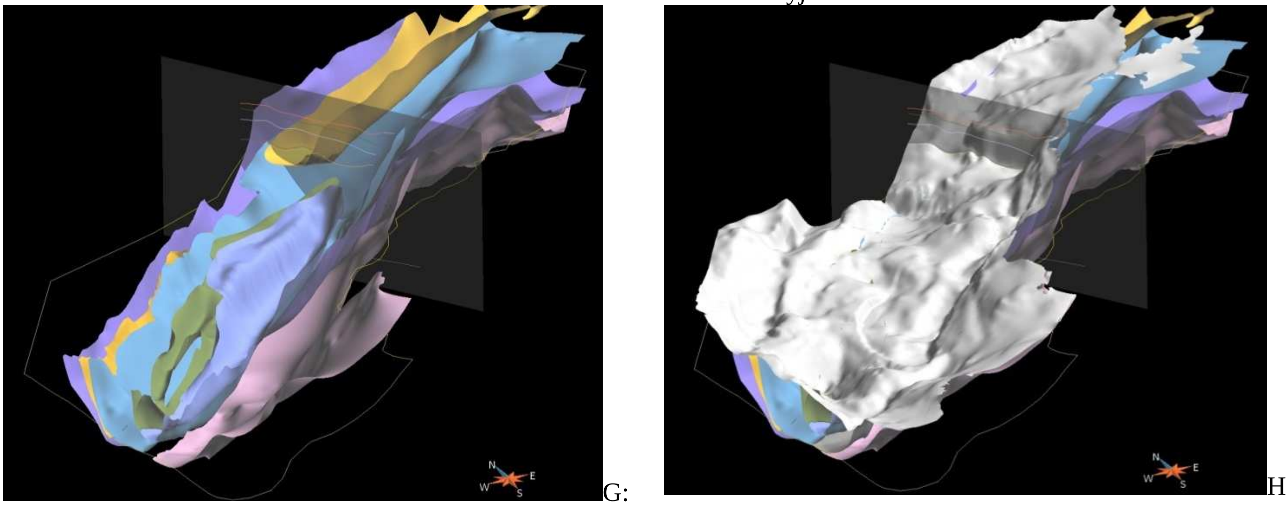


E:

Blue: base of Tirolic Units

F:

Green: base of Gruenbach Gosau; yellow: base of Brezová-Myjava area Gosau

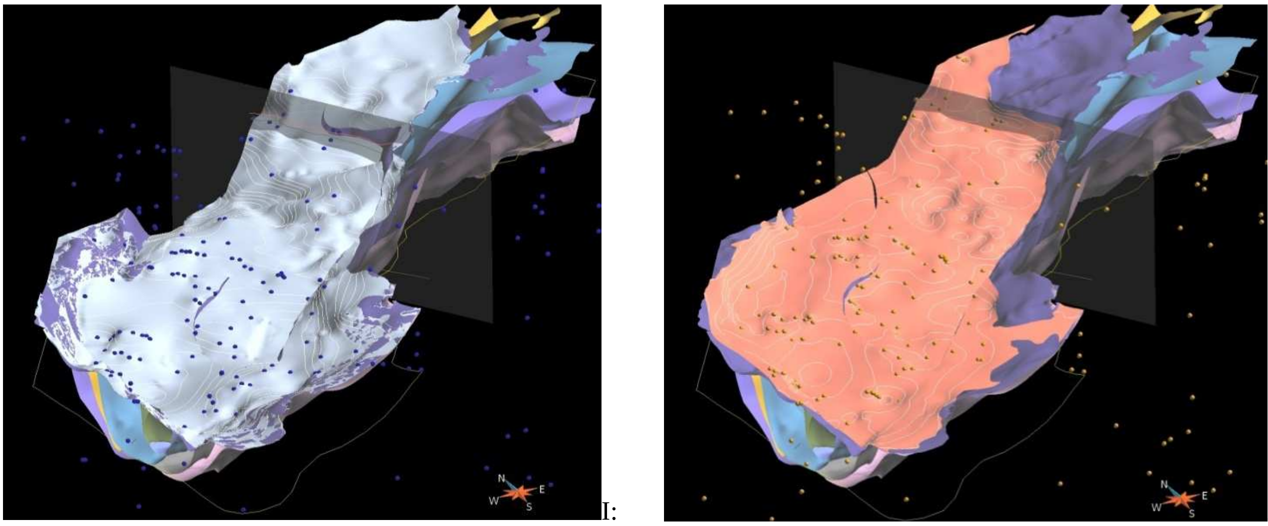


G:

Lavender: base of Juvavic Units

H:

Light grey: base of Neogene Sediments



I:

Light blue: base of Badenian, blue dots: well markers, white lines: 200 m contours

J:

Coral: base of Pannonian, orange dots: well markers, white lines: 200 m contours

Fig. 38. A – J: Sequence of screenshots of cross-sections and surfaces within the Vienna Basin pilot area GOCAD - model.

## 5.3 Lutzmansburg–Zsira

### 5.3.1 Geological frame and history

The Lutzmannsburg – Zsira area is partly built up of a basement high, cropping over the sedimentary cover, which forms a marginal part of the Kisalföld. It has no natural, geologic borders. The basement consists mainly of crystalline rocks of the Austroalpin (Semmering-Wechsel System) and the Penninic (Rechnitz window) units. The Rechnitz Series consists of two complexes: an ophiolite massif with serpentinised ultramafic, metagabbro, greenschist and blueschist association and a metasediment rock complex with calcareous phyllite, quartz-phyllite, metaconglomerate bodies. The Penninic outcrops form the basement at the NW part of the area. Lithologically the Penninic Unit consists of Mesozoic detrital rocks metamorphosed in greenschist facies evolved from basic volcanites (quartzphyllite, calcareous phyllite, meta-conglomerate and different greenschists) that can be examined directly in surface exposures in the Kőszeg Hills with maximal thickness of 594 m in borehole. The age of the original rocks is Jurassic or Early Cretaceous (Császár 1997). The metamorphosis took place during the Eocene and Oligocene, while the uplift, associated to the cooling of the unit occured during the Miocene (Balogh et al. 1983, Dunkl & Demény 1997). Both are affected by low-grade Alpine metamorphism. Similar "Bündenschiefer" and greenschist sequences are exposed in the Tauern Window. The Unit is strongly folded, consists of several internal nappes (Ratschbacher et al. 1990; Dudko & Younes 1990; Neubauer et al. 1992). The protolites are Jurassic oceanic crust formations and pelagic sediments which were rich in marly pelites (Dunkl & Koller 2001). This sequence was subducted during the closure of the South Penninic Ocean and obducted and thrusted in nappe systems during the Tertiary. It was exhumed during the Middle Miocene crustal extension (Tari and Bally 1990, Dunkl & Demény 1997). Units representing a basement high and belonging to the Lower Austro-Alpine nappe unit can be found in the northern part of the area in 1000–2000 m depth and consist of polymetamorphic gneiss and mica-schist. In the SE in 1000–1500 m depth the Devonian marble and calcareous slate belonging to the Upper Austro-Alpine nappes appear.

The pre-Upper Permian formations are traditionally subdivided into low-grade (Szentgotthard Phyllite, Mihály Phyllite, Bük Dolomite, Ölbö Carbonatephyllite) and very low-grade (Nemeskolta Sandstoneschist, Sótony Metabasalt) metamorphic formations. All of them belong to the Rábamente Metamorphic Complex that correlate with the Graz Paleozoic, and are known from the deep drillings from the Szentgotthárd through, the Ölbő area as far as the NNE margin of the Mihályi ridge. Further southward towards Slovenia it probably occurs in the basement along a narrow stripe near the Austrian border. The succession reached by the deep drillings on the Mihályi ridge and its surroundings was interpreted as the result of an Early Paleozoic (Silurian?–Devonian) sedimentary cycle by Fülöp (1990) who considered the Nemeskolta Sandstone as the basal unit of the cycle, then different phyllites (Mihályi Phyllite) would follow with volcanic intercalations (Sótony Metavolcanite) and Devonian carbonate (Bük Dolomite) closes the sequence. The carbonaceous deposition becomes more significant upwards in the sequence. The correlation of the schist at Szentgotthárd with the Mihályi Phyllite is uncertain, so they are treated separately. Part of these rocks can be attributed to the Lower Paleozoic rocks of the Transdanubian Range, and they have Paleozoic K-Ar ages around 315 Ma (Árkai & Balogh 1989). On the other hand, schist of Szentgotthárd, and the phyllite of Mihályi show K-Ar ages of 180 to 116 Ma (Árkai & Balogh 1989). This refers to the effect of the Alpine orogeny in the discussed rocks, thus the K-Ar data can be interpreted as mixed ages that partly became rejuvenated. Among others, this makes it possible to distinguish these rocks from the very similar low-grade metamorphites of the Transdanubian Range Unit.

In a few boreholes, the metasediments contain fossils (Lombardia?, Tintinnida?, Echinodermata?) which might suggest Late Juassic?–Early Cretaceous? depositional age. Although this paleontological result was not confirmed, Haas et al. (2010) figured a small unit composed of late Mesozoic metasediments, the Ikervár unit. Its structural position is probably between the Graz Paleozoic and Transdanubian Range units.

The main basement formation of the area is the Bük Dolomite, which was exposed in numerous boreholes around the SE part of the pilot arae (Bük, Ölbö, Rábasömjén, Nemeskolta, Ikervár). The maximal thickness of Bük Dolomite Formation is 280 m.

The non-metamorphic sedimentary cover starts with Early Miocene (eggenburgian) rocks. The basin fill sequence summary is presented at the Danube basin pilot area. The Miocen-Pannonian porous sediment series has growing thickness toward E-SE. The maximum thichness is 2000 m at the eastern part of the region. The lithostratigraphic-chronostratigraphic harmonization of the Neogene sedimentary cover sequence is the task of the Slovakian, Austrian and Hungarian participants by means of e.g. Császár et al. (1998).

During the Eggenburgian and Ottnangian the study area was characterized by continental sedimentation on the erosional surface of the paleo-mezozoic rocks. It unconformably overlies the tectonically pre-, and synformed Mesozoic basement, and is unconformably overlain by the Szilágyi, Kozárdi, Lajta or younger ‘Pannonian’ formations. In the middle (HU) and the northern (A) region (in foreland of Kőszeg Mts.) limnic, marsh or deep paludal succession with lignite seams and with unsorted clastic basal beds were deposited (Brennberg Formation). It is assigned to the Ottnangian only on the basis of its overlying succession of Karpatian-lower Badenian age (Ligeterdő Gravel Formation, “Auwaldschotter”), which is made up mainly of fluvial, subordinately brackish water gravel, conglomerate, sand and marl. Starting from the base the first two members (Alsóligeterdő Gravel Member and Felsőligeterdő Gravel Member) are fluvial sandstones or conglomerates with pebbles derived from the crystalline basement.

Due to early Badenian tectonic movements the main sedimentary basin existed in the area of the region: the Csapod Trough in its southeastern part (it came into being due to early Badenian tectonic movements). This marine depression was divided by the Mihályi Ridge. The lower part of the lower Badenian is missing all over the area due to early Badenian tectonic movements and erosion. Badenian successions start with the upper part of the lower Badenian with abrasional basal breccia and conglomerate, locally with calcareous matrix (Pusztamiske Formation). In marginal, shallow marine facies it is overlain by corallinacean limestone (“Leithakalk”, Lajta Formation). Nearshore facies are characterized by grey, greenish-grey sand-sandstone (Pusztamiske Formation). Offshore deep-basin (shallow bathyal) facies are represented by fine siliciclastic sediments: sandy silt, silty clay marl with sandstone intercalations (Tekeres Formation), and sandy-silty claymarl, which in spite of being an “atypical Baden Clay” (formerly known as “Tortonian Schlier”), has been classified into the Baden Formation. In several borehole sections thick siliciclastic successions can be observed, which, based on biostratigraphic investigations, can be divided into lower and upper Badenian (the deposition of upper Badenian siliciclastic sediments (Szilágy Clay Marl Formation) and are due to the renewed flooding in the late Badenian. Lithologically, the top of the lower Badenian can locally be marked by the appearance of gypsum and dolomite laminae, which can be correlated with the sea level drop at about 14.2 Ma. In shallow marine environments deposition of the „Leithakalk” went on.

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 (mollusc-bearing limestone, and oolithic limestone, Cerithium limestone) of shoreline facies (Tinnye Formation) and fine-siliciclastic sediments (grey, greenish-grey clay marl, sand, silty clay marl) of shallow-marine facies (Kozárd Formation) were deposited. The upper Sarmatian carbonate successions indicate a considerably productive carbonate factory of subtropical climate (Persian-Gulf-type ooids), reflecting to hypersaline or hypercalcareous conditions, thus the previous brackish-water hypothesis is under debate.

The Pannonian sequence in the study area is a shelf-slope system prograded chiefly from northwest to southeast. During the Upper Miocene (Pannonian) a more or less uniform Pannonian Basin developed, the formation of which may have been started in the late Sarmatian. Predominantly fine-siliciclastic sequences of different facies accumulated in the Csapod-trough along the synsedimentary normal fault to the basin on the southeastern part of the area (Endrőd Fm.). The overwhelming part of the successions of the deeper basin facies (Endrőd Formation) is made up homogeneous pelitic deposits; distal turbidites are represented by separate sand bodies (Szolnok Formation). Underwater slope (delta slope and basin slope) sediments are represented predominantly by dark grey clay marl as coarser sediments were carried further basinwards to be deposited as turbidites (Algyő Formation). Sand bodies occurring along the fluvial delta fronts belong to the Újfalu Formation on the northwestern part of area. Deposits of the alluvial plain are represented by the frequent alternation of fluvial and lacustrine fine grained sand, silt, clay and clay marl beds locally with lignite strips (Zagyva Formation).

By the end of the Late Miocene, rivers running down from the neighbouring mountains filled up the basin, and a continental terrain came into being in the area of the former basin).

### 5.3.2 Additional horizons

The geological horizons are shown in Enclosures 4.1 − 4.15. Extra horizon in the Lutzmannsburg-Zsira pilot area is the “basement of Devonian formations”. The low grade metamorphic Devonian carbonate formation (Bük F.) is the main reservoirs of thermal water, therefore it is very important for the hydrogeological model. Basement of Devonian Bük formation are the very low grade metamorphic Nemeskolta Sandstone/schits and Sótony Metabasalt formations. All of these formations occur in the subsurface below the Bük Formation near Bük and more deeply downsliped by the synrift Répce-fault near Ölbő.

The Devonian formations occur in two patches in the area. The boundary of the Devonian formations in the northwestern patch are the thrust front between Upper and Lower Austroalpine Units on the northwestern, and younger normal fault on the southeastern part. The boundaries of the southeastern patch are stratigraphical on the southern and the eastern part, and structural (younger normal faults) on the northwestern part.

### 5.3.3 Descriptions of additional horizon’s formations

No extra formations identified in addition to Graz Paleozoic (SD_G) and Bük Formation (Dmb) which description is provided in chapter 4.2.

### 5.3.4 Geophysical evaluations: gravity, seismics, magnetotellury

Across the project area, 11 main 2D seismic profiles were available for us: just from the Hungarian part of the project area. The images of the profiles in electronic format (SEG-Y files) have been visualized and interpreted in KINGDOM 8.5 sotfware. This software makes it possible to track the identified horizons and fault and nappe surfaces along the profiles, to correlate them at the intersections and to export their interpreted positions. In the exported datasets, the horizons are sampled with X, Y, Z coordinates in intervals of 100-200 m along each profile.

### 5.3.5 Tectonics

The basement of the area NW of the Rába river (Rába tectonic line) is made up of metamorphic rocks, which crop out to the surface in the Sopron Mts. and Kőszeg Mts., and represent the extensions of the East Alpine nappe units towards Hungary.

There are two main thrust planes constructed by Alpine tectogenetical cycle. The Alpine thrust planes are located on the margin of Rechnitz-window between Penninic and Upper Austroalpine Units in the middle of the area. Furthermore, another thrust plane is located between the Upper and Lower Austroalpine Units on the northern part of the area (Figure 39). Both of these tectonic planes occur as significant lines in the seismic profiles.

The thrust planes, formed in the Middle and Upper Cretaceous were separated by normal faults in the Paleogene (Balogh & Dunkl 2005) and Early Miocene (prerift phase of the Pannonian Basin). This normal fault tectonics was connected to the basement exhumation structure of the Rechnitz-window core-complex (Tari 1994).

The Lower Miocene siliciclastic and debris sediments have been deposited in the morphological lowlands on the tectonically preformed surface of the crystalline units. The subsequent Miocene depositional sequence covered the thrusts in Badenian.

The third main structural element of the pilot area is a younger normal fault which formed in the synrift phase of the Pannonian Basin. The repeatedly reactivated normal fault is located in the southeastern part of the pilot area (in Hungary). The NE-SW strike normal fault is detected in the boreholes of Bük to the southeast and northwest of Ölbő boreholes, cutting across the Lower Pannonian basement, the Miocene formations and faulted the formations of the Upper Austroalpine Units including the Bük Dolomite Formation (Fig. 37) and the thrust plane between the Upper and Lower Austroalpine Units (out of pilot area). This significant fault was called „Répce-fault” by Tari (1994).

On the eastern side of the younger normal fault (on the hanging wall) faulted Badenian, Sarmatian and upper part of Lower Pannonian deep water sediments are found, indicating the synsedimentary nature of the normal fault. The normal fault is covered by the basinward prograding Lower Pannonian delta slope and Upper Pannonian delta front, delta plain, alluvial and alluvial plain sediments.

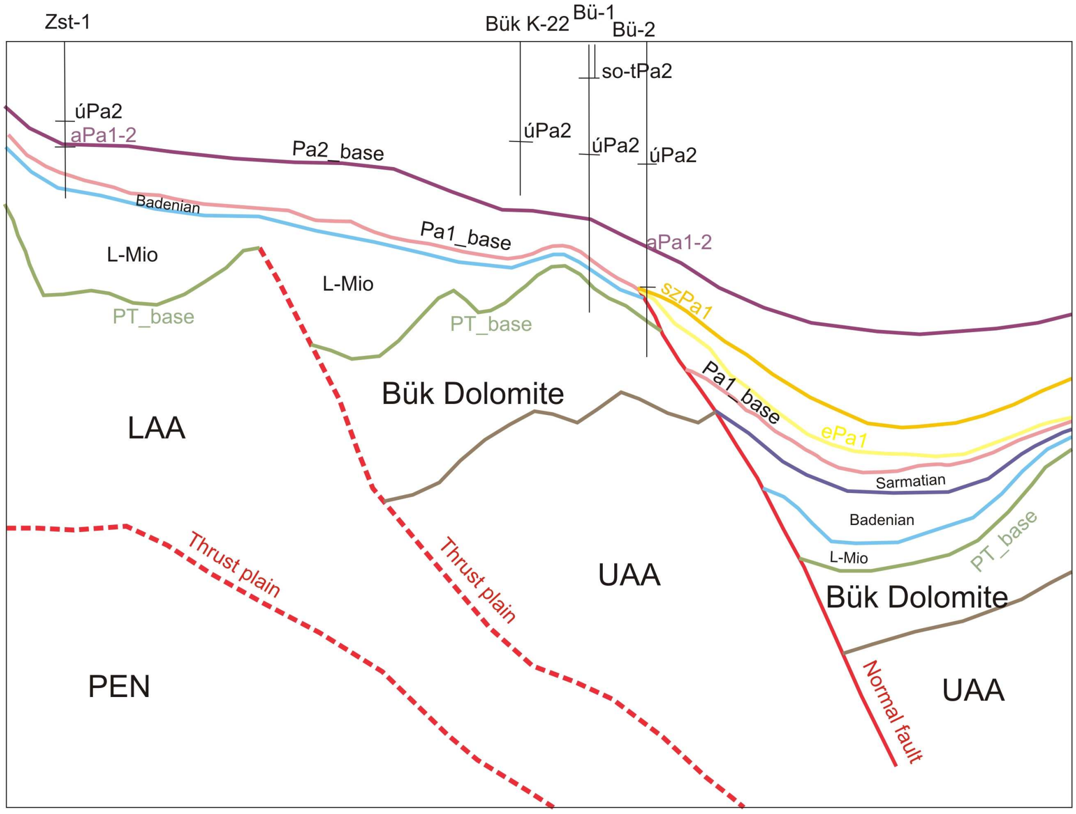


Fig. 39. Main structural elements in the seismic section at the eastern part of the Lutzmannsburg-Zsira pilot area (Hungary). UAA – Upper Austroalpine Unit, LAA – Lower Austroalpine Unit, PEN – Penninic Unit

### 5.3.6 Cross sections

Two geological cross sections were edited in the Lutzmannsburg-Zsira pilot area (Fig. 40, Encl. 4.16.). The 70 km long NW-SE direction geological cross sections (PT_L_1) is cutting the main structural elements, and demonstrate well the geological buildup of the area. The PT_L_1 geological cross sections is located along two seismic profiles (XK-489 and VCSA 17) and goes through some key-boreholes (Zst-1, Bü-1, Bü-2) which are important for the hydrogeological models. It can be concluded that the Alpine thrusting and later reactivation of these thrusts is important in the amount of area of the crystalline metamorphic and low grade metamorphic carbonate in the basement. At the same time the distribution of the younger sediments is controlled by the synrift normal faults on the eastern part of the area. The geological cross sections show well the thickening of the Pannonian layers to the east and the synsedimentary fault activity in the Middle and Upper Miocene (Pannonian) times.

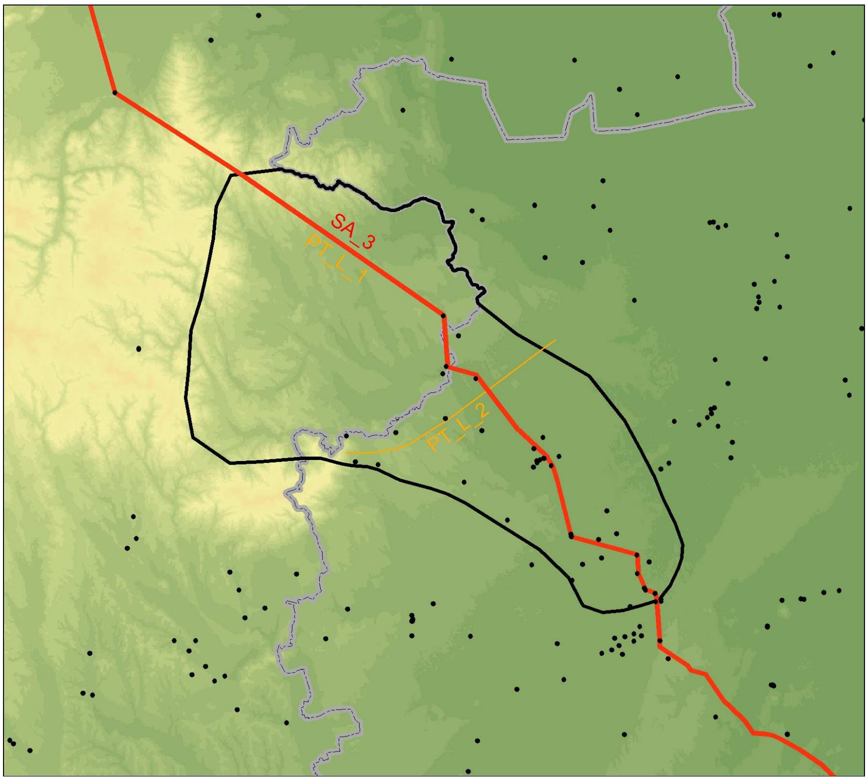


Fig. 40. Cross section lines in the Lutzmansburg-Zsira Pilot area

On the northwestern part of the pilot area the younger layers pinched out on the pre-Terciary surface.

The 25 km long NE-SW strike geological cross section (PT_L_2) is approximately parallel to the the strikes of the basinfill sediments, but cross cutting the two main alpine thrust planes. The geological profile shows well the connection of the Upper Austroalpine and the Penninic Units.

### 5.3.7 Modelling

The geological model of the Lutmannsburg-Zsira pilot area was done by the software Jewel. The 3D geological modelling started with the collection of base datasets, which included borehole data, previously compiled surface models and linear shapes, like the area boundary and the geological map contents (i.e. tectonic lines).

The coordinates of the modelling area was derived from the minimum and maximum coordinates of the sub area shape with a 1000m puffer zone, thus a rectangular block was defined in the modelling environment which gave the frames of the 3D model in the process. The fence coordinates of the modelling area in UTM-33N:

Easting: 596780 – 650675
Northing: 5232019 – 5280328

Due to the planned modelling workflow, the model horizons of the pilot area derived from the supra regional subsurface horizons in those cases, where it was available. Firstly all previously compiled horizons were clipped to fit in the modelling area. The original 100x100 m grid resolutions of the horizon-models were preserved.

Linear elements, like the tectonic lines, the intersections and the boundaries of the main horizons were collected from the geological maps and were draped onto the subsurface horizons respectively.

The 3D objects of the faults and thrusts were processed manually in accordance with the map data until the desired geometry of the fault surfaces were created, however the original datasets of the tectonic elements were created from 2D seismic data. Total number of tectonic objects for the Lutzmannsburg-Zsira pilot area is 5 (Table 3.).

Table 3. Named tectonic surfaces and their parameters in the geological model of the Lutzmannsburg-Zsira pilot area.

| | Object | Points No | Mean dip (deg) | Mean azimuth (deg) |
|---|---|---|---|---|
| 1 | Penninian nappe thrust | 5824 | 24.8 | 116 |
| 2 | Intra-Upper AuAlp normal fault | 2679 | 31 | 104 |
| 3 | Lower-Upper AuAlp nappe thrust | 13901 | 27.6 | 148 |
| 4 | Lower-Upper AuAlp nappe thrust hw (unsure) | 964 | 33.7 | 139 |
| 5 | Penninian nappe thrust_erroded | 5413 | 22 | 154 |
| 6 | Lower-Upper AuAlp nappe thrust _1 | 449 | 22.3 | 152 |

In JewelSuite the well, top, and horizon data should all be conform with each-other in order to create the 3D model. Thus after importing the base data, horizon-well correlations were executed. The inconsistencies, revealed by the data validation of the model, were corrected in the modelling environ, and the final model was verified for each horizon using kriging with isometric exponential function.

Some modeled surfaces for the Lutzmannsburg-Zsira ara are shown on Figures 41-45.

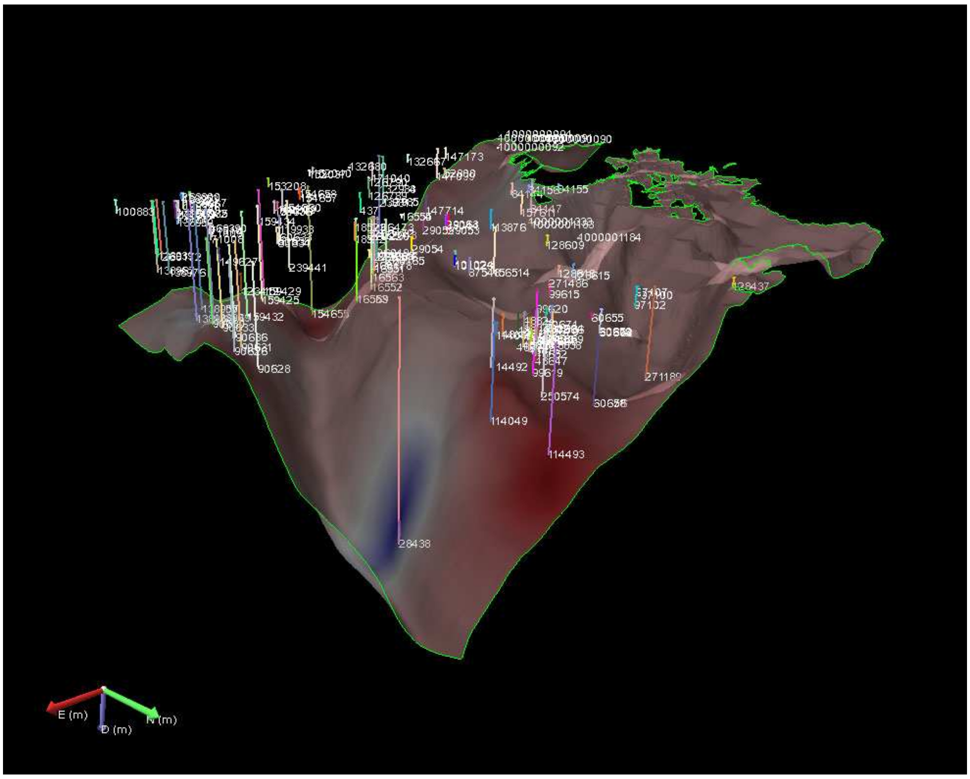


Fig. 41. Pre-Cenozoic horizon model of the Lutzmannsburg-Zsira pilot area from NE viewpoint.

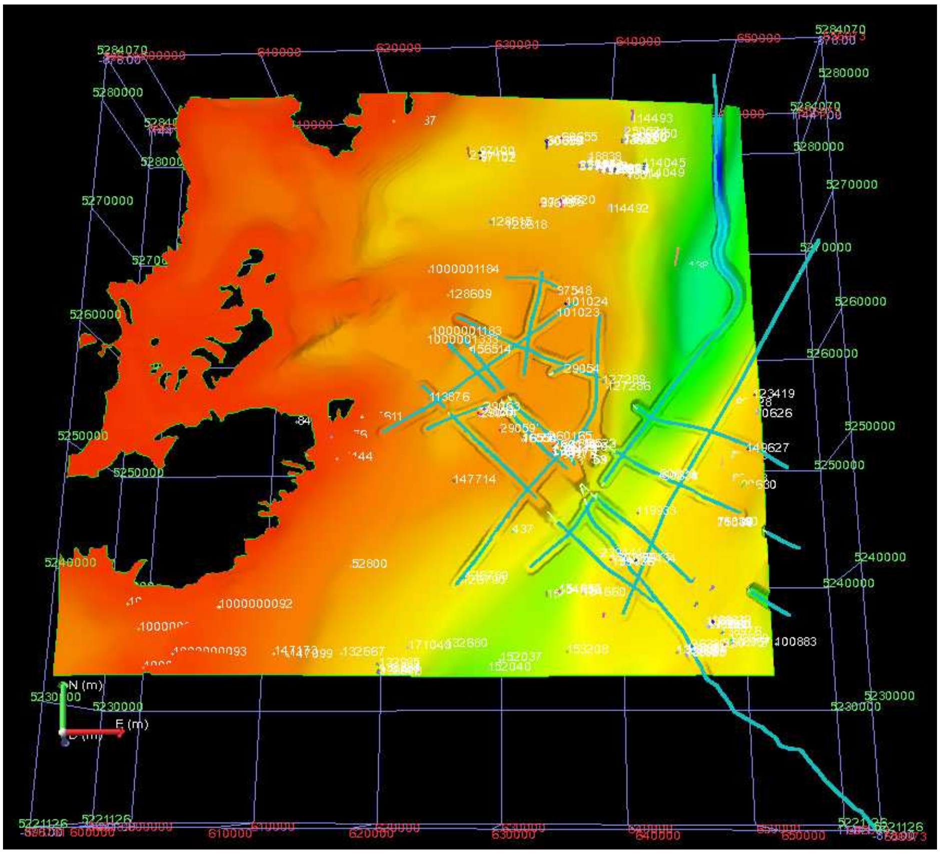


Fig. 42. Pre-Cenozoic horizon model of the Lutzmannsburg-Zsira pilot area with seismic data

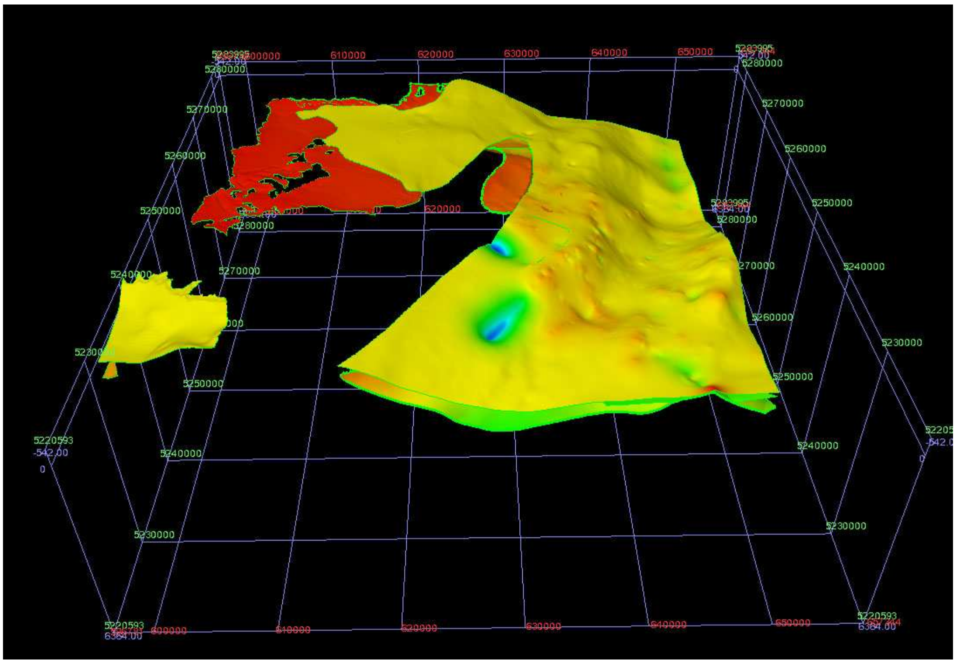


Fig. 43. Pre-Pannonian horizon model of the Lutzmannsburg-Zsira pilot area without SRTM, from the south viewpoint.

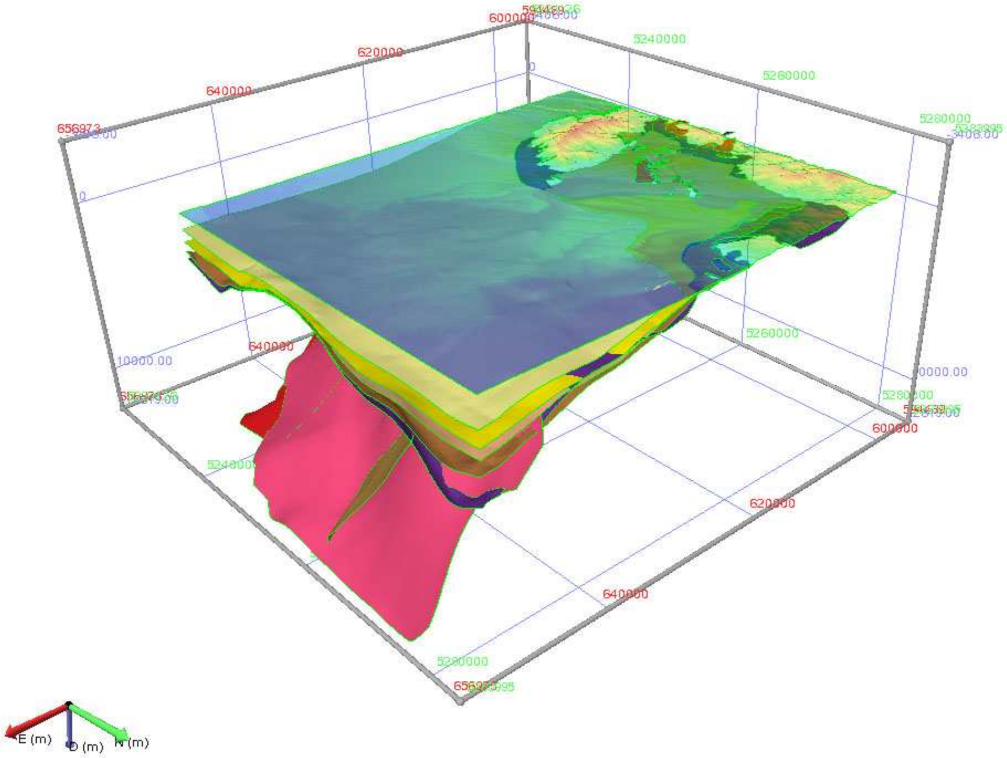


Fig. 44. 3D model of the Lutzmannsburg-Zsira pilot area from the NE.

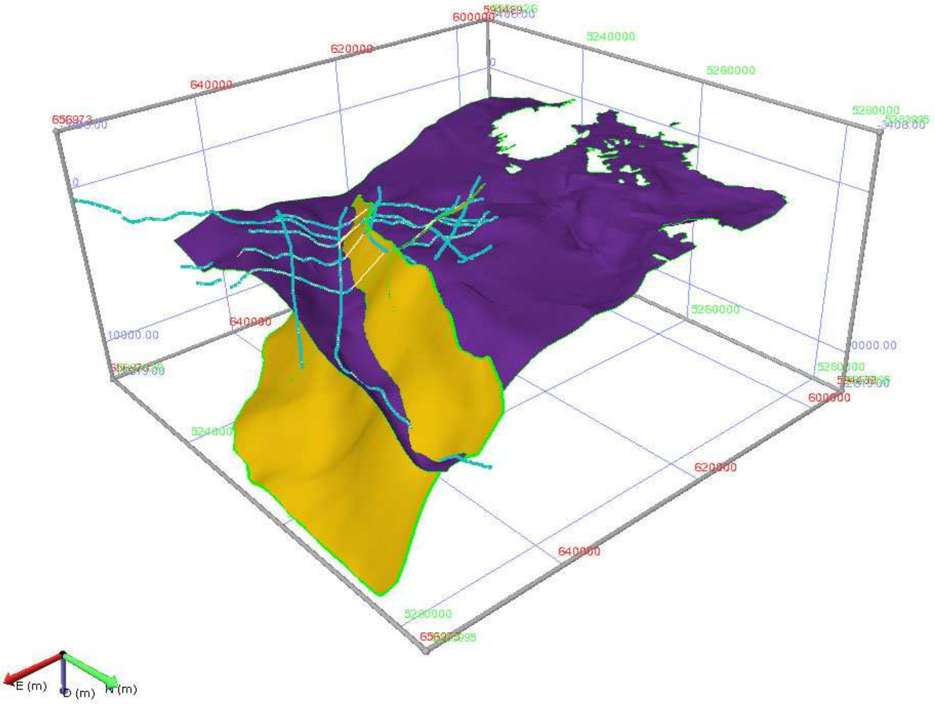


Fig 45. The models of the Pre-Cenozoic horizon and the Intra-Austro-Alpian normal fault from the NE. The seismic data was imported to enhance the model of the horizons.

## 5.4 Bad Radkersburg–Hodos

### 5.4.1 Geological frame and history

The Bad Radkersburg–Hodos pilot area is situated in the southwestern part of the supra area. The bulk of the pilot area occupies the southwestern part of the Transdanubian Range Unit bordered by the Rába Line to the northwest. To the west, the pilot area encompasses a small portion of the Styrian Basin. Along the Rába line, the Southburgenland Swell divides the Mureck Sub-basin (a southernmost part of the Styrian Basin) from the Radgona–Vas Subbasin (eroneously named also Mureck Sub-basin by some authors). To the south, the pilot area encompasses the Radgona–Vas Sub-basin and the nothwestern part of the Murska Sobota High. To the north-east, the Bad Radkersburg–Hodos pilot area includes also the East Mura–Őrség Sub-basin. The latter is bounded by the NNW trending Baján fault to the west.

Relatively large part of the pilot area basement is represented by the Koralpe-Pohorje-Wölz megaunit, representing the deepest rock unit. It extends from the pre-Cenozoic base of the Syrian Basin via the Southburgenland Swell in Austria to Slovenia, and plunges eastward under the thick Mesozoic sedimentary sequences in Hungary. It is composed of polymetamorphic rocks, which are strongly affected by Alpine tectonothermal events. Lithologically gneisses, micaschists and amphibolites prevail, showing high pressure and even ultra-high pressure metamorphism, detected at the easternmost edge of the Pohorje Massif near Slovenska Bistrica (Janák et al. 2006). Upper Cretaceous collision built up the nappe structure of the area. Three major thrusts (thrust sheets) are known: Strojna thrust, Dravograd thrust and the biggest one (also called nappe), Remschnig thrust. The Strojna thrust consists of chlorite-amphibole and biotite chlorite schists (lower part of the Kobansko and Phyllite Fm.: *CaOph*, excluding phyllonites and mylonites). The overlying Dravograd thrust is represented by phyllite (upper part of the Kobansko and Phyllite Fm), while the uppermost Remschnig thrust consists of the Magdalensberg phyllitoid rocks (Magdalensberg Fm.: *OSsh*). This succession is not continuous. Namely, the Dravograd and the Remschnig thrusts can be thrusted directly onto the Pohorje Fm. Internally, the thrust sheets show decreasing metamorphic degree from the uppermost to the lowermost greenschist facies. Together these thrusts form Krško nappe (Gurktaler Decke), a structural duplex with imbricated internal structure. Relatively thick layer of mylonites and locally phyllonites formed as a result of thrusting. Due to lack of data, these units are not strictly divided in the deep parts of the pilot area entering the Hungarian territory, where none of the boreholes reached them. Therefore they are merged into the common Paleozoic-Mesozoic unit (*Pz_Mz*).

Most of these tectonic structures have been cross-cut and dismembered by east-west strike slip tectonics represented by a wider tectonic zone of the Rába Line, continuing to the Radgona–Vas Subbasin. They were reactivated in later tectonic events, which resulted in relatively good fracture porosity of the otherwise impermeable basement rocks.

After a considerable tectono-stratigraphic gap, Permian clastic rocks (Pt) were deposited on the Magdalensberg phyllitoids. The only locality of their occurrence is in the Šom-1 borehole NE of Maribor. As their deposition was mostly fluvial within restricted basins, it is not surprising that they are not more widespread.

Very limited sheets of Triassic dolomites overlay Permian and metamorphic basement within the Radgona–Vas Subbasin, and also on the northern slope of the Murska Sobota High. They have thrust boundary with the underlying formations and are interpreted as remnants of the North Karavanke thrust (nappe). The dolomites are strongly brecciated and are determined as belonging to the Upper Triassic Main Dolomite Fm (T3d).

In association with the dolomite, but tectonically bounded, the occurrence of the Gosau Fm rocks (KPg_G) are shown in the area of the NE slope of the Murska Sobota High. This only about 200 m thick patch represents remnant of the restricted Upper Cretaceous basin dismembered by the strike-slip tectonics. As already mentioned, the Mesozoic rocks and particularly the Senonian formations reach significantly greater spread and thickness eastwards, in the Hungarian part of the pilot area, east of the Baján detachment fault.

The bulk of this thick Mesozoic succession is built up of Upper Triassic deposits. The Upper Triassic begins with an intraplatform basin marl and calcareous marl (Veszprém Fm, Tkbls) with limestone intercalations in its upper part (Sándorhegy Fm, Tkbls). Norian–Rhaetian is represented by thick (probably up to a few thousand meters) shallow marine carbonates. Within them, the lower deposit is Main Dolomite (T3d), which is overlain by Kössen Marl (T3bls) with high organic content and thickness up to 400 m. That can be covered by Dachstein Limestone (T3ls), which is followed by the relatively thick (condensed) layers of chiefly pelagic Jurassic sediments (J) in the succession of the Transdanubian Range Unit, but they are mostly eroded in the studied area. However, deposits of the next sedimentary cycle (the Senonian) occur in a large part of the pilot area. The Senonian strata are composed of marls (Jákó and Polány Fm, K2ml) with interfingering limestones (Ugod Limestone, K2ls).

Tectonic events in Early Miocene rearranged the relief significantly. Newly formed large basins were separated by the swells into sub-basins. In the pilot area the Southburgenland Swell separates Mureck and Radgona–Vas Sub-basins (Figure 46). The Murska Sobota High also acts as a swell bounding the Radgona–Vas Sub-basin to the southeast. To the northeast, the East Mura–Őrség Sub-basin was formed along the Baján fault. Subsided basins were filled by coarse-grained poorly sorted limno-fluvial and fan deposits followed by the finer grained “schlier-like” sedimentation (*Mkb*). In Mureck and the Radgona–Vas Sub-basins these deposits are Ottnangian to Middle Badenian age; in the central region of the Mureck Sub-basin, some Upper Badenian sediments can be also found (well Mureck 1). Limno-fluvial deposits (attaining thickness up to 500 m) prevail in the Ottnangian in the Mureck Sub-basin. A similar unit appears somewhat later, presumably in the Karpatian (as Haloze Formation) in the Radgona–Vas Sub-basin according to Jelen et al. (2006). Relatively uplifted areas (the Southburgenland swell and the Murska Sobota High) were exposed to erosion at that time, except for the southwesternmost part of the Southburgenland Swell, which was transgressed in the Karpatian. In the East Mura–Őrség Sub-basin the sedimentation begun in the uppermost Ottnangian with coarse-grained Ligeterdő Fm (*M1fc*) and continued into the lower part of the finer grained Tekeres (schlier) Formation (*Mkb_czt*, *Mkb*) of Karpatian to Badenian age.

A substantial volcano was active along the north-western margin of the Southburgenland Swell during the Karpatian and Badenian. The trachyandesitic to dacitic volcanites are present on the Austrian part of the pilot area as “Gleichenberg volcanic rocks”, while in Slovenia relatively thin Ranča tuff beds (Mbtu) presumably reflect the Badenian activity of this volcano. These tuff beds are a part of the Haloze Formation.

After the Styrian unconformity (Karpatian/Badenian) marking a short tectonic inversion associated with sea level drop, another transgression followed accompanied by subsidence. In the flooded areas sand, limestone and sandstones, sandy shales and occasional gravels deposited in the shallow water. Vast areas were covered by the sea at that time. Sedimentation of hemipelagic mud took place only in the distal parts of the Sub-basins.. In the southern (Slovenian) part of the pilot area, lower part of the Špilje Formation represents mostly shallow water deposits, as the western part of the Radgona–Vas Sub-basin was already filled up by the end of Badenian. In the northeast, in the East Mura–Őrség Sub-basin in the Hungarian part of the pilot area, the lower part of Špilje Formation is correlated with the upper part of the Tekeres Formation and the Szilágy Formation.

In the Mureck Sub-basin, the marine-basinal Badenian deposits (clayey marl, sandy marl – Mkb) can reach a thickness up to 450 m. Similar sediments with lower thickness cover the previously drowned part of the Southburgenland swell (in the transition zone to Radgona–Vas Sub-basin). The continuation of the swell to northeast (around the country border point of Slovenia, Austria and Hungary) was also flooded by shallow water in the Badenian, allowing the deposition of the Leitha Limestone (Mbls). Further to northeast, a part of the swell was tectonically deepened establishing a connection to the Raab Trough ("Weichselbaum depression") in the area of Jennersdorf. However, Badenian deposits are not present on the northeasternmost part of the Southburgenland Swell.

Regression in the early Sarmatian marks the boundary between the syn-rift and the post-rift stage. Lower Sarmatian is therefore characterised by the sand rich turbidites in the basins and the uplift and consequently erosion of the relatively elevated areas. Tidal sands and occasional limestones (Msls) are varying with the shallow water marls and occasional gravels in the Southern part of the pilot area, where these sediments (Msmf) form the upper part of the Špilje Formation. To the north-east, it is correlated with the Kozárd Formation in Hungary. In Austria, the Sarmatian deposits cover large areas of the Gleichenberg volcanites. Sarmatian sedimentation probably also took place in the Mureck Sub-basin, however, this succession (with estimated original thickness exceeding 300 m) has been eroded since then.

Transgression flooded vast areas in the Lower Pannonian, however, the marine connection of the basin had ceased for that time. As the sub-basins in the western part of the pilot area were already filled up, deposition of the shallow water sandy marls and clays took place there. These sediments still belong to the upper part of the Špilje Formation. To the east, the East Mura–Őrség Sub-basin still existed, and the deposition of the deepwater transgressional Endrőd Marl Formation (Mpcm) took place there.

Due to ongoing erosion of the Alps in the northwest, large delta and shelf-slope systems evolved in the north-western part of the pilot area. Prograding deltas and shelf-slopes provided the material for the sandy turbidites (Mptb) which make up the lower part (Jeruzalem Member) of the Lendava Formation, which is equivalent to the Szolnok Formation in the northwestern part in Hungary. The shelf-slope was formed between the prograding delta fronts and the deep basins (the latter providing space for the deposition of turbidites). Slope deposits are built up of mostly fine-grained sediments, which eventually covered the turbidites as the whole system prograded basinwards. The fine-grained slope deposits (Mplf) represent the Algyő Formation in the northeastern part of the pilot area, and correspond to the upper part (Sodinci Member) of the Lendava Formation in Slovenia.

The sediments of the prograding deltaic system belong to Mura Formation in Slovenia, and Újfalu Formation in Hungary. This part of the succession can be divided into two parts. The lower one (Mdr) represents mostly sandy delta front deposits, while the upper part (Md) represents delta plain sedimentation characterised by prevailing silt and clay with occurrences of coal and occasional gravel channels.

Sediments of the alluvial plain (*MPl_f*) are deposited on top of the delta plain. In Slovenia they are represented by the Ptuj–Grad formation (containing numerous gravel bodies) corresponding to the sandy to muddy Zagyva and Nagyalföld Formations in Hungary. Because these alluvial sediments cannot be divided from the underlying delta plain deposits, they are not modelled separately, but merged with the underlying deltaic sediments.

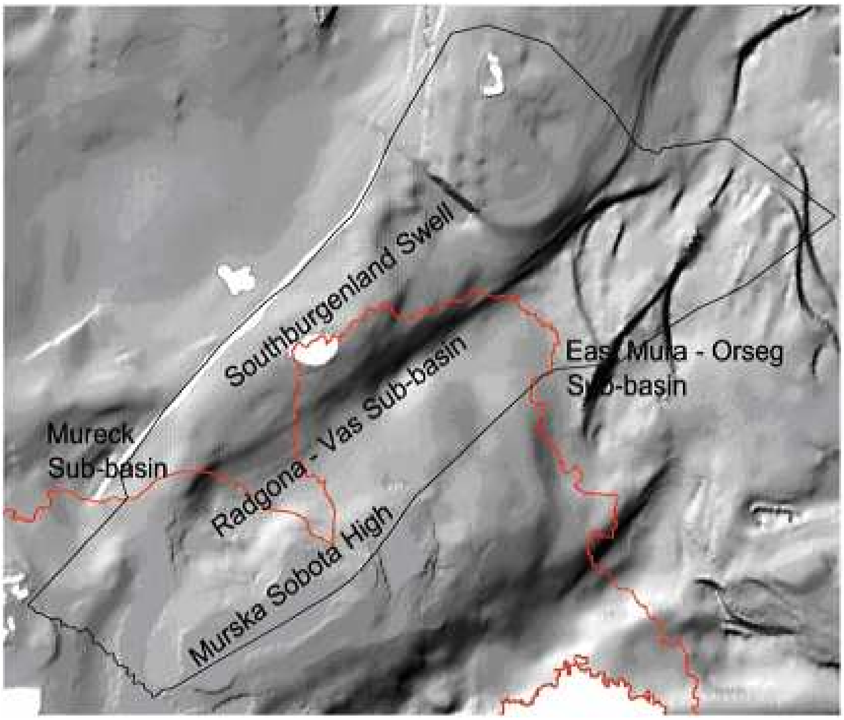


Fig. 46. Sub-basins of the Bad Radkensburg-Hodos pilot area

### 5.4.2 Additional horizons

Apart from the horizons modeled in the supra area (Encl. 5.1, 5.5-5.9), the following additional ones are modeled in the BRH Pilot area: delta front top horizon (Encl.5.2), and top of the Pannonian turbidites (Encl.5.4).

*Delta front top horizon (Encl. 5.2.)*

Delta front top horizon is modeled because it represents the upper boundary of a unit chiefly composed of large, relatively homogenous sheets of sand deposited on the ancient delta fronts. It is an equivalent of the lower part of the Újfalu Formation (’Mindszent Member’) in Hungary. The surface was determined according to the available well logs, where the distinction between prevailing coarsening upward sequences characteristic for the delta front sediments is followed. The horizon is important because it is bounded by two far less permeable sedimentary bodies: on top of delta front, mostly fine grained silty and clayey delta plain sediments lie with occasional sand or gravel channels and coal. In the base of the delta front sands, the quite homogenous fine-grained slope sediments are present, belonging to the upper part of the Lendava Formation corresponding to the Algyő Formation in Hungary.

*Top turbidite (Encl.5.4.)*

Between the Pre-Upper Pannonian and Pre-Lower Pannonian horizons another distinctive horizon is recognized and modeled. Similarly to delta front sands, the turbidites also represent permeable sand bodies surrounded by much less permeable layers of pelagic mud. The Pannonian turbidites belong to the Szolnok Formation in Hungary, an equivalent of the lower part of the Lendava formation (Jeruzalem Mb.) in Slovenia.

Turbidites are present in the eastern part of the BRH pilot area. They are thickened in the Radgona–Vas Sub-basin where they reach up to 400 m. To the east, their thickness is reduced above the Baján fault, suggesting its persistent activity. In the East Mura–Őrség Sub-basin the turbidites thicken again to ca. 400 m and more.

The boundary between turbidites and the overlying impermeable fine-grained slope deposits is also defined by well logs and seismic profiles.

### 5.4.3 Descriptions of additional horizon's formations

There are two further formations (over the ones described for the supra area) shown on the maps of the extra horizons defined for this pilot area.

The unit formed by the lower part of Mura and Újfalu Formations (Presika-Petišovci and Mindszent Members) is widespread in the deeper parts of the Pannonian Basin and its sub-basins, but it is missing along the basin margins. In the pilot area, it is present as a narrow strip in the Radgona–Vas Sub-basin, but significantly widens towards the east.

The occurrence of the Lower Pannonian turbidites (Jeruzalem Mb. of Lendava Fm. + Szolnok Fm.) is similarly limited to the central, deeper regions of the basins.

*Lower part of the Mura Fm (Presika-Petišovci Mb.) – Lower part of the Újfalu Formation (Mindszent Mb.)*

1. Synonimes, correlated formations: equal to some parts of Čáry Fm (Slovakia)
2. Lithology (colour, texture, grainsize): grey to yellow coarsening-upward bodies of sand and sandstone (thickness: few to 20–25 m), containing some gravelly intervals + intercalating layers of chiefly grey silt, marl, clayey marl, marly clay, clay, sandy and silty clay and some traces of coal
3. Facies: deltaic and shallow lacustrine
4. Paleoenvironment: mouth bars and shoreface
5. Thickness: 0–380 m
6. Average sandiness rate: 70%
7. Porosity type: grain
8. Estimated porosity: 12–14%
9. Tendencies mainly in time: at a given location, the unit is relatively uniform vertically
10. Tendencies mainly in space: the thickest sandbodies and the highest overall sand ratio can be expected in the central parts of the basins, where the thickness of the formation is the highest
11. Tectonic situation: post-rift phase of Pannonian Basin

*Lower part of the Lendava Fm (Jeruzalem Mb.) – Szolnok Formation*

The Pannonian turbidites are distinguished from the underlying and overlying formations due to their permeability. They are mostly sand turbidites derived from the river input at the basin margin. As the river delta formed and prograded into the basin, the turbidites were released and advanced towards the north-east. The turbidites are usually from several meters to several tens of meters thick and bounded by far less permeable carbonate silts. Their age in the eastern part is Late Lower Pannonian to Late Upper Pannonian.

1. Synonimes, correlated formations: equal to some parts of Ivánka Fm (Slovakia)

2. Lithology (colour, texture, grainsize): grey to light brown bodies of fine-grained sand and sandstone with variable thickness (usually 3–15 m) separated by 2–20 m thick intercalations of siltstone, clay marl and marl
3. Facies: deep lacustrine turbiditic
4. Paleoenvironment: sublittoral, with repeated turbidity currents on the lake floor
5. Thickness: 0–700 m
6. Average sandiness rate: 50%
7. Porosity type: grain
8. Estimated porosity: 9–10%
9. Tendencies mainly in time: sand ratio is slightly lower in the upper one-third of the formation
10. Tendencies mainly in space: the thickest sandbodies and the highest overall sand ratio can be expected along the axis of deep basement troughs
11. Tectonic situation: post-rift phase of Pannonian Basin

## 5.4.4 Geophysical evaluations: gravity, seismics, magnetotellury

### 5.4.4.1 Geophysical data

Gravity, magnetic, geoelectric and seismic reflection data, which were acquired in the Mura-Zala basin during more than 55 years, were compiled from different published and unpublished sources. Potential field data (gravity, magnetic) were mostly measured in the 1950's and 1960's. They are preserved in the archives of Geoinženiring d.o.o. and Geological Survey of Slovenia (Gosar, 2005a). Magnetotelluric method has not been used yet in Slovenia.

The Bouguer anomaly gravity map of the Mura-Zala basin that is shown in a paper by Gosar (2005a, Fig. 3 therein) was constructed from 3700 points measured with average density of 1.5 points/km2 using Worden gravity meters (Urh, 1956; Pleničar, 1970). Bouguer anomalies were calculated using reference density values between 1.9 and 2.2 g/cm$^3$ that derive from several profiles with use of the Nettleton method. Data were reduced to the datum plane of 150 m a.s.l. which is very close to the lowest elevation of the surface in northeastern Slovenia. Similar pattern of Bouguer anomalies in Slovenia are presented also on the gravimetric map of former Yugoslavia (Bilibajkić et al., 1979). More detailed gravimetric surveys were done in certain limited areas, such as around Cmurek, Pečarovci and Dankovci, predominantly within the underground gas storage aquifers investigations (Starčević, 1987a, 1987b, 1990).

A magnetic map of the Mura-Zala basin that is presented by Gosar (2005a, Fig. 4 therein) was extracted from the regional map of the vertical component of the magnetic field in Slovenia (Stopar, 1996-2000). The latter is based on the surface magnetic measurements with an average density of 2 points/km$^2$ using balance magnetometer Ruska and torsion magnetometer Askania (Novak, 1958, 1959; Miklič, 1969). Smaller parts of the Mura-Zala depression were later prospected for the project of underground gas storage also with proton precession magnetometer (Gosar, 2005a). No aeromagnetic survey has been carried out in this region yet. In the area of Cmurek a more detailed magnetometric research was also performed for the purpose of underground gas storage investigations (Starčević, 1987a).

For the purpose of searching for the possible underground gas storage aquifers many geoelectrical soundings were measured in several different areas of the Mura-Zala basin. An overview of older geological and geophysical investigations in the area of Lenart and

Cerkvenjak on the Murska Sobota extension block has been compiled by Mioč et al (1984). All these different areas are located on the Murska Sobota extension block in the Slovenske Gorice region (Car, 1987b; Mladenović, 1959; Ravnik & Vida, 1984), around Gabernik in the Ptuj-Ljutomer-Budafa synform (Car, 1986a), north of the Radgona–Vas half-graben at Cmurek (Car, 1987a). Some geoelectrical soundings were carried out within the thermal or mineral water aquifer investigations, especially for tertiary aquifers at Radenci (Car, 1990, 1994) or near Lenart (Ravnik & Podreka, 1983) and for searching the aquifers in the fault zones of metamorphic rocks in Maribor (Živanović, 1991).

Reflection seismic profiles were acquired predominantly for hydrocarbon prospecting. The density of seismic profiles varies considerably, therefore data coverage in the pilot area is not as good as in the vicinity of Lendava (in SE part of the Mura-Zala basin), where the major oil and gas fields are located. Most of the profiles were recorded by Geofizika Co. Zagreb using the line explosive sources (Geoflex and Primacord). The distance between the geophone groups was 30-40 m and CMP (common-midpoint) coverage 24 to 30 fold (Gosar, 2005a). Some more recent profiles were recorded using the Vibroseis source. Data processing was performed mostly by INA Naftaplin Co. in Zagreb using the standard processing flowchart (Djurasek, 1988b).

#### 5.4.4.2 Structure of the pre-Tertiary basement from geophysical data

The structural map of the pre-Tertiary basement by Djurasek (1988a) was modified with newly acquired data and using improved seismic velocity information from reflection profiling and measurements in the boreholes, which allowed more accurate time to depth conversion (Gosar, 2005a, 2005b).

The topography of the pre-Tertiary basement is very nicely reflected in the Bouguer anomalies map which shows the main structures stretching in a SW-NE direction. The axes of antiform structures correspond fairly well with the gravity maxima; on the other hand there is a discrepancy between the axis of synform structures (Radgona–Vas half-graben, Ptuj–Ljutomer synform) and gravity minimums (Gosar, 2005a). The main tectonic units are not so well reflected in the magnetic map as in gravity data, especially in the SE part of the Mura–Zala basin (Gosar, 2005a). Lateral variations in susceptibility or deeper structures may have greater influence on the magnetic anomalies than topography of the metamorphic rocks. The metamorphic basement was hit by drillings in about 42 boreholes (including the Maribor area) that are grouped in certain areas. Consequently, the boundaries between different lithological units are only roughly known. In addition, metamorphic rocks are covered in places with Mesozoic carbonates and clastic sediments in the Radgona–Vas half-graben and in the SE part of the Ptuj–Ljutomer synform (Gosar, 2005a).

At Rdeči breg area the only outcrops of metamorphic rocks within the Mura–Zala basin in Slovenia are those with quartz-sericite schists and phyllite at the border between Slovenia and Austria as a part of so the called South Burgenland swell (Gosar, 2005a). They are marked as positive magnetic (+75 nT) and gravity (+46 mGal) anomalies. Gravity anomaly extends to the southwest into the Cmurek anticline (+18 mGal). Both gravity and magnetic anomalies are the eastward continuation of the Kozjak Metamorphic Complex (Gosar, 2005a). The Radgona–Vas Sub-basin is located south of the South Burgenland swell, which separates the Mura–Zala Basin from the Steiermark basin (Gosar, 2005a). The pre-Tertiary basement dips in a northeast direction from a depth of 1700 m at Cankova to 4100 m at Dolenci (Fodor et al., 2011, http://www.t-jam.eu/ ). The NW slope of the subbasin towards the Rdeči breg is pretty steep with a lateral gravity gradient of 5-7 mGal/km (Gosar, 2005a). Radgona–Vas Sub-basin has two closed minimum areas in Slovenia: +5 mGal between Lenart and Gornja Radgona and +3 mGal at Cankova, giving a hint to two smaller subbasins. The third minimum to the NE at Šalovci has about 0 mGal, but continues further into Hungary. The axis of these gravity minimums is shifted to the SE with respect to the axis of the basement topography in this subbasin, the latter is derived from seismic reflection data (Gosar, 2005a). There is not yet enough data about the lateral extent of individual lithological units and their densities because only 7 boreholes all together in NE Slovenia drilled through the Mesozoic carbonates and clastic sediments to the metamorphic rocks. So, this observation can't be explained yet (Gosar, 2005a). The Radgona–Vas Sub-basin is expressed with magnetic data in its SW part as elongated negative anomaly (-25 nT). The smaller circular positive anomaly (+75 nT) NW of Mačkovci is related to the Upper Pliocene basalts and basaltic tuffs (Gosar, 2005a).

The Murska Sobota extensional block is a direct continuation of the Pohorje Metamorphic Complex below the Neogene sediments. It is very clearly reflected in gravity and magnetic data (Gosar, 2005a) and it is split into two ridges near Krog: the northern one is the Murska Sobota ridge and the southern the Martjanci ridge. In the SW part of the massif the depth to the basement is 400 to 500 m, while at the Murska Sobota it is about 1100 to 1300 m (Fodor et al., 2011, http://www.t-jam.eu/ ). In the gravity map the Murska Sobota extensional block is expressed as a distinctive elongated positive anomaly with two maximums (+13 mGal and +12 mGal). East of Murska Sobota there is a wide plateau (+6 mGal) that is separated from larger positive elongated anomaly by the Martjanci gulf. Besides, the magnetic map shows a larger positive anomaly (+150 nT), which is clearly shifted towards the SE with regard to the structural height of the Murska Sobota extensional block is (Gosar, 2005a). There are only four boreholes (Peč-1, Dan-1, Mt-3, Šal-2) in the transitional area between Radgona–Vas half-graben and NE part of the Murska Sobota extensional block that were drilled through the Mesozoic carbonates and clastic sediments and finished in the metamorphic rocks. Therefore, it is still difficult to make estimation on lateral lithological variations in the metamorphic rocks that may cause such a discrepancy (Gosar, 2005a). The amphibolites, pyroxenite and gneiss prevail in the area, and their measured susceptibility is at least 10-times greater than that of carbonates and clastic rocks, therefore, this fact still cannot explain the relatively high amplitude of this anomaly. So, the most probable cause is a deeper unknown structure composed of magmatic rather than metamorphic rocks with much higher susceptibility. Two structures (Pečarovci and Dankovci) in the transitional area between Radgona–Vas half-graben and NE part of the Murska Sobota extensional block, having potential for underground gas storage in aquifers, were also explored in detail (Gosar, 2005b).

A separate paper by Gosar (2005b) presents a more detailed seismic reflection investigation carried out for underground storage of gas in aquifers of the Pečarovci and Dankovci structures that are located in the transitional area between Radgona–Vas half-graben and NE part of the Murska Sobota extensional block.

### 5.4.5 Tectonics

The Bad Radkersburg–Hodos pilot area comprises two main subvertical tectonic lines, which represent continuation of the Rába Line zone into the Radgona–Vas tectonic half graben. Inbetween these two lines, the zone is strongly tectonized, including diverse lithological units, mostly as lenses and imbricates. In cases when Mesozoic carbonate rocks are present, lenses bounding, minor and less inclined, wrapping faults are considered. Both main tectonic lines were formed at the time of the main strike-slip tectonics in Oligocene–lower Miocene. Later deformational phases reactivated and deformed them. The latest subrecent, inversional compression inclined them from mostly subvertical position to north-vergent. The depth of the two structures is not known, but due to the regional significance of the strike-slip phase (in Oligocene–lower Miocene), they should cut considerable part of the pre-Cenozoic rock sequence. There is no data evidence for the faults to continue into the Tertiary formations. Therefore, the upward deformation is interpreted only as folding in order to avoid unnecessary complication in geometry for which we have no evidence. Nevertheless, Neogene deformations most probably include at least minor normal and reversely reactivated faults. Due to the mentioned compressional deformations the Radgona–Vas tectonic half graben is asymmetrically closing and its westward continuation terminates NE of Maribor.

Towards the east, on the Slovenian–Hungarian border, the metamorphic sequences plunge under the thick Mesozoic cover, separated along the Baján detachment fault, a low-angle fault zone probably crosscutting the whole Austroalpine nappe system. The Baján detachment fault was active in the Late Cretaceous, as it is proven by borehole Baján M-I. Miocene activity is also unambigous, as East Mura–Őrség Sub-basin, a large half-graben filled with Miocene deposits was formed in the hanging wall. Associated to the detachment surface, a series of normal faults can be observed; these often bound asymmetric tilted blocks. Drag folds commonly occur along the normal faults.

### 5.4.6 Cross sections

Two (trans-national) geological cross sections were chosen to describe the Bad Radkersburg–Hodoš (BRH) pilot project area, the PT_BR_1 and PT_BR_2 (Figures 47-49). The PT_BR_1 Cross section begins a few kilometers east of Maribor and continues to the NNE between Mureck and Bad Radkersburg, through Goričko and into Hungary along the south-eastern margin of the BRH pilot project area.

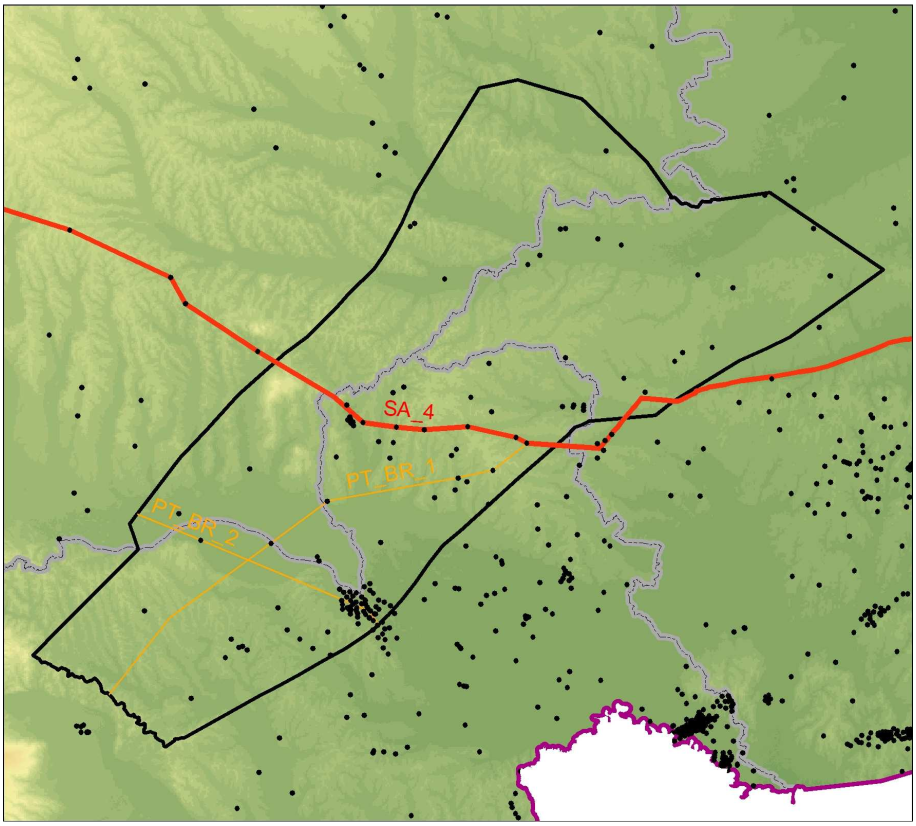


Fig. 47. Cross section lines in the Bad Radkersburg–Hodoš Pilot area

#### 5.4.6.1 PT_BR_1 Cross section

In the west, the P-1 cross-section begins in the south-westernmost part of the Radgona–Vas Sub-basin. North of Bad Radkersburg, the PT_BR_1 cross-section trace adopts more easterly trend and across the Bajan fault continues into the East Mura–Őrség Sub-basin (Figure 48).

The western part of the cross-section in the Pre-Cenozoic basement cuts predominantly rocks of the Pohorje Formation. Thin slices of the Kobansko and Phyllite Formation rocks of the Strojna and Dravograd thrusts, comprising the underlying phyllonites and mylonitized Pohorje Formation rocks cover flattened areas of the eastward subsided blocks. Several small lenses of Triassic dolomites occur as remnants of the North Karavanke thrust on the northern slope of the Murska Sobota high near Korovci and Pečarovci. In continuation, tectonically bounded Senonian Gosau Fm. rocks occur in the area of Dankovci. The Triassic, as well as the Senonian rocks are underlain by the Kobansko and Phyllite Formation rocks. The whole sequence is eastward subsided along the Baján detachment fault for more than 1000 m.

The step-like Cenozoic basement relief refers to the Southburgenland swell along which the Radgona–Vas Sub-basin is subsided in Lower Miocene. To the east, the Baján fault marks another boundary along which the East Mura–Őrség Sub-basin was subsided in the same time. To the east, the Radgona–Vas Sub-basin is filled with Haloze formation, thinning out towards the east, suggesting the transport direction from the NW to the SE. The basin is filed up with the sediments of the Lower Miocene Haloze Formation corresponding to the lower part of the Tekeres Formation in Hungary. Across the Baján fault, the thickness of the Lower Miocene deposits is increased in a few grabens along the secondary faults belonging to the Baján fault system. More than 1000 m of Lower Miocene sediments are present in the western part of the Radgona–Vas Sub-basin and in the East Mura–Őrség Sub-basin.

Pre-Badenian deposits are mostly arbitrary defined in the subsurface due to lack of data. The Badenian lower part of the Špilje Formation fills up the western half of the Radgona–Vas Sub-basin, and moderately thins up towards the east, keeping approximately the same thickness until the eastern margin of the East Mura–Őrség Sub-basin. Across the Bajan fault the lower part of Špilje Formation corresponds to the merged upper part of Tekeres Formation and Szilágy Formation with thickness up to 1200 m in the eastern part. Like in case of the Lower Miocene, the geometry of the Badenian sediments also shows that the basin was filled from the NE, where the sediments are the thickest.

The Sarmatian deposits are significantly thinner and show rather uniform thickness across the entire cross section. The upper part of Špilje Formation (in Slovenia) of roughly Sarmatian (subordinately lowermost Pannonian) age is correlated to the joined Kozárd and Endrőd Formations in Hungary. The thickness of the Sarmatian deposits in the cross section is up to 500 m.

Lower Pannonian formations are represented by the Lendava Formation in Slovenia corresponding to the merged Szolnok and Algyő Formations in Hungary. These sediments begin only in the central part of the cross section, because the Radgona–Vas Sub-basin was already filled up by then. The formation is significantly reduced in thickness along the Baján fault and thickens again to the east, suggesting that the eastern bloc (hanging wall) of the Baján fault was still subsiding in the Pannonian. In the Radgona–Vas Sub-Basin there are up to 500 m of the Lower Pannonian deposits and up to 900 m in the East Mura Sub-basin in Hungary.

The geometry of the merged Upper Pannonian and Pre-Quaternary sediments is essentially the same. The merged Upper Pannonian deltaic, and Pre-Quaternary fluvial deposits represent the Mura Formation (delta front and delta plain) merged with the Ptuj–Grad (alluvial) Formation. These sediments are thickest in the eastern part of the cross-section, up to 1300 m. Above the Bajan fault the thickness of these formations is reduced to mere 300 m, and pinching out towards the west in the vicinity of the Bad Radkersburg area.

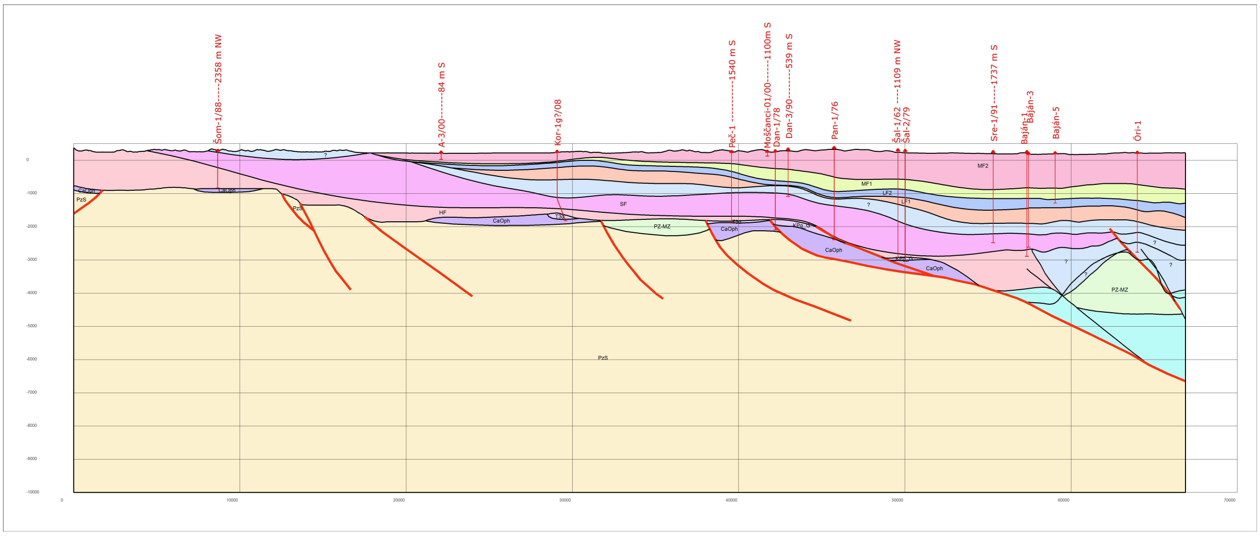


Fig. 48 PT_BR_1 Cross section of the Bad-Radkensburg-Hodos pilot area

### 5.4.6.2 PT_BR_2 Cross section

The PT_BR_2 geological cross section runs roughly in NW–SE direction. In the north, it begins in Austria a few kilometres NW of Mureck and continues just south of Bad Radkersburg, and ends in Slovenia, a few kilometres SE of Radenci along the SE boundary of the Pilot project area (Figure 49). The PT_BR_2 cross section starts in the south-eastern part of the Western Styrian Basin, crosses the western part of the Southburgenland swell and the Radgona–Vas Sub-basin, and ends up on the Murska Sobota High.

The northern part of the cross section in the Pre-Cenozoic basement cuts the rocks of the Koralpe–Pohorje–Wölz unit. Thin thrust layer of the Kobansko and Phyllite Formation rocks lie on the unit on the northern side of the Southburgenland swell, covered by a thick Neogene succession. The southward prolongation of the Koralpe–Pohorje–Wölz unit, the Pohorje Formation, is subsided, forming the base of the Radgona–Vas Sub-basin. Further to the south, the Murska Sobota High is transpressed along the reversely reactivated, roughly E-W trending fault. Thin slice of the Kobansko and Phyllite Formation rocks occur on its northern slope and cover flattened area on the top.

In the north, the oldest Neogene sediments lie on top of the Koralpe–Pohorje–Wölz unit. The oldest Neogene sediments belong to the Ottnangian and Karpathian on the northern side of the Southburgenland swell. These sediments are roughly correlated with the Lower Miocene Haloze Formation in Slovenia. On the southern side of the Southburgenland swell, the Haloze formation fills up the Radgona–Vas Sub-basin, but not the Murska Sobota High. In general, the thickness of the Lower Miocene deposits in the Styrian Basin as well as in the Radgona– Vas Sub-basin exceeds 1000 m.

The Badenian sedimentary succession represented by the lower part of the Špilje Formation is almost 500 m thick on the northern side of the swell, and significantly thickens in the Radgona–Vas Sub-basin. Due to lack of deep boreholes in this area, the exact thickness of the Badenian and Lower Miocene formations are just roughly interpreted. The Badenian sedimentation reached also the Murska Sobota High, meaning that it was flooded during the Badenian transgression. Sarmatian deposits are only present in the southern part of the P-8 cross-section in moderate thickness less than 180 m.

Lower Pannonian formations are not present in the cross-section, because the basin was filled up by the Sarmatian already. The Upper Pannonian formations (merged Mura and the Ptuj–Grad Formations) are present only above the central part of the Radgona–Vas Sub-basin, and in the southernmost part of the cross-section on the Murska Sobota High.

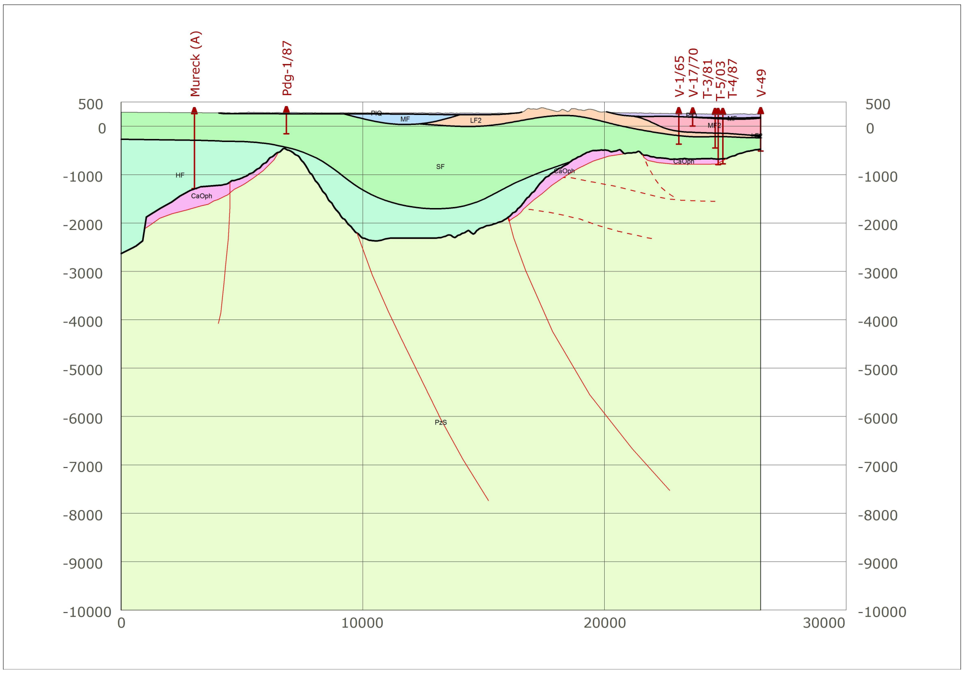


Fig. 49 PT_BR_2 Cross section of the Bad-Radkensburg-Hodos pilot area

## 5.4.7 Modeling

The geological model of the Bad-Radkensburg-Hodos arae was performed by the software JewelSuite, similar way as it was described at the Lutzmannsburg-Zsira pilot area in chapter 5.3.7). Building the 3D geological model of the pilot area started with the collection of base datasets, which included borehole data, previously compiled surface models and linear shapes, like the area boundary and the geological map contents (i.e. tectonic lines).

Due to the planned modelling workflow, the model horizons of the pilot area were derived from the supra regional subsurface horizons in those cases, where it was available. The topographic surface was the SRTM (Shuttle Radar Topographic Mission). Firstly all previously compiled horizons were clipped to fit in the modelling area. The original 100x100 m grid resolutions of the horizon-models were preserved.

In JewelSuite the well, top, and horizon data should all be conform to each-other in order to create the 3D model. Thus after importing the base data, horizon-well correlations were executed. The inconsistencies, revealed by the data validation of the model, were corrected in the modelling environ, and the final model was verified for each horizon using kriging with isometric exponential function.

Some results of the model are shown on Figures 50-52.

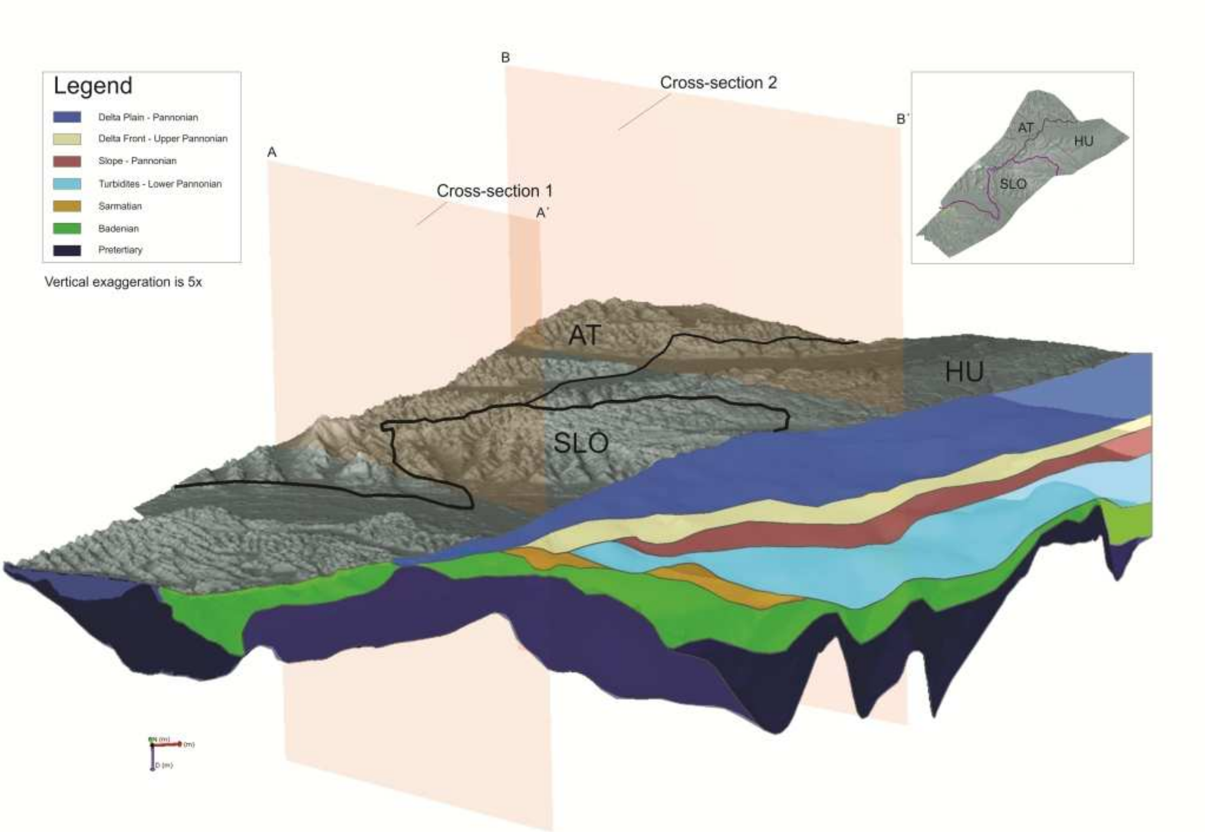


Fig. 50 3D model of the Bad Radkensbug-Hodos pilot area

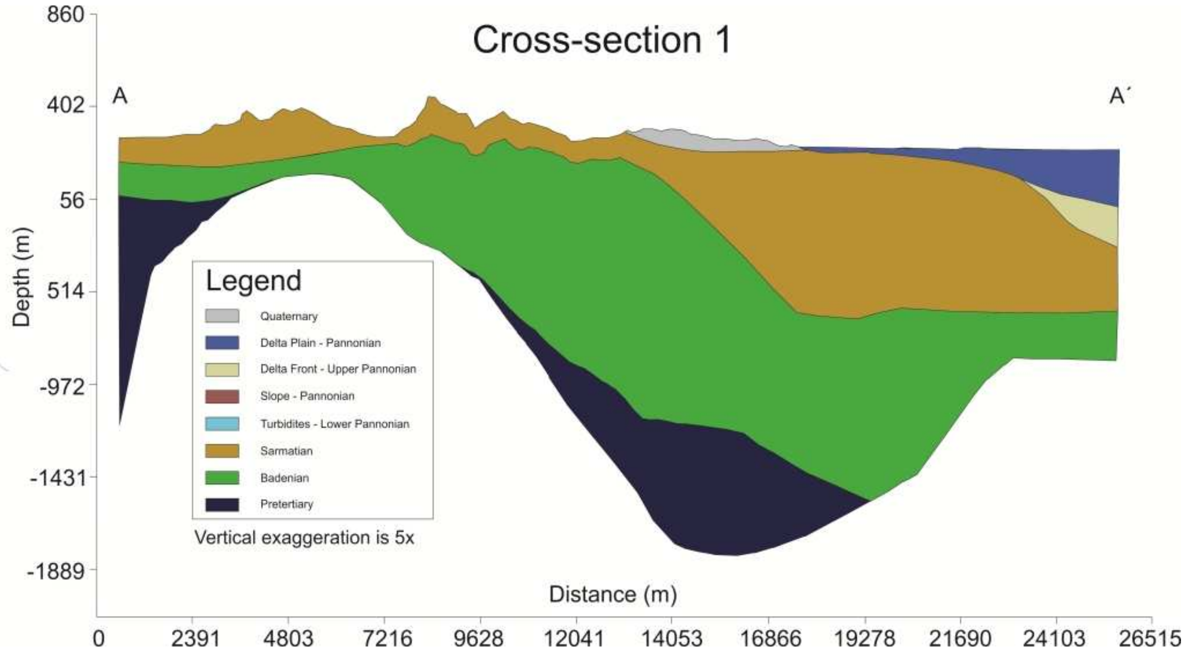


Fig. 51 Cross section prepared by JewelSuite (for location see Fig. 50)

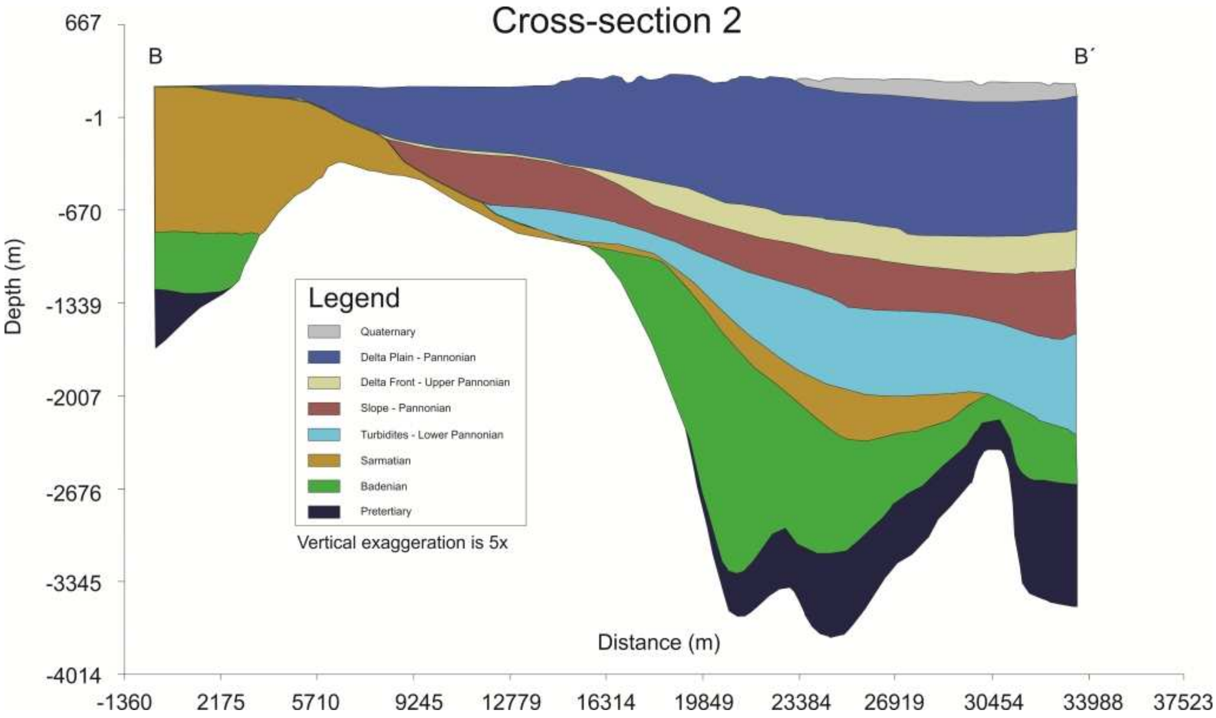


Fig. 52 Cross section prepared by JewelSuite (for location see Fig. 50)

## 5.5 Komarno–Sturovo

### 5.5.1 Geological frame and history

The area is consisted of low and moderately elevated hills, low mountains and part of the Danube lowland. The hills are part of the Transdanubian Range of Hungary. The area comprises the Pilis Hills, the northern margin of the Buda Hills, the whole Gerecse Hills, and the northern margin of the Vértes Hills. The western part of the study area extends to the easternmost margin of the Danube Basin.

In the northernmost part of the study area a small part of the Vepor Unit can be found below Cenozoic rocks, which is bordered by the Hurbanovo-Diósjenő Line from south. The crystalline complex, which is several km thick, is covered in the Hungarian part by Palaeogene and Neogene rocks. In Slovakia (Komárno block) even by Carboniferous, Permian and Mesozoic cover sequences (Vozárová & Vozár 1996) can be found, which is built largerly of Triassic dolomites and limestones up to 1000 m in thickness. The crystalline series is built up of biotite-gneiss, biotite-schist with greenschist intercalations. Structurally it is a north vergent, Cretaceous (“pre-Gosau”) nappe.

In the northeastern part of the study area, the Buda, Visegrád Hills and Börzsöny Mountains, the Neogene volcanic–volcanosedimentary rocks dominate the geology.

The bulk of Transdanubian Range is formed by Middle to Upper Triassic platform carbonates, which were deposited on the passive margin of the Tethys Ocean. During an Early and Middle Jurassic rifting, the shallow water carbonates were covered by a thin, reduced pelagic Jurassic limestones, marls, and cherty limestones. The carbonate succession continues with a Lower Cretaceous clastic sequence, unique in the Transdanubian Range. The siliciclastic marl, sandstone, conglomerate of Berriasian–Albian age is about 600 m thick. In the western foreland of the Gerecse and Vértes Hills, the succession continued during the middle and late Albian with terrestrial clastics, shallow-water limestones, and finally turned to open-marine marl. No sediments younger than Cenomanian was preserved.

The Mesozoic succession was deformed by several Cretaceous deformation phases. The main result would be the nappe emplacement of the whole Transdanubian range over other units, probably over the Veporic unit as well. Other effects are the gentle folding and small-scale imbrication of the unit. These deformations started during the Berriasian, amplified during the Albian but reoccurred during the Cenomanian-Coniacian.

They were followed by an extensive denudation period, which resulted in development of subtropical denudation surfaces and strong karstification in carbonates. The long period of denudation ended in the Middle Eocene, when the weathering residue was preserved in form of bauxite lenses of industrial qunatity.

The denudation was ended by a new basin-forming process in the Middle Eocene. The sediments of the Hungarian Palaeogene Basin started to be deposited in a compressional setting (Tari et al. 1993). The Eocene succession starts with a transgressive sequence: continental, carbonaceous deposits are followed by neritic nummulitic limestones and bathyal (locally turbiditic) marls. The transgressive Eocene sequence has been extensively, the regressive sequence has been completely eroded in the area during an early Oligocene denudation event. Basin subsidence accelerated in the late Early Oligocene. In the western part of the region the Eocene rocks are succeeded immediately by Oligocene fluvial layers, which gradually pass eastward and upward into brackish, then open marine rocks. The transgressive sediments can be found north of the Hurbanovo-Diósjenő Line as sandstones then pelitic rocks. The basin was filled up by sandstones and siltstones during the late Oligocene.

The Neogene basin fill sequence is similar to the Danube basin pilot area, see its description there.

In the western foreland of the Grecse Hills the Neogene sedimentation started in the late Early Miocene (Eggenburgian–Karpatian: Somlóvásárhely Formation). This fluvial-limnic successions made up of pebble, sand, marl, variegated clay, locally with thin coal seams can be traced in boreholes drilled in the Kisalföld, eastward to the western foot of the Gerecse Mts. The subsidence of the Danube Basin commenced at the end of the Early and the beginning of Middle Miocene. The main part of the syn-rift phase acted during the Karpatian to Middle Miocene and the post-rift, or thermal phase during Late Miocene and Pliocene. The Karpatian and Badenian sediments occur in the western foreland of the Gerecse, in the eastern margin of the Danube basin and in the Zeliezovce embayment of the Danube basin in southern Slovakia. Along the eastern margin of the Danube Basin transgressive conglomerates, sandstones and volcaniclastics are overlain by neritic calcareous clays, siltstones and subordinately sandstones (Bajtava Formation). No early to Middle Miocene sediments were preserved on the elevated parts of the Gerecse, Pilis Hills. Terrestrial sediments occur, however, in the southernpart of the area, in the Zsámbék Basin. The upper Badenian succession comprises calcareous clays, siltstones and sandstones with volcanoclastics, as well as biogenic limestones in the margins.

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 (mollusc-bearing limestone, and oolithic limestone, Cerithium limestone) of shoreline facies (Tinnye Formation) and fine-siliciclastic sediments (grey, greenish-grey clay marl, sand, silty clay marl) of shallow-marine facies (Kozárd Formation) were deposited. The upper Sarmatian carbonate successions indicate a considerably productive carbonate factory of subtropical climate (Persian-Gulf-type ooids), reflecting to hypersaline or hypercalcareous conditions, thus the previous brackish-water hypothesis is under debate.

Late Miocene is marked by a thin succession near the elevated Mesozoic outcrops, but reaches the normal thickness in the northernmost part of the area, in Slovakia. The thin succession is marked by the lacustrine Szák Formation, and is covered by poorly developed delta and fluvial sediments, which are difficult to separate. Pliocene is only present in Slovakia, while Quaternary is mostly represented by fluvial sediments, loess, and slope deposites.

### 5.5.2 Additional horizons

For the Komarno-Sturovo pilot area the Pre-Oligocene and the Pre-Senonian horizons were compiled additionally. The compilation was based not only on the available well data, but on the previously published maps also, which were imported into the model.

### 5.5.3 Descriptions of additional horizon's formations

The additional horizons did not contain formations that are not included in the harmonized legend (chapter 4.2.).

### 5.5.4 Geophysical evaluations: gravity, seismics, magnetotellury

For the construction of the different maps diverse geophysical data were used. Namely, few seismic reflection profiles touched the boundary of the study area. Magnetotelluric data generally indicate a good conductivity layer below the Transdanubian Range, It is generally considered as the nappe base, detachment zone, along which the Transdanubian Range was emplaced onto lower structural units.

The most extensively used geophysical data was the gravity data set. Bouguer-anomaly map and derivate maps clearly indicate major Cenozoic depressions. Derivate map was used for construction of the fault pattern, particularly at areas, where borehole data were lacking or scarse.

### 5.5.5 Tectonics

The structure of the Komarno-Sturovo area is quite complex. Several phases of deformation can be recognised on the basis of the different structural horizons. From a detailed study of the nearby Vértes Hills, and from basin-wide regional studies 13 deformation phases were reconstructed (Budai, Fodor 2008, Fodor 2010). Most of these phases created map-scale faults, but it is difficult to classify all faults to single deformation phases. Instead, most faults suffered reactivation and belong to several phases with different fault kinematics.

The southern margin of the area touches an important fault, the Vértessomló fault. This is a Cretaceous thrust, which places Upper Triassic rocks over Cretaceous sediments and causes apparent sinistral displacement of Mesozoic formations up to 6km (Balla, Dudko 1989). The true slip is reverse-dextral (Fodor in Budai, Fodor 2008). This fault may perturb the fluid-flow system of the Transdanubian Range karst reservoir.

The northernmost margin of the study area approaches the Hurbanovo-Diósjenő Zone. This is a complex deformation zone, along which the Transdanubian Permo-mesozoic sequence is in contact with the Veporic Unit with metamorphic crystalline and Permo-Mesozoic sedimentary rocks. The nature of the faults zone is still debated (Balla 1989, Koroknai et al. 2001). It was probably a Cretaceous nappe boundary, with nothwestern vergency. In the late Cretaceous it was probably reactivated as low-angle normal fault (Fodor, Koroknai 2000). It was further deformed in the latest Cretaceous and Tertiary as strike-slip fault and finally could by reactivated as north-facing normal fault in the Miocene.

Other smaller scale reverse faults can be detected in the pre-Tertiary map. Repetition of the whole Mesozoic pile, from the Upper Triassic to Lower Cretaceous is present in the Pilis Hills, and at the western margin of the Dorog Basin. Folding was associated with these deformation phases. Folds are gentle, with subvertical axial planes. Several repetition of the sequence is interpreted as folds, instead of faults on the Pre-Tertiary level, mainly in the western foreland of the Gerecse Hills.

Early Miocene strike-slip faults also play important role in the study area. E-W trending dextral and NNW-SSE trending sinistral faults could accumulate several hundred to km scale displacement. These faults frequently reactivate Paleogene structural elements. During the Eocene and Oligocene E-W trending faults could have normal separation. The best example is the Nagysáp basin and also the margin of the Dorog basin, where syn-sedimentary slip can be documented by thickening Paleogene sediment pile in the hanging wall blocks.

Several important NW-SE, N-S to NE-SW trending faults cut across the study area. These faults could have a long slip history. However, they were certainly active during different phases related to the formation of the Pannonian Basin. These could be normal or oblique normal faults during the main rifting phases of late Early to mid-Miocene ages (D9 and D10 of Fodor 2010). Most of these faults were still active during the late Miocene D12 phase as normal faults. These faults seem to be connected to ENE-WNW trending faults in the Slovak part of the area; here the faults could have sinistral-normal kinematics.

Major faults bound tilted blocks, generally half-grabens of different size and depth. The largest could be the Zsámbék, Mány, Tarján Basins. Cumulative offset along boundary faults could be in the range of 500-1000m. In the Dorog Basin NW-SE trending margin faults also have more than 500m separation and formed during the main syn-rift phase.

The modelled tectonic surfaces are shown on Figure 53.

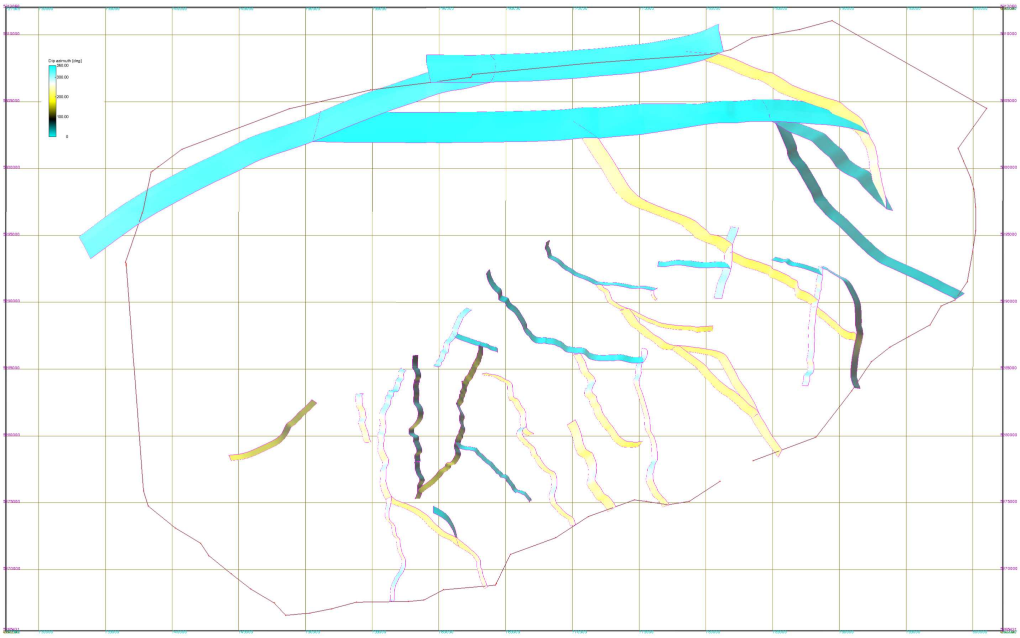


Fig. 53 Modelled tectonic surfaces of the Komarno-Sturovo pilot area

### 5.5.6 Cross sections

3 profiles across the study area were constructed (Figure 54, Encl. 6.19). The sections follow important boreholes. In addition, other boreholes were projected from the close vicinity. We also used the surface formations (and topography), and the pre-Cenozoic top surface from diverse databases, namely from the Supra area map, and earlier maps. We prepared a database for both the faults and formation boundaries observed in the detailed geological sections. This database intends to permit separate visualisation of faults and boundaries of different types and/or rank (size). Equally, formation boundaries are grouped into discordance and normal boundary classes, with different signs. Formation tops are also separated by colours. These boundaries are also classified using importance (rank). The most important boundary is the top of Mesozoic rocks, which is equally important for hydrogeology. Other major boundaries are the Triassic/Jurassic, Jurassic/Cretaceous, and the Paleogene/Miocene boundaries. Formation boundaries can be used for detailed interpretation.

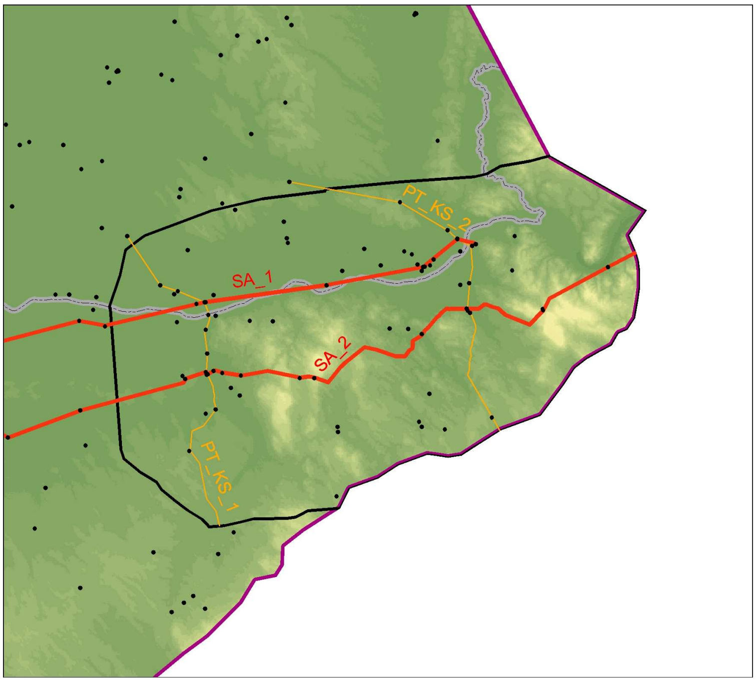


Fig. 54. Cross section lines in the Komarno–Sturovo Pilot area

Cross sections show the intense tectonic deformation of the area together with maps. Sections visualise better the mostly asymmetric geometry of the major half-grabens. They were formed in divers tectonic phase, partly during the Paleogene (Dorog, and Nagysáp Basins), partly during the divers phases related to the formation of the Pannonian Basin. Sections show the generally slightly tilted geometry of the Cenozoic fill. Below the Cenozoic rocks Mesozoic succession is more tilted than Cenozoic cover, but dip degree rarely exceeds 30 degree. Several tectonic elements do not cross the Cenozoic base, but a number of them were reactivated during Cenozoic events. Reverse faults occur in the Mesozoic rocks. Folds are restricted to pre-Cenozoic rocks, expect for local drags of formations near major normal or strike-slip faults: these fault-related folds were observed in the field and showed in sections. The general structure of the Transdanubian Range is a folded structure, which is reflected in cross sections.

### 5.5.7 Modeling

The geological model of the Komarno-Sturovo pilot area was also performed by the software JewelSuite. Similarly to the Lutzmannsburg-Zsira area building the 3D geological model of the pilot area started with the collection of base datasets, which included borehole data, previously compiled surface models and linear shapes, like the area boundary and the geological map contents (i.e. tectonic lines). The coordinates of the modelling area were derived from the minimum and maximum coordinates of the pilot area shape with a 1000m puffer zone, thus a rectangular block was defined in the modelling environment which gave the frames of the 3D model in the process.

Due to the planned modelling workflow, the model horizons of the pilot area were derived from the supra regional subsurface horizons in those cases, where it was available. The topographic surface was the SRTM (Shuttle Radar Topographic Mission). Firstly all previously compiled horizons were clipped to fit in the modelling area. The original 100x100 m grid resolutions of the horizon-models were preserved.

Linear elements, like the tectonic lines, the intersections and the boundaries of the main horizons were collected from the geological maps and were draped onto the subsurface horizons respectively. Attribute data were attached to each linear object to mark their relations to the main model-horizons. The query of these “smart” 3D linear elements was carried out with GIS applications (Autodesk and ArcGIS). The lines were used as references in the modelling application to refine the original horizons. 3D lines from the compiled cross-sections were also imported into the model with similar method (Figure 55).

The model contains only limited number of boreholes (92 wells). These are the ones which were included into the Transenergy projet database and lies within the boundaries of the pilot-area, however the subsurface horizons were compiled from all available borehole data.

The linear objects of the faults were processed manually in accordance with the map data until the desired geometry of the fault surfaces were created. Seismic data were not available for the pilot area.

Each individual fault was named after a geographic location nearby, their rank and the dip direction as the letters of the points on the compass. (i.e.: T1-NagyGeteNy_N). Total number of fault surfaces is for the Komarno-Sturovo pilot area is 38 (Table 4).

Table 4. Named tectonic surfaces and their parameters in the geological model of the Komarno-Sturovo pilot area.

| | Object | Points No | Mean dip (deg) | Mean azimuth (deg) |
|---|---|---|---|---|
| 1 | T1-BajnaOrhegyNy_JN | 684 | 57.3 | 234 |
| 2 | T1-TataDK_N | 665 | 64.3 | 144 |
| 3 | T1-VertesszolosNy_N | 315 | 58.7 | 260 |
| 4 | T1-TatabanyaDNy_BN | 724 | 62.1 | 223 |
| 5 | T1-KeselohegyEK_B | 178 | 64.8 | 45.4 |
| 6 | T1-Gbelce-LelaE_J | 5430 | 63.2 | 315 |
| 7 | T1-Komarno-GbelceENy_NB | 5956 | 60.7 | 338 |
| 8 | T1-VasztelyNyDNy_N | 624 | 49.5 | 243 |
| 9 | T1-CsurgohegyEK_N | 567 | 67.9 | 39.5 |
| 10 | T1-SzomorNyDNy_N | 958 | 63.8 | 262 |
| 11 | T1-NagysapEEK_NJ_new | 1641 | 62.8 | 74.6 |
| 12 | T1-TatabanyaNy_N | 1161 | 55.4 | 274 |
| 13 | T2-TatabanyaNy_N | 643 | 65.6 | 272 |
| 14 | T3-OregKovacsK_N | 218 | 61.2 | 87.7 |
| 15 | T1-OregKovacsK_N | 527 | 62.7 | 88.7 |
| 16 | T2-OregKovacsK_N | 159 | 55.2 | 83.9 |
| 17 | T1-GerecseDK_N | 1008 | 60.3 | 111 |
| 18 | T1-GerecseENy_N | 489 | 60.2 | 301 |
| 19 | T1-GerecseEK_N | 244 | 63.4 | 22.1 |
| 20 | T1-HeregKisSomlyoNy_N | 514 | 61.8 | 237 |
| 21 | T1-KatonacsapasNyDNy_N | 908 | 63.2 | 247 |
| 22 | T1-MogyorosbanyaEEK_NJ | 553 | 67.3 | 55.3 |
| 23 | T1-NagyGeteNy_N | 59 | 59.3 | 249 |
| 24 | T1-MagoshegyD_NJ | 652 | 67 | 202 |
| 25 | T1-DagDNy_N | 1142 | 60.6 | 220 |
| 26 | T1-TinnyeDNy_N | 1041 | 58.9 | 225 |
| 27 | T1-BaranyhegyNy_N | 550 | 51.9 | 276 |
| 28 | T1-PilisDNy_N | 293 | 53 | 214 |
| 29 | T1-FeherSzirtDK_N | 594 | 48.7 | 211 |

| | | | | |
|---|---|---|---|---|
| 30 | T1-NagyStrazsahegyDNy_N | 1665 | 58.2 | 223 |
| 31 | T2-LencsehegyE-N | 433 | 57.4 | 282 |
| 32 | T1-DorogE_N | 466 | 68.8 | 154 |
| 33 | T1-DobogokoEK_NJ | 1856 | 54.8 | 43.4 |
| 34 | T1-PilismarotEK_N | 1515 | 63.2 | 36.2 |
| 35 | T1-Modrany-NanaE_J | 7280 | 55.8 | 180 |
| 36 | T1-ZebegenyNy_N | 2599 | 65.4 | 218 |
| 37 | T1-PilisDK_N | 549 | 55.5 | 74.5 |
| 38 | T1-FeketehegyEK_I | 186 | 58.9 | 28.4 |

Explanation: T1: first order tectonic element (movement on fault >= 400 m); the E, D, K, Ny letters after the geographic names indicate the Northern (E), Southern (D), Eastern (K) and Western (Ny) sub area of the given territory. N indicates that the object is a fault, while I is an inverted fault (or thrust fault) and J or B is a dextral or sinister horizontal fault. The last part of the name string indicates the orientation of the plane as letters, which are similar to the ones referring to the geographic orientation.

In JewelSuite the well, top, and horizon data should all be conform to each-other in order to create the 3D model. Thus after importing the base data, horizon-well correlations were executed. The inconsistencies, revealed by the data validation of the model, were corrected in the modelling environ, and the final model was verified for each horizon using kriging with isometric exponential function.

As part of the modelling a 3D voxel grid was created (Figure 56) from the surfaces and borehole top data. The model definition based on the average thicknesses of the geological formations on those area, where no well data was available. The final sub-surface horizons were derived from the 3D voxel grid.

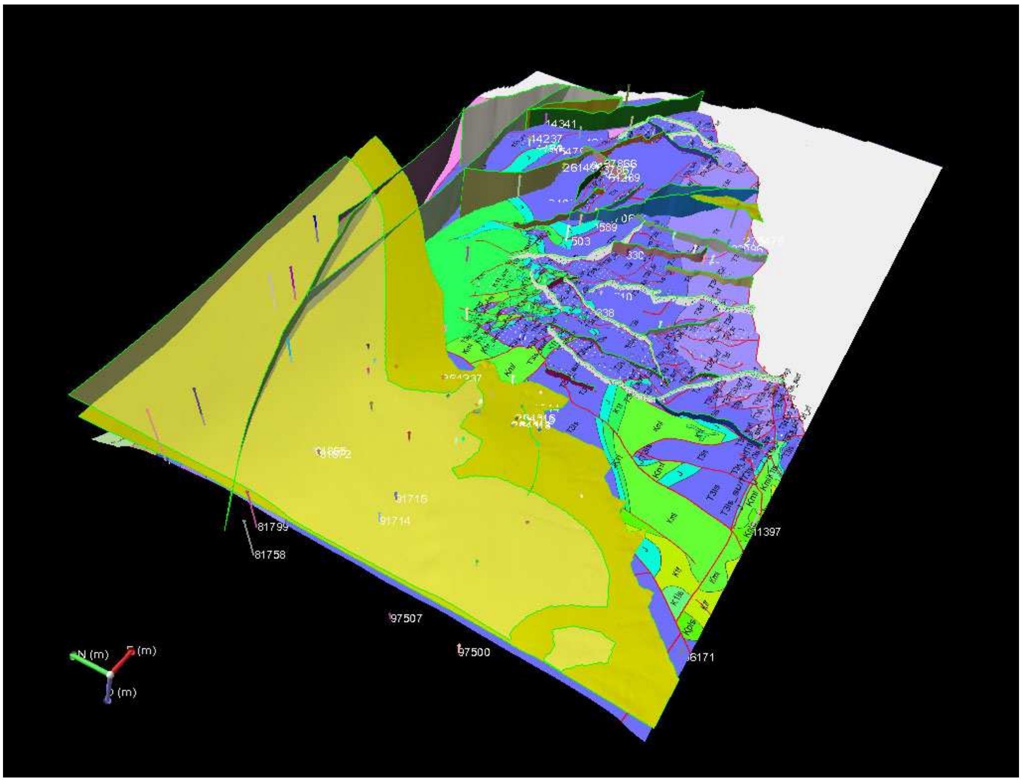


Fig.55 The models of the Pre-Cainozoic, Pre-Pannonian and Pre-Upper Pannonian horizons with the tectonic surfaces. The map of the Pre-Cainozoic horizon was draped onto the surface model.

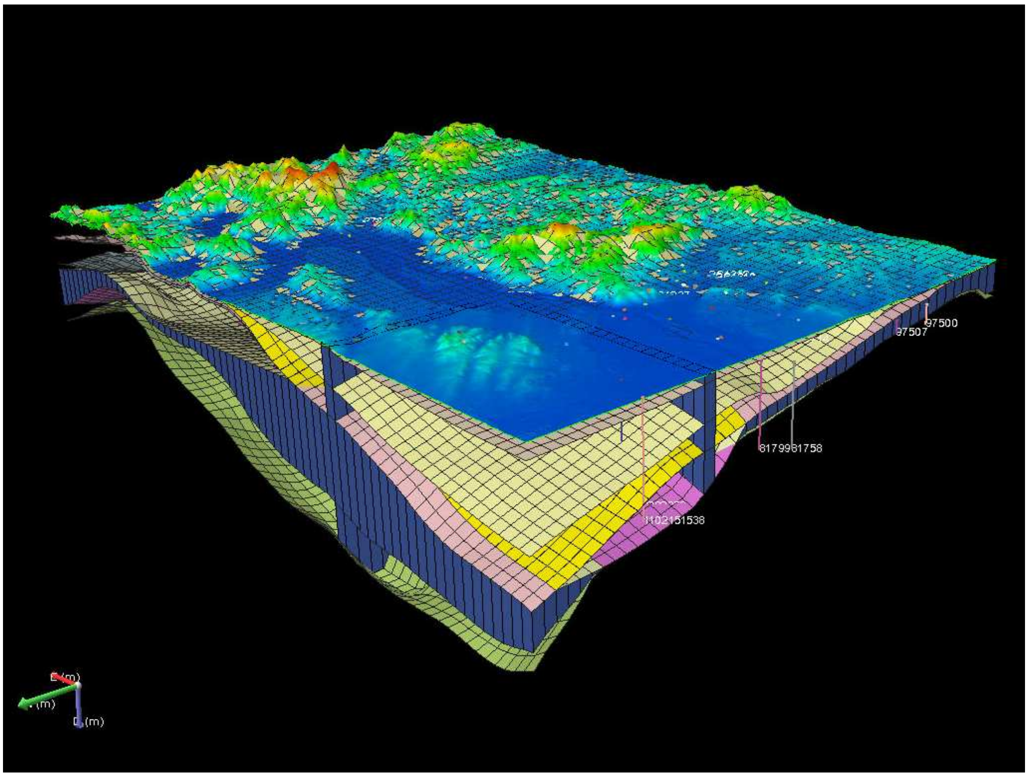


Fig. 56   3D voxel grid model of the Komarno-Sturovo pilot area from the NW.

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