DELIVERABLE D.T3.3.1
ACTIVITY REPORT ON 3D MODELING

Part 1: Detailed description of static models including estimation of errors

Version 1:
02 2019

Authors:
Clemens Porpaczy, Gregor Götzl, Martin Fuchsluger -LP-GBA
Ines Goerz-PP04-LfULG
Jan Franěk, Jan Jelinek - PP05-CGS
Jaromir Svasta, Radovan Cernak - PP06-SGIDS
Dejan Šram, Mitja Janža, Matevž Novak, Andrej Lapanje - PP07-GeoZS;
Urzula Wyrwalska, Wiesław Kozdrój, Margozata Ziółkowska-Kozdrój -PP08-PGI NRI
Michał Michna, Marek Hajto, Bartosz Papiernik, Gabriel Ząbek - PP09 - AGH UST

The involved GeoPLASMA-CE team

1. Introduction- Aim and scope of this deliverable

The GeoPLASMA-Ce project comprises 3D modelling of the major subsurface units and structures as a basis for the calculation of the shallow geothermal potential. Structural 3D models have been produced in six pilot areas. Three of them are crossing national boundaries and require steps of data harmonization and preparation connecting geological knowledge and classification of different countries. The project partners had to specify, which units and structures are included in the models and how to correlate and combine the model parts. The other pilot areas cover urban regions and usually represent areas with very large density of the primary data. These data also had to be harmonized prior to 3D modelling. Data preparation usually comprised 50-80% of the modelling work. The 3D modelling was performed with various software packages like Skua-Gocad, Petrel, Move 3D and JewelSuite. The modelling results had to be converterted into a uniform data structure (Gocad-ASCII files) and the model parts had to be connected properly without gaps and overlaps. Finally, the 3D models are used for the calculation of the shallow geothermal potential and saved at the web-platform, where they can be queried for the construction of virtual boreholes.

This report is a documentation of all worksteps performed during 3D modelling in all pilot areas. It presents the steps of data preparation, 3D modelling and provides an evaluation of the modelling results.

2. Activity report on the 3D geometric and structural models

2.1. Pilot area Ljubljana

The Ljubljana pilot area (275 km^2), which corresponds to the area of the City of Ljubljana (**Figure 1**) is one of the most urbanised and developed areas in Slovenia. The central flat landscape of the area is divided by hills in the middle and surrounded by hilly hinterland. The northern part of the pilot area (Ljubljansko polje alluvial plain) is composed of permeable gravel and sand beds with significant quantities of groundwater which is the main resource exploited for the public water supply of the city of Ljubljana. The basement of the Quaternary aquifer consists of Carboniferous and Permian rocks which also compose the hills and hilly hinterland. The southern part of the pilot area covers northern part of aquifer Ljubljansko barje that is composed of alternating fluvial and lacustrine deposits with a heterogeneous composition (silt, clay, sand, gravel). The top clay layer in the northern part of Ljubljansko barje is 10-20 meters thick. The upper Pleistocene aquifer is heterogeneous, low permeable and about 20 meters thick. It is separated by a thick clay layer from the lower Pleistocene aquifer that consists of gravel and contains water of good quality. It is a confined or semi-confined aquifer with artesian to subartesian conditions.

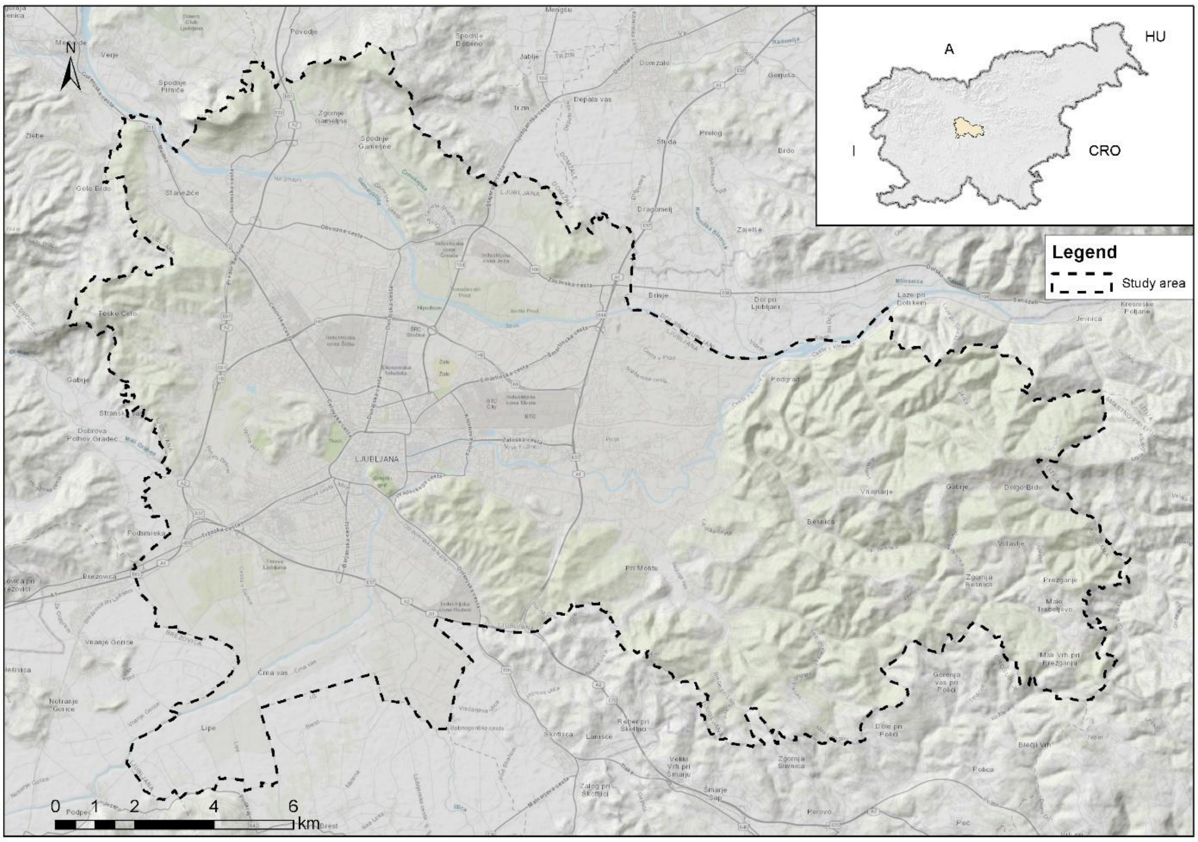


Figure 1: Study area.

2.1.1. Units and structures represented in the 3D model

2.1.1.1. Standard geological column

The basis for 3D geological modelling was the Basic Geological Map of SFR Yugoslavia 1:100,000 which covers the study area with four sheets, namely: Kranj (Grad and Ferjančič, 1974), Ljubljana (Premru, 1983), Postojna (Buser et al., 1967), and Ribnica (Buser, 1969). The newer and revised Geological Map of Slovenia 1:250,000 (Buser, 2009) was used for emendations and harmonization, while several maps of larger scales were used for fine tuning and adjusting the model to the data from the boreholes (e.g. Novak, 2000). The standard geological column was created based on the input data (**Figure 2, Figure 3 and Table 1**).

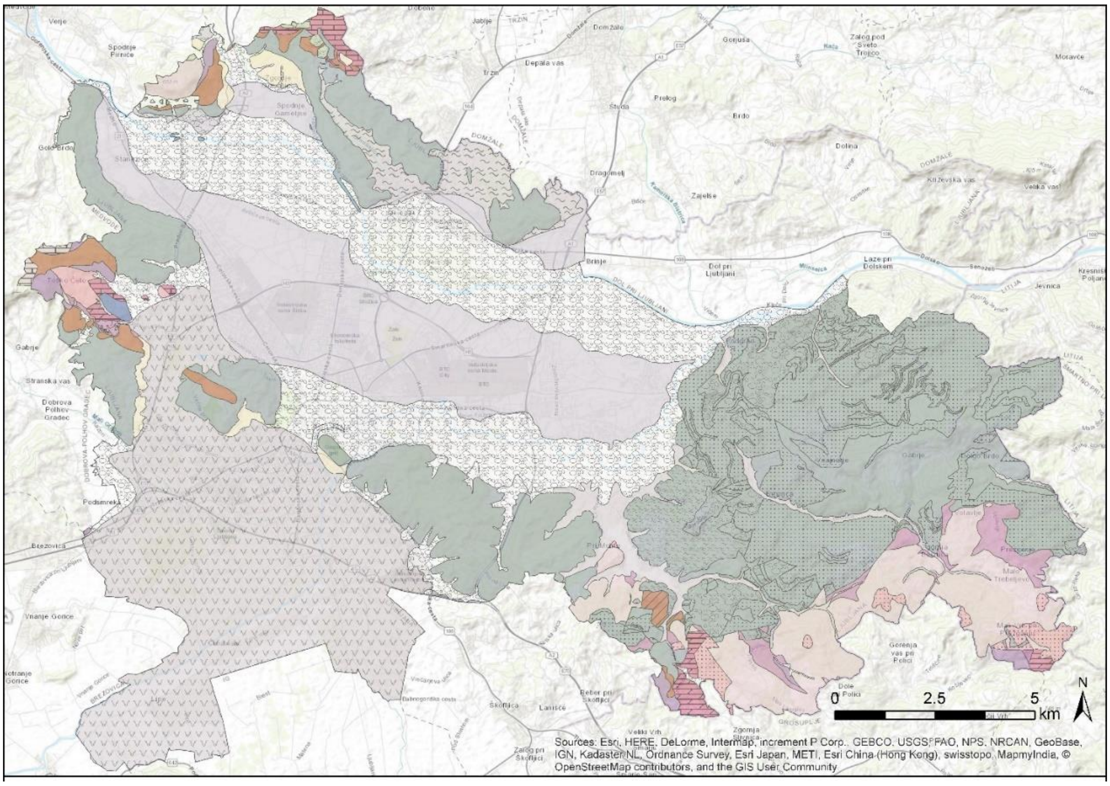


Figure 2: Harmonised geological map 1 : 25 000 (Janža et al., 2017).

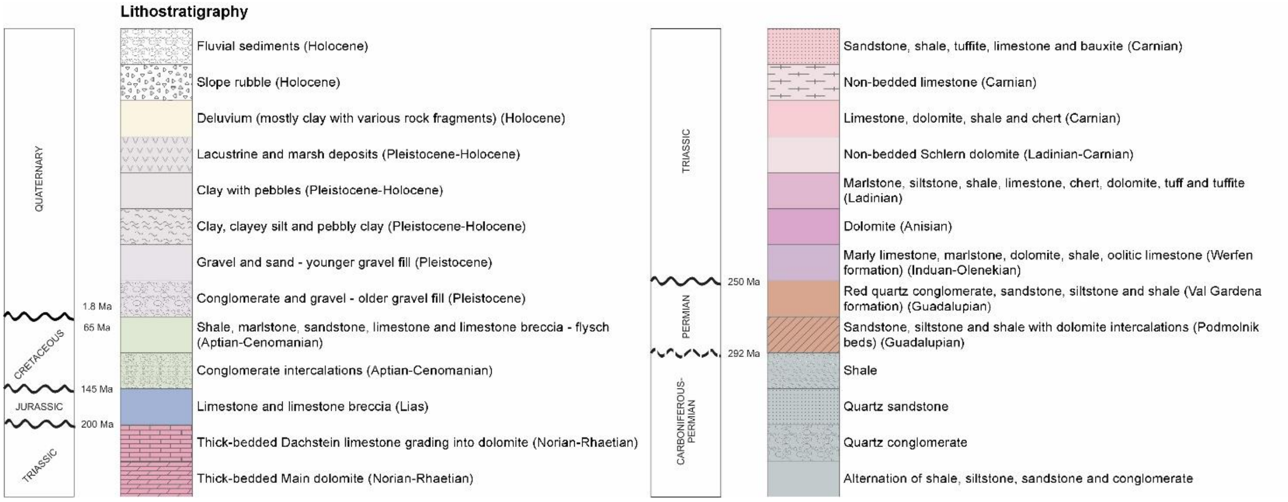


Figure 3: Geological column.

Table 1: Lithological unit from harmonised gelogical map 1 : 25 000.

Number	Lithology	Age
1	Fluvial sediments	Quaternary (Holocene)
2	Slope rubble	Quaternary (Holocene)
3	Deluvium (mostly clay with various rock fragments)	Quaternary (Holocene)
4	Lacustrine and marsh deposits	Quaternary (Pleistocene-Holocene)
5	Clay with pebbles	Quaternary (Pleistocene-Holocene)
6	Clay, clayey silt and pebbly clay	Quaternary (Pleistocene-Holocene)
7	Gravel and sand - Younger gravel fill	Quaternary (Pleistocene)
8	Conglomerate and gravel - Older gravel fill	Quaternary (Pleistocene)
9	Shale and marlstone, sandstone, limestone and limestone breccia - flysch	Lower-Upper Cretaceous (Aptian-Cenomanian)
10	Conglomerate intercalations	Lower-Upper Cretaceous (Aptian-Cenomanian)
11	Limestone and limestone breccia	Lower Jurassic (Lias)
12	Thick-bedded Dachstein limestone grading into dolomite	Upper Triassic (Norian-Rhaetian)
13	Thick-bedded Main dolomite	Upper Triassic (Norian-Rhaetian)
15	Sandstone, shale, tuffite, limestone and bauxite	Upper Triassic (Carnian)
16	Non-bedded limestone	Upper Triassic (Carnian)
17	Limestone, dolomite, shale and chert	Upper Triassic (Carnian)
18	Non-bedded Schlern dolomite	Middle-Upper Triassic (Ladinian-Carnian)
19	Marlstone, siltstone, shale, limestone, chert, dolomite, tuff and tuffite	Middle Triassic (Ladinian)
20	Dolomite	Middle Triassic (Anisian)
21	Marly limestone, marlstone, dolomite, shale, oolitic limestone (Werfen formation)	Lover Triassic (Induan-Olenekian)
22	Red quartz conglomerate, sandstone, siltstone and shale (Val Gardena formation)	Middle Permian
23	Sandstone, siltstone and shale with dolomite intercalations (Podmolnik beds)	Middle Permian
24	Shale	Carboniferous-Permian
25	Quartz sandstone	Carboniferous-Permian
26	Quartz conglomerate	Carboniferous-Permian
27	Shale, siltstone, sandstone and conglomerate	Carboniferous-Permian

2.1.1.2. Fault network

A fault network isn’t included into the 3D geometric and structural model due to lack of data and relative small importance for the constructed model up to 200 m depth.

2.1.1.3. Scheme of geological units

The pilot area is composed of a Paleozoic to Mesozoic basement, overlain by a relatively thick succession of Quaternary predominantly fluvial and to a lesser extent lacustrine sediments. Structurally, the basement comprises Southern Alpine (early Neogene) nappes, mainly composed of Mesozoic carbonates overthrust on Mesozoic carbonate or Paleozoic siliciclastic basement with the most important being the Litija nappe in the northern part of the pilot area. The middle to upper-Neogene Sava folds, with the most important structure being the Litija anticline, are partially superimposed on this structure. Quaternary sediments fill two basins: the Ljubljansko barje in the south and Ljubljansko polje in the north. The Ljubljansko barje is filled with up to 140 m of Middle to Late Pleistocene and Holocene gravels and lacustrine sediments. The Ljubljansko polje is filled with up to 110 m predominantly fluvial sediments.

2.1.2. Data preparation

2.1.2.1. Processing of the raw data

All available data in the pilot area were gathered and prepared in the way they can be used for 3D modelling. First, all available data were digitalised and transformed to a common coordinate system. Because the majority of data were already processed in Gauss-Krueger D48 this was initial and working coordinate system. Later, the layers of 3D geological model were projected to the ETRS_1989_ETRS-TM33 (EPSG: 3045) coordinate system that was used as referenced coordinate system in GeoPLASMA-CE project.

2.1.2.2. Input data for 3D modelling

Following contour maps, cross-Sections & borehole profiles were used to construct the 3D model:

- Digital elevation model with cell size 25 x 25 m (MESP, 2011),
- Harmonised geological map in scale of 1 : 25 000 (Janža et al. 2017),
- Outline of alluvial aquifer,
- 2 Cross sections (Novak, 2000),
- 4 Cross sections (Janža et al., 2017),
- Contour maps of Quaternary aquifer basement and
- Borehole profiles.

2.1.3. 3D modelling

Since the fault network wasn’t implemented into the model, most of the modelling has been done with the ArcGIS 10.3 software. The tops of all geological units are presented by isolines and were interpolated to grids using the Topo to Raster interpolation method. Once all surfaces had been modelled, they were imported into the JewelSuite software for final visual inspection and export as GOCAD triangulated surfaces (*.ts).

Most data was available for the central part of the pilot area in the area of Ljubljansko polje and Ljubljansko barje aquifers. This area is under investigation already for decades, because of the important quantities of groundwater which are used for public water supply. Geological layers which comprise the constructed model up to 200 m depth are:

- Digital elevation model (25 x 25m),
- Top of Pre-Quaternary bedrock and
- Bottom of model at 200 m depth.

We have used available contour maps and depth grids (Mencej, 1990; Kristensen et al., 2000) for modelling the surface tops of the pre-Quaternary bedrocks, and we have updated them with borehole data which have reached the Quaternary aquifer base (Janža et al., 2017).

In the southern part of the pilot area (Northern part of Ljubljansko barje aquifer) the top of the confined aquifer was delineated.

2.2. Pilot area Vienna

The pilot area Vienna covers the districts 21 and 22 of Vienna and adjacent communities in Lower Austria east of the river Danube (**Figure 4**). The city of Vienna is located in the Vienna basin, which accompanies Neogene and Quaternary sediments. The Quaternary sediments east of the river Danube form the Marchfeld groundwater body, which plays an important role for shallow geothermal applications. The total extent of the pilot area is 220 km^2. The major part comprises the districts 21 (Floridsdorf) and 22 (Donaustadt). A minor part of the pilot area is covered by adjacent municipalities in Lower Austria (Gerasdorf bei Wien, Groß-Enzersdorf, Oberhausen, Wittau, Probstdorf, Mühlleiten, Schönau an der Donau). The outline of the pilot area follows the boundary of the ground water body Marchfeld and the urban catchment area of the city of Vienna. The river Danube constitutes the southwestern border of the pilot area. Elevations in the pilot area only range between 200 m a.s.l. in the north (Bisamberg) and 145 m a.s.l. in the south, where the Danube exits the city limits towards southeast.

A total of 339,356 people are registered in the pilot area, whereof 95% live in Vienna. The population density is also higher in Vienna with 2,214 inhabitants per square kilometre compared to 193 inhabitants per square kilometre in the municipalities of Lower Austria. However, the difference in inhabitants between the two states might not be as high as indicated, since they neglect a population growth in Lower Austria in the last 10 years.

Figure 4: The pilot area Vienna viewed from South. City limits of the Vienna indicated in light blue.

2.2.1. Units and structures represented in the 3D model

The 3D model represents top horizons of internal sedimentary units of the Miocene infill of the Vienna basin. In detail, modelled units reflect regional stratigraphic stages of the central paratethys system, which is in use to classify sedimentary deposits occurring in the Alpine-Carpathian Foredeep and intra-Alpine basins in central Europe. Lithological content mainly accounts for sand, clay, marl, gravel and calcareous deposits derived from terrigenous and marine sedimentation processes during the formation of these basins. Starting from the surface down towards the bottom of the Vienna basin, the top horizons of the following units of the sedimentary deposits have been modelled in the pilot area:

- Upper Pannonian
- Middle Pannonian
- Lower Pannonian
- Sarmatian
- Badenian

The underlying surface of the Basement of the Vienna basin has also been modelled. Therefore, the 3D Model of the pilot area Vienna consists of six geologic-stratigraphic surfaces. No fault planes have been implemented into the model.

2.2.1.1. Standard geological column

The Austrian Stratigraphic Chart (Piller et al. 2004) can be considered as the standard geological column including the aforementioned stratigraphic stages of the Miocene basin infill (**Figure 5**), which differ from the global chronostratigraphic chart published annually by the International Commission on Stratigraphy (Cohen et al. 2017).

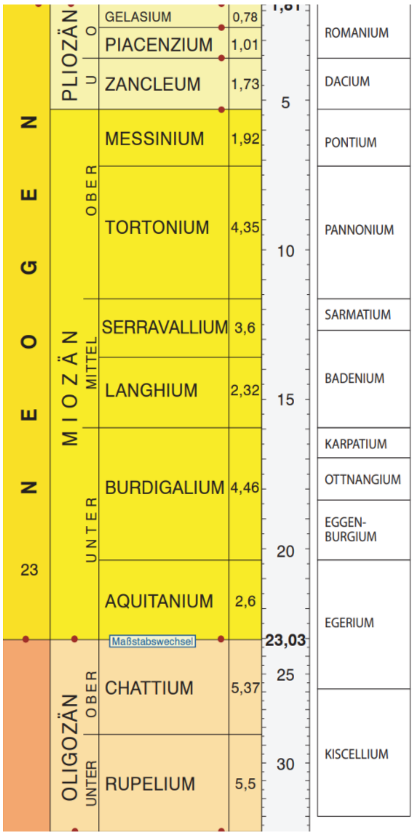


Figure 5: Section of the Austrian Stratigraphic Chart (2004). The coloured section displays the global stages from the international chronostratigraphic chart, whereas the plain white stages depict the regional stages including Pannonian, Sarmatian and Badenian, which were modelled in the pilot area. Subdivision of the Pannonian stage into Upper, Middle and Lower Pannonian is not defined in the stratigraphic chart, although these subdivision is made in all available geodata (contourmaps, boreholes, geological studies). Numbers indicate absolute ages in Ma.

2.2.1.2. Fault network

The local fault network is characterised by a conjugated fault system striking N-S through the northern part of the pilot area. The eastern, west-dipping fault splays of the this system are associated with the Aderklaa-Bockfließ Fault system, representing antithetic normal faults converging into the synthetic, east-dipping normal fault of the Leopoldsdorfer Fault system at higher depths. The vertical thickness of sedimentary units therefore is higher in the area above the fault junction.

2.2.1.3. Scheme of geological units

The Vienna basin, which contains the pilot area Vienna, is one of the world's most studied pull-apart basins. The Miocene fault systems, which formed the Vienna basin, remains seismically active until today (Salcher et al. 2012). Alpine and Carpathian nappes constitute the basement formations. A transgressional phase succeeded the creation of the pull-apart structure and clastic sediments, primarily fine grained silts and sands, filled the basin. These Neogene sedimentary layers reach a total thickness up to 5,000 m. Deposition of sediments continued up to Upper Pannonian. Seismic activities resumed during the Quaternary and the former homogenous sedimentary unit was disrupted into horst and graben structures.

The simultaneous subsidence of the graben sections and the deposition of sediments resulted in greater thicknesses of Quaternary sediments in the graben sections rather than on the horsts.

2.2.2. Data preparation

2.2.2.1. Processing of the raw data

Contour maps have been available in digital formats and were, if necessary, transformed into the joint coordinate System of GeoPLASMA-CE (ETRS89 / UTM zone 33N - EPSG: 25833). Cross sections were digitalised and georeferenced. Borehole profiles were available in a database format and therefore implemented into the model without major processing.

2.2.2.2. Input data for 3D modelling

The following Contour maps, Cross-Sections & Borehole profiles act as control points for surface interpolation in the 3D model:

- Digital Elevation model 10m
- Top Tertiary (Pfleiderer et al., 2007)
- Top Middle Pannonian (Friedl, 1955a; Friedl, 1955b; Friedl, 1955c;Bernhard, 1993)
- Top Sarmatian (Brix, 1969; Unterwelz et al., 1979; Bernhard 1993)
- Top Badenian (Bernhard, 1993)
- Base Neogene (Kröll and Wessely, 1993)
- 2510 Borehole Profiles (Nowy et al., 2001)
- 40 Cross-sections (Nowy et al., 2001)

2.2.3. 3D modelling

2.2.3.1. Modelled objects and modelling methodology

Geological surfaces are represented by triangulated irregular networks (TIN's), which were modelled using the SKUA-GOCAD software suite provided by EMERSON-PARADIGM. SKUA-GOCAD uses the Discrete Smooth Interpolation (DSI) algorithm to generate triangulated surfaces constrained by control points, which can include wellmarkers, contourlines, cross-section lines or seismic interpretation lines.

2.2.3.2. Model assumptions/specifications

In general, borehole profiles acted as main data source for the geological modelling processes. However, as shallow and deep wells are bound to settlement areas and regions of proven and unproven subsurface commodities, data density shows uneven distribution. Concerning the pilot area Vienna, this circumstance affects the uncertainty of the modelled layers. Modelling areas showing greater distance from the city centre west of the pilot area therefore exhibit larger uncertainties regarding depth and thickness of the respective stratigraphic horizons.

2.2.3.3. Model topology

2.2.4. Modelling results

Depth values for modelled top horizons of Miocene sedimentary units are increasing towards the centre of the Vienna basin in the southeast and east of the pilot area. Respective layers reach maximum thickness values above a local graben structure (Schwechater Tief) in the southeast, where the top of the basement horizon is located at 5000 m below ground level (**Figure 6**). Miocene units show onlaps and pinchout geometries towards the northwest in conjunction with rising basement units to shallower depth. At the northwestern tip of the pilot area, basement units are exposed in surface outcrops close to the gate of the Danube, opening up into the Vienna basin.

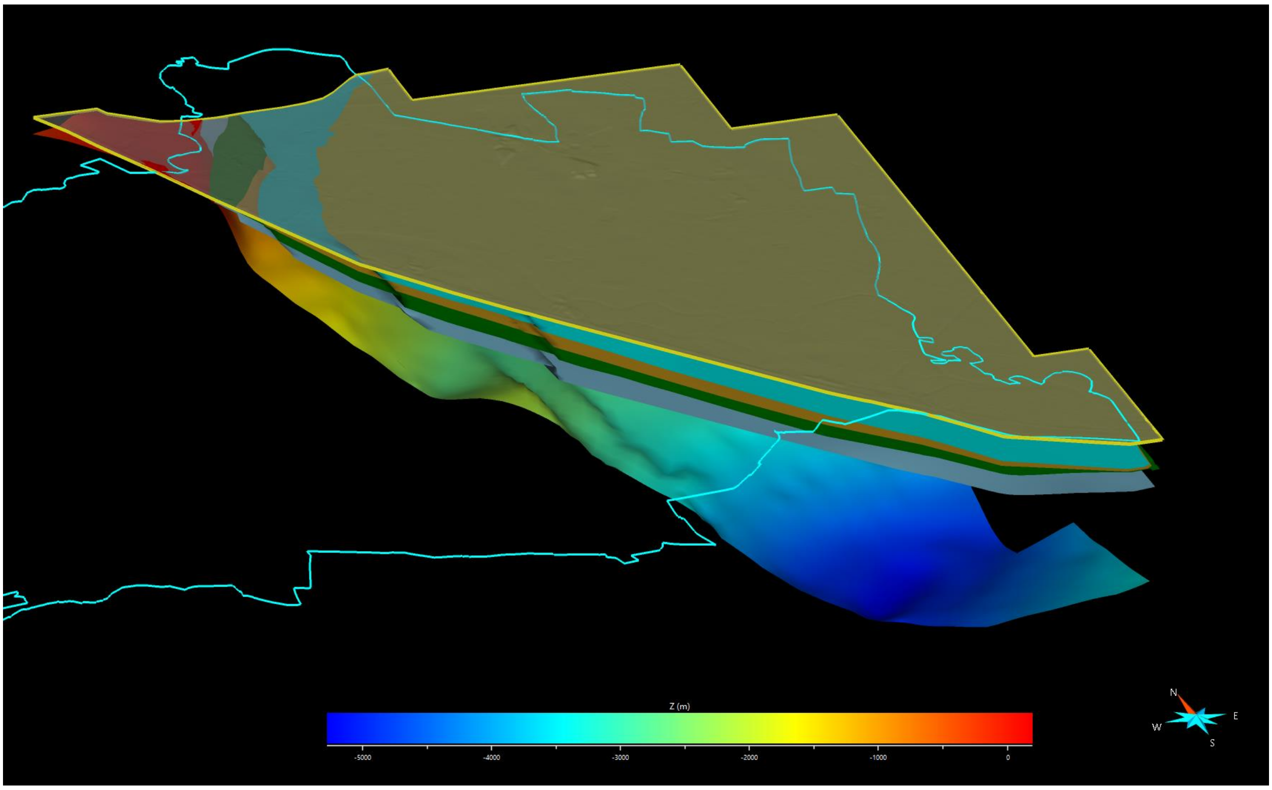


Figure 6: View towards northeast onto the 3D model of the pilot area east of the Danube, showing the modelled horizons of the Miocene basin units and the pre-Neogene basement of the Vienna basin: City border of Vienna (turquoise), Upper Pannonian (yellow), Middle Pannonian (turquoise), Lower Pannonian (beige), Sarmatian (green), Badenian (light blue), basement (colour coded according to elevation).

2.2.4.1. Modelling uncertainties and errors

Geostatistical methods have not been applied to calculate uncertainty values for the 3D model. However, as the abundance of well data in the pilot area is usually prevalent in the shallow subsurface decreasing with depth, therefore the model uncertainties are increasing with depth below surface. Lateral data density variations mostly reflect areas of infrastructural objects including settlement areas and transport connections e.g. streets, bridges, railway lines, tunnels, sewage networks, energy grids (e.g. electrical, district heating, gas distribution system). Furthermore, geological borehole profile descriptions proved to be highly inconsistent due to different well interpreters. Additionally, inaccurate measurements of borehole elevation, which did not match with the topographic DEM surface, hampered proper modelling.

2.3. Pilot area Bratislava-Hainburg

The pilot area Bratislava-Hainburg covers a crossborder area of 603 km² between Slovakia and Austria at the vicinity to Hungary (**Figure 7**). The river courses of Danube, Leitha and March confine the area towards the west, whereas the eastern border is synonymous with the city limits of Bratislava. The Austrian/Slovakian border dissects the pilot area into the rural, Austrian part in the southwest and the urban, Slovakian part of Bratislava in the northeast. Therefore, the total population in the entire pilot area of ca. 450 000 is also concentrated on in the Slovak part. Topographic Elevation ranges from 480 m a.s.l. in the Male Karpaty mountains in the northern section to 125 m a.s.l. in the east, where the Danube exits the pilot area towards the Hungarian Plain. At the northern part, the Danube crosses the NE-SW-striking Male Karpaty and Hainburg Mountain Range, draining the Vienna basin located northwest of the Pilot area and entering the Danube/Pannonian basin towards the southeast. The Mountain Range, composed of crystalline rocks of the Alpine-Carpathian Orogene, therefore acts as the border between these two central European basins.

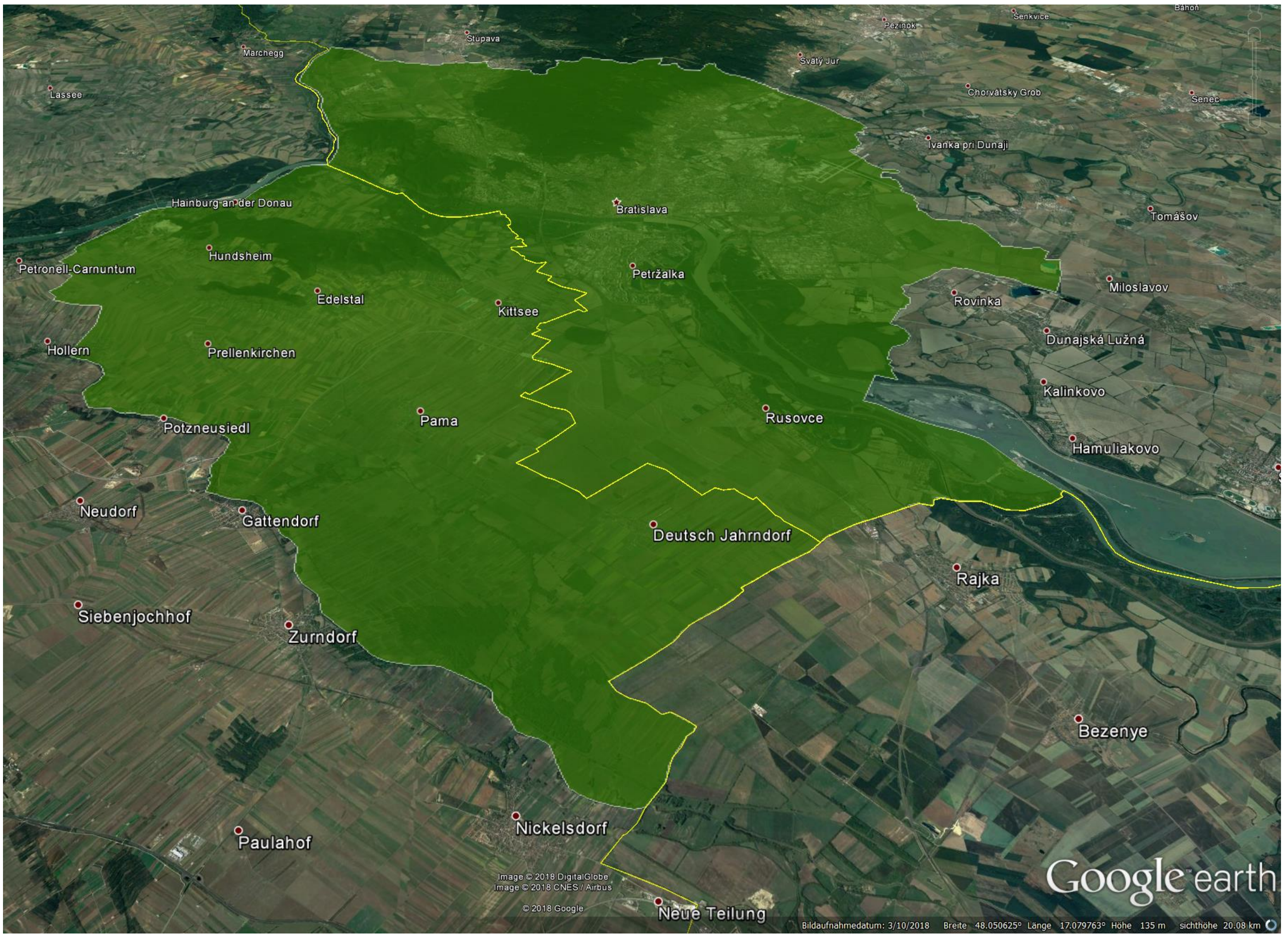


Figure 7: Extent of the pilot area Bratislava-Hainburg viewed from South.

2.3.1. Units and structures represented in the 3D model

Modeling units were defined by the project partner SGIDS in coordination with regional geologists of their mapping department. Holocene and Pleistocene units of the Quaternary period were modelled due to the different lithological content affecting their hydrogeological characteristics. Neogene deposits were modelled en bloc, as subunits show similar lithological characteristics. Hardrock units were subdivided into Mesozoic Carbonates and Mesozoic Quartzites, occurring in the western section of the Pilot area, as well as in crystalline units of Granites and Schists, forming the bedrock of the Male Karpaty and Hundsheimer mountains. The modelled units depict the base horizons of the respective, stratigraphic layers, with exception of the crystalline bedrock as lowermost unit.

- Holocene (loam, clay, & sand)
- Pleistocene (Quaternary gravel terraces of river deposits by rivers Danube, Leitha and March)
- Neogene (clay, marl & sand)
- Mesozoic Carbonates (grey and dark dolomite and limestone)
- Mesozoic Quartzites
- Crystalline (granite, gneis and schist ranging from Neoproterozoic to Carboniferous age)

Main normal fault planes confining the Vienna and Danube basin were modelled based on fault sticks from geologic cross-sections.

2.3.1.1. Standard geological column

Modelling units reflect a combination of stratigraphic stages and lithological units. Stratigraphic units reflect stages of the global chronostratigraphic chart published annually by the International Commission on Stratigraphy (Cohen et al. 2017)(**Figure 8**).

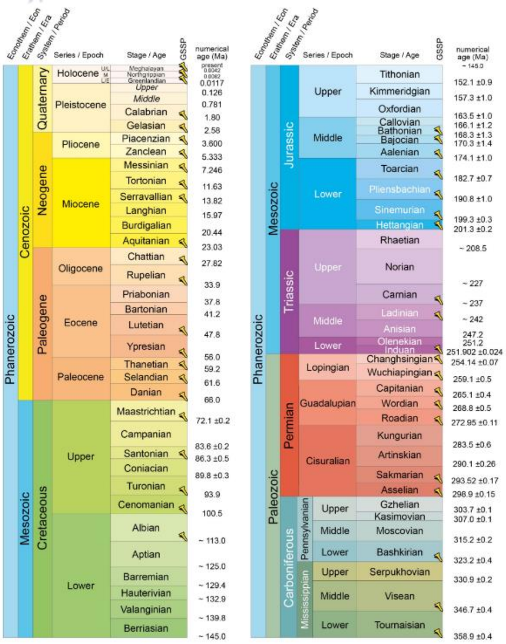


Figure 8: Section of the international Stratigraphic Chart. Mesozoic Quartzites predate overlying Mesozoic Carbonates. In detail, Quartzites have originated in the Lower Triassic in a desert environment, whereas Carbonates are showing Middle Triassic characteristics from a shallow marine environment.

2.3.1.2. Fault network

The Fault network in the pilot area features two distinct fault systems linked to the formation of the Vienna basin and the Danube basin, respectively. NE-SW trending, steeply NW dipping faults bordering the Male Karpaty mountains towards NW are associated with fault splays of the Vienna basin Transfer Fault strike-slip fault system. The NE-SW trending, SE dipping normal faults between the Male Karpaty mountains and the lowlands of the Bratislava city area exhibit a fault system, which confines the Danube basin towards the northwest, vertically offsetting Miocene basin sediments towards southeast.

2.3.1.3. Scheme of geological units

Prior to the start of the modelling process, a harmonized geological map of the pilot area was established based on geological maps from Slovakia (scale 1: 50 000) and Austria (1:200 000). Mapped formations were grouped in order to show the surface extent of defined modelling units (Figure **9**). The pilot Area Bratislava-Hainburg is located at the crossover between Alps (Vienna basin) and Carpathian mountains (Danube basin/Pannonian basin). Quaternary deposits predominantly originate from the Danube and Leitha river. Miocene sediments account for the main infill of the Vienna and Danube basin, occurring at the surface on the western slopes of the NE-SW trending Male Karpaty mountains in Slovakia and Hundsheimer mountains in Austria). Outcrops of Carbonates and Quartzites of Mesozoic origin occur in the western half of the pilot area at Spitzerberg, Braunsberg and Pfaffenberg (Quarry Deutsch Altenburg) steeply dipping towards west beneath the Miocene deposits of the Vienna basin. The crystalline core of the Male Karpaty and Hundsheimer mountains is composed of granites, gneisses and schists representing the transition zone between Lower Alpine Nappe units in the SW and Lower Western Carpathian units (Tatrikum) in the NE.

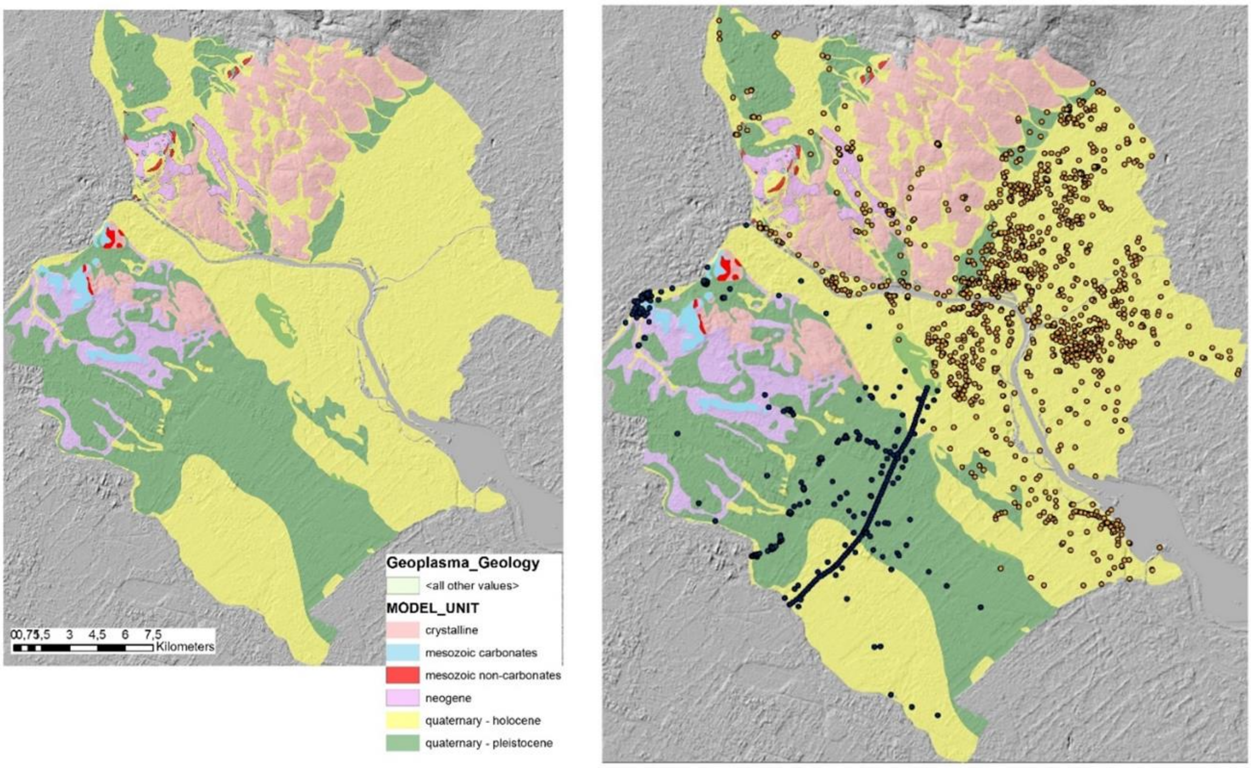


Figure 9: Left: Combined geological map of the pilot area, showing the extent of modelling units at the surface. Right: Location of wells which have been used as input data for modelling. Note difference in data density of wells in the Slovak part (orange), in contrast to wells on the Austrian side.

2.3.2. Data preparation

2.3.2.1. Processing of the raw data

Geological maps for Lower Austria (1:200 000) and Eastern Slovakia (1:50 000) have been available in digital vector formats. Polygons of geological units have been merged in order to create outline polygons for the surface extent of previously defined modelling units. The harmonized map for the entire pilot area served as one of the main input datasets for the creation of the 3D model. Contour lines for the base horizon of Quaternary sediments have been calculated based on isopach maps, using the digital elevation model as reference. Rasterdata of seven geological cross-sections were digitalised and georeferenced. Borehole profiles were available in one database from Slovakia and two databases from Austria, containing stratigraphic and lithological information. The well databases have been merged manually, in order to generate a harmonized wellmarker database for previously defined modelling units for the pilot area Bratislava-Hainburg.

2.3.2.2. Input data for 3D modelling

Digital Elevation Model 90m (SRTM Data),

- 1482 Borehole Profiles from various, existing databases: 1215 (SGIDS) and 267 (GBA),
- Geological Map 1: 50 000 (SGIDS),
- Geological Map 1: 200 000 (Schnabel et al., 2002),
- Isopach Map Quarternary 1: 50 000 (Malík et al., 2007),
- Isopach Map Quarternary (Zámolyi et al., 2017),
- 5 cross-sections created within the project by mapping geologists of SGIDS in 2017,
- 2 published cross-sections (Wessely, 2006),
- Contour map Base Neogene (Kröll and Wessely, 1993),
- Base Neogene Pointset & Base Mesozoic TIN (Transenergy Project 2010-2013).

2.3.3. 3D modelling

2.3.3.1. Modelled objects and modelling methodology

The base of the modelled geological units is represented by triangulated irregular networks (TIN’s), which were modelled using the SKUA-GOCAD software suite of EMERSON-PARADIGM. SKUA-GOCAD uses the Discrete Smooth Interpolation (DSI) algorithm to create triangulated surfaces constrained by control points, which can include wellmarkers, contourlines, cross-section polygons.

2.3.3.2. Modell assumptions/specifications

If no borehole data was available, the thickness of the uppermost unit Holocene was set to 2m. Borehole data were taken into consideration, if the documented thickness of Holocene was larger than 2m, however, only very few well profiles included a description of the Holocene. Contour maps for the base horizon of Quaternary sediments were taken into account to model the base horizon of the Pleistocene unit, as Pleistocene terrace bodies depict the lowermost Quaternary sequence. Outlines of modelled Quarternary and Neogene deposits were set in areas with sufficient well data density and thickness of the respective layer. Areas with thickness of layers below 10m were discarded. As no borehole information on the base depth of Mesozoic Carbonates and Quartzites was available, these units were solely modelled according to information retrieved from cross-sections. Therefore, the Mesozoic units are based on geological concepts with high uncertainties regarding distribution and thickness.

2.3.3.3. Model topology

2.3.4. Modelling results

The geological 3D model of the pilot area Bratislava-Hainburg depicts the geological border area between the Vienna basin in der northwest and the Danube basin in the southeast, dissected by a NE-SW trending crystalline horst, composed of Alpine and Carpathian tectonic units. This crystalline core of the Male Karpaty and Hundheimer mountains plunges towards southwest with a dip of about 3 degrees. The modelling units of Holocene, Pleistocene and Neogene sediments cover almost the entire pilot area, except the mountainous region, where Quaternary units are absent or exhibit insufficient layer thickness for proper modelling (**Figure 10**). The thickness of Pleistocene and Neogene layers increase towards the basins centre in the NW and SE, respectively. Mesozoic modelling units of Carbonate and Quartzite rock suites solely occur on the NW slopes of the crystalline core beneath the Vienna basin.

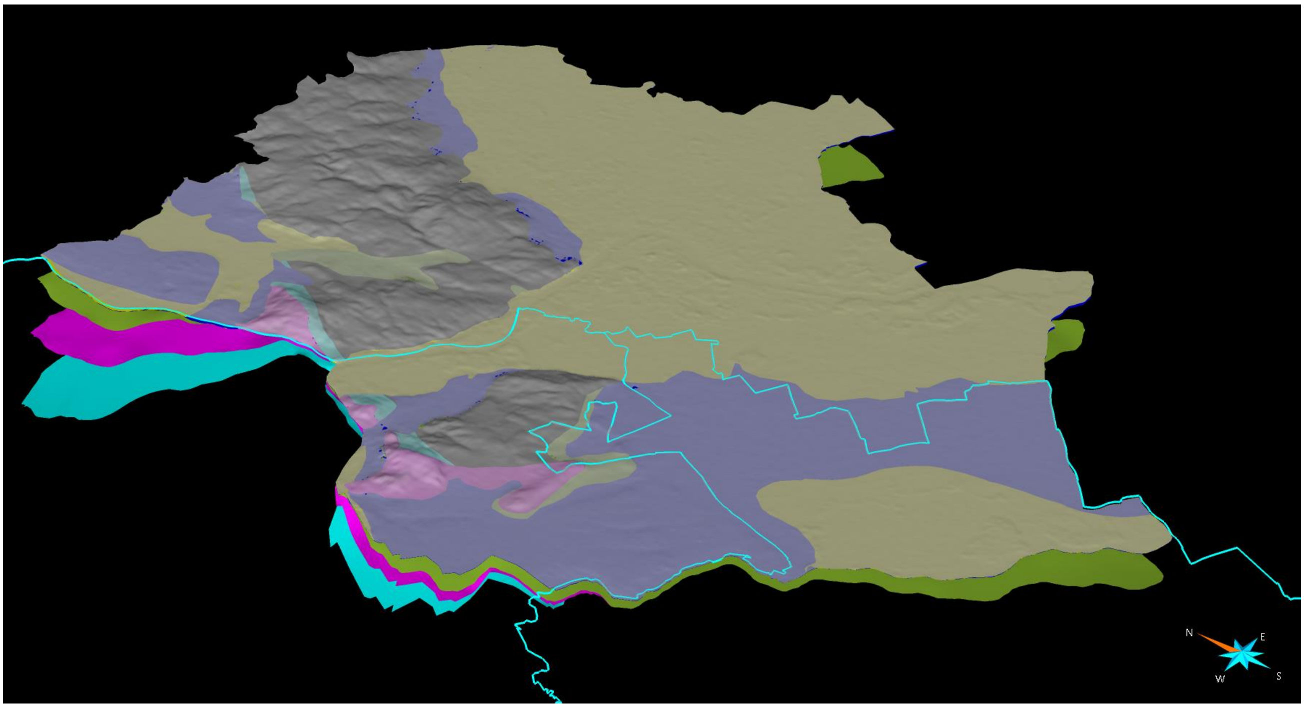


Figure 10: View towards NE onto the 3D model of the pilot area Bratislava-Hainburg: national and federal borders of Austria (turquoise), Holocene (yellow), Pleistocene (violet) Neogene (green), Mesozoic Carbonates (pink), Mesozoic Quartzites (turquoise).

2.3.4.1. Modelling uncertainties and errors

Geostatistical methods have not been applied to calculated uncertainty values for the 3D Model. However, as abundance of well data in the pilot area are usually prevalent in the shallow subsurface decreasing with depth, so are model uncertainties increasing with depth below surface. Furthermore, geological descriptions of borehole profiles proved to be defective due to various interpreters, resulting in heterogeneous well databases. Absolute height values of well locations were often not accurate and therefore did not coincide with the surface of the digital terrain model imported into the 3D model.

2.4. Pilot area Krakow

The Kraków pilot area (**Figure 11**) covers 327 km^2. The city is located in Lesser Poland and is characterized by a high degree of urbanization. The population of the Kraków consists of approximately 770 000 citizens. According to the physical-geographical distribution of Poland by Kondracki (2002) the Kraków agglomeration is located in a transitional zone between the valleys of Auschwitz and Sandomierz and belongs to the geomorphological unit called the Kraków Gate. The area is bordered by the Wieliczka Foothills in the south, and by the Częstochowa Upland and Nida Trough in the north. The area of the Kraków Gate unit, in the Kraków agglomeration, is divided into subunits: the Skawina Graben, Cholerzyn Depression and Kraków Bridge. The axis of the city is the valley of the Vistula River running from west to east with its lowest elevation of 195 m a.s.l. in the eastern part of the city. The highest elevation point in the administrative borders of Kraków is approximately 360 m a.s.l. in the western part of the city in the Las Wolski area.

Kraków's Bridge structure forms a circuit of limestone hills and tectonic depressions, where the Vistula River flows. The main hills are Tyniec, Sowinec, Pychowice, Krzemionki, Wawel and Skalka Hill. Almost all of the geomorphological structure of the Kraków's Bridge is located within the agglomeration of Kraków, therefore a very large differentiation in the natural environmental conditions, mainly of anthropogenic origin, can be observed. The north-eastern part of Kraków is located in the area of the Nida Through (Proszowice Plateau) and the eastern part belongs to the western scrap of the Sandomierz Cirque (NadWisłanska Lowland).

Figure 11: Pilot area Kraków viewed from South. Krakow City administrative border indicated by a black line.

2.4.1. Units and structures represented in the 3D model

The main modelling units were defined in coordination with regional geological maps and hydrogeological condition. Some layers divided to permeable (aquifer) and poorly permeable due to combination of lithology and hydrogeological conditions in Krakow Pilot Area.

The goal of constructing that structural model was to prepare horizons and grids for further static and dynamic hydrogeological modelling (**Table 2**).

Table 2: Stratigraphic units modeled in Kraków area.

Number of layer	Stratigraphy	Type of layer
I	Quaternary	semipermeable
II	Quaternary	aquife
III	Tr+K (Carpathian Flysch)	aquifer
IV	Tr+K (Carpathian Flysch)	poorly permeable
V	Neogene (Miocene)	poorly permeable
VI	Neogene (Miocene)	aquifer
VII	Neogene (Miocene)	poorly permeable
VIII	Neogene (Miocene)	aquifer
IX	Neogene (Miocene)	poorly permeable
X	Neogene (Miocene)	aquifer
XI	Neogene (Miocene)	poorly permeable
XII	Cretaceous (Upper)	aquifer
XIII	Cretaceous (Upper)	poorly permeable
XIV	Jurassic (Upper)	aquifer
XV	Jurassic (Upper)	poorly permeable
XVI	Jurassic (Middle)	aquifer / poorly permeable
XVII	Carboniferous+ Devonian+ Cambrian	aquifer
		poorly permeable

2.4.1.1. Standard geological column

The modelling units reflect a combination of stratigraphic era, series and lithological units. Stratigraphic units reflect stages of the global chronostratigraphic chart published annually by the International Commission on Stratigraphy (Cohen et al. 2017),(**Figure 12**).

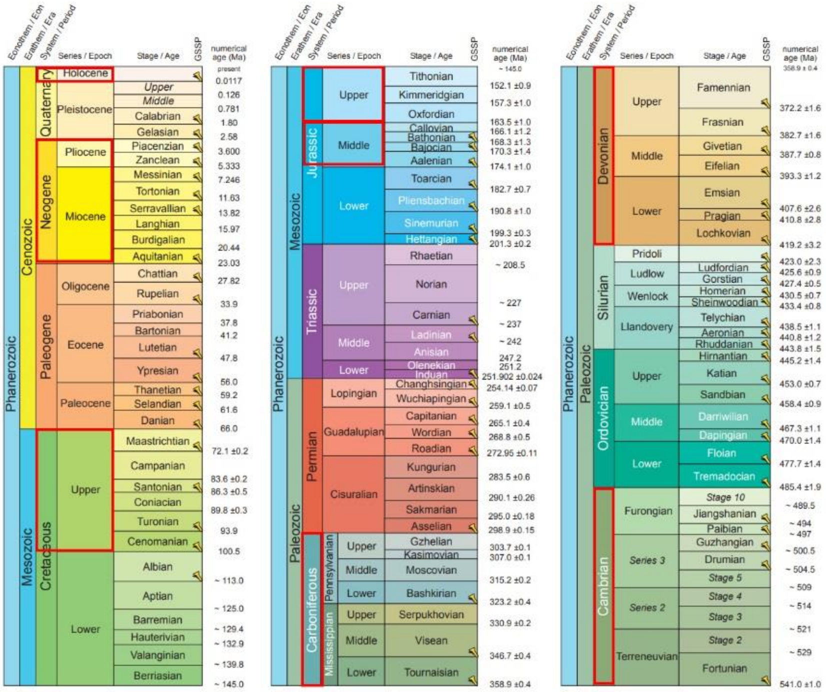


Figure 12: Section of the international Stratigraphic Chart with sections present in Kraków model area (marked with red line).

2.4.1.2. Fault network

The tectonic interpretation is based on analyses of DEM variability, fault lines published in legacy data and analyses of the extent of geological complexes. Two main fault directions can be distinguished within the modelled area. The first set of faults has a N-E strike. The direction of the second set of the faults is not so consistent, but may be described by a general N-S strike. The ault network consists of 303 individual faults, approximately 100of them are located in the Kraków pilot Area (**Figure 13**).

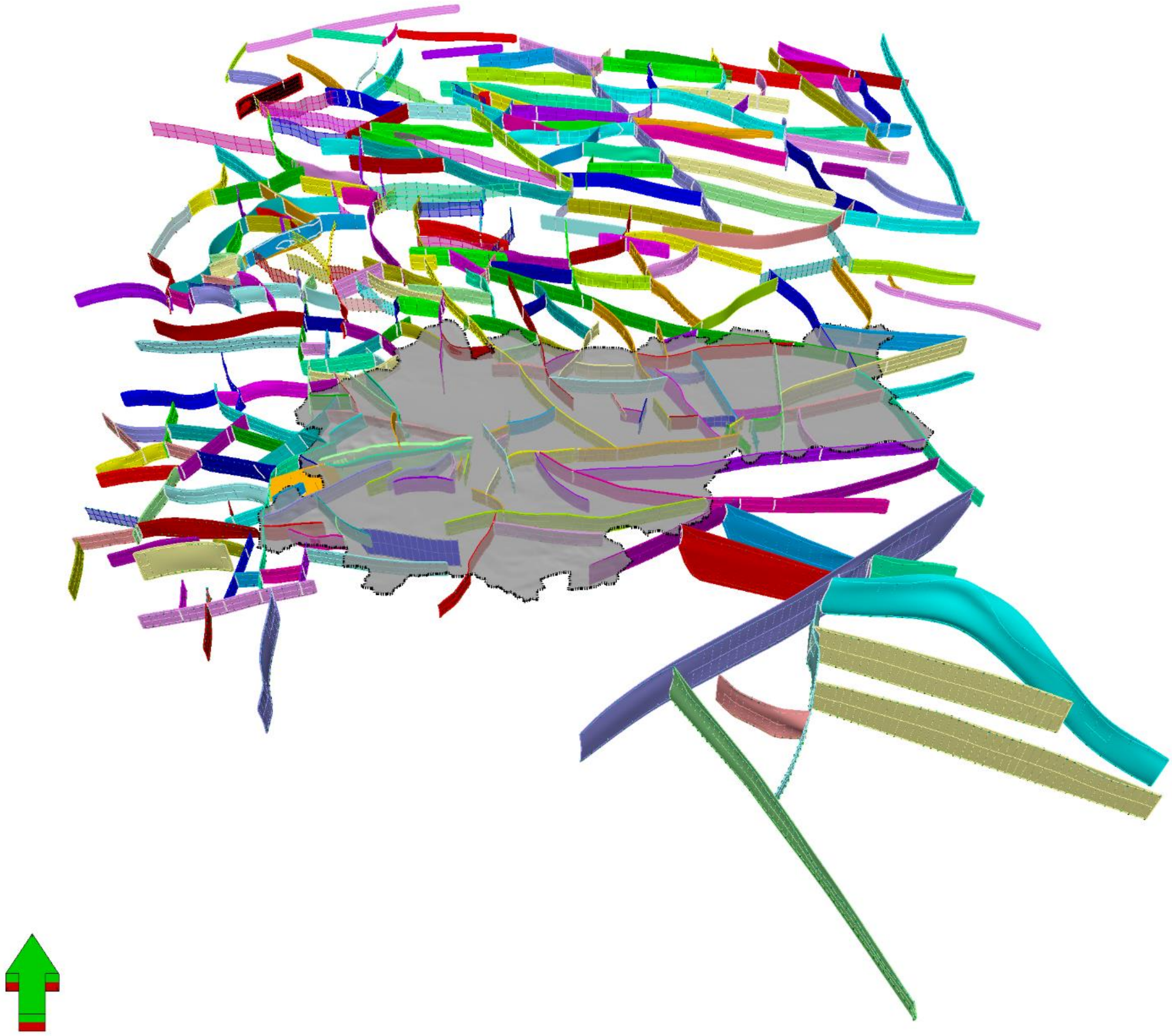


Figure 13: Fault network within Kraków geological model area.

2.4.1.3. Scheme of geological units

Quaternary sediments fill the ancient valley of the Vistula River in the area of the Kraków city (**Figure 14**), creating a series of terraces and alluvial cones of Pradnik and Rudawa rivers (Duda et al., 1997). These sediments are mainly sand and gravel of fluvial and fluvioglacial origin. In the southern part of research area thrusted, Carpathian Flysch complex occurs. This complex is composed of sandstones and shales. Underlaying Neogene seddiments are comeposed of altenating water-bearing porous sands and poorly permeable clays, mudstones and sometimes limestones marls and gypsum. These sediments filled erosional valleys. Mesozoic strata comprising carbonates of the Upper Cretaceous and Upper Jurassic, as well as mostly clastic strata of Middle Jurassic (also Upper Triassic far to the north from Cracow) deposits are present below the Miocene. An underlying Early Paleozoic carbonate complex of the Lower Carboniferous – Upper Devonian is present in the modelled area. The last and lowest complex is represented by Early Paleozoic clastic rocks of Silurian - Cambrian (Precambrian ?) age.

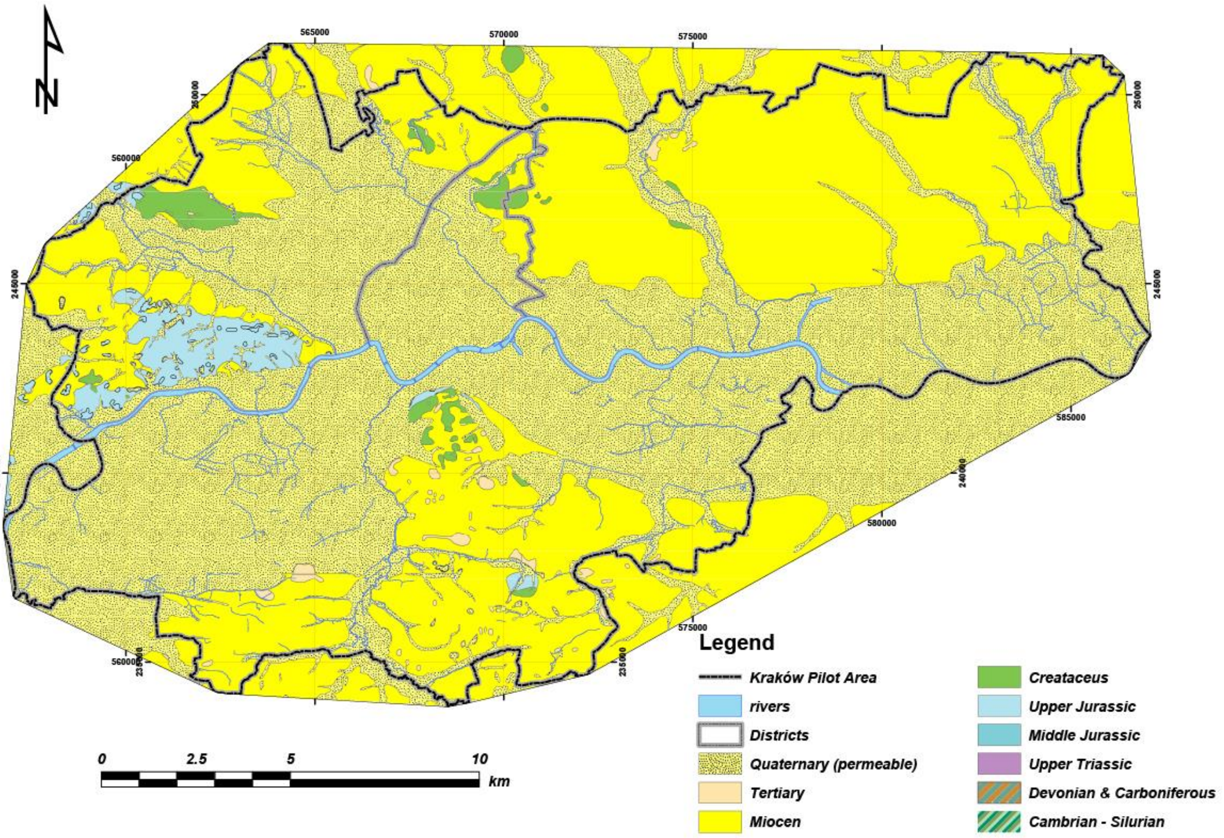


Figure 14: Geological map (without 1st semipermeable layer) of Kraków Pilot Area.

2.4.2. Data preparation

2.4.2.1. Processing of the raw data

Detailed Geological Maps of Poland (1:50 000) have been available mostly in digital vector formats. Two of them were available only in raster form, so the geological boundaries were digitized. Based on geological maps and publications polygons of geological units have been merged in order to create outline polygons for the surface extent of previously defined modelling units. The harmonized map for the entire pilot area served as one of the main input datasets for the creation of the 3D model. Rasterdata of geological cross-sections were digitalised and georeferenced. Borehole profiles were available in tree databases: CBDG, BDGi, and CBDH (CE177_D.T.3.1.2), containing stratigraphic and lithological information. Well databases have been merged manually, in order to generate a harmonized wellmarker and litology profile database for previously defined modelling units for the Krakow pilot area.

2.4.2.2. Input data for 3D modelling

- Digital Elevation Model
- 25302 Borehole Profiles from various, existing databases: 23012 (BDGI), 1618 (CBDH) & 672 (CBDG)

Detailed Geological Map of Poland, scale 1:50 000 (SMGP; four map sheets):

- 973 Kraków (Rutkowski, 1989) also available in GIS format;
- 974 Niepołomice (Gradziński, 1955) also available in GIS format;
- 996 Myślenice (Pawlak and Zając, 1978);
- 997 Wieliczka (Burtan, 1954);

Lithogenic Map of Poland, scale 1:50 000:

- 973 Kraków (Wichowska, 2010) also available in GIS format

Geological map of Poland horizontal cut, scale 1:1 000 000:

- Horizontal cut at -500, -1000 and -2000 m.a.s.l, also in GIS format
- Geological map of Poland without Cenozoic deposits, scale 1 :1 000 000 (Dadlez et al., 2000);

Geological-engineering Atlas of Kraków (the whole Kraków area) PGI-NRI, 2005

- Documentation map, scale 1:10 000;
- Map of soil at 1 m depth, scale 1:10 000;
- Map of soil at 2 m depth, scale 1:10 000;
- Map of soil at 4 m depth, scale 1:10 000;
- Map of anthropogenic deposits, scale 1:10 000;
- Maps of the depth of the first groundwater table, scale 1:10 000;
- Map of building conditions, scale 1:10 000;
- Map of Quaternary basement, scale 1:10 000;
- Map of land development 1:10 000;
- Map of threats and protected areas 1: 10 000;
- Map of outlying Mesozoic deposits, scale 1:50 000;
- Geomorphological map, scale 1:50 000.

Geological and structural Atlas of the Paleozoic basin of the Outer Carpathians and the Carpathian Foredeep (Buła and Habryn, 2008):

- Location of the boreholes reaching the Palaeozoic and Precambrian rocks;
- Geological and structural map of the top of Paleozoic strata (without Permian and Precambrian rocks);
- Structural map of the base of Ordovician strata on the Małopolska Block;
- Structural map of the base of Silurian strata on the Małopolska Block;
- Geological map to Carbon strata on the Małopolska Block;
- Structural map of Devonian-Carboniferous carbonate rocks complex on the Upper Silesia and Małopolska Block.
- Tectonic outline of the Western Carpathians (Żytko et al., 1989)
- The basement of the tertiary of the Western Carpathians (Oszczypko et al., 1989)

- The cross-section and maps from publications (Cyran, 2008; Duliński et al., 2002; Habryn et al., 2007; Haładus et al., 1990; Szklarczyk and Kaczmarczyk, 2015; Szklarczyk, 2015, Szklarczyk, 2016)

2.4.3. 3D modelling

2.4.3.1. Modelled objects and modelling methodology

Mapping tasks in the research were based on utilisation of Schlumberger's, Petrel Software Platform. It allows for extensive integration of different kind of data (geological, geophysical, cartographic, petrophysical, production, etc.), accurate quantitative digital mapping, and structural modelling and parametric modelling (facies, temperatures, petrophysical or geomechanical parameters, etc.). In this philosophy of geological modelling the centre of all performed analyses is the digital geomodel (Petrel Project). A Corner Point Grid is created by pillar gridding in which the faults define the shape of a 3D grid. This is a classical process where faults define breaks in the grid. General lateral resolution is set in pillar gridding process. During Horizons modelling process independent geological horizons are built. The space between the horizons is represented by a hexahedral structure which may be divided into smaller cells using the layering process. As a result of this, a complete structural model is created.

2.4.3.2. Modell assumptions/specifications

In the area of the project, structural and tectonic variability is well recognised only at the ground surface. Kraków area is characterized by seismic surveys and deep wells containing geophysical logs. On the other side, the area is well controlled with hydrogeological and engineering wells, and a few legacy, deep exploration wells also exist. In total, it is > 10,000 boreholes. Geological interpretations in publications are e.g. hydrogeological interpretations covering the area in very local scale - often only in schematic cross sections, or on a very general regional point of view, concentrating on deeply buried horizons.

The area displays an extremely complicated geological setting. Six structurally independent geological complexes can be observed in depths up to 500 m below the ground surface:

- Quaternary complex;
- thrusted Carpathian Flysch complex in the southern part of research area;
- Miocene complex, filling erosional valleys;
- Mesozoic strata, comprising carbonates of Upper Cretaceous and Upper Jurassic, as well as, mostly clastic, strata of Middle Jurassic (also Upper Triassic far to the north from Cracow) deposits;
- Late Paleozoic carbonate complex of Lower Carboniferous – Upper Devonian;
- Early Paleozoic - clastic complex of Silurian - Cambrian (Precambrian ?) age.

Five tectonic units can be distinguished in publications describing the Kraków area :

- Outer Carpathians (south part of the area);
- Carpathian Foredeep (strongly developing to the east);
- Southern margin of the Silesian-Cracow Monocline;
- Paleozoic Silesian Block;
- Małoposka Block.

The tectonic interpretation is based on analyses of DEM variability, fault lines published in legacy data and analyses of the extent of geological units. The structural reconstructions are based on legacy data, especially borehole data.

2.4.4. Modelling results

The results of modelling strongly reflect the multistage geological evolution of the area (**Figure 15**). Strong tectonic activity (last phase of deformation in Miocene) together with long periods of erosion resulted in a very complex pattern of outcrops and sub-crops, from Miocene through Cretaceous to Upper Jurassic strata in the Kraków area.

The thickness and structural variability reflect the very complex geological evolution. Both 2D grids and 3D models were elaborated with a horizontal resolution of 25 m. The presented model was divided into the following geological complexes:

- Quaternary complex (comprising 2 subcomplexes of model);
- Flysch complex in the southern part of research area (2 sub-complexes);
- Miocene complex (7 sub-complexes);
- Mesozoic complex (6 sub-complexes);
- Late Paleozoic complex - composed of undivided Devonian & Carboniferous deposits;
- Early Paleozoic - undivided complex of Silurian – Cambrian.

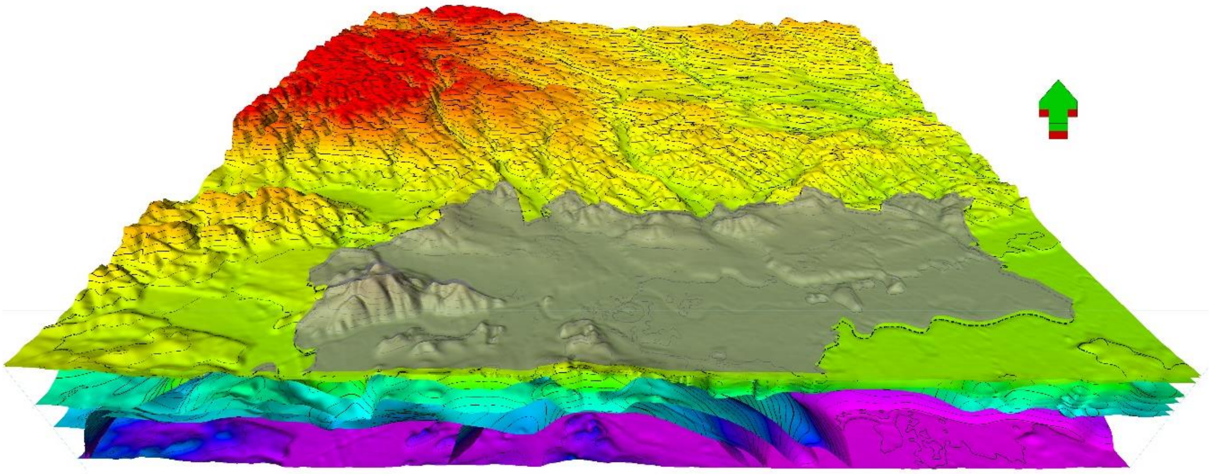


Figure 15: Simplified 3D geological model comprising the main stratigraphic units in the Kraków pilot area.

2.4.4.1. Modelling uncertainties and errors

The 3D model was constructed without geostatistical uncertainty analysis. Nevertheless, several uncertainty elements, mainly associated with input data were distinguished. First, archival cross-sections which were georeferenced and imported into geodatabase seem to be mostly conceptual in many places. Also, archival tectonic maps were inconsistent.

The digitised fault framework is inconsistent regarding the rotation angle, but not in pattern and general trend. The 3D fault framework was generally constructed by vertical faults. A lack of accurate fault surface mapping led to a generalisation which may affect the dip angle. Furthermore, geological descriptions of borehole profiles mostly related to lithology qualification of geological engineering boreholes proved to be defective. This was due to various interpreters sometimes caused by inexperienced field personnel performing drilling. Uncertainty of the presented result raises considerably with the increase of depth.

2.5. Pilot area Walbrzych-Broumov

The transboundary Wałbrzych / Broumov pilot area covers a total area of appr. 1,245 km^2, including Pthe olish part - i.e. Wałbrzych area – of ca 767 km^2 and the Czech area of 478 km^2 (**Figure 16**). The modelled area is increased by a buffer zone, which enlarges the total area to 1,536 km^2. In terms of administrative division, the Wałbrzych area is located in the southern part of the Lower Silesian Voivodship and comprises the territory of the Wałbrzych City (town with district rights) and the whole Wałbrzych district (**Figure 16A**). The Broumov area on the Czech side includes the northern part of the Náchod district and the eastern part of the Trutnov district. Geographically, the main part of the Wałbrzych / Broumov area is located in the Central Sudety mountains. This area is morphologically very differentiated and includes fragments of several mesoregions (Fehler! Verweisquelle konnte nicht gefunden werden.**6B**).

Due to generally mountainous character, average heights of the Wałbrzych area vary from 300-400 m a.s.l. in the N and up to 800-940 m a.s.l. in the S (Kamienne mountains.). The main rivers flowing through the area are the Lesk, the Pełcznica, the Ścinawka, the Bystrzyca and the Zadrna.

2.5.1. Units and structures represented in the 3D model

The Wałbrzych / Broumov area belongs to the Central Sudety mountains. block and includes several geological sub-units (**Figure 17**). About two thirds of its territory is built by one transboundary geological unit - the Intra-Sudetic basin (or Synclinorium) - filled with sedimentary and volcanic rocks. A small belt of the Kaczawa mountains. metamorphic complex and the Świebodzice basin is located at the northern edge of the Wałbrzych / Broumov area and in its NE corner, respectively. The eastern part of the area is made by a fragment of the Sowie mountains. gneiss complex. The listed geological units are characterized by complicated tectonic structure and by high diversity of the lithostratigraphic rock formations, ranging in age from Lower Paleozoic reported in the basement, metamorphic complexes and Świebodzice basin to Upper Paleozoic and Mesozoic in the Inta-Sudetic basin. The young cover of Neogene (Tertiary) and Quaternary sediments is of minor significance and spatial distribution.

2.5.1.1. Standard geological column

The 3D geological model for the Broumov-Wałbrzych pilot area includes 32 lithological-stratigraphic units established jointly by the Polish-Czech team of geologists.

Featured units are presented in **Table 3**.

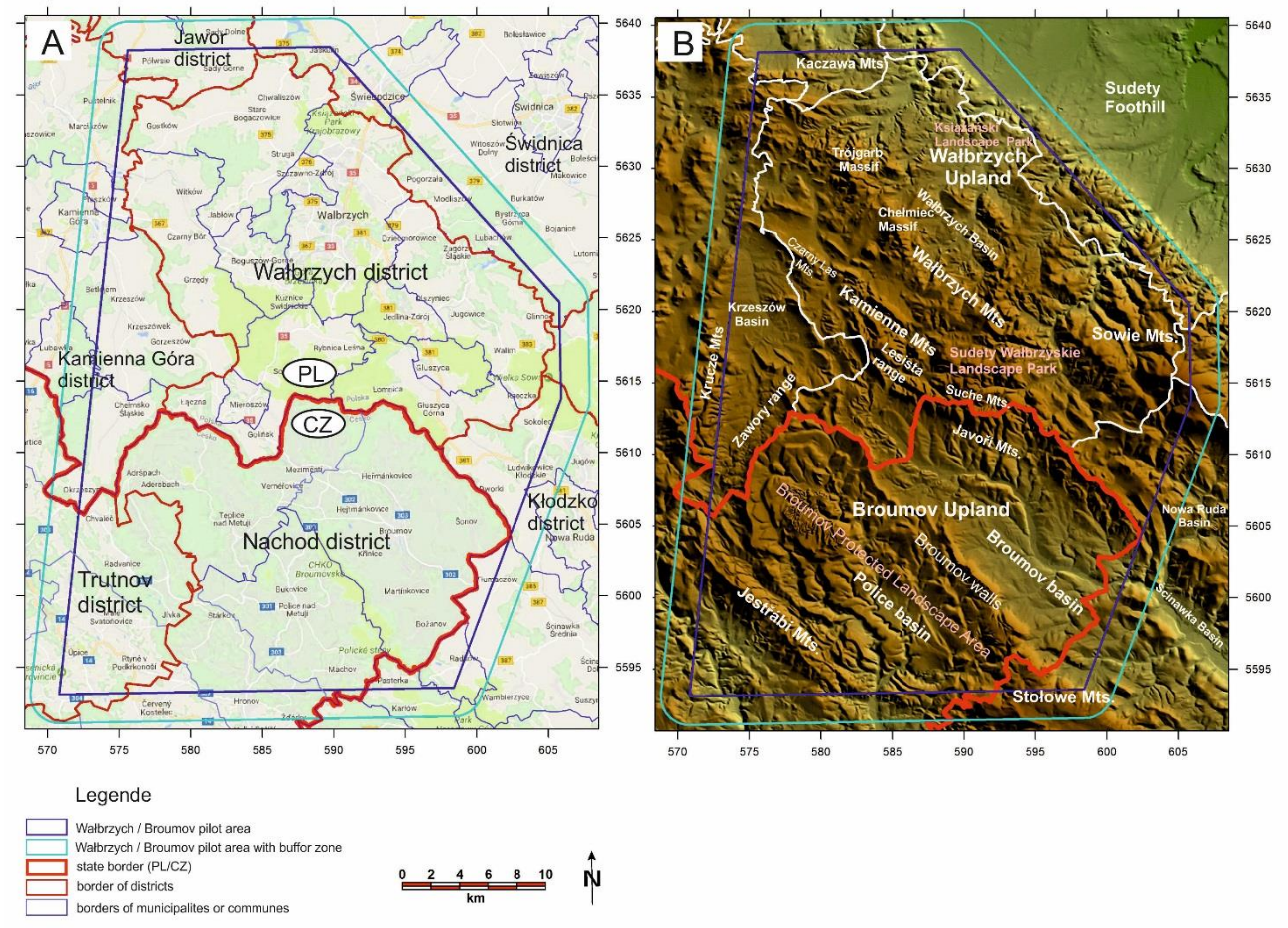


Figure 16: A. Location of the Wałbrzych / Broumov pilot area on the topographic map. B. Morphological (physiographic units) of the investigated area shown on the background of the Digital Elevation Model (DEM).

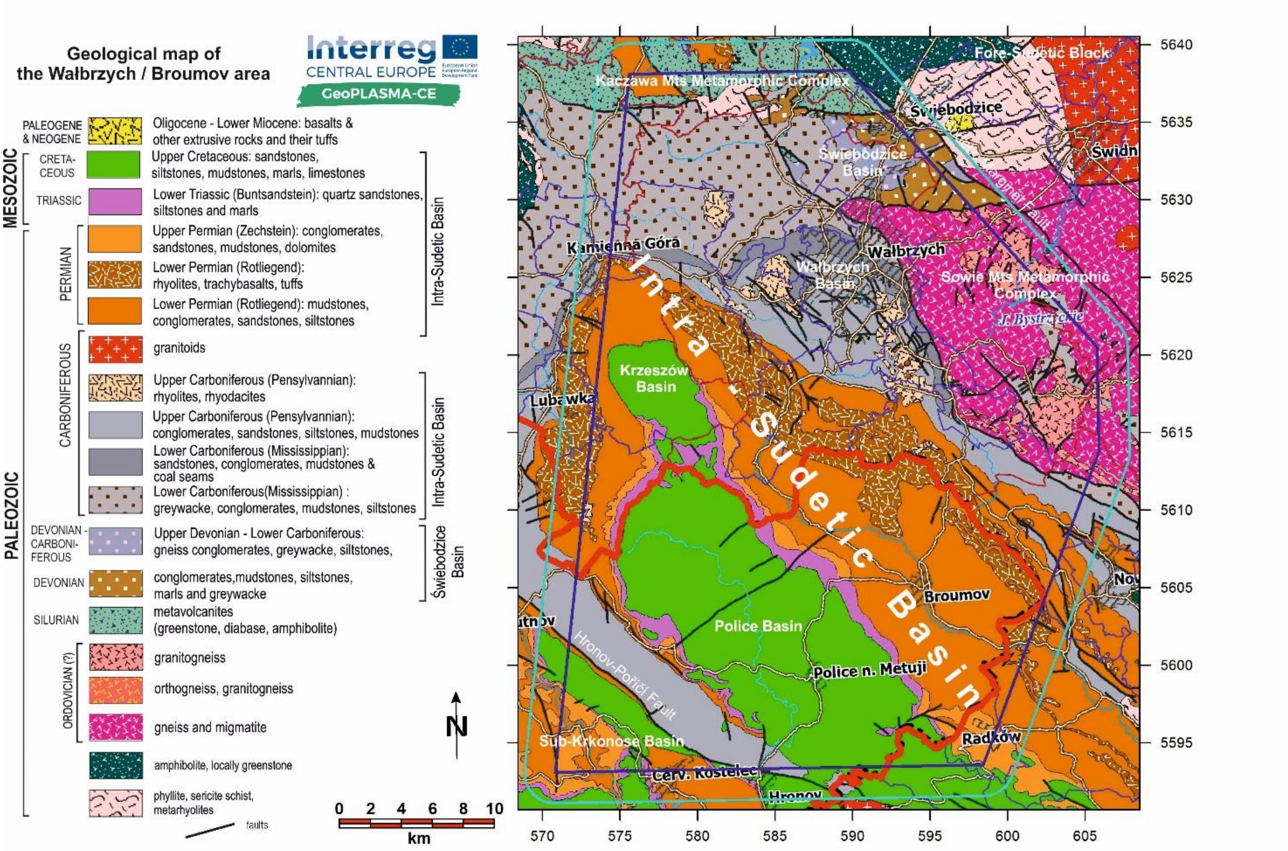


Figure 17: Simplified geological map of the Wałbrzych / Broumov area.

Table 3: Harmonized geological column GeoPLASMA-CE, pilot area Walbrzych – Broumov.

ID	new "HGK"	age	description in English	ID	new "HGK"	age	description in English	ID	new "HGK"	age	description in English
1	011010	Holocene	Anthropogenic works (heaps, embankments)	12	036120	Lower Turonian / Cenomanian	Lower Turonian / Cenomanian mudstones, sandstones	23	074230	Upper Carboniferous	Upper Carboniferous (Namurian) sandstones, conglomerates, mudstones, claystones with hard coal
2	011020		Fluvial deposits (sand, gravel, muds)	13	037130	Cenomanian	Cenomanian sandstones	24	075240	Lower Carboniferous	Lower Carboniferous conglomerates, sandstones, mudstones, andesites
3	011030		Deluvial deposits (Slope deposits) clay, rock rubble, sand, gravel	14	051140	Lower Triassic	Lower Triassic sandstones	25	081250	Upper Devonian	Upper Devonian sandstones, conglomerates, mudstones and carbonate
4	012040	Pleistocene	Loesses	15	061150	Upper Permian	Upper Permian (Thuryngian) sandstones, conglomerates, mudstones, carbonate sediments	26	088260	Sylurian/Devonian	Sylurian/Devonian gabbros
5	012050		Sands and gravels of floodplains	16	062160	Lower Permian	Lower Permian (Saxonian/Autunian) sedimentary series (mudstones, claystones,sandstones, conglomerates , carbonate) over volcanic complex	27	090270	Sylurian	Sylurian phyllites and greenstones
6	012060		Glacial tills (Saale glaciation)	17	062170	Lower Permian	Lower Permian (Autunian) volcanic complex III (rhyolites and tuffs)	28	100280	Ordovician/Devonian	Ordovician/Devonian amphibolites
7	012070		Glaciofluvial sands and gravels (Saale glaciation)	18	062180	Lower Permian	Lower Permian (Autunian) sedimentary series (sandstones, mudstones, claystones, conglomerates) under volcanic complex	29	100290	Ordovician	Ordovician phyllites, quartzites, metatrachites
8	012080		Glacial tills (Elstera glaciation)	19	071190	Upper Carboniferous	Upper Carboniferous (Stephanian) conglomerates, sandstones, claystones, mudstones	30	100300	Ordovician	Ordovician gneiss, migmatite, granulites
9	012090		Glaciofluvial sands and gravels (Elstera glaciation)	20	071200	Upper Carboniferous	Upper Carboniferous (Stephanian) volcanic complex II (trachyandesites, rhyolites, tuffs)	31	110310	Cambrian/Ordovician	Cambrian/Ordovician metagranites, mylonites, cataclasites
10	020100	Tertiary	Clay and sands locally with brown coal	21	072210	Upper Carboniferous	Upper Carboniferous (Westphalian) sandstones, conglomerates, mudstones, claystones	32	110320	Cambrian/Ordovician	Cambrian/Ordovician greenstones, greenstone schists
11	035110	Upper Turonian/ Middle Turonian	Upper/Middle Turonian sandstones	22	073220	Upper Carboniferous	Upper Carboniferous (Westphalian) volcanic complex I (rhyodacites, rhyolites)				

The Quaternary cover is composed of 10 layers. Only 5 layers are located both in the Polish and Czech territory. Glacial or fluvioglacial sediments do not occur in CZ. Quaternary sediment (fluvial, deluvial, loesses, sediments of floodplains and sediments of anthropogenic works) have been created in the CZ part of the model.

The boundary determination of quaternary bodies was based on geological maps, boreholes and a digital terrain model of 4th generation (DTM 4G). The final interconnection of CZ and PL Quaternary geological bodies was performed after consultation of the CZ and PL team. The Quaternary geological bodies to be modelled were selected, too.

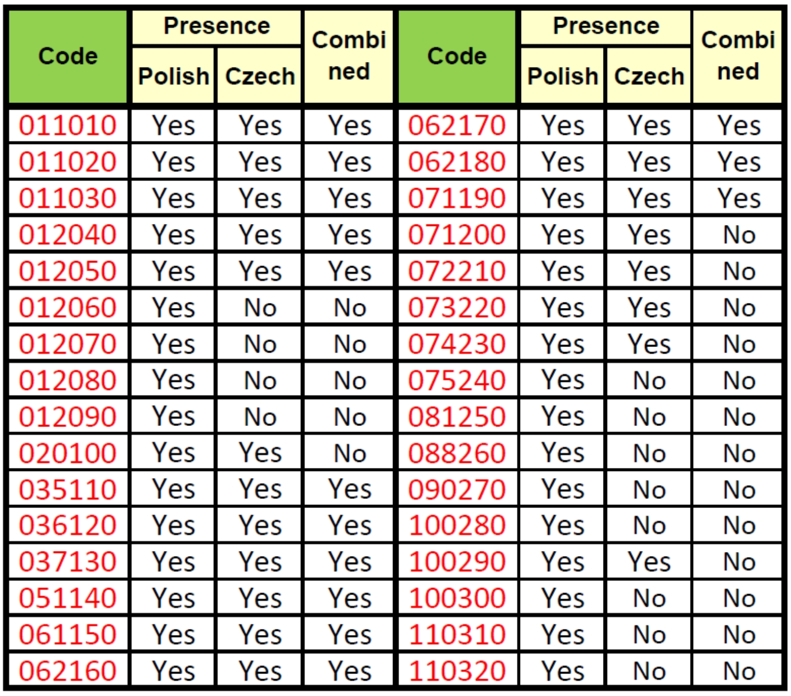
Four horizons of Mesocoic sediments (one Triassic and three Cretaceous layers) were modelled. Permian sediments (061150, 062160, 062170 and 062180) and the Upper Carboniferous sediments (071190, 071200, 072210, 073220, 074230) from the Paleazoic.

The Cretaceous or Triassic individual geological bodies that occurred in the buffer zone were modelled by the CZ or PL team depending on the occurrence. If a geological body occurred more than 50% in the Czech Republic then was modelled by CZ team. If it occurred more than 50% in Poland then the body was modelled by PL team.

Crystalline rocks occurs only in one region of the CZ part of the model (a tectonic block in the Hronov-Poříčí tectonic zone). The crystalline rock is represented by the modelling unit 100290 (Ordovician phyllites, quartzites and metatrachites). The modelling unit has not been correlated or combined with PL because the link with the Polish part lies deeply under the model base.

All older lower sedimentary layers were modelled up to the northern border of the Polish buffer zone. The Polish team did the same. They modelled geological bodies to the southern boundary of the CZ buffer zone. All layers of Permian and one layer of Carboniferous (071190) have been merged together at the intersection. Other Carboniferous units do not have large area extent or they interconnect deeply below the base of the model. A list of correlated and combined layers is show **Table 4**.

Table 4: List of correlated and combined layers, pilot area Walbrzych – Broumov.



Code	Presence		Combined	Code	Presence		Combined
	Polish	Czech			Polish	Czech	
011010	Yes	Yes	Yes	062170	Yes	Yes	Yes
011020	Yes	Yes	Yes	062180	Yes	Yes	Yes
011030	Yes	Yes	Yes	071190	Yes	Yes	Yes
012040	Yes	Yes	Yes	071200	Yes	Yes	No
012050	Yes	Yes	Yes	072210	Yes	Yes	No
012060	Yes	No	No	073220	Yes	Yes	No
012070	Yes	No	No	074230	Yes	Yes	No
012080	Yes	No	No	075240	Yes	No	No
012090	Yes	No	No	081250	Yes	No	No
020100	Yes	Yes	No	088260	Yes	No	No
035110	Yes	Yes	Yes	090270	Yes	No	No
036120	Yes	Yes	Yes	100280	Yes	No	No
037130	Yes	Yes	Yes	100290	Yes	Yes	No
051140	Yes	Yes	Yes	100300	Yes	No	No
061150	Yes	Yes	Yes	110310	Yes	No	No
062160	Yes	Yes	Yes	110320	Yes	No	No

2.5.1.2. Fault network

The network of faults has been established jointly for the whole Wałbrzych-Broumov pilot area (**Figure 18**). On the Polish side of the pilot area, the modelled faults mark the main boundaries between the first order lithological-stratigraphic units, ie. between the Intra-Sudetic basin and the neighboring units: Sowie mountains. Gneiss Complex, Kaczawa mountains Metamorphic Complex and Świebodzice unit. The faults have different dipping angles and lengths, however as the bottom surface of the 3D model was only set up to ca 200 m of depth, all the faults are treated as vertical surfaces in the model. A dense and complicated tectonic pattern of the faults with predominant NW-SE strike is observed in the Intra-Sudetic basin within an appr. 5-10 km wide border zone along the SW edge of the Sowie mountains. Gneiss Complex.

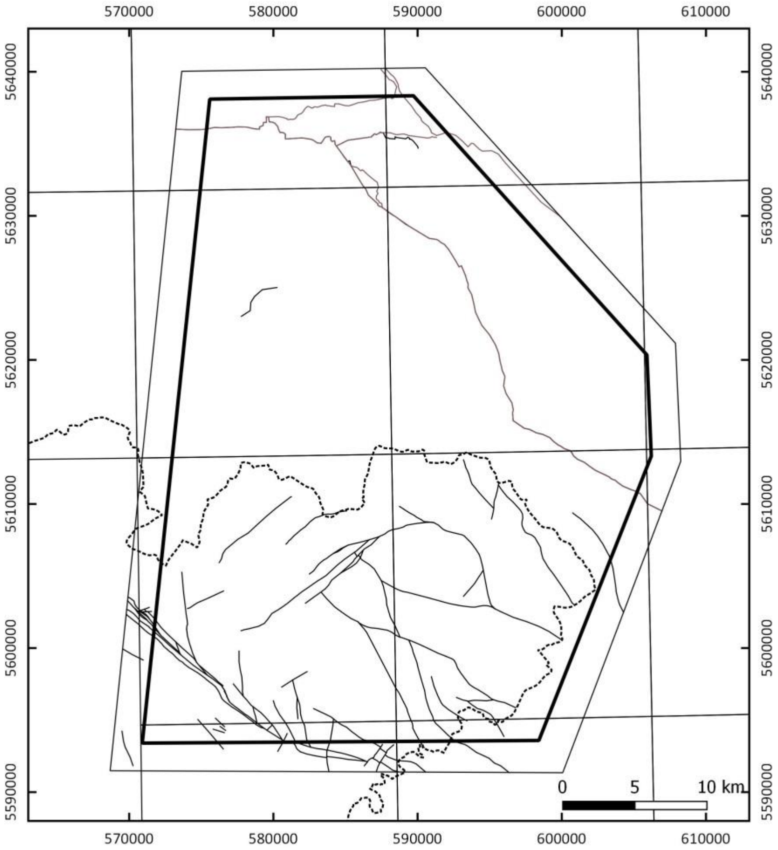


Figure 18: Fault network within the the Wałbrzych / Broumov area.

On the Czech side, there are more second-order internal faults occurring within the Intra-Sudetic basin and along its SW boundary with the Sub-Krkonoše basin (= Krkonoše Piedmont basin). The main faults (fault zones) are located in the Police basin and indicate about hundred meters of throw.

The Czech fault network is a compilation of all accessible old reports, scientific articles, geological maps and cross-sections (Geological map of Czech Republic – 50CR M 1:50 000 and some older geological maps M 1:25 000; Čech and Gawlikowska, 1999; Krásný et al., 2012; Tásler et al., 1979). Fault networks of all authors were digitized. Unfortunately, their opinion on the geological genesis of the area is not exactly the same and therefore the fault networks do not match (**Figure 19**). Most faults are without information about dip and sense of movement. Many faults are identified only by the morphology of DTM.

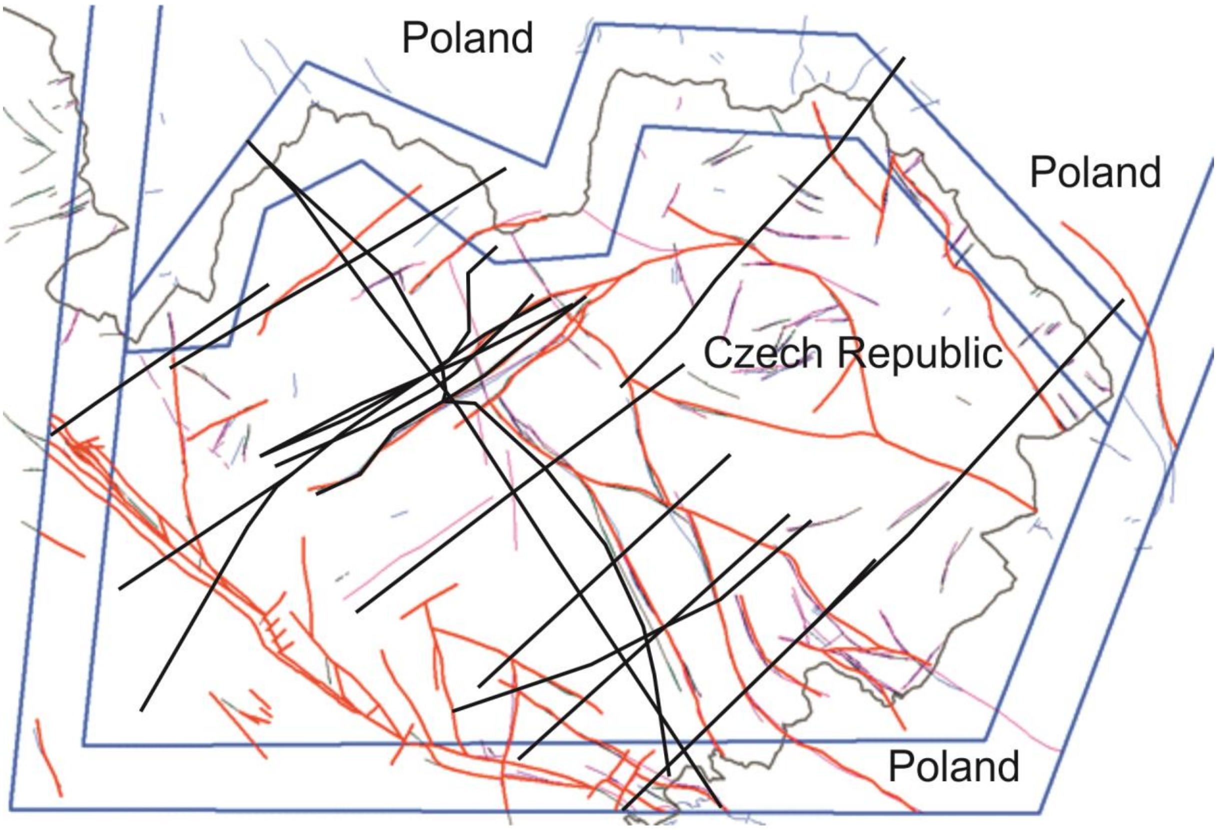


Figure 19: Positions of digitized faults from different sources. The red lines show the final fault network used to build the model. The blue lines show the boundaries of the model and the buffer zone. The grey line shows the state border. Black lines show archival cross-sections.

The fault network used for 3D modelling was created after consultation with geologists working in the area for a long time. This fault network was created in accordance with the genesis of the Bohemian Cretaceous basin (Uličný et al., 2009). Faults of less than 5 km length were excluded.

2.5.1.3. Scheme of geological units

A newly created geological map was prepared for the needs of a 3D modelling (**Figure 20**). The map presents 32 correlated units.

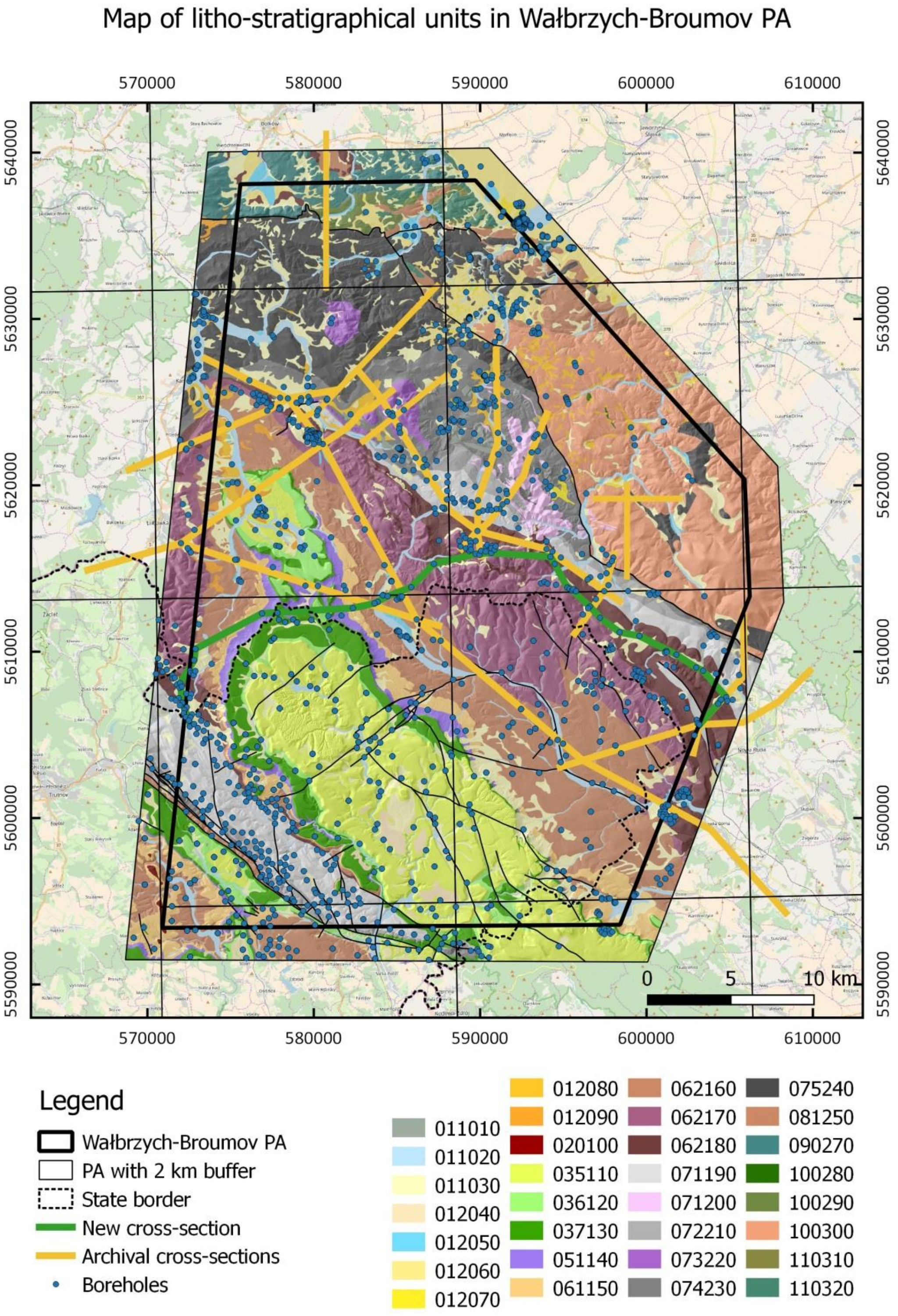


Figure 20: A newly created joint PL-CZ geological map for the Wałbrzych-Broumov pilot area prepared for 3D modelling. Cross sections are shown only for the Polish side. Colour boxes and numbers refer to litho-stratigraphical units presented in Table 3.

Holocene sediments were modelled as three individual units covering anthropogenic soils (embankments, heaps), the youngest river sediments and slope, deluvial deposits. The Quaternary strata include 6 units, which consist of mostly clastic rocks and tills deposited during past glaciations. Both Holocene and Quaternary rocks are mostly of small thickness, however have numerous outcrops irregular in shape. The majority of them occurs within the Polish part of the Wałbrzych-Bromov area. The Tertiary period is represented by only two units, which are present in a small area in the north-eastern part of the Polish territory and the south-western part of the Czech territory.

About two thirds of the Wałbrzych-Broumov area is built by one, transboundary geological unit - the Intra-Sudetic basin (or Synclinorium) - filled with huge, few km thick, sedimentary and volcanic formations ranging in age from Upper Cretaceous to Lower Carboniferous. Upper Cretaceous marine platform formations are represented by three units. There are other Mesozoic and Permo-Carboniferous formations, which lie below Cretaceous rocks with a big stratigraphic gap (hiatus) comprising the Lower Cretaceous and Jurassic periods. These are: platform Triassic clastic sediments (one unit), Permian, terrigenous sedimentary and volcanic series (4 units) and Carboniferous deposits (6 units), which represent syn- to post-orogenic Variscan molasses deposits. In the Carboniferous section, 2 units have the character of intrusions that cut through older host rocks.

Lower Paleozoic, partly metamorphic rocks forming the inner part of the Variscan orogenic prism are divided into seven separate rock categories. They occur in adjacent geological units: The Świebodzice basin, Kaczawa mountains metamorphic complex and Sowie mountains metamorphic complex.

Predominantly sedimentary rocks occur in the CZ part of the model. Several volcanic complexes occur in some Carboniferous model units. All model units are modelled as sedimentary structures. The unconformities exist almost between all model layers. The first lowest unconformity exists between the metamorphic rocks (layer 100290) and the Carboniferous layer (071190) in the partial tectonic block of the Hronov-Poříči tectonic zone. A conformity exists between the Carboniferous layers 071180 and 071190. The Permian unit 062180 discordantly lies on the Carboniferous units. Further unconformities exist between layers of volcanic complexes and surrounding rocks (062170, 071200). Other larger unconformities exist between layers of the Upper Permian and Triassic. Less important unconformities also exist between the Triassic and Cretaceous units. These partial unconformities occur mainly in the southeastern and southern parts of the Police basin. They are related to changes of the sedimentary environment in the Permian, Triassic and Cretaceous.

The fault network corresponds to the concept of Uličný et al. (2009). The major complicated fault zone called the Hronov-Poříčí tectonic zone runs through the southwestern part of the model area. It is a horst structure formed by the main faults of NW-SE direction and by the accompanying faults of NNW-SSE direction. A half-graben consisting of Permian - Cretaceous sediments is located in the south-west from the horst structure. The Police basin with a NW-SE axis is located to the northeast of this half-graben. In the north-western part, the basin has shape of brachysynclinal closure. The dip of the limbs of the open brachysyncline is mostly up to 15˚. The axis of the basin is gently folded and broken by transversal faults of the NE-SW direction. Permian and Carboniferous sediments occur beneath this basin. The axis of the Permian basin has approximately the same strike as the Cretaceous basin. However, the limbs are gently folded and the subordinate fold axes are gently folded too. The north-eastern limb has the character of a flat and very open flexure with a large wavelength. The general dip of limbs is mostly up to 15˚, but in some places increases to 30˚.

Both of these basins are broken by strike-slip faults as described by Uličný et al. (2009). These faults have the direction NW-SE or NNW-SSE and are interconnected. This fault system is broken by the faults of NE-SW direction. These faults are often normal faults with a horizontal component of slip.

2.5.1.4. Data preparation

2.5.1.5. Processing of the raw data

The 3D model for the Wałbrzych area was made using compilations of digital versions of serial maps sheets of the Detailed Geological Map of Poland in the scale of 1:50 000 and processed borehole data recorded in the PGI-NRI geological, hydrogeological and geological-engineering data bases.

A unified, simplified special geological map for the model (**Figure 20**) was prepared on the basis of the archive maps, which are often mutually different or sometimes even contradictory. A geological map of Czech Republic at a scale 1:50 000 was used as basic data set for construction of a simplified geological map containing only model units. The Geological map of the Czech Republic exists in vector format and is available at https://mapy.geology.cz/geocr50/. The map was compiled from old maps of various scales. These old maps have been created by various geologists in different times. The maps reflect the different opinions of geologists on the genesis of the area, as well as the quality and amount of data used by them. Verification of geological data in the scale 1:25 000 has never been done thoroughly, so this map contains an uncertainties. These uncertainties comprise mainly the position or existence of faults, lithological boundaries and the position of Quaternary sediments.

All these archive maps are part of a GIS project created during data preparation in ArcMap SW. The most probable boundary positions were identified by a qualified estimate and the lithology type was simultaneously defined, constituting a basis for defining the lithostratigraphic units of the model, the horizons in the software MOVE. The formulation of a set of lithologic types and shapes of the individual rock bodies was based on the project requirement of merging petrographically and hydraulically similar rock types on the basis of an expert estimate and to simplify locally excessively complicated contours of geological bodies (e.g., by omission of small lenticular bodies), which are insignificant in the context of the follow-up calculations and evaluation of the model from the shalow geothermal perspective.

In the process of the model construction a DEM of cell size of 20 m was used. The project requirement was to ensure that generalization of the geological situation in the Quarternary units was kept to a minimum; the geology was more generalised in the case of pre-quarternary sediments and crystalline rocks.

All types of Quaternary bodies were digitalized according to the digital terrain model of 4th generation (DTM 4G), which was constructed from the LIDAR data and generated at a resolution of 5×5 m. All the bodies with a thickness above 2 m (according to an available borehole data) were digitalized. The bodies (without a borehole) at which supposed thickness was over 2 m were digitalized too.

17 cross-sections were used for the construction of the 3D model of the Czech part. These cross-sections were created by different geological teams at different times. Most of the geological works were focused on the Police basin. Only one work includes the Hronov-Poříčí fault zone. These available archive vertical geological sections were imported into MOVE in the form of raster images, and set to scale along their course (according to the available map data). Subsequently, the boundaries that correspond to the newly created model units were digitized.

Subsequently, a visual spatial control of the digitized lines was performed. Unfortunately, it has been shown that the opinions of individual teams differ not only in the position of the faults but also in the position of the individual geological boundaries. In addition, many boundaries did not fit with the lithological boundaries drawn in a geological map on the terrain surface. It was necessary to reinterpret these geological cross-sections. A newly created reinterpreted fault network was used as a control. The first was reinterpreted by a main cross-section passing through the Police basin with the axis of NW-SE direction. This section was reinterpreted in accordance with the newly created fault network. According to this reinterpreted main cross-section and the fault network, transverse cross-sections were also reinterpreted. Geological sections were used during model building to constrain the model in areas where no borehole data were available.

Borehole data were selected according to the density of the boreholes, position and depth. All boreholes with a depth less than 2 m were excluded. Another criterion was density and position of the boreholes. If many boreholes were located in one lithological unit, the deepest borehole of each cluster was chosen. 421 boreholes were used for the construction of the Czech part of the model. The geological profiles of the selected boreholes were reclassified according to the geological column of the model units (**Table 3**).

The borehole data were prepared in the form of two ASCII tables in the *.txt format. The first table contained the name of the borehole, its accurate location (X, Y and Z coordinates) and absolute depth. The second table contained the individual lithological horizons and their position in the borehole in metres. The depth of the individual horizons was given in re-calculated Z coordinates, or as the depth in metres; the depth in metres was used in practically all cases.

The orientation of ductile structures presented on maps were transformed into a digital tabular form. The resulting table was imported into MOVE. The individual measurements were visualized in terms of the given orientation and were used for the construction of the rock bodies. The archive structures comprised only information about bedding.

2.5.1.6. Input data for 3D modelling

The above described data were then prepared for import into the modelling MOVE SW. In particular it comprised Esri SHP file format for lines and polygons, floating point TIFF file format including complementary GIS world files for grids, JPEG format for raster images (in particular scanned geological and geophysical vertical profiles) and structured TXT file format with TAB delimiter for borehole data (borehole positions and profiles), earthquake data and structural data (foliations etc. – positions and orientation). All these files were progressively imported into MOVE SW during the model building process.

To construct the 3D model for the Broumov area, profiles of the selected 421 boreholes deeper than 2 m were reclassified according to the unified legend. Similar codification was applied for determination of the real, horizontal range of newly distinguished 32 model units to be shown in the 3D model, as well as geological cross-sections. The 3D model in the Czech part of the area has 17 built-in, digitalized and georeferenced, archival sections (**Figure 19**) and many structural data.

Profiles of the selected 1016 boreholes deeper than 10 m were reclassified according to the unified legend for the Walbrzych area. Similar codification was applied for determination of the real, horizontal range of newly distinguished 32 lithological-stratigraphic units to be shown in the 3D model, as well as the geological cross-sections. The 3D model in the Polish part of the area has 14 built-in, digitalized and georeferenced, archival sections and one new cross-section located along the trans-border area. A set of real boreholes was supplemented with virtual holes in areas with insufficient borehole data coverage and geological cross-sections.

2.5.2. 3D modelling

2.5.2.1. Modelled objects and modelling methodology

Technically, the 3D geological model consists of meshes, i.e. TINs that represent two types of geological objects – tops of litho-stragraphic units and fault planes. The top of the model represents a DTM grid with a resolution of 20x20m based on 5G LIDAR data, the sides of the model are vertical and the base of the model was created by a smoothed and down-ward shifted surface DTM at a depth of approx. 200 m.

The model construction was based on the digital processing of the available geological data.

Quarternary units were re-digitized so that they match the DEM relief. Objects smaller than 2 ha have been included in the surrounding units. Only borehole data for lithological-stratigraphic units of a minimum thickness of 2 m were established. Layers of lesser thickness were connected to adjacent upper or lower units.

The SKUA-GOCAD software was applied to prepare the 3D model for the Wałbrzych area. Some initial versions of modelled top surfaces were prepared with a use of the Surfer and Voxler software.

The MOVE software was used for the construction of the 3D model of the Broumov pilot area. Extensive data preparation and some steps of modelling that involved grid calculations were performed in ArcMap GIS because MOVE does not offer tools needed for the grid operations. Tops of the modelled units were directly created using the MOVE software. All geological surfaces are represented by triangulated irregular networks (TIN's).

Linear interpolation was used for modelling in the MOVE software, that is most suitable for surface construction of irregularly distributed spatial data. In Gocad a regression plane through the data is calculated and splitted into triangles. The data points are applied as interpolation constraints, the interpolation method is DSI.

The bottoms of all units were modelled with the Surfer software using different interpolation methods depending on the available data in the Polish part of the pilot area. After modelling all the bottom surfaces of units, they will be converted into unit tops starting from the youngest strata.

2.5.2.2. Modell assumptions/specifications

During the construction of the 3D model, the following principles were assumed. The minimum thickness of the modelled units and the minimum unit thickness in the borehole is 2 m. The model is constructed to a depth of ca 200 m from the ground surface.

If no borehole data were available, the thickness of the anthropogenic deposits shown on the geological map was set to 2m. Borehole data were taken into consideration, if the documented thickness of the anthropogenic unit was larger than 2m. If the thickness of the anthropogenic layer was smaller than 2m, the 2m thick unit was modelled.

The Quaternary bodies were modelled with constant thickness each and with vertical boundaries, due to general lack of data on depth variability of these generally very thin and very irregular bodies.

Faults were grouped, and a constant dip was assigned to each group based on known dip of one fault in the group, or estimation of the dip based on a regionally important fault of the same direction near the pilot area. If none of such estimations was available, the fault plane was modelled as vertical.

2.5.2.3. Model topology

Due to highly complicated tectonic features of the Świebodzice basin, Kaczawa mountains metamorphic complex and Sowie mountains metamorphic complex, their oldest lithostratigraphic units (Cambrian – Lower Carboniferous) composed mostly of the metamorphic or magmatic rocks are modelled as irregular bodies separated by vertical geological boundaries. Most faults between individual litho-stratigraphical units were treated as vertical surfaces in the Intra-Sudetic basin. All sedimentary and volcanic units of the Intra-Sudetic basin, from the oldest – Lower Carboniferous in age to the youngest – Upper Cretaceous, have the character of horizontally layered locally folded successions. Carboniferous series are additionally cut by intrusive rocks belonging to two units of the Upper Carboniferous age.

Modelling of geological bodies was performed by two principally different approaches that reflect differences in spatial distribution and genesis of the modelled geological bodies:

1. Quaternary bodies were modelled at a depth constant for each of the modelled bodies. The depth was defined based on borehole data if available. In case of bodies with no borehole data the depth was estimated based on expert estimate combined with consideration of neighbouring bodies. Boundaries of the Quaternary bodies were considered always vertical partly also due to technical limitations of MOVE. Vertical inaccuracies in meshes ranging up to 2 m were repeatedly identified during modelling process and strongly affected the snapping of the Quaternary meshes. Modelling of inclined Quaternary boundaries, in combination with limited amount of borehole data and uncertainties in areal extent of the bodies, then appeared as the best solution to keep model topologically correct.
2. Cretaceous - Carboniferous sediments were modelled as subhorizontal surfaces using depth information from reinterpreted boreholes and vertexes of surface boundaries of outcrops of the corresponding units.

The fault network was modelled by extrusion of the map trace of the faults, according to dip estimated for each of the fault groups as described above. The modelled fault network was then used as one of constraints when modelling adjacent lithological bodies.

2.5.3. Modelling results

2.5.3.1. Modelling uncertainties and errors

Modelling uncertainties are caused by data errors (boreholes, maps and cross-sections), lack of data, and the methodology of modelling. The highest credibility was assigned to the borehole data and the geological map.

Uncertainties and errors of the modelling methodology were derived from the interpolation method used. Linear interpolation was used for modelling in the MOVE software that is most suitable for surface construction of irregularly distributed spatial data. At small thicknesses of modelled units, the meshes locally crossed each other on a scale of 1-2 m. This problem appeared mainly in Quaternary units, but also elsewhere, where the dip of the units was very small and combined with a small thickness of adjacent units. In these cases, it was decided that the boundary of the underlying model unit was locally shifted by 2 or 3 m downwards manually, to correct this purely artificial inconsistency.

The geological map used for model construction was created by compiling and simplifying archive geological maps of various scales. Each model unit combines multiple lithological or stratigraphical units displayed in the original geological maps. These maps have been created by various geologists who have different opinions on the geological genesis of the area of interest. The verification of lithological boundaries or fault networks by geological mapping has never taken place thoroughly.

The extent of individual quaternary bodies in the original geological maps seems to be very often imprecise to misleading. The boundaries of the quaternary bodies were strongly corrected using the DTM 4G. The accuracy of these bodies corresponds to the precision of the DTM 4G (grid unit 5×5 m) and the experience of the quaternary geologist. Significant terrain verification could not take place with regard to the project schedule.

The inaccuracies of the model unit boundaries are also related to the inaccuracy of the fault network. The used fault network was created as a compilation of all available tectonic interpretations and maps. Similarly to the maps above, each author had different opinion on the fault network, therefore, the map fault networks do not match when plotted together (**Figure 19**). The dip or sense of movement has not been established at many faults. Many faults were missing according to the DTM, so that missing major faults were newly complemented by morpho-structural analysis and consultation with responsible geologists for the area.

The reinterpreted cross-sections were created by the compilation of cross-sections of many authors (Čech, Gawlikowska, 1999; Krásný et al., 2012; Tásler et al., 1979). The differences were again not only in the location of faults but also in their number. Most of the geological work was focused on the Police basin. Only one work includes the Hronov-Poříčí fault zone.

Further uncertainties are in determination of the depth of model units. The cross-sections shows mainly stratigraphic position of layers that do not correspond with the modelled units. Only two the correlation boundaries can be directly used - the base of the Cretaceous sediments and the base of Triassic sediments. After compilation of all cross-sections in 3D it was revealed that many boundaries did not fit to the lithological boundaries in the geological map, or even the cross-sections do not match to each other at their crossing. The error in determining of depth the model unit boundaries reaches locally tens of meters.

Borehole data contain these three principal types of errors:

1. Determination of the model unit boundaries – particularly in sedimentary sequences this feature represents the most important source of errors, due to often lower quality of borehole description combined with complex (sedimentary) succession. Borehole profiles were reclassified according to the created model legend. Unfortunately, some boundaries of model units in borehole profiles are poorly determined or missing. To recognize model units mainly in Cretaceous or Permian sediments is often difficult.
2. Position of borehole – errors appears relatively scarcely, often of a scale of several meters. The borehole is located in the model unit on the geological map, but in its profile the model unit is missing. There is also a problem with altitude localization. Some boreholes are located a few meters under the terrain (the error is somewhere over 10 meters).
3. Lack of inclinometry – the uncertainty then generally increases with depth. None of the boreholes has inclinometry. Therefore, the boreholes, showed as vertical in the model, pass through faults into another tectonic block and thus into another model unit.

2.6. Pilot area Vogtland-W-Bohemia

2.6.1. Units and structures represented in the 3D model

The pilot area Vogtland-W-Bohemia consists of Variscan basement that is covered by Tertiary to Quarternary sediments. The pilot area consists of two major Variscan geological complexes, the Vogtland synform in the NW and the Ore mountains-Fichtelgebirge Zone in the S and SE. The Vogtland synform consists of Cambrian to Carboniferous volcano-sedimentary units of a typical deep-marine shelf-sedimentation, which were compressed in NW direction, folded, faulted and metamorphized at low grades. From the geothermal point of view, quarzitc rocks that are intercalated in the Paleozoic shales have to be mentioned, because they are characterized by a large specific thermal conductivity. The boundary to the Ore mountains is not well defined, since both zones comprise similar lithologies. However, the metamorphic grade of the rocks is increasing SE-wards, such the crystalline rocks like phyllites, slates and gneisses can be found near the German-Czech border. Both zones are characterized by mylonitization and intense deformation in multiple narrow thrust zones, such that the lithology may vary at very short distances. This peculiarity is one challenge for modelling the geothermal properties. Granitic rocks intruded in both zones. The granites are characterized by a large specific heat production rate, which makes these rocks interesting for a geothermal use.

The Cheb basin in Western Bohemia is a shallow Cenozoic depositional centre which developed on the Variscan beasement at the intersection of two tectonic structures Špičáková et al. (2000): NE striking Ohře/Eger Graben and NW trending Cheb-Domažlice Graben. The Cheb basin developed jointly with other Krušné hory/Erzgebirge mountains as a part of the NE striking Ohře/Eger Graben from late Oligocene to mid-Miocene (Rajchl et al. 2008, 2009). The NW-SE striking faults were preferentially activated since the early Pliocene, and the basin gradually developed as a part of an asymmetrical Cheb-Domažlice Graben that was controlled by the Mariánské Lázně Fault in the east and superimposed by the Ohře/Eger Graben (Malkovský, 1987; Špičáková et al., 2000). The Cheb basin is a centre of recent geodynamic activity represented by repeating earthquake swarms with the largest earthquakes of magnitudes up to 4.6 and massive degassing of CO_2 of upper mantle origin (Bräuer et al., 2005; Fischer et al., 2014).

In the east, the Cheb basin is controlled by the Eastern Marginal Fault, which is a northern segment of the Mariánské Lázně Fault Zone, an important NW-SE tectonic line, which was reactivated several times during the geological history of the Western Bohemia region (Švancara et al., 2008). The crystalline basement is composed of phyllites to lower-grade paragneisses of presumably lower-Palaeozoic age, containing numerous intercalations mainly of quartzitic composition (e.g. Škvor, 1974; Škvor and Sattran, 1974; Hoth et al., 1995; Muller et al., 1998).

Outside of the Cheb basin, Cenozoic loose rocks occur only in river valleys, no important aquifers are available in the Vogtland part of the pilot area. Ground water is mainly conducted along fractures. Deep thermal water is ascending along fault systems and is used in Spas.

2.6.1.1. Standard geological column

The standard geological column used for modelling (**Table 5**) was created after mutual discussions of CZ and DE experts covering Quarternary geology, Tertiary sedimentology and crystalline geology of the broader region. It comprises 47 lithostratigraphic units that were planned to model in the initial phase of the project, based on regional geological knowledge, petrographic and stratigraphic arguments. During data assemblage and reinterpretation it gradually appeared, that not all of the planned units could be distinguished unambiguously throughout the entire modelled region, mainly due to scarcity / bad quality of archive data. For this reason, not all of the planned units are used in the 3D geological model. At the same time, not all of the units used are present in both parts of the joint 3D model. The southern part of geological model that was constructed by Czech Geological Survey consists of 22 lithostratigraphic units, the northern part that was modelled by the Saxon Geological Survey consists of 24 units.

During the preparation of the standard column, it was confirmed that the glacial cycles on Czech and German territory, which are related to river terraces development, correlate exactly, having just different national nomenclature:

- Würm = Weichsel,
- Riß = Saale,
- Hosskirchen/Mindel= Elster,
- Günz = Elbe.

Table 5: Harmonized geological column GeoPLASMA-CE, pilot area Vogtland-W-Bohemia.

GeoPLASMA-Petkey	HGU-number	HGU-name
020216000000000000	**0**	**Anthropogenic fillings**
020208000000000000	**1**	**Organic sediments**

020201030000000000	2	Holocene fluviatile sediments
020201010018160800	3	Haugh
020201030000030000	4	Sands and gravels of alluvial meadows: rivers
020201030000030000	5	Sands and gravels of alluvial meadows: creek
020201030000310000	6	Alluvial fan
020201030000310000	7	Colluvial sediments
020201030000080416	8	Loess
020201030000030000	9	Boulders
020201010000020400	10	Terrace lower
020201010000020400	11	Terrace main (medium terrace - lower part)
020201010000020400	12	Medium terrace connected with river
020201010000020400	13	Terrace Elster
020201010000020400	14	Glaciofluvial sediments
020201010000020400	15	Medium terrace - middle part
020201010000020400	16	Terrace Tertiary
020201020000310000	17	Vildštejn strata
020201010018160000	18	Cypris strata
020208000024000000	19	Main brown coal formation (with coal beds Antonín and Anežka) with underlying clastics
020201010000200000	20	lower sand - clay strata
020201010000060000	21	Basal Staré sedlo formation (basal sandy formation: gravels, sands)
200000000000000000	22	Pre-miocenic weathered rocks
010102010512000000	23	Tertiary basaltiods
010402060000000000	24	Contact inner

010101010004000000	**25**	**Granite Eibenstock**
010101010004000000	**26**	**Granite Fichtelgebirge**
010101010004000000	**27**	**Granite Bergen**
010101010004000000	**28**	**Granite Kirchberg**
010201030000000000	**29**	**Sediments Carboniferous (Kulm)**
010204020064000000	**30**	**Limestone Carboniferous**
010101010512080000	**31**	**Microgabbro**
010204020064000000	**32**	**Limestone upper Devonian**
010201030000030000	**33**	**Conglomerate Devonian**
010102010256000000	**34**	**Volcanics upper Devonian**
010203000000000000	**35**	**Sediments Devonian**
010201014616000000	**36**	**Limestone tentaculites**
010201010018160000	**37**	**Cherts and alumcherts**
010404020132000216	**38**	**Phyllites Ordovician**
010201010002040000	**39**	**Quartzite - Hauptquartzite**
010201010002040000	**40**	**Quartzite Ordovician**
010101010002000000	**41**	**Early Paleozoic magmatite**
010404020132000216	**42**	**Cheb phyllites**
010404020132000216	**43**	**Phyllites Cambro-Ordovician (Klingenthal-group)**
010404080208000000	**44**	**Micaschist (Raun-group)**
010404080202020000	**45**	**Gneiss Cambro-Ordovician (Brambach group)**
010101010008000000	**46**	**Cadomian Granite**

2.6.1.2. Fault network

The fault network in this pilot area (**Figure 21**) exhibits a complex geometry and multistage evolution from the final stages of Variscan collision through probable Mesozoic activity to significant Tertiary rifting and Tertiary to Quarternary extension. This brittle tectonic history resulted in the development of a dense fault network, whose precise localization is often hard to determine due to the sedimentary cover and generally mild topography. Additionally, the fault network will not be used in the calculation of the shallow geothermal potential. For these reasons, many faults have been ignored and only principal regional faults and fault zones are present in the 3D geological model. The selected faults were grouped with respect to their strike which presumably indicates their genetic and geometric relationship. The only fault in this region, which exhibit persistent morphological indications of subrecent activity, is the Mariánské Lázně fault, which is responsible for the second phase of Cheb basin development (e.g. Špičáková et al., 2000).

In total 49 faults were modelled in this pilot area, with majority of the faults located in the tectonically complex Cheb basin with its surroundings.

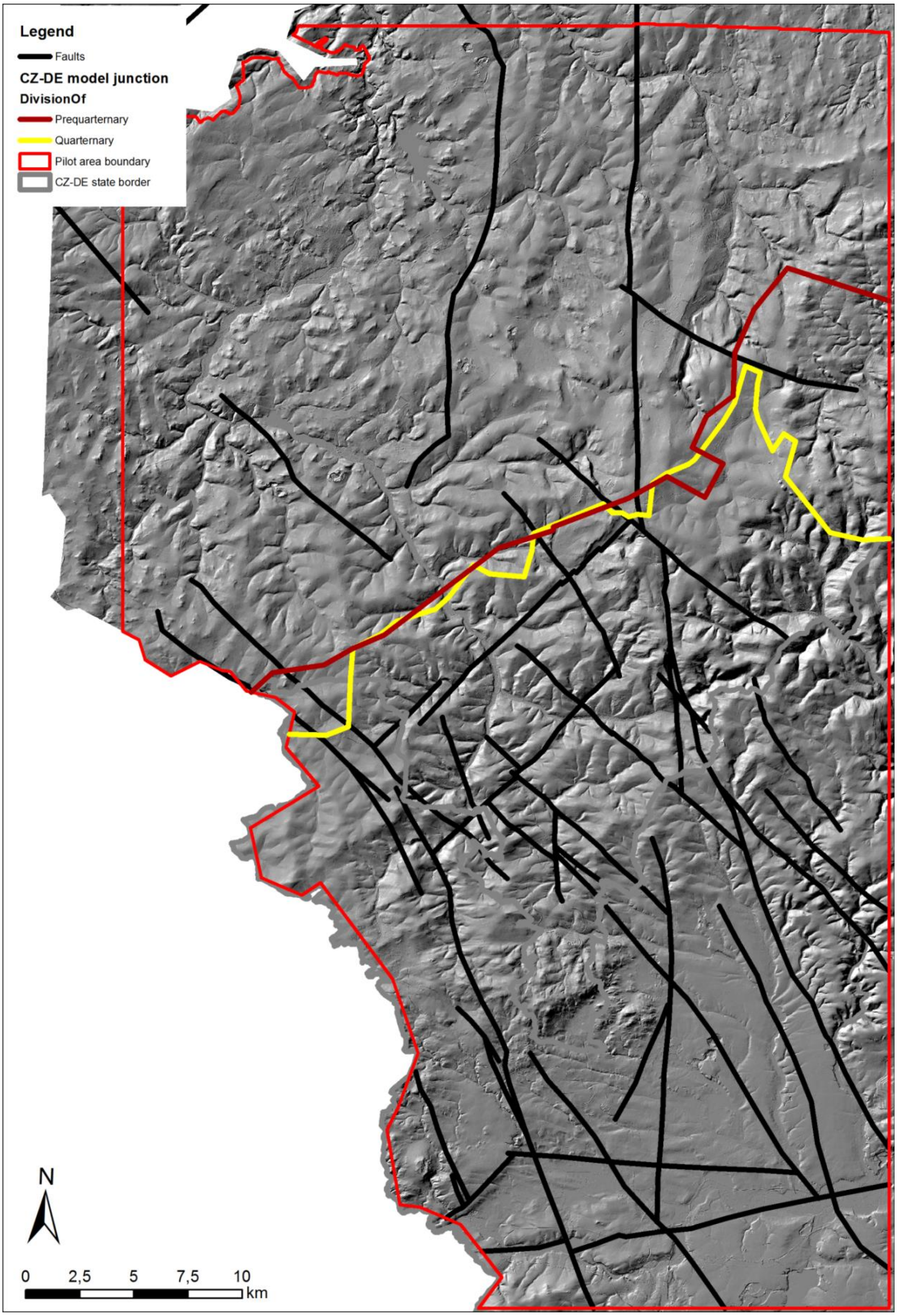


Figure 21: Fault network within the Vogtland-W-Bohemia pilot area.

2.6.1.3. Scheme of geological units

Quarternary modelling

Colluvial and Alluvial units (generally very irregularly shaped, Fehler! Verweisquelle konnte nicht gefunden werden.) do not overlap with each other, but they are often snapped. They are modelled as layers of constant thickness (parallel to DEM surface), by a constant minimum thickness, thickness based on borehole data and/or on expert estimates where boreholes are insufficient or missing. In case of long valleys filled with these sediments, the bodies will be splitted and several different thicknesses will be modelled for their parts (e.g. 2 m in upper part of a long valley and 4 m in its lower part). Alluvials were modelled vertically stratified as 2 layers: upper 1/3 mud (= clay + silt + loam), lower 2/3 coarse alluvial (sand + gravel).

Anthropogenic was approximated as the extent of villages and towns at constant depth of 1.5 m to avoid problems with overlap with organics (peat) base.

Organics (peat) on German side was modelled usually as a constant 1-1.2m thick layer. In the Czech Republic the organic sediments (peat) were modelled at 1.8 m thickness as expert estimate, due to larger extent of the bodies in Czech Republic.

Quarternary units are all modelled with vertical or steep boundaries. One reason for this simplification is the too complex fragmentation of the top of the crystalline basement. The other reason is the disputable extent of Quarternary in archival maps, while neither vertical nor steeply inclined boundaries actually do mimic the reality which is much more complex in detail and at such a large scale can be never enough borehole data to model Quarternary 1-5m deep precisely.

Four units representing river terraces were modelled subparallel to the Earth surface, using simplification of the base of these bodies. The 4 terrace generations do not overlap with each other in the map view.

In case of all the Quarternary units the younger unit crosscut the older, therefore, their boundaries were treated as unconformities. The same counts for the infill of the Cheb basin, where the basal surface is a large unconformity.

Tertiary modelling

The late Tertiary to early Quarternary Vildštejn Formation is a major erosional unconformity, marking a period of partial uplift and erosion of the underlying Cypris Formation (Špičáková et al. 2000). The upper surface is either the recent erosional surface or the base of the much younger Quaternary deposits. The depositional system of the Vildštejn Formation includes fluvial, floodplain, and alluvial facies.

The deposition of the Cypris Formation (represented dominantly by clay lithologies) is characterized by the evolution of a widespread lacustrine system over most of the Cheb basin. The basal boundary surface of the Cypris Formation is interpreted by us as a major flooding surface, marking the onset of lacustrine conditions.

Because of the lack of reliable correlation criteria in the deposits of the underlying Seam Formation, the first stratigraphic unit in the Cheb basin groups together the Lower Clay and Sand Formation, including volcanics and volcaniclastics, the Main Seam Formation, and also the clastics dated as Eocene. We admit that this brings a degree of inconsistency, but the quality and low density of subsurface data, combined with complex basin tectonosedimentary history, does not allow greater detail. The Cheb basin region was characterized by relatively small localized depocenters separated by relative palaeohighs during this episode. Whereas the depocenters contain deposits of alluvial/fluvial depositional systems, basaltic volcanic bodies and coal, the main (central) palaeohigh, running across the present-day basin in NW direction, is overlain by only a thin cover of clastics, is mostly devoid of coal seams, and, locally, shows even no preserved deposits of this episode.

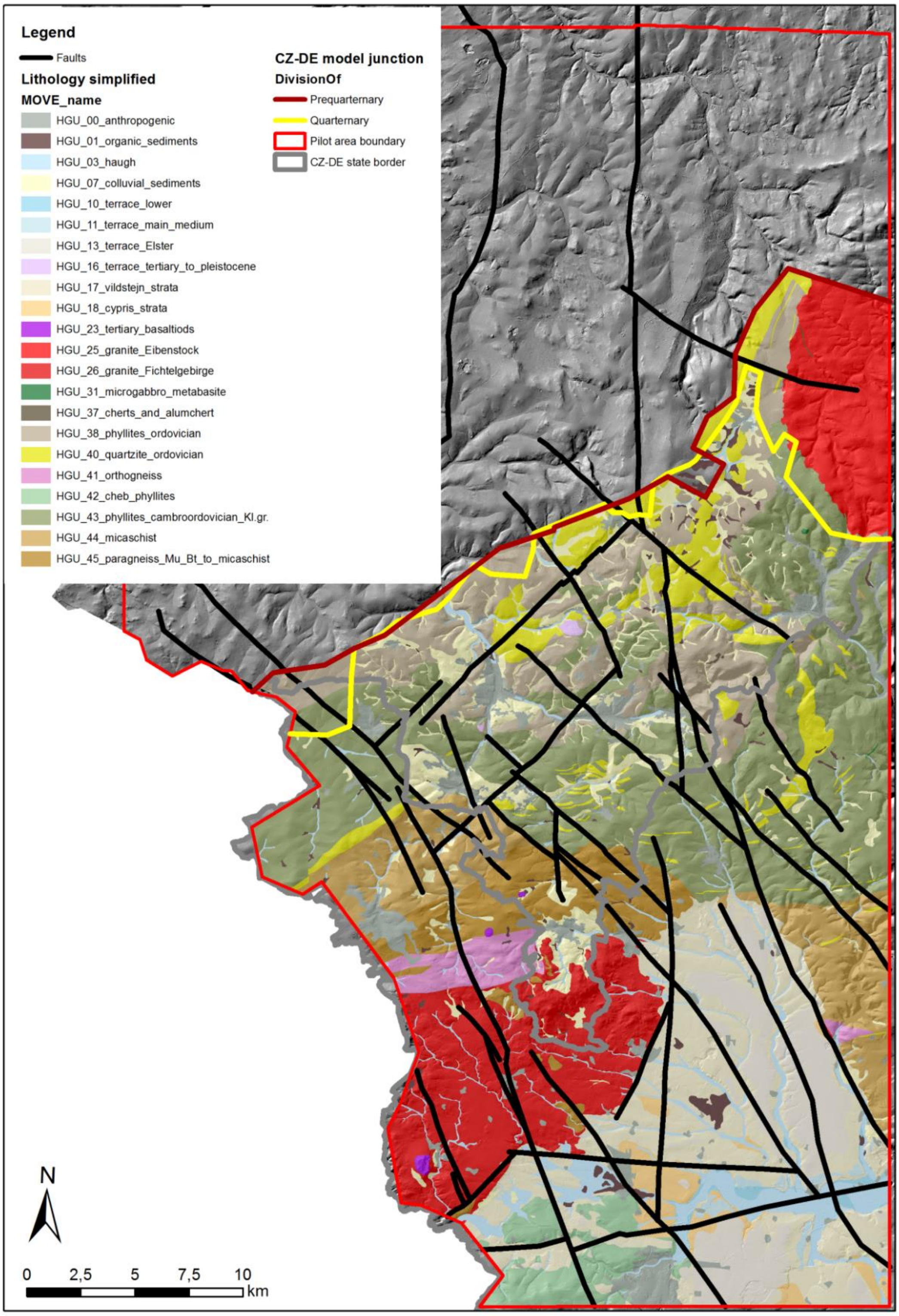


Figure 22: Newly created simplified CZ-DE geological map for the southern part of the Vogtland-W-Bohemia pilot area prepared for 3D modelling by the Czech Geoplasma team. Colour boxes and numbers refer to lithostratigraphic units presented in Table 5.

Several occurrences of Tertiary volcanics were modelled as vertical cylindrical bodies cutting through all older units, as feeding paths for the already eroded volcanoes.

Crystalline modelling

The basement rocks are composed of low- to medium-grade metasedimentary and volcanic rocks of Paleozoic and Ediacaran age. This succession was strongly affected by folding and faulting during Variscan orogeny. Since the internal fold structure is very complex, it could not be reconstructed in the 3D model. The modelled litholological boundaries are often fault-related, the dip of the units was either taken from field-measurements or reconstructed from the geological map by the three-point-method. Late-Variscan granitic plutons post-deformationally intruded the volcano-sedimentary units, crosscut the structures of the sedimentary and metamorphic rocks and are surrounded by contact-metamorphic rocks. In the vicinity of the Cheb basin, all these crystalline rocks are deeply weathered to depths up to more tens of meters, thanks to Tertiary subtropical climate.

2.6.2. Data preparation

2.6.2.1. Processing of the raw data

A unified, simplified geological map for the model was prepared on the basis of the archive maps (**Figure 22**), which are often mutually different or sometimes even contradictory. All these archive maps are part of a GIS project created during data preparation in ArcMap software. The most probable boundary positions were identified by a qualified estimate and the lithology type was simultaneously defined, constituting a basis for the definition of the lithostratigraphic units, represented by horizons in the 3D modelling software. The formulation of a set of lithology types and shapes of the individual rock bodies was based on the project requirement of merging petrographically and hydraulically similar rocks on the basis of an expert estimate (e.g. merging of 2 similar varieties of granites) and to simplify complicated contours of geological bodies (e.g., by omission of small lenticular bodies), which are insignificant in the context of the follow-up calculations and evaluation of the model from the shallow geothermal perspective.

The geological map of the Czech Republic of 1 : 50 000 scale and the map Erzgebirge-Vogtland 1:50000 were reclassified according to the standard geological column (**Table 5**). The contour of units and fault traces were then improved using archive geological maps 1 : 25 000, that are available for most of this pilot area. Additionally, fault traces and extent of Quarternary bodies were further improved by morphotectonic analysis using a detailed DEM 5x5m (for the Czech part) and of 2x2m (for the German part).

A DEM of cell size of 50 m was used for the model. The project requirement was to ensure that generalization of the geological situation in the Quarternary units was kept to a minimum; the geology was more generalised in the case of pre-Quarternary sediments and crystalline rocks. Thus, on the basis of the expert estimate, only rock bodies smaller than ~ 2500 m^2 were neglected in the research area, or, alternatively, discontinuous bands of these rocks were approximated by a single body superimposed on such bands. At the same time, complicated boundaries of rock types in these areas were simplified by omitting the subordinate intercalation of rock types (e.g., the complicated interpenetration of two similar types of phyllite was approximated by a single type phyllite – according to the locally predominant lithology). Consequently, these maps were confronted with the results of limited field work to validate the performed simplifications. The compiled geological map was used for construction of the geological 3D models.

Boreholes data were selected according to the density of the boreholes and their depth. All boreholes with a depth less than 2 m were excluded. If boreholes were clustered in one lithological unit, then the deepest or best documented borehole of each cluster was chosen. The geological profiles of the selected boreholes were reclassified according to the standard geological column (**Table 5**).

The borehole data were structured in two ASCII tables in the *.txt format. The first table contained the name of the borehole, its accurate location (X, Y and Z coordinates) and total depth. The second table contained the individual lithological horizons and their position in the borehole in metres. The depth of the individual horizons was given in re-calculated Z coordinates, or as the depth in metres; the depth in metres was used in practically all cases.

The location and orientation of the Mariánské Lázně fault Confirmation estimated by a local seismic profile (Fischer et al., 2018). These data were imported into MOVE and they were used for corrections to the fault network in the area of the 3D model. Additionally, a large dataset of earthquake hypocentres including magnitude estimates was downloaded from the web sites of the geophysical institute of the Czech academy of sciences in order to better constrain the dip of some faults near the famous occurrence of earthquakes in the Nový kostel area.

The orientation of ductile structures presented on maps were transformed into a digital tabular form. The resulting table was imported into MOVE. The individual measurements were visualized in terms of the given orientation and were used for the construction of the rock bodies. The archive structures comprised only information about bedding.

The available archive vertical geological sections were imported into MOVE and Gocad in the form of raster images, and set to scale along their trace (according to the available map data). They were used during the model building to constrain the model in areas where no borehole data were available.

2.6.2.2. Input data for 3D modellling

The above described data were then prepared for import into the 3D modelling software. The Czech team worked with MOVE, the German team with Gocad. The Esri SHP file format was used for lines and polygons, floating point TIFF file format including complementary GIS world files for grids, the JPEG format for raster images (in particular scanned geological and geophysical vertical profiles) and a structured TXT file format with TAB delimitier for the borehole data (borehole positions and profiles), earthquake data and structural data (foliations etc – positions and orientation). All these files were progressively imported into MOVE SW during the model building process.

2.6.3. 3D modellling

2.6.3.1. Modellled objects and modellling methodology

Technically, the 3D geological model consists of meshes, i.e. TINs that represent two types of geological objects – tops of lithostragraphic units and fault planes. The top of the model is represented by a DEM with 50x50m resolution, the sides of the model are vertical and the base of the model was created as a strongly smoothed DEM surface shifted to a depth of approx. 500 m. The exception is the Cheb basin where the model is created down to approx. 300m depth, where the base of the basin is located.

Objects smaller than 2500 m^2 (1 cell of the DEM grid) have not been modelled. Quarternary units were re-digitized so that they match the DEM relief. The borehole profiles were reinterpreted using only those lithostratigraphic units present in the model, with a minimum thickness of 2 m. Layers of smaller thickness were merged with an appropriate adjacent unit.

Extensive data preparation and some steps of modelling that involved grid calculations were performed in ArcMap GIS because MOVE and Gocad do not offer tools needed for the grid operations. The tops of the modelled units were directly created.

2.6.3.2. Modell assumptions/specifications

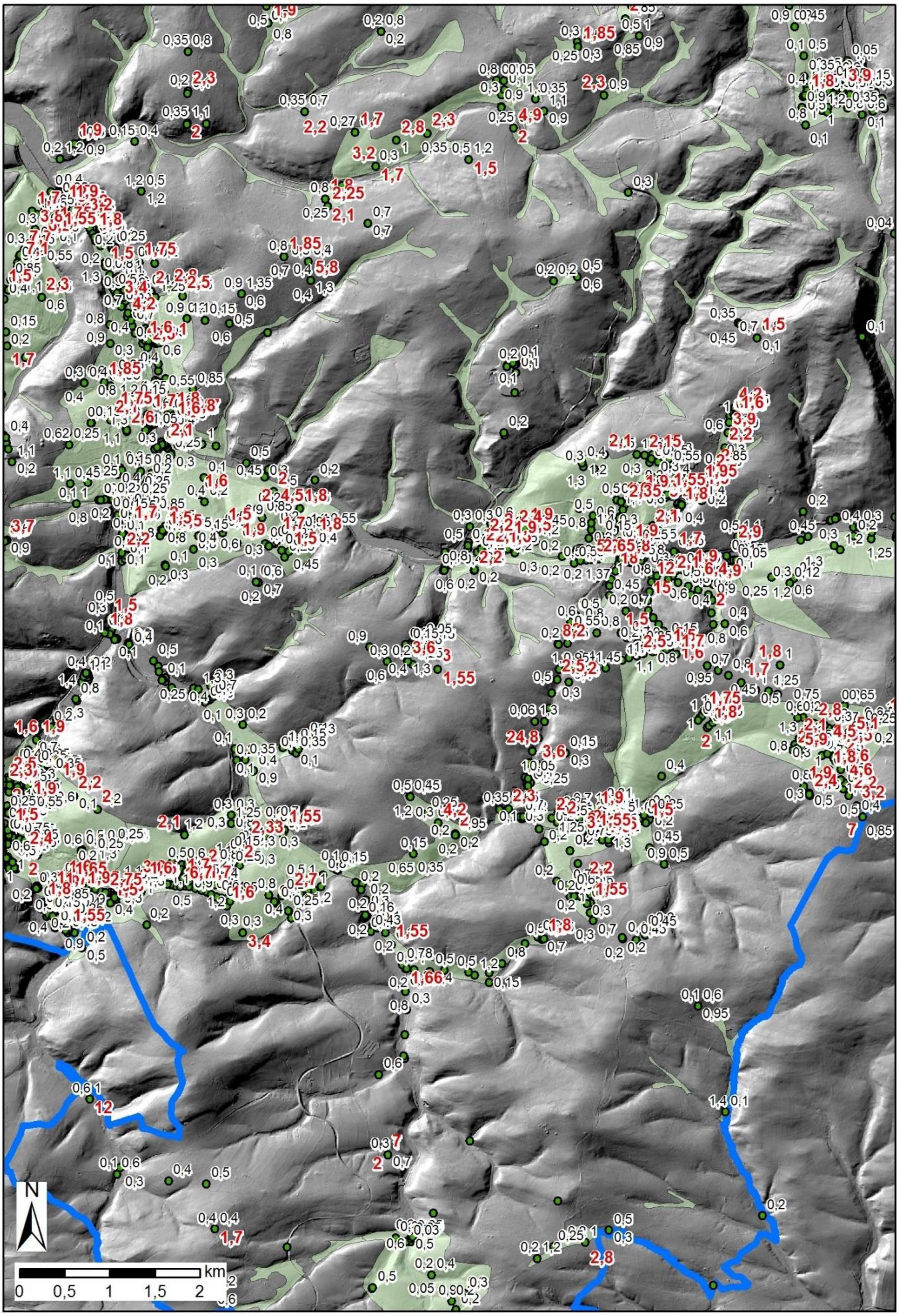
Several assumptions have to be made to finish the model with a lack of important data. First, faults were grouped and a constant dip was assigned to each group based on known dip of one fault in the group or estimated by the dip a regionally important fault of the same strike near the pilot area. If none of such estimations were available, the fault plane was modelled as vertical. Small bodies of metamorphic rocks (e.g. quartzites) were modelled as lenses, with the largest extent on the Earth’s surface getting smaller downwards. The Quarternary bodies were modelled with a constant thickness for each lense and with vertical or steep boundaries, due to a lack of data on the depth variability of these generally very thin and irregular bodies. If no borehole data were available, the thickness of the Quarternary bodies was based purely on an expert estimate of a Quarternary geologist.

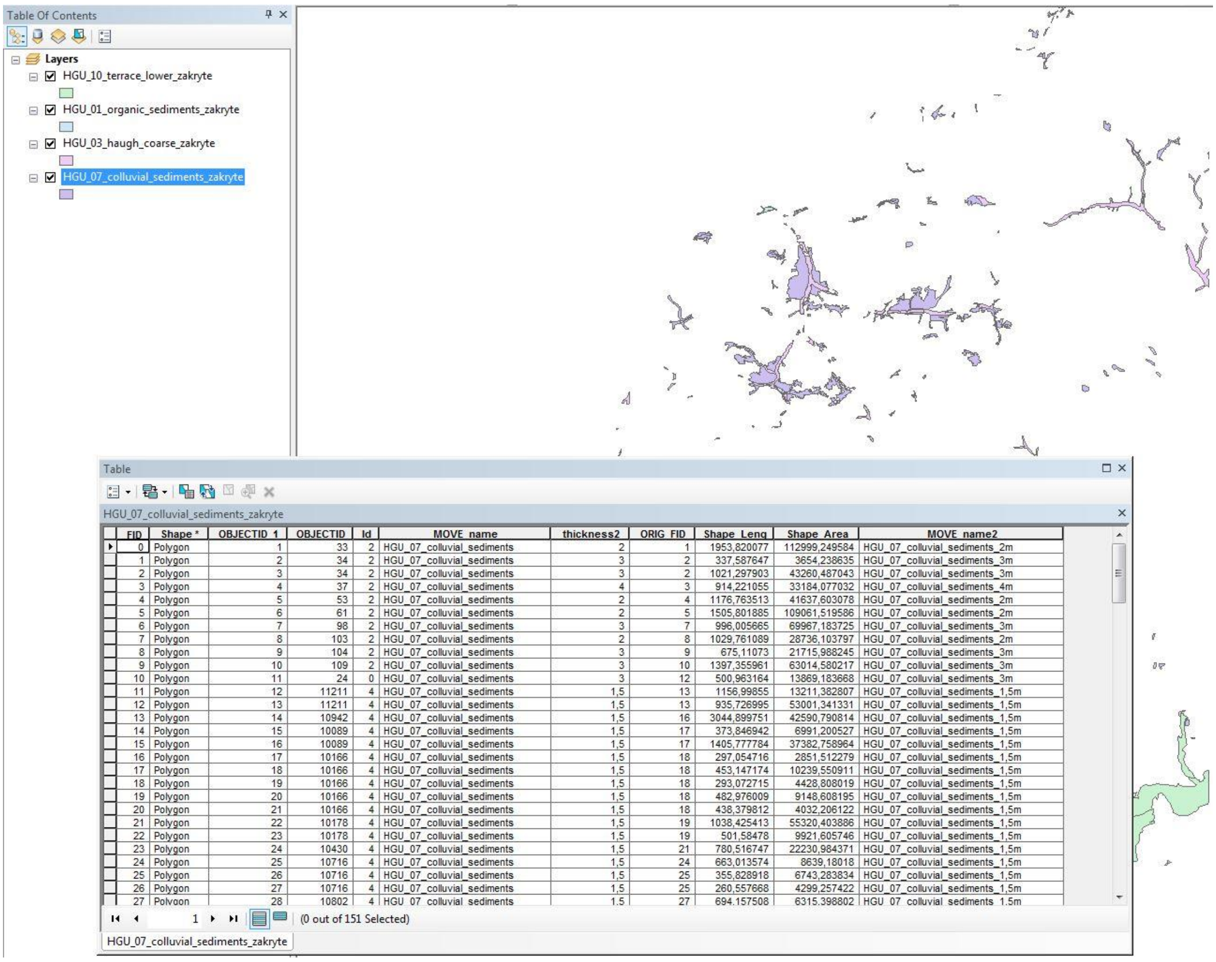
2.6.3.3. Model topology

During the whole modelling process a general geological rule was applied for lithological boundaries: younger lithostratigraphic units crosscut older units. Concerning faults, the crosscutting relations could not be applied because of repeated reactivation of individual fault populations during the prolonged brittle tectonic history of this area ranging from late Variscan times (340 Ma) through Mesozoic and Cenozoic as documented by numerous Earthquake swarms from 20th and also 21th century.

Modelling of geological bodies was performed by three principally different approaches, that reflect differences in spatial distribution and genesis of the modelled geological bodies:

Quarternary bodies were modelled at a depth constant for each of the modelled bodies. The depth was defined based on borehole data if available (**Figure 23**). In case of bodies with no borehole data, the depth was estimated based on expert estimate combined with consideration of neighbouring bodies.


N
0
0,5
1
1,5
2
km



HGU_07_colluvial_sediments_zakryte

FID	Shape *	OBJECTID 1	OBJECTID	Id	MOVE name	thickness2	ORIG FID	Shape Leng	Shape Area	MOVE name2
0	Polygon	1	33	2	HGU_07_colluvial_sediments	2	1	1953,820077	112999,249584	HGU_07_colluvial_sediments_2m
1	Polygon	2	34	2	HGU_07_colluvial_sediments	3	2	337,587647	3654,238635	HGU_07_colluvial_sediments_3m
2	Polygon	3	34	2	HGU_07_colluvial_sediments	3	2	1021,297903	43260,487043	HGU_07_colluvial_sediments_3m
3	Polygon	4	37	2	HGU_07_colluvial_sediments	4	3	914,221055	33184,077032	HGU_07_colluvial_sediments_4m
4	Polygon	5	53	2	HGU_07_colluvial_sediments	2	4	1176,763513	41637,603078	HGU_07_colluvial_sediments_2m
5	Polygon	6	61	2	HGU_07_colluvial_sediments	2	5	1505,801885	109061,519586	HGU_07_colluvial_sediments_2m
6	Polygon	7	98	2	HGU_07_colluvial_sediments	3	7	996,005665	69967,183725	HGU_07_colluvial_sediments_3m
7	Polygon	8	103	2	HGU_07_colluvial_sediments	2	8	1029,761089	28736,103797	HGU_07_colluvial_sediments_2m
8	Polygon	9	104	2	HGU_07_colluvial_sediments	3	9	675,11073	21715,988245	HGU_07_colluvial_sediments_3m
9	Polygon	10	109	2	HGU_07_colluvial_sediments	3	10	1397,355961	63014,580217	HGU_07_colluvial_sediments_3m
10	Polygon	11	24	0	HGU_07_colluvial_sediments	3	12	500,963164	13869,183668	HGU_07_colluvial_sediments_3m
11	Polygon	12	11211	4	HGU_07_colluvial_sediments	1,5	13	1156,99855	13211,382807	HGU_07_colluvial_sediments_1,5m
12	Polygon	13	11211	4	HGU_07_colluvial_sediments	1,5	13	935,726995	53001,341331	HGU_07_colluvial_sediments_1,5m
13	Polygon	14	10942	4	HGU_07_colluvial_sediments	1,5	16	3044,899751	42590,790814	HGU_07_colluvial_sediments_1,5m
14	Polygon	15	10089	4	HGU_07_colluvial_sediments	1,5	17	373,846942	6991,200527	HGU_07_colluvial_sediments_1,5m
15	Polygon	16	10089	4	HGU_07_colluvial_sediments	1,5	17	1405,777784	37382,758964	HGU_07_colluvial_sediments_1,5m
16	Polygon	17	10166	4	HGU_07_colluvial_sediments	1,5	18	297,054716	2851,512279	HGU_07_colluvial_sediments_1,5m
17	Polygon	18	10166	4	HGU_07_colluvial_sediments	1,5	18	453,147174	10239,550911	HGU_07_colluvial_sediments_1,5m
18	Polygon	19	10166	4	HGU_07_colluvial_sediments	1,5	18	293,072715	4428,808019	HGU_07_colluvial_sediments_1,5m
19	Polygon	20	10166	4	HGU_07_colluvial_sediments	1,5	18	482,976009	9148,608195	HGU_07_colluvial_sediments_1,5m
20	Polygon	21	10166	4	HGU_07_colluvial_sediments	1,5	18	438,379812	4032,206122	HGU_07_colluvial_sediments_1,5m
21	Polygon	22	10178	4	HGU_07_colluvial_sediments	1,5	19	1038,425413	55320,403886	HGU_07_colluvial_sediments_1,5m
22	Polygon	23	10178	4	HGU_07_colluvial_sediments	1,5	19	501,58478	9921,605746	HGU_07_colluvial_sediments_1,5m
23	Polygon	24	10430	4	HGU_07_colluvial_sediments	1,5	21	780,516747	22230,984371	HGU_07_colluvial_sediments_1,5m
24	Polygon	25	10716	4	HGU_07_colluvial_sediments	1,5	24	663,013574	8639,18018	HGU_07_colluvial_sediments_1,5m
25	Polygon	26	10716	4	HGU_07_colluvial_sediments	1,5	25	355,828918	6743,283834	HGU_07_colluvial_sediments_1,5m
26	Polygon	27	10716	4	HGU_07_colluvial_sediments	1,5	25	260,557668	4299,257422	HGU_07_colluvial_sediments_1,5m
27	Polygon	28	10802	4	HGU_07_colluvial_sediments	1,5	27	694,157508	6315,398802	HGU_07_colluvial_sediments_1,5m

(0 out of 151 Selected)

HGU_07_colluvial_sediments_zakryte

Figure 23: Two snapshots from ArcMap GIS preparation of Quarternary bodies for 3D modelling. (a) At first the thickness of Quarternary sediments in individual archive boreholes is plotted on the DEM and Quarternary bodies (colluvials in this case), with red-enhanced labelling of boreholes with more than 1,5m of Quarternary sediments. (b) After expert appraisal of these borehole data, the individual bodies acquire manually a thickness estimate in their attribute table (field „thickness2") based on the above borehole data.

The Tertiary sediments of the Cheb basin were modelled as subhorizontal surfaces also in ArcMap GIS using depth information from reinterpreted boreholes and vertexes of surface boundaries of outcrops of the corresponding units. These point data were then used for the grid calculation using a Spline with Barriers GIS tool. Again, the subsurface extent of each Tertiary unit was then plotted on this grid in MOVE. As the Tertiary rocks are affected by faulting, the resulting meshes were manually splitted and edited to respect also the modelled fault network and published geological sections.

Crystalline units represent lithologically varied, deformationally strongly flattened and mildly folded succession. For this reason, two similar approaches were used. Small bodies (up to ca 10.000 m^2) elongated parallel to the foliation were modelled as lenses conventionally shrinking downwards and running parallel to foliation known from neighbouring rock outcrops (**Figure 24**). Boundaries of large geological bodies and several volcanites were then modelled manually and individually, based on expert assessment of the geological position and structural data from vicinity of each body.

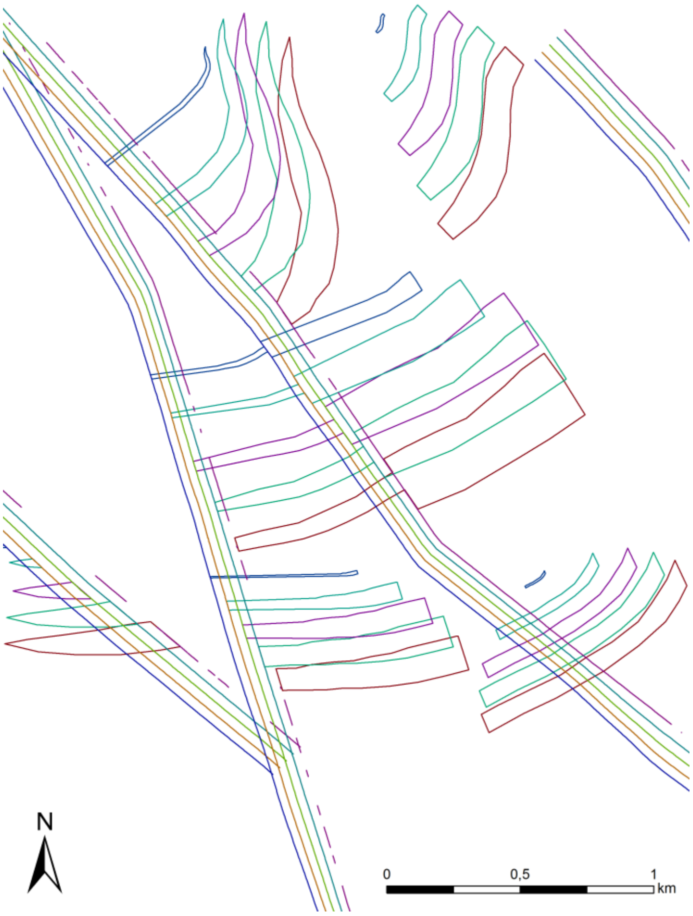


Figure 24: Map view of modelling of elongated quartzite intercalations in phyllites. Different colours mark different horizontal sections of the 3D model throughout the modelled volume of subsurface rocks. The quartzite bodies are inclined to N-NW according to foliation documented on nearby outcrops. Moreover the bodies are crosscut by inclined faults, on which the bodies change geometry.

The fault network was modelled by extrusion of the map trace of the faults, according to the dip estimated for each of the fault groups as described above. The modelled fault network was then used as one of constraints when modelling adjacent lithological bodies.

2.6.4. Modellling results

2.6.4.1. Presentation and validation of modelling results

The models of the Czech and German parts of the pilot area were merged. A Validation of the models is hardly possible without expensive technical works including drilling, geophysical research and exploration or geological mapping of significant areas of the modelled pilot area.

2.6.4.2. Modelling uncertainties and errors

3D geological models are often created from ambiguous and uncertain data which are subject to error propagation during data acquisition and interpretation. Further the data are often scarce and heterogeneous, so that the modeller depends on model-based interpretation, e.g. by assuming a certain tectonic regime or deformation style. Apart from the small scale models of the resource industries, these uncertainties are often neither evaluated nor shown to the users and stakeholders because there is currently no standardized approach to quantify the uncertainties for such complex and large – scale cases. According to results of this project, the quantification of uncertainty would require the compilation of different sources of uncertainty, classification of the different types of uncertainty formulated and data sets for the different types of uncertainty provided. Subsequently these data sets would have to be used to test existing and develop new visualization methods from computer graphics. None of such approaches was published so far for comparable geological 3D models.

In case of this pilot area, the modelling uncertainties are caused by data errors (boreholes, maps and cross-sections), lack of data, and the methodology of modelling. The highest credibility was assigned to the boreholes data and the geological map.

Modelling errors errors are derived from the interpolation methods. Linear interpolation was used for modelling in the MOVE software, that is most suitable for surface construction of irregularly distributed spatial data. At small thicknesses of modelled units, the meshes locally crossed each other on a scale of 1-2 m. This problem appeared mainly with Quaternary units, but it also occurred elsewhere, where the dip of the units was very small combined with limited thickness of adjacent units. Similar problems appeared in the Gocad model. In these cases, it was decided that the boundary of the underlying model unit was locally shifted by 2 or 3 m downwards manually, to correct this purely artificial inconsistency.

The geological map was compiled from various maps of different scale produced by different authors who have different opinions on the geological genesis of the area of interest. The verification of lithological boundaries or fault networks by geological mapping has never taken place thoroughly.

The extent of individual quaternary bodies in the original geological maps seems to be very often imprecise to misleading. The boundaries of the quaternary bodies were strongly corrected using the DTM 4G. Accuracy of these bodies corresponds to the precision of the DTM and the experience of the quaternary geologist. Significant terrain verification could not take place with regard to the project schedule.

The inaccuracies of the model unit boundaries are also related to the inaccuracy of the fault network. The used fault network was created as a compilation of all available tectonic interpretations and maps. Again, each author had different opinion on the fault network and therefore, the map fault networks do not match with each other. The dip or sense of movement has not been established at many faults.

The cross-sections used to create the 3D model are of variable quality that is hard to asses. Uncertainties comprise number and location of faults, as well as determination of the depth of model units.

The borehole data contain three principal types of errors:

1. Determination of the unit boundaries – particularly in sedimentary sequences this feature represents the most important source of errors, due to often lower quality of borehole description combined with complex (sedimentary) successions. Borehole profiles were reclassified according to the standard geological column. Unfortunately, some boundaries of the model units are poorly determined or missing in borehole profiles. To recognize model units mainly in Tertiary sediments is often difficult.

2. Position of borehole – errors appears relatively scarcely, often in a scale of several meters. The borehole is located in the model unit on the geological map, but in its profile the model unit is missing. There is also a problem with altitude localization. Some boreholes are located a few meters under or above the terrain (the error is somewhere over 10 meters).

3. Lack of inclinometry – the uncertainty then generally increases with depth. None of the boreholes has inclinometry. Therefore, the boreholes, are assumed to be vertical in the model and pass through faults into another tectonic block and thus into another model unit.

3. Summary and conclusions

Six static structural 3D models were produced in the GeoPLASMA-CE project. They represent 4 -44 geological units per model.

All models are based on the harmonization and simplification of the geological data availabele among the project partners. This work step was especially important in the international pilot areas.

The models represent the tops of the geological units with properties relevant for shallow geothermal use. Additionally, the fault networks were analysed by the partners and either simplified or neglected for the modelling.

The accuracy of the model could not be quantified by any of the partners. This is a general problem in geological 3D modelling: since the density of data is decreasing with depth and repeated data acquisition is too expensive, no indications on the accuracy and reliability of the geological models can be made. In general, the accuracy of the models is better near the Earth's surface and decreasing with depth. The accuracy of the model is better in regions with many borehole data and worse in regions with few boreholes.

The completed 3D models will be used for the calculation of the shallow geothermal potential and saved at the web-platform, where they can be queried for the construction of virtual boreholes.

4. References

Bräuer K., Kämpf H., Niedermann S., Strauch G., 2005. Evidence for ascending upper mantle derived melt beneath the Cheb basin, central Europe. Geophys. Res. Lett., 32, L08303, DOI: 10.1929/2004GL022205.

Buła Z., Habryn R. (red.), 2008. Atlas geologiczno-strukturalny paleozoicznego podłoża Karpat zewnętrznych i zapadliska przedkarpackiego. Państw. Inst. Geol., Warsaw.

Čech S., Gawlikowska E., 1999. Góry Stolowe, Adršpašsko-teplické skály. Geologická mapa pro turisty. 1:50 000.- Państwowy Instytut Geologiczny-Český geologický ústav. Warszawa-Praha.

Buser S., Grad K., Pleničar M., 1967. Osnovna geološka karta SFRJ 1 : 100.000, List Postojna. (Basic Geological Map of SFRY 1 : 100,000. Sheet Postojna). Zvezni geološki zavod, Beograd.

Buser S., 1969. Osnovna geološka karta SFRJ 1 : 100.000, List Ribnica. (Basic Geological Map of SFRY 1 : 100,000. Sheet Ribnica). Zvezni geološki zavod, Beograd.

Buser S., 2009. Geološka karta Slovenije 1 : 250.000. (Basic Geological Map of Slovenia 1 : 250,000). Geološki zavod Slovenije, Ljubljana.

Cyran K., 2008 .Tektonika mioceńskich złóż soli w Polsce. AGH Kraków. Rozprawa doktorska, 1-266.

Dadlez, Marek, Pokorski, 2000. Mapa geologiczna Polski bez utworów kenozoiku, Państwowy Instytut Geologiczny, Warsaw.

Duda R., Haładus A., Witczak S., 1997. Hydrogeological Map of Poland. 1:50 000, Kraków. Polish Geological Institute. Warsaw.

Duliński M., Kania J., Karlikowska J., Opoka, M., Różański K., Śliwka I., Witczak S., Zuber A., 2002. Hydrochemistry of Bogucice Sands aquifer as related to ages of water. Jakość i podatność wód podziemnych na zanieczyszczenie, Prace Wydziału Nauk o Ziemi Uniwersytetu Śląskiego, 22.

Fischer T., Horálek J., Hrubcová P., Vavryčuk V., Bräuer K., Kämpf H., 2014. Intra-continental earthquake swarms in West-Bohemia and Vogtland: a review. Tectonophysics, 611, 1-27, DOI: 10.1016/j.tecto.2013.11.001.

Grad K., Ferjančič L., 1974. Osnovna geološka karta SFRJ 1 : 100.000, List Kranj. (Basic Geological Map of SFRY 1 : 100,000. Sheet Kranj). Zvezni geološki zavod, Beograd.

Habryn R., Buła Z., Chmura A., 2007. Dokumentacja geologiczna otworu badawczego Trojanowice-2. Zintegrowany program płytkich wierceń badawczych dla rozwiązania istotnych problemów budowy geologicznej Polski. Problem 10. Geologiczno-strukturalne rozpoznanie strefy rozłamu Kraków Lubliniec na odcinku krakowskim. Centr. Arch. Geol. Państw. Inst. Geol., Warszawa.

Haładus A., Kulma R., Motyka J., 1990. Prognoza zmian stosunków wodnych w otoczeniu kamieniołomu „Zakrzówek” w Krakowie, Zesz. Nauk. AGH, Geol., 16, 65-87.

Hecht L., Vigneresse J.-L., Morteani G., 1997. Constraints on the origin of zonation of the granite complexes in the Fichtelgebirge (Germany and Czech Republic): evidence from a gravity and geochemical study. Geol. Rundsch., 86, S93-S109.

Hoth K., Wasternack H., Berger J., Breiter K., Mlčoch B., Schovánek P., 1995. Geologisch Karte Erzgebirge - Vogtland 1 : 100 000. Freiberg.

Janža M., Lapanje A., Šram D., Rajver D., Novak M., 2017. Research of the geological and geothermal conditions for the assessment of the shallow geothermal potential in the area of Ljubljana, Slovenia. GEOLOGIJA 60/2, 309-327, Ljubljana 2017, https://doi.org/10.5474/geologija.2017.022.

Krásný J., Císlerová M., Čurda S., Datel J.V., Dvořák J., Grmela A., Hrkal Z., Kříž H., Marszałek H., Šantrůček J., Šilar, J., 2012. Podzemní vody České republiky, Regionální hydrogeologie prostých a minerálních vod. Česká geologická služba, Praha.

Kondracki J., 2002. The Regional Geography of Poland. Ed. 3 Suppl. Pwn. Warsaw, 440pp.

Kristensen M., Andersson U., Sorensen H.R., Refsgaard A., 2000. Water Resources Management Model for Ljubljansko Polje and Ljubljansko Barje - Model Report. DHI Water & Environment, Horsholm.

Mencej Z., 1990. Prodni zasipi pod jezerskimi sedimenti Ljubljanskega barja. (The gravel fill beneath the lacustrine sediments of the Ljubljansko barje). Geologija, 31/32, 517-554.

Ministry of the Envirorment and Spatial Planning (MESP), The Surveying and Mapping Authority of the Republic of Slovenia, 2011: Digital elevation model (DEM), raster file (cell size 25 x 25 m), http://www.e-prostor.gov.si/.

Muller V., Burda J., Dubec O., Hrazdíra P., Hrkal Z., Jinochová J., Lochmann Z., Majer V., Manová M., Mlčoch B., Rejcht M., Sáňka V., Schovánek P., Skácelová D., Šalanský K., Šantrůček P., 1998. Explanatory text to geological and ecological maps of natural resources 1 : 50 000, sheets 11-13 Hazlov and 11-14 Cheb. 75 pp, ČGÚ Prague.

Novak, M., 2000. Geološka zgradba ozemlja med Podutikom in Toškim Čelom. BSc Thesis, University of Ljubljana. Ljubljana, 72 pp.

Premru U., 1983. Osnovna geološka karta SFRJ 1 : 100.000, List Ljubljana. (Basic Geological Map of SFRY 1: 100,000. Sheet Ljubljana). Zvezni geološki zavod, Beograd.

Rajchl M., Uličný D., Mach K., 2008. Interplay between tectonics and compaction in a rift-margin, lacustrine delta system: Miocene of the Eger Graben, Czech Republic. Sedimentology 55, 1419–1447. DOI 10.1111/j.1365-3091.2008.00951.x

Rajchl M., Uličný D., Grygar R., and Mach K., 2009. Evolution of basin architecture in an incipient continental rift: the Cenozoic Most basin, Eger Graben Central Europe. Basin Research 21, 269-294. doi: 10.1111/j.1365-2117.2008.00393.x

Salcher B. C. B., Meurers J., Smit K., Decker M., Wagreich M., 2012. Strike-Slip Tectonics and Quaternary Basin Formation along the Vienna Basin Fault System Inferred from Bouguer Gravity Derivatives. Tectonics.

Škvor V., 1974. Geologie české části Krušných hor a Smrčin. Knih. Ústř. Úst. geol., 48. Praha.

Škvor V., Sattran V., 1974. Krušné hory západní část, soubor oblastních geologických map 1 : 50 000. ÚÚG Prague.

Špičáková L., Uličný D., Koudelková G., 2000. Tectonosedimentary evolution of the Cheb basin NW Bohemia, Czech Republic: between Late Oligocene and Pliocene: a preliminary note. Stud. Geophys. Geod. 44, 556–580.

Švancara J., Havíř J., Conrad W., 2008. Derived gravity field of the seismogenic upper crust of SE Germany and West Bohemia and its comparison with seismicity. Stud. Geophys. Geod., 52, 567-588.

Szklarczy T., Kaczmarczyk R., 2015a. Ekspertyza określająca warunki hydrogeologiczne i geotechniczne pod płytą fundamentową w budynku biurowo-handlowo-usługowego w Krakowie przy ul. Kapelanka.

Szklarczyk T., 2015b. Opinia techniczna dotycząca przewidywanych ryzyk geologicznych oraz hydrogeologicznych dla planowanej inwestycji „SKAŃSKA” przy ul. Pawiej w Krakowie.

Szklarczyk T., 2016. Ekspertyza techniczna dotycząca warunków hydrogeologicznych dla planowanej inwestycji budowy budynków mieszkalnych, wielorodzinnych przy ul. Konopnickiej w Krakowie.

Tásler, R., Čadková, Z., Dvořák, J., Fediuk, F., Chaloupovská, J., Jetel, J., Kaiserová-Kalibová, M., Prouza, V., Schovánková-Hrdličková, D., Středa, J., Střída, M. & Šetlík, J. (1979): Geologie české části vnitrosudetské pánve. Oblastní regionální Geologie ČSR. Československá akademie věd. Praha.

Uličný D., Špičáková L., Grygar R., Svobodová M., Čech H. S., Laurin, J., 2009. Palaeodrainage systems at the basal unconformity of the Bohemian Cretaceous basin: roles of inherited fault systems and basement lithology during the onset of basin filling. Bulletin of Geosciences 84/4, 577–610.

Żytko K., Gucik S., Ryłko W., Oszczypko N., Zając R., Garlicka I., 1989. Geological map of the western Outer Carpathians and their foreland without Quaternary formations. In: A. Kawecka & J. Zając (Eds.), Geological atlas of the western outer Carpathians and their foreland : scale 1:500 000. Warszawa: Wydawnictwa Geologiczne.