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The three-dimensional regional geological model of the Mura-Zala Basin, northeastern Slovenia

Tridimenzionalni regionalni geološki model Mursko-zalskega bazena, severovzhodna Slovenija

Dejan ŠRAM[1], Nina RMAN[2], Igor RIŽNAR[3] & Andrej LAPANJE[4]

[1,2,4] Geološki zavod Slovenije, Dimičeva ulica 14, SI–1000 Ljubljana,
e-mails: dejan.sram@geo-zs.si, nina.rman@geo-zs.si, andrej.lapanje@geo-zs.si
[3] G.E. Igor Rižnar s.p., e-mail: igor.riznar@telemach.net

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Ključne besede: geološki model, Haloška formacija, Špiljska formacija, Lendavska formacija, Murska formacija, Ptujsko-grajska formacija, GeoMol, 3D-Explorer

Abstract

The Mura-Zala sedimentary Basin is a Neogene basin with many competing geopotentials, spanning parts of Slovenia, Austria, Croatia and Hungary. Here we present the 3D regional geological model of the Slovenian part of the Mura-Zala Basin, which was developed to integrate the latest information on the geological structure of NE Slovenia and to publish the model in an open-access mode for easier and faster assessment of geopotentials. This was achieved through the harmonisation of the legacy geological models, the reinterpretation of 145 borehole logs, the construction of the 3D numerical geological model in JewelSuite™, and delivering it into a 3D-Explorer environment. The model comprises nine lithostratigraphical units. The Pre-Neogene basement rocks are covered by the Haloze Formation; the Špilje Formation – Badenian and Sarmatian; the Lendava Formation – turbidites and slope; the Mura Formation – delta front and delta plain; and the alluvial Ptuj-Grad Formation. The model has two principal shortcomings, related to currently unavailable seismic reflection data faults were not implemented, and the Quaternary formations were not delimited. The model is useful for regional-scale studies and may reduce geological risks related to exploration in NE Slovenia. It will also support a better assessment of geopotentials and a more feasible approach to their development, and, eventually, will enable the harmonized management of our subsurface in 3D space. This can be achieved using the 3D-Explorer platform which enables the creation of arbitrary vertical cross-sections, horizontal slices and virtual boreholes.

Izvleček

Mursko-zalski sedimentacijski bazen je neogenski bazen s številnimi konkurenčnimi geopotenciali, ki se razširja v Sloveniji, Avstriji, Hrvaški in na Madžarskem. V članku predstavljamo 3D regionalni geološki model slovenskega dela Mursko-zalskega bazena. Razvit je za prikaz najnovejših informacij o geološki zgradbi SV Slovenije in objavo v prosto dostopni obliki, ki omogoča lažjo in hitrejšo oceno geopotencialov. To smo dosegli z uskladitvijo predhodnih geoloških modelov, reinterpretacijo 145 geofizikalnih popisov globokih vrtin, izdelavo 3D matematičnega modela s programom JewelSuite™ in njegovo implementacijo v orodju 3D-Explorer. Model prikazuje devet litostratigrafskih enot. Pred-neogenske kamnine v podlagi bazena so prekrite s Haloško formacijo, Špiljsko formacijo - sarmatij in badenij, Lendavsko formacijo - pobočje in turbiditi, Mursko formacijo - deltno čelo in ravnica ter aluvialno Ptujsko-grajsko formacijo. Model ima dve poglavitni slabosti, kot posledica nedostopnosti seizmičnih podatkov vanj niso vključeni prelomi in sedimenti kvartarne starosti niso razmejeni. Model je primeren za regionalne študije in zato lahko zniža geološko tveganje pri raziskavah v SV Sloveniji. S tem, ko podpira boljšo oceno geopotencialov in primernejši pristop k njihovem razvoju, bo sčasoma omogočil usklajeno upravljanje našega podpovršja v tridimenzionalnem prostoru. Raba 3D-Explorerja omogoča izdelavo poljubnih navpičnih in vodoravnih prerezov ter navideznih vrtin.

Introduction

The Pannonian Basin is a Tertiary sedimentary basin, which is considered to be a continental back-arc basin of the Carpathian orogeny (Jelen & Rifelj, 2005; Horváth et al., 2015). It is characterised by a major system of Neogene basins resting on a highly deformed and complexly faulted substrate of Mesozoic, Paleozoic, and Precambrian rocks of the Inner Carpathian foldbelt. Shared by several Central and Eastern European countries, the Pannonian Basin features a variety of vast and diverse geopotentials.

The Slovenian part of the Mura-Zala Basin (Fig. 1) is located on the western margin of the Pannonian Basin and continues on to Austria, Croatia and Hungary (Nádor et al., 2012).

In the past, the basin was called the Mura Depression (Vončina, 1966; Royden & Horváth, 1988; Mioč & Žnidarčič, 1989; Gosar, 1995) or the Mura Basin (Kralj & Kralj, 2000), and the Međimurje-Zala Basin (in Vrzel (2012) after Žižek (2006)).

The Mura-Zala basin is important for oil and gas production (e.g. Pleničar, 1954; Bader, 1976; Djurasek, 1988; Mioč & Žnidarčič, 1996; Lučić et al., 2001; Dolton, 2006; Kurevija & Vulin, 2011; Markič, 2013), for gas storage (e.g. Gosar, 2005), thermal water (e.g. Rman et al., 2012, 2015; Horváth et al., 2015), coal (e.g. Markič et al., 2011), CCS (e.g. Presečnik, 2008; Vangkilde-Pedersen et al., 2009), and its extensive groundwater reservoirs (e.g. Nosan, 1973; Žlebnik & Drobne, 1999; Kralj & Kralj, 2000; Rajver et al., 2012; Szőcs et al., 2013). New types of geopotentials, such as CO_2 and natural gas storage are competing with traditional uses, for example as a source of drinking and thermal water, and for oil and gas. Therefore, sustainable management of subsurface geopotentials requires an understanding of geology and geological structures, which can be facilitated by visualizing these reservoirs in 3D. Understanding 3D spatial relationships is a major challenge for spatial planning and licensing authorities, who need a clear picture of the subsurface on order to mitigate possible conflicts among the many users and countries involved.

Several geological studies provide a large public data repository as a web tool that is freely accessible online (see http://akvamarin.geo-zs.si/t-jam_boreholes/ or http://transenergy-eu.geologie.ac.at/). However, their value and attractiveness for stakeholders is rather poor due to the lack of an effective tool for visualising subsurface data in 3D.

The 3D regional geological model of the Slovenian part of the Mura-Zala Basin presented in this paper was developed by the Slovenian members of the project GeoMol (The GeoMol Team, 2015). The model aims to:

- publish available 3D spatial information on the geological structure of NE Slovenia,
- present the data using the latest lithostratigraphical characterisation of the Basin,
- enable open, faster and easier assessment of geopotentials.

This was achieved by reinterpretation and harmonisation of existing geological models, reinterpretation and digitalisation of log data, development of the 3D numerical geological model, and its implementation in the 3D-Explorer. This way, the opportunity to identify new areas for development of various geopotentials is freely available to everybody, without any special software.

Geological setting

The Mura-Zala Basin extends across most of north-eastern Slovenia (Fig. 1). Basin fill consists of Neogene sediments belonging to the Central Paratethys paleogeographic domain (Royden & Horváth, 1988). Regional stages in use for the Central Paratethys are therefore used to describe the formations in the model (Piller et al., 2007).

The lithostratigraphy of the Mura-Zala Basin was first interpreted for purposes of oil and gas research in the 1950s-1960s (Pleničar, 1954; Cigit, 1958; Vončina, 1966), which was followed by a geological mapping for the Basic Geological Map of Yugoslavia (Pleničar, 1968; Mioč & Žnidarčič, 1978, 1998; Aničić & Juriša, 1984; Žnidarčič & Mioč, 1987; Marković & Mioč, 1988). The determination of Miocene formations was based on lithological, biostratigraphical and geophysical markers (Naftaplin, 1966; Grandić et al., 1986; Turk, 1993; Mioč & Žnidarčič, 1996). Previously, earlier Miocene formations were also jointly named the Murska Sobota Formation (Fm.) while all Pontian to Quaternary sediments were named the Mura Fm. (Turk, 1993; Kralj & Kralj, 2000). The stratigraphy was upgraded during the latest regional reinterpretations based on a dynamic process approach and focusing on the evolution of sedimentary environments performed in several transnational projects, such as the AT-SLO project TRANSTHERMAL (Lapanje et al., 2007), the HU-SLO project T-JAM (Nádor et al., 2012), and the AT-HU-SK-SLO project TRANSENERGY (Rman & Lapanje, 2013), as well as separately (Lučić et al., 2001; Fodor et al., 2002, 2005; Jelen et al., 2006; Pavšič & Horvat, 2009). Currently, the most important publication on the regional lithostratigraphical settings is the Surface lithostratigraphic and tectonic structural map of the T-JAM project area, northeaster Slovenia, at 1:100,000 (Jelen & Rifelj, 2011), where the Neogene units are reinterpreted.

The Mura-Zala Basin was formed at the western margin of the continental rift that was active from the Late Ottnangian to the mid-Badenian (Márton et al., 2002; Jelen et al., 2006; Maros et al., 2012). An ENE – WSW to E – W oriented Ottnangian extension produced cascading subsidence along the dextral-transtensional Donat Fault zone in the south, and along the Raba extensional corridor (also left lateral transfer zone) in the north (Fig. 1). Along these fault zones, sub-basins were formed in half-grabens (Jelen & Rifelj, 2005; Jelen et al., 2006). The Mura-Zala Basin is characterized by two ENE – WSW trending sub-basins: the Haloze – Ljutomer – Budafa Sub-basin in the south along the Ljutomer and Donat Faults, and the Radgona – Vas Sub-basin in the north along the Rába Fault. A basement high named the Murska Sobota extensional block separates the two sub-basins. The northern and southern

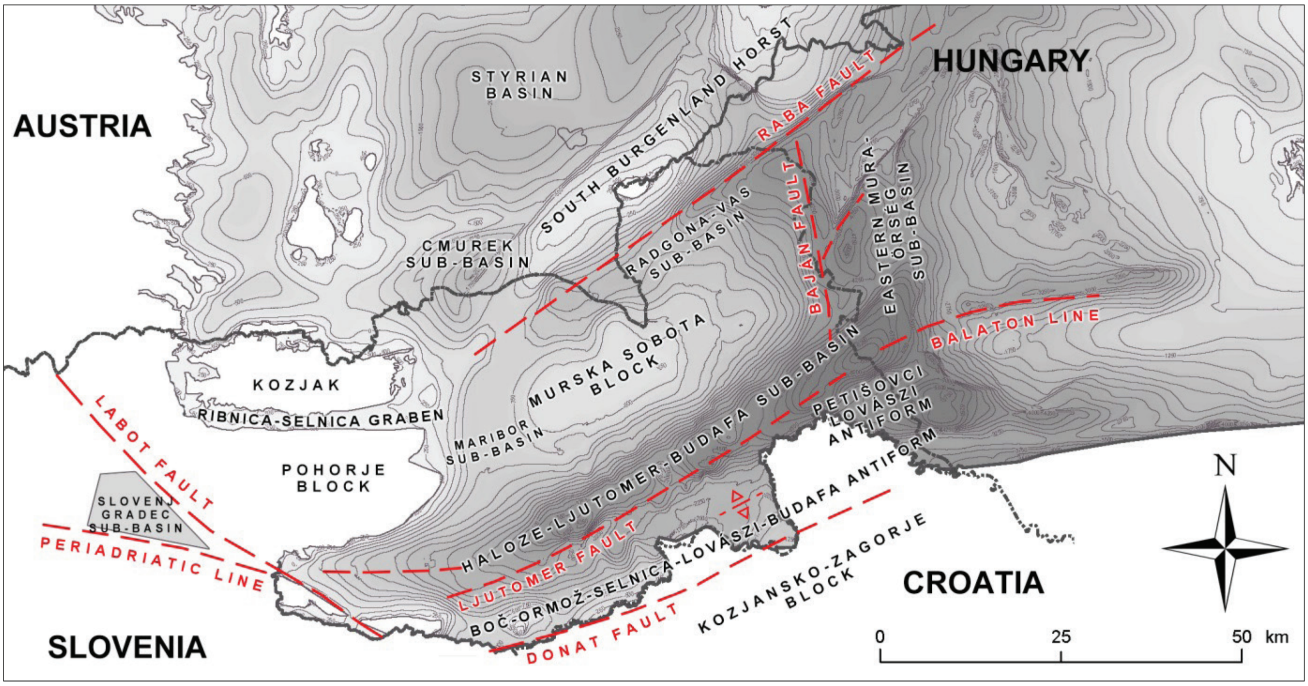

Fig. 1. Contour map of the pre-Neogene basement with major tectonic features (adapted from reports of Jelen et al., 2006, Maros et al., 2012). The extent of the Slovenj Gradec Sub-basin is only schematic and no information was available for Croatia.

margins of the Mura-Zala Basin are formed by the South Burgenland Horst and the Kozjansko – Zagorje tectonic block, respectively. The Pohorje and Murska Sobota extensional blocks formed along roughly N – S trending listric extensional faults between the Rába and Donat Fault zones. The Maribor Sub-basin formed above the faulted boundary between the two blocks. The Eastern Mura – Örseg Sub-basin subsided along the Bajan Fault running along the eastern side of the Murska Sobota block, roughly along the border between Slovenia and Hungary.

The lithostratigraphical description, sedimentary environmental and dynamic infill of the basin is summarised from Fodor et al. (2011), Jelen & Rifelj (2011) and Maros et al. (2012). The oldest Neogene sediments belong to the Early to mid-Miocene (Ottnangian to Early Badenian) Haloze Fm. The continental muddy breccias and conglomerates at the bottom of the sub-basins represent the initial phase of their filling, but higher up, the sediments soon turn into fine-grained deposits of marine character. The upper part of the Haloze Fm. includes also tuff and shallow marine deposits, e.g. Lithotamnian limestone, corresponding to a deposition in a short tectonic inversion and simultaneous sea level drop in the Early Badenian. These sediments have mostly low permeability.

The Špilje Fm. begins with the mid-Miocene (Badenian) transgression due to eustatic sea level rise and continuing the subsidence of the sub-basins. Shorelines shifted far inland and a connection between the Central and Mediterranean Paratethys was established. Poorly-permeable fine grained mud-rich turbidites deposited along the basin margins, and hemipelagic mud in the deepest parts of the sub-basins. Shallow marine deposition prevailed throughout the mid-Miocene (Badenian and Sarmatian) on the Murska Sobota extensional block, as well as to the south and north of the basin margins. Transgression was interrupted by the Late Badenian regression phase, which produced erosional surfaces in previously submerged areas. Coarse-grained clastic sediments of heterolithic facies were derived from the uplifted basement. Even limestones formed along the new shorelines that were established after regression. These shallow-water and coarse-grained deposits are generally highly permeable. After this short-lived regression, the deposition of low-permeability sediments continued and the western parts of the sub-basins were filled up by the end of the Sarmatian, by which time the connection with the rest of the Tethys was also severed.

In the Late Miocene (Pannonian), the area turned into a vast lake system. Rivers from the rising Eastern Alps continuously filled the still subsiding sub-basins with prograding deltas. Continuous subsidence and the Pannonian transgression led to the submergence of the Murska Sobota extensional block. Deposition of hemipelagic marl took place in the deepest parts of the sub-basins, and deltas prograded from the W and NW. The Lendava Fm. comprises turbidites fed from the prograding delta, which are overlain by fine-grained slope deposits. The sandy turbidites occur as isolated permeable bodies, whereas the fine-grained slope deposits represent a very low-permeability horizon covering the turbidites.

Well-permeable coarse-grained turbiditic sandstone and limestone of the Špilje and Lendava Fms. store significant quantities of oil and gas (Hasenhüttl et al., 2001) and oil-prone thermal water (Kralj & Kralj, 2000).

The deltaic sediments of the Mura Fm. are divided into delta front and delta plain facies. The delta front is represented by permeable tabular sand bodies deposited at the delta mouth, which are the most extensive and widely exploited geothermal aquifers in the region (Kralj, 2001; Kralj & Kralj, 2012; Rman et al., 2012; Rman, 2014). The delta plain sediments are mostly fine-grained silts with occurrences of coal (Markič et al., 2011). Permeable gravel lenses originating in distribution channels connect this part of the sequence with the delta front facies. The age of strata in the Mura Fm. generally decreases from W to E in the direction away from the former land surface.

In Pliocene, sediment deposition overwhelmed the subsidence, and delta plain sedimentation changed to an alluvial type of deposition, producing the Ptuj-Grad Fm. A phase of tectonic compression in Pliocene (Tomljenović & Csontos, 2001) induced inversion and folding that was restricted mainly to the Donat Fault zone. Alluvial sediments slowly covered the deltas and indicated a new organization of the drainage system in the Paratethyan domain. The Ptuj-Grad Fm. is quite permeable but does not contain extensive geothermal or freshwater aquifers (Žlebnik, 1978; Szőcs et al., 2013; Rman, 2014). The youngest sediments are mostly gravelly alluvial deposits of the Drava and Mura rivers. They are of Quaternary age and an important drinking water resource (Andjelov et al., 2006).

Methodology

Modelling procedure

Building a 3D geological model is a continuous process that includes several steps, depending on the type. Data pre-processing includes collecting, structuring and reinterpreting data. Maps and cross-sections are digitized and managed as vector data in GIS software where necessary. The final step is to integrate all this data into software for the 3D modelling process (Kaufmann & Martin, 2008). These steps are repeated each time new data is available. For a geological model, the process can be performed each time a new borehole is drilled, a new reflection seismic profile is made or a new geological map is published. In order to be able to update the existing model as quickly as possible, we have followed several methodological steps (Fig. 2).

We created a 3D model using several different software applications: MS Office Excel for the borehole database, AutoCAD (Internet) for constructing cross-sections, ArcMap (ESRI, 2014) for processing two dimensional data, and JewelSuite™ (Baker Hughes, 2014) for handling 3D models from previous studies and constructing the final three dimensional model. Building a model uses the data both ways, as a continuous exchange between software formats is necessary due to their reprocessing.

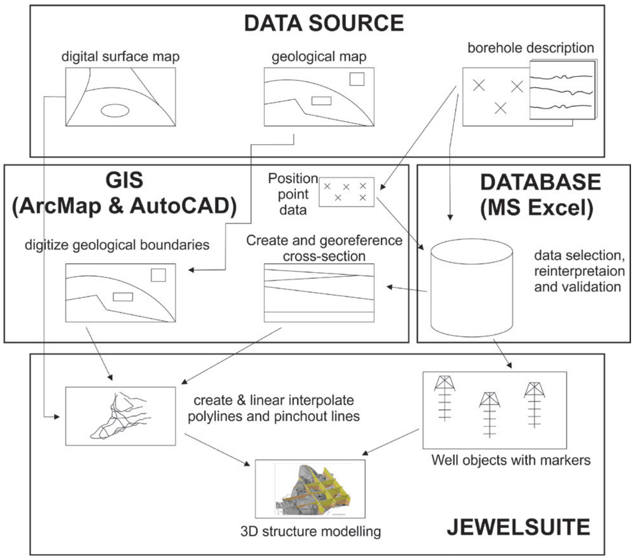

Fig. 2. Organigram of the methodology used to produce a 3D geological model (modified after Kaufmann & Martin, 2008).

Initially, we used mostly vector data (points, polylines and polygons) to create cross-sections. Some were derived from the raster data (by digitizing maps) but the raster data (digital surface map – CIAT, 2004) was also used. We collected four types of available source data:

- Published geological surface map (Mioč & Marković, 1998; Jelen & Rifelj, 2011),
- Models from previous studies of the area (Lapanje et al., 2007, Fodor et al., 2011, Maros et al., 2012, Rman, 2013),
- Digital surface map (CIAT, 2004) and
- Borehole lithological logs.

The information on boreholes was first collected and organized in an MS Excel database, and later harmonized and reinterpreted. Additionally, we created six interpretative cross-sections using AutoCAD: three in SW–NE and three in the NW–SE direction (Fig. 3). They are deliberately spatially equally distributed over the study area and intersect the most representative boreholes. These sections constituted the main input for the building of the 3D model, together with the 453 formation penetration points (FPP) from 145 reinterpreted borehole logs (see Table 3). Boreholes are very unevenly distributed over the model area, clustered in and around urban areas as well as in areas richer in oil and gas, and according to other geopotential probability, i.e. near Lendava, Gornja Radgona and Murska Sobota (Fig. 3).

Together with these cross-sections, the 3D models from previous studies were imported into the JewelSuite™ software. Based on all of the data, polylines in the three dimensional space were created. Additionally, boreholes (X, Y, Z, inclination and azimuth) and their formation penetration points were also imported. Using a combination of newly created polylines, the digitized surface geological map, and information on the horizontal extent of formations (from FPP),

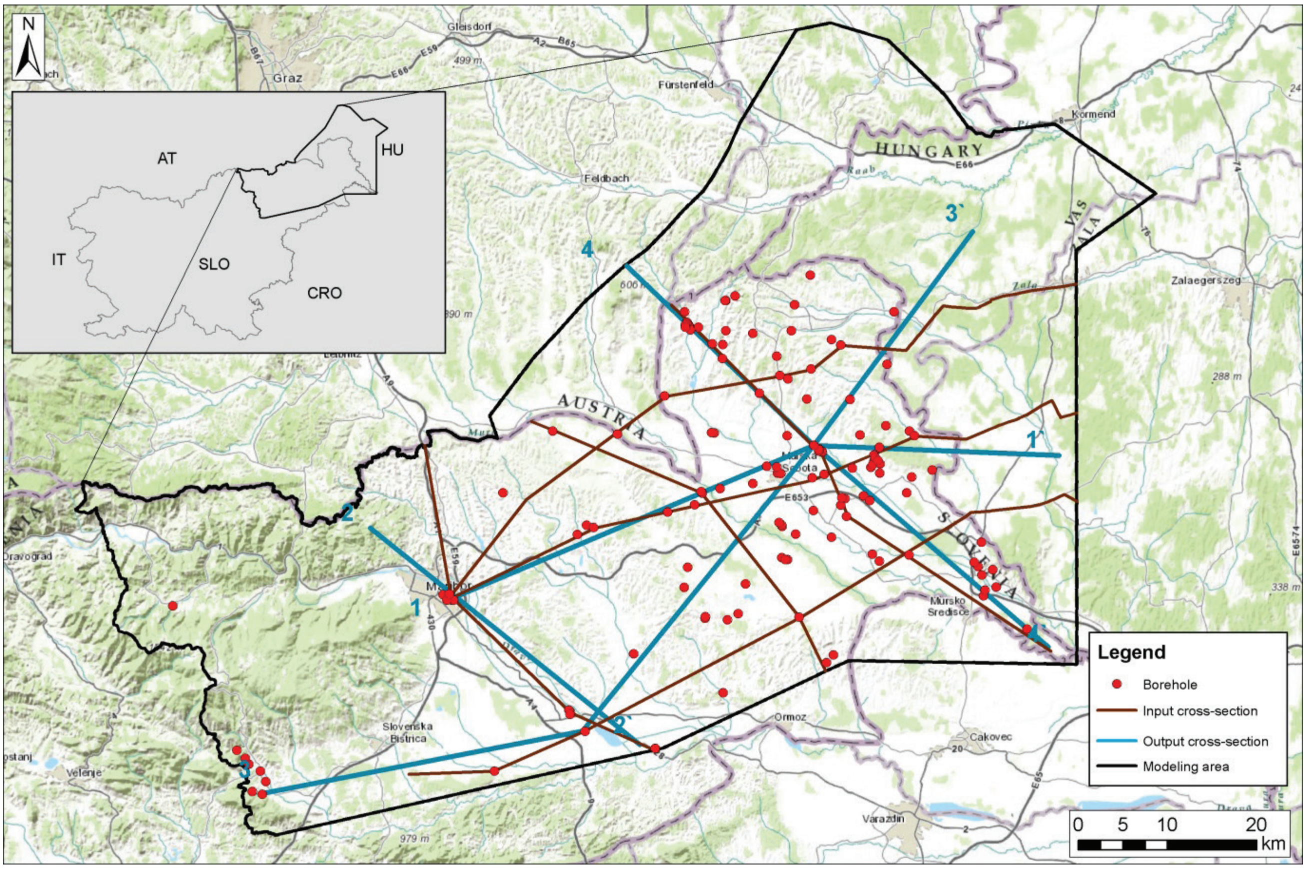

Fig. 3. Outline of the model area (black line) with locations of the input data: boreholes (red dots) and cross-sections (brown lines), as well as the cross-sections derived from the modelling (blue lines), which appear in Figure 5.

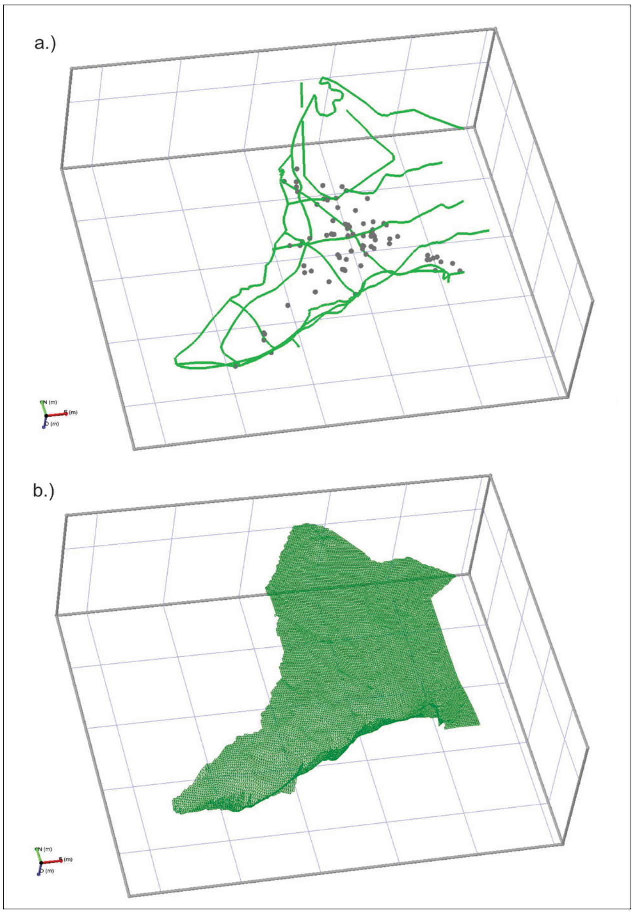

Fig. 4. Digitized polylines from cross-sections with FPP (a) and created trimesh from polylines (b) for one layer.

we created pinchout lines for all formations and defined their terminations (Fig. 4a). The pinchout lines were created using the JewelSuite™ and ArcMap simultaneously, being iteratively connected with the polylines, and determining the shape of the layers. These newly connected polylines were triangulated to a triangular mesh using a linear interpolation method (Fig. 4b).

Meshes of individual layers were additionally vertically fitted using the reinterpreted borehole data (FPP). The resulting model is a three dimensional trimesh layer model. Subsequently, the stratigraphic boundary surfaces were converted to regular gridded surfaces with a cell size of 500 × 500 m in order to have the possibility of using it with other software later (e.g. with FeFlow, ArcMap).

Extent and boundaries of the model

The 3D model covers NE Slovenia, with smaller parts entering Austria, Hungary and Croatia (Fig. 3). Geographically, the model is referenced in UTM 33 N projection using WGS84 datum. It extends 121 km in the E – W direction and 91 km in the N – S direction, over a total area of 5404 km^2. To the NW, the model is bounded by the state border between Slovenia and Austria, while it extends to the NE along the border of the TRANSENERGY pilot area (Fuks & Janža, 2013). Its eastern and southern boundaries are controlled by the extent of the model from Rman (2013), which was constrained by the data available and the trace of the Ljutomer Fault. The western model boundary follows the groundwater bodies that close the Mura-Zala Basin.

Vertically, the model stretches from the Earth's surface down to the base of Neogene rocks. Enhanced digital surface data from the Shuttle Radar Topography Mission (CIAT, 2004) was used for the Earth surface. The base of Neogene rocks forms a basement surface of the Basin, whose geometry was adopted from earlier works (Fodor et al., 2011; Maros et al., 2012). Maximum elevation in the model is approximately 1500 m a.s.l. and the minimum approximately 6600 m b.s.l., being modelled north of Lendava.

Datasets and delineated units

Key stratigraphic units of the Mura-Zala Basin were reinterpreted using earlier geological models, existing mainly in 2D format: i) the pre-Neogene basement depth map (Lapanje et al., 2007), ii) the 1:100,000 Basic Geological Map of Yugoslavia and Slovenia, iii) the 1:100,000 Surface litostratigraphic and tectonic structural map of the T-JAM project area in northeastern Slovenia (Jelen & Rifelj, 2011), iv) the geological model of the T-JAM project (Fodor et al., 2011), v) the geological model of the TRANSENERGY project (Maros et al., 2012), and vi) the geological model of the PhD thesis of Rman (2013). A comparison of the defined formations is given in Table 1.

This new geological model of the Mura-Zala Basin comprises eight lithostratigraphical units, from pre-Quaternary deposits to the Haloze Fm. (Table 2).

Well logs from 145 boreholes (see locations in Fig. 3) were reinterpreted using lithological descriptions of cores and drilling chips, and available paleontological data to distinguish between sedimentary paleo-environments within the same formations that were not effectively separated in previous models. Since each formation was deposited in a distinct sedimentary paleo-environment, various sedimentological and hydrogeological characteristics can be used for classification instead of the very similar lithology of alternating mud (silt – clay), silt, and sand (Table 2). As clastic sediments prevail, spontaneous potential, resistivity and natural gamma-ray logs were used owing to their strong dependence on grain-size variation. Finally, as the architecture of the Quaternary sediments is currently under interpretation, they were not included in this geological model.

Due to time constrains the subdivision of the Špilje Fm. into Badenian and Sarmatian was performed on only 20 borehole logs used to create the six interpretative cross-sections. The division is based on the occurrence of Lithotamnian limestone.

The number of boreholes that reached different formation does not decrease with depth, from Ptuj-Grad Fm. to pre-Neogene basement rocks. This is because that not all formations occur over the entire study area, and therefore some boreholes in the western part of the model penetrate, for example, only the outcropping Špilje Fm., while others that should stratigraphically lie above it are not developed.

Table 1. Comparison of formation definitions with previous projects.

<table>
<tr><th rowspan="2">Formation</th><th rowspan="2">Subdivision</th><th rowspan="2">TRANS-THERMAL (Lapanje et al., 2007)</th><th rowspan="2">T-JAM (Fodor et al., 2011)</th><th colspan="2">TRANSENERGY</th><th rowspan="2">Rman (2013)</th></tr>
<tr><th>supraregional (Maros et al., 2012)</th><th>pilot area (Maros et al., 2012, Fuks et al. 2013)</th></tr>
<tr><td>Ptuj-Grad Fm.</td><td>/</td><td>yes</td><td>yes</td><td rowspan="3">not subdivided</td><td>yes</td><td>yes</td></tr>
<tr><td rowspan="2">Mura Fm.</td><td>delta plain facies</td><td rowspan="2">not subdivided</td><td>yes</td><td>yes</td><td>yes</td></tr>
<tr><td>delta front facies</td><td>yes</td><td>yes</td><td>yes</td></tr>
<tr><td rowspan="2">Lendava Fm.</td><td>slope facies</td><td rowspan="2">not subdivided</td><td>yes</td><td>yes</td><td>yes</td><td rowspan="5">not subdivided</td></tr>
<tr><td>turbidites</td><td>yes</td><td>yes</td><td>yes</td></tr>
<tr><td rowspan="2">Špilje Fm.</td><td>Sarmatian age</td><td rowspan="3">not subdivided</td><td rowspan="2">not subdivided</td><td>yes</td><td>yes</td></tr>
<tr><td>Badenian age</td><td>yes</td><td>yes</td></tr>
<tr><td>Haloze Fm.</td><td>/</td><td>yes</td><td>yes</td><td>yes</td></tr>
<tr><td>pre-Neogene rocks</td><td>/</td><td>yes</td><td>yes</td><td>yes</td><td>yes</td><td>yes</td></tr>
</table>

Table 2. Characteristics of separated formations in the 3D regional geological model as summarised from Maros et al. (2012). Note that Quaternary deposits were not distinguished.

Formation	**Lithological description (after Jelen & Rifelj, 2011)**	**Distinguishing criteria of borehole logs**	**Average sand content**	**Sedimentary environment**	**Time period**	**Porosity**
Ptuj-Grad Fm.	alternation of gravel, sandy, silty and clayey gravel, sand, gravely and silty sand, silt, sandy and silty clay, basaltic tuff, tuffite and basalt, isolated coal occurrences	specific lithology and paleontological determination, superposition	15%	alluvial plain	Latest Pannonian to Pliocene	10%
Mura Fm.	alternation of silty clay, clay, silt, gravely, sandy and clayey silt, sand, silty and gravely sand, sandy gravel and coal	specific lithology and paleontological determination, alternation of fining- and coarsening- upward sand bodies from geophysical borehole logs, coal occurrences	50%	delta plain	earliest Pannonian to Late Pontian	10%
	alternation of sand/ sandstone, silt, marl, clayey marl, clay, marly, sandy and silty clay, coal	specific lithology and paleontological determination, thick, coarsening-upward sand bodies from geophysical borehole logs, coal occurrences	70%	delta front		12-14%
Lendava Fm.	sandy silt, marly clay, occasional sand bodies	superposition and the presence of approx. 200 m thick uniform silt horizon without distinct stratification	5%	slope	Early Pontian	5%
	alternation of sand/ sandstone, silt, sandy, silty and clayey marl, clay	specific lithology and paleontological determination, sand bodies with occasional gravel, predominately non-graded from geophysical borehole logs	30% (turbidites 50%, silt 5%)	deep lacustrine turbiditic	Late Pannonian	7% (turbidites 10%, silt 5%)
Špilje Fm.	alternation of sand, sandstone, sandy and silty marlstone, silt, siltstone, marly and silty clay, conglomerate, locally sandy algal and oolitic limestone, dolomite, coal	specific lithology and paleontological determination	50%	Sarmatian shallow (and deep) marine, fluvial, terrestrial	Mid Badenian to Early Pannonian	7%
	alternation of silty and clayey marl, sandstone, locally algal limestone, conglomerate, dolomite, coal	specific lithology and paleontological determination	30%, shallow areas more permeable	Badenian shallow (and deep) marine	Early Badenian to Sarmatian	5%
Haloze Fm.	alternation of sandy and silty marl, sandstone, conglomerate, muddy breccia, oyster banks, tuff	specific lithology and paleontological determination	30%	shallow (and deep) marine, terrestrial	Karpatian to Early Badenian	5%
pre-Neogene rocks	Metamorphic and carbonate rocks, marl, sand/sandstone, conglomerate	/	/	metamorphic, marine, brackish, lacustrine	Paleozoic to Oligocene	/

As many as 453 formation penetration points were available from the 145 reinterpreted borehole logs (Table 3). Despite the fact that only 59 boreholes penetrated to the pre-Neogene basement rock, the total length of penetrated layers amounts to 156,436 m.

Lack of seismic sections and other data on the structural inventory of the area meant that the fault network could not be considered in this model. Publications imply that displacements along the faults affect mostly older Miocene sedimentary rocks and are estimated to measure a few tens of metres vertically, which is generally much less than laterally (Žlebnik, 1978; Gosar, 1995). The Ljutomer Fault (Fig. 1) is one of the most important faults in the investigated area. It is a large active strike-slip fault in a transpressive regime with a complex multiphase history (Mioč & Marković, 1998; Placer, 1999; Márton et al., 2002; Fodor et al., 2005; Placer, 2008). The Ptuj – Ljutomer – Budafa half-graben along it formed the Haloze – Ljutomer – Budafa Sub-basin by the Late Pontian. The Ptuj and Ljutomer parts remained a sub-basin and were renamed the Ptuj – Ljutomer Sub-basin, while the Haloze and Budafa parts were positively inverted to the Boč – Ormož – Selnica – Lovászi – Budafa antiform approximately in the Pliocene. The antiform consists of several anti- and synclines and was pushed on the Ptuj – Ljutomer Sub-basin (Sachsenhofer et al., 2001; Fodor et al., 2002; Jelen & Rifelj, 2006). The low-permeability layers of the Haloze, Špilje and Lendava Fms. were tilted into a subvertical position along the western part of the fault near Ptuj, therefore they form a lithological boundary which significantly restricts groundwater flow from south to north (Žlebnik, 1975, 1978; Jelen & Rifelj, 2006; Klasinc, 2013). This supports our decision to set the south boundary of the 3D model along the Ljutomer Fault trace. To the south-east of the model, we also included some area south of this fault, as the Neogene layers plunging eastward show some folding, but are not expected to form a hydraulic barrier for groundwater flow in the Mura and younger Fms.

Results and Discussion

Lithostratigraphical horizons

The pre-Neogene basement map and the Earth surface topography were used as input boundary constraints in the model. Between those two boundaries, eight Neogene lithostratigraphical boundaries were modelled. Thicknesses of formations is highly variable in space and can locally be far greater than the average thickness, depending largely on the sedimentary and paleogeographical environment, as explained in Geological Settings.

The average thickness of modelled formations is 381 m, varying from 201 m for the Lendava Fm. - slope to 638 m for the Mura Fm. – delta plain (Table 3). The Lendava Fm. slope sediments do not exceed 650 m; while maximum thickness of the Ptuj-Grad Fm., the Mura Fm. – delta front, and the Lendava Fm. – turbidites vary from 952 to 1161 m (Table 3). Areas of maximum formation thickness do not coincide in space. For example, the Ptuj – Grad Fm. reaches its maximum thickness at the southern boundary of the model (in the Ptuj – Ljutomer Sub-basin) along the Ljutomer Fault (Fig. 5), whereas the Mura Fm. – delta front sediments are thickest in the SE part of the model near the SLO-HU border (Fig. 6).

The Mura Fm. – delta plain, the Špilje and the Haloze Fms. reach maximum thickness at 1533 to 2005 m (Table 3), but since they largely consist of low-permeability sediments this does not, unfortunately result in favourable geopotentials.

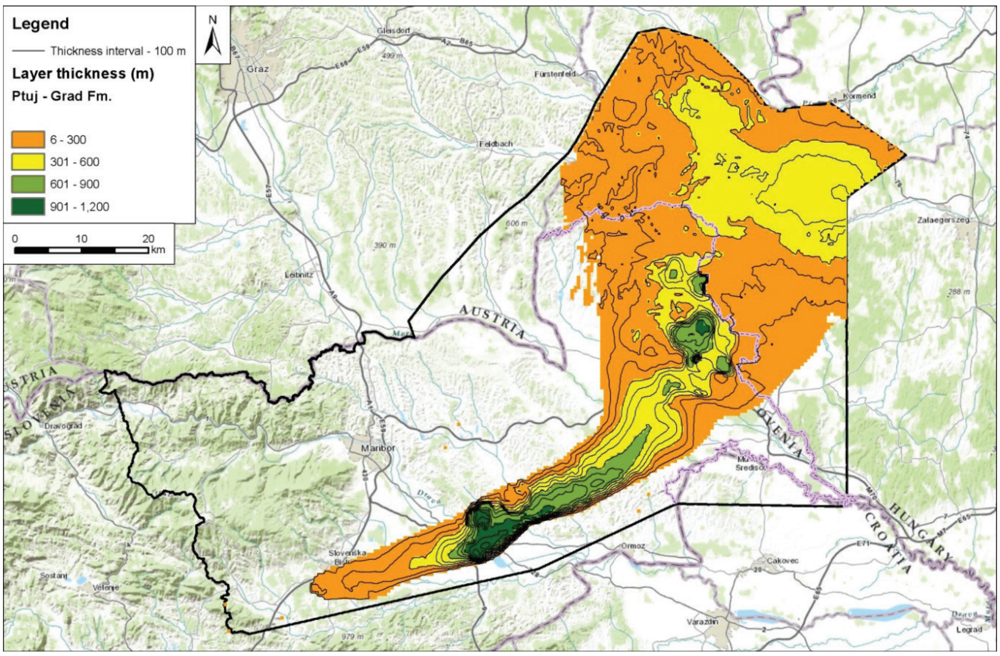

Fig. 5. Thickness of the modelled Ptuj-Grad Fm. alluvial sediments, which represent a moderately productive intergranular aquifer with fresh and lukewarm water.

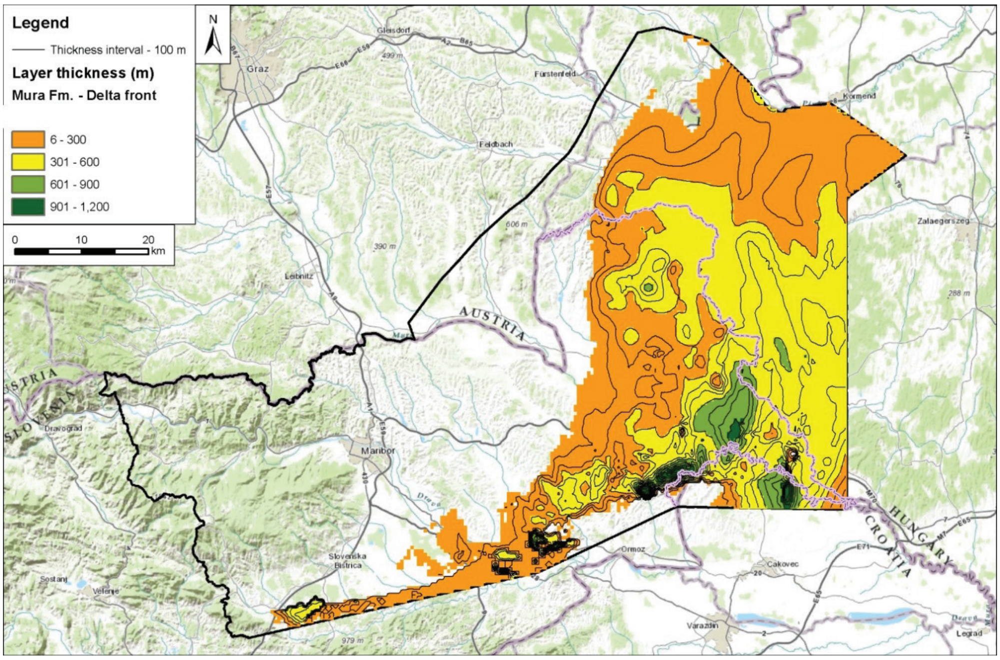

Fig. 6. Thickness of the modelled Mura Fm. – delta front sediments, which represent a highly productive intergranular geothermal aquifer.

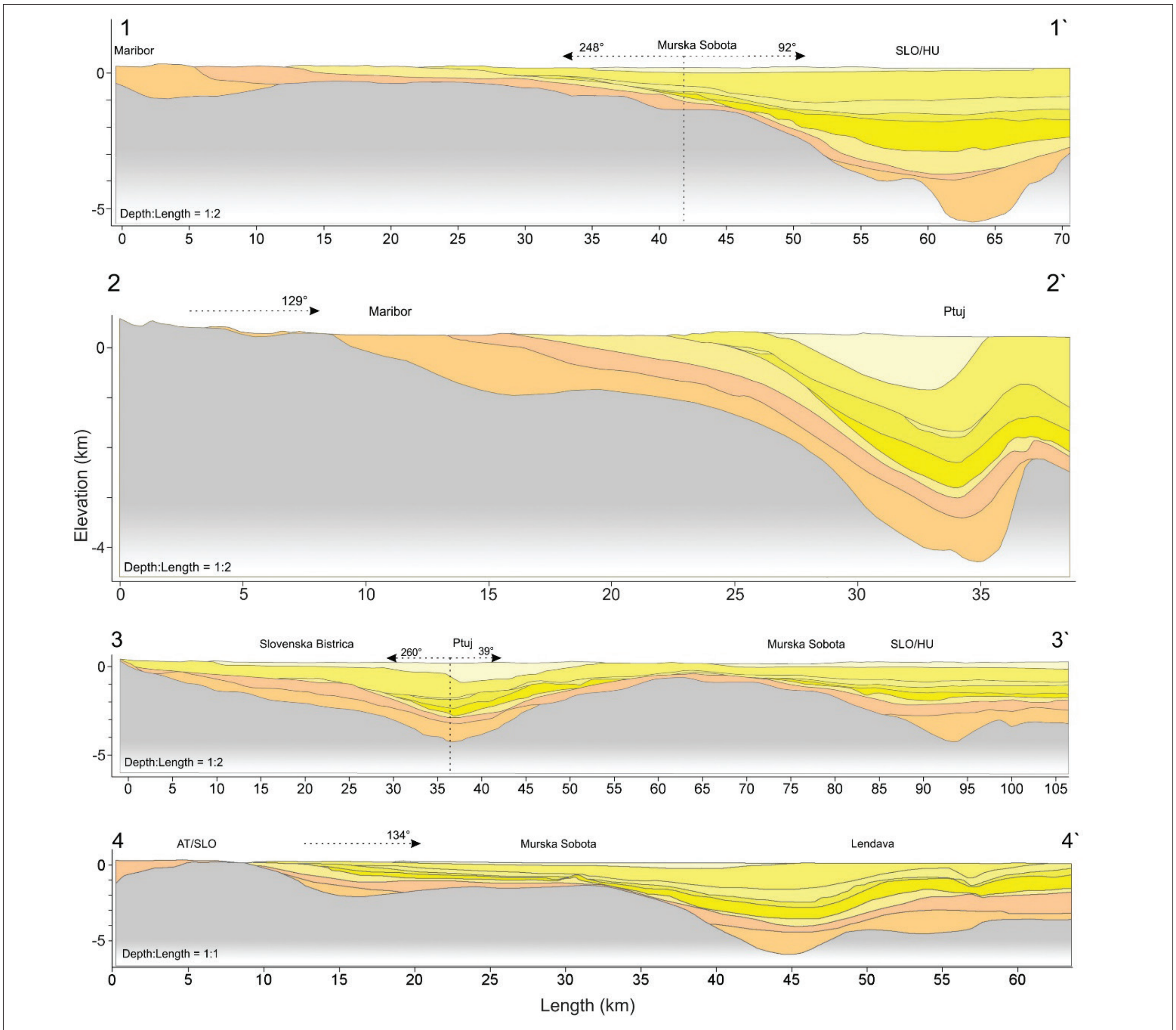

Fig. 7. Four sample cross-sections through the 3D regional geological model of the Mura-Zala Basin. For their position see Fig. 3, for a legend of geological units see Fig. 8. Note that the vertical scale in sections 1-1’, 2-2’ and 3-3’ is 2 x vertically exaggerated. Arrows indicate the azimuth angle of the respective section.

2D visualization of the model

Four arbitrary cross-sections in various directions were made across the resulting regional geological model (Fig. 7). In order to gain a better spatial perspective of the entire modelled area, the model is also displayed in the form of a fence diagram (Fig. 8). While this visualization is useful in recognition and differentiation of spatial relationships in the model, it is still unsuitable for further application. Therefore, the 3D regional geological model was transferred to newly developed open-access GST 3D Explorer platform, as described in the following section.

3D visualization of the model

Transnational data exchange is very difficult in practice because it is complicated and constrained by diverse data policies, database systems and software solutions. In order to overcome this issue, the regional-scale 3D geological model of the Mura-Zala Basin has been converted for use in the 3D browser-analysis tool for visualisation and query, called the 3D-Explorer. This free online tool is based on a software development technology called GST (**G**eo Sciences in **S**pace and **T**ime) and is available through the web portal http://www.geomol.eu/3dexplorer. The aim of the project is to distribute open-source multi-dimensional geo-information from different sources as a joint and harmonised picture merged from different national repositories (The GeoMol Team, 2015). This tool interconnects the geological models that are maintained and continuously updated by the Geological Surveys with interested stakeholders, who are free to explore and query the subsurface at arbitrary depths and locations. Further technical details and instructions for use are described in the GeoMol project final report (The GeoMol Team, 2015, pages 158-165 and references therein).

The 3D-Explorer requires web a browser such as Firefox, Chrome, Opera or Safari. A public login without any username or password provides open access to the available 3D models. The input data can be dynamically visualised either as a set of stratigraphical surfaces (formation base and top horizons), point data, or volumes. A preferred spatial reference system with arbitrary coordinate transformation can be chosen. Topographic maps can be added to the visualization to facilitate orientation in space in addition to current coordinates, which are displayed at the cursor position. Exaggeration of the z-scale can be set to improve one's insight into the geometry of the 3D model (Fig. 9a). The slice-through feature enables fast creation of model cut-outs as a series of arbitrary vertical cross-sections and horizontal slices (Fig. 9b). Finally, a virtual borehole feature can generate information on depths of modelled units below any arbitrary point on the surface. All these visualizations can be exported for further use.

Quality of the model and open issues for further work

The 3D geological model is in a continuous stage of development. It was built according to a methodology that allows updating and improvements each time new data is available. The model was built with available data, hence its quality could not be verified by information from new/unused boreholes or cross-sections at this stage. Therefore, we challenge all interested parties to test and evaluate it with their own data, and provide us with feedback on possible improvements.

It became apparent that comparing the average and maximum thicknesses between borehole

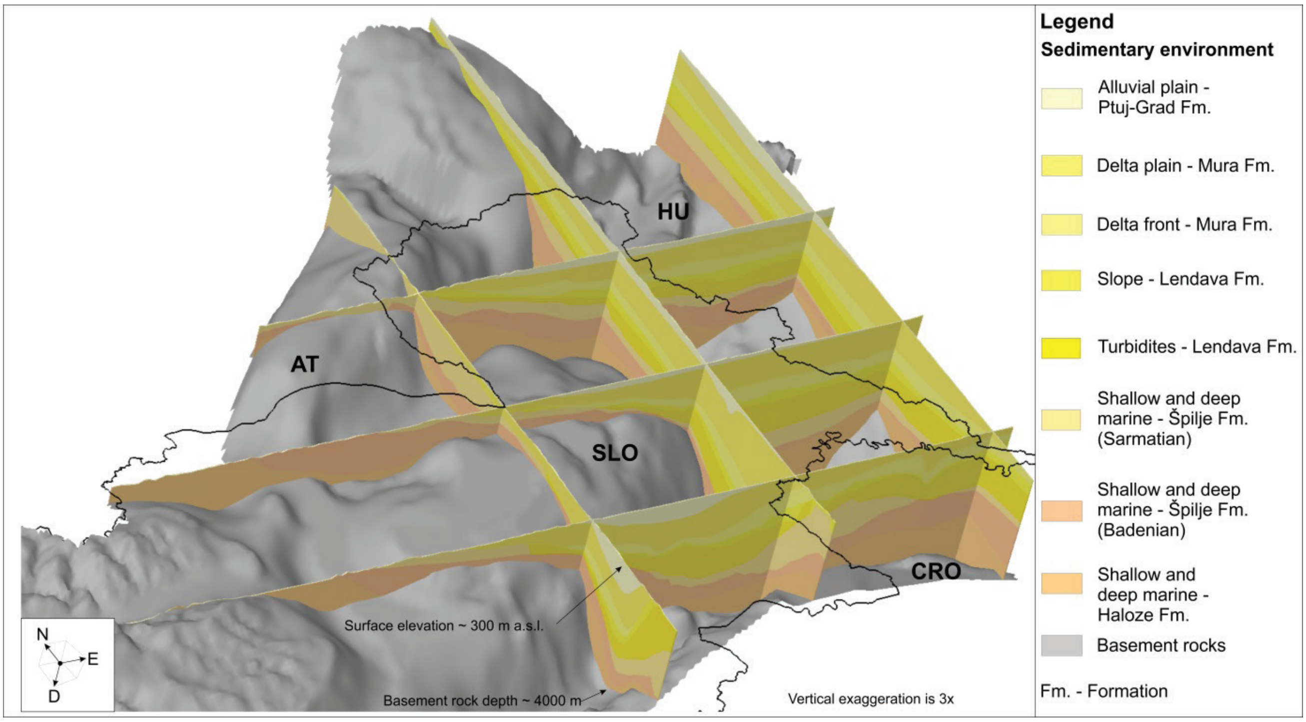

Fig. 8. Perpendicular fence diagram of the Mura-Zala Basin fill superimposed on the pre-Neogene basement. View from SW.

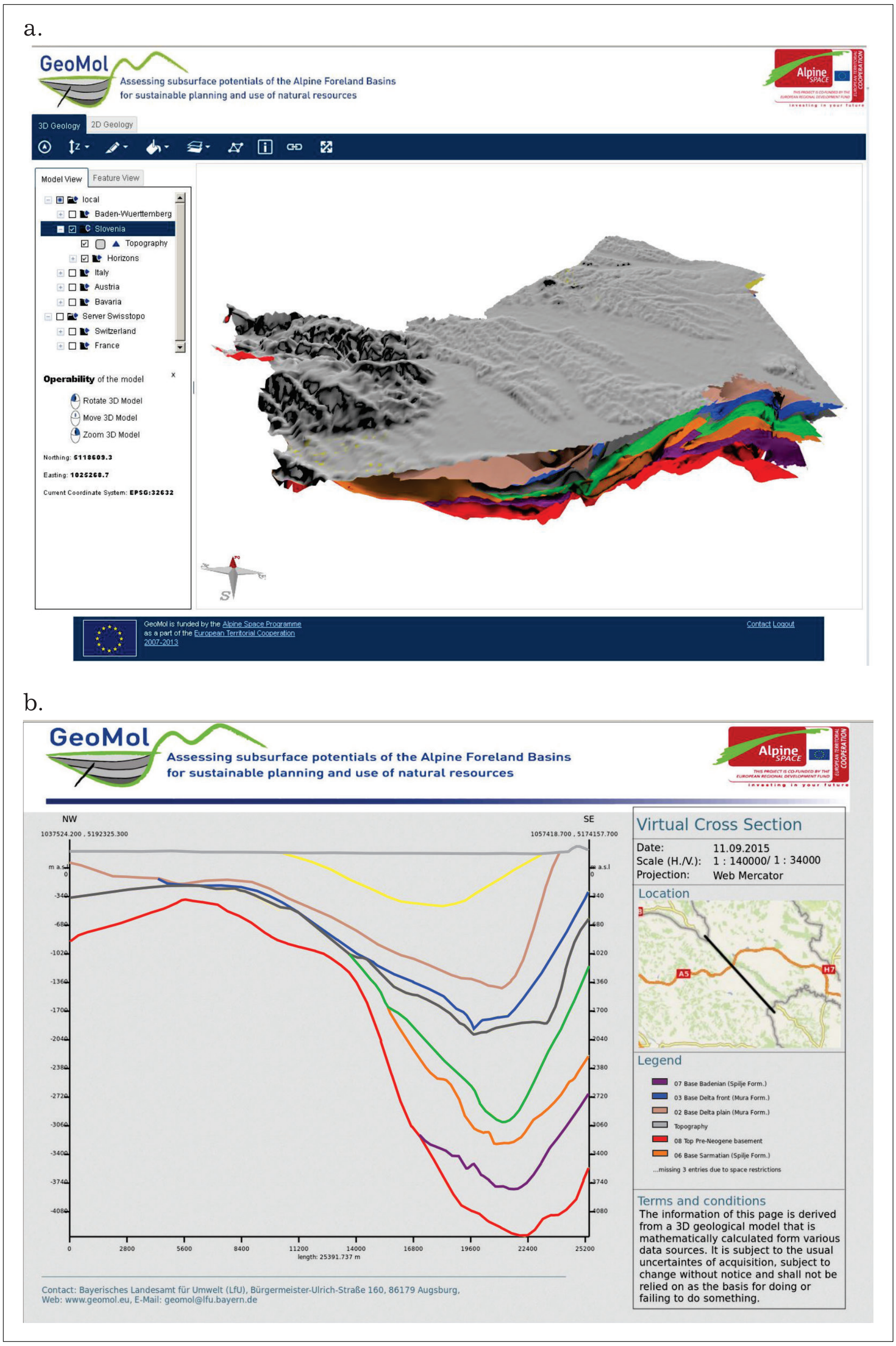

Fig. 9. Example of visualisation of the 3D geological model in the 3D-Explorer (a.) and arbitrary cross-section (b.).

logs and the model is not a straight forward process. The boreholes were available only for the Slovenian part of the model, but the model also includes parts of Austria, Hungary and Croatia (Fig. 3), which caused noticeable discrepancies between compared values. Across the state border the model was constructed based on data from previous models (see Methodology), and therefore exhibits a higher level of uncertainty compared to the central part of the model. Another issue arise in the Croatian territory, where the model was built based only on data from the surface geological maps (Mioč & Marković, 1998; Jelen & Rifelj, 2011).

We verified the Slovenian part of the model by comparing the modelled average and maximum formation thickness to data from borehole logs (Table 3). Discrepancies of maximum formation thickness range from 107 % to 232 %, for Lendava Fm. – turbidites and Haloze Fm., respectively. Surpluses of the rest, except for the Špilje Fm., are attributed to the fact that the boreholes do not penetrate the synclinal axis of the Ptuj-Grad Fm. in the Ptuj – Ljutomer Sub-basin (Figs. 1, 3, 5). The largest discrepancy occurs for the Haloze Fm., penetrated only by 25 boreholes. The surplus occurs in areas where no boreholes reach the Haloze Fm.

Table 3. Comparison of average and maximum formation thicknesses evaluated from borehole log information and the model, and the number of boreholes penetrating each formation.

Formation	**Subdivision**	**No. of boreholes penetrating the formation**	**Borehole log**		**Model**		**Difference (%) (model/borehole log)**	
			average	**max**	**average**	**max**	**average**	**max**
Ptuj – Grad Fm.	/	45	367	939	312	1161	85	124
Mura Fm.	delta plain	59	552	1240	638	2005	116	162
	delta front	68	262	541	273	952	104	176
Lendava Fm.	slope	65	155	482	201	650	130	135
	turbidites	55	412	1077	408	1150	99	107
Špilje Fm.	Sarmatian	77	485	1978	299	1820	/	/
	Badenian				517	1533		
Haloze Fm.	/	25	368	733	404	1700	110	232
pre-Neogene basement rocks	/	59	/	/	/	/	/	/

Comparison of average formation thicknesses ranges from 85 % to 130 % (Table 3). The largest discrepancy is observed for the Ptuj-Grad Fm. and Lendava Fm. – slope. We assume that the thicker Lendava Fm. - slope layer probably reduced the thickness of Ptuj-Grad Fm.

The major drawback with our model is that it currently does not include faults. Since many structural traps are fault-controlled, the absence of faults is a major shortcoming, for the assessment of oil and gas reservoirs or storage sites among others. Unfortunately, the Ljutomer Fault could not be introduced into the model: due to significantly different degrees of deformation along the fault (Fodor et al., 2002, Fig. 12), lack of quality seismic reflection data and other information along the fault, especially for the area south of the fault, made it impossible to interpret the geometry and offset of its stratigraphic horizons with a reasonable degree of accuracy. Therefore, the southern boundary of the model was assigned to follow its trace. However, in areas where density of borehole data is high enough, like in Lendava and the surroundings, our model reveals flexures and stair-like structures in the modelled stratigraphic surfaces that we interpret as resulting from offsets along the fault planes.

The quality of the modelled 3D lithostratigraphical boundaries can be assessed as very good along the six input cross-sections, in areas with high borehole density and in the vicinity of boreholes with information on formation penetration points. The model properly describes the regional geometry in the selected scale due to a reliable conceptual model, which is constructed based on previous studies of this area (see Methodology).

Several issues still remain: well-permeable shallow marine coarse-grained clastic rocks and limestone of the Špilje Fm., which may form important hydrocarbon or hydrogeothermal reservoirs, could not be better distinguished in the model due to a lack of seismic reflection data. The boundary between the Badenian and Sarmatian part of the Špilje Fm. is poorly constrained, with delineation based only on paleontological data and six interpretative cross-sections. The slope facies of the Lendava Fm. is very heterogeneous, which sometimes made it difficult to interpret its regional extent and separate it into two units – the turbidites and the slope. Moreover, where turbidites of the Lendava and Špilje Fms. are in direct contact – which is the case in deeper parts of the basin – they are difficult to differentiate. Consequently, the boundary between these formations is sometimes unreliable.

The Quaternary sediments were not modelled as a separate formation owing to two issues: their irrelevance for the evaluation of deep geopotentials, and because lithostratigraphical reinterpretation is still in process. Therefore, the current model needs to be combined with the latest open-access surface geological map of Jelen & Rifelj (2011) in order to identify areas where Quaternary sediments overlie the Neogene units. The cross-sections and virtual boreholes derived from the model must be treated with discretion in such areas.

Usability of the model

The presented 3D regional geological model is intended for use as a general overview of the geological setting of NE Slovenia. The key formations that hold out at least some perspective for various geopotentials are delineated in the entire area of the Slovenian part of the Mura-Zala Basin based on the overall average rock composition at a regional scale. Consequently, the model should not be used for detailed local studies. Potential users of the model are notified about this in a disclaimer that appears when accessing the 3D-Explorer. Generally, the level of detail of the provided information is not suitable for any visualisation or query at a scale more detailed than 1 : 80,000.

The model is very useful for creating virtual boreholes and cross-sections at an arbitrary position in space, which enables quick preliminary testing whether a specific site of interest may have any geopotentials. Realistic assessments of investor expectations can be made quickly, e.g. whether they might find thermal water or not, and at what depth the aquifer is expected to occur. This should indirectly result in reduced geological risk, more feasible approaches to exploration, and lower financial investments. Similarly, this 3D model may serve as a source of input data for regional hydrogeological, geothermal, hydrogeochemical, etc. numerical models that enable the appraisal of volumes and capacities of reservoirs, simulation of regional groundwater flow, heat and mass flow, and similar.

The presented model currently exhibits a 3D layer shape. In the future, should be upgraded to a 3D solid model with assigned properties, such as porosity and hydraulic conductivity. That way the model will be far more usable and efficient, and speed up the evaluation of various geopotentials.

Conclusions

The presented 3D framework regional geological model of the Slovenian part of the Mura-Zala Basin represents a starting point for future developers, users and managers of our subsurface. This is the first 3D geological model in Slovenia that is published according to the principles of open-access, and incorporates the latest lithostratigraphical information about the area. In the long-term, the model will enable better assessment of geopotentials since better forecasting of subsurface geological structure facilitates faster and easier delineation of favourable areas for the exploitation of various commodities, like groundwater and raw materials, or for locating waste disposal sites. Therefore, focused and harmonized management can be achieved when various authorities begin to use the model to visualise 3D spatial distribution of the main lithostratigraphic units that hold various geopotentials.

Obtaining and interpreting the archived seismic reflection data is a key to any significant future improvement of the model. The incorporation of such will enable the inclusion of faults and individual high-permeability horizons, which will greatly improve the model's reliability. Another issue arises from the transboundary character of the Mura-Zala Basin (Nádor et al., 2012). The delineated units have been harmonised as much as possible with the Austrian and Hungarian geologists, but a sizeable gap in information appears along the border with Croatia. Continuation of geological structures and geopotentials to Croatia is undisputable (for example see Borović et al., in print), which is why new transboundary projects are desperately needed to harmonize the data at the triple-state junction of Slovenia, Croatia and Hungary.

We would like to invite all interested parties to test the model, available at http://www.geomol.eu/3dexplorer/, to evaluate it with their own data, and provide us with feedback on possible improvements.

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