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Geoenergy potential of the Croatian part of Pannonian Basin: insights from the reconstruction of the pre-Neogene basement unconformity

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ABSTRACT

Presented work focuses on the importance of unconformity that separates the Neogene infill from older Palaeozoic and Mesozoic rocks in the Croatian part of Pannonian Basin. Structure map of this horizon nearly represents the thickness map of the Neogene and Quaternary basin fill. Rock formations just below the unconformity are significantly weathered, which results in favourable petrophysical properties, making them interesting from the aspect of geoenergy potential. The pre-Neogene surface was constructed in 1:400,000 scale using publicly available subsurface maps of different scale and different level of detail. Harmonization and compilation of these maps enabled construction of a structured surface with near-vertical fault planes. Supplemental maps were constructed via basin modelling, showing the temperature distribution in the subsurface, potential source rock maturity near the mapped horizon, surface heat flow and geothermal gradient distribution. Constructed maps illustrate the importance of the mapped interval for regional planning of future geoenergy-related research..

1. Introduction

Geoenergy today is not anymore related to fossil fuels and exploration for oil and gas. It is more and more oriented to using the developed methods for investigating the deep subsurface rock formations in order to map other resources – deep geothermal, shallow geothermal, CO_2 geological storage and energy storage. Some of these resources, like geothermal, have already emerged and are being hastily developed, while others, CO_2 geological storage and energy storage are still investigated throughout the World, and not only in the economically developed countries. When evaluating the geoenergy potential of a certain area, it is of utmost importance to understand its subsurface geology and thicknesses of the most important prospective formations. This kind of insight can only be obtained by a construction of a geological model from a set of maps that define the subsurface volume.

Study area covers the Croatian part of the Pannonian Basin (CPB, Main Map) which spreads over the entire northern part of Croatia. Commonly, publicly available subsurface maps of the study area are made either in a large scale, showing only a small portion of the area, naturally in greater detail (e. g. Baketarić & Cvetković, 2015; Novak Zelenika, Cvetković, Malvić, Velić, & Sremac, 2013; Špelić, Malvić, Saraf, & Zalović, 2016) or cover the whole study area but lack in detail, illustrating only the major features (e.g. Saftić, Velić, Sztanó, Juhász, & Ivković, 2003; Velić, Weisser, Saftić, Vrbanac, & Ivković, 2002). To create a regional scale map with sufficient detail necessary for evaluation of the subsurface potential, a compilation of both groups of maps is needed.

In this work, the constructed map (Main Map) shows the depth of the pre-Neogene basement, which is overlain by a thick succession of dominantly Neogene sediments (up to 7000 m thick in the Drava Depression; according to Saftić et al., 2003 and Velić, 2007) that are in most parts of the CPB covered with locally thick Quaternary deposits (>400 m thick; Brkić, 2017; Hernitz, Kovačević, Velić, & Urli, 1981; Prelogović & Velić, 1992). Pre-Neogene basement surface represents one of the most important correlation horizons in CPB. In contrast to other horizons within the Neogene sedimentary succession, it can be recognized on most of the well and seismic data as it marks a strong unconformity (Saftić et al., 2003; Velić, 2007).

Since the mapped unconformity surface presents the depth of a base of an interval comprising the Neogene–Quaternary basin infill in which majority of the Croatian hydrocarbon reserves are found, it also represents an isopach map on a regional scale. It marks an interesting horizon underneath which hydrocarbon

accumulations and geothermal reservoirs can occur in the fractured and weathered basement rocks. The sediments of the Neogene age basin fill, situated just above or near the unconformity, can contain source rocks whose maturity level depends on the depth, age and temperature distribution in the subsurface. Several thematic supplemental maps were constructed that are important from the aspect of geoenergy potential. These present the surface heat flow distribution (mW/m^2), averaged geothermal gradient (°C/100 m), temperature distribution along the pre-Neogene unconformity (°C) and maturity of the source rocks near the pre-Neogene unconformity based on vitrinite reflectance values (%Ro). The maps were constructed by means of basin modelling. The Main Map, together with supplemental maps enables the general inferences on geoenergy potential of the study area.

2. Geological setting

Pannonian Basin (PB) is the largest Miocene-Quaternary basin within the Alpine-Carpathian-Dinaridic orogenic system (Figure 1; e.g. Prelogović et al., 1998; Lučić et al., 2001; Saftić et al., 2003). Only a small portion of this large regional tectonostratigraphic domain belongs to Croatia (CPB), more specifically, it's southwestern part (Figure 1 and Main Map). The tectonic evolution of the PB started by the Cretaceous–Paleogene collision of Adria Microplate and European foreland, and eastward lateral extrusion of ALCAPA crustal block and rotation of the TISZA crustal block along the major transcurrent fault zones (e.g. Csontos & Nagymarosy, 1998; Ratschbacher, Frisch, Linzer, & Merle, 1991; Ustaszewski et al., 2008). In the Early to Late Miocene, European plate roll-back subduction induced lithospheric extension and back-arc-type extension in the PB area (e.g. Cloetingh et al., 2006; Schmid et al., 2008 with references). Extension occurred before cca 20 Ma along extensional detachments i.e. NNW-striking listric faults that created deep half-grabens i.e. depressions (Fodor, Csontos, Bada, Győrfi, & Benkovics, 1999; Schmid et al., 2008; Tari, Horváth, & Rumpler, 1992). In the Oligocene to Middle Miocene, especially along the southwestern margin of PB, E-W extension conveyed exhumation of Pre-Neogene footwall complexes, i.e. metamorphic rocks overlain by nonmetamorphic Paleozoic and Mesozoic units (Balázs, Granjeon, Matenco, Sztanó, & Cloetingh, 2017; Ustaszewski et al., 2010). In the southwestern part of PB, i.e. CPB, extension reached the peak of its development during the Badenian, (Pavelić, 2001). This extension is characterized with sin-rift deposition along the NW-striking normal faults, i.e. 'marginal faults' or 'depression faults' (e.g. Pavelić, 2001; Tomljenović & Csontos, 2001) that locally probably reactivated older pre-Neogene thrust contacts (Balázs et al., 2017; Tari et al., 1992). End of

the sin-rift phase, characterized by shortening and uplift in Sarmatian, commenced along inherited normal faults that were reversely reactivated, whereas strike-slip faults maintained transpressional movements. As a result of tectonic activity, Sarmatian deposits in the basement hanging wall were both overthrusted or intensively eroded (Horváth, 1995; Horváth & Tari, 1999; Pavelić, 2001; Tomljenović & Csontos, 2001 with references). The Pannonian post-rift tectonic phase is characterized by deepening of the PB and its rapid thermal subsidence due to lithospheric cooling (Horváth et al., 2006). The Pliocene and Quaternary tectonic evolution of the CPB is characterized by the gradual replacement of post-rift thermal subsidence processes with a basin-scale contraction, tectonic reactivation and intensive inversion (Matoš, 2014; Tomljenović & Csontos, 2001 with references, Pavelić, 2001 with references).

In the CPB, the pre-Neogene basement rocks incorporate carbonate, igneous and metamorphic rock units of Mesozoic and Palaeozoic age that are occasionally overprinted by Early Cretaceous metamorphism (Matoš, 2014 with references). These rocks are found on the surface, on inselbergs in the western and central part of continental Croatia (Figure 1), but also in nearby mountains in northern Bosnia, north-western Serbia and southern Hungary (Pamić, 1998).

Sedimentary rocks of Palaeozoic and Mesozoic age are characterized by numerous lithotypes, which are associated with changes in paleogeographical environments from Devonian to Cretaceous time (Jamičić, Vragović, & Matičec, 1989). Palaeozoic and Mesozoic sedimentary successions are proven hydrocarbon reservoirs within a predominantly Neogene petroleum system in the southern part of PB. Triassic dolomites are known reservoirs in the Mura Depression, whereas mixed Palaeozoic–Mesozoic tectonized carbonates and breccia–conglomerates are the most important reservoirs in the western part of Drava Depression (Tadej, 2011; Velić, 2007). Mesozoic dolomite massif is the principal source of clastic material in certain reservoirs in the eastern part of Drava Depression, whereas Palaeozoic to Mesozoic sandstones, limestones and schists are known petroleum reservoirs in the Slavonia-Srijem Depression (Tišljar, 1993; Velić, 2007). Also, the reservoir of the Velika Ciglena geothermal field is situated in fractured Triassic carbonates in the area between Sava and Drava Depression.

Neogene sedimentary succession in the PB area commenced with synrift sedimentation in Early Miocene (Royden, 1988) and continued through the entire Miocene and Pliocene within different paleogeographic environments of Central Paratethys and its remnants (Lučić et al., 2001; Pavelić & Kovačić, 2018; Royden & Horvath, 1988; Saftić et al., 2003). The onset of marine sedimentation related to PB embayment and extension of the pre-Neogene basement was not
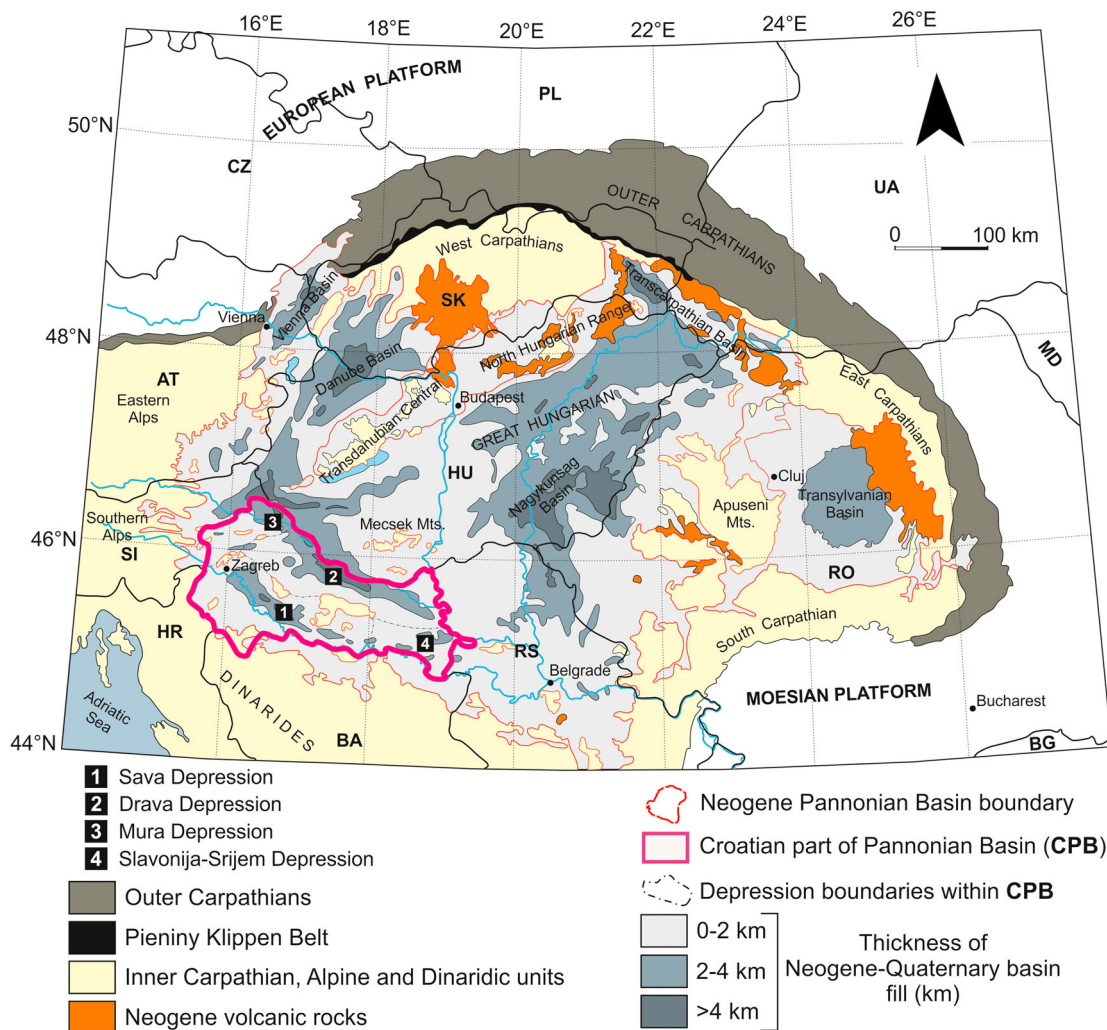
Figure 1. Map of principal tectonic and geographic units of the Alps, Carpathians, Dinarides, and the PB with its subbasins and depocentres (after Dolton, 2006 with references; Schmid et al., 2008). The Neogene Pannonian basin boundary is shown in red line, while CPB is shown with a polygon.

simultaneous within CPB (Lučić et al., 2001; Saftić et al., 2003). The Middle Badenian marine transgression encompassed the majority of Depressions in CPB, except the Mura Depression and Zagorje Basin, where marine environments existed even prior to Badenian, presumably in Eggenburgian (Lučić et al., 2001). Badenian sediments show a high variation in lithological composition from lagoon marls (Zečević, Velić, Sremac, Troskot-Čorbić, & Garašić, 2010), variety of limestones deposited in various depths and facies (Kováč et al., 2007; Pavelić, 2001), to clastic lithofacies originating from erosion of uplifted crystalline basement (Pavelić, 2001). Sarmatian sediments dominated by marls were deposited in shallower 'caspi-brackish' depositional environment that eventually turned into a lake environment (Rögl, 1996; 1998; Vrbanac, 1996; Zečević et al., 2010). Sedimentation in Pannonian continued in a large lake environment with the continuous decrease of salinity to the end of Pannonian with dominant lithofacies of sandstone and marls (Pavelić & Kovačić, 2018). In Pliocene lake environments further decreased and evolved into shallow lake/marsh environments with

deposition of clastic succession, i.e. mixture of sands, clay and gravel with occasional coal layers (Cvetković, 2016; Kurečić, 2017; Mandić, Kurečić, Neubauer, & Harzhauser, 2015).

3. Materials and methods

Construction of a structured subsurface map and supplemental maps showing the geoenergy potential requires several steps. These include preparation of input data, simple surface construction, construction of a structured surface and basin modelling. ArcMap 10.1 (input data preparation, legacy data digitalization), Schlumberger Petrel (simple and structured surface construction) and Schlumberger PetroMod (basin modelling) software were used in process of construction of the Main Map and supplemental maps.

3.1. Input data

Within this work, an extensive input dataset was compiled from different sources, then evaluated and in part

interpreted in order to construct the Main Map and the supplemental maps that are related to the characterization of the geoenergy potential.

3.1.1. Input data for the Main Map

Input data for the pre-Neogene basement surface construction can be divided into the dataset for the construction of simple, non-faulted surface and fault geometry information for the construction of a structured surface. Data for simple surface construction was gathered from various published sources, which differ greatly in quality in respect of the input data available in time of construction of these previous maps. Regarding the data quality, four categories can be defined (Figure 2).

First category of the input data relates to the regions where the information about the surface geometry was extracted directly from geological models which were constructed based on the interpretation of the seismic data acquired by recent exploration. These represent the most accurate and reliable data for the construction of a regional surface as the data points are densely spaced and the interpretation is based on the most up-to-date data augmented with some vintage data (interpreted seismic sections acquired from 1960 to 2000). This data were extracted from Matoš (2014), Rukavina (2015) and Rukavina, Matoš, Tomljenović, and Saftić (2016).

Second category input data were obtained from digitized legacy subsurface maps (Hernitz, 1980; Kisovar, 1979; Velić, 1980) showing structured surfaces including fault traces. Part of the maps was digitized in subsequent works (Baketarić, 2015; Jarić, 2016; Podbojec, 2015; Stopar, 2015; Vuić, 2015 and Paškov, 2016) while the remaining were digitized within this work. Areas covered with the second category data are also shown in Figure 2.

Third category data (Figure 2) were derived from interpreted profiles and maps in regional scale (e.g. Saftić et al., 2003; Tomljenović & Csontos, 2001).

Fourth category data are related to surface survey derived data on pre-Neogene surface from geological maps covering the exploration area (Aničić & Juriša, 1984; Basch, 1981; Brkić, Kalović, & Buzaljko, 1989; Galović & Marković, 1979; Jamičić, 1989; Jamičić & Brkić, 1987; Jovanović, 1986; Korolija & Crnko, 1985; Korolija & Jamičić, 1989; Magaš, 1987; Mioč & Marković, 1998; Pikija, 1987; Šikić et al.1977; Šimunić, Pikija, & Hećimović, 1982; Šparica, Juriša, Crnko, & Šimunić, 1979, 1983, 1986) in conjunction with values from digital elevation models (DEM) obtained from open sources (EUDEM, 2013). This type of data was unavoidably incorporated into the construction of the surface to avoid geologically inconsistent relations that can occur because of the nature of the mapping algorithm in the interpolated and extrapolated areas,
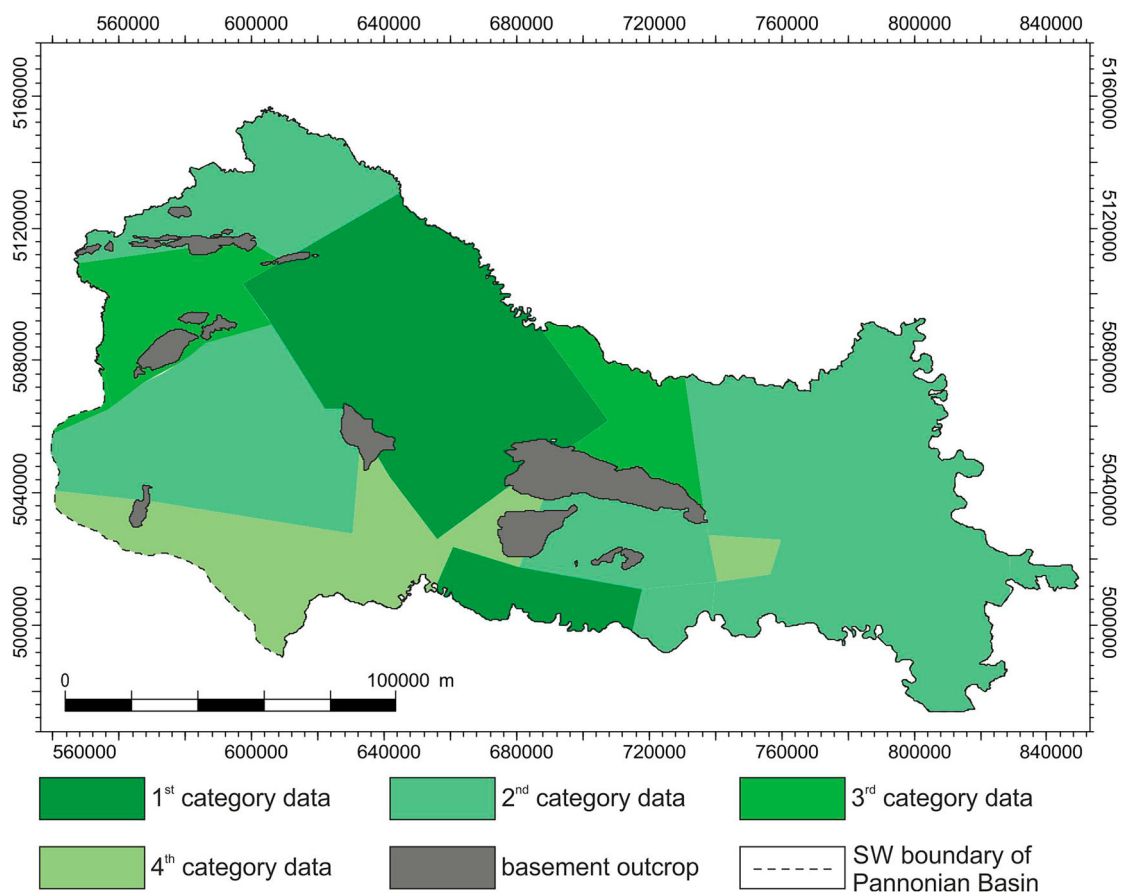

Figure 2. Spatial distribution of the quality of input data for the pre-Neogene surface construction.
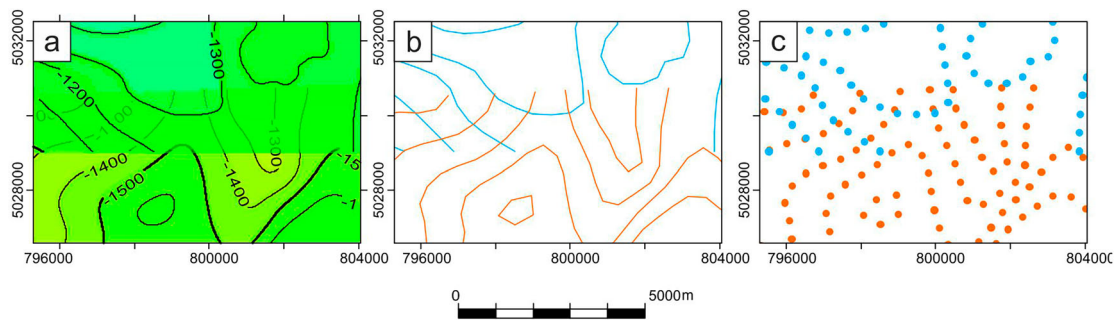
Figure 3. Downscaling of the high-resolution data from initial surfaces (a) to polylines (b) and point data in the end (c).

especially in areas near outcrops of the pre-Neogene basement rocks.

For subsequent structured surface construction, fault geometry information was extracted from all four category data sources. As previously mentioned, sources differ greatly in resolution and quality, thus the extracted fault geometry was reduced to relatively simple polylines representing the intersection of the fault plane with the Pre-Neogene basement surface.

3.1.2. Input data for the supplemental maps

Main objective of the supplemental maps' construction was to enable outlining of the prospective areas along the pre-Neogene basement unconformity that should be further explored for geoenergy potential. For the construction of supplemental data, a basin modelling process has been applied (Hantschel & Kauerauf, 2009), which requires additional input for subsurface characterization. Crucial input data for such a task consist of stratigraphic and lithological properties of the pre-Neogene basement and Neogene–Quaternary infill, thermal settings of the exploration area (heat flow distribution) and calibration data for the basin modelling.

Stratigraphic and lithological outline was obtained from Lučić et al., 2001; Saftić et al., 2003 and Pavelić & Kovačić, 2018, in which the main stratigraphic contacts are defined with their corresponding ages and lithological composition of stratigraphic units. For

estimation of the heat flow, the input data were obtained from works that are of regional coverage (Békési et al., 2017; Lenkey, Dövényi, Horváth, & Cloething, 2002) with local corrections from Cvetković, Emanović, Stopar, and Slavinić (2018) and calibration data from wells acquired from published sources (Energy Institute Hrvoje Požar & Orkustofnun, 2017; Kolenković, 2012; Kurevija & Vulin, 2011; Kurevija, Kljaić, & Vulin, 2010; Kurevija, Vulin, & Macenić, 2014; Macenić & Kurevija, 2018; Novak Zelenika, 2005). Input data regarding paleo-water depth (PWD) values were taken from regional studies (Ćorić et al., 2009; Krijgsman, Stoica, Vasiliev, & Popov, 2010; Lučić et al., 2001; Magyar, Geary, & Müller, 1999; Pavelić, 2001; Pavelić & Kovačić, 2018; Rögl, 1996, 1998). Vitrinite reflectance data for calibration of paleo-heat flow was obtained from Vulama (1994), Troskot-Čorbić, Velić, and Malvić (2009) and Cvetković et al. (2018).

3.2. Workflow

After the preparation of the legacy input data in ArcMap 10.1 software, modelling was performed as a three-step process. The simple surface construction, structured surface construction and preparation of the basin model were performed in Schlumberger Petrel, while basin model simulation and calibration were performed in Schlumberger PetroMod.
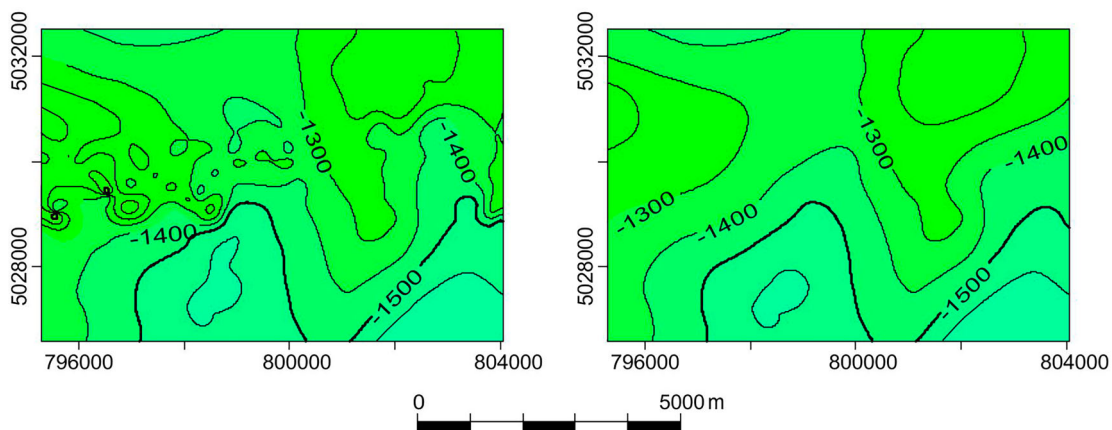

Figure 4. Representation of the overlapping area of different input data for surface construction before (left) and after corrections (right).

3.2.1. Simple surface construction

For the construction of the simple pre-Neogene surface, only the information about the surface geometry was regarded, without the incorporation of the fault trace information. Data were organized separately according to its origin/source and georeferenced to the same coordinate system, which is in this case WGS84 projected in UTM 33N zone. As the data were gathered from different sources, the spatial data overlapping and differences in the quality/resolution of the input data were emphasized. So, the data had to be harmonized. High-resolution data (first and second category data) were downscaled from modelled surface (Figure 3(a)) firstly to polyline data – by extraction of the contour lines with 100 m increment (Figure 3(b)) with node spacing of 500 m along the polyline and subsequently reduced to point data (Figure 3(c)).

In the marginal parts of the areas covered by different data sources, certain differences occurred, resulting from different input datasets used in original interpretations and the fact that marginal parts are usually characterized by the uncertainty of interpretation due to the lower data density. Since surface morphology became erratic when both datasets in the marginal/overlapping parts of two neighbouring data sources were included (Figure 4), one input dataset had to be deleted (Figure 4) to achieve more consistent resulting surface. Relevancy of input data for describing the surface morphology in the overlapping area was defined with respect to the data category, under the presumption that the higher category data provides better quality input.

Area representing outcrops of pre-Neogene basement rocks were subtracted from publicly available DEM models and used as an additional input in the surface generation to avoid surface inconsistencies in the marginal part of the PB or near outcrops of pre-Neogene rocks. Area within the polygons that describe the pre-Neogene outcrops were later removed in the final phase of the map construction as they represent the topographic relief rather than the contact of pre-Neogene basement with younger sediments but were necessary for the map construction.

3.2.2. Structured surface construction

After the completion of the simple surface, the next step included the construction of the fault planes from fault traces in order to generate displacement of the surface along the fault planes. As the presentation of pre-Neogene structured surface was the principal aim of the research and mapping is of regional scale, the fault planes geometry was considerably simplified. This means that the fault planes were modelled as sub-vertical planes from polylines representing the fault intersection with the pre-Neogene surface. Plane geometry was extrapolated vertically so the fault could cover the vertical extent of the modelled surface for computation of the displacement within the structural modelling process. In some instances, the physical aspects of fault intersections/displacements from legacy data could not be honoured due to the subsurface volumes that needed to be displaced. This was only the case in non-model derived data, i.e. 2nd to 4th category data. Once the faults are modelled without volume errors, the simple surface that was constructed in the previous step could now be re-constructed honouring displacements in the near-fault areas, thus resulting in a valid structured surface (Figure 5).

3.2.3. Basin modelling

As geothermal gradient can differ in vertical scale due to the differences in conductivity of the rocks (Eppelbaum, Kutasov, & Pilchin, 2014), simple estimation of temperature at depth using averaged geothermal gradient values can yield significant errors. In order to determine the subsurface temperature values, 3D basin modelling procedure has been used. 3D basin modelling was also necessary to provide the information about the possible maturity, presented as possible vitrinite reflectance (%Ro) values, of the source rocks situated near the pre-Neogene unconformity. For this process, the subsurface rock formations were grouped into four layers representing four distinct stratigraphic and lithological intervals. The first layer represents the pre-Neogene basement rocks constituted of magmatic and metamorphic rocks (dominantly) or Palaeozoic and Mesozoic sedimentary
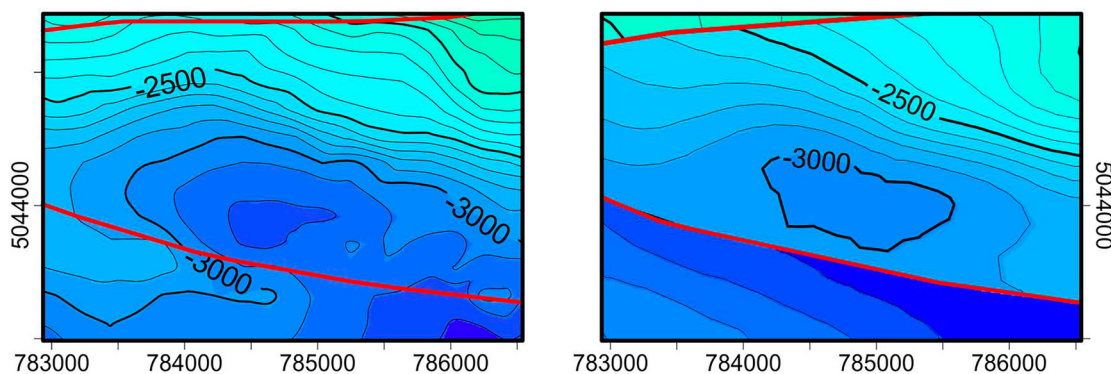

Figure 5. Difference between the simple surface and fault trace polyline (left) and their integration in the structured surface (right).

rocks (subordinate). Neogene infill was subdivided in three layers which represent sediments belonging to Lower/Middle Miocene, Upper Miocene and Pliocene, Pleistocene and Holocene. Thickness of each layer was approximated based on the assumed share of each layer in the thickness of the Neogene–Quaternary sequence. The percentage itself was determined from spatial analysis of thickness distribution of each interval from Saftić et al. (2003). After the input of all parameters, including average lithological composition per layer, heat flow (HF) values, PWD values and sediment-water interference temperature (SWIT, Wygrala, 1989), the model was calibrated based on temperatures obtained from drill-stem-tests (DST), bottom hole static temperatures (BHST) and %Ro values. Three values – the temperature on pre-Neogene surface, vitrinite reflectance and surface heat flow corrected after calibration process were extracted from the basin model, while the geothermal gradient was calculated. All of them are generalized and presented as supplemental maps below the Main Map.

4. Discussion and conclusion

Constructed map shows a structured surface of the pre-Neogene unconformity representing the depth to the base of the interval in which most of northern Croatia's geoenergy potential is located. The Map depicts complex fault systems and associated map-scale structures (i.e. depressions and structural highs) within the CPB that were formed during the Neogene–Quaternary tectonic evolution of the study area. Constructed surface indicates inherited pre-Neogene paleorelief that is the result of Late Cretaceous-Paleogene compressional/transpressional tectonic features (Csontos & Nagymarosy, 1998; Ratschbacher et al., 1991; Ustaszewski et al., 2010 with references). Majority of the NW–SE and NE–SW striking faults mapped both parallel and perpendicular to CPB depressions are normal faults with listric geometries that have accommodated an E–W extension, i.e. opening and deepening of the CPB depressions during Early to Middle Miocene (Matoš, 2014; Tomljenović & Csontos, 2001 with references). In the same time, NW–SE and NE–SW elongated depressions with depth ≥3000 m (e.g. Drava Depression with max. depth of 7000 m; see Main Map) are mainly bordered by pre-Neogene structural highs, i.e. inselbergs (e.g. Mt. Medvednica, Mt. Moslavačka gora, Mt. Kalnik, etc.) and their subsurface prolongations, which affected sedimentation rates and lithofacies distributions within the CPB.

Fault traces represent important features on the surface as they can be fairways for hydrocarbon and hydrothermal fluid migration from deeper formations or can be boundaries of hydrocarbon traps primarily influenced by near-fault petrophysical properties of rocks. Additionally, they can also be very valuable in determining the possibility of CO_2 storage as larger faults can be related to an active fault area and possible paths of leakage of injected CO_2.

Supplemental maps are a result of basin modelling and do not represent only the legacy data values as structured surface on the Main map. The three 'modelled maps' presented confirm the regional settings of the studied PB area as having elevated heat flow values (Lenkey et al., 2002), higher than average 65 mW/m^2 estimated for continents (Jaupart, Labrosse, Lucazeau, & Mareschal, 2015; Pollack, Hurter, & Johnson, 1993), resulting in higher geothermal gradient than Earth's average. Although, it is worth noting that, surface heat flow values determined in the calibration process of the 3D basin modelling in certain places showed significantly lower results than those presented in Lenkey et al. (2002) and Békési et al. (2017). Also, estimated values of geothermal gradient were in certain areas lower than those presented in Jelić, Kevrić, and Krasić (1995) and Kurevija et al. (2014).

The first direct consequence of the elevated heat flow is the source rock maturity reached at relatively shallow interval (early oil window onset at only −1600 m) making it a proliferous hydrocarbon exploration area. Modelled Ro values and hydrocarbon maturity windows are in accordance with the up to date discoveries in the CPB. Favourable areas for directing future petroleum explorations can easily be outlined based on the modelled %Ro values presented in the Map.

Supplemental map of averaged geothermal gradient along with the Main map can be used to geographically focus the exploration of geothermal resources. It can be used to delineate areas prospective for exploration of hydrothermal systems as well as areas that are potentially interesting for exploration of enhanced geothermal systems (hot-dry-rocks). As it was previously mentioned, the presented map of averaged geothermal gradient shows certain differences in comparison with previously published maps (Jelić et al., 1995; Kurevija et al., 2014), mainly related to generally lower averaged geothermal gradient values in the Sava Depression. It should be noted that the more prominent difference of averaged geothermal gradient values in Sava and Drava Depression visible in this supplemental map is in accordance with the difference of Earth's crust thickness between the Sava and Drava Depression (after Horváth et al., 2006).

The importance of the Main Map from the aspect of exploration aiming to CO_2 geological storage capacity estimation is manifested mainly in the definition of depth of pre-Neogene basement unconformity as well as identification of deep discontinuities that represent potential leakage paths for CO_2 from geological storage objects. So far, regional exploration of CO_2 storage capacity estimates has been mainly focused on Upper Miocene sandstones as potential regional storage formations, while storage in fractured basement reservoirs

has not been assessed. Furthermore, estimates were based on interpretation of well data to enable correlation and mapping of storage unit thickness (e.g. Kolenković, Saftić, & Perešin, 2013) and this approach partly disregarded structural analysis. In that respect, Main map can be used to direct further exploration to areas where pre-Neogene basement unconformity is situated shallower than 2500 m and where faults are not densely situated.

Presented Map is a most detailed publicly available structured surface of the Base Neogene unconformity covering the CPB. Constructed maps are important for planning of regional research of the geoenergy potential, including conventional and unconventional hydrocarbon resources, geothermal energy, CO_2 geological storage capacity and of the subsurface energy storage potential as well. Implications of developing this research are two-fold. Firstly, northern Croatia is a mature petroleum province with many oil and gas fields discovered and partly already depleted. This means that either the quest for the by-passed oil in the existing exploitation blocks is inevitable (which is ongoing) or one should also consider if some regional elements of petroleum systems have been omitted or underexplored, which would render additional HC resources, both conventional and unconventional. Secondly, the already developed subsurface exploration and results offer the opportunity for using this as an impetus to more quickly develop emerging resources that are becoming increasingly important in the light of energy transition to renewables or needs for decarbonization of both the energy and industrial sector. Regarding the renewables, deep geothermal potential is a non-intermittent source and as such is highly desirable in the energy mix which means that if Croatia will be able to speed up the development of this resource it is bound to have a significant impact on the national economy.

Software

For the preparation of the data for the map construction, ArcGIS ArcMap 10.1 and Schlumberger Petrel 2017 software were used. Construction of the Main Map and maps with supplemental data were performed using Schlumberger Petrel 2017 and PetroMod 2017 software. Final map layout was drafted in CorelDraw X4 software.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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References

Aničić, B., & Juriša, M. (1984). Osnovna geološka karta SFRJ 1:100 000, list Rogatec [Basic Geological Map of Yugoslavia 1:100 000, tile Rogatec]. Belgrade: Federal Geological department.

Baketarić, T. (2015). *Digitalizacija i strukturno modeliranje potpovršinskih odnosa u Savskoj depresiji, šira okolica polja Stružec [Digitalization and structural subsurface modelling of Sava Depression, wider surrounding of Stružec oil field]* (Unpublished Master thesis). University of Zagreb, Faculty of Mining, Geology and Petroleum Engineering.

Baketarić, T., & Cvetković, M. (2015). Subsurface modelling of the Neogene-Quaternary sediments in part of the Sava Depression based on digitalization of legacy map data. *Rudarsko-geološko-naftni zbornik*, 30(2), 67–84.

Balázs, A., Granjeon, D., Matenco, L., Sztanó, O., & Cloetingh, S. (2017). Tectonic and climatic controls on asymmetric Half-Graben sedimentation: Inferences from 3-D numerical modeling. *Tectonics*, 36(10), 2123–2141.

Basch, O. (1981). Osnovna geološka karta SFRJ 1:100 000, list Ivanić-Grad [Basic Geological Map of Yugoslavia 1:100 000, tile Ivanić-Grad]. Belgrade: Federal Geological department.

Békési, E., Lenkey, L., Limberger, J., Porkoláb, K., Balázs, A., Bonté, D., … van Wees, J. (2017). Subsurface temperature model of the Hungarian part of the Pannonian Basin. *Global and Planetary Change. Advance Online Publication*, doi:10.1016/j.gloplacha.2017.09.020

Brkić, M., Kalović, I., & Buzaljko, R. (1989). Osnovna geološka karta SFRJ 1:100 000, list Vinkovci [Basic Geological Map of Yugoslavia 1:100 000, tile Vinkovci]. Belgrade: Federal Geological department.

Brkić, Ž. (2017). The relationship of the geological framework to the Quaternary aquifer system in the Sava River valley (Croatia). *Geologia Croatica*, 70(3), 201–2013. doi:10.4154/gc.2017.12

Cloetingh, S., Bada, G., Matenco, L., Lankreijer, A., Horvath, F., & Dinu, C. (2006). Modes of basin (de)formation, lithospheric strength and vertical motions in the Pannonian–Carpathian system: Inferences from thermomechanical modeling. *Geological Society, London, Memoirs*, 32, 207–221.

Ćorić, S., Pavelić, D., Rögl, F., Mandic, O., Vrabac, S., Avanić, R., … Vranjković, A. (2009). Revised middle Miocene datum for initial marine flooding of North Croatian basins (Pannonian basin system, central paratethys). *Geologia Croatica*, 62, 31–43.

Csontos, L., & Nagymarosy, A. (1998). The Mid-Hungarian line: A zone of repeated tectonic inversions. *Tectonophysics*, 297, 51–71.

Cvetković, M. (2016). Modelling of maturation, expulsion and accumulation of bacterial methane within Ravneš

Member (Pliocene age). *Croatia Onshore. Open Geosciences*, 8(1), 5–13. doi:10.1515/geo-2016-0002

Cvetković, M., Emanović, I., Stopar, A., & Slavinić, P. (2018). Petroleum system modelling and assessment of the remaining hydrocarbon potential in the eastern part of Drava Depression. *Interpretation-A Journal of Subsurface Characterization*, 6(1), SB11–SB21. doi:10.1190/INT-2017-0078.1

Digital Elevation Model over Europe (EU-DEM). (2013). Data accessed 1st of May 2018 at https://www.eea.europa.eu/data-and-maps/data/copernicus-land-monitoring-service-eu-dem

Dolton, G. L. (2006). Pannonian Basin Province, Central Europe (Province 4808) – Petroleum Geology, Total Petroleum Systems, and Petroleum Resource Assessment (Report No. Bulletin 2204–B). Reston, Virginia: U. S. Geological Survey.

Energy Institute Hrvoje Požar & Orkustofnun. (2017). Geothermal energy utilisation potential in Croatia – Field and study visits' Report. Retrieved from Orkustofnun website: https://orkustofnun.is/gogn/Skyrslur/OS-2017/OS-2017-02.pdf

Eppelbaum, L., Kutasov, I., & Pilchin, A. (2014). *Applied Geothermics*. New York, NY: Springer.

Fodor, L., Csontos, L., Bada, G., Györfi, I., & Benkovics, L. (1999). Tertiary tectonic evolution of the Pannonian Basin system and neighbouring orogens: A new synthesis of palaeostress data. *Geological Society, London, Special Publications*, 156(1), 295–334.

Galović, I., & Marković, S. (1979). Osnovna geološka karta SFRJ 1:100 000, list Virovitica [Basic Geological Map of Yugoslavia 1:100 000, tile Virovitica]. Belgrade: Federal Geological department.

Hantschel, T., & Kauerauf, A. I. (2009). *Fundamentals of Basin and Petroleum Systems Modeling*. Berlin: Springer.

Hernitz, Z. (1980). *Dubinski strukturno-tektonski odnosi u području istočne Slavonije [Subsurface structural-tectonic relations in the area of Eastern Slavonia]* (Unpublished doctoral dissertation). University of Zagreb, Faculty of Mining, Geology and Petroleum Engineering.

Hernitz, Z., Kovačević, S., Velić, J., & Urli, M. (1981). Primjer kompleksnih geološko-geofizičkih istraživanja kvartarnih naslaga u okolici Prevlake [An example of complex geological-geophysical exploration of the Quaternary deposits in the vicinity of Prevlaka]. *Geološki vjesnik*, 33, 11–34.

Horváth, F. (1995). Phases of compression during the evolution of the Pannonian Basin and its bearing on hydrocarbon exploration. *Marine and Petroleum Geology*, 12(8), 837–844. doi:10.1016/0264-8172(95)98851-U

Horváth, F., Bada, G., Szafián, P., Tari, G., Ádám, A., & Cloetingh, S. (2006). Formation and deformation of the Pannonian Basin: Constraints from observational dana. *Geol. Soc. Lond. Mem*, 32(1), 191–206.

Horváth, F., & Tari, G. (1999). IBS Pannonian Basin project: A review of the main results and their bearings on hydrocarbon exploration. *Special Publication of Geological Society in London*, 156, 195–213.

Jamičić, D. (1989). Osnovna geološka karta SFRJ 1:100 000, list Daruvar [Basic Geological Map of Yugoslavia 1:100 000, tile Daruvar]. Belgrade: Federal Geological department.

Jamičić, D., & Brkić, M. (1987). Osnovna geološka karta SFRJ 1:100 000, list Orahovica [Basic Geological Map of Yugoslavia 1:100 000, tile Orahovica]. Belgrade: Federal Geological department.

Jamičić, D., Vragović, M., & Matičec, D. (1989). Osnovna geološka karta SFRJ 1:100 000, tumač za list Daruvar [Basic Geological Map of Yugoslavia 1:100 000, tile Daruvar Supplementary text]. Belgrade: Federal Geological department.

Jarić, A. (2016). *Modeliranje potpovršinskih odnosa na području široke okolice Velike Gorice [Modelling of the subsurface relations in the wider soroundings of the town of Velika Gorica]* (Unpublished Master thesis). Zagreb: University of Zagreb, Faculty of Mining, Geology and Petroleum Engineering.

Jaupart, C., Labrosse, S., Lucazeau, F., & Mareschal, J.-C. (2015). Temperatures, heat, and energy in the mantle of the earth. In G. Schubert (Ed.), *Treatise on geophysics* (2nd edn, pp. 253–303). Amsterdam: Elsevier.

Jelić, K., Kevrić, I., & Krasić, O. (1995). Temperatura i toplinski tok u tlu Hrvatske [Temperature and heat flow in the soil of Croatia].·*Proceedings of the First Croatian Geological Congress*,1, 245–249, Opatija, Croatia.

Jovanović, Č. (1986). Osnovna geološka karta SFRJ 1:100 000, list Kostajnica [Basic Geological Map of Yugoslavia 1:100 000, tile Kostajnica]. Belgrade: Federal Geological department.

Kisovar, M. (1979). Prilog rješavanju strukturnih odnos a našeg dijela Murske depresije [Contribution to the solution of the structural relationship in our part of the Mura depression]. In B. Šebečić (Ed.), *Proceedings of 3rd Annual Scientific Conference of the Section for Applied Geology, Geophysics and Geochemistry of the Scientific Committee for Petroleum* (pp. 311–322). Novi Sad: Jugoslav Academy of Science and Arts.

Kolenković, I. (2012). *Mogućnosti za geološko skladištenje ugljičnoga dioksida u gornjomiocenskim pješčenjacima zapadnoga dijela Savske depresije [Potential for geological storage of carbon dioxide in Upper Miocene Sandstones of the Western part of Sava depression]* (Unpublished doctoral dissertation). Zagreb: University of Zagreb, Faculty of Mining, Geology and Petroleum Engineering.

Kolenković, I., Saftić, B., & Perešin, D. (2013). Regional capacity estimates for CO2 geological storage in deep saline aquifers – Upper Miocene sandstones in the SW part of the Pannonian Basin. *International Journal of Greenhouse Gas Control*, 16, 180–186.

Korolija, B., & Crnko, J. (1985). Osnovna geološka karta SFRJ 1:100 000, list Bjelovar [Basic Geological Map of Yugoslavia 1:100 000, tile Bjelovar]. Belgrade: Federal Geological department.

Korolija, B., & Jamičić, D. (1989). Osnovna geološka karta SFRJ 1:100 000, list Našice [Basic Geological Map of Yugoslavia 1:100 000, tile Našice]. Belgrade: Federal Geological department.

Kováč, M., Andreyeva-grigorovich, A., Bajraktarević, Z., Brzobohatý, R., Filipescu, S., Fodor, L., … Studencka, B. (2007). Badenian evolution of the Central Paratethys Sea: Paleogeography, climate and eustatic sea-level changes. *Geologica Carpathica*, 58, 579–606.

Krijgsman, W., Stoica, M., Vasiliev, I., & Popov, V. (2010). Rise and fall of the Paratethys Sea during the Messinian Salinity Crisis. *Earth and Planetary Science Letters*, 290, 183–191.

Kurečić, T. (2017). *Sedimentologija i paleoekologija pliocenskih Viviparus slojeva Vukomeričkih gorica [Sedimentology and paleoecology of Pliocene Viviparus beds from the area of Vukomeričke gorice]* (Unpublished doctoral dissertation). University of Zagreb.

Kurevija, T., Kljaić, Ž, & Vulin, D. (2010). Analysis of geothermal energy exploitation on Karlovac geothermal field. *Nafta*, 61(4), 191–197.

Kurevija, T., & Vulin, D. (2011). High enthalpy geothermal potential of the Deep Gas Fields in Central Drava Basin, Croatia. *Water Resources Management, 25*(12), 3041–3052. doi:10.1007/s11269-011-9789-y

Kurevija, T., Vulin, D., & Macenić, M. (2014). Impact of geothermal gradient on ground source heat pump system modelling. *Rudarsko-geološko-naftni Zbornik, 28*(1), 39–45.

Lenkey, L., Dövényi, P., Horváth, F., & Cloething, S. A. P. L. (2002). Geothermics of the Pannonian basin and its bearing on the neotectonics. *EGU Stephan Mueller Special Publication Series, 3*, 29–40.

Lučić, D., Saftić, B., Krizmanić, K., Prelogović, E., Britvić, V., Mesić, I., & Tadej, J. (2001). The Neogene evolution and hydrocarbon potential of the Pannonian Basin in Croatia. *Marine and Petroleum Geology, 18*, 133–147.

Macenić, M., & Kurevija, T. (2018). Revitalization of abandoned oil and gas wells for a geothermal heat exploitation by means of closed circulation: Case study of the deep dry well Pčelić-1. *Interpretation-A Journal of Subsurface Characterization, 6*(1), SB1–SB9.

Magaš, N. (1987). Osnovna geološka karta SFRJ 1:100 000, list Osijek [Basic Geological Map of Yugoslavia 1:100 000, tile Osijek]. Belgrade: Federal Geological department.

Magyar, I., Geary, D. H., & Müller, P. (1999). Paleogeographic evolution of the Late Miocene Lake Pannon in Central Europe. *Palaeogeography, Palaeoclimatology, Palaeoecology, 147*, 151–167.

Mandić, O., Kurečić, T., Neubauer, T. A., & Harzhauser, M. (2015). Stratigraphic and paleogeographic significance of lacustrine mollusks from the Pliocene Viviparus beds in central Croatia. *Geologia Croatica, 68*(3), 179–207. doi:10.4154/gc.2015.15

Matoš, B. (2014). Neotectonic and recently active faults in Bilogora Mountain area and assessment of their seismogenic potential (Unpublished doctoral dissertation). University of Zagreb, Faculty of Mining, Geology and Petroleum Engineering, Zagreb.

Mioč, P., & Marković, S. (1998). Osnovna geološka karta Republike Hrvatske i Republike Slovenije 1:100 000, list Čakovec [Basic Geological Map of the Republic of Croatia and Republic of Slovenia 1:100 000, tile Čakovec]. Zagreb & Ljubljana, Institute for Geology, Geotechnics and Geophysics ¸& Institute for Geological research.

Novak Zelenika, K. (2005). *Naftnogeološki odnosi polja Vukanovec* [Petroleum geological settings of oil field Vukanovec] (Unpublished Master's Thesis). University of Zagreb, Faculty of Mining, Geology and Petroleum Engineering, Zagreb.

Novak Zelenika, K., Cvetković, M., Malvić, T., Velić, J., & Sremac, J. (2013). Sequential indicator simulations maps of porosity, depth and thickness of Miocene clastic sediments in the Kloštar Field, Northern Croatia. *Journal of Maps, 9*(4), 550–557. doi:10.1080/17445647.2013.829410

Pamić, J. (1998). Crystalline basement of the South Pannonian Basin based on surface and subsurface data. *Nafta, 49*(12), 371–390.

Paškov, T. (2016). *Potpovršinsko modeliranje područja Karlovačke uleknine, Savska depresija [Subsurface Modeling of Karlovac Subdepression, Sava Depression]* (Unpublished Master thesis). Zagreb: University of Zagreb, Faculty of Mining, Geology and Petroleum Engineering.

Pavelić, D. (2001). Tectonostratigraphic model for the North Croatian and North Bosnian sector of the Miocene Pannonian Basin System. *Basin Research, 13*, 359–376.

Pavelić, D., & Kovačić, M. (2018). Sedimentology and stratigraphy of the Neogene rift-type North Croatian Basin (Pannonian Basin System, Croatia): A review. *Marine and Petroleum Geology, 91*, 455–469.

Pikija, M. (1987). Osnovna geološka karta SFRJ 1:100 000, list Sisak [Basic Geological Map of Yugoslavia 1:100 000, tile Sisak]. Belgrade: Federal Geological department.

Podbojec, M. (2015). *Digitalizacija potpovršinskih strukturnih karata i izrada geološkog modela na području Savske depresije, okolica Ivanić-Grada [Digitalization of subsurface structural maps and creation of geological model of part of Sava Depression, surrounding of Ivanić-Grad].* (Unpublished Master thesis). Zagreb: University of Zagreb, Faculty of Mining, Geology and Petroleum Engineering.

Pollack, H. N., Hurter, S. J., & Johnson, J. R. (1993). Heat flow from the Earth's interior: Analysis of the Global Data Set. *Reviews of Geophysics, 31*, 267–280.

Prelogović, E., Saftić, B., Kuk, V., Velić, J., Dragaš, M., & Lučić, D. (1998). Tectonic activity in the Croatian part of the Pannonian basin. *Tectonophysics, 297*, 283–293.

Prelogović, E., & Velić, J. (1992). Correlation of quaternary sediments and tectonic activity of the eastern part of the Drava River Depression. *Geologia Croatica, 45*, 151–162.

Ratschbacher, L., Frisch, W., Linzer, H.-G., & Merle, O. (1991). Lateral extrusion in the Eastern Alps, Part II: Structural analysis. *Tectonics, 10*, 257–271.

Rögl, F. (1996). Stratigraphic correlation of the paratethys oligocene and Miocene. *Mitteilungen Ges. Geologie und Bergbaustudenten Österreich, 41*, 65–73.

Rögl, F. (1998). Palaeographic consideration for mediterranean and paratethys seaways (Oligocene to Miocene). *Annalen des Naturhistorischen Museums in Wien, 99A*, 279–310.

Royden, L. H. (1988). Late Cenozoic Tectonics of the Pannonian Basin system. In L. H. Royden & F. Horváth (Eds.), *The Pannonian Basin: A study in Basin Evolution Vol. 45* (pp. 27–48). Tulsa: American Association of Petroleum Geologists.

Royden, L. H., & Horvath, F. (1988). The Pannonian Basin: A case study in Basin Evolution. *AAPG Memoir, 45*, 394.

Rukavina, D. (2015). *Strukturna analiza i interpretacija tektonske evolucije istočnog dijela Savske depresije [Structural analysis and interpretation of tectonic evolution in the eastern part of Sava depresion]* (Unpublished Master thesis). Zagreb: University of Zagreb, Faculty of Mining, Geology and Petroleum Engineering.

Rukavina, D., Matoš, B., Tomljenović, B., & Saftić, B. (2016). Neotectonic active faults in the Eastern Part of Sava Depression: implications to tectonic evolution based on 2D seismic data and 3D subsurface structural modelling. In M. Cvetković, K. Novak Zelenika, J. Horvath, & I. G. Hatvani (Eds.), *Proceedings of 8th Croatian-Hungarian and 19th Hungarian geomathematical congress 'Geomathematics – present and future of geological modelling'* (pp. 129–136). Trakošćan: Croatian Geological Society.

Saftić, B., Velić, J., Sztanó, O., Juhász, G., & Ivković, Ž. (2003). Tertiary subsurface facies, source rocks and hydrocrbon resevoirs in the SW part of the Pannonian Basin (Northern Croatia and South-Western Hungary). *Geologia Croatica, 56*(1), 101–122.

Schmid, S. M., Bernoulli, D., Fügenschuh, B., Matenco, L., Schefer, S., Schuster, R., … Ustaszewski, K. (2008). The Alpine-Carpathian-Dinaridic orogenic system: Correlation and evolution of tectonic units. *Swiss Journal of Geosciences, 101*(1), 139–183.

Šikić, K., Basch, O., & Šimunić, A. (1977). Osnovna geološka karta SFRJ 1:100 000, list Zagreb [Basic Geological Map of Yugoslavia 1:100 000, tile Zagreb]. Belgrade: Federal Geological department.

Šimunić, A., Pikija, M., & Hećimović, I. (1982). Osnovna geološka karta SFRJ 1:100 000, list Varaždin [Basic Geological Map of Yugoslavia 1:100 000, tile Varaždin]. Belgrade: Federal Geological department.

Šparica, A., Juriša, M., Crnko, J., & Šimunić, A. (1979). Osnovna geološka karta SFRJ 1:100 000, list Nova Kapela [Basic Geological Map of Yugoslavia 1:100 000, tile Nova Kapela]. Belgrade: Federal Geological department.

Šparica, M. (1986). Osnovna geološka karta SFRJ 1:100 000, list Slavonski Brod [Basic Geological Map of Yugoslavia 1:100 000, tile Slavonski Brod]. Belgrade: Federal Geological department.

Šparica, M., Buzaljko, R., & Jovanović, Č. (1983). Osnovna geološka karta SFRJ 1:100 000, list Nova Gradiška [Basic Geological Map of Yugoslavia 1:100 000, tile Nova Gradiška]. Belgrade: Federal Geological department.

Špelić, M., Malvić, T., Saraf, V., & Zalović, M. (2016). Remapping of depth of e-log markers between Neogene basement and Lower/Upper Pannonian border in the Bjelovar Subdepression. *Journal of Maps*, *12*(1), 45–52. doi:10.1080/17445647.2014.978909

Stopar, A. (2015). *Potpovršinsko modeliranje područja istočnog dijela Dravske Depresije [Subsurface modeling of eastern part of Drava Depression]* (Unpublished Master thesis). Zagreb: University of Zagreb, Faculty of Mining, Geology and Petroleum Engineering.

Tadej, J. (2011). Evolution of the Early and Middle Miocene sedimentary environments in the north-western part of the Drava depression based on the well analysis data. PhD Thesis. University of Zagreb, Faculty of Mining, Geology and Petroleum Engineering. 168.

Tari, G., Horváth, F., & Rumpler, J. (1992). Styles of extension in the Pannonian Basin. *Tectonophysics*, *208*(1–3), 2.

Tišljar, J. (1993). Sedimentary bodies and depositional models for the Miocene oil-producing areas Ladislavci, Beničanci and Obod (Croatia). *Nafta*, *44*(10), 531–542.

Tomljenović, B., & Csontos, L. (2001). Neogene-Quaternary structures in the border zone between Alps, Dinarides and Pannonian Basin (Hrvatsko Zagorje and Karlovac Basins, Croatia). *International Journal of Earth Sciences*, *90*, 560–578. doi:10.1007/s005310000176

Troskot-Čorbić, T., Velić, J., & Malvić, T. (2009). Comparison of the Middle Miocene and the Upper Miocene source rock formations in the Sava Depression (Pannonian Basin, Croatia). *Geologia Croatica*, *62*(2), 1233–1133. doi:10.4154/GC.2009.11

Ustaszewski, K., Kounov, A., Schmid, S. M., Schaltegger, U., Krenn, E., Frank, W., & Fungenschuh, B. (2010). Evolution of the Adria-Europe plate boundary in the northern Dinarides: From continent-continent collision to back-arc extension. *Tectonics*, *29*(6), 1–34. doi:10.1029/2010TC002668

Ustaszewski, K., Schmid, S. M., Fügenschuh, B., Tischler, M., Kissling, E., & Spakman, W. (2008). A map-view restoration of the Alpine-Carpathian-Dinaridic system for Early Miocene. *Swiss Journal of Geosciences*, *101*(1), 273–294.

Velić, J. (1980). Geološka građa zapadnog dijela Savske depresije [Geological structures of western part of Sava Depression] (Unpublished doctoral dissertation). University of Zagreb, Faculty of Mining, Geology and Petroleum Engineering, Zagreb.

Velić, J. (2007). *Geologija ležišta nafte i plina [Geology of Oil and Gas Accumulations]*. Zagreb: University of Zagreb, Faculty of Mining, Geology and Petroleum Engineering.

Velić, J., Weisser, M., Saftić, B., Vrbanac, B., & Ivković, Ž. (2002). Petroleum-geological characheristics and exploration level of the three Neogene depositional megacycles in the Croatian part of the Pannonian basin. *Nafta*, *53*(6–7), 239–249. Zagreb.

Vrbanac, B. (1996). *Paleostrukturne i sedimentološke analize gornjopanonskih naslaga formacije Ivanić-Grad u Savskoj depresiji [Paleostructural and sedimentological analysis of the Upper Pannonian sediments of the Ivanić -Grad formation in the Sava Depression]* (Unpublished doctoral dissertation). Zagreb: University of Zagreb, Faculty of Science.

Vuić, I. (2015). *Strukturni odnosi i potpovršinsko modeliranje šire okolice Vinkovaca kao rezultat digitalizacije regionalnih dubinskogeoloških karata [Structural relations and subsurface modelling of wider surroundings of vinkovci city as a result of digitalization of regional subsurface maps]* (Unpublished Master thesis). Zagreb: University of Zagreb, Faculty of Mining, Geology and Petroleum Engineering.

Vulama, I. (1994). Source rock potential of the Eastern Drava Depression and some other source rock localities in Croatia as evaluated from Well Log Data. *Geologia Croatica*, *47*, 205–214.

Wygrala, B. P. (1989). *Integrated study of an oil field in the southern Po Basin, northern Italy (Unpublished doctoral dissertation)*. University of Köln.

Zečević, M., Velić, J., Sremac, J., Troskot-Čorbić, T., & Garašić, V. (2010). Significance of the Badenian petroleum source rocks from the Krndija Mt. (Pannonian Basin, Croatia). *Geologia Croatica*, *63*, 225–239.