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Subsurface Modelling of the Neogene-Quaternary Sediments in Part of the Sava Depression Based on Digitalization of Legacy Map Data

Tomislav Baketarić [1]; Marko Cvetković [2];

[1]Geology and Geophysics Department, Exploration sector; INA - Industry of Oil Plc., Zagreb, Croatia; tomislav.baketaric@ina.hr

[2]Faculty of Mining, Geology and Petroleum Engineering, University of Zagreb, Pierottijeva 6, Zagreb, Croatia; marko.cvetkovic@rgn.hr

Abstract

The aim of research was the accurate digitalization and subsurface modelling of the legacy data, namely paper-based geological maps. The research area covers approximately 1053 km² and is located in the Croatian part of the Pannonian Basin System, the Sava Depression, i.e. in the region of the Stružec Oil Field. Data input for the structural analysis were structural maps which were previously made in the 1980. The set included five structural maps based on regional E-log markers and one map of pre-Neogene surface. All were digitalized in the ArcGIS program, and later modelled in Petrel. Structural contours and a total of 134 faults were exported into Petrel software where they were further processed and regrouped. From such digitalized and processed data, the geological model (geomodel) was made using complex fault framework. The study concerned the advantages and errors that occur during the creation of such a geomodel. It clearly displays the relationships between major and minor faults and fault slips, geological structures and structural traps in 3D (e.g. anticline of the Stružec Field). Another advantage is the multicolored presentation of depths and faults, which facilitates the recognition of geological structures and potential traps for hydrocarbons. Errors and issues can occur during the digitalization of contour lines, the selection of the appropriate algorithm and later, after the model has already been created. A low error rate between the two approaches indicates the accuracy of digitalization of data and subsurface modelling. Uncertainty models (maps of statistical percentage deviation) were made in the Petrel Software for the display of the deviation between handmade maps and Petrel models for each E-log marker and one pre-Neogene top.

Keywords

Stružec Field, Sava Depression, subsurface modelling, digitalization

1. Introduction

In this paper, six legacy structural maps interpolated by hand (**Velić, 1980**) of the western part of the Sava Depression (Pannonian Basin System) were analysed and digitalized. Previous digitalization of a map, from a nearby area, was made (**Špelić et al., 2014**) based on grid data but those kinds of maps do not show faults and are thus less valuable in geomodelling. A more detailed approach of map digitalization and creation of geological models based on previous hand interpolated maps were made by **Podbojec (2015)** and **Baketarić (2015a & 2015b)**. The goal was the building of a 3D subsurface model which includes faults. Digitalization and processing of data was performed using computer software ArcMap 10.1 and Petrel™ 2013. The aim of this study was not structural reinterpretation but digitalization of existing structural solutions.

Corresponding author: Tomislav Baketarić
tomislav.baketaric@ina.hr

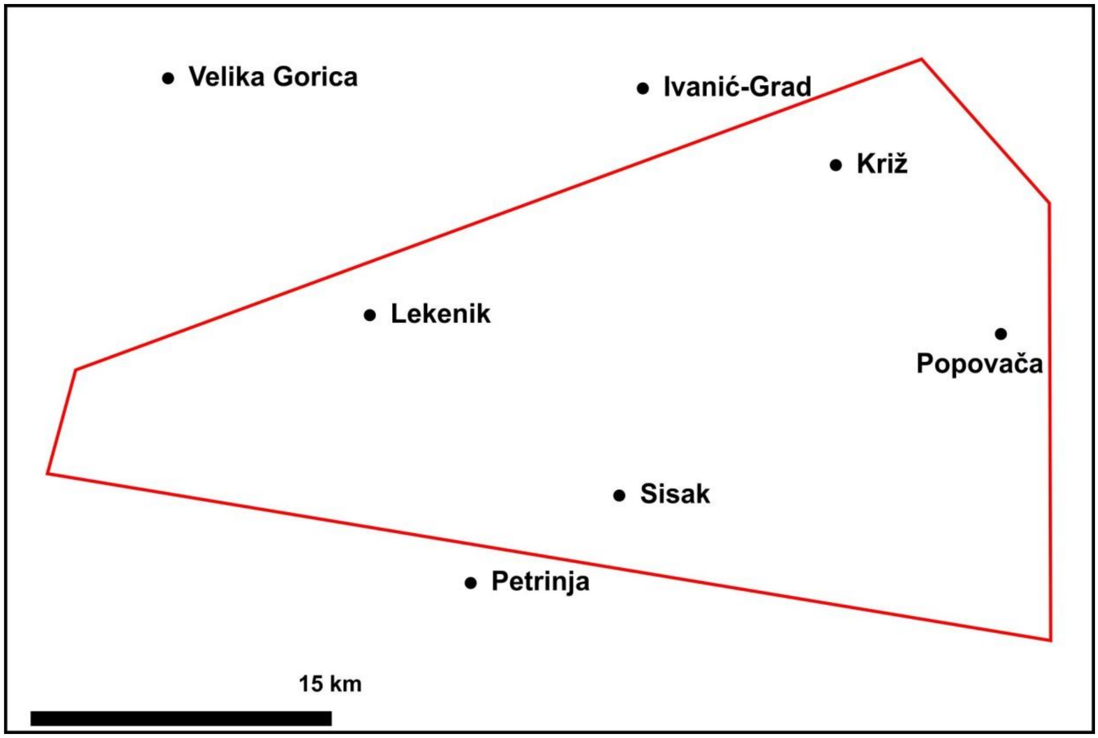

Figure 1: *Area of subsurface modelling bounded by red polygon*

The area of geomodelling is located in the central part of Croatia and it covers 1053.2 km^2 (**Figure 1**.). There are five oil and gas fields within the modelled area: Bunjani, Žutica, Vezišće, Okoli and part of Voloder.

2. Geology of the explored area

Stratigraphy of the exploration area is described in detail by **Šimon (1973), Velić (2007)** and **Malvić and Velić (2011)**. This chapter describes the lithostratigraphic units approximately correlated with chronostratigraphic units. Lithostratigraphic units are separated by regional E–log markers ("Rs7", "Rs5", "Z'", "Rφ" and "α'") and one pre – Neogene border ("Tg"). **Vrbanac (2002)** came to the conclusion that E–logs represent a reflection of the change between the distribution of average sized particles and the type of sedimentation, which continues to affect the value of the porosity and permeability of sediments deposited in the same conditions and at the same time. The basement of Neogene – Quaternary sediments consists of magmatic-metamorphic and partly sedimentary complex rocks of the Paleozoic, Mesozoic and Paleogene ages. According to the paleogeological map of basement of Neogene - Quaternary deposits in the western part of the Sava Depression in the scale of 1: 500 000 (**Velić, 1980**), Paleozoic rocks are the most widespread in the modelled area. Recent studies have shown that the part of the crystalline mass in underlying Neogene – Quaternary sediments is of Mesozoic age. (**Cvetković, 2006; Petrinec, 2013**). The basement also consists of Eocene sediments in the southwestern part of geomodelling area, proven in the Komarevo-1 well.

Rs7 separates the Prečec and Prkos Formation, ie. Sarmatian and Pannonian sediments. Rs5 divides Prkos and Ivanić-Grad Formation (Lower and Upper Pannonian). The Rs7-Rs5 interval includes „Croatica sediments". According to **Velić (2007)** E-logs Rs5 and Rs7 have a dual character in some parts of the Depression: according to the current practice, both markers are accepted as chronohorizons and as erosional unconformities. The Ivanić-Grad and Kloštar Ivanić Formations (Upper Pannonian and Lower Pontian) are divided by E–log marker Z'. The Rs5 – Z' interval comprises "Banatica deposits". Rφ separates the Kloštar-Ivanić and Široko Polje Formation (Lower and Upper Pontian). The Z' - Rφ interval combines "Abichi deposits". α' splits Široko Polje and the Lonja Formation (Upper Pont and Pliocene, Pleistocene and Holocene). The Rφ - α' interval contains "Rhomboidea deposits". The α' - recent sediments (ground level) interval covers "Paludina sediments". According to **Velić et al. (2002)** and **Saftić et al. (2003)** in the Croatian part of the Pannonian Basin

System (CPBS), sedimentation in the Neogene took place successively in three sedimentary "megacycles" resulting from significant changes in the tectonic evolution of the CPBS. Structures are developed during Miocene, starting with the transtensional tectonics in the opening of the Pannonian basin and the uplifting of the Apennines and the Dinarides (**Velić & Malvić, 2011**). The Pannonian basin was opened due to two phases of transtension and two of transpressions. Transtensions were periods of main sediment accumulation and transpression of uplifting and structural formation (**Velić & Malvić, 2011**). The 1st transtensional phase in CPBS reached its maximum in the Badenian, when strike-slip tectonics was the main mechanism of structural development. The 1st transpression took place in Sarmatian after a series of transgressive - regressive cycles in the Badenian, it was followed by an overall regression during the Sarmatian (**Pavelić, 2002**; **Velić & Malvić, 2011**). Sediments of Middle Miocene are common reservoir, seal and source rocks. These are the earliest sediments deposited during Neogene transgression covering the entire CPBS (**Ćorić et al., 2009**). The 2nd transtensional localized strike-slip tectonics took place in the Early Pannonian. In a large lacustrine, brackish and, eventually, fresh-water environment, characterized by depths of up to several hundred metres, salinity was continuously reduced owing to fresh-water inflow and a lack of connection with other open-sea environments (**Vrbanac et al., 2010; Velić & Malvić, 2011**). The Late Pontian (6.3-5.6 Ma), Pliocene and Quaternary (2.6 to 0.0 Ma) were the periods of the 2nd transpressional phase, when negative flower structures and faulted anticlines had been uplifted (**Velić & Malvić, 2011**). During the 2nd transtensional and transpressional phases, the Sava depression was a lacustrine part of the CPBS. It was 25 km wide and 100 km long. In this period PBS was an open lake system. The consequences are numerous fault zones that separate regional tectonic blocks. From geological maps (**Velić, 1980**) radial tectonic with anticlines, synclines, horst – anticlines, structural noses, terraces and structural saddles can be seen. All faults in the area of geomodelling at the time were determined as normal and with very steep fault planes. Previous studies have not detected reverse faults, unlike other parts of the same depression. According to their direction, faults are divided into three groups: NW–SE, SW–NE, N–S (**Velić, 1980**). Formal litostratigraphic and chronostratigraphic units, E-log markers and megacycles valid for the Sava Depression are shown in **Figure 2**.

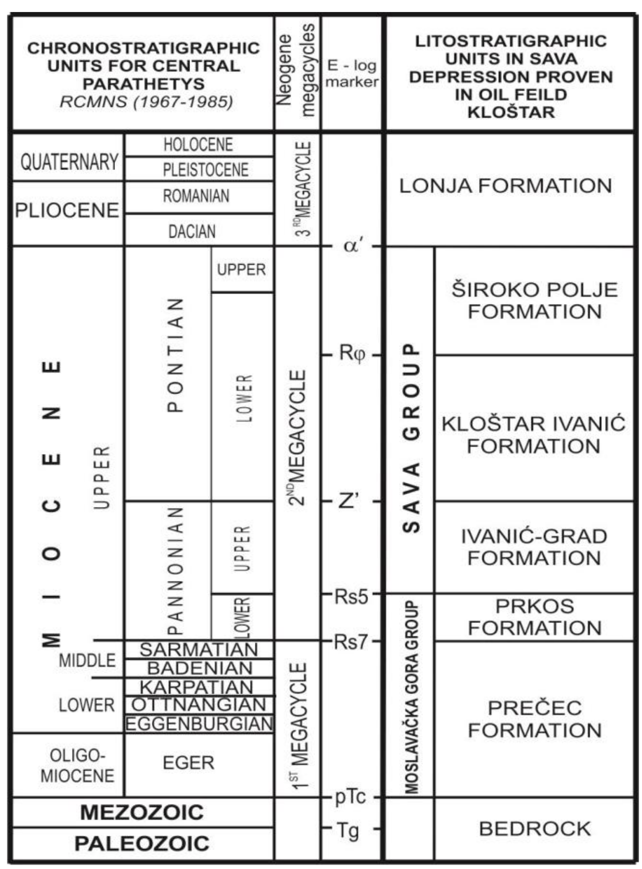

***Figure 2.** Formal litostratigraphic and chronostratigraphic units and e-log markers valid for the Sava Depression (Velić et al., 2011)*

3. Methodology

The data input for subsurface modelling was derived by **Velić (1980)** from previously made (interpolated) structural maps. The set included five structural maps based on regional e-log markers (“Rs7“, “Rs5“, “Z' “, “Rφ“ and “α'“) and one map of pre-Neogene top (“Tg”). Six maps were scanned and saved in the graphic format TIFF (*Tagged Image File Format*) because of the high-resolution provided by the specified format. All maps were digitalized in the ArcMap program. ArcMap is the main component of ESRI's (*Environmental Systems Research Institute*) ArcGIS suite of geospatial processing programs, and is used primarily to view, edit, create, and analyze geospatial data. After the maps were imported into ArcMap, a Geodatabase was created. By creating the Geodatabase, a coordinate system is determined so further-processed data could be accurately accommodated in 3D. Selected coordinate system is WGS84 ellipsoid. It is a geocentric coordinate system whose origin is at the center of the mass of Earth. The Z-axis was directed towards the middle position of the 1900 - 1905 North Pole. The X-axis laid in the equatorial plane and passed through the secondary Greenwich Meridian. The Y-axis was perpendicular to the X and Z axes and is directed towards the East. Afterwards, the research area was defined and is characterized as a closed polygon so it can mark the border of the digitalized data. Each map consists of three different types of data which need to be digitalized: contour lines, fault lines and lines that mark the borders of mapped E–logs. For each one of its components, *Feature Class* is created. Therefore, 18 different classes of components were created that are going to be used as input data. All the faults were digitalized as lines. Lines that mark the borders of mapped E–logs on maps are digitalized as closed polygons. During the digitalization of contour maps the depth value of each of them must be specified. For example, digitalized data of structural map of pre – Neogene top can be seen in **Figure 3**.

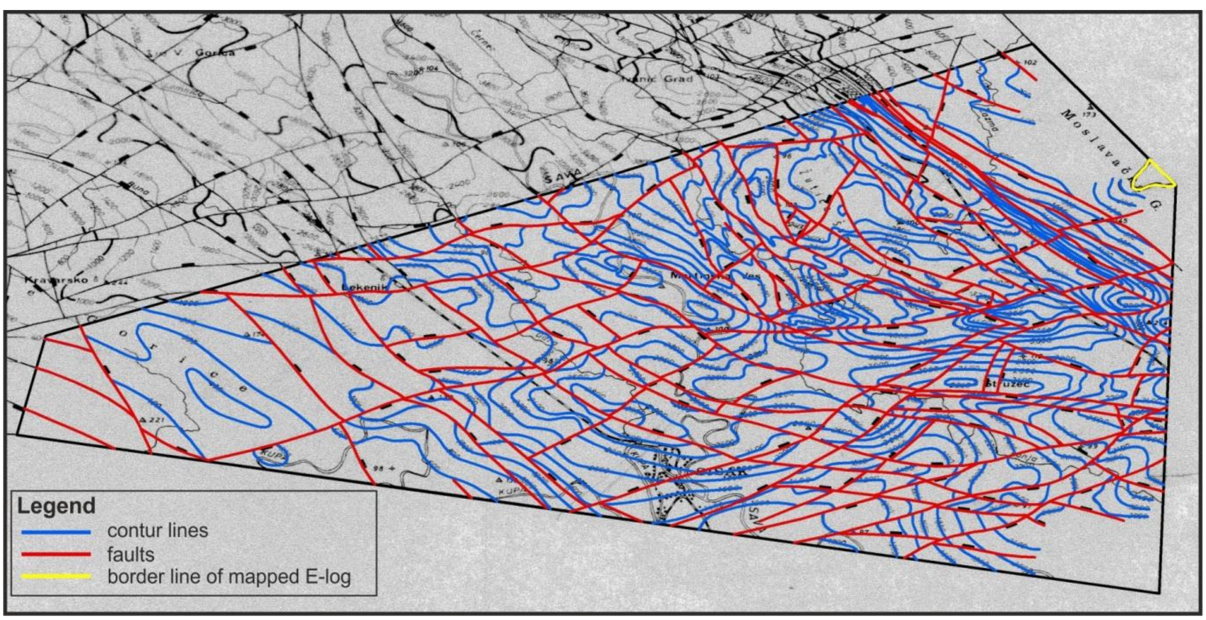

Figure 3. *Digitalized faults, contour lines and lines which mark the borders of mapped E-logs on structural map of pre–Neogene top*

After they are all digitalized, feature classes are exported and saved as *shapefiles* (.shp). The shapefile format is a geospatial vector data format for geographic information system (GIS) software. The *shapefiles* were imported into Petrel software. Petrel is a Schlumberger owned software platform that provides an integrated solution from exploration to production. From imported contour lines surfaces were made along the plane of each E-log marker and one pre-Neogene border. The tool used was *Make/edit surface* as it can be seen in **Figure 4**. Further on, surfaces were used as one of the input data for subsurface modelling. After the faults were imported, they were refined using the *Equal space* tool, so that they could later be easily modified as needed in the *Make/edit polygons* program tool. Faults were “pasted” to their corresponding surfaces by equalizing the Z coordinate (depth) from the newly made surface and the Z value of the fault node (value 0 previously assigned by default) (**Figure 5**).

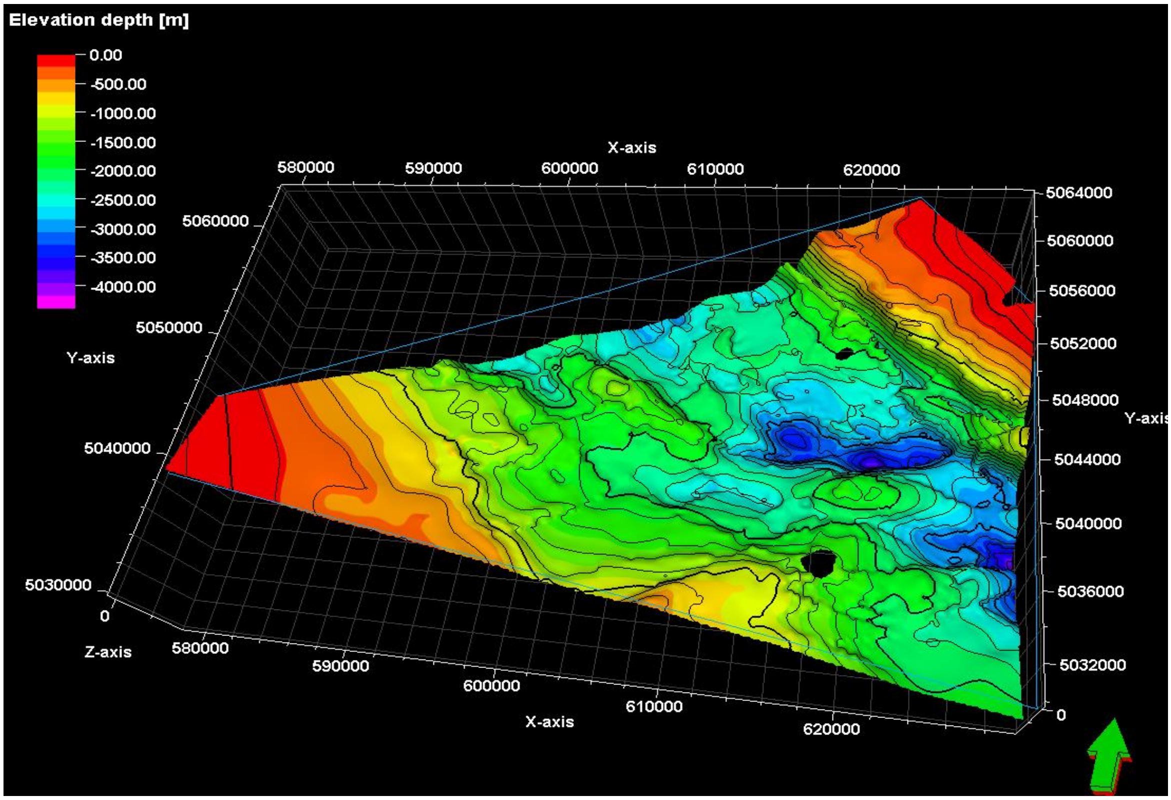

Figure 4: *Surface along the plane of E–log marker"Rs7"*

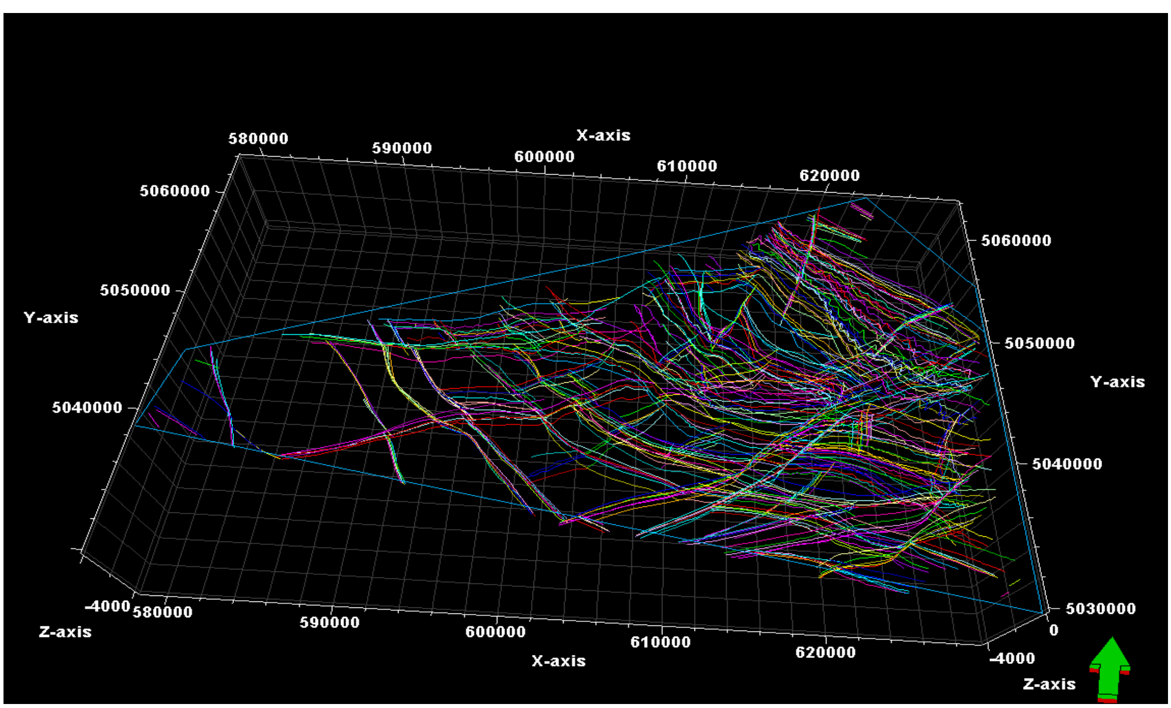

Figure 5: *"Pasted" faults*

Faults from each map were imported as groups of faults, so each one of them was split into polygons by using the *Split* tool. Polygons that represent the same faults, but at different surfaces, were regrouped and sorted into folders. The variety of colours provided by the program greatly simplifies the grouping of polygons into folders. Polygons are sorted into 134 folders and each folder represents a fault that is located in the study area. After the interpretation and grouping of faults, structural framework was made by the *Fault framework modelling* tool. One of the tool's options is to specify the value of extrapolation distance and to smooth the faults. The relationships between the faults' contacts needed to be set. Defining major and minor faults corrects some of the possible errors that occur during the process. For example, an inconsistent contact between two faults can be seen in **Figure 6**. Lines which mark the borders of mapped E-logs are "pasted" as closed polygons and, by setting the relation between various closed polygons, they were cut out. The next in line was *Horizon modelling*. Input data for subsurface modelling are border cut surfaces made from contour lines and structural framework. The surface along the pre-Neogene surface "Tg" is set as the base and all others are set as conformable. E-logs Rs7 and α' are erosional but if we set them in Petrel as erosional instead of conformable to the base, they wipe and sweep the base of Neogene and that is not the case in the subsurface. By turning on the *refine and create zone model* option, three-dimensional zones between E-log markers are created. During the creation of the model, errors recognized by the software are shown in the form of a red sphere. After all the errors are fixed, the making of the model is restarted. Errors usually occur if the program recognizes that some relationships between fault contacts are inconsistent or, if the fault is abnormally curved, which makes the contact line between two faults kinked or sharp (**Figure 7**). These errors are corrected by setting the value of the *Smoothing* option or manually shifting and smoothing of polygon points in space, using the *Make/edit polygons* tool. If the contact between two faults is incomplete it can be repaired by increasing the value of *Extrapolation distance* for a specific fault. The subsurface model is completed when the software no longer reports any feedback about the possible errors after the creation of the model.

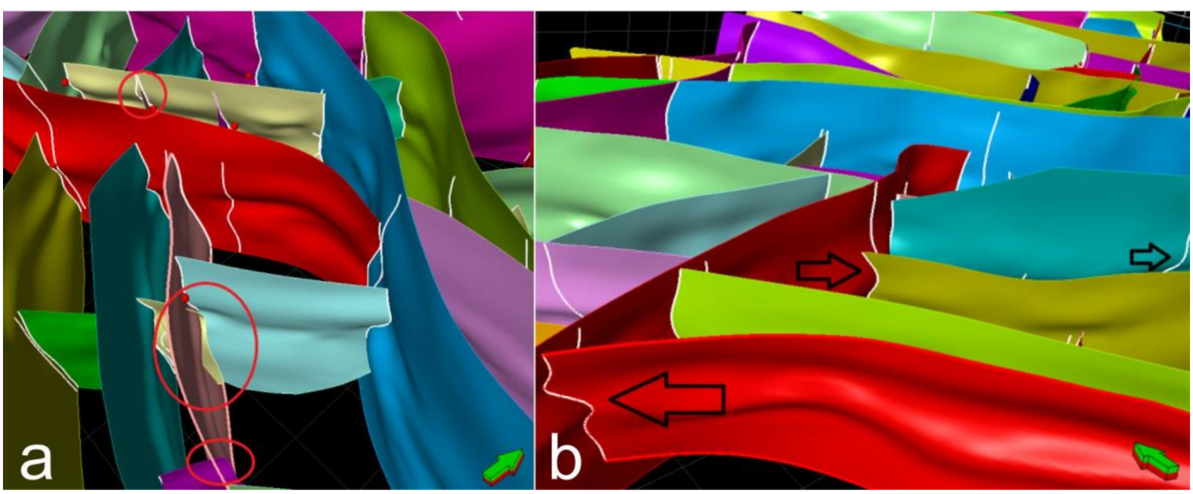

Figure 6: a) *Inconsistent fault contact between two faults;* ***b)*** *kinked or sharp truncations*

4. Results

The results of digitalization are provided through steps needed to make and complete a geomodel model, as well as through checking the quality of the digitized data. These are fault framework, subsurface modelling, cross sections and uncertainty models.

4.1. Fault framework

Fault framework consists of 134 normal faults. The model clearly shows the relationships between the major and minor faults. The most important faults are the Glina – Stružec – Popovača fault (orange), a part of the Sava fault in the central part and the South Marginal Depression Fault in the western part of the investigated area (**Figure 7**). According to their direction, the faults are divided into NW–SE, SW–NE, N–S. The majority of the faults penetrate each E-log marker and some of them only reach the bottom three E–log markers. It should be mentioned that a detailed structural reinterpretation was not made for this purpose, but instead structural maps were the starting point data for the digitization and creation of subsurface Petrel model.

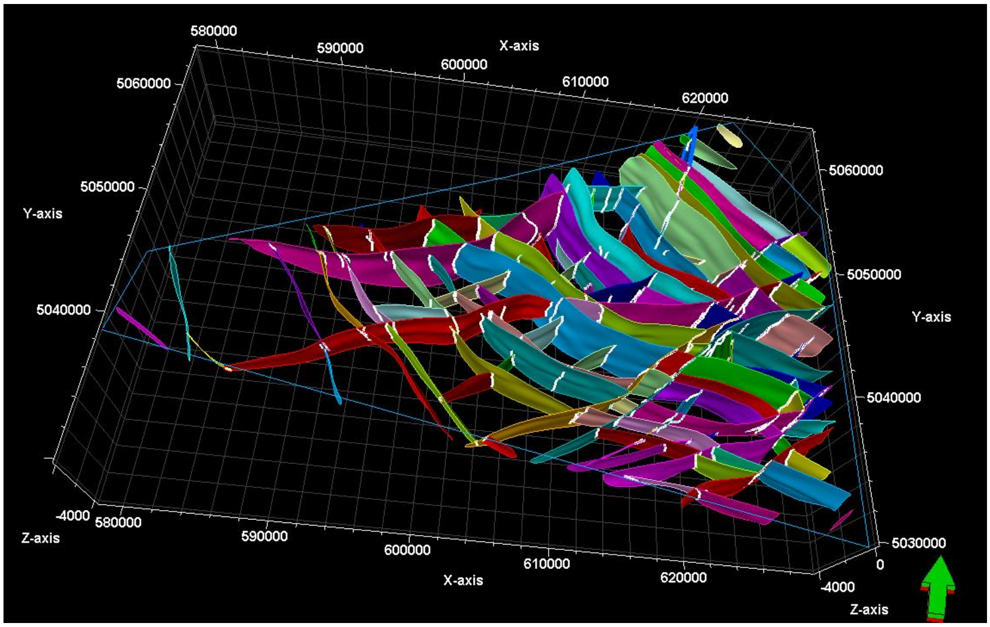

Figure 7: *Fault framework*

4.2. Subsurface model

Multi-coloured presentation of depths and faults enables easier recognition of geological structures and potential hydrocarbon traps. In **Figure 9,** a model of Neogene – Quaternary basement sediments is shown along the Tg plain. The Stružec oil field anticline can be very clearly seen on the subsurface models (pink pointer in **Figures 9-13**). The Žutica Anticline is shown by red pointer (**Figures 9-12**). The Bunjani Oil and Gas Field is shown by a purple, the Okoli by a green and Vezišće by a yellow pointer (**Figures 9-13**). The light blue arrow points to a part of the Voloder anticline (**Figures 10 and 11**). The impact of fault shifts on the shape of the surface can be very clearly seen. The northeastern part of the terrain was elevated because of the uplift of the Moslavačka gora. From the subsurface models, radial tectonic with anticlines, synclines, horst – anticlines, structural noses, terraces and structural saddles can be observed.

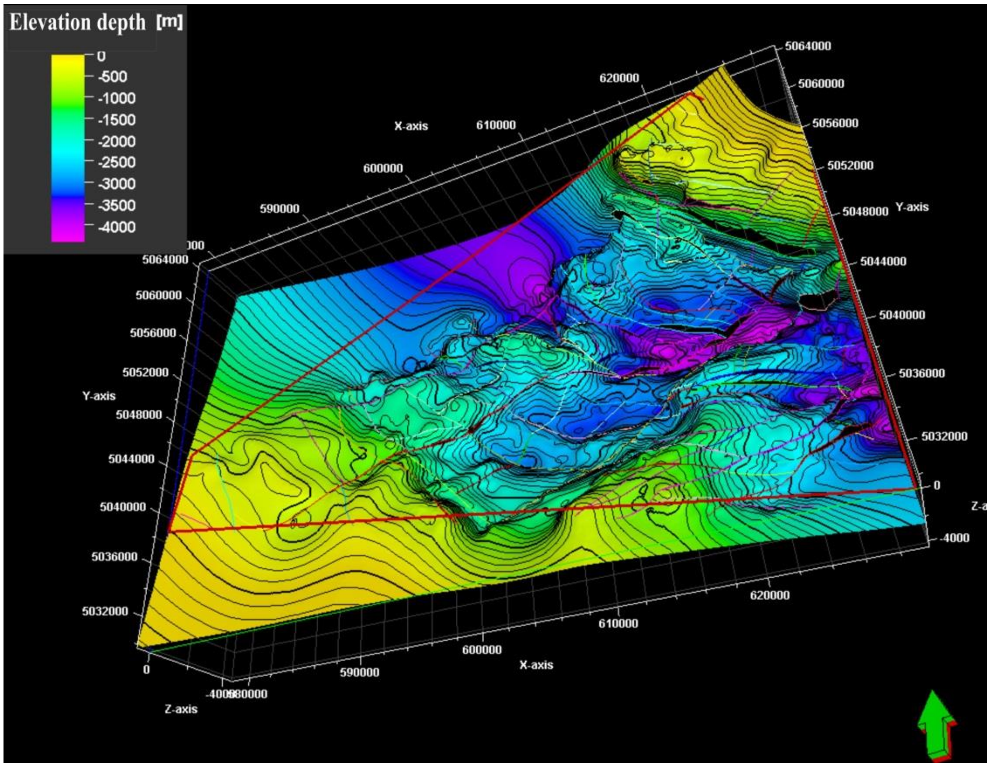

Figure 8: Subsurface model along the plane of pre-Neogene top ("Tg")

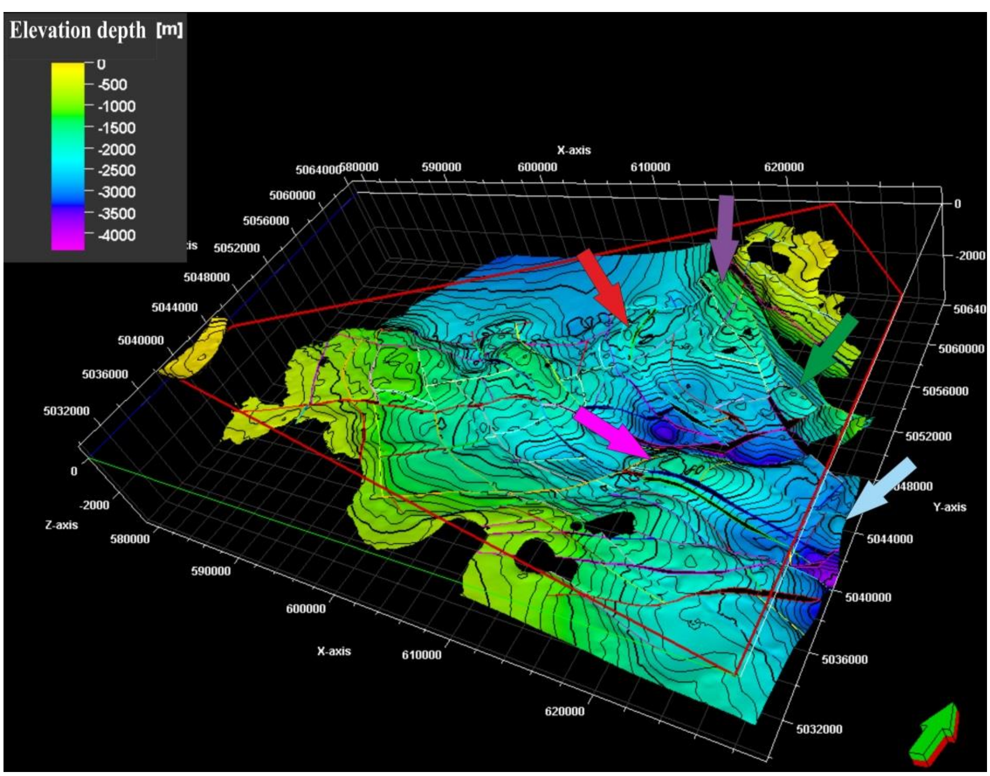

Figure 9: Subsurface model along the plane of e-log marker "Rs7"

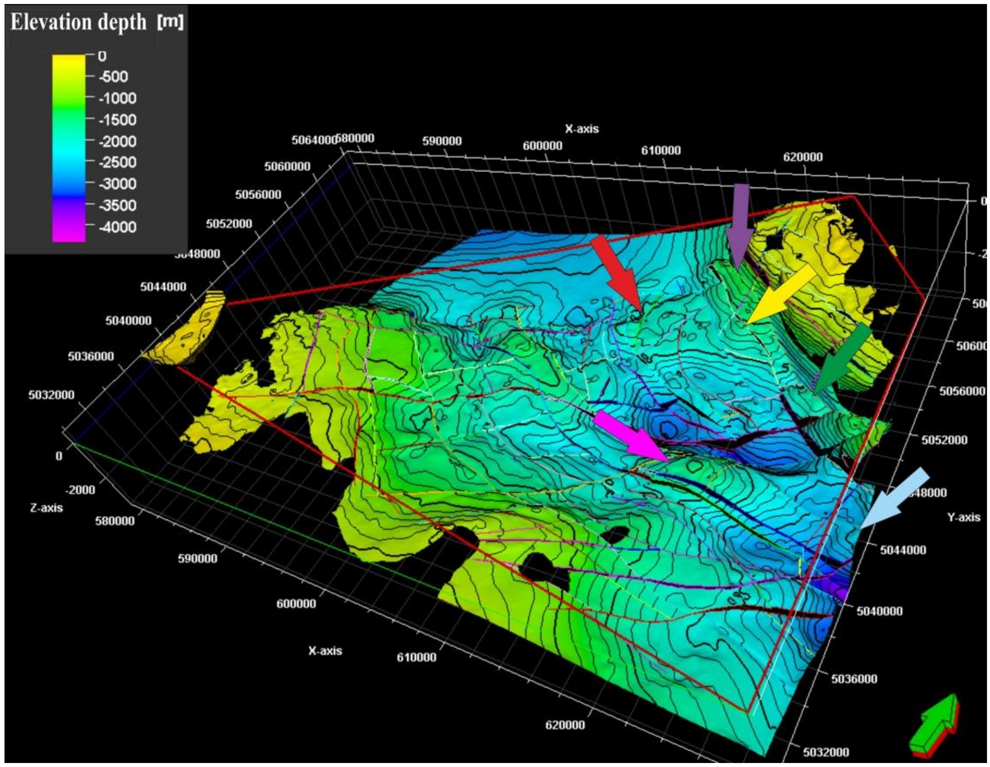

Figure 10: *Subsurface model along the plane of e-log marker "Rs5"*

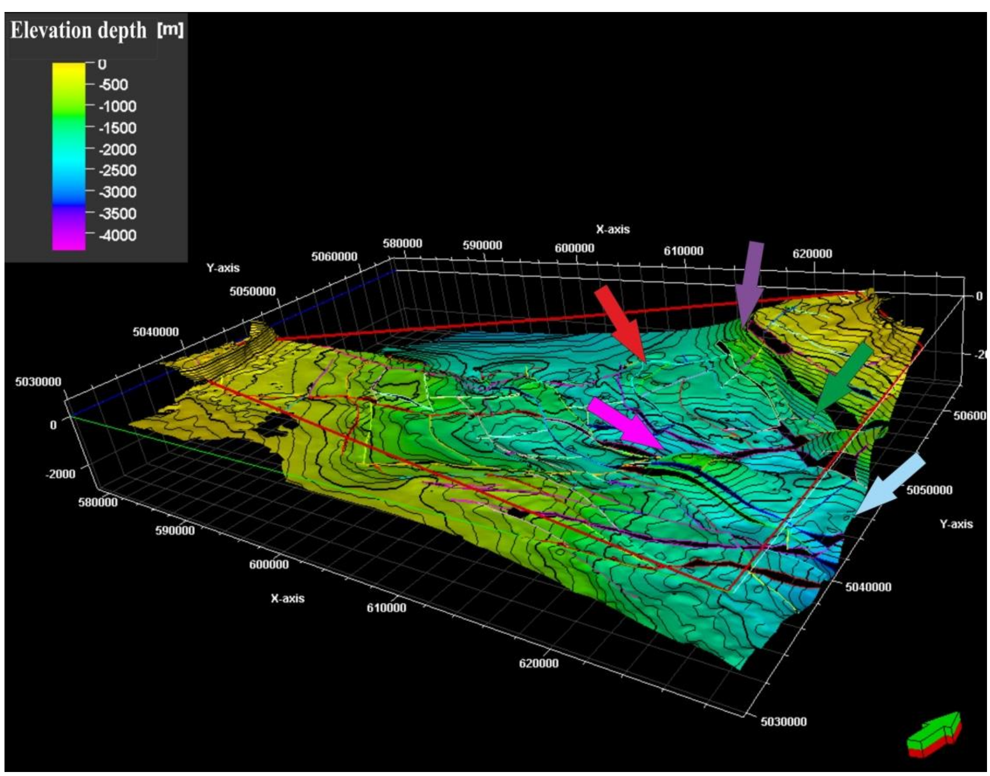

Figure 11: *Subsurface model along the plane of e-log marker "Z' "*

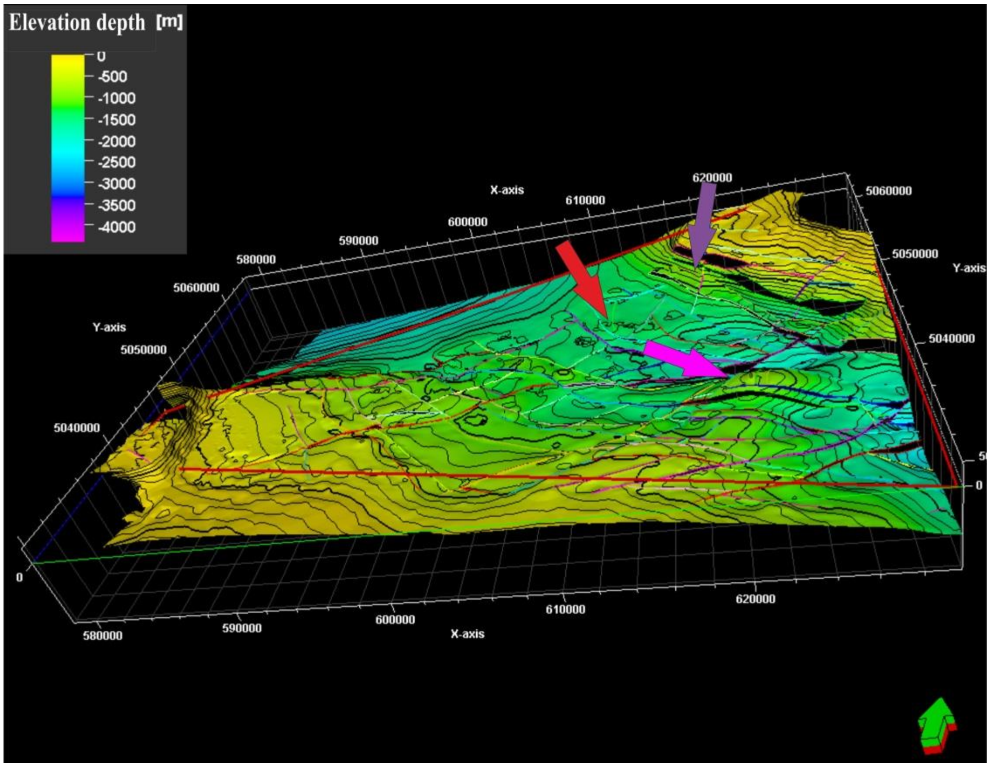

Figure 12 *Subsurface model along the plane of e-log marker "Rφ"*

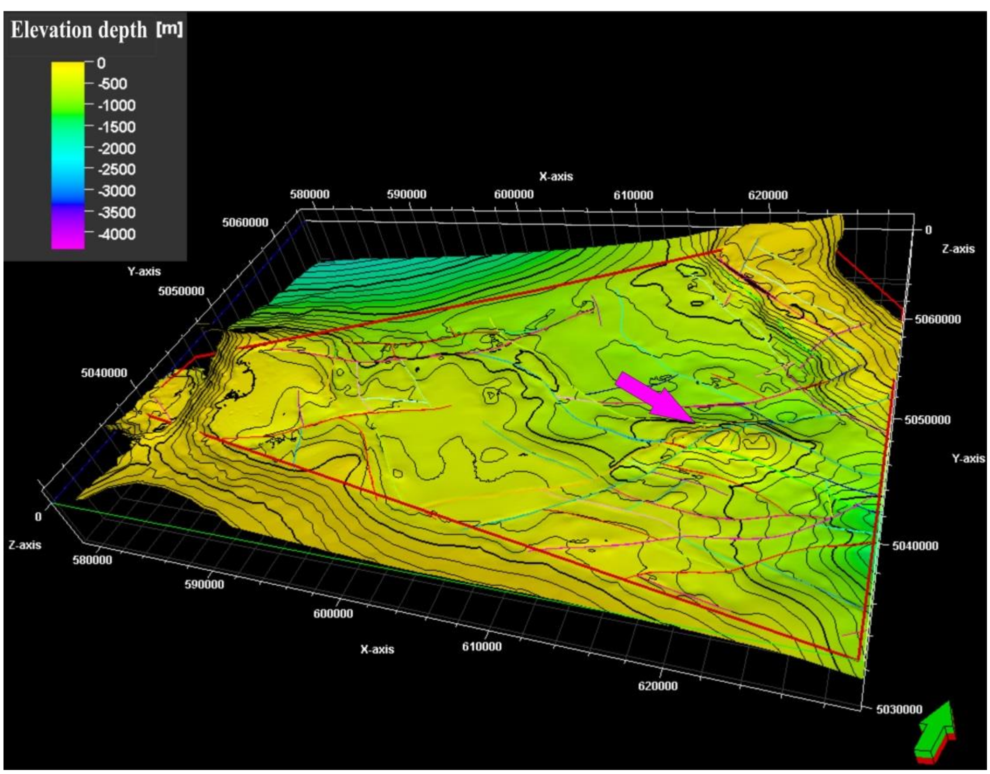

Figure 13: *Subsurface model along the plane of e-log marker "α' "*

4.3. Cross sections derived from the model

Three different cross sections were made in this article. The A – A’ cross section has a 0° orientation, the B – B’ cross section has a 110° orientation, and the C – C’ cross section has a 45° orientation. The northeastern and the southwestern parts of the modelling area are uplifted because of the fault action, which can be seen on A – A’ and C – C’ cross sections. The Glina – Stružec – Popovača fault, which deliniates the area shown by black pointer, can be seen in **Figures 14-15**. The south depression fault can be seen in **Figure 15** (green pointer). The Stružec anticline can also be seen on two cross sections (**Figures 14 and 15**), next to the Glina – Stružec – Popovača fault. The Stružec oil and gas field is divided into three blocks with transverse faults of north – south orientation to the eastern, middle and western block. The division can be seen in the B – B’ cross section.

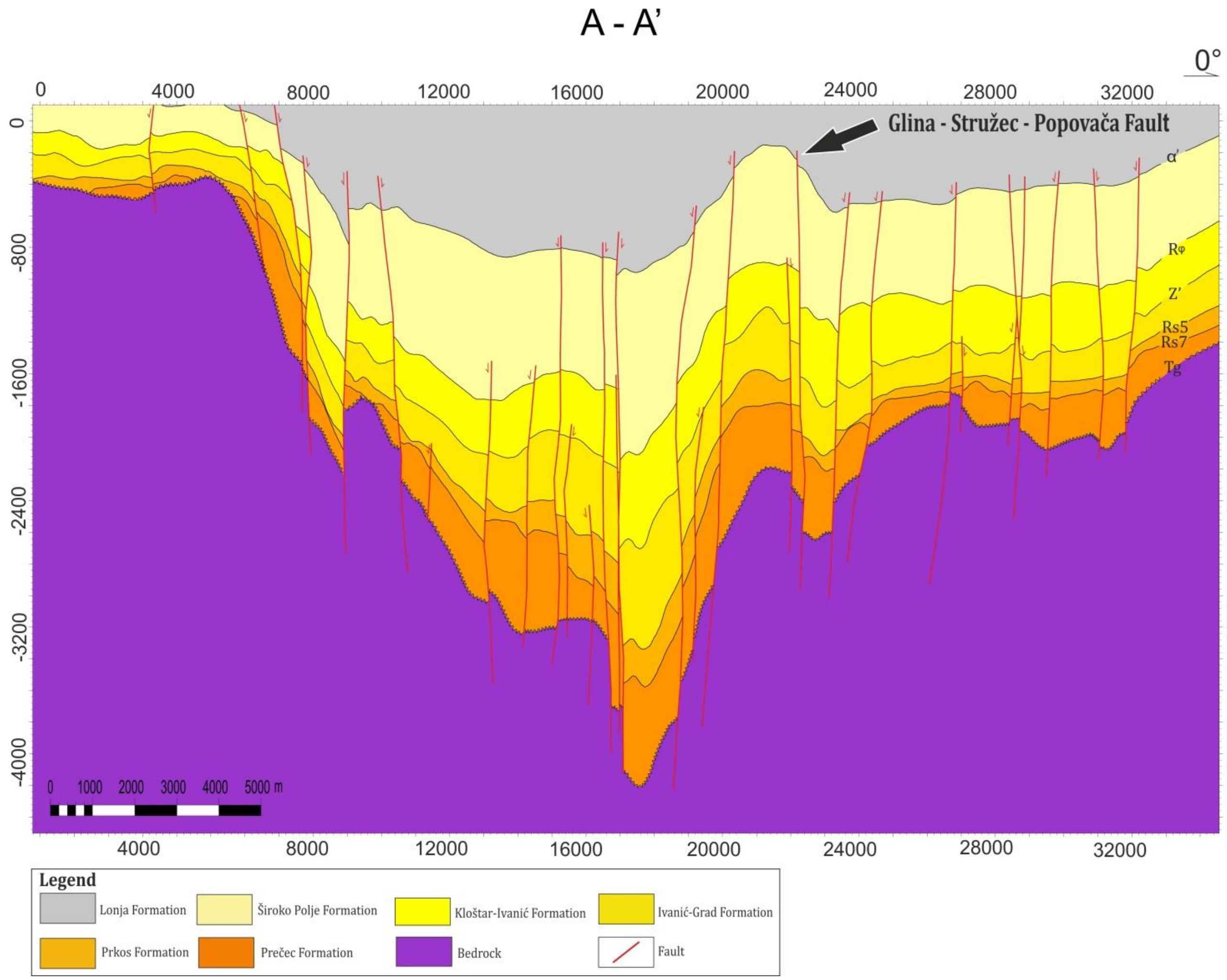

Figure 14: *A – A’ cross section*

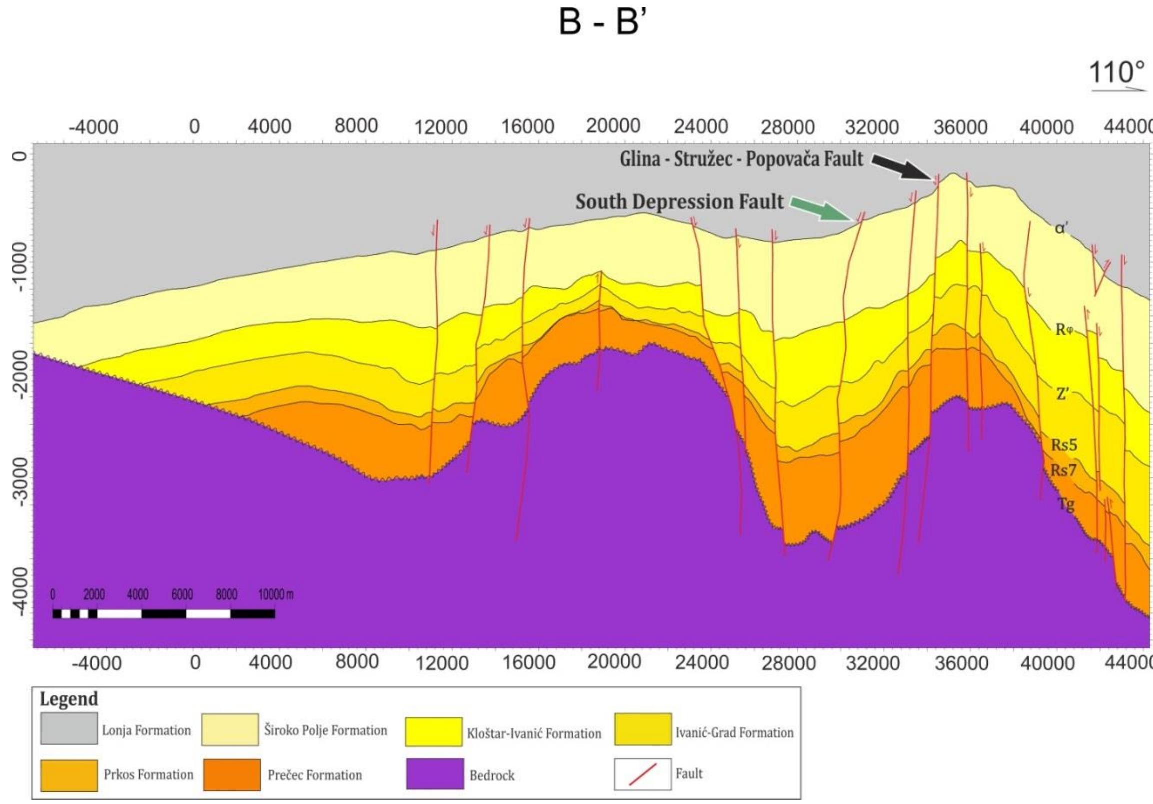

Figure 15: *B – B' cross section*

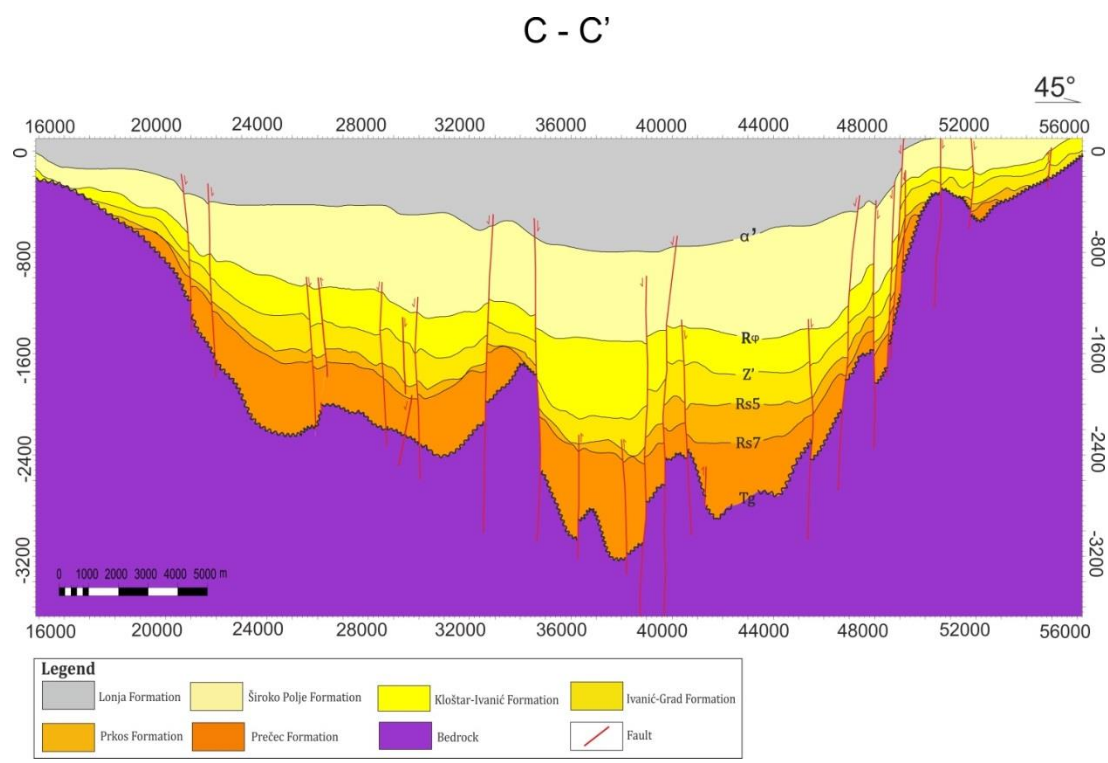

Figure 16: *C – C' cross section*

4.4. The calculation of differences/deviations between models and maps

For the calculation of deviations between handmade maps **(Velić, 1980)** and models, values of depths were gathered at 660 points. For each tested coordinate, point values X and Y are equal for both the legacy and the modelled maps, but the third value Z, which represents depth, in this case must be acquired from six modelled and corresponding legacy maps. Points on legacy maps are located accurately on contour lines; otherwise, depth values would have to be assumed. The percentage of relative errors is calculated for each point using equation (1):

$$\left|\frac{Z(A)-Z(B)}{Z(A)}\right| = X \cdot 100 \qquad (1)$$

where:
Z (A) is the depth value of a single point at legacy maps,
Z (B) is the depth value of a single point of the model and *X* is the ratio between the difference and the original value.

As a result of arithmetic mean of all ratios, average deviation between six modelled and legacy maps of E-log markers and borders were calculated.

Table 1. *Mean values of the percentage deviation between models and handmade maps*

E–log marker/border	Mean values of the deviation percentage (%)
α′	0.5939 %
Rφ	1.3291 %
Z′	0.4261 %
Rs5	0.1834 %
Rs7	0.545 %
Tg	0.8309 %

Maps of statistical deviation percentage (**Figures 17-22**) were made to show the spatial distribution of deviation between maps in which only legacy isoline data was used for making the surface and modelled ones for each E-log marker and one pre-Neogene border. Spatial distribution of the deviation values was calculated using the *Calculator* tool, according to the equation (4-1) where, contour lines imported from ArcMap were used instead of *Z (A)*, and newly made surfaces from the final subsurface model were used instead of *Z (B)* (**Figures 8-13**). The main differences or the largest deviation values can be observed in the near-fault, as is expected. This method is able to show the deviation values for each spatial point/grid node of the maps. Blank spaces in the maps represent the faults for which it was not possible to calculate the deviation because the deviation is based only on the values of depth, and in this model faults are seen as a separate unit.

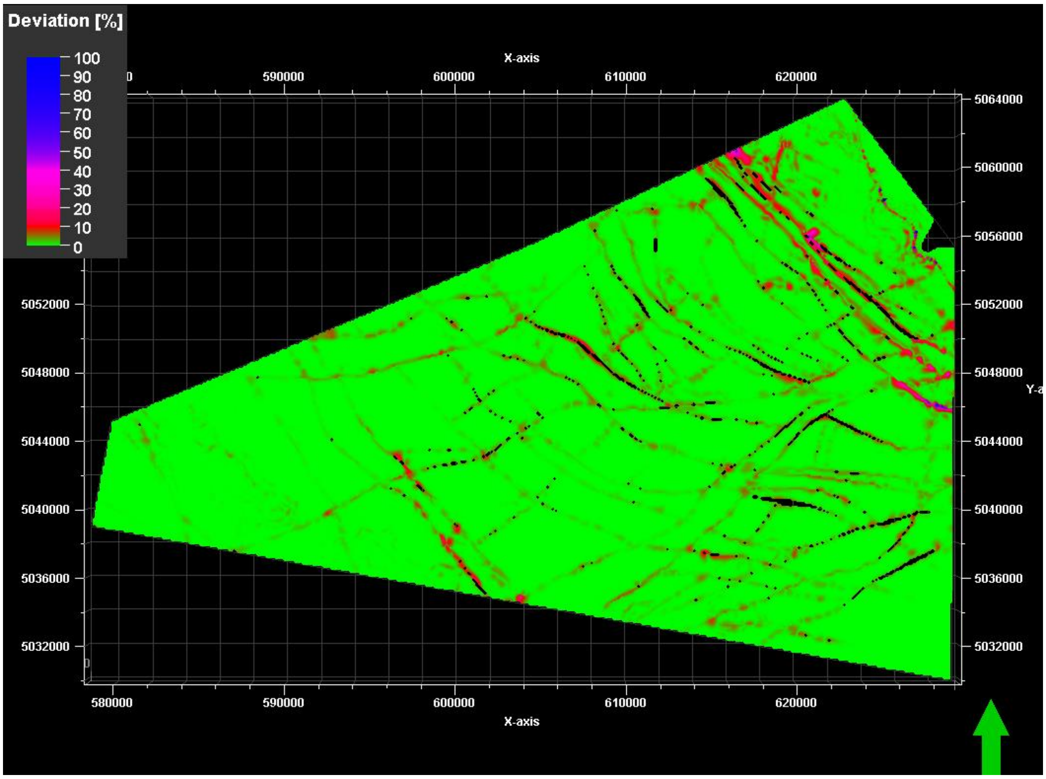

Figure 17: *Deviation percentage map per pre-Neogene top Tg*

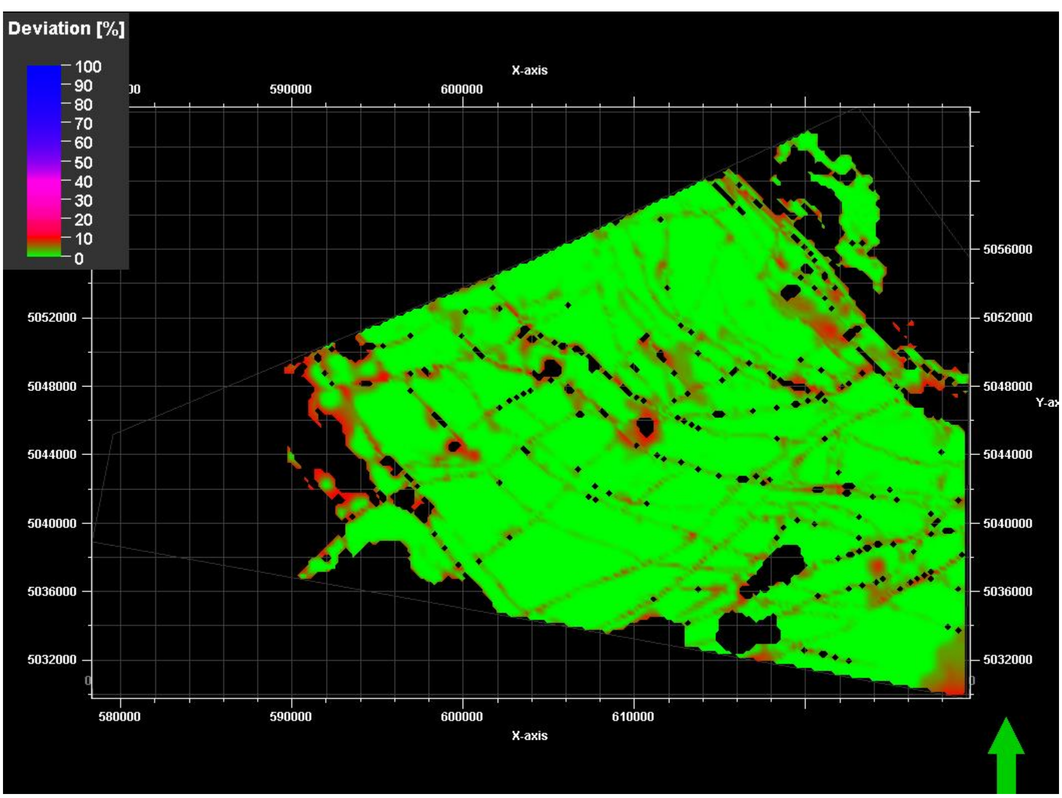

Figure 18: *Deviation percentage map per E-log Rs7*

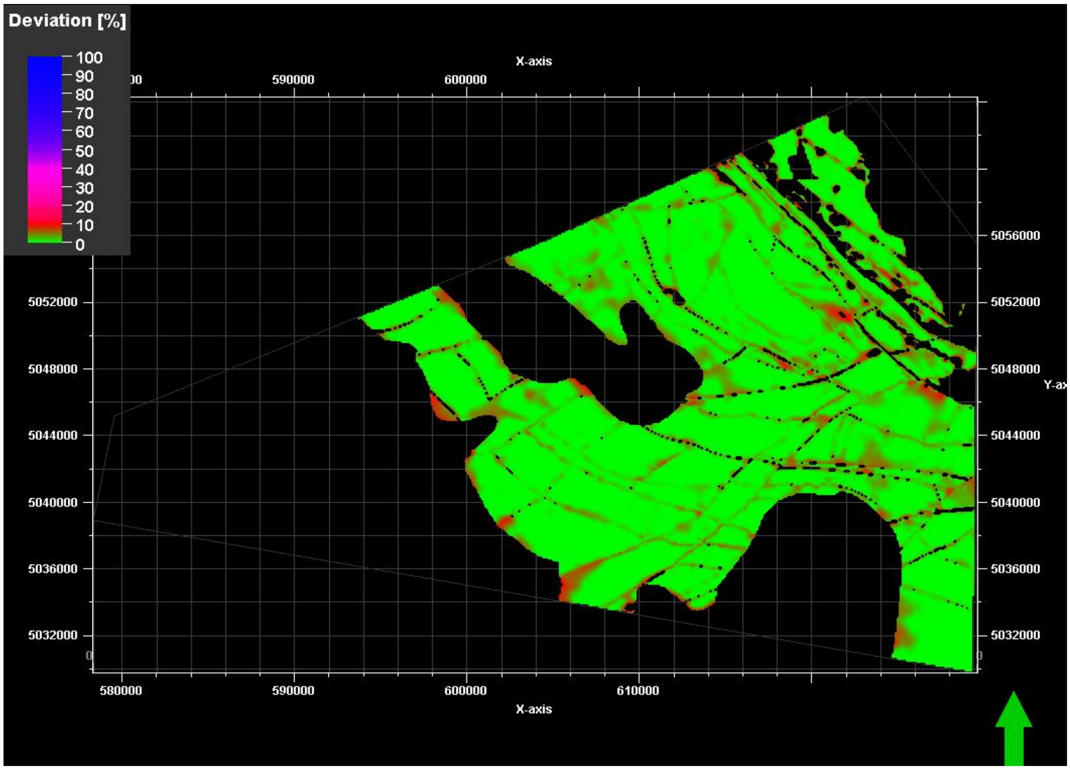

Figure 19: *Deviation percentage map per E-log Rs5*

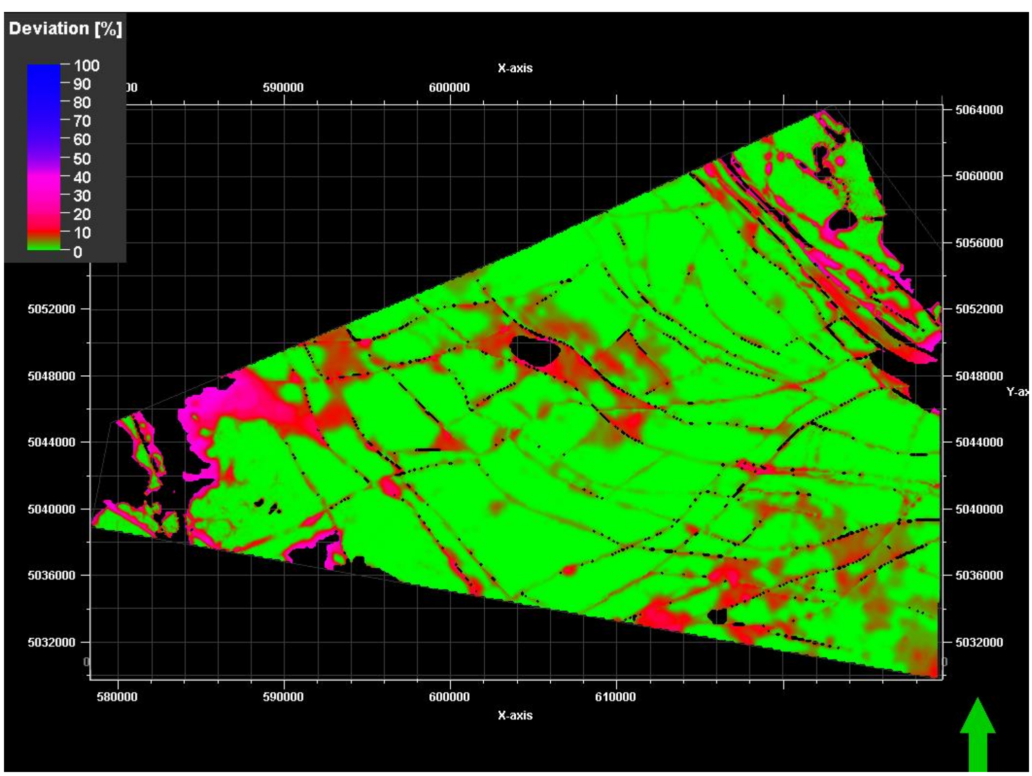

Figure 20: *Deviation percentage map per E-log Z'*

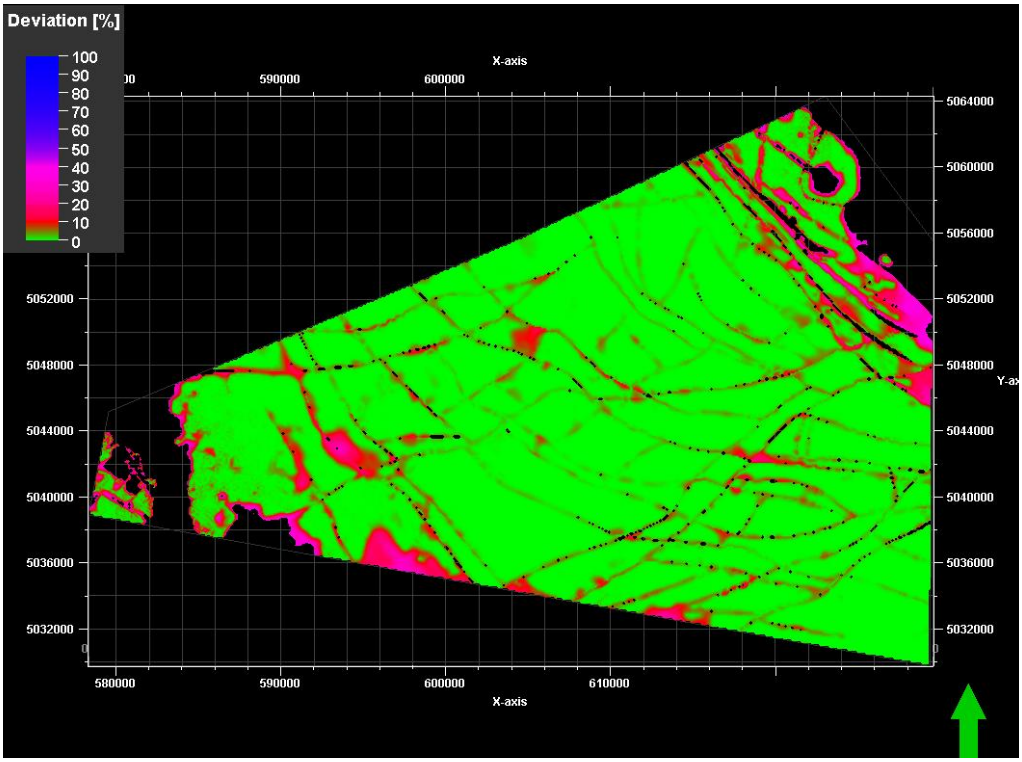

Figure 21: *Deviation percentage map per E-log Rφ*

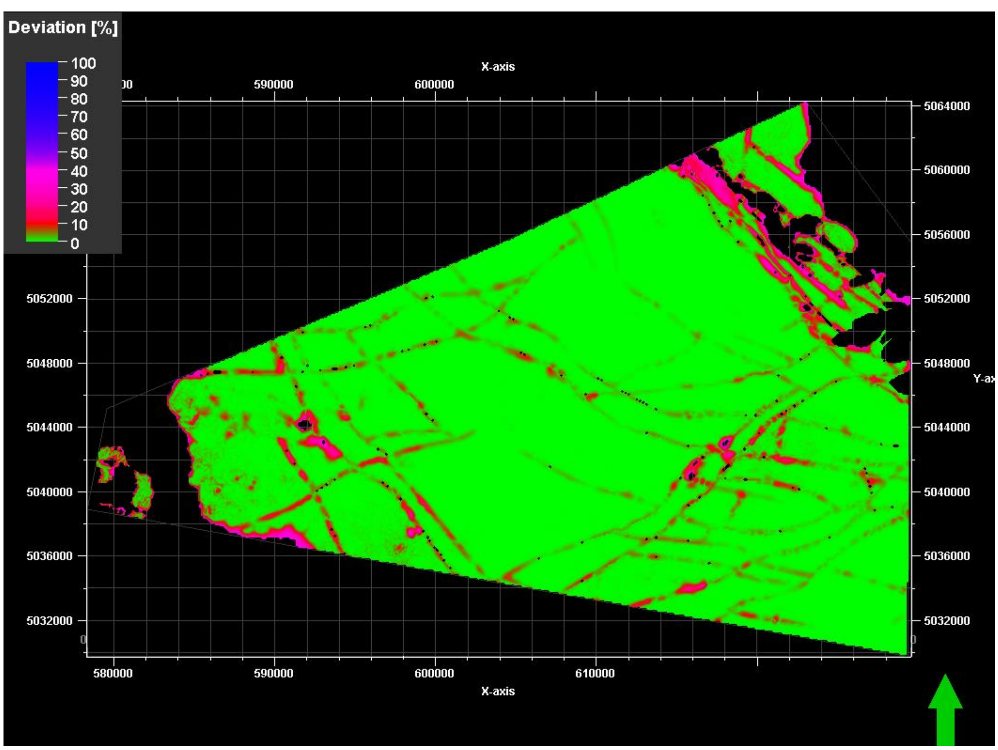

Figure 22: *Deviation percentage map per E-log α'*

In **Figures 17 – 22** green signifies the range of deviation from 0-5%, red from 5-10%, pink 10-40%, and blue 40-100%. It is noted that parts located near the fault contacts, or parts of the field where the terrain is deformed and visibly shifted due to the effects of faults, show higher values of deviation (red and pink) from those points which are located on the non-faulted parts of the area (green). This is good evidence that maps without faults are not suitable for hydrocarbon explorations, especially if the targeted traps in the area are of structural, faulted type. The total mean difference between two approaches is **0.6514 %**.

5. Conclusion

The goal of digitalized data is their use in further petrophysical modelling or basin analysis. Through the digitalization of the data and subsurface modelling in Petrel, structural relationships can be clearly seen in 3D. The diversity of colours for depths and faults facilitates recognition of geological structures and potential hydrocarbon traps in 3D. Relationships between faults and the accurate determination of structures are provided by subsurface modelling. Calculated average value of deviation between models and handmade maps clearly demonstrates the validity of the work methodology. Cross sections can be easily made from subsurface models with corresponding faults. For the successful development of the hydrocarbon reservoirs it is essential to know the position and character of the fault and the location and type of the structural trap. Low error value indicates the accuracy of the digitalization of data and subsurface modelling. Presented deviation percentage maps clearly show that for a detailed hydrocarbon analysis in the rank of plays faulted horizon maps are necessary.

6. Acknowledgment

We would like to thank the Schlumberger Company for providing the Petrel software to the Faculty without which this kind of analysis would not be possible. Also, we would like to thank the Faculty of Mining, Geology and Petroleum Engineering for the opportunity to work with adequate computer equipment.

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Sažetak (abstract in Croatian)

U okviru ovog rada digitalizirani su i obrađeni podatci iz već postojećih strukturnih potpovršinskih karata područja zapadnog dijela Savske depresije (Panonski bazenski sustav), dobivenih na temelju dotadašnjih površinskih geoloških i geofizičkih istraživanja, bušenja i njihove interpretacije. Strukturne karte napravljene su po plohama šest elektrokarotažnih repera i markera koji odjeljuju litostratigrafske jedinice, a to su: „Tg“, „Rs7“, „Rs5“, „Z'“, „Rϕ“ i „α'“. Područje modeliranja prekriva 1053,2 km² površine, a nalazi se u središnjem dijelu Hrvatske, najvećim dijelom u Sisačko – moslavačkoj županiji. Digitalizacija i obrada podataka napravljena je pomoću računalnih programa ArcMap 10.1 te Petrel™ 2013. Dobiveni geološki model jasno pokazuje odnose između glavnih i sporednih rasjeda, geološke strukture, strukturne zamke te utjecaj rasjeda na oblikovanje ploha u podzemlju. Napravljeni trodimenzionalni prikazi strukturnih odnosa, razvoja geoloških struktura po različitim plohama EK – repera i markera te pomaci terena uzorkovani rasjedima uvelike obogaćuju sliku i razumijevanje dijela podzemlja zapadnog dijela Savske depresije. Načinjena su i tri profila A-A’, B-B’ i C-C’ na kojima se jasno uočavaju antiklinale i glavni rasjedi geomodeliranog područja. Računanjem prosječne vrijednosti odstupanja modela od ručno izrađenih strukturnih karata, koje iznosi 0,65 %, utvrđena je velika točnost i preciznost same obrade podataka. Također za svaku potpovršinsku kartu napravljen je i model nesigurnosti koji ukazuje da se najveća statistička odstupanja odnose na vrlo rasjednuta područja. Navedenim postupcima digitalizacije i geološkog modeliranja opisane su i prikazane prednosti i pogrješke koje nastaju tijekom izrađivanja geološkog modela.

Ključne riječi

Naftno-plinsko polje Stružec, Savska depresija, potpovršinsko modeliranje, digitalizacija