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SYNRIFT AND POSTRIFT MIOCENE SEDIMENTS OF NORTHERN BANAT, SERBIA

SINRIFTNI I POSTRIFTNI MIOCENSKI SEDIMENTI SEVERNOG BANATA U SRBIJI

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Abstract: A large number of high-quality data obtained during many years of oil and gas exploration on the territory of Vojvodina has enabled the creation of a subsurface model of northern Banat. Special emphasis is placed on the Miocene sediments which are the most important part of sedimentary cover due to its geological and economic potential. The rifting phase varies through time and space across the Serbian part of Pannonian Basin. The Lower Miocene, Badenian and Sarmatian sediments belong to synrift in broader sense, while Pannonian and Pontian sediments are assigned as postrift sediments. The depositional environment determination of postrift sediments were enabled with use of lithostratigraphy method.

Key words: Miocene, Pannonian Basin, Northern Banat, rifting, Lithostratigraphy

Apstrakt: Veliki broj kvalitetnih podatka dobijenih višegodišnjim istraživanjima nafte i gasa na prostoru Vojvodine omogućio je izradu potpovršinskog modela severnog Banata. Poseban akcenat je stavljen na miocenske sedimente koji predstavljaju najznačajniji deo sedimentnog pokrivača zbog svog geološkog i ekonomskog potencijala. Riftogeneza u srpskom delu Panonskog basena se menja u vremenu i prostoru. Donjomiocenski, badenski i sarmatski sedimenti pripadaju sinriftogenetskoj fazi u širem smislu, dok fazi postriftogeneze pripadaju panonski i pontski sedimenti. Primenom litostratigrafske metode bilo je moguće izdvojiti depozicione sredine u okviru postriftnih sedimenata.

Ključne reči: miocen, Panonski basen, severni Banat, riftogeneza, litostratigrafija

1. INTRODUCTION

The exploration area of northern Banat is located in the southeastern part of the Pannonian basin settled between the mountain ranges of the Carpathians, the Alps and the Dinarides (Figure 1). In the area of northern Banat, a large number of

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commercial oil and gas fields were discovered, which makes this area economically significant. The most important part of the hydrocarbon system represents the Miocene sediments, which are the main source, reservoir and seal rocks in the Pannonian Basin. The geological significance of this area is the presence of both, the deepest depressions in Serbia and different tectonic units in the base of the underlying Neogene sediments (Figure 1 and 2).

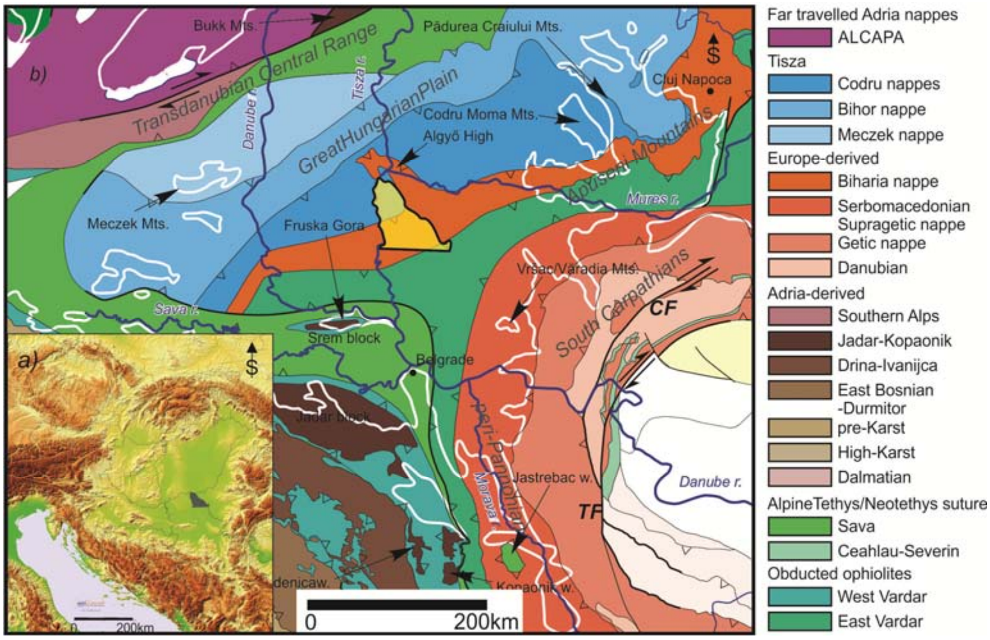

Figure 1 - a) Satellite map of Pannonian Basin region, black polygon represents the study area of northern Banat; b) Detailed tectonic map of the connection between the Dinarides, South Carpathians and Pannonian Basin (modified from Schmid et al. 2008; Matenco and Radivojević 2012). Yellow polygon represents the northern Banat area. CF – Cerna – Jiu Fault; TF – Timok Fault

One favorable aspect during geological and geophysical interpretation was the fact that the northern Banat falls into a well-researched area. There are a large number of data obtained during deep exploration and development drilling for oil and gas, while additionally, investigated area had the most seismic surveys in the Serbian part of the Pannonian Basin. During the geological interpretation more than 700 2D seismic lines with a total length of 6 000 km, 300 km^2 of 3D seismic and well logging and geological data from 800 wells in 75 localities were used. Also, for better understanding of tectonics, Miocene sediments progradation and sequence stratigraphy relationships, extensive data from the entire Serbian part of the Pannonian Basin, as well as information from neighboring Hungary and Romania were used. Unfortunately, during working on the project no unique 3D survey existed which would enable use of all modern software applications.

The biggest problem when creating a subsurface model was the "industry" - chronostratigraphic division of Upper Miocene sediments, which in an intense progradation environment inevitably leads to a false correlation. Use of lithostratigraphy helps to overcome this problem and enabled dividing of the depositional environments in the thickest Miocene sediment sequence in northern Banat. Another problem was the rift system axis migration, as a result of asymmetric opening and migration of the depositional area in time and space. Asymmetric Pannonian basin continental rifting does not allow a simple division of Miocene sediments to syn- and post-rift ones. Upper Miocene sediments can be found in both phases, so these terms are used in a broad sense – *sensu lato*.

2. GEOLOGICAL SETTING

The Pannonian Basin was part of Paratethys, which once covered the area from the Gulf of Lion in Western Europe to the Caspian Sea in Central Asia (Steiniger et al. 1988; Rögl 1999). The Paratethys was typical back-arc basin with much thinned continental crust (Balla 1986; Horváth 1993; Horváth et al. 2006; Royden 1988). The major tectonic units present on the territory of northern Banat are Tisza unit (Codru nappes), Dacia unit (Biharia nappes) and the East Vardar Zone (Figure 1).

Tisa unit is located in the far northwestern part, with Triassic sediments preserved only in places that have not undergone block uplifting and erosion during the Miocene extension. The Triassic sedimentary facies and geometry of Tisa unit is similar to Codru and Bihor nappes in the Apuseni Mountains (Bleahu et al. 1981; Čanović and Kemenci 1988; Matenco and Radivojević 2012).

Biharia unit can be extended from the Apuseni Mountains, over the Algyő High (in south-eastern Hungary) (Lelkes-Felvári et al. 2005; Schmid et al. 2008), to the central part of Vojvodina. This zone, with rough east-west orientation, is characterized by metamorphic basement that is covered by Lower Cretaceous (shallow water to pelagic) and the Upper Cretaceous (deep-sea) sediments. The exception is easternmost part of the unit, where over metamorphic rocks lie non-metamorphosed to slightly metamorphosed Middle Triassic sediments. From this it can be concluded that the degree of metamorphism decreases along this unit, from highly metamorphosed at north to fully non-metamorphosed units at the south (Matenco and Radivojević, 2012).

Only small part of East Vardar zone is present at northern Banat area. Two-vergent shape of East Vardar ophiolite is the result of poly-phase deformation. Vardar ophiolites had a significantly higher distribution to the north and northeast before the exhumation and erosion.

The four local structures could be notice in the investigated area (Figure 2), Velebit and Kikinda-Mokrin High and Banatsko Aranđelovo and Srpska Crnja Trough (Radivojević, 2014). The Banatsko Aranđelovo depression correspond to Hungarian Szeged Depression, Srpska Crnja Trough is equivalent of Mako Trough, while Kikinda-Mokrin High correspond to Algyő High.

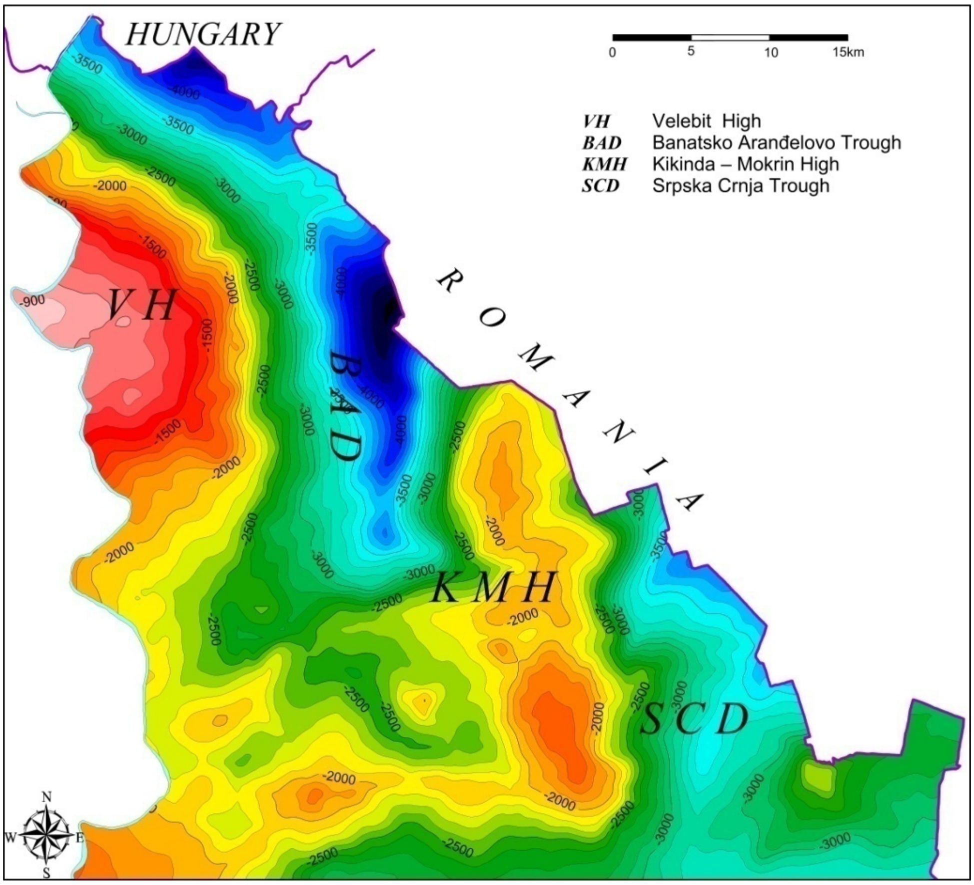

Figure 2 - Depth - structural map of Neogene basement (Radivojević, 2014)

3. MATERIAL AND METHODOLOGY

The subsurface geology of northern Banat was made with contribution of data obtained by seismic surveys, oil and gas deep drilling, geophysical well logging, core and cuttings analysis, etc.

Within geophysical works different methods like gravity, magnetism, seismic, well logging and vertical seismic profiling (VSP) were applied. The most important role in the development of the regional subsurface model had a reflective seismic method, which were followed by well logging and VSP. Regarding previous geophysical surveys northern Banat could be considered as well matured exploration area with high quantity and quality data.

Since the folding of seismic lines acquired before 90's was low, for subsurface interpretation mostly newer seismic lines were used whenever that was possible, Also, well logging quality is dictated by the year of execution of works and equipment used at that time. In the area of northern Banat, well logging was conducted at 75 sites in about 800 open-hole and cased-hole wells.

Integrating borehole and seismic data were obtained by use of VSP. A first VSP survey in northern Banat was performed in 1990, and even though the quality of measurement in the first phase was not satisfactory, with the improvement of technology and equipment, measurement reached the level of high quality data. Based on thirty VSP measurements in northern Banat, average velocity model for different geological environment was made and used for time-depth conversion.

The most important data for subsurface geology interpretation were obtained from exploration drilling. Data collected from cuttings and cores and their examination allowed detailed interpretation of stratigraphy, sedimentology, paleogeography, petroleum geology as well as facies and depositional environment interpretation.

For an exploration of hydrocarbon, hydro and geothermal energy in northern Banat more than 250 wildcat and appraisal wells were drilled. Besides that, for oil production increasing a numerous development and exploitation wells were drilled which were also used for subsurface model interpretation.

Two different independent sets of data collected by drilling were used for interpretation of lithology, stratigraphy and depositional environments. The first set of data (cuttings, cores and drilling parameters) is obtained directly during drilling. Before well logging method start to be implemented the only data about subsurface geology were presented by mud logging. Mud logging is detailed geological record made during the drilling consisted of lithology, rate of penetration, the bit data, calcimetry, gas and oil shows, etc. Second set of data is presented by well log measurements which helped in lithological, stratigraphic and depositional environment interpretation.

The core is the only physical undisturbed sample from the well which was used to analyze petrological, mineralogical and sedimentological conditions, as well as for micro and macro paleontological analysis. In addition to the core, determining the micropaleopalynological analysis was carried out on cuttings. Geochemical studies made from cuttings in over 100 wells allowed the numerous conclusion about the source rock potential, kerogen types, total organic carbon (TOC), migration processes, type and volume of remaining hydrocarbon and conditions for their generation, accumulation and preservation.

The first phase of creating the subsurface model was quality control of all geophysical and geological data. The next stage includes determination of lithology, stratigraphy and depositional environments based on data obtained from drilling and well log measurements. At this stage both, seismic interpretation and velocity model were developed which allowed time-depth conversion of structural maps. The third and final stage was seismic stratigraphy and sequence stratigraphy interpretation of Miocene sediments (Radivojević, 2014). When creating a subsurface model well logging, seismic, seismic stratigraphy and tectonostratigraphy methods were used (Radivojević, 2014), while for the more precise correlation purpose and regional understanding data from neighboring areas were considered.

4. RESEARCH RESULTS AND DISCUSSION

Due to the different biostratigraphic and tectonic evolution of the Neogene, Laskarev (1924) separated the northern bioprovince Paratethys from the Mediterranean bioprovince Tethys. Because of the intensive tectonic activity which lead to significant paleogeographic and biogeographic difference stratigraphic correlation between Paratethys and Mediterranean is difficult. Biostratigraphic correlations between the Pannonian Basin, as part of the Central Paratethys and the Mediterranean are fairly simple to the Upper Miocene, when complete and final separation of bioprovince come in on the stage.

In the area of northern Banat, Miocene sediments are present in their full development (Table 1).

Table 1 - Top/bottom of Miocene units

	Upper Pontian	Lower Pontian	Pannonian	Sarmatian	Badenian	Lower Miocene
Number of wells	202	186	127	31	66	3
Top [m]						
Highest	867	852	1362	1878	1403	2628
Average	1160	1439	1970	2080	2204	2774
Lowest	1507	2020	3312	2504	3509	3000
Bottom [m]						
Highest	852	926	1403	1890	1438	2764
Average	1496	1878	2089	2099	2252	2939
Lowest	2020	3359	3509	2521	3570	3252

Lower Miocene sediments have very limited distribution and were confirmed in just three wells. Middle Miocene has a much larger distribution, with well developed Badenian (especially its lower part) and very limited development of Sarmatian sediments. Upper Miocene (Pannonian, Pontian) sediments are the most widely distributed, both horizontally and vertically.

4.1. Synrift sediments *sensu lato*

The extension of the Pannonian Basin has not occurred simultaneously throughout the area, and it is possible to speak only about synrift and a postrift stage in the broad sense (*sensu lato*). In the area of northern Banat, to synrift stage sediments of the Lower and Middle (Baden and Sarmatian) Miocene could be assigned. The exception is Srpska Crnja depression, where synrift phase is somewhat younger and correspond to the Upper Miocene (Pannonian) (Figure 3). The mechanism of Pannonian Basin opening is explained in detail in the paper from Matenco and Radivojević (2012) and Radivojević (2014).

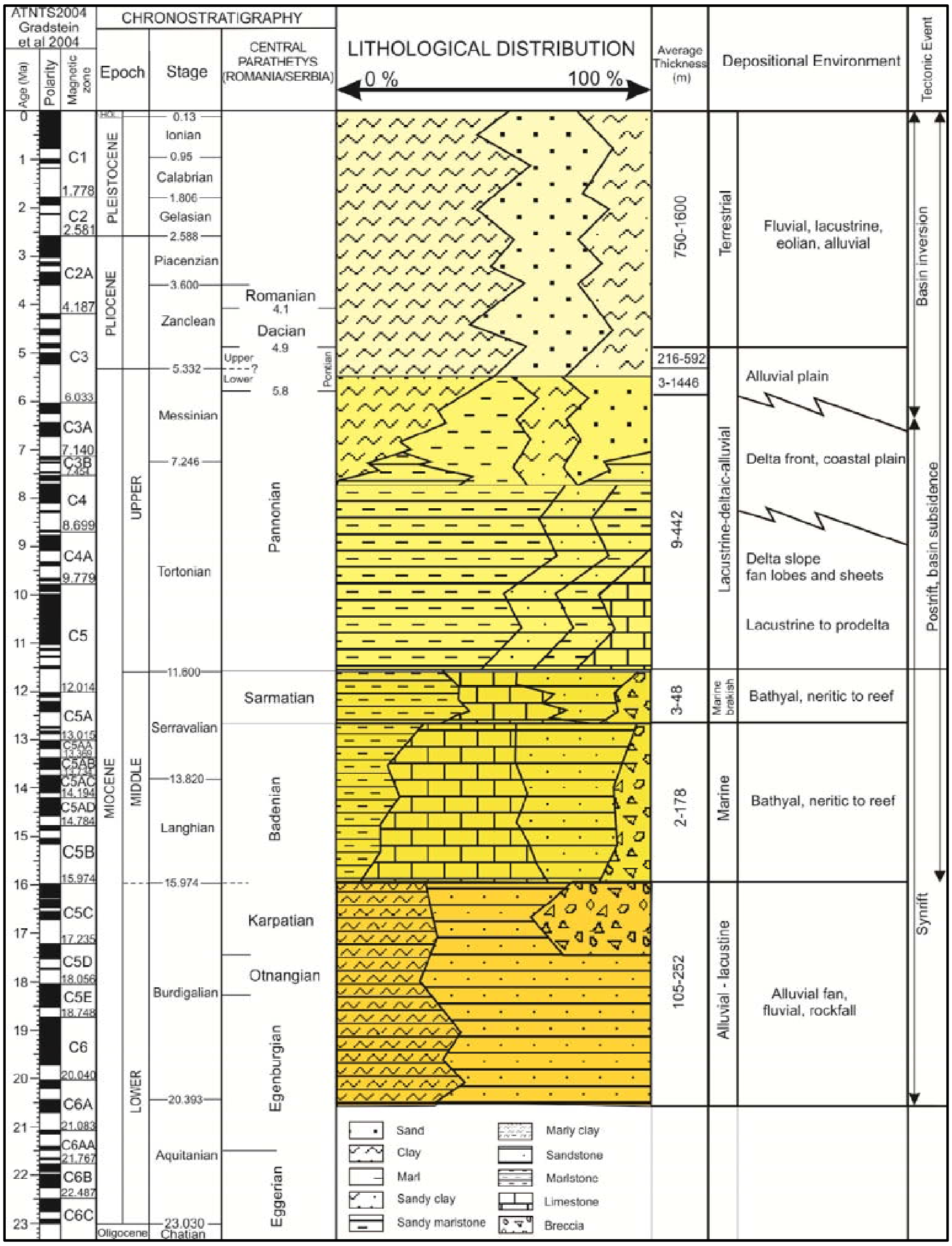

Figure 3 - Lithostratigraphic column of the Miocene sediments of the northern Banat (Gradstein et al. 2004; Rögl 1996; Vasiliev et al. 2005, 2010; Pigott and Radivojević 2010; Radivojević et al. 2010; Matenco and Radivojević 2012; Radivojević, 2014)

4.1.1. Undivided Lower Miocene

Directly below biostratigraphically confirmed Middle Miocene lays Lower Miocene sediments. The fossil remains are completely absent and not found at any of the well, which drilled Lower Miocene, so that their age was generated based on the analogy with the neighboring areas. Because of the lack of fossils it is also not possible to conclude to which stage of Lower Miocene those sediments belong, so they are assigned as undivided. Lower Miocene in the territory of northern Banat has an extremely limited distribution (Table 1), because of which for this stratigraphic level no structural map was made, while its presence is indicated on the depth structural map of Badenian sediments (Figure 4).

Series of iron rich polymictic conglomerates, breccias and sandstones without fossil presence was found in a large number of wells in central Banat and three wells in northern Banat (Čanović and Kemenci, 1988). In one of the wells, series of iron rich sandstones, conglomerates and breccias (molasses?) are covered with Badenian sediments, while they are overlying Upper Cretaceous (Turonian-Senon) deposits. The youngest reworked rocks are particles of neritic Upper Senonian limestones and Upper Cretaceous silts and sandstones with pelagic microfossils (globigerinas, globigerinelas, herohelicidas). The age of these formations is not precisely determined because of the complete absence of *in situ* fossils. Still based on existing fragments of Upper Senonian limestone, one could conclude that the coarse grained formation is younger than Senonian. The presence of spores and pollen indicates the Middle Tertiary – probably the Lower Miocene (Hajder, 2003) age. Probably to the forth mentioned series also belong iron rich sandstone and conglomerate deposits from the well in the southeast (Figure 4, Čanović and Kemenci, 1988). This series lays over crystalline basement, while it is covered by Pannonian and Pontian sediments.

The Lower Miocene sediments in southernmost well (Figure 4) is represented with polymictic conglomerates, coarse sandstones, sandy limestones, silts, marlstones and claystones. Conglomerate particles were made of diabase, aggregate granoblastic quartz, cataclized granite, chlorite schists, silts, micritic limestone, organic dolomitic limestone, quartzite and fine grained greywacke. Sandstones have similar composition like conglomerates with sandy matrix and sparicalcite. In single limestone fragment M. Čanović, determinate Triassic mollusc which confirms the post Triassic age of these sediments (Hajder, 2003). The pollen and spore analysis confirm presence of Middle Tertiary microflora, while Mesozoic forms are missing, which led to conclusion that these sediments are of Lower Miocene age or somewhat older (Šećerov in the period 1975-1987).

4.1.2. Badenian

Badenian sediments are drilled and paleontologicaly proven in a large number of wells (Table 1) in the northern Banat area. Badenian sediments transgressively lay over granitoids and metamorphic rocks of Paleozoic age, and Lower and Middle Triassic and Lower Miocene sediments. Badenian is mostly present with its lower part, so usually the hiatus towards the younger formations is present. The thickness of the Badenian sediments in northern Banat is a few dozen meters, while their thickness significantly increases toward the south (Radivojević, 2014). In a number of wells, this stratigraphic unit is assumed on the basis of lithological and stratigraphic correlations and well log interpretation. The Badenian sediments are deepest in Banatsko Aranđelovo and Srpska Crnja Trough (3.5 km to 4 km), while in central (Kikinda Mokrin) and northwestern (Velebit) Highs they are missing due to erosion and non-deposition (Figure 4).

Lower Badenian sediments diverse lithologicaly and are represented by detrital, carbonate-detrital, carbonate and volcaniclastic formations. Breccias with sandy matrix and sandstones are made of different rock particles like quartz grains, pieces of feldspars, muscovite, chlorite, garnet (pyrop), zircon, epidote and pyrite. Sometimes it is possible to find sandstones with high glauconite content, even up to 30%. The clastic sediments often show a transition towards the limestone when the amount of carbonate increase, while the portion of clastic component drops (Pigott and Radivojević, 2010).

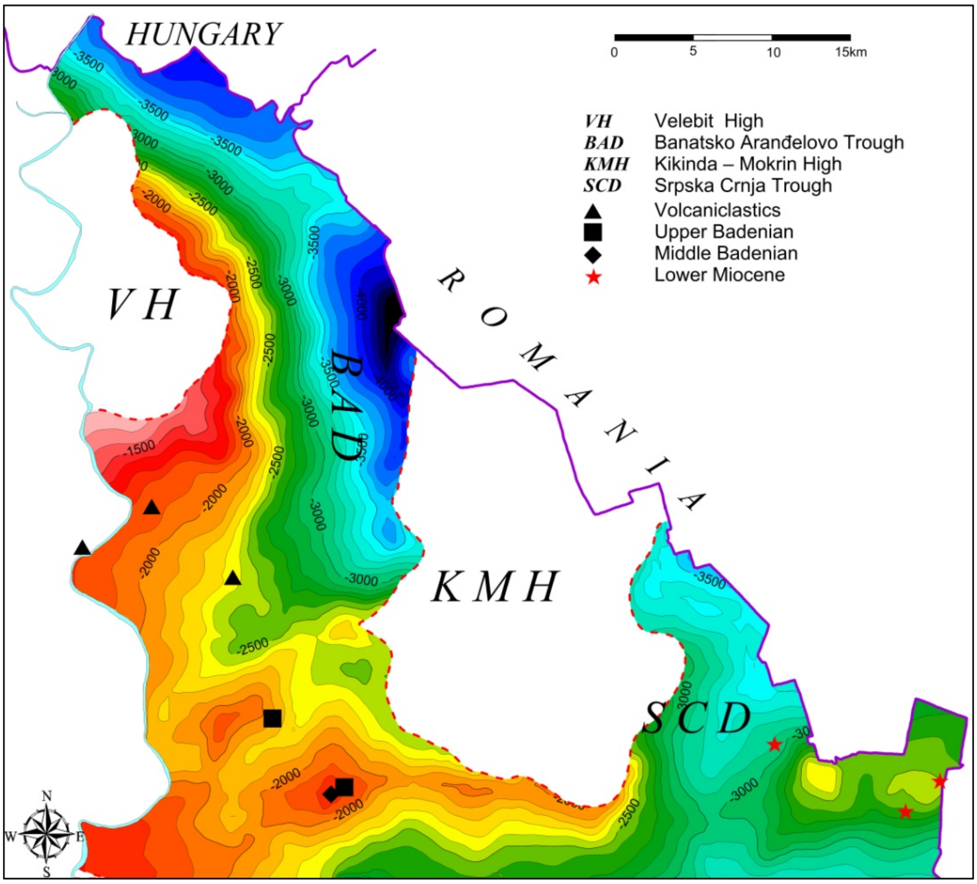

Figure 4 - Depth - structural map of Badenian sediments (Radivojević, 2014)

Fossil fauna in these area were determined in last sixty years (Marković 1954-1984; Buljan 1964-1983; Čanović 1967-1991; Bogićević 2000-2013; Gajić 2000-2013; Radivojević et al. 2010) and featured with rare samples of shallow-water benthic foraminifera (*Heterostegina, Amphistegina, Elphidium, Cibicides* etc.), molluscs and echinoderms detritus and fragments of red algae and bryozoans. Clastic sediments of northern Banat showing the fining-upward trend in the upper part of the stratigraphic column (from conglomerate toward silt) litofacialy correspond to the Hungarian Mako formation. Limestones are micritic (biomicrite, intramcrite) or sparitic, gray-brown, gray to white colour, massive or laminated texture, abundant with reef complex fossils (*Lithothamnium, Lithophylum*, bryozoa, large benthic foraminifera, molluscs, echinoids etc.). At the same time, in the deeper water pelitic limestones with numerous Lower Badenian pelagic foraminifera *Praeorbulina glomerosa circularis, Orbulina suturalis, Globigerinoides bisphericus, G. trilobus, G. quadrilobatus, Globigerinopsis grilli, Globigerina praebulloides, Globigerina bulloides, G. concinna*, etc., (Marković in the period 1954-1984; Radivojević et al. 2010) were deposited. Carbonate part of Badenian sediments corresponds to Ebes formation in Hungary and Leithakalk in Austria. Volcanoclastic, represented by tuffs and tuffites were confirmed in only three wells in the western part of the exploration area (Figure 4). Tuffs are built from the basic material, crystalloclasts, lithoclasts and vitroclasts. The base material is made of glass, carbonate and cryptocristal minerals (quartz, feldspar, kaolinite, sericite) formed during devitrification of volcanic glass. Crystalloclasts are made of quartz, plagioclase, biotite, chlorite and metal-minerals, while the lithoclasts are approximately the same size, different shape and represented by limestones, cherts, sandstones, volcanics, shales, granites and quartz-sericite schist. Vitroclasts are transparent and colorless, generally irregular shape, although there could be also ellipsoidal and round. Rare fossil shells (*Praeorbulina glomerosa circularis, Orbulina suturalis, Globigerinoides trilobus, Nonion soldanii, Cibicides dutemplei, Gyroidina soldanii* etc.) filled with microsparite are proven during micropaleontological studies (Marković in the period from 1954 to 1984; Radivojević et al. 2010). The structure of this rock is pelitic to psamitic, while the texture is sometimes laminated from the presence of parts that are rich with carbonate and pyroclastic material.

Middle Badenian age is paleontologicaly confirmed only in one borehole in the southwestern part of investigated area (Figure 4). These sediments settled below Lower Pontian sediments are represented by fine to coarse grained, whitish, light gray to gray coloured, quartz-limy sandstones and whitish to gray-white organogenic limestones. Following fossil asociation (*Elphidium crispum*, *E. flexuosum*, *Asterigerina planorbis*, *Globulina gibba*, *Marginulina* sp., *Globorotalia menardii*, *Globigerina bulloides*, *Orbulina suturalis*, *Amphistegina haueri*, *Anomalina rotula*, *Aurila* aff. *cicatricosa*, *Loxoconcha* sp., *Nonion boueanum*, *Rotalia boueana* etc.) confirm the Middle Badenian age of those sediments (Marković in the period 1954-1984; Radivojević et al. 2010).

The sediments of the Upper Badenian are documented in only two wells in the southwestern part of the exploration area (Figure 4). At the base of the Pannonian and Lower Pontian sediments there are yellowish-white, marly Lithotamnion limestones with following microfossil association (*Elphidium crispum*, *Globulina gibba*, *Ammonia beccarii*, *Amphistegina*, *Nonion communis*, *Globigerina bulloides*, *Cibicides lobatulus*, *Discorbis dubia, Asterigerina planorbis*), which according to V. Marković and Radivojević et al., belong to shallow limestone facies of the Upper Badenian. Below these limestones, there are light gray, fine-grained, calcareous sandstones as well as light gray, conglomeratic sandstones without fossil content. Still, based on the correlation of lithologic characteristics with the corresponding stratigraphic horizons in adjacent wells Badenian age could be assumed.

4.1.3. Sarmatian

Sarmatian sediments are much less present then Badenian one and could be found in a small part of Banatsko Aranđelovo Trough and at the Kikinda-Mokrin High (Figure 5). These sediments have a smaller thickness, generally less than 50 m (Radivojević, 2014). At the bottom of these formations usually are metamorphic and magmatic rocks (very rarely Badenian sediments), while the top of a formation is represented by Pannonian sediments. According to Kemenci (1991) and Radivojević et al. (2010), there is no sedimentation discontinuity toward Pannonian sediments.

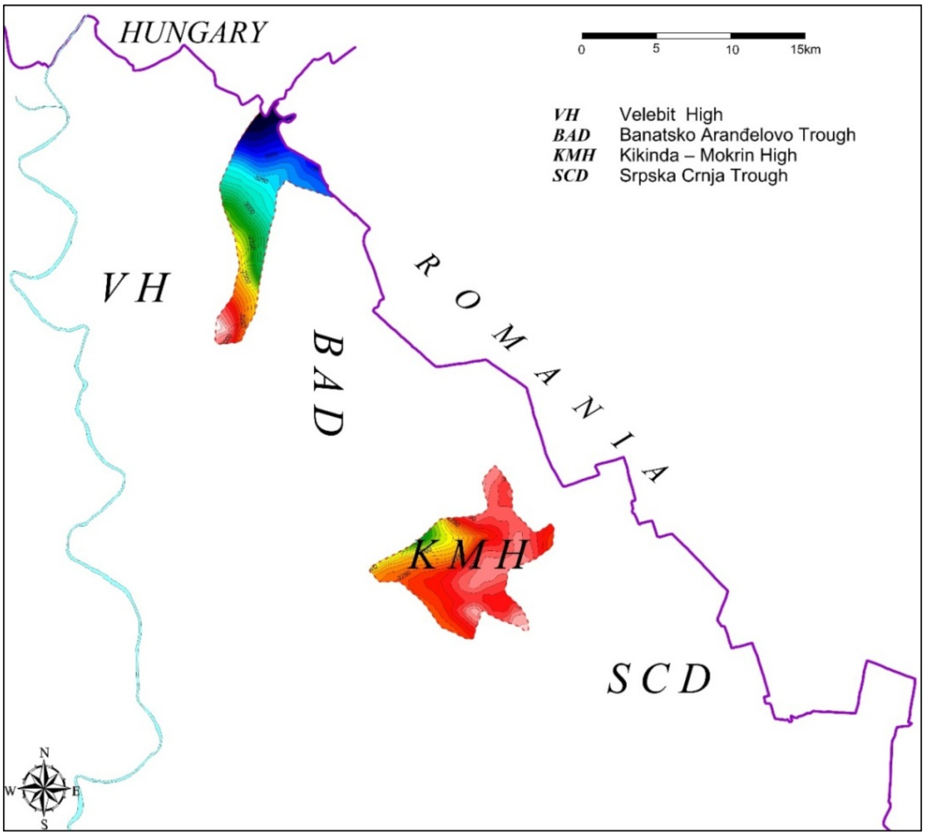

Figure 5 - Depth - structural map of Sarmatian sediments (Radivojević, 2014)

Sarmatian sediments always show a regressive trend (Kemenci 1991; Radivojević et al. 2010) with the deposit of clastic rocks, limestone and rarely marlstone. Clastics were presented by fine to coarse grained, conglomeratic and/or breccoid sandstones (mainly arkose), conglomerates, breccias and conglobreccias. Siliciclastics light gray, gray-green or yellow-white color are always heterogeneous with poorly sorted, bad rounded or angular fragments made of rocks particles, minerals, shell fragments and fossils. The rock particles are mostly made of fragments of granitoids and crystalline schists while less present are mylonite, limestones, siltstones, metasandstones, quartzite, felsic volcanics, gneisses and fine grained sandstone. From minerals most common are quartz, feldspar, plagioclase, muscovite, biotite, chlorite, and small amounts of garnet, zircon, tourmaline, chalcedony and metallic minerals. Carbonate shells and their fragments are often present in cuttings. Sarmatian sediments are besides clastics represented also with more or less detritic limestones.

Marković (in the period 1954-1984) and Radivojević et al. (2010) has designated a rich fossil material indicating the Sarmatian age: *Quinqueloculina longirostra*, *Q. hauerina*, *Q. akneriana*, *Elphidium aculeatum*, *E. crispum*, *E. antoninum*, *E. josephinum*, *E. hauerinum*, *Porosononion granosum*, *Triloculina consobrina*, *T. austriaca*, *T. inflata*, *Aurila notata* etc. In addition, Buljan (in period 1964-1983) and Radivojević et al. (2010) established a diverse fauna of brackish molluscs with the following species: *Modiolus incrassatus*, *Irus gregarius*, *I. vitalianus*, *Pirenella picta*, *Hydrobia frauenfeldi*, *Calliostoma conitesta*, *Calliostoma* sp., *Cardium* sp., *Mactra* sp., *Ervilla* sp., *Gibbula* sp., *Dorsanum* sp.

4.2. Postrift sediments *sensu lato*

The Pannonian, Pontian, Pliocene and Quaternary sediments belong to postrift stage in the broader sense and lays unconformably over the Middle Miocene. A division of Miocene sediments is straightforward until its upper part. Correlation between the Sarmatian and the Upper Miocene of Central and Eastern Paratethys (Ter Borgh et al. 2013), including a proposal for the introduction of Transdanubian (Sacchi and Horvath, 2002) is given in Figure 6.

Lake Pannon was covering the Pannonian Basin during the Upper Miocene. Based on the last accepted stratigraphic division of the Central Paratethys sediments deposited at time of Lake Pannon belongs to the Pannonian and Pontian stage. Due to delta sediments progradation from the northwest direction toward southeast, these sediments are younger in Serbia than in neighboring Hungary (Magyar et al. 2013; Radivojević 2014). The sedimentation of the Upper Neogene in the Pannonian Basin for long has been poorly understood because the lithostratigraphic units were correlated and interpreted in chronostratigraphic sense.

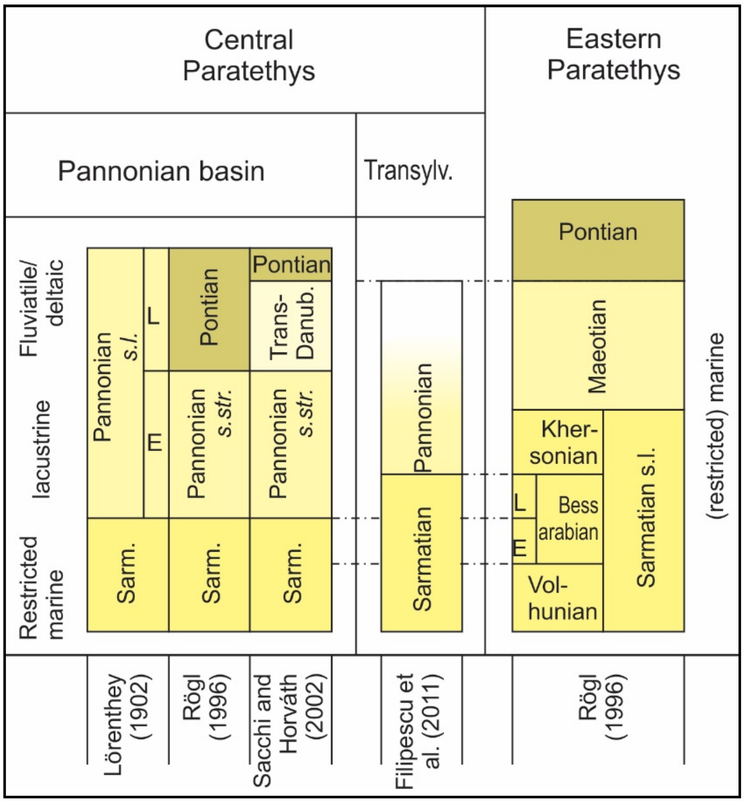

Figure 6 - A comparative stratigraphic division of the Upper Miocene of the Central and Eastern Paratethys (after Ter Borgh et al. 2013).

In neighbouring Hungary, in oil and hydrothermal industry, lithostratigraphy is exclusively used for correlation purposes. Detailed, extensive research of cored postrift material confirmed that lithostratigraphic units correspond to major depositional facies units (Berczi and Phillips 1985; Berczi et al. 1988; Révész et al. 1989; Jámbor 1989; Juhász 1991, 1992, 1994; Phillips et al. 1994; Molenaar et al. 1994, Juhász et al. 2007). Correlation between lithofacial groups and units in Hungary is shown in Figure 7 (Magyar et al. 2006).

In the northern Banat area Pannonian sediments can be correlated with the Hungarian Endrőd and Szolnok formations, while Algyő and Ujfalu formations are well correlated with the Pontian deposits. Pannonian-Pontian fluvial-deltaic deposits make up the largest part of the sediment which filled the Pannonian Basin (Table 1).

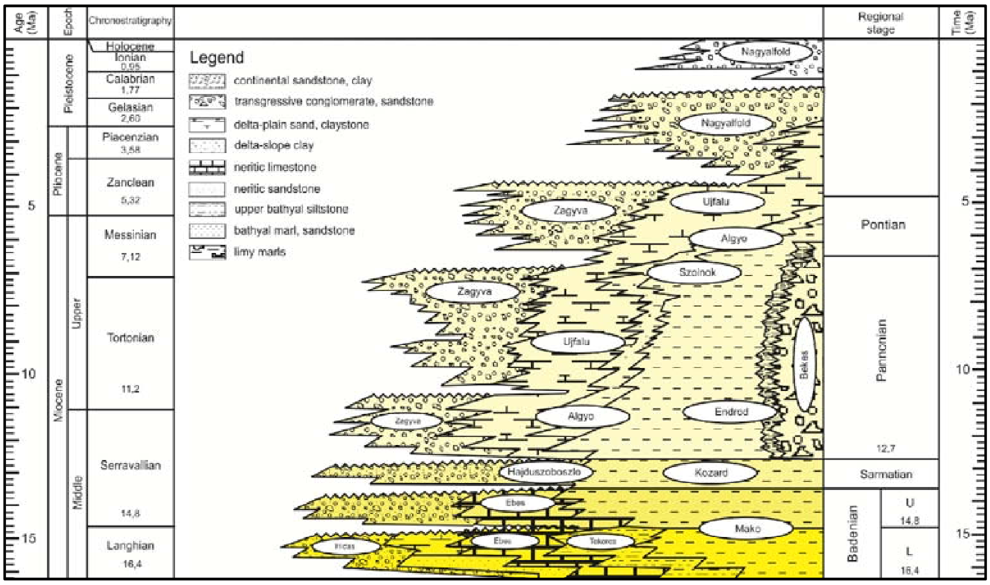

Figure 7 - The Pannonian Basin Neogene with the regional (Central Paratethyan) stages and Miocene-Pliocene lithostratigraphic chart (Tari 1994; Csaszar 1997; Vakarcs 1997; Magyar et al. 2006; modified by Radivojević, 2014).

4.2.1. Pannonian

Pannonian sediments are deepest in Banatsko Aranđelovo and Srpska Crnja Trough (more than 3 km), while they are shallowest in pinch-out area of around 2 km (Figure 8). Pannonian is also confirmed at Velebit High and in the southeastern part, while it is frequently eroded or pinching out at structural crests where there is hiatus between Pontian and Pre-Panonnian sediments. Above Pannonian there are always Pontian sediments. Due to the frequent absence of fossil material and the lack of sedimentological-paleontological analyzes, the Pannonian age of these formations is confirmed only in some wells. In a number of wells Pannonian sediments are assumed based on correlation of petrological-sedimentological characteristics, well log interpretation and correlation, as well as the position of those sediments in the stratigraphic column.

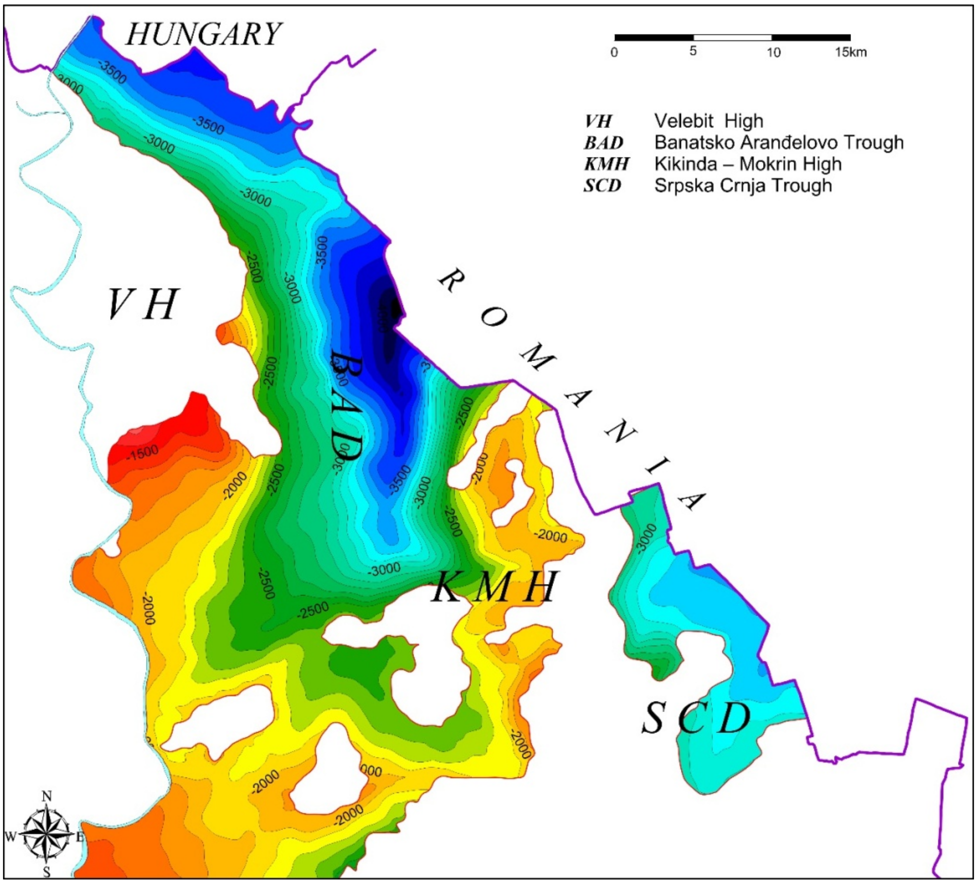

Figure 8 - Depth - structural map of Pannonian sediments (Radivojević, 2014)

Pannonian sediments are represented mainly with clastics - fine, medium and coarse grain sandstones and siltstones, shales, marlstones and limestones. Deep water Lake Pannon basinal successions can be correlated with Endrőd and Szolnok formations (Figure 9). Hemipelagic marlstone and shale (correlative with Endrőd formation), which are typical for starved basins are covered with deep water turbiditic sandstones (correlative with the Szolnok Formation) limited to the deepest parts of the basin. A thick succession of gravitational sediment is built of fine-grained sandstones and siltstones with marl laminas, indicating increased influx of clastic rocks from basin margins.

The recognition of these lithostratigraphic units is quite straightforward on well logs and seismic lines, given the huge difference between lithostratigraphic units (Pigott and Radivojević, 2010). Also, core material allows good correlation between well logs and depositional environment. The characteristic seismic facies which correspond to lithostratigraphic formations are observed on seismic sections (more in Magyar et al. 2013).

Although chronostratigraphicaly insignificant, lithological (facies) border between the slope and shelf sediments have its practical significance. The same also applies to other major facial borders in basinal succession. According to the Stratigraphic Commission of Hungary, sedimentary bodies between these limits are determined by the lithostratigraphic units (formations), each of which has a well-defined facies association, but clearly diachronous limits (Császár, 1997).

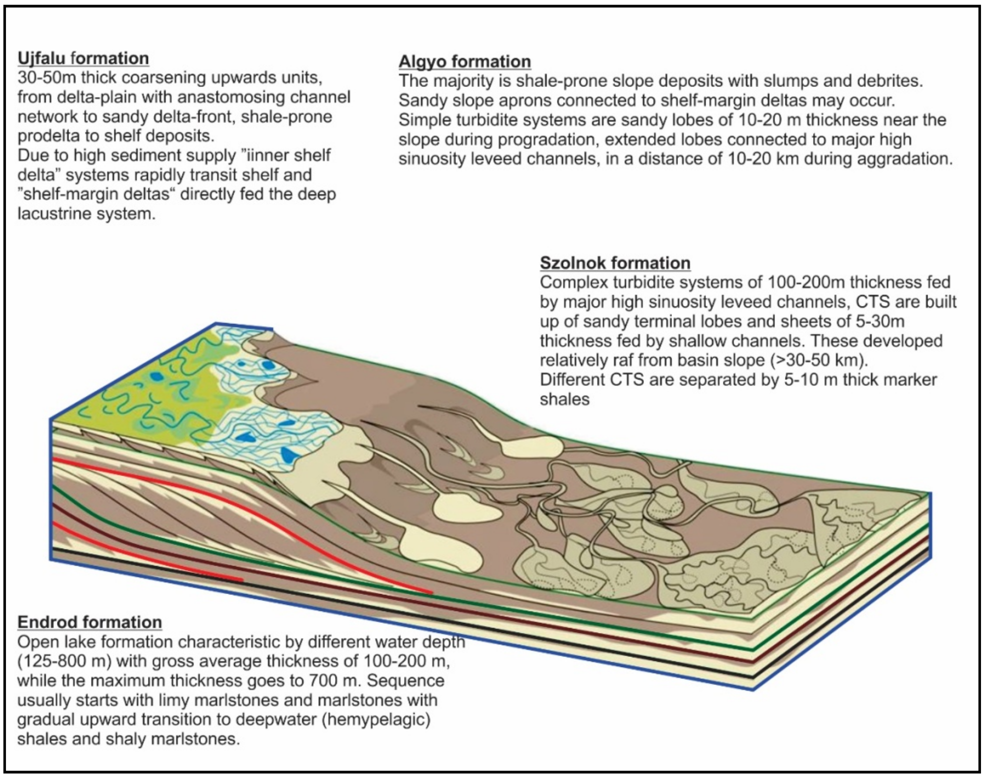

Figure 9 - Depositional system of Lake Pannon (Sztano et al. 2013; modified by Radivojević 2014).

The lowest part of the thick Pannonian sequence is represented by sandy siltstones, limy marlstones rich in organic matter (with intercalations of coarse grained clastics) and silty clayey marlstones. The calcareous marlstones from Srpska Crnja depression, were deposited in conditions of open lake environment and include Upper Miocene brackish microfossils (Sztano et al. 2013). In the marlstones can be found interlayers of conglomerates (Berczi et al. 1988), sandstone, and reworked Middle Miocene marine microfossils (Szuromi-Korecz et al. 2004). These sediments were formed by erosion of synrif sediments, mainly from Kikinda-Mokrin High. The top third of the formation is mostly homogeneous and shows slow sediment infill from shelf edge-slope, while the reduction of carbonate component and an increasing of clay content, as well as intercalation of thin siltstone point to development of this system.

About seven million years ago, the shelf-slope system crossed the greatest elevation in the northern Pannonian Basin (Sztano et al. 2013) and reached the Mako Trough (Srpska Crnja Trough). Hemipelagic marls are covered with deepwater sandstones only in the deepest parts of the depression.

In Pannonian sediments the following fossils were confirmed by paleontological surveys; molluscs *(Micromelania striata, Gyraulus dubius, G. praeponticus, Paradacna syrmiense, P. abichiformis, Velutinopsis velutina, Limnocardium cekusi, L. syrmiense, L. multistriatum, Dreissenomya digitifera, Pisidium protractum, Provalenciennesia sp., Orygoceras sp., Congeria sp., Dreissena sp.)* indicating caspibrakish environment, fragments of *(Leptocythere /Amnicythere/ servica, Candona /Lineocypris/ nonreticulata, Lineocypris sp.), silicoplacentinas (Silicoplacentina irregularis, S. inflata),* micromolluscs etc., (Radivojević et al., 2010). Palinological surveys confirmed the presence of characteristic palinomorphas of terrestrial and marine origin.

4.2.2. Pontian

Pontian sediments have the largest horizontal and vertical distribution of all Miocene sediments (Table 1) and forms an extremely thick lithostratigraphic unit. They are represented by the toplap of clayey marlstones and siltstones and shallow water succession of sandy-shale sediments. Onlap clinoforms are characteristic for delta front progradation in relatively stable environments and could correlate with the Hungarian Algyő formation. The thick sediment sequence is deposited in shallow water environment and presented with deltaic distributary channels, delta front and delta and coastal plain sediments. A succession which could be correlated with the Hungarian Ujfalu formation is consist of sandstones frequently intercalated with siltstones, shales, marlstones and locally lignite. With use of paleontological methods and well log correlation Pontian is divided into Lower (Novorossian) and Upper (Portaferian). Upper border toward Pliocene sediments is sometimes very difficult to mark, but it is considered that the border is determined by the disappearance of the last Limnocardids and the end of the caspibrakish/beginning of lake-river depositional conditions.

Due to the progradational character of Pannonian-Pontian sediments and very often vague and imprecise upper limit of Pontian sediments, at this point it is not possible to create correct structural depth map of Pontian sediments. This problem can be solved in the future by covering the area with 3D seismic and use of modern techniques of seismic data interpretation (seismic attribute analysis and frequency content, spectral decomposition) and data obtained by well logging.

Slope sediments were presented with silty-shaly marlstones and siltstones that in the lower parts have thick sandy intercalation (up to 40 m), which originate from the massive flows (Figure 9) (Berczi and Phillips 1985; Juhász 1991). Delta slope prograde over 60 km long Mako Trough (Srpska Crnja Depression) for less than a million years (Sztano et al. 2013). The top part of the deepwater lake (basinal) succession, which is widespread throughout the Pannonian Basin, is represented with clay marlstones and siltstones. The clay-marl succession contains sandy intercalation (turbidite) of different origin. Unlike thick turbidite sandstones, sandstones in the lower part of this formation have a thickness between 2 m and 40 m, are separated by shaly sections and have a coarser clastics in the upper part.

Thick, well-developed sandy successions (Ujfalu formation) deposited in shallow water environments of delta front, delta plain and the coastal plain cover the marlstones. The sandtones are most dominant in this succession and they are mostly interlayered with siltstones, shales and marlstones, while locally the lignite layers are present. The delta front sediments are presented with silty sandy sediments with coarse clastics in the upper part of the sequence. The delta and coastal plain sediments are characterized by sandy sediments of distributary channels, and interlayering of shales and sandstones (flooding sediments), and bay and wetland sediments. The sediments of delta front are dominant in a delta complex of northern Banat, while the amount of delta plain sediments gradually increases toward the northeast (Radivojević, 2014).

The following fauna characteric for caspibrakish enviroment are found in Pontian sediments; moluscs *Congeria zagrabiensis*, *Limnocardium otiophorum*, *L. lenzi*, *L. asperocostatum*, *Didacna otiophora*, *Paradacna abichiformis*, *P. syrmiense*, *P. abichi*, *P. radiata, Monodacna simplex, Caladacna steindachneri, Dreissena sabbae*, *D.* cf. *cucullata, D. rostriformis*, *D. minima*, *D. superfoetat*, *D. auricularis, D. auricularis simplex, Dreissenomya digitifera*, *Pisidium protractrum*, *Plagiodacna auingeri, Prosodacna* sp. (*P.* cf. *vodopici*)) i puževa (*Gyraulus turkovici*, *Valenciennesia* reussi, *Melanopsis (Melanopsis)* cf. *cognata, M. canthidomus*, *M. sandbergeri*, *Zagrabica cyclostomopsis*, *Z.* cf. *rossii, Radix cobelti, Micromellania turitellina, Valvata* sp., *Hydrobia* sp., *Provalenciennesia* sp.), as well as microfauna: *Hemicytheria pejinovicensis*, *Bacunella dorsoarcuata*, *Bacunella abhazica*, *Candona (Lineocypris) trapezoidea*, *C. (Pontoniella) acuminata*, *C.* (*Caspiocypris*) *alta*, *C.* (Caspiocypris) *labiata*, *C. (Caspiolla) lobata*, *C. (Caspiolla) balcanica*, *C. (Lineocypris) nonreticulata*, *Leptocythere andrusowi*, *L. multituberculata*, *L. cornutocostata*, *L. palimpsesta*, *L. servica, Loxoconcha schweyeri*, *Xestoleberis* (*Pontoleberis*) *pontica*, *X.* (*Pontoleberis*) *gramanni*, *Silicoplacentina hungarica*, *S. majzoni*, *S. inflata*, *S. irregularis*, *Lithoglyphus* sp., etc., (Radivojević et al., 2010).

5. CONCLUSION

The most important results of Miocene sediment study could be summed up as follows:

- Based on analogies with neighboring areas, sediments without fossil remains that are lying directly below biostratigraphically proven Middle Miocene are classified as the undivided Lower Miocene. These sediments have limited distribution and were found in only three wells in the northern Banat area.
- The Badenian is mainly represented with its lower part, so the hiatus toward younger formations is present. It is represented by detrital, carbonate-detrital, carbonate and volcaniclastic formations. The Badenian sediments are deepest in Banatsko Aranđelovo and Srpska Crnja Depression (3.5 km to 4 km), while at the structural elevations in central (Kikinda-Mokrin High) and northwestern (Velebit High) part they are missing because of erosion and non deposition.

- The Sarmatian sediments represented by clastics, limestone and rarely marlstones, were confirmed only in a small part of the Banatsko Aranđelovo Depression and structural elevation of Kikinda-Mokrin High.
- The Pannonian sediments are deepest in Banatsko Aranđelovo and Srpska Crnja Trough at more than 3 km, while in a pinch-out zone they are shallowest at about 2 km. Those sediments are not present at Velebit High as well as in southeastern part of northern Banat. Additionally, they are often eroded and pinching out at structure apex where hiatus between Pontian and Pre-Pannonian sediments appear.
- The northern Banat Pannonian deepwater lake succession can be correlated with the Hungarian Endrőd and Szolnok lithostratigraphic formations. Endrőd formation is presented with hemipelagic marlstones/shales, above which in the deeper parts of the basin lay turbiditic sandstone corresponding to Szolnok formation.
- The Pontian clayey shales and siltstones with well developed clinoforms can be correlated with the Hungarian Algyő formation, while overlying thick shallow water sequence corresponds to Ujfalu formation. Those sediments have the largest horizontal and vertical distribution from all the Miocene members.

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