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Review paper
Прегледни рад

Evolution of the southeastern part of the Pannonian Basin and its implications

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Abstract. The southeastern part of the Pannonian Basin System probably represents the most important area for determining its origin and evolution. The geodynamics also influenced the way that sediments fill the basin and therefore the economic resources that can be found in these sediments. All this led to the fact that the Pannonian Basin is the most developed part of our country. The great scientific value of this area is found in the fact that it represents an excellent training ground for the demonstration of the opening of the Pannonian basin system as well as the progradation of sediments from the southern and southeastern directions. In addition to the already confirmed economic importance through the exploitation of hydrocarbons, geothermal and hydrothermal waters, coal and construction materials, there is great potential in geoheritage and geotourism.

Key words:
asymmetric simple shearing, Lake Pannon, progradation, geological formations, petroleum geology.

Апстракт. Југоисточни део система Панонског басена вероватно представља најважније подручје за одређивање његовог настанка и еволуције. Геодинамика је утицала и на начин његовог запуњавања, а самим тим и на економске ресурсе који се могу наћи у овим седиментима. Све ово довело је до тога да Панонски басен представља најразвијени део наше земље. Велики научни значај овог простора се налази у чињеници да представља одличан полигон за демонстрацију отварања система Панонског басена као и проградације седимената из правца југа и југоистока. Поред економског значаја, који је већ потврђен експлоатацијом угљоводоника, геотермалних и хидротермалних вода, угља и грађевинског материјала, велики потенцијал се налази у геонаслеђу и геотуризму.

Кључне речи:
асиметрична рифтогенеза, језеро Панон, проградација, геолошке формације, нафтна геологија.

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Introduction

The regional investigation of the broader Pannonian Basin area has provided a more comprehensive understanding of its geological evolution and significance. A diverse range of geophysical and geological data sets were utilized to develop a model depicting the basin's formation and subsequent sedimentation. These data sets encompassed 700 two-dimensional (2D) seismic profiles spanning a total length of 6,000 kilometres, 300 square kilometres of three-dimensional (3D) seismic data, well logging measurements, geological data obtained from 800 boreholes across 75 locations, as well as extensive surface surveys. The analysis employed multiple methodologies, including seismic stratigraphy, tectonostratigraphy, rift sequence stratigraphy, paleontological-petrological-sedimentological approaches, and geophysical well logging.

The researched area represents a convergence zone that includes parts of continental units of Europe and Adria, obducted ophiolitic sequences, the Sava Zone, as well as syn-rift and post-rift sediments. Of particular significance, the post-rift sediments serve as both a prominent economic resource and represent the final phase of the former Lake Pannon (Magyar et al., 1999). The subsequent sections of this study present the geodynamic, stratigraphic-sedimentological, and economic importance of this region.

Geodynamics

The basin reconstruction was performed by interpreting regional seismic transects calibrated with borehole data. Average interval velocities, obtained from vertical seismic profiling in representative boreholes within the broader study area, were utilized for the time-to-depth conversion. Additionally, the seismic interpretation was correlated with the geological information from outcrop studies along the Dinarides edge of the basin and near the margins of the Pannonian Basin.

The seismic interpretation also relied on published works addressing the pre-Neogene basement and sedimentary cover of the Pannonian Basin in Serbia, Hungary, Romania, and Croatia (Pavelić, 2001; Saftić et al., 2003; Tari & Horvath, 2006; Tulucan, 2007; Schmid et al., 2008; Răbăgia, 2009; Ustaszewski et al., 2010; Schefer, 2010; Stojadinović et al., 2013; Toljić et al., 2013). A total of forty-two structures were identified, and contacts between tectonic units were determined (Fig. 1, Matenco & Radivojević, 2012).

The pre-Neogene basement in the northwestern part of the Serbian region of the Pannonian Basin (Fig. 1) generally exhibits a shallower depth compared to other parts of the basin. This characteristic can be attributed to the presence of numerous normal faults with relatively small vertical displacements, which contrasts with the more significant activity observed in faults located in the eastern part of the study area.

The Čantavir and Bačka Topola depressions were generated by the activity of a system of normal listric faults with a southeast and south-southeast dip direction (Fig. 2, adapted from Matenco & Radivojević, 2012). Within the Bačka Topola depression, tilted synkinematic reflections indicate that the stages of initial rifting, maximum rifting, and immediate post-rifting occurred during the Early Miocene. Conversely, in the Čantavir depression, synkinematic reflections suggest the initiation of rifting and its maximum phase during the Badenian.

The contact between the Sava suture Zone and the European margin is challenging to map due to the Late Cretaceous turbidites deposited over the Dacia continental unit and its overlying eastern Vardar ophiolites. The contact between the Sava Zone and the European margin is anticipated to be situated north of the Fruška Gora, characterized by a sedimentary basement, sedimentary cover, and ophiolites that exhibit a West Vardar affinity. Convergence between the Sava Zone and the European margin is likely to occur along a prominent reverse fault located north of the Slankamen uplift. In the eastern region, the contact between the two zones is positioned near the western boundary of the Zrenjanin depression (Fig. 1), where borehole data indicate a lateral transition. In this area, Early Cretaceous clastic sediments and shallow-water Urgonian carbonates with a European affinity are deposited, while in the west, obducted West Vardar ophiolites and ophiolitic melange can be observed.

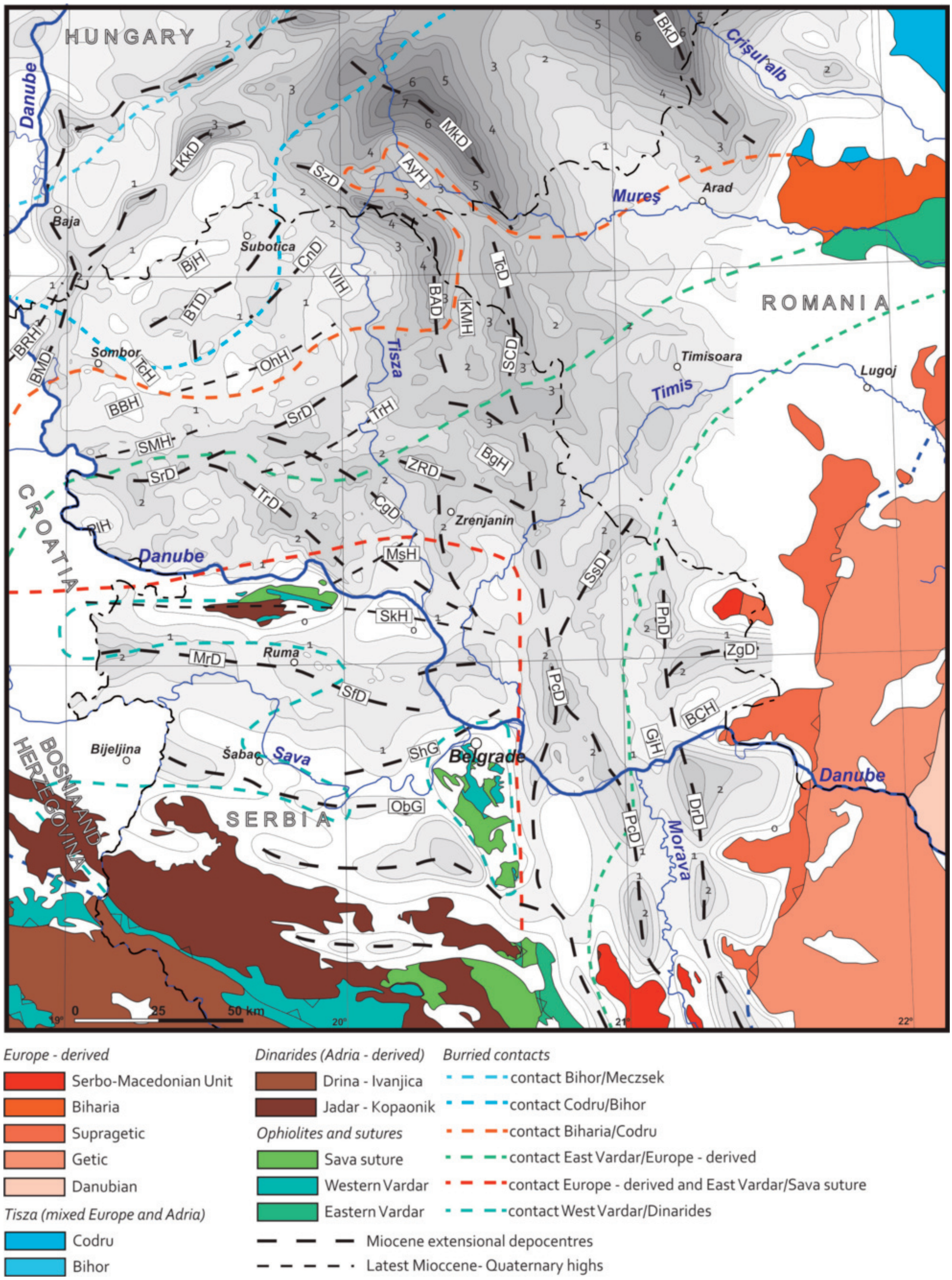

Fig. 1. *Structural map of the pre-Neogene basement of the Pannonian Basin in Serbia, part of Hungary, and Romania (from* MATENCO *&* RADIVOJEVIĆ*, 2012). The referenced publication contains a list of all the structures.*

In the Pančevo Depression (Fig 1), Late Jurassic obducted ophiolites and/or ophiolitic melange are overlain by shallow-water Lower Cretaceous sediments (limestones and "paraflysch") and/or deep-water Upper Cretaceous turbidites (Čanović & Kemenci, 1988). Drilling in the eastern part of the Serbian section of the Pannonian Basin has revealed the presence of a metamorphic basement directly beneath the Miocene sediments. This metamorphic basement can be correlated with outcrops of highly metamorphosed rocks of the Serbian-Macedonian unit in the south.

A high-angle normal fault that delineates the Zagajica Depression in the east corresponds to the contact between the Supragetic Unit and the Serbian-Macedonian unit (Fig. 1). At this location, high-grade metamorphic rocks (gneisses, granodiorites, amphibolites) of the Serbian-Macedonian unit are in contact with low-grade metamorphic units (biotite-chlorite schists of low metamorphism, albite gneisses) of the Supragetic cover unit (Kräutner & Bindea, 2002, Kräutner & Krstić, 2003).

Through the interpretation of regional transects, the opening of the southeastern part of the Pannonian Basin via an asymmetric simple shearing mechanism has been demonstrated. Basins progressively become younger when moving from west to east or from south to north. The extension process spans a period of nearly 15 million years, from the Early Miocene near the Dinarides to the Late Pannonian near the Apuseni Mountains and Southern Carpathians. The phase of extension and graben formation was followed by Pannonian-Quaternary thermal subsidence. The Pliocene-Quaternary inversion, which led to the formation of large-scale deformations in other areas in the center or on the margins of the Great Hungarian Plain, is significantly reduced in the Serbian part of the Pannonian Basin.

Stratigraphy and sedimentology

The style of extension directly influences sedimentological facies and biostratigraphic evolution. The onset of Early Miocene asymmetric extension results in widely distributed continental, alluvial to lacustrine facies during the early riftogenesis. Several shallow, isolated basins from the early to middle Miocene, filled with continental sediments, are still preserved in the Dinarides. These basins, at their junction with the Eastern Alps, form the Dinaride Lake System (Harzhauser & Mandic, 2008; De Leeuw et al., 2010). An outstanding example of this endemic continental system can be found along the Morava River in central and southern Serbia, where it is characterized by the presence of coarse-grained alluvial conglomerates and sandstones overlain by freshwater lake marls (Matenco & Radivojević, 2012).

In previous decades, the utilization of biostratigraphic and lithostratigraphic correlation has presented a significant challenge in the context of the highly progradational sedimentation model of Lake Pannon. In Serbia, the Upper Miocene-Pliocene sediments of the Lake Pannon are traditionally divided into the Pannonian and Pontian stages, with the Pontian stage further divided into lower and upper substages. This division is partly based on diachronous lithofacies and therefore fails to meet the requirements of chronostratigraphic units. Furthermore, the age of the Pontian stage is geochronologically established at 6–5.6 Ma in the Black Sea region, where the stratotype of the Pontian stage is located (Krijgsman et al. 2010). However, sediments locally referred to as Pontian in the Pannonian Basin can be as old as 9.6 Ma (first appearance of *Dreissenomya digitifera*) or even 10.6 Ma (identified by the ostracod zone D). Consequently, the Pontian stage has been omitted from the chronostratigraphic framework of the Pannonian Basin, with the Pannonian stage encompassing the interval from 11.6 to 2.6 Ma (Hilgen et al. 2012; Raffi et al. 2020). The thick Pannonian stage is subdivided into biochronozones based on endemic molluscs and dinoflagellates (Magyar & Geary, 2012).

The uplift of the Carpathian Mountains resulted in the formation of Lake Pannon, which was filled by the progradation of sediments from the margins of the basin. Seismic interpretation, exploratory drilling, and fieldwork were conducted to study the progradation systems. The two most significant progradation systems are the north and northwest-oriented paleo-Danube system and the paleo-Tisza

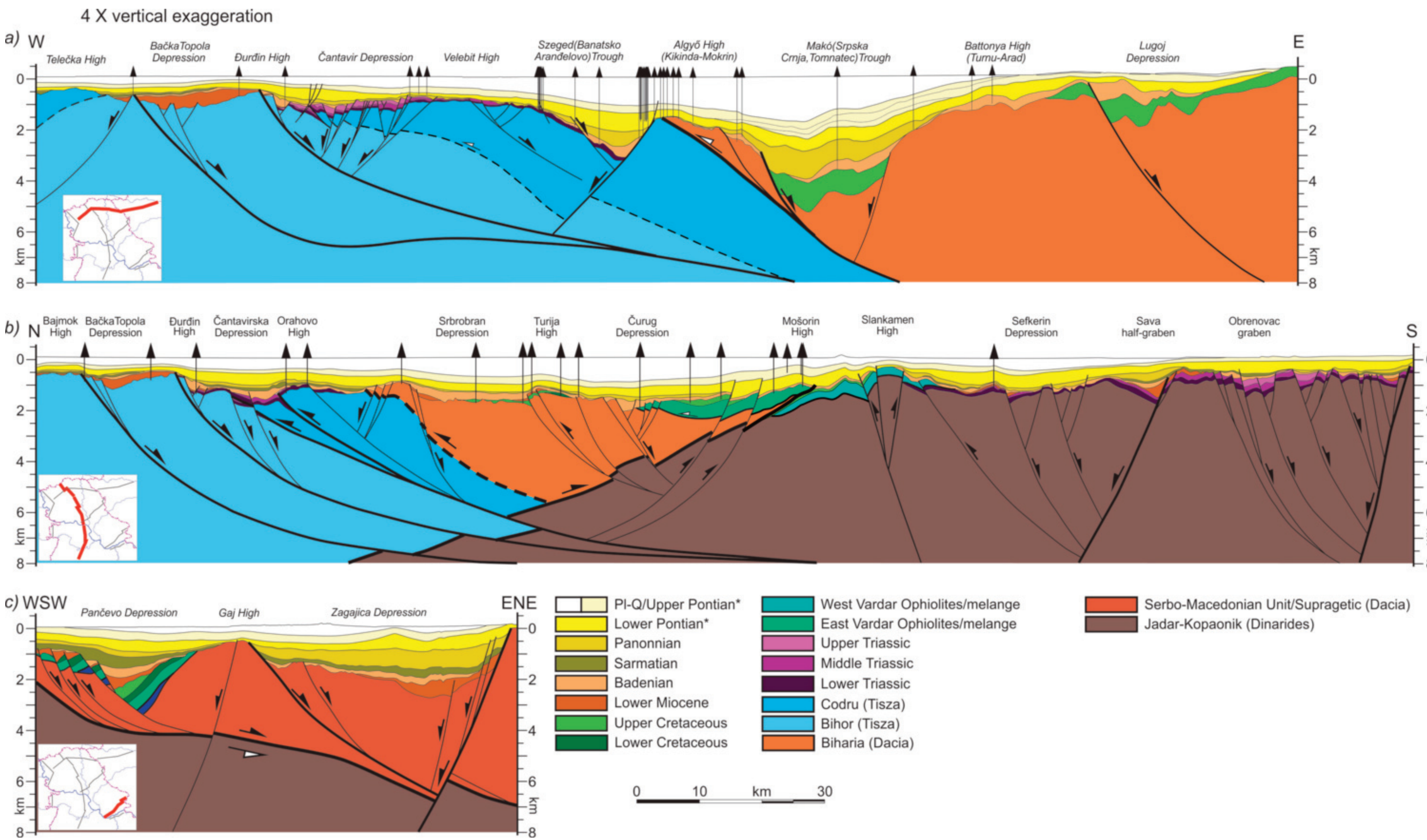

Fig. 2. a) *Depth regional transect through the Serbian and Romanian parts of the Pannonian Basin,* ***b)*** *depth regional transect through Bačka and Srem,* ***c)*** *depth regional tranches through the southern Banat (from MATENCO & RADIVOJEVIĆ, 2012). Note the old use of the Pontian stage suggested with an asterisk in the figure.*

system, which brought material from the Alps and northeastern and eastern Carpathians. Additional local systems delivered sediments from the eastern and western directions along the eastern margins and the southern and northern directions along the southern margins of the Pannonian Basin (Fig. 3). The oldest slope of the paleo-Danube shelf margin, ernmost part of the Southern Carpathians towards the basin centre in the northwest was investigated in the wider vicinity of the Vršac Mountains. Following the inundation of the Southern Carpathian foothills by the waters of Lake Pannon during the period of 9.6–9.1 million years ago, a shelf was formed. The average progradation rate of this shelf,

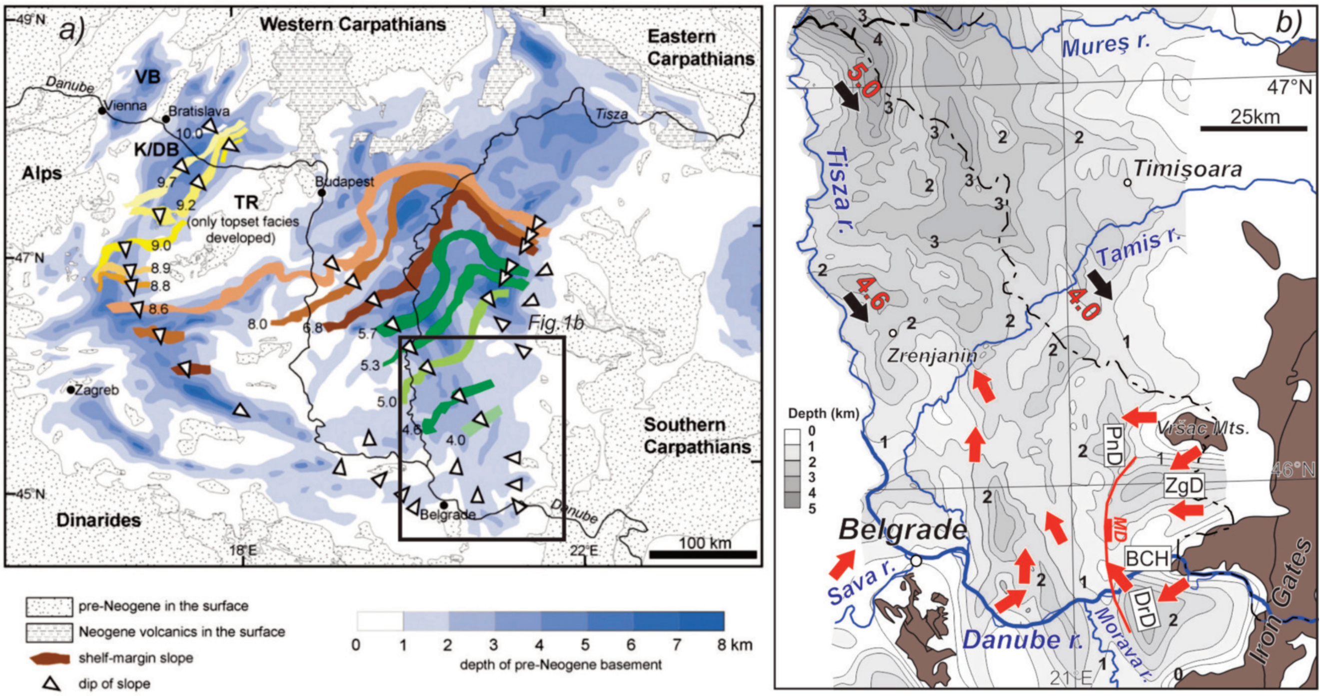

Fig. 3. The right side of the figure shows the progradation of the shelf edge of the paleo-Danube, paleo-Tisza, and minor shelf edges in the opposite direction of Lake Pannon during the Late Neogene (more details in Magyar et al., 2013). On the left side (outlined in the figure on the right), a depth structural map is presented, depicting the main progradation systems of the shelf edge in the Serbian region of Banat (more details in Radivojević et al., 2022).

dating back 10 million years, was identified in the Danube sub-basin. Over the subsequent 6 million years, it prograded approximately 400 km in the southeast direction, with an average advance of the slope of 67 km/million years (Magyar et al., 2013). Based on the successive positions of the shelf edges, it was concluded that 2/3 of the basin was filled with sediments transported from the northwest, from the Alps and Western Carpathians. The final phase of the existence of Lake Pannon occurred approximately 4 million years ago when the shelf margins of the paleo-Danube and the shelf supplying sediments from the opposite direction merged in the southeastern part of the Pannonian Basin system (Radivojević et al., 2014; ter Borgh et al., 2015).

The local progradation originating from the west- at 10 km/million years, is nearly seven times lower than the progradation rate of the paleo-Danube on the opposite side of the lake (Figure 4, Radivojević et al., 2022).

Despite the divergence in progradation directions, correlation is enabled by the development of similar depositional environments. Following basin subsidence, rapid deepening occurred, resulting in the creation of accommodation space for sediment deposition at a significantly faster rate than its filling (deepwater lake formation), followed by a phase of rapid filling with Pannonian sediments. Within the Pannonian Basin system, distinct depositional environments can be identified, including basin plain-turbidites-slopes-delta fronts-delta plain-lake and fluvial, which have been formally or infor-

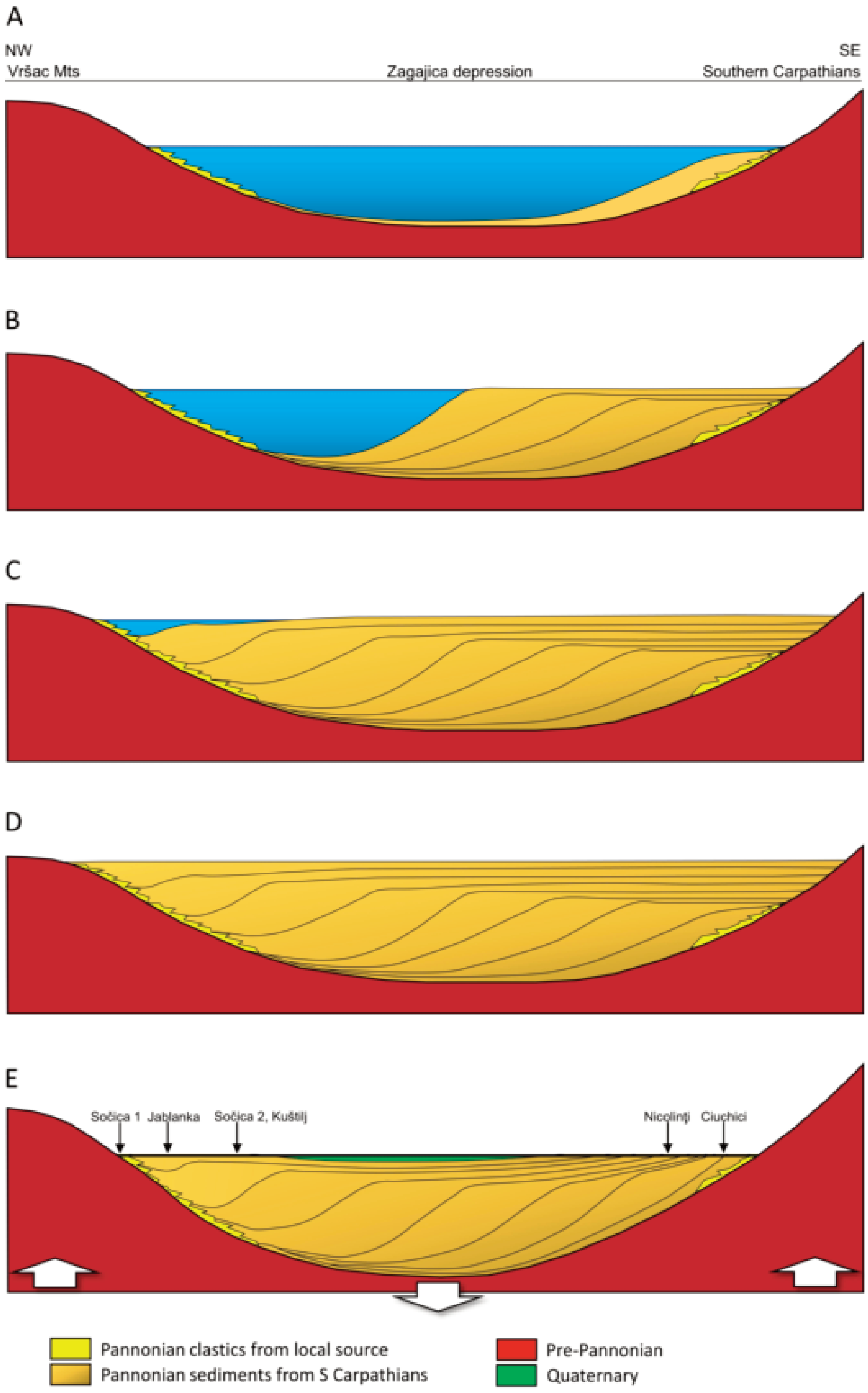

Fig. 4. *Schematic representation of the evolution between the Southern Carpathians and the Vršac Mountains (adapted from* Radivojević *et al., 2022).* ***A.*** *Initiation of shelf edge formation in the Southern Carpathians (9.7–9.6 Ma);* ***B.*** *Progradation of the shelf edge along the Zagajica Depression (9.6–7.6 Ma);* ***C.*** *Transgression onto the slopes of the Vršac Mountains (7.6 Ma);* ***D.*** *Progradation of the shelf edge filling the Zagajica Depression and continuing across the Vršac Mountains (7.1 Ma);* ***E.*** *Present-day conditions shaped by Quaternary basin inversion, deposition in the basin centre, and erosion on the mountain slopes.*

mally recognized as formations in most countries encompassing the Lake Pannon region (Malvić & Cvetković, 2013; Sztanó et al., 2016; Kovačić 2018; Sebe et al., 2020; Anđelković & Radivojević, 2021).

In Serbia, the sediments of the Pannonian Lake filled the basin from three distinct directions (southeast, north, and northwest), leading to their division into formations. The formations found in northern Banat exhibit a correlation with the neighbouring Great Hungarian Plain (Fig. 5, Anđelković & Radivojević, 2021).

The progradation system in the Srem region exhibits a reduced scale and can be linked to the basins in northern Croatia. Conversely, in the southern Banat region, where a contrary progradation direction and distinct material origin are observed, recently proposed formations have been identified. These formations have the potential to extend southward towards the Danube region. (Fig. 5, Anđelković & Radivojević, 2021).

Economic geology and geoheritage

The sediments of the Central Paratethys and its successor, Lake Pannon, hold considerable economic significance, particularly concerning the petroleum industry, geothermal energy, groundwater resources, and construction materials. The exploitation of oil

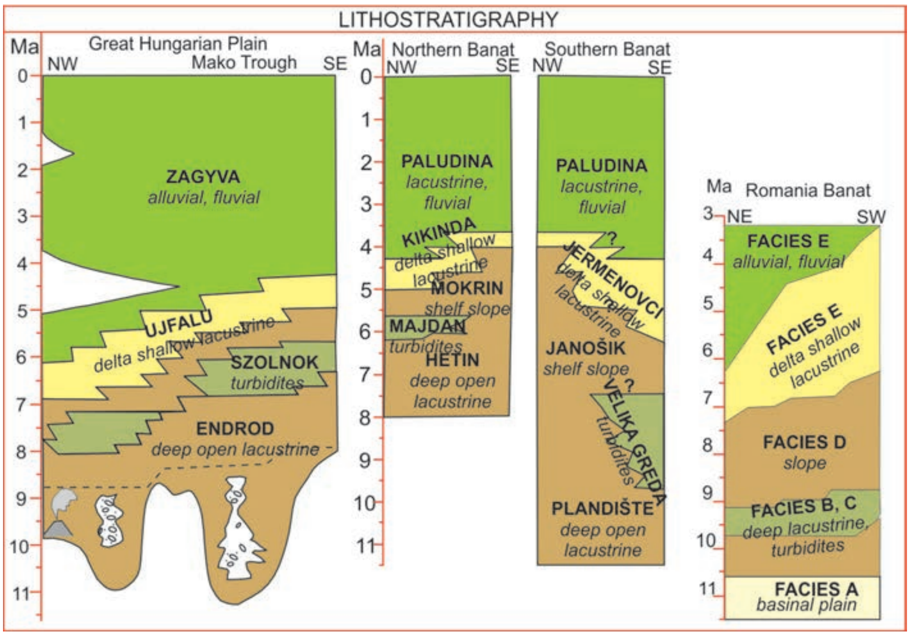

Fig. 5. Correlation of Lake Pannon formations in Hungary, Romania, and Serbia (from Anđelković & Radivojević, 2021).

and gas has undoubtedly had the most substantial financial impact thus far. In Serbia, these resources are currently in a mature stage of exploration, necessitating the use of contemporary exploration concepts and techniques.

All major discovered fields in the Vojvodina region are associated with the contacts between tectonic units and the main progradation directions (Figure 6). Since the privatization of the Petroleum Industry of Serbia (Nafta Industrija Srbije - NIS) and the initial increase in production (reaching 1.694 million tons in 2012) attributed to hydraulic fracturing techniques, the installation of Electric Submersible Pumps (ESP), horizontal drilling, and the opening of new intervals in existing wells, there has been a decline in production of over 30% in the following ten years (reaching 1.2 million tons in 2021) (data from official reports of NIS GPN company).

The petroleum system is primarily associated with Miocene sediments. The most significant source rocks are mainly related to early Pannonian shales and middle Miocene deepwater sediments, which, due to the elevated position of the asthenosphere resulting from rifting, have undergone rapid maturation and generated hydrocarbons. Deltaic plain sands and basal conglomerates above structural highs (late Pannonian) constitute the predominant reservoir rocks. Turbiditic sands (early Pannonian) represent another important reservoir type, while deltaic sands in wrench structural traps (late Pannonian) rank third in importance. Alluvial fan sands below the unconformity on the inverted basins' slope are the fourth most significant reservoirs. Analysis of field size distribution diagrams and the cumulative hydrocarbon reserves creaming curve suggests that several additional deposits (3–4) with reserves ranging from 500,000 to 1,000,000 tons, as well as multiple smaller-scale deposits, are expected to be discovered in the northern Banat region (Radivojević, 2014).

In the region of Vojvodina, Serbia, one can find the Vrdnik coal mine, which is the oldest in the country, along with the currently active Kovin mine, known for its unique underwater extraction process. Additionally, the significant lignite coal mines of Kolubara and Kostolac are associated with the peri-Pannonian realm. Various quarries are also present in the area, including the NEXE baked clay factory in Sremski Karlovci, the Lafarge cement plant in Beočin, and the trachyte exploitation in Kišnjeva Glava and Srebro (Ledinci Lake). Furthermore, the Leitha limestone quarries in Lajkovac, Bešenovo, and Rakovac contribute to the local mining activities.

Mesozoic carbonates play a crucial role in the provision of high-quality water and the operation of the Jazak water factory. Moreover, the presence of a high thermal gradient and the existence of healing waters contribute to the development of spa tourism in Vrdnik, Kanjiža, Rusanda, Melenci, and Prigrevica. Additionally, these resources are utilized for water heating purposes in Bečej, the Junaković spa, and Kupinovo.

The specific evolutionary processes in this region

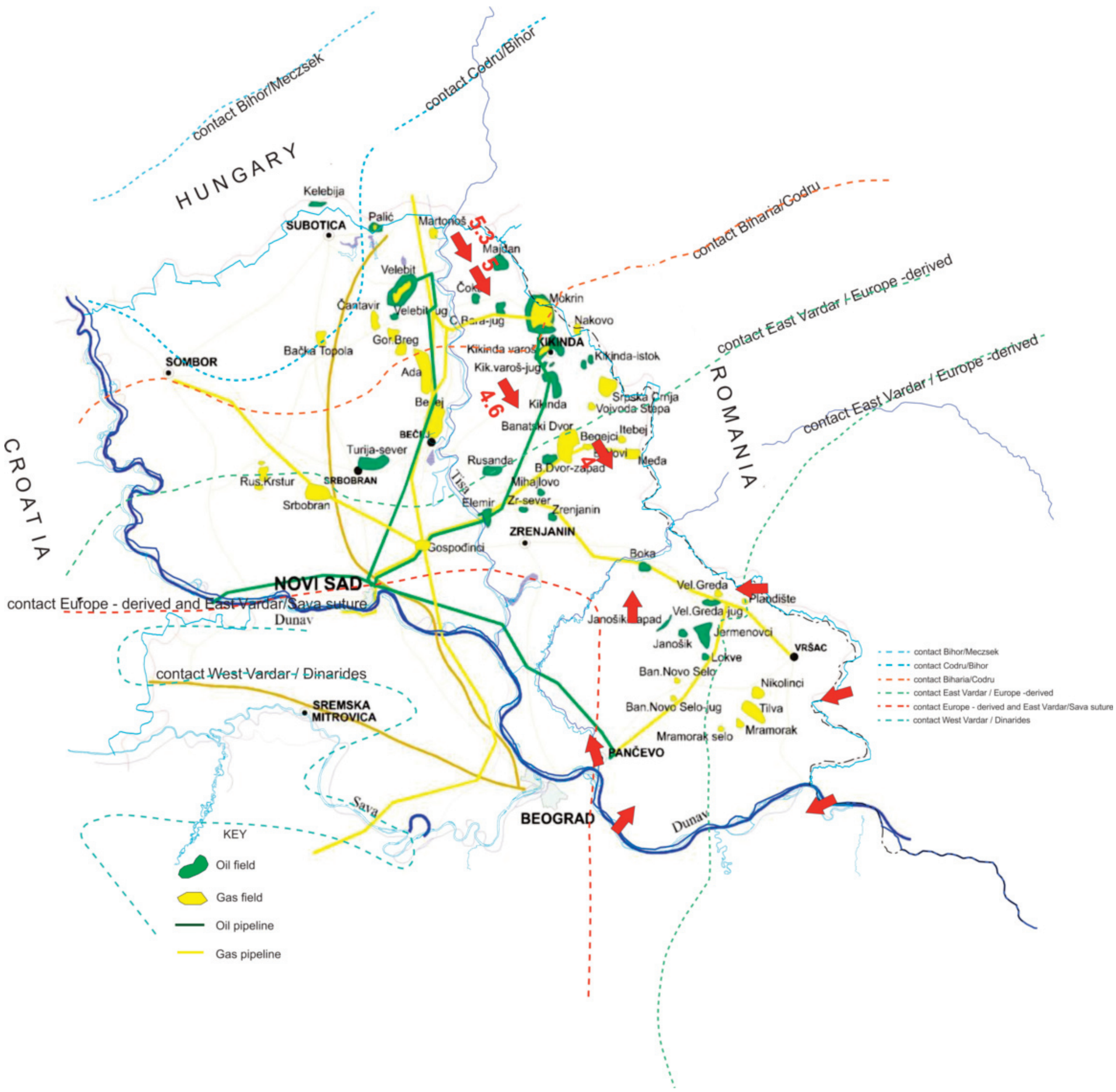

Fig. 6. Compilation map of major hydrocarbon fields (from Radivojević*, 2014), tectonic units (*Schmid *et al., 2020), and progradation directions (*Magyar *et al., 2013).*

have given rise to a substantial number of geodiversity and geoheritage features. These include formations associated with loess deposition, such as the Srem loess plateau, Titel Hill, Surduk, Zemun Kapela, Batajnica, and the Bačka loess plateau. Additionally, the area is characterized by the presence of special nature reserves, namely Zasavica, Obedska Bara, Titel Hill, Selevenjske Pustare, Deliblato Sands, Slano Kopovo, Carska Bara, and Ludaš Lake. Notable geological landmarks encompass Grgeteg, Beočin, Čerevićki Potok, and the noteworthy discovery of the Kika mammoth in Kikinda.

Conclusions

The interpretation of seismic sections calibrated with deep boreholes and incorporating all available studies, has yielded novel insights into the evolution of the key southeastern part of the Pannonian Basin, where the Dinarides, Southern Carpathians, and Apuseni Mountains merge. The opening of the basin occurred through an asymmetric simple shear extension mechanism, with normal faulting underging temporal and spatial migration between 20 to 5.5 million years ago. The final phase of the extension during the Pannonian Age formed deep, asymmetric grabens and half-grabens close to the orogeny, followed by late Pannonian-Quaternary thermal subsidence, displaying a significantly greater spatial extent owing to substantial uplift of the asthenosphere. Notably, the Pliocene-Quaternary inversion in this part of the basin is limited compared to the central or peripheral parts of the Great Hungarian Plain.

During the transition between the Middle and Late Miocene, three significant events occurred that set the stage for the final phase of Central Paratethys evolution. Firstly, there was a gradual cessation of extension in the Pannonian Basin. Secondly, the formation of the paleo-Danube took place as a result of drainage reorganization in the Alps. Lastly, the uplift of the Carpathians isolated the Central Paratethys from marine environments.

The cessation of extension led to a reduction in accommodation space, while the change in drainage direction resulted in a significant increase in sediment influx. The latter factor led to the formation of the Lake Pannon, which diminished the influence of eustatic sea-level changes. Subsequently, the filling of Lake Pannon occurred through progradation from all margins of the basin. The dominant progradation occurred from the northern and eastern margins, although progradation from the southern and western margins was also observed (albeit at a sevenfold smaller scale than the dominant progradation). The two prograding margins eventually merged in the southeastern part of the basin near Zrenjanin. Chronostratigraphic correlation and interpretation of lithostratigraphic units posed significant challenges in the stratigraphy of the Pannonian Basin, as biozones corresponded to specific depositional environments and their locations within the prograding delta, rather than the timing of sedimentation. Moreover, the utilization of local formation names for equivalent depositional environments further complicated correlation efforts.

The confluence of various geological factors, including tectonics, stratigraphy, and sedimentology, accounts for the remarkable economic and geological importance of this region. Apart from the documented and exploited reserves of hydrocarbons and minerals, there exists considerable untapped potential in terms of geodiversity and geotourism.

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Резиме

Еволуција југоисточног дела Панонског басена и њене импликације

Југоисточни део система Панонског басена, смештен у Србији, има изузетан геолошки и економски значај. Подаци из овог подручја омогућавају проучавање пре-неогенске орогене еволуције зоне спајања Динарида и Карпата, која укључује теране, обдуковане офиолитске секвенце, Савску зону сутуре, као и синрифтне и пострифтне седименте. Интерпретација регионалних профила показује да се југоисточни део система Панонског басена отварао системом асиметричне рифтогенезе. Процес екстензије обухвата период од готово 15 милиона година, од раног миоцена до касног панона. Басени су све млађи идући са запада на исток и са југа на север. Фазу екстензије и формирање грабена пратило је панонско-квартарно термално тоњење. Плиоценско-квартарна инверзија, која је формирала велике деформације на другим деловима у центру басена и на маргинама Велике Мађарске равнице, знатно је смањена у српском делу система Панонског басена.

Издизање Карпата је довело до формирања Језера Панон, које је било испуњено седиментима који су проградирали са маргина басена. На основу података добијених сеизмичком интерпретацијом, истражним бушењем и теренским истраживањима, спроведено је проучавање проградационих система. Два најважнија проградациона система су систем палео-Дунава оријентисан север североисток и систем палео-Тиса који доноси седименте са североисточних и источних Карпата. Додатни локални системи транспортовали су седименте с истока и запада дуж источних маргина и са југа и севера дуж

јужних маргина система Панонског басена. Најстарија падина ивице шелфа Дунава од 10 милиона година налазила се у Дунавском суббасену. Током следећих 6 милиона година, падина ивице шелфа је напредовала око 400 км на југоисток са просечном стопом напредовања од 67 км/милион година. Овај проградациони систем испунио је око 2/3 басена седиментима који су долазили из Алпа и Западних Карпата. Локална проградација са западних делова Јужних Карпата према центру басена на северозападу проучавана је у ширем подручју Вршачких планина. Након плављења јужних падина Јужних Карпата језером Панон пре 9,6–9,1 милиона година, формирана је падина ивице шелфа са просечном стопом проградације од 10 км/милион година, што је скоро седам пута мање од стопе проградације палео-Дунава са супротне стране језера. Завршна фаза постојања Језера Панон догодила се пре око 4 милиона година када су се маргине палео-Дунавске падине ивице шелфа и падина ивице шалфа која доноси седименте из супротног смера спојиле у југоисточном делу система Панонског басена.

У претходним деценијама, употреба биостратиграфске корелације у односу на литостратиграфску била је велики проблем у изразито проградационом седиментационом моделу језера Панон. Унутар система Панонског басена, могу се издвојити следеће депозиционе средине басенска равница – турбидити – падина делте – делта фронт – делтна равница – језерске и алувијалне средине, које се формално проглашавају формацијама у већини земаља које заузимају подручје језера Панон.

Седименти Централног Паратетиса и језера Панон имају велики економски значај, пре свега у вези са налазиштима угљоводоника, геотермалном енергијом, подземним водама и грађевинским материјалима. Свакако, највећи финансијски утицај има индустрија угљоводоника, која се налази у зрелој фази истраживања у Србији, те захтева примену модерних концепата и техника истраживања.

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