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Overview of geologic evolution and hydrocarbon generation of the Pannonian Basin

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Abstract

The Pannonian Basin is an intraorogenic extensional region floored by a complex system of Alpine orogenic terranes and oceanic suture zones. Its formation dates back to the beginning of the Miocene, and initial fluvial-lacustrine deposits pass into shallow to open marine strata, including a large amount of calc-alkaline volcanic materials erupted during the culmination of the synrift phase. The onset of the postrift phase occurred during the Late Miocene, when the basin became isolated and a large Pannonian lake developed. Early lacustrine marls are overlain by turbiditic sandstones and silts related to a progradational shelf slope and a delta plain sequence passing upward into alluvial plain deposits and eolian sands. A remarkable nonconformity at the top of lacustrine strata associated with a significant (4–7 my) time gap at large parts of the basin documents a neotectonic phase of activity, manifested by regional strike-slip faulting and kilometer-scale differential vertical movements, with erosion and redeposition. Subsidence and burial history modeling indicate that Middle and Late Miocene, fairly organic-rich marine and lacustrine (respectively) shales entered into the oil-generation window at about the beginning of the Pliocene in depocenters deeper than 2.5–3 km, and even reached the wet to dry gas-generation zone at depths exceeding 4–4.5 km. Migration out of these kitchens has been going on since the latest Miocene toward basement highs, where anticlines and flower structures offered adequate trapping conditions for hydrocarbons. We argue that compaction of thick sedimentary piles, in addition to neotectonic structures, has also been important in trap formation within the Pannonian Basin.

Introduction

The Pannonian Basin represents an extensional region within the Alpine orogenic belt (Figure 1). Large-scale rifting commenced in early Miocene time when two orogenic terranes were extruded from the East Alpine and Dinaric collision zone toward the Carpathian embayment containing the Magura ocean, a remnant of the Alpine Tethys (Handy et al., 2014; Horváth et al., 2015). These terranes are the Alcapa and Tisza-Dacia megatectonic units, which occupied different paleogeographic positions and are characterized by distinct evolutionary history (Schmid et al., 2008; Haas, 2012). During juxtaposition of the two units, a complex system of accreted oceanic sutures developed in-between and at their peripheries (Figure 2).

Intensive calc-alkaline magmatism took place during the Early and Middle Miocene time representing the main synrift phase of basin evolution. The lithosphere thinned out significantly resulting in increased heat flow and temperature gradient values (Dövényi and Horváth, 1988; Horváth et al., 2015).

Hydrocarbon exploration in the area started a century ago and resulted in the discovery of hundreds of small and a few medium-size fields (Dank, 1988; Tari and Bérczi, personal communication, 2017). The main purpose of this paper is to review the geologic evolution of the basin and offer a generalized model for formation of its hydrocarbon resources. We suggest that migration of hydrocarbon fluids is a fairly recent process (approximately 7 Ma to present); hence, neotectonic activity and compaction of basin-fill sedimentary strata are the main controlling factors of trap formation.

Overview of structural evolution

Figure 2 shows the tectonic map of the Pannonian Basin indicating the thickness of the basin fill, and Alcapa and Tisza-Dacia megatectonic units in the surrounding orogens and exposed basement blocks within the basin ("island mountains"). Alcapa is mostly made up of the Austroalpine nappe complex, which originally developed at the Adriatic margin and was thrust as a whole onto the suture of the Alpine Tethys and deformed

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European margin during the Late Eocene (Schmid et al., 2008; Handy et al., 2014). Tisza-Dacia is a composite terrane rifted apart from the European margin separately, welded together in the Late Jurassic, was strongly deformed at the Dinaric margin during the Alpine orogenic phases (Schmid et al., 2008; Horváth et al., 2015). Two oceanic domains, the Neotethys (east and west Vardar, Sava) and the Alpine Tethys (Penninic, Rhenodanubian and Magura, Ceahlau-Severin) separated these megatectonic units. They are now preserved as accreational prisms and/or exposed in tectonic windows (Figure 2).

Formation of the Pannonian Basin is related to tectonic escape of the Alcapa and the Tisza-Dacia terranes from collisional zones toward the east, where rollback of the Magura ocean occured during late Oligocene to Middle Miocene (Matenco and Radivojevic, 2012; Horváth et al., 2015). This was an extensional process that began at the beginning of the Miocene (approximately 21–20 Ma). The age of the process is inferred from dating the sedimentation and volcanism in the basal series of rift grabens (Konecny et al., 2002; Pécskay et al., 2006; Harangi and Lenkey, 2007). The peak period of extension was at Karpatian and Badenian times (Figure 3), when the main rift grabens of the basin were developed (e.g., Horváth et al., 2015; Balázs et al., 2016).

Crustal extension was associated with exhumation of metamorphic rocks (Subpenninic and/or Penninic nappes) in the Tauern and Rechnitz windows (Scharf et al., 2013), as well as the Pohorje dome (Lower Austroalpine nappe) of the Eastern Alps (Fodor et al., 2008).

There is an interesting new observation, confirming the prediction of Tari et al. (1999) that a set of exhumed middle crustal rocks occur at the southern margin of the Pannonian Basin, where the internal Dinaric nappes were overthrust by the Sava and Tisza units (Figure 2). Extensional disintegration of the upper Sava and/or Tisza nappes exhumed the Dinaric footwall during the 18–12 Ma time period according to thermochronological data and structural interpretations (Ustaszewski et al., 2010; Schefer et al., 2011; Stojadinovic et al., 2013).

During the main period of rifting opposite rotations of the Alcapa and Tisza-Dacia terranes occurred (Balla, 1987; Márton and Fodor, 2003; Márton et al., 2007; Ustaszewski et al., 2008; van Hinsbergen et al., 2008; Tomljenovic et al., 2008). Eastward extrusion of terranes has been driven by continental indentation of Adria and facilitated by the creation of "free boundary" due to rollback and consumption of the Magura oceanic lithosphere in the Carpathian embayment (Ratschbacher et al., 1991; Scharf et al., 2013; Horváth et al., 2015). This process terminated during the Late Miocene by soft collision with the European margin leading to final accretion of the Magura, Skole-Tarcau, and external flysch rocks, and the Mid-Hungarian Fault Zone (MHFZ) (Csontos and Nagymarosy, 1998). At the same time, extension in the Pannonian Basin gradually diminished and eventually finished. This was a process, rather than

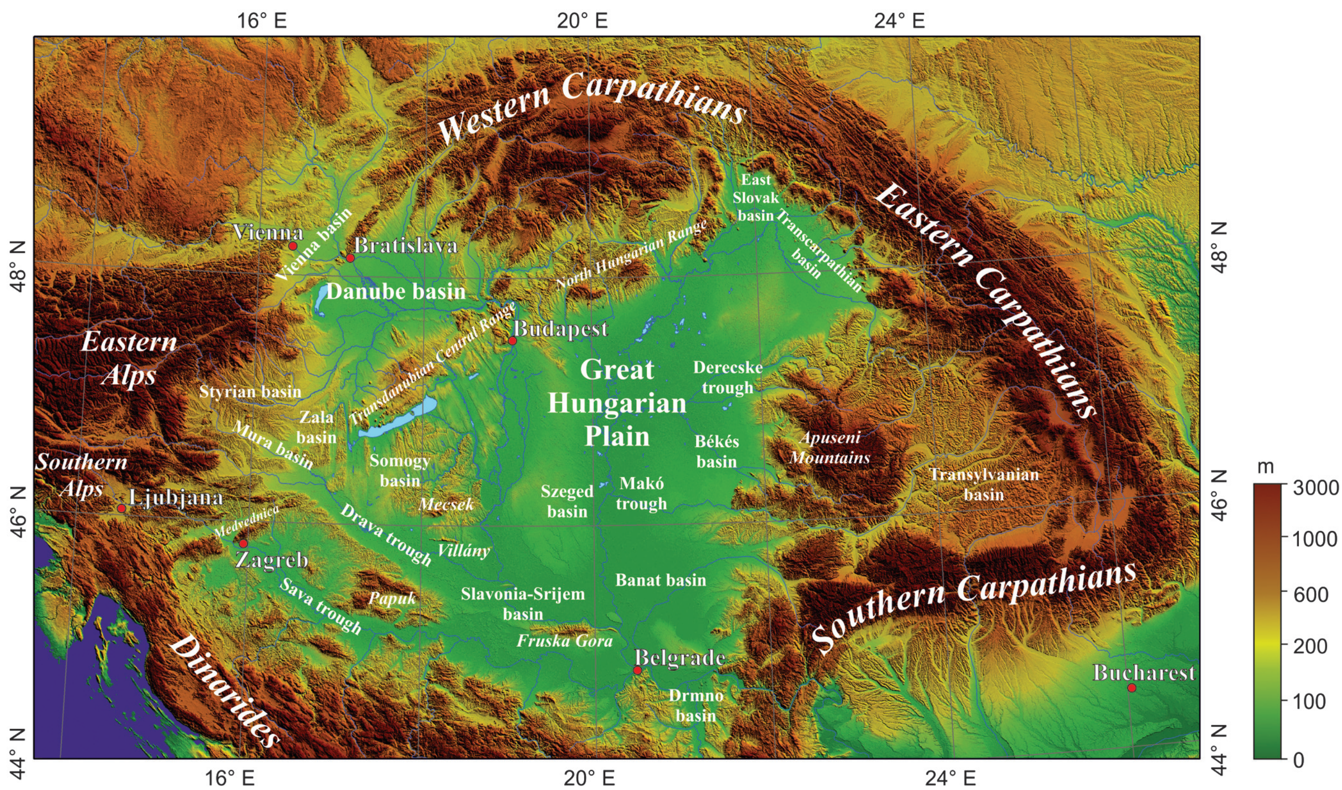

Figure 1. Digital terrain model of the Pannonian Basin to show its position within the surrounding mountain belts and the location of different subunits. The color scale is nonlinear: Green to yellow represents areas with 80–200 m a.s.l., and brown to dark brown indicates elevated areas from 500 to approximately 3000 m a.s.l. (based on Shuttle Radar Topography Mission data by NASA).

an event, which explains the time transgressive character of the synrift/postrift boundary in the Pannonian Basin (Balázs et al., 2016).

Counterclockwise rotation of Adria, however, has continued and led to a stress-field transition from extensional toward a compressional regime during the Pliocene through Quaternary time. This is the neotectonic phase of the evolution of the Pannonian Basin (Grenerczy et al., 2005; Horváth et al., 2006; Bada et al., 2007).

Stratigraphy and tectonics of the basin

Development of the Pannonian Basin from the beginning of the Miocene to Present resulted in a variable basin morphology characterized by 5–8 km deep troughs, shallower basin areas typically with a depth of 1–3 km, and island mountains, which are outcrops of the pre-Cenozoic basin floor (Figure 2). The present geometry of the basin system is the end product of normal and transfer fault controlled synrift graben formation (Early and Middle Miocene), general postrift subsidence (Late Miocene), regional strike-slip faulting, and events of basin inversion during the neotectonic phase (Pliocene through Quaternary).

The basin-fill sedimentary and volcanic rocks can be divided into three tectono-stratigraphic megasequences (Saftić et al., 2003; Horváth et al., 2015) by two regional unconformities (Figure 3). The relationship of the Central Paratethys and standard stages can be seen in Figures 4 and 5. The lower megasequence developed during the Early and Middle Miocene, when the initial terrestrial-lacustrine depositional environment was flooded by the Paratethys sea (Szentgyörgyi and Teleki, 1994; Piller et al., 2007; Mandic et al., 2011; de Leeuw et al., 2012; Malvic, 2012). Due to the Paratethys sea-level fall and uplift of the surrounding mountains, marine connections were closed and subareal erosion and/or change of the depositional environments led to the development of the base-Pannonian unconformity

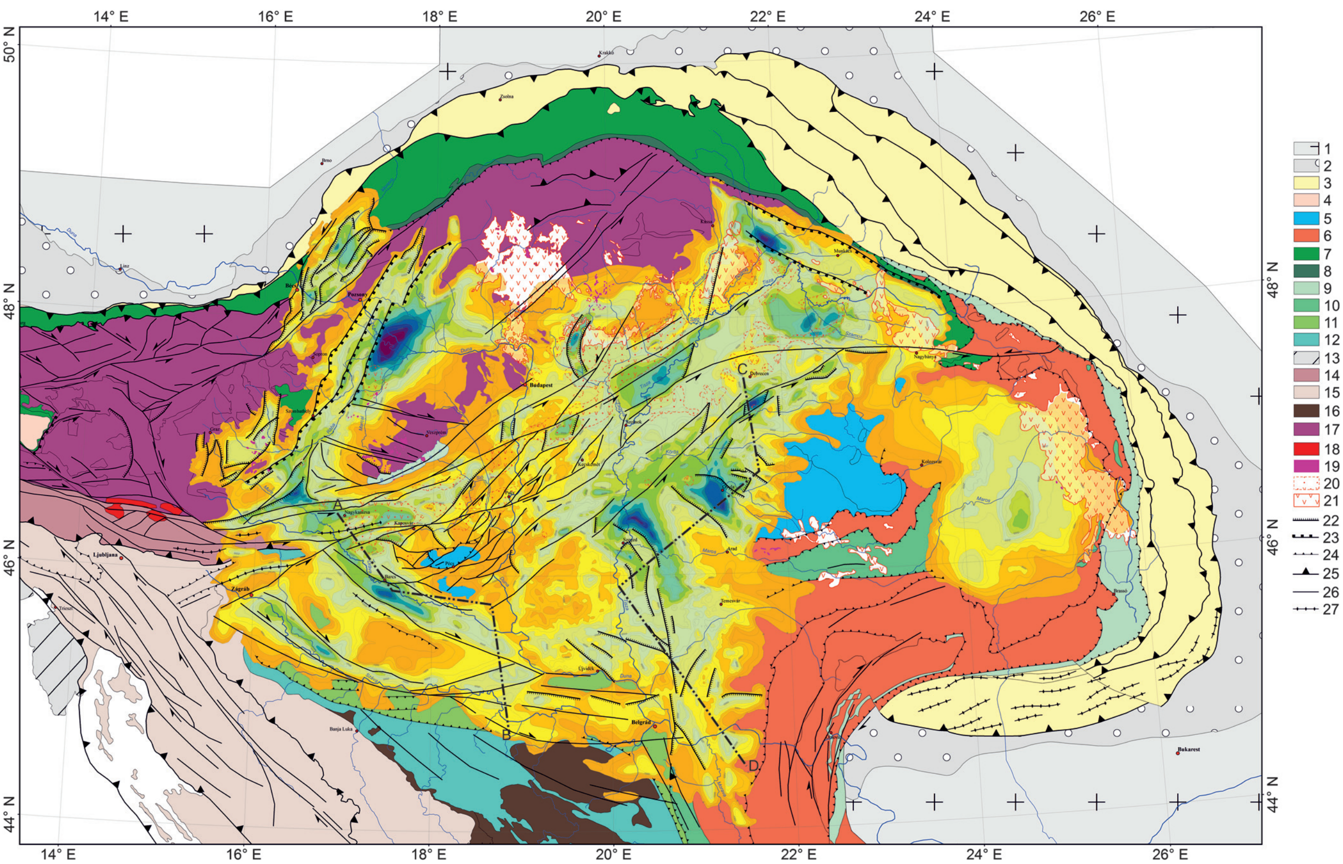

Figure 2. Tectonic map of the Pannonian Basin and surrounding orogens. Isolines and color scale (see Figure 6) with 250 and 500 m spacing (respectively) shows the depth (b.s.l.) to pre-Neogene substrata ("basement"). Geology and tectonic affinity of the exposed Mesozoic-Paleozoic rocks (derived from Europe or Adria, and intervening oceanic realms) are simplified after Schmid et al. (2008). The broken-dotted lines show the position of two regional sections (A-B and C-D) in Figure 3a and 3b. Legend: European continent and its deformed margin: 1 = foreland, 2 = foreland molasse, 3 = external flysch nappes, 4 = sub-Penninic nappes. Megatectonic units derived from Europe: 5 = Tisza, 6 = Dacia, Alpine Tethys sutures: 7 = Penninic, Rhenodanubian, Magura, 8 = Pieniny, 9 = Ceahlau-Severin, Neo-Tethys sutures: 10 = East-Vardar, Transylvanian, 11 = Sava, 12 = West-Vardar, Adriatic continent and its deformed margin: 13 = foreland, 14 = southern Alps, 15 = external Dinarides, 16 = internal Dinaric massives, megatectonic unit derived from Adria: 17 = Austroalpine nappes, magmatites: 18 = periadriatic plutons, 19 = Miocene-Pliocene basalts, 20, 21 = exposed and covered Miocene to Quaternary calc-alcaline volcanics, Tectonic symbols: 22 = normal faults, 23 = detachment fault, 24 = Cretaceous to Eocene thrust, 25 = Neogene thrust, 26 = strike-slip fault, and 27 = axis of anticline.

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(ter Borgh et al.,2012). The middle megasequence developed during the Late Miocene to Early Pliocene, when the large Lake Pannon existed and gradually vanished (Magyar et al., 1999, 2013; Juhász et al., 2007; Sztanó et al., 2013). The upper megasequence overlies the top-Pannonian regional unconformity and is made up from terrestrial deposits, such as red clays, loess-paleosol sequences, and alluvial plain deposits of Late Pliocene and Quaternary age (Kovács et al., 2011; Markovic et al., 2015). The top-Pannonian unconformity is associated with a significant hiatus of erosional origin, and it represents a manifestation of the neotectonic phase of evolution.

Figure 4a and 4b shows the tectonostratigraphic charts that show the different lithostratigraphic units and phases of tectonic activity in subbasins along the two regional profiles A-B and C-D (Figure 5a and 5b). Location of profiles is shown in Figure 2, and the names of the crossed subbasins are shown in Figure 1. The western section (A-B) starts in the Zala-Somogy Basin, crosses the western and eastern Drava Trough, and terminates in the Slavonia-Srijem Basin. The eastern section (C-D) starts in the Mid-Hungarian Fault Zone, passes the Derecske Trough and Békés Basin, the Makó Trough and Szeged Basin, and reaches the Banat and Drmno Basins in Serbia.

Central Paratethys megasequence

Figure 5a and 5b shows that the dominant structural style accomodating synrift strata is a set of distinct half-grabens all over the Pannonian Basin (Figure 2). The initial synrift sedimentary rocks are composed mostly of basal conlomerates, fluvial to lacustrine gravels, and sands, muds, and locally lignite seams. Recent studies have suggested the existence of a large Early Miocene wrench fault-controlled lake system in the inner Dinarides and the southern Pannonian Basin (Mandic et al., 2011; de Leeuw et al., 2012). Sedimentary rocks of about the same age in the central part of the basin suggest that this lake system was more extended and represented a typical environment during the early synrift phase. A fluvial-lacustrine formation locally as thick as 800 m with frequent intercalations of rhyolite tuff layers with a minimum age of 23–20 Ma can be observed. This initial volcanism continued and large eruption of more silicic volcanic rocks occurred in the 21–12 Ma time period (Pécskay et al., 2006). Accumulations of several hundred meters of rhyolitic ignimbrites and tuffs are drilled mostly in the Mid-Hungarian Fault Zone, Zala, and Somogy Basins, and at the foothills of the Mátra, Bükk, and Tokaj mountains, northeast Pannonian Basin (Figure 2).

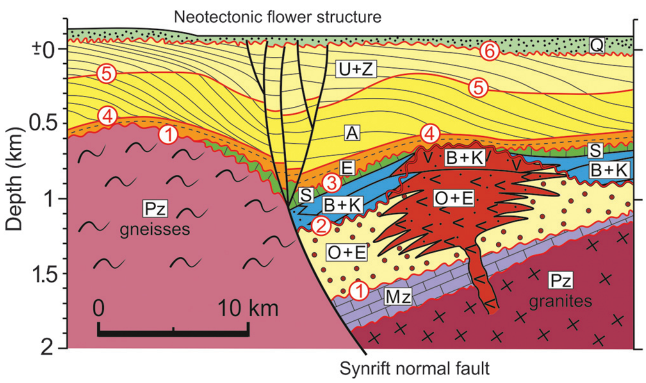

Figure 3. Generalized cross section of the Pannonian Basin showing the three stratigraphic megasequences (between unconformities 1 and 3, 3 and 7, and 7 to surface) and a synrift half-graben with a typical scenario when the bounding master-fault is associated with an overlying flower structure due to strike slip activity. Stratigraphic division is after Sztanó et al. (2013) and Balázs et al., (2016). Legend: 1 = basement unconformity, 2 = surface at the top of lower to middle Miocene volcanic and clastic rocks, 3 = surface at the top of marine middle Miocene strata, 4 = top of Endrőd Marl, 5 = top of Algyő Formation, 6 = base Quaternary unconformity, Q = Quaternary strata, U + Z = Újfalu and Zagyva Formations combined, A = Algyő Formation, E = Endrőd Formation, S = Sarmatian strata, B + K = Badenian and Karpatian marine strata and volcanics, O + E = Ottnangian and Eggenburgien terrestrial clastics and volcanics, and Mz/Pz = Mesozoic and Paleozoic basement.

This early terrestrial environment was replaced by marine conditions due to transgression of the Central Paratethys sea. Karpatian strata are made up of siltstone, claymarl, sandstone, and conglomerate beds. Continued sea-level rise led to widespread Badenian open-marine strata, composed of monotonous gray clay and claymarl. At the margin of deep basins, paralic sedimentation took place accompanied by biogenic limestones, which are overlain at many places by very similar Sarmatian limestones. Elsewhere, accumulation of Sarmatian claymarls took place in a nearshore environment. This was followed by latest Sarmatian to earliest Pannonian phase of basin uplift and erosion, which created a truncated surface except in areas at the periphery of the Pannonian Basin, where thick Sarmatian deposits accumulated (Nagymarosy and Hámor, 2012; Balázs et al., 2016).

Lake Pannon megasequence

The exposed land started to subside at early Pannonian time, which resulted in the birth of the Lake Pannon (Magyar et al., 1999, 2007). Rapid subsidence at many places led to 800–1000 m water depths, and development of a single, large lake. Probably, only a few peaks of volcanoes elevated above the lake level. In the early lake (until approximately 10 Ma) deposition of calcareous marl from suspension (lower part of the Endrőd Formation) occured, creating a blanket on a large part of the basin floor (Figure 5a and 5b).

In addition, clastic infill was also observed in the south from the internal Dinaric and South Carpathian mountains by smaller rivers. This resulted in the deposition of early sandstone bodies in the Drmno and Banat Basins (Figure 4b). In a large part of the Pannonian Basin, frequent mass flows derived from the shelf slopes led to a transition of the marls to the turbiditic Szolnok Formation, which is built up from alternating fine-grained sandstone and silt layers. The sediments deposited on the prograding slope itself are defined as the

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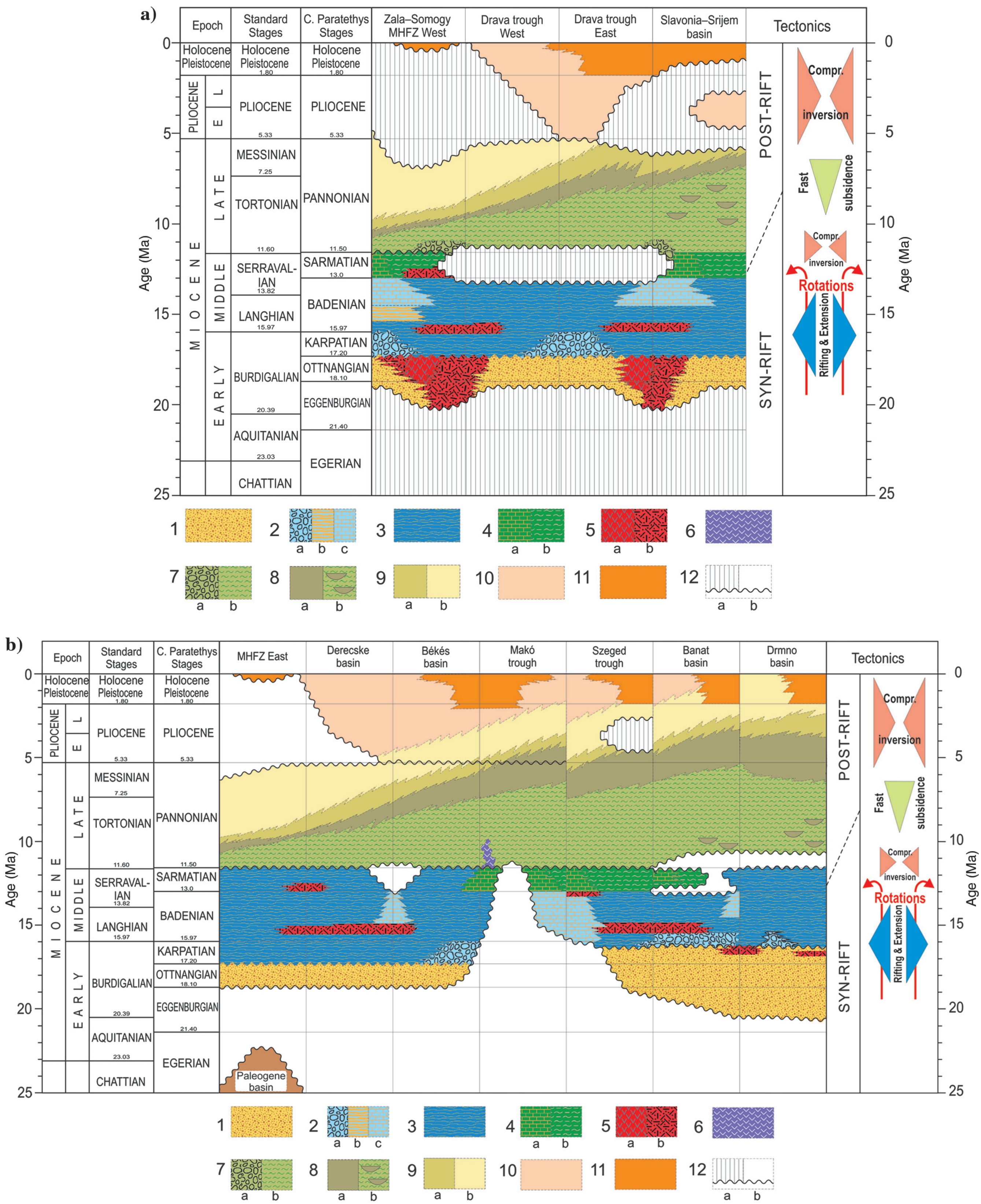

Figure 4. Tectonostratigraphic charts of the main syn- and postrift formations in subbasins along the sections A-B and C-D in Figure 5a and 5b. Legend: 1 = basal conglomerate, fluvial-lacustrine clastics; 2 = marine basin margin: (a) gravel, near shore mud, and limestone with (b) lignite and (c) biogenic limestone; 3 = open-marine clay and marl; 4 = brackish water (a) biogenic limestone and (b) offshore marl; 5 = volcanites: (a) andesites, (b) rhyolitic ignimbrites and tuffs; 6 = volcanites: alkali basalts; 7 = lacustrine (a) shoreline conglomerate, and (b) open-water marl; 8 = turbidites from the (a) shelf slope, and (b) local sources; 9 = shelf slope (a), and (b) shelf margin to plain sequence; 10 = alluvial plain deposits; 11 = red clays and loesses with paleosols, windblown sand and silt, river gravel and sand; 12 = unconformity with (a) stratigraphic gap and (b) correlative conformity.

Algyő Formation, comprising mainly silt and argillaceous marl, with subordinate sandy intercalations related to slope chanels. The thickness of this formation reflects the depth of the water body, in other words, coeval lake floor bathymetry in which the progradation took place. We can observe on the cross sections (Figure 5a and 5b) that the smallest thicknesses are associated with elevated parts of the basement (e.g., Villány area), and the largest values (locally, more than 1000 m decompacted thickness) can be found in deep depressions, such as the Derecske Trough and Békés Basin. It is an interesting finding that the eastern Drava Trough and Slavonia-Srijem Basin were characterized by quite shallow (less than 300 m) water depth in Lake Pannon.

The thick complex that is accumulated on top of the slope deposits is called the Újfalu Formation. The lower part of this formation is made up of sand sheets separated by silty beds. Its upper part is composed of siltstones and marls with local sand bodies and lignite beds. The uppermost part of the Pannonian strata is related to the vanishing lake and formation of a large alluvial plain, such as the present-day Great Hungarian plain (Figure 1) sediments are floodplain and marsh deposits with river channel sands and gravels.

Terrestrial megasequence

In the course of termination of Lake Pannon in eastern Croatia and central Serbia (Paludina Lake, Harzhauser and Mandic, 2008), neotectonic vertical movements led to uplift and erosion in many parts of the basin followed by deposition of the Late Pliocene to Early Pleistocene red clays, Middle to Late Pleistocene loess sequences, and Late Pleistocene and Holocene fluvial deposits and aeolian sands (Kovács et al., 2011; Fitzsimmons et al., 2012). At the same time, continued subsidence in deepest basins, such as the Makó Trough, Békés, Banat, and Drmno Basins, resulted in continuous sedimentation in the Late Miocene through Quaternary time interval (Figure 5a and 5b).

Neotectonic deformations are actually best reflected by the present shape of the Algyő Formation because its upper boundary corresponds to a paleo-shelf plain, which should have represented a nearly horizontal paleo surface. Its present undulation is the consequence of

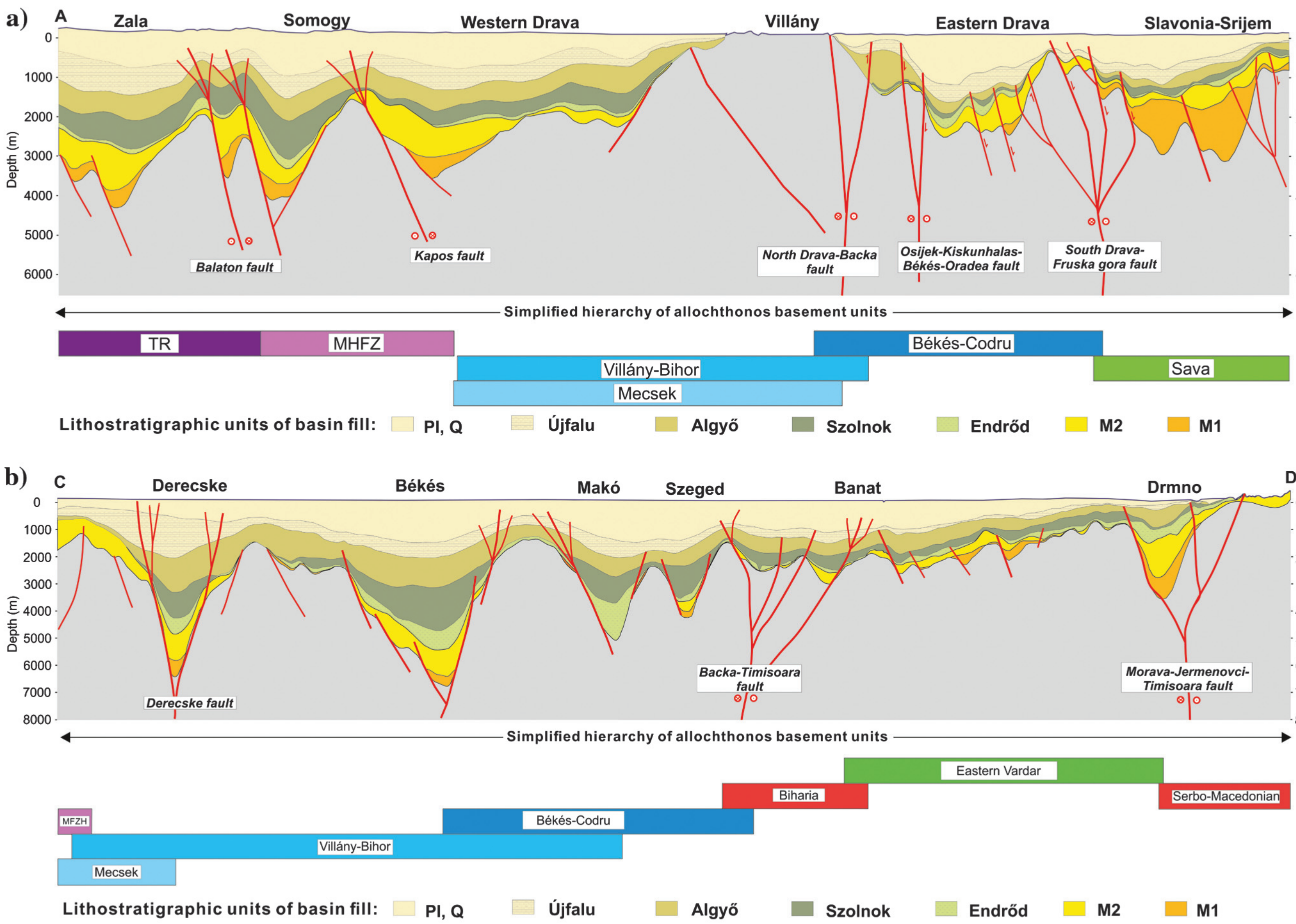

Figure 5. Geologic section A-B from the Zala Basin (Hungary) to the Slavonia-Srijem depression (Croatia) and C-D from the Mid-Hungarian Fault Zone to the Drmno Basin in Serbia. Stratigraphic units are simplified, the lower (M1) and middle (M2) Miocene formations are shown together. The Pannonian Formations are those defined in the concept of shelf migration in the Pannonian Lake (Magyar et al., 2013; Sztanó et al., 2013) as is seen in Figure 4a and 4b. The very complex basement is also shown schematically; only the hierarchy of basement nappes are indicated. The length of the A-B section is approximately 300 km, and the vertical exaggeration is 1:100. The length of the C-D section is approximately 450 km, and the vertical exaggeration is 1:100.

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neotectonic differential vertical movements (Figure 5a and 5b). Another manifestation of the neotectonic movements is represented by young strike-slip faults, which are regional features transversing generally the entire Pannonian Basin (Figure 2). They are composed of east–northeast/west—southwest-striking master faults and several splays with northwest–southeast orientation. In a cross-sectional view, they represent kilometer-wide shear zones associated with positive or negative flower structures.

Generalized mechanism of hydrocarbon formation

As has been demonstrated since the 1980s, most of the known hydrocarbon pools in the Pannonian Basin are located and generated in the Neogene Basin fill (Dank, 1988; Clayton et al., 1994; Velic et al., 2012) (Figure 6). Vitrinite reflectance (Ro) data and maturation history modeling show that, in general, the oil-generation window (0.6% < Ro < 1.3%) is located in the depth range of 2–5 km, as is shown in Figure 7 (Horváth et al., 1988; Clayton et al., 1994; Kostić and Ercegovac, 2002; Malvic and Busic, 2012). The figure also shows as a comparison the avarage temperature and maturity conditions of the Jurassic source rocks in the North Sea Central Graben rift structure (Kubala et al., 2003). This comparison indicates that the Miocene Pannonian Basin developed indeed under very high temperature conditions as a much shorter time interval for hydrocarbon generation (approximately 5–7 my) resulted in a more mature basin.

Karpatian and Badenian marine strata and lower Pannonian lacustrine shales are characterized by total organic carbon content of 1%–2%, and very locally as

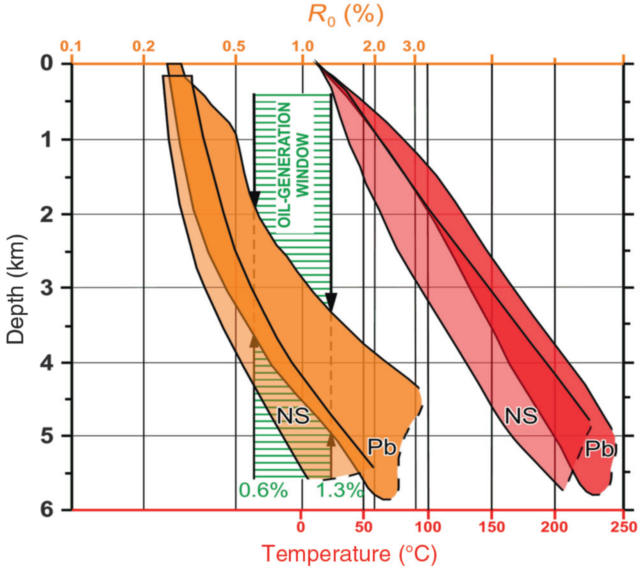

Figure 7. Range of vitrinite reflectance (R0, with light and dark orange) and temperature (with light and dark red) versus depth variations in the Pannonian Basin and North Sea (Horváth et al., 1988; Kubala et al., 2003). NS = North Sea, Pb = Pannonian Basin.

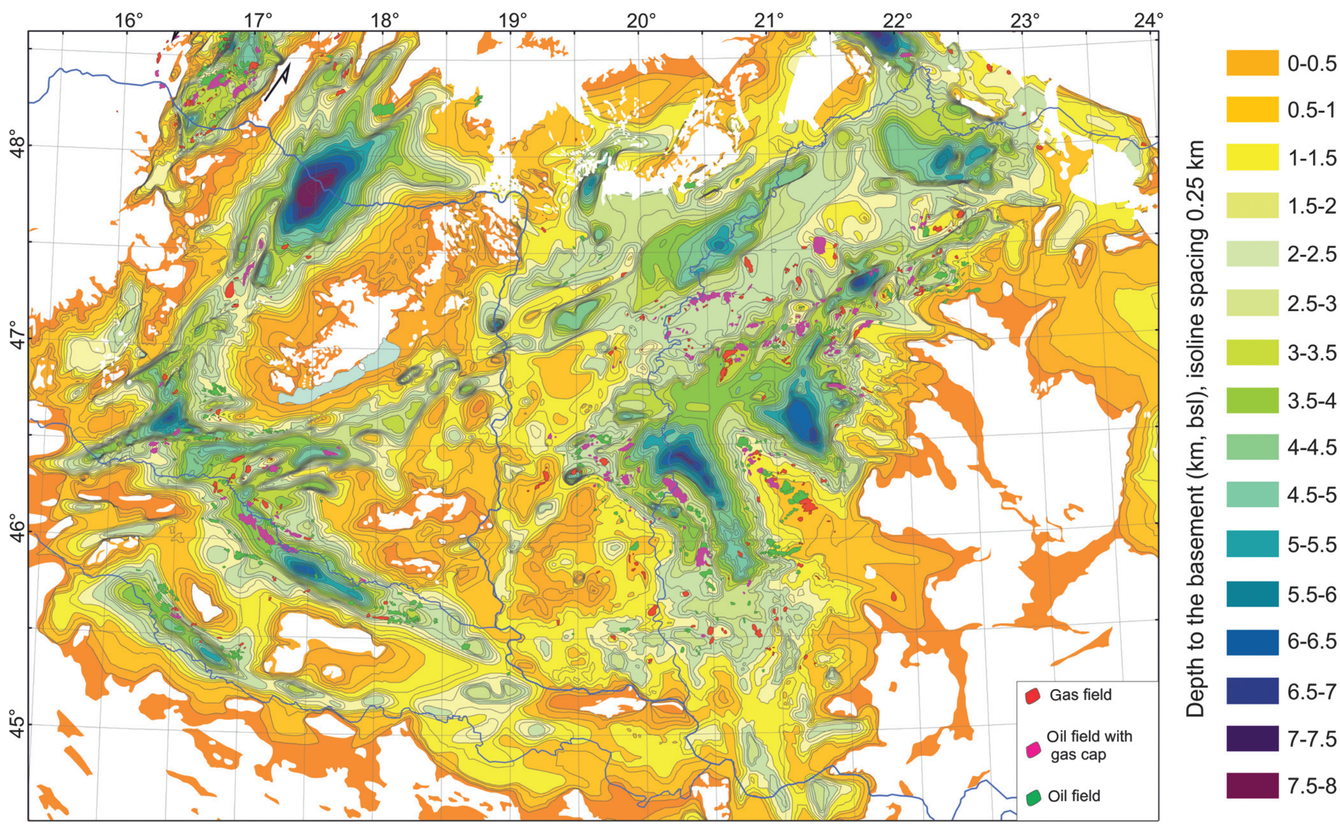

Figure 6. An overview map showing thickness of the basin fill (basement depth) and hydrocarbon fields in the Pannonian Basin (updated after Tari and Horváth, 2006).

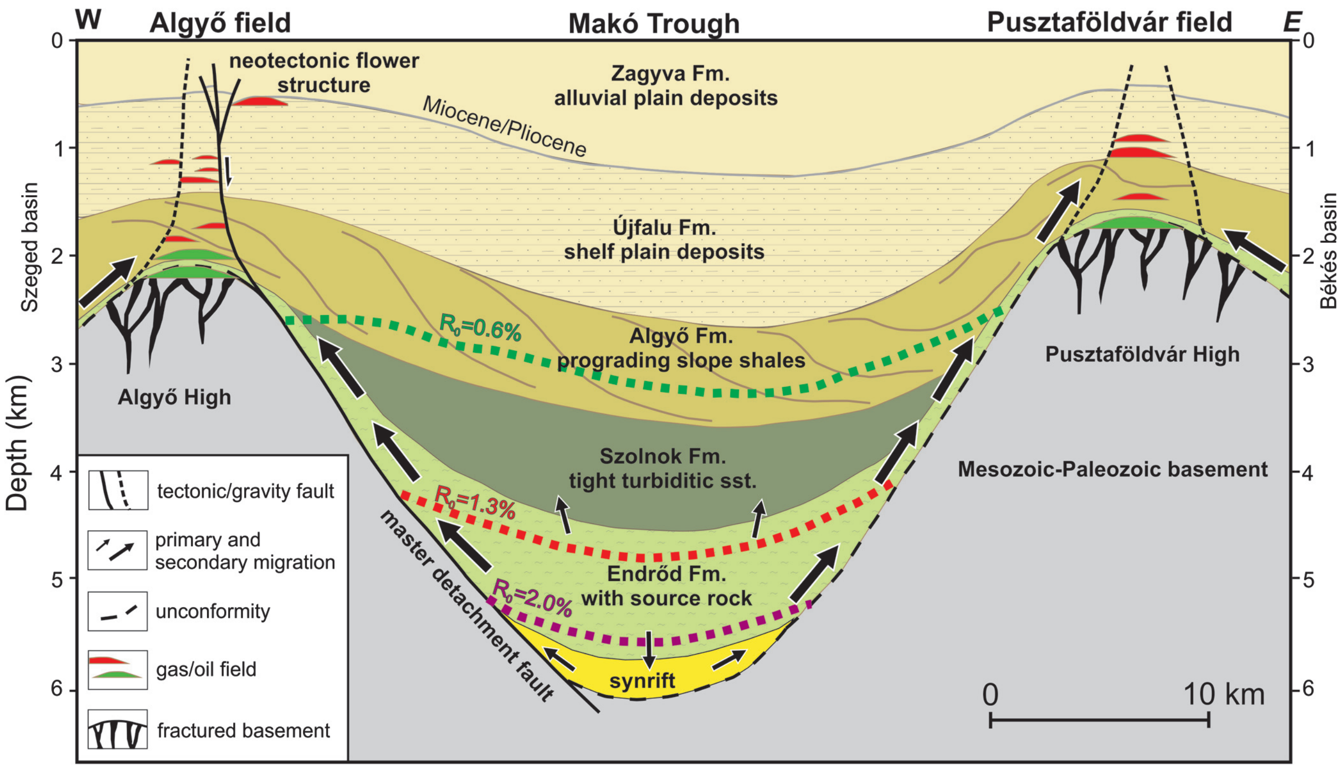

Figure 8. Generalized model illustrating the generation, migration, and trapping of hydrocarbons in the southern part of the Pannonian Basin (modified after Horváth et al., 1987).

high as 3%. Rock-Eval pyrolysis studies indicate that they contain type III and also mixed types II–III kerogens; hence, the generation of oil and gas has occurred (Horváth et al., 1988; Šolević et al., 2008; Mrkić et al., 2011; Badics and Vető, 2012).

Maturity history modeling shows that the onset of hydrocarbon generation of Miocene source rocks in the Pannonian Basin is quite young; its onset varies between 7 and 5 Ma, and it is still going on in the deeper parts of the main depocenters (Horváth et al., 1988; Dolton, 2006).

Secondary migration pathways were provided mostly by the unconformity at the top of the basement and associated faults (Figure 8). Structural closures form traps in different structural settings, most typically above basement highs in compactional anticlines, provided that reservoir rocks and adequate seals are available. Neotectonic faults often offer good conduits to charge relatively shallow structures developed during strike-slip faulting, e.g., rollover anticlines and stratal termination (Tari and Horváth, 2006).

The largest pools in compactional anticlines can be found in the southeastern part of the Great Hungarian Plain, above basement highs at the flanks of the Makó Trough and Szeged Basin, e.g., the Algyő field (Magyar et al., 2006). This setting continues to Serbia, where the most significant similar findings are the Kikinda and Velebit fields.

Individual oil, gas, and mixed pools can be found in the following stratigraphic units: fractured basement and the overlying basal conglomerate, shelf slope-toe turbiditic sandstones, and shelf-plain channel fill and point-bar deposits (e.g., Tari and Horváth, 2006). The most favorable reservoirs are the shelf-plain sandstones, with porosities and permeabilities up to 29% and 235 mD, respectively. Figure 8 also illustrates that conducting faults, of tectonic and compactional origin (Balázs et al., 2017), play an essential role in the formation of pools at higher stratigraphic levels above the anticline. The Algyő field is associated with a large-scale gentle anticlinal feature, and its formation can be explained by the compaction of the deep Szeged Basin and Makó Trough on the flanks of the Algyő high (Magyar et al., 2006; Balázs et al., 2017).

It should be emphasized that the anticline play has been an obvious target of hydrocarbon exploration in the Pannonian Basin, and most of the seismically detected structures have been already tested by drilling, as is shown by the creaming curve of the Hungarian part of the basin (Tari and Bérczi, personal communication, 2017).

Conclusion

The formation and evolution of the Pannonian Basin is quite well-understood to establish a realistic view on its remaining hydrocarbon potential. On one hand, the basin substrata at a depth of more than 3–4 km are strongly overmature; on the other hand, tectonic conditions in the basement are so complex that reliable structural models cannot be easily applied (see Figure 5a and

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5b). However, the latest generation acquisition and seismic imaging technology and new ideas on trap formations particularly in off-anticline settings in the Neogene basin fill and Alpine folded belts in the pre-Cenozoic basement can lead to further economic petroleum findings.

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