doi: 10.2478/v10096-012-0037-z

Unconventional hydrocarbon resources of the Bjelovar Subdepression (Pannonian Basin System) in Croatia: an overview

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(Manuscript received December 8, 2011; accepted in revised form June 13, 2012)

Abstract: The Croatian part of the Pannonian Basin System includes several Miocene chronostratigraphic (sub)stages mostly characterized by weak permeable clastic sediments. They are often also mature source rocks at depths of more than 2500 m, from Late Badenian to Early Pannonian ages, represented by marls and calcitic marls, and kerogene Types II and III. The other types of weakly permeable sediments are tight sandstone mostly of Badenian age. Those two lithotypes are potential unconventional reservoirs described in the Bjelovar Subdepression, regarding their age, geological evolution, lithology, porosity and permeability. Domination of kerogene Type III and low total organic carbon defined marls as gas-bearing source rocks. Both marls and tight sandstones mostly have porosity less than 10 % and permeability less than 10^{-3} μm^2. It is about 10–100 times lesser permeability than in conventional reservoirs. Weakly permeable zones are highly stochastically distributed and fluid flows are relatively short (several meters), which could be enhanced only by the using hydraulic or other fracturing techniques.

Key words: Miocene, Croatia, Bjelovar Subdepression, tight sandstones, marls, unconventional reservoirs, hydrocarbon gas.

Introduction

Hydrocarbon reservoirs can contain oil, condensate and/or gas. The conventional approach considers a reservoir as rock with reservoir properties, namely enough highly effective porosity and permeability for hydrocarbon recovery with application of primary, secondary or tertiary recovery methods. However, due to wettability, capillary forces and saturation, only part of the total hydrocarbon reserves (Original Hydrocarbons In Place, abbr. OHIP) can be recovered from reservoirs. Average recoveries are about 60 % for gas and 20–30 % for oil reservoirs. However, parts of hydrocarbons remain in reservoir and those remaining quantities are larger in weakly permeable reservoirs, like tight sandstones. Part is also kept in the source rocks where hydrocarbons are generated, and only reached primary migration inside source rocks initiated by capillary forces and pressures. The range of primary migration is on a scale of hundreds meters, and of secondary (from source to reservoir rocks) on a kilometer scale.

The term of unconventional reserves covers hydrocarbons associated with tight sandstones, shales or marls, coal bed methane, gas hydrate deposits, heavy oil, tar sands (i.e. weakly permeable rocks) and reservoirs characterized by high pressure and temperature. Unconventional reservoirs of hydrocarbon contain chemically the same hydrocarbons as the conventional ones, but trapped in the weakly permeable rock, which are often also source rocks where it was generated. The unconventional reservoirs are also often located geographically inside the same borders that delineated the surface projection of the hydrocarbon field with conventional reserves. In such cases unconventional reservoirs are on higher depths, where their rocks, rich in organic matter, reached thermal maturity, generated hydrocarbons (mostly during catagenesis) and due to expulsion, that is secondary migration, had been trapped in conventional reservoirs with high primary or secondary porosity (sandstones, breccia, fractured carbonates, etc.).

The geological properties of such reservoirs in northern Croatia are shown here. Some previous preliminary geological studies and numerical calculations for such reservoir systems in Croatia defined some petroleum engineering and fracturing properties (e.g. Page & Miskimins 2009) as well as geological potential (e.g. Miskimins 2006).

Overview of geology and petroleum potential of the Croatian part of the Pannonian Basin System

The Pannonian Basin System (PBS) is a back-arc basin system superimposed on an earlier, mostly Cretaceous, compressional realm (Tari & Horváth 2006). Royden (1988) provided a modern understanding of the Neoalpine evolution of the PBS and relation to the Carpathians. However, the pre-Neogene evolution of the PBS substrata has been discussed only in a few studies (e.g. Tari 1994, 1995). During the Middle Miocene the PBS (Fig. 1) was mostly covered by the Central Paratethys, and later by younger brackish and freshwater basins and lakes formed from the Paratethys.

The PBS was formed mainly due to the continental collision in the Carpathians to the north and northeast. At the southern and southwestern margin convergence and subduction resulted from moving of the Apulian Plate under the Dinarides

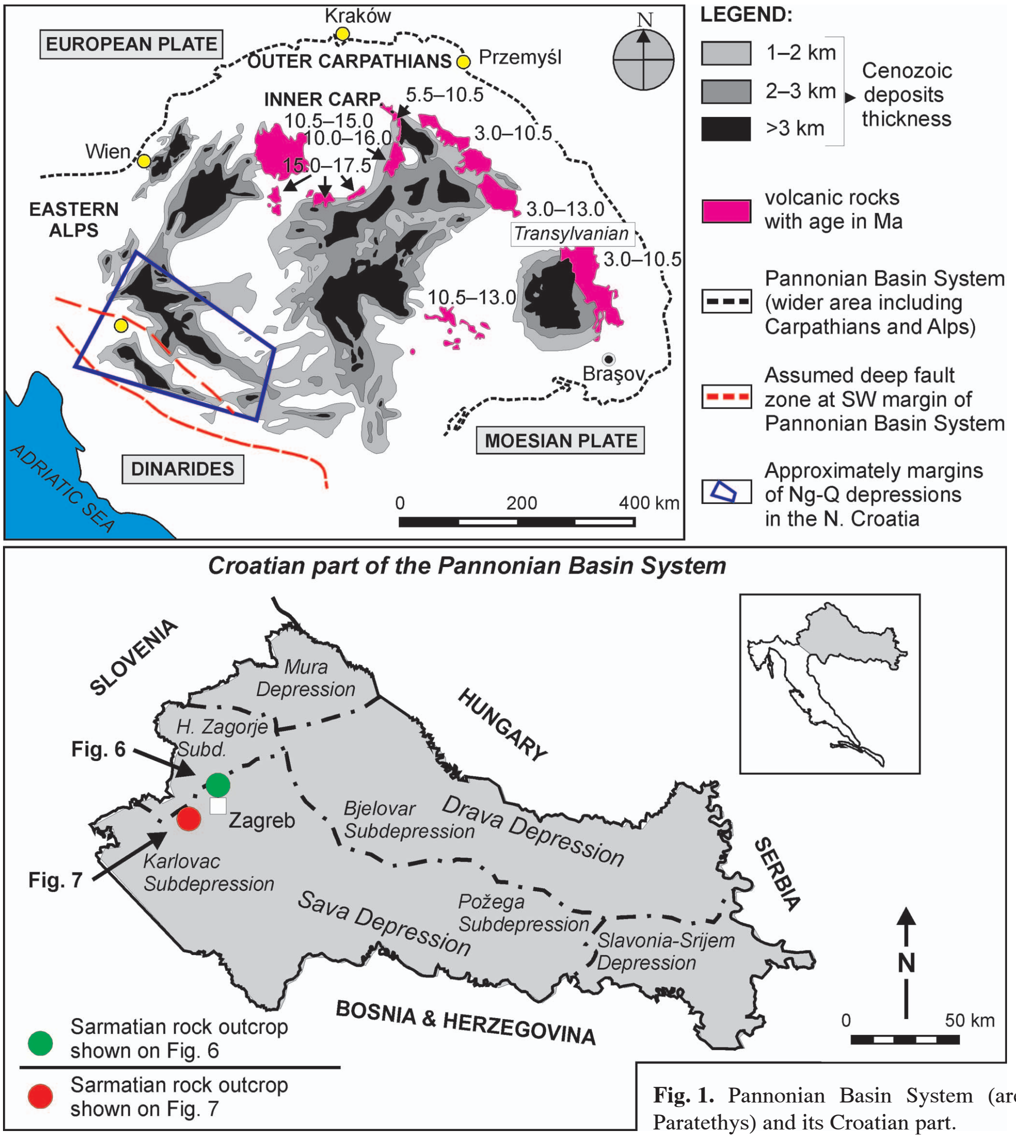

Fig. 1. Pannonian Basin System (area of Central Paratethys) and its Croatian part.

during the Styrian orogenic phase. That created, e.g. the Periadriatic-Vardar lineament and some other regional features. However, Pavelić (2002) even located the southwestern boundary of Central Paratethys more to the south from the Periadriatic-Vardar lineament in area of small and fresh-water within Dinarides. Those basins were never flooded by marine transgression in the Paratethys.

The very first extensions in the PBS were initiated in the Ottnangian (Royden 1988; Rögl 1996, 1998), but were documented only locally, and continued through the Karpatian when lacustrine and fluvial sediments were locally deposited also in the different surrounding areas of the PBS like the Apuseni Mts, Carpathians and Podolian Upland as well as on the margin of the Alps and the Bohemian Massif (Rögl 1996, 1998).

The Badenian was period of the largest extensional displacements and maximal extensions of the marine environment (e.g. Rögl 1996, 1998; Vrbanac 1996), mostly because of the existence of connections (through Trans-Tethyan trench corridors) with the Mediterranean in the southwest and the Indo-Pacific in the southeast. These connections resulted in two regional transgressions. The first happened in the Early Badenian and covered the entire basin system, from Austria to Romania (Transylvania) and from the Carpathians to the Dinarides. The second followed in the Middle Badenian, caused development of the marine environment of normal salinity in the western part of the Central Paratethys (i.e. parts of Poland, Hungary, Slovenia and Croatia). The evaporate sediments in other parts are documents of regression and increased salinity. Such thick evaporate sediments are described as the Middle Badenian salinity crisis, and documented in the Transcarpathian and Transylvanian Basins as well as the Carpathian Foredeep (Kováč et al. 2007). The trench corridors that connected the Paratethys and Mediterranean, or Indo-Pacific were eventually closed in the Late Badenian (e.g. Steininger et al. 1978). This caused another, this time final deposition of regional evaporates, as in the Carpathian Foredeep and the Transylvanian Basin (Andreyeva-Grigorovich et al. 1997; Mărunteanu 1999; Peryt 1999; Chira 2000). In the Croatian part of the Pannonian Basin System (CPBS), Vrbanac (1996) interpreted the Badenian as a stage with a marine environment when present-day mountains were islands or shallow submarine uplifted paleoreliefs and beginning of initial marine transgression (Ćorić et al. 2009). Pavelić (2001) described the Late Badenian as a period when an extensional had been gradually transformed into a post-extensional period, when tectonics were caused mostly by thermal subsidence and had a dominant compressional character. During the entire Badenian, as a result of weathering of uplifted paleorelief and carbonate reefs as well as the activities of numerous alluvial fans, large quantities of coarse-grained sediments were deposited.

In the Sarmatian the marine environment was progressively reduced. This eventually finished with the formation of more or less isolated brackish and freshwater lakes during the Late Miocene across the entire basin system (e.g. Rögl 1996, 1998). Dominantly pelitic sediments, mostly marls and calcitic marls, were deposited. Royden (1988) pointed out the Early Pannonian as a period when a major extensional phase finished over most of the PBS. It was followed by a post-extensional phase, generated by thermal subsidence, and accompanied by local alkali volcanic activity. Turbidites were a characteristic transport mechanism in the CPBS, moving silty and sandy detritus that originated from the Eastern Alps. They were activated due to gravitational and tectonic instability mostly on depression margins, or ramps (e.g. Vrbanac et al. 2010; Malvić & Velić 2011).

The Late Pontian, and especially the Pliocene and Quaternary were characterized by fluvial, lacustrine and marshy sedimentation. Aeolian sediments, namely loess, are very often found in some parts of the CPBS and dated to the latest Pleistocene. This final phase of formation of the PBS was characterized by dominant compressional tectonic styles, where are often documented reactivation of fault planes with inversion displacements (e.g. Velić 2007). During the entire Neogene–Quaternary period Malvić & Velić (2011) described for the CPBS two transtensional (Badenian and Pannonian–Early Pontian) and two transpressional (Sarmatian and Late Pontian–Quaternary) regional tectonic phases.

Unconventional hydrocarbon resources of the Bjelovar Subdepression, Croatian part of the Pannonian Basin System

The area of the Bjelovar Subdepression covers about 2900 km^2 and has been explored with more than 500 deep wells, dozens of seismic sections and gravimetric surveys on the west and northwest (Malvić 2003a; Malvić & Đureković 2004). It is a large southwestern branch of the Drava Depression (Fig. 1), separated from the central depression zone during the Pliocene and Quaternary. The most data is available

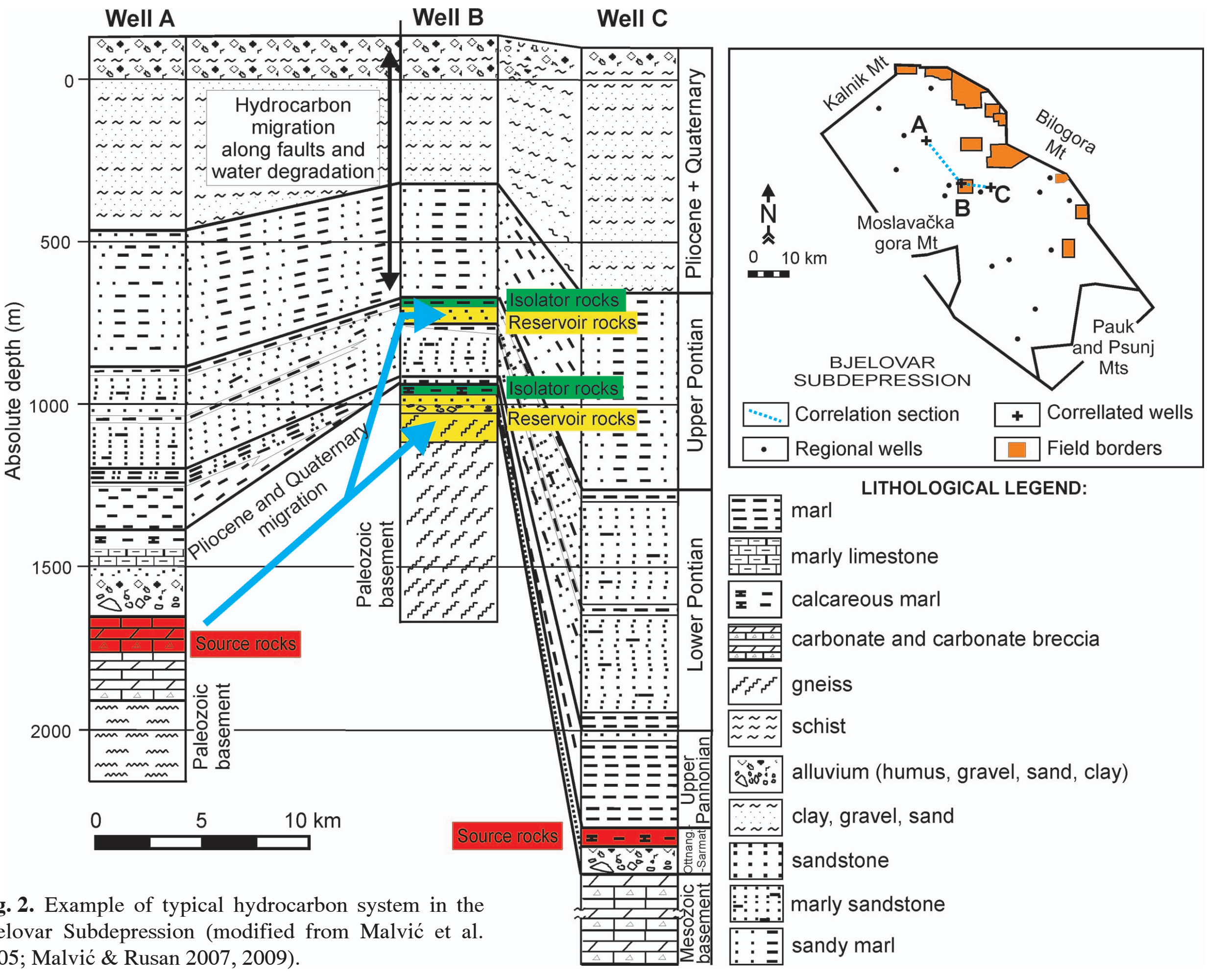

Fig. 2. Example of typical hydrocarbon system in the Bjelovar Subdepression (modified from Malvić et al. 2005; Malvić & Rusan 2007, 2009).

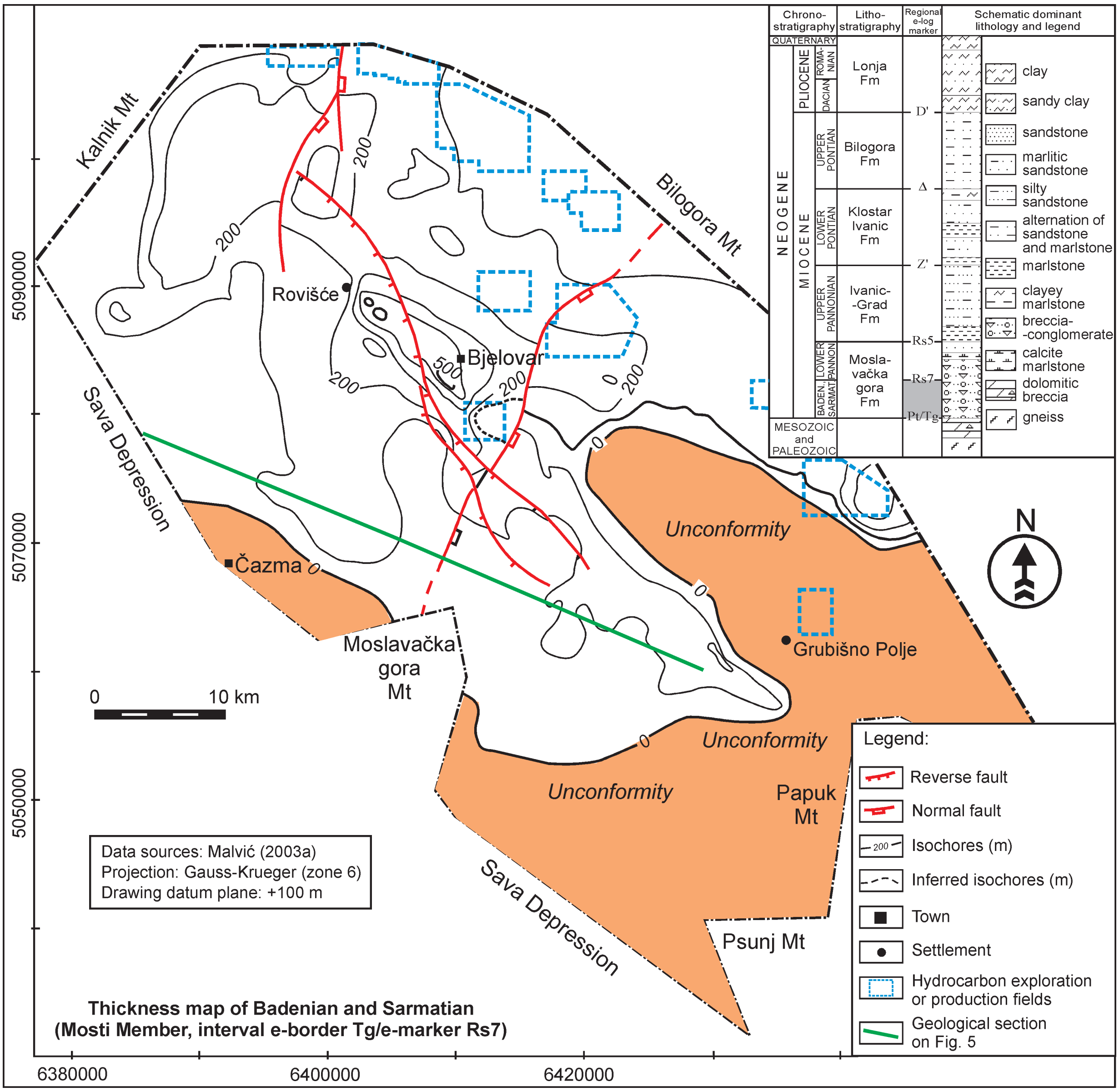

Fig. 3. Thickness maps of Badenian and Sarmatian sediments (Moslavačka gora Formation), the Bjelovar Subdepression (modified from Malvić 2011).

from the 12 hydrocarbon fields of different sizes, located mostly on the subdepression margins (Fig. 2). The remaining (about 4 %) wells are classified as regional. There are several lithostratigraphic formations defined inside the Neogene and Quaternary sediments. The oldest one, Moslavačka gora Formation (Fig. 2), comprises the rocks that define the entire hydrocarbon system. The reservoirs (mostly breccia and conglomerates) and traps are of possible Early (16.4–15.0 Ma) and certainly Middle (15.0–13.5 Ma) Badenian age. The source rocks are of Late Badenian (13.5–13.0 Ma), Sarmatian (13.0–11.5 Ma) and Early Pannonian (11.5–9.3 Ma) ages. The younger regional reservoirs are medium- and fine-grained sandstones, which belong to the Late Pannonian (9.3–7.1 Ma) and Early Pontian (7.1–6.3 Ma) substages, that is lithostratigraphically to the Ivanić grad and Kloštar-Ivanić Formations (Croatian lithostratigraphic nomenclature is given on Figs. 3 and 4). Chronostratigraphic time spans listed for particular (sub)stages are given according to the values published in Haq & Eysinga (1988), Ldi (2006) and Malvić (2011). A palinspastic reconstruction on the transversal section through the Bjelovar Subdepression is given in Fig. 5 to observe evolution of thicknesses and main faulting through the Neogene and Quaternary.

The conventional reservoirs of Badenian age are often connected in single hydrodynamic unit with the shallowest part (about 10–15 meters) of the Paleozoic or Mesozoic basement rocks. It is result of a long period of continental weathering during the Paleogene and locally even longer. Badenian transgression and deposition of coarse-grained sediments with high primary porosity overlaid such eroded, weathered and even cataclized basement rocks where secondary porosity previously formed, making common space for fluid migration.

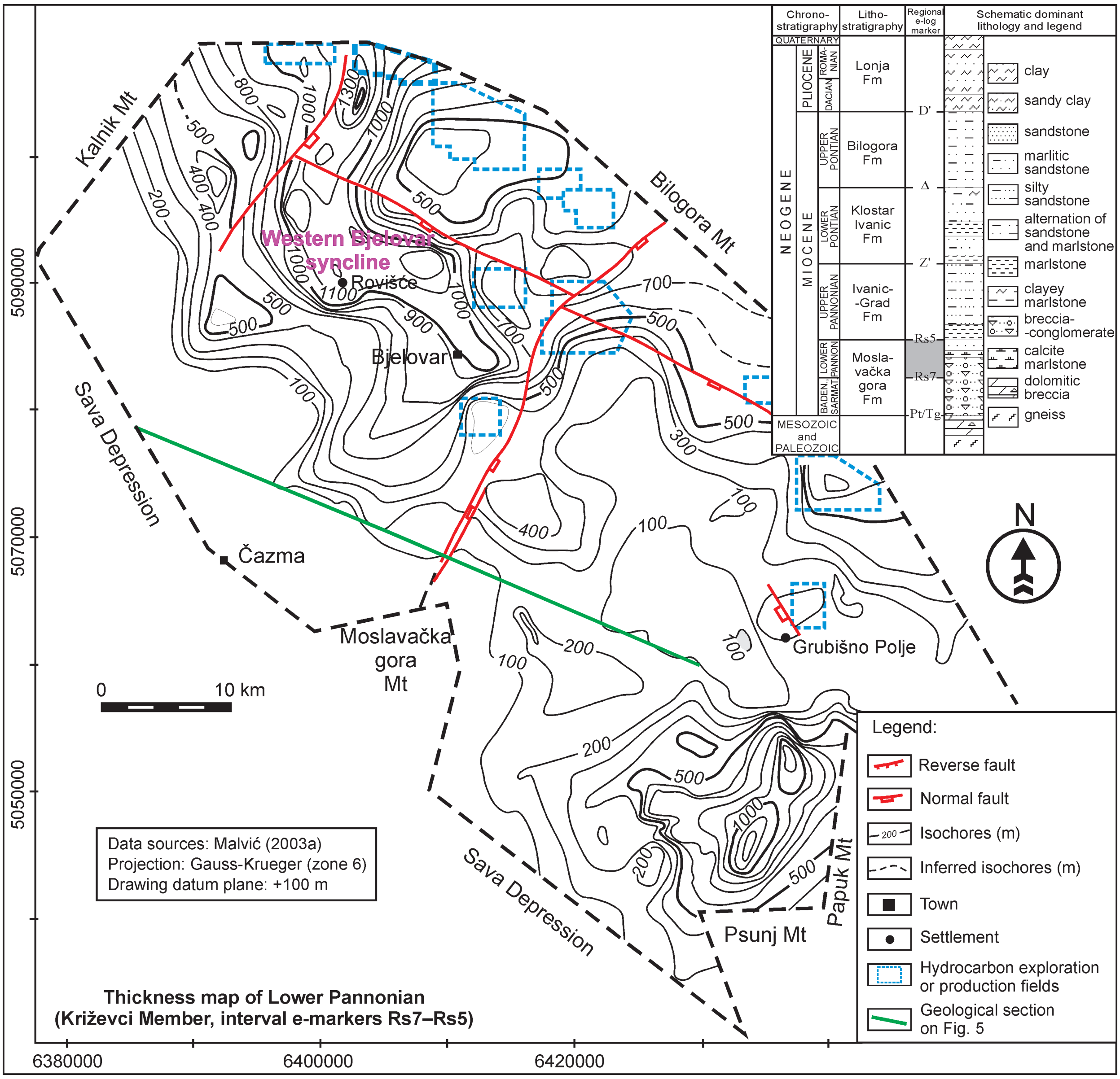

Fig. 4. Thickness maps of Lower Pannonian sediments (Moslavačka gora Formation), the Bjelovar Subdepression (modified from Malvić 2011).

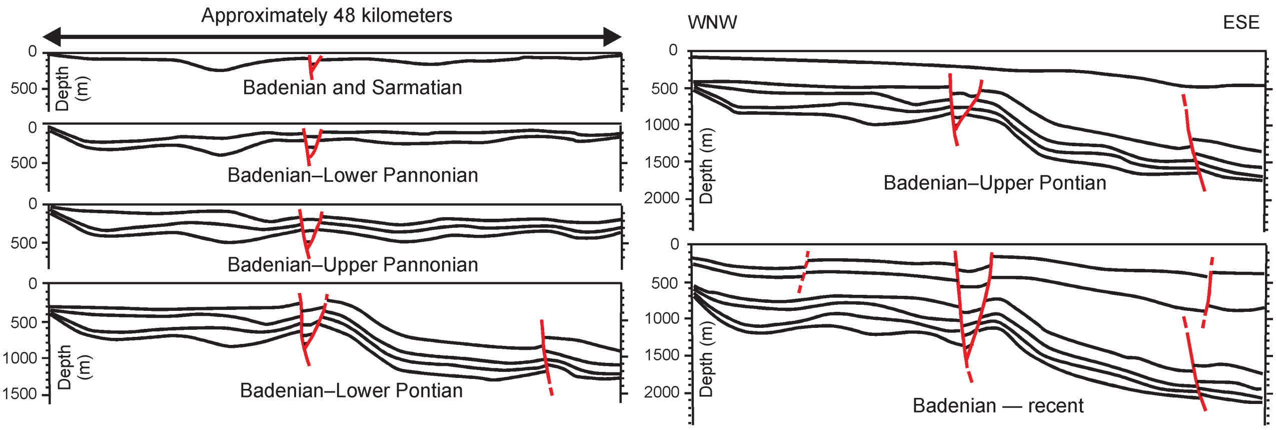

Fig. 5. Transversal palinspastic sections through the Bjelovar Subdepression (modified from Malvić 2003a).

The Badenian sediments are characterized by average total porosity of about 10 % (or locally more in non-cemented breccia) and permeability of few hundreds 10^{-15} m^2 (Malvić 2003b). Upper Miocene conventional reservoirs (sandstones) have good petrophysical properties only in the northern and (partially) northeastern Bjelovar Subdepression and elsewhere they are often completely replaced by impermeable sediments, especially on the south and southwest. The average total porosity ranges very wide (10–30 %) reflecting a wide range of permeabilities (Malvić 2003b).

Sediments of the Upper Badenian, Sarmatian and Lower Pannonian, which belong to the Moslavačka gora Formation are considered as potential source rocks, regarding total organic carbon (TOC) and thermal maturation. The thickness of the entire formation can reach more than 1000 meters (Figs. 3 and 4), where those sediments reached the relevant depth for maturity in two synclines, Rovišće on the west and Velika Ciglena on the east (Fig. 2, points A and C). These two structures cover about 18.5 % of the total subdepression area (Malvić 2003a).

The complete set of paleostructural maps (structural and thickness maps) has been interpolated (Malvić 2003a, 2011) using hand-drawing of isochors. Thicknesses calculated between electro-log markers (determined on the curves of spontaneous potential and apparent resistivity) that separate particular members in the Moslavačka gora Formation (Mosti Member — Badenian and Sarmatian at Fig. 3, and Križevci Member — Early Pannonian at Fig. 4) were used as control points. The control points were located along seismic sections and regional wells inside the Bjelovar Subdepression. Their locations are given on A0 maps published in Malvić (2003a).

The thickness maps related to rocks of the Moslavačka gora Formation have been statistically analysed (Majstorović Bušić 2011) with the goal of calculating the volumes of particular lithostratigraphic members as well as determining the end of the 1st transpressional phase in this part of the CPBS. Despite the general opinion that the 1st transpression phase in the CPBS finished in the Lower Pannonian, in the Bjelovar Subdepression its end is observed at the end of the Sarmatian.

The methodology of volume calculation has been based on estimation of the grid point's thickness value extrapolated from the closest isochore. Using this approach, the sum of all grid node thicknesses has been divided by the number of used nodes. The result is the average thickness. That value for the Badenian–Sarmatian interval (Moslavačka gora Formation, Mosti Member) is 192 m, and for the Lower Pannonian (Moslavačka gora Formation, Križevci Member) is 465 m. The average thickness (m) was multiplied by the subdepression area (m^2) shown with borders on Figs. 3 and 4. The volume of Badenian-Sarmatian rocks is $35{,}040 \times 10^5$ m^3. The volume of the Lower Pannonian interval is $127{,}875 \times 10^5$ m^3. The pelitic sediments that could reach the stage of mature source rocks approximately belong to the younger half part of the Mosti Member and to the entire Križevci Member.

The surface outcrops of the Sarmatian sediments, as typical pelitic rocks with increased total organic carbon content in the CPBS, are found on the margins of the most present-day mountains in Northern Croatia. Here are given photos of two characteristic sequences located (locations are given on Fig. 1b) at Medvednica Mt (Fig. 6) and Samoborsko gorje Mt (Fig. 7), that is on the very southwestern margin of the CPBS. Lithologically these are marls and calcitic marls, with more or less sandy component. The sand in such rocks is the result of deposition in a near-shore and so shallow environment, in the range of local alluvial fans.

Table 1: Geochemical values C_{org}, S_2, HI, OI of core samples from Badenian to Lower Pannonian in the Bjelovar Subdepression (Malvić 2003).

Samples from Badenian–Sarmatian (age 16.4–11.5 Ma)	**Mean**	**Minimum**	**Maximum**
C_{org}	1.14	0.01	5.30
S_2	6.91	0.01	22.91
HI	237.81	120.00	397.78
OI	447.83	107.30	1100.00
Samples from Lower Pannonian (age 11.5–9.3 Ma)	**Mean**	**Minimum**	**Maximum**
C_{org}	0.61	0.19	1.41
S_2	1.64	0.92	2.89
HI	271.74	184.00	433.00
OI	76.70	31.53	121.87

In the entire CPBS and PBS in general from Late Badenian to Early Pannonian sedimentation was characterized by pelitic rocks like marlstone, limestone, calcitic marlstone and marly limestone (Royden 1988; Rögl 1996, 1998; Vrbanac 1996). It was a result of a shallow and calm brackish environment favourable for preservation of organic matter, transformed into kerogene Types II and III. Pelitic sediments in the CPBS, today at depths of more than 2500 m are mostly in the catagenesis phase. The Bjelovar Subdepression source rocks are dominantly characterized by kerogene Type III, which is mostly a precursor for gas. The generation potential of samples collected in the subdepression is described with several geochemical variables (given in Table 1). These were organic matter content (C_{org}) representing total carbon in sediments (%). S_2 represents hydrocarbon volume generated during pyrolysis (420–460 °C) and is expressed as g HC/kg rock. Hydrogen index (HI) represents the S_2/C_{org} ratio, which indicates the rock maturation level. Oxygen index (OI) is expressed as the ratio S_3/C_{org}, where S_3 is carbon dioxide volume created in pyrolysis (g CO_2/kg rock).

All the values given in Table 1 are indicated on kerogene Type III, sometimes even oxidized, which mostly generates gas with expelling efficiency usually less then 20 %. It is interesting to compare with kerogene Type II (average $C_{org} > 1.5$ %), where expelling efficiency can reach 60–90 %. The expelling process is less efficient from lean source rocks (i.e. thin and/or source rocks with low generative potential). In such cases the generated volumes are small, but also most of hydrocarbons remain trapped in the source rocks (especially oil because of viscosity) (Cooles et al. 1986).

Figure 8 presents such a system of thin and interlaying conventional and unconventional reservoirs in Badenian sediments, connected in a single hydrodynamic unit with reservoirs in fractured and weathered Paleozoic rocks in the basement. Frequent alteration of numerous Badenian thin layers, characterized by different clastic lithologies (breccias,

Fig. 6. Calcitic marl blocks outcrop (vertical scale about 10 m, Zagreb, Trzinove pećine locality, Medvednica Mt, N 45° 50. 321′, E 015° 54. 178′, altitude 264.4 m) (photo Majstorović Bušić, 4. 11. 2011). Location is shown onto Figure 1.

Fig. 7. Calcitic marl blocks outcrop (scale is hammer, Sveta Nedjelja hill locality, Samoborsko gorje Mt, N 45° 46.779′, E 015° 44. 868′, altitude 249.4 m) (photo Majstorović Bušić, 5. 11. 2011). Location is shown on Figure 1.

sandstones, tight sandstones, sandy marls, marls) consequently resulted in different permeability zones, where even weakly permeable sediments had been saturated during secondary migration of gas. Trapping in such thin and tight reservoirs is additionally supported by frequent alternation of isolator rocks (sandy marls and marls) which formed hydrodynamic subunits that very slowly communicate among themselves or temporarily even reached naturally stable state of saturation.

The example shown in Fig. 8 belongs to the field discovered on the east of the Bjelovar Subdepression (right-most location on Figs. 3 and 4). The described tight gas sandstones in alternation with breccias and marls are one of two expected types of unconventional reservoirs in the Middle Miocene sediments in the analysed subdepression, but also in the entire CPBS. The second are marls and calcitic marls of Late Badenian to Early Pannonian age, which are regionally proven as the source rocks with mixture of kerogene Types II and III (in the Bjelovar Subdepression kerogene Type III is dominant). Exploration of these two types of unconventional reservoir is different, although major data for both cases come from reflection seismic sections and regional wells. Production and exploration wells on existing conventional fields can be useful only if weakly permeable and source sediments have been drilled and examined together with conventional reservoirs. However, such analyses are rare because these sediments were not exploration and production targets in the past.

Furthermore, tight sandstones can also be expected in Upper Miocene sandstone sequences, where the main conventional reservoirs in Croatia have been proven, namely in medium-grained sandstones, with thicknesses of a few to dozens of meters and porosity 15–20 % and saturated both with oil and gas. Due to depositional conditions in the Upper Miocene (e.g. Malvić & Velić 2011) such channel sandstones laterally are gradually replaced with weakly perme-

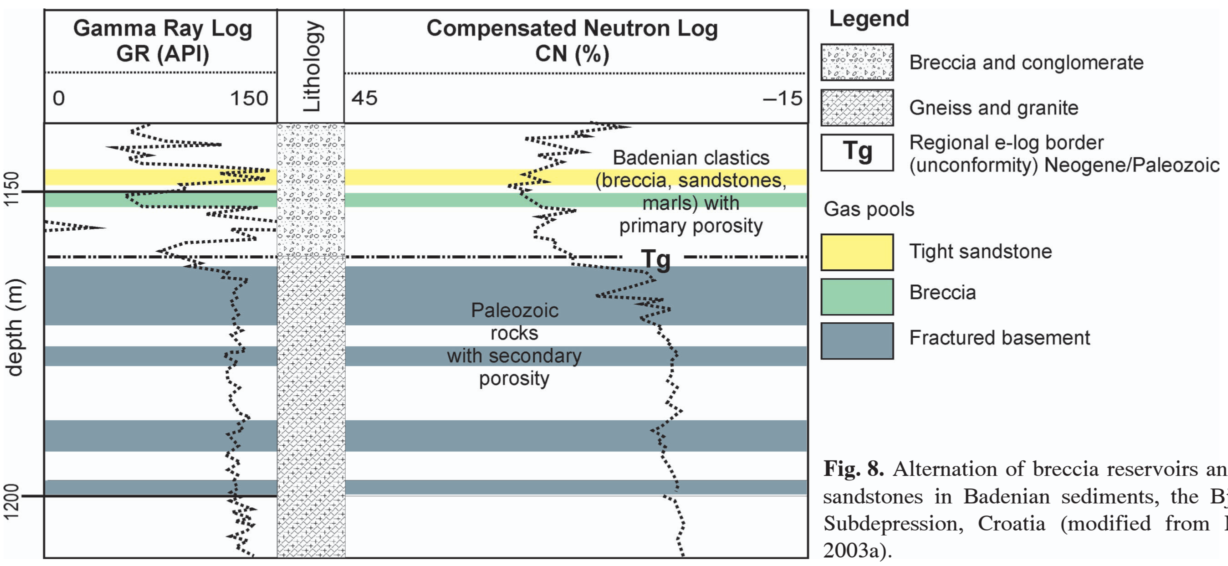

Fig. 8. Alternation of breccia reservoirs and tight sandstones in Badenian sediments, the Bjelovar Subdepression, Croatia (modified from Malvić 2003a).

able and thin lithofacies of marlitic sandstones or sandy marlstone, but such unconventional play needs to be more explored before it can be outlined as potential.

However, the above mentioned pelitic sediments of source rocks (marls, calcitic marls) are deposited over a longer geological period in a relatively calm environment and the thicknesses are significantly larger (dozen or hundred meters). Consequently they will be much easier to follow on seismic sections, even if only a few regional wells with interpreted e.log markers are available.

Observing the example given in Fig. 8, the unconventional Badenian play includes both marls and (proven gas saturated) tight sandstones. The measured petrophysical values are significantly lower than in the "conventional" part of Badenian reservoirs (coarse-grained sandstones and breccias). In "tight sandstones" porosity is slightly higher than 10 % and in the naturally fractured marls and carbonates about 6 % (Table 2).

Table 2: Porosities and variogram ranges of core samples from Badenian to Lower Pannonian in the Bjelovar Subdepression (Malvić 2003a).

Average porosity (%)	12.86	12.03	6.14	6.01
Vertical variogram range (m)	0.70	4.28	0.63	1.25

Consequently, their permeability is less than 10^{-3} μm^2 (or 1 millidarcy) which is about 10–100 times less than in conventional ones in the analysed field. Moreover, weakly permeable zones are highly stochastically distributed. Consequently, zones favourable for fluid flow are relatively short, as is proven by variogram analyses (Malvić 2003b) calculated for porosity data from the Neogene reservoir's sediments collected in the Bjelovar Subdepression (Table 2). Vertical variogram ranges calculated for sandy marls were not longer than 4.3 meters, although such entire depositional sequence can reach several tens of meters. The presented variogram ranges in Table 2 can be considered as limits of approximately isotropic zones for fluid flow in sediments belonging to the Moslavačka gora Formation. It means that natural flow rates in such unconventional reservoirs would be low, with drainage on the scale of several meters, which could be enhanced only by the using hydraulic or other fracturing techniques.

Conclusions

The presented geological analysis of one larger hydrocarbon province in the Croatian part of the Pannonian Basin System (CPBS), named the Bjelovar Subdepression, outlined the lithological and lithostratigraphical units that included potential unconventional hydrocarbon reservoirs. These are tight sandstones of Middle and Late Miocene ages, and source marls of Late Badenian to Early Pontian ages. Those sediments are proven in all CPBS depressions (Sava, Drava, Mura, Slavonija-Srijem), often distinguished only by their different depths (marls also in maturity level).

Here are outlined the main conclusions valid for such reservoirs analysed in the Bjelovar Subdepression:

a) Unconventional reserves in source rocks are located in the sediments of Upper Badenian, Sarmatian and Lower Pannonian stages;

b) Such rocks are dominantly gas-bearing due to dominant kerogene Type III;

c) Their organic carbon content in source rocks of that age is about 1 %, and the depth for reaching thermal maturity would need to be more than 2500 m;

d) Those unconventional reservoirs could be tight sandstones of Badenian age also assumed deeper than 2500 m;

e) The sandy marls, as weakly permeable sediments, are proven only on sites located along paleo-shore, but with very low or absent TOC due to re-working of sediments;

f) The permeability of potential unconventional reservoirs is lower than 10^{-3} μm^2 which means that any production such reservoirs could be depending on artificial fracturing.

The future production from such reservoirs in Croatia depends on several factors (like fracture density, drainage radius, production period, miscibility of possible injected fluids). Such values could be calculated only after the first pilot-project, including early production stage.

Acknowledgments: The results presented here are derived from the work developed during 2011 and 2012 as part of the Project "Stratigraphical and geomathematical research of petroleum geological systems in Croatia" (No. 195-1951293-0237), financed by the Croatian Ministry of Science, Education and Sport. The authors would like to thank reviewers Prof. Piotr Krzywiec and Dr. Jozef Vozár.

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