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Professional paper

The relationship between sandstone depositional environment and water injection system, a case study from the Upper Miocene hydrocarbon reservoir in northern Croatia

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Abstract
In the Sava Depression (in Northern Croatia), typical Lower Pontian (Neogene) sandstone reservoir "K", and the largest hydrodynamic units "K1" are present. The reservoir lithology has been strongly influenced by the regional geological settings, especially lacustrine depositional environments with periodically active turbidites. A contour (isopach) map and correlation section showed an increase of pelitic detritus into reservoir sandstones and/or pinching out. Moreover, marginal fault zones create strike-slip pull-apart during Lower Pontian, which have lately been inverted into present day faulted anticlines (pop-up). Such geological settings affected the entire production process and equipment for water injection and separation. An appropriate selection of technology has improved the hydrocarbon recovery in terms of absolute volumes as well as the oil - water ratio. A similar approach was very successful for long-term hydrocarbon production on other fields in the Sava Depression, i.e. in heterogeneous sandstone reservoirs, with a large portion of pelitic detritus.

Keywords: Neogene, sandstones, hydrocarbons, injection, dehydration, Croatia

1. Introduction

The hydrocarbon reservoirs, especially the sandstone ones, are mostly managed with water injection in the later phases of their recovery. Every such production system is unique, but there are some general rules for their management, mostly based on reservoir lithology. Sandstones are the most abundant hydrocarbon reservoirs in Croatia, especially in the northern part of the country. The Sava Depression in the historically famous petroleum province belongs to the southwestern branch (Croatian part, abbr. CPBS) of the Pannonian Basin System (abbr. PBS), located in Central and Eastern Europe. The history of hydrocarbon production is long, dating from the second part of 19th century (e.g., **Velić et al., 2012; Velić et al., 2016**). The majority of sandstone reservoirs in the CPBS belong to the Upper Miocene lacustrine environments, developed in several sub-lithofacies (e.g., **Vrbanac et al., 2010a; Velić et al., 2015**). During the Pannonian period, the area belonged to the southern part of the Lake Pannon. In the Pontian period, a large lake was disintegrated and its remains in Croatia eventually formed the Lake Slavonia, which lasted into the Pliocene period and finished with continental environments in the Quaternary period.

Analysed hydrocarbon reservoirs are saturated with hydrocarbons and formation water in different portions. Over time, the rate of produced water (free and bound water inside the oil or drops of water inside the gas stream) in the recovered fluid is variable, and mostly increased in a later phase. Such water is separated in the process of dehydration (e.g., **Ivšinović and Dekanić 2015**), removing also fine-grained sandy as well as silty and clayey particles. Such fine detritus is part of heterogeneous sandstones, and lithological heterogeneity is in the CPBS resulted from the Neogene depositional environments. In mature fields, the water injection system also includes separation, which is crucial for maintaining recovery. Results presented in this study are obtained from the selected field in the Sava Depression (part of the CPBS). That is a typical production system from Neogene sandstone reservoirs in Northern Croatia (e.g., **Gospić Miočev, et al., 2015; Ivšinović, 2016; Ivšinović et al., 2018**). This field is currently in the mature stage and produced from sandstone reservoirs (e.g., **Zelić, 1987; Zelić and Petrović, 1990**). The presented injection-separation system is the key for maintaining production and overall recovery in heterogeneous reservoirs with a large water front.

2. Notes about regional geological settings of the CPBS

In order to understand a typical Neogene sandstone reservoir in Northern Croatia, the basics of a depositional model are summarized. The CPBS is a unique part of the PBS, located in the south-western branch of that area (here "branch" is

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used as a term for a separated part of the system, with characteristic form). Its marginal position and regional pre-Neogene, Neogene and Quaternary tectonics caused the diversification of the CPBS into elongated (northwestern to south-eastern) regionally subsided depressions (Sava, Drava, Mura, Slavonia-Srijem; see **Figure 1**).

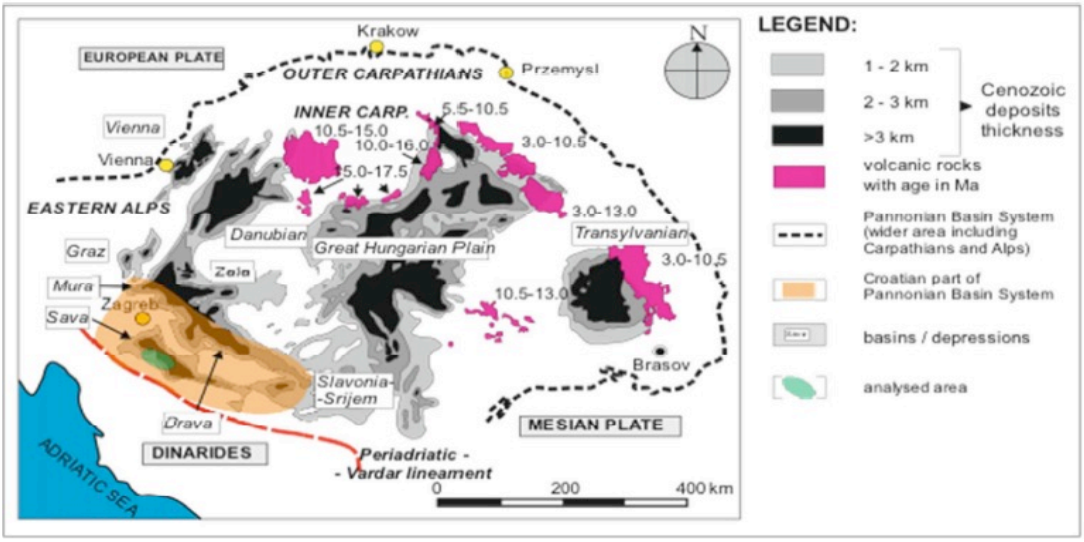

Figure 1: Geotectonic units of the Pannonian Basin System and its Croatian part (modified after **Malvić, 2012; Royden, 1988**)

As the position of those depressions is marginal regarding the central part of the PBS, they were mostly covered with shallow and periodically isolated water systems. Time scales of particular geological ages are taken after **Malvić and Velić (2011), Malvić (2012) and Ćorić et al. (2009)**. The Paratethys covered the CPBS during the Badenian and Sarmatian periods (approx. 16.0-11.5 Ma). It was followed by the isolated, large Lake Pannon (Early Pannonian; 11.5-9.3 Ma), followed by the smaller Lake Slavonia (which periodically may have been disintegrated into lakes like Sava, Drava, etc.). Lake Pannon probably also existed during the Late Pannonian (9.3-7.1 Ma) and part Pontian (7.1- 5.7 Ma) period, when it was followed by smaller lacustrine environments that lasted to the end of the Pliocene period. Pavelić and Kovačić (2018) defined single lacustrine, fresh-water, Lake Slavonia that developed from the middle Pliocene to the early Pleistocene period. The process of shallowing finished with dominant continental (inland) environments that lasted locally from the Late Pliocene and dominated during the Quaternary period. The main tectonic and depositional properties of the CPBS, regarding geological stages (see **Figure 2**), were published by **Malvić and Velić (2011)**. Also, for that area, all geological categories that could define hydrocarbon systems are described, with probabilities of their geological events, in **Malvić and Rusan (2009)**. Here it is also necessary to summarize present-day problems with the Pontian stage in the Pannonian Basin System or approximately the area that had been covered with the Central Paratethys during the Middle Miocene period. The Pontian had been defined with a typical locality in the realm of the Eastern Paratethys (Black Sea). Despite this, many authors accepted Pontian as a valid or assumed stage in the entire Pannonian Basin System (e.g., **Kázmér, 1990; Piller et al., 2007; Popov et al., 2004, 2006; Steininger and Wessely, 2000**). However, recently some authors published some new depositional models of the Upper Miocene period that could revise the Pontian as a stage applied in the CPBS (e.g., **Pavelić and Kovačić, 2018**), similar to when the Hungarian part of the PBS had been proposed to replace the "Pontian" succession with Upper Pannonian (e.g., **Sacchi and Horváth, 2002**). Just for simplicity, in this work the "classical" Pontian age and markers, were used in the same ways as they were used in the last decades in the CPBS (and cited works).

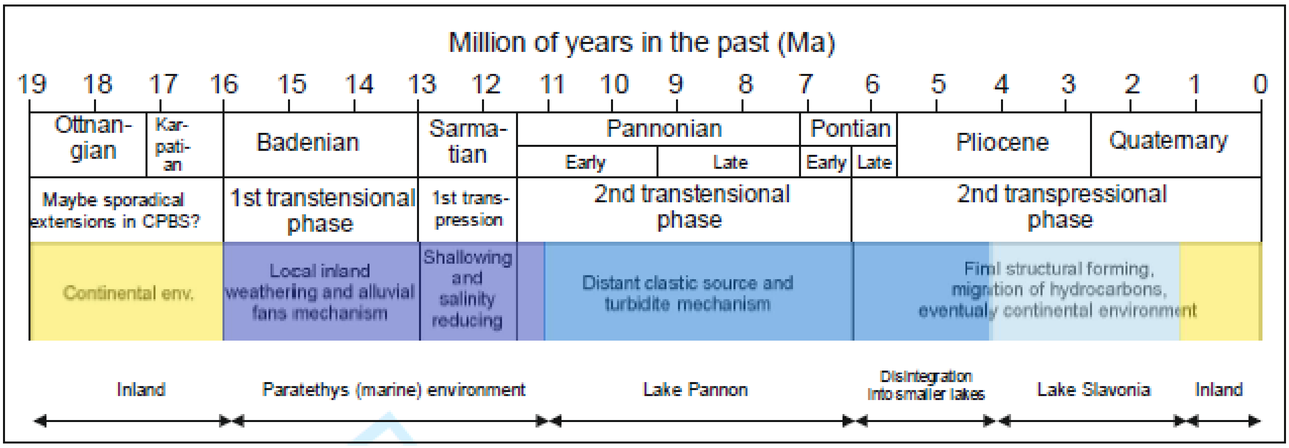

Figure 2: Time-scales of the main tectonic and depositional events in the Neogene and Quaternary in the CPBS (modified after **Malvić, 2012**)

The entire area of the CPBS from the Late Pannonian until the Late Pontian period is considered as a dominant clastic environment, with enormously large volumes of sandy and silty detritus deposited from turbidites. Lacustrine marls, from the same period, represent sediments from "calm" periods. Such a lacustrine environment (see **Figure 3**), with periodically active turbidites, characterised the entire CPBS during Upper Miocene (e.g., **Malvić, 2003, 2012**).

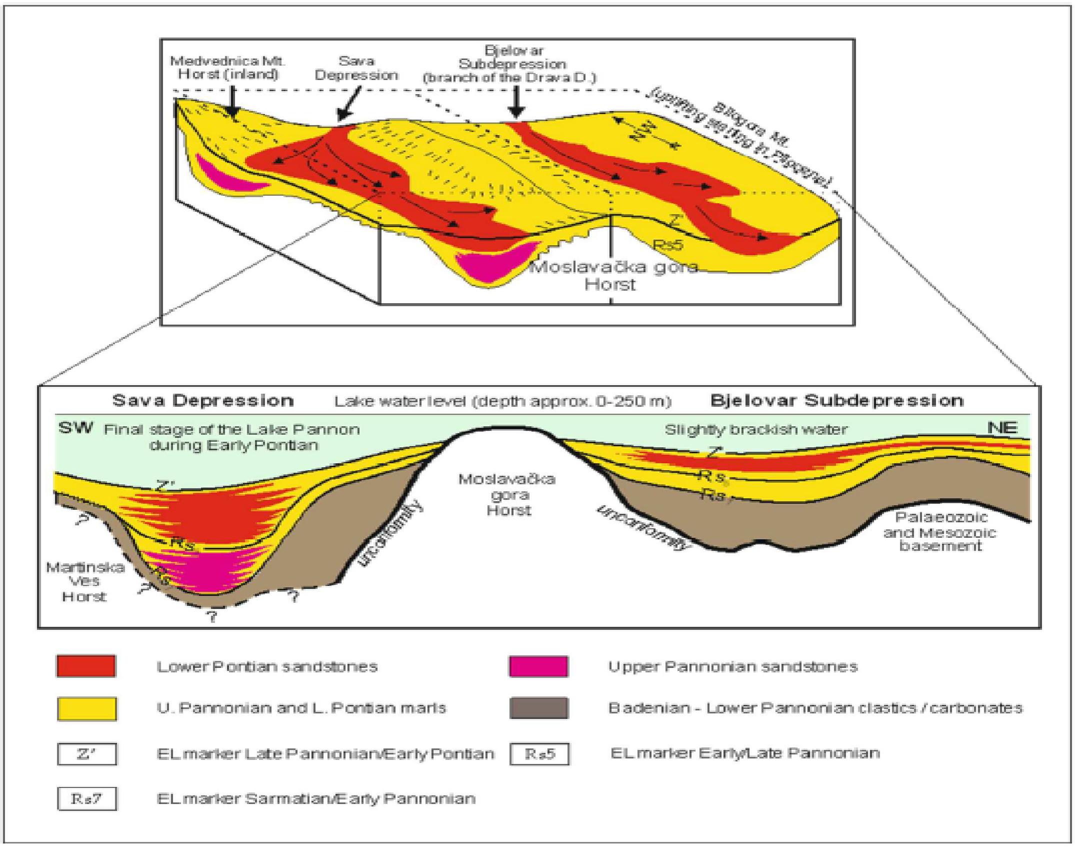

Figure 3: Schematic review of regional lacustrine environment and exchange of lacustrine pelitic and turbiditic deposits at the border between the Sava and Drava Depressions (taken from **Malvić, 2012**, compiled after **Vrbanac et al., 2010b; Malvić and Velić, 2011**)

Consequently, the hydrocarbon reservoirs discovered in the Upper Pannonian and Lower Pontian sandstones are of turbiditic origin. Such turbidites are characterised with transitional lithofacies, which varies from sand in the central part to clayey silt at the margins (see **Table 1**). Their depositional settings reflect the reservoir lithology, comprising "pure sandstones" only in the central part, with the domination of the heaviest, psammitic detritus. In the marginal parts, the reservoir lithology is represented with silty, clayey or even marly sandstone. All those lithological heterogeneities had strong reflections firstly in the hydrocarbon secondary migration and, today, in the production regime and recovery rate (see **Table 1**). Currently, the water injection is the most frequent secondary method in Croatia applied for increasing hydrocarbon recovery, exclusively into Neogene sandstones of the CPBS. It is highly influenced by reservoir lithofacies, fault zones and permeability distribution.

Table 1: Qualitative relation among field zones, lithofacies and recovery in the Neogene clastic environments active in the CPBS

Depositional sub-environment	Dominant lithofacies	Heterogeneity degree	Hydrocarbon recovery
The central part of fields, inside bottoms local depressional strike slips	Medium (rarely coarse) grained sands	Low	High, any post-primary regime production will, at least temporary, boost recovery.
Central part of fields, highly faulted structure	Medium (fine (in faulted zones) grained sands	Medium	Medium, strongly depends on fault's sizes and permeabilities
Marginal parts of fields, toward basin marls	Fine grained sands to silts (medium clay content)	High	Due to two or three lithotypes, the permeability is local, the recovery low

3. Geographic location and local geological settings of the analysed area (the "JM" Field, Sava Depression)

The analysed "JM" Field is located in the western part of the Sava Depression (see **Figure 4**). The field is located about 90 km south-east from the Croatian capital Zagreb. The southern part of the field zone is a valley with an average altitude of 120 m, which is increased to 231 m in its north-eastern part. The absolute depths of the Neogene reservoirs are between 1000 and 2000 m with the reservoir pressure about 10 % higher than hydrostatic and the average temperature gradient of 0.036 °C/m. The hydrocarbon production started in 1970 and 1971. According to **Brod (1945)** classification, the reservoirs are layered, trapped with overlaying strata, and laterally sealed with impermeable rocks or tectonic structures. Here, the largest "K" reservoir is analysed, considered also as an informal lithostratigraphic bed. The "K" reservoir is the most important Lower Pontian hydrocarbon reservoir in the analysed field. That reservoir, as well as all other Upper Miocene formations, in that field, are a result of turbiditic deposition in the lacustrine environment (the Lake Pannon, later the local Lake Slavonia).

The analysed reservoir includes more than 13 % of proven hydrocarbon reserves of the field "JM", with a 25.6 % recovery. The average porosity is 24 %, the permeability $10\text{-}250 \cdot 10^{-3}$ μm^2 and the effective thickness 9-10 m. Up to now, several recovering methods have been applied, i.e., gas cap, dissolute gas and water injection. All 26 wells are used for production, where currently 15 are still in production, and 9 are used for measuring. There are also 3 additional injection wells. The well section given at Fig. 5 has been selected as a typical well's lithological column in the field. The majority of wells reached the Lower Pontian (the Kloštar Ivanić Formation), due to the fact that hydrocarbon reservoirs were discovered inside that formation.

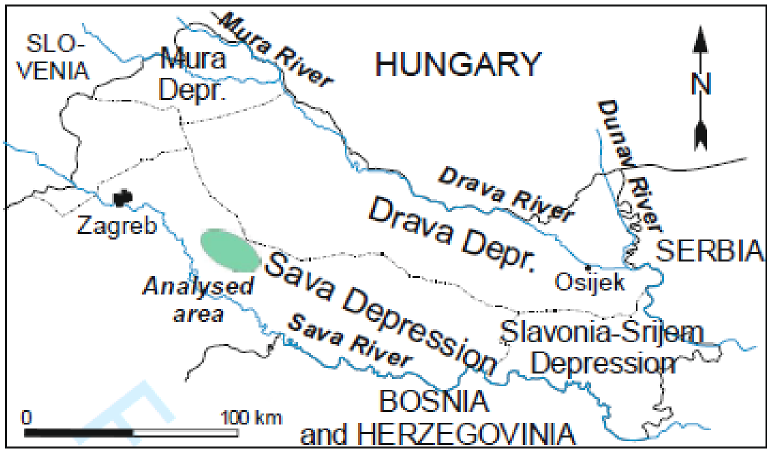

Figure 4: Enlarged position of the wider field zone inside the Sava Depression. The location of the Sava Depression inside the CPBS is given at **Figure 1**.

The complete Quaternary and Upper Miocene lithological sequence is given in **Figure 5**. The Quaternary deposits (the Lonja Formation) are 20-30 m thick and consist of grey and brown-grey clays, sands and humus. The Pliocene is represented by weakly consolidated sandstones, claystones and marls. Its thickness is about 600 m. The Upper Pontian (the Široko Polje Formation) includes mostly light grey marlstones, about 90 m thick. The Lower Pontian (the Kloštar Ivanić Formation) is represented with an alternation of sandstones and marls. Several sandstone layers are saturated with hydrocarbons, making them reservoirs. Such sandstones are well-sorted and medium grained with a thickness of 20-150 m. They are separated by marls, with an average thickness of 30-150 m.

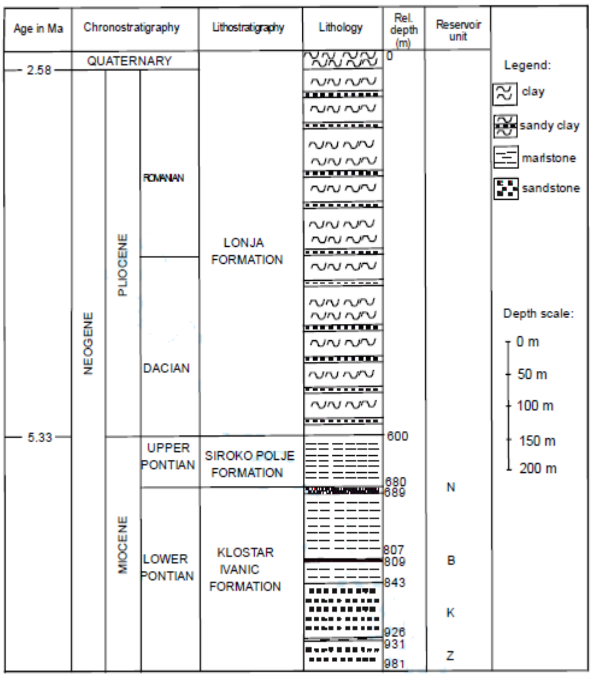

Figure 5: Typical geological section of the analysed field with formal (formations) and informal (reservoirs) lithostratigraphic units. Ages are according to International Commission on Stratigraphy (**Int. Chronostratigraphic Chart, v2017/02**).

The "K" reservoir borders are defined by marginal impermeable fault zones. That is also the main production target, which has several hydrodynamic units. The contour (isopach) map of the "K" reservoir such largest unit (the "K1" unit) is shown in **Figure 6**. The partially permeable, "middle" fault zone (strike ENE-WSW), divided the unit at approximately similar sandstone volumes. The "K1" hydrodynamic unit is the most important production volume inside the "K" reservoir, where the water flooding began in 1993.

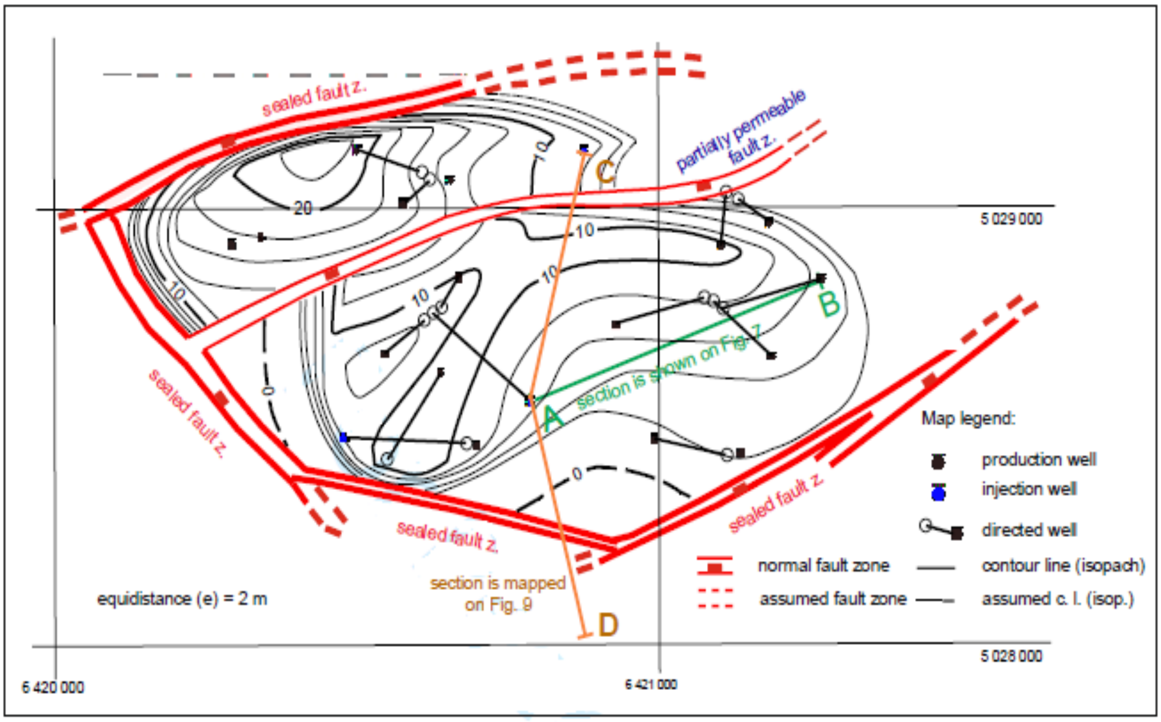

Figure 6: Isopach map of the "K1" hydrodynamic units, as the largest production volume inside the "K" reservoir (redrawn after data available with permission from archive of INA Plc.)

The areal extension of "K1" unit can be easily observed in Figures 6 and 7, where the isopach "0 m" mostly follows the sealed fault zones on margins. The thickest isopach ("22 m") in the NW part indicates the location of the depositional centre, where the largest volumes of psammitic detritus had been deposited. Oppositely, on the margins, especially ESE, the thicknesses are significantly lower, and sandy detritus included significant quantities of silt and clay. The entire structure had been defined by fault zones during its evolution, which created a strike-slip structure. Consequently, reservoir sandstones locally pinch out, caused by fault zones and/or transitional lithofacies at the margins (see **Figure 7**). In such systems, hydrocarbon recovery is not simple, even in the case of water flooding, because such injection plans and volumes can be validated only after some production period, i.e. based on «reservoir variable response» like pressure or water ratio.

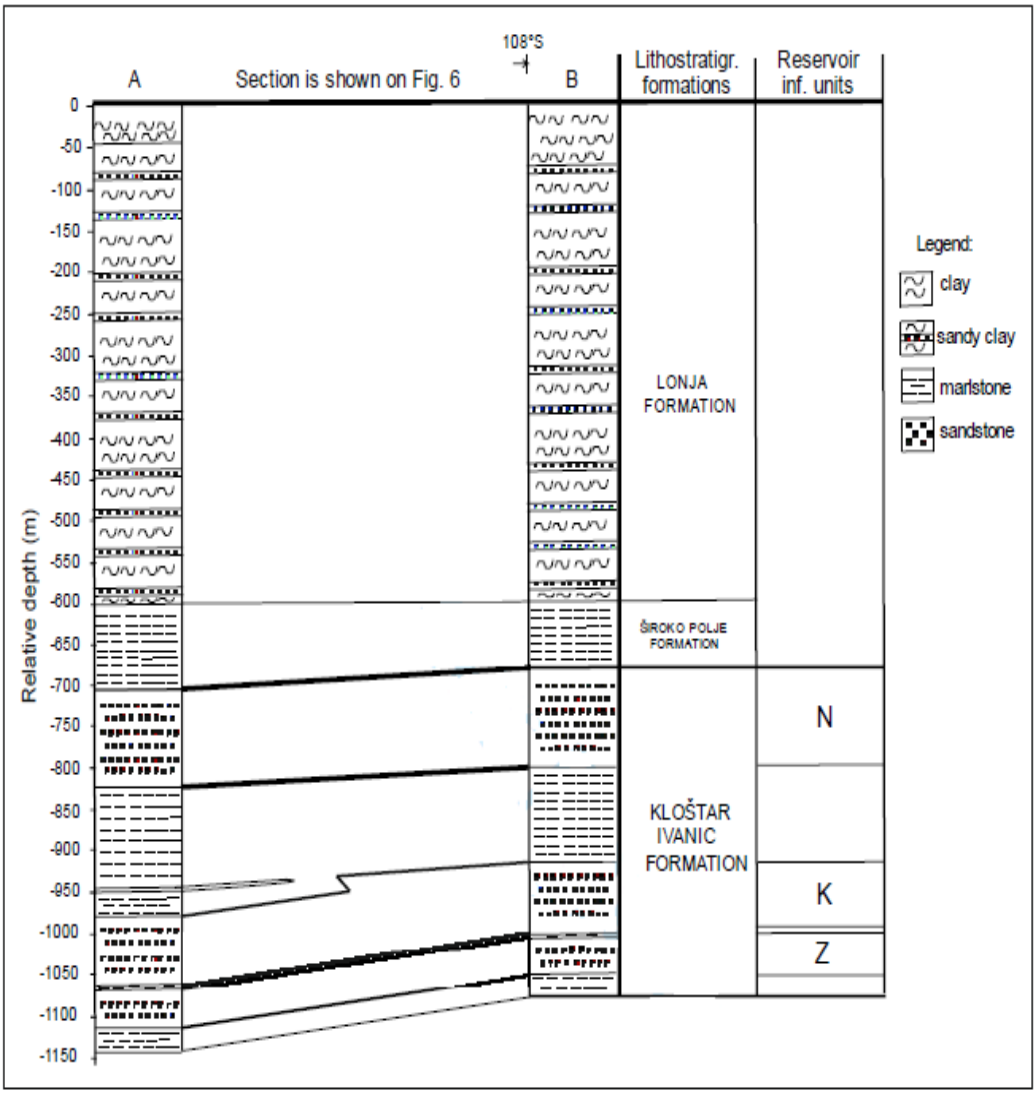

Figure 7: The geological section A (injection well) – B (production well). It is also shown on **Figure 6**

4. Water separation-injection system applied in the analysed sandstone reservoir ("K")

The production of hydrocarbons and water had been measured in five measuring stations and collected in the dispatching station (see **Figure 8A**). The dehydration process has been modified according to the reservoir characteristics and, especially, the issue regarding the sand in the produced fluids. Such a production process is crucial regarding the heterogeneity of the reservoir, because in produced fluid, the water content and portion of fine-psammitic and pelitic detritus are relatively high. Furthermore, some of the shallowest Upper Pontian reservoirs are weakly consolidated which resulted in a larger portion of detritus in fluid and represents an additional load for the desanding separator.

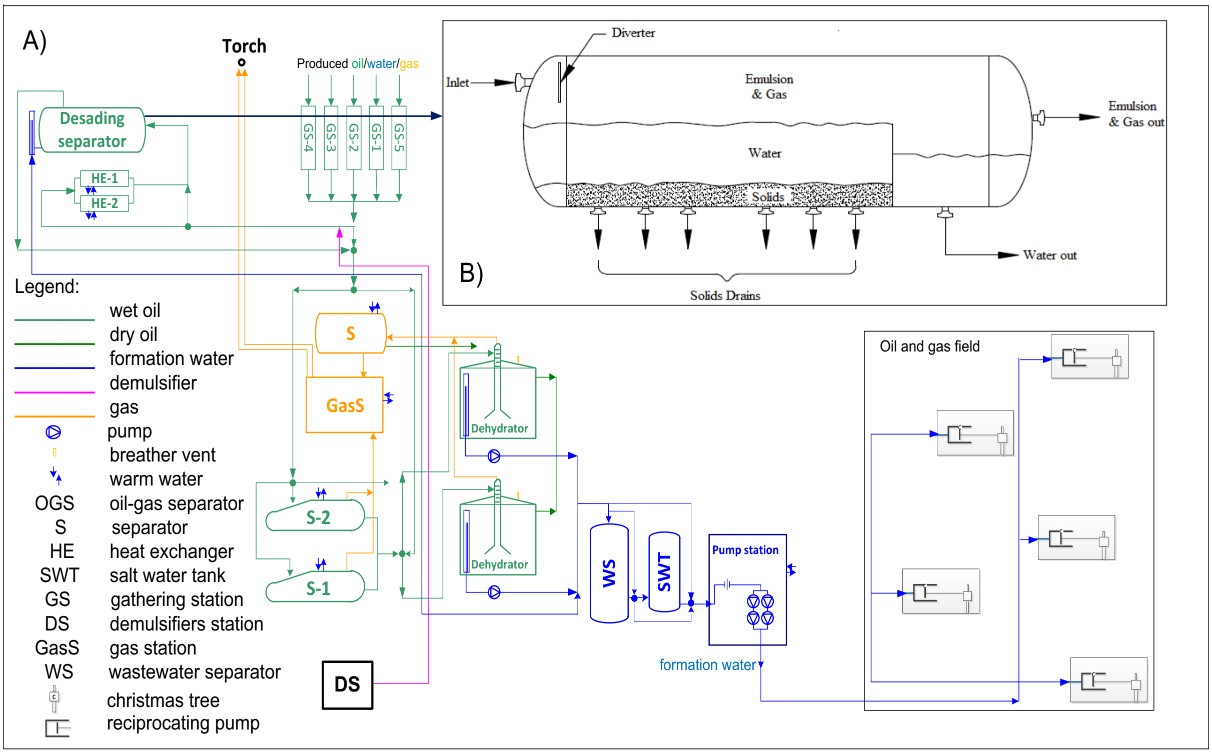

Figure 8: A) A schematic sketch of water separation and the injection process in the analysed reservoir (redrawn after data available with permission from archive of INA Plc.). B) Side view of the desanding separator applied for the "K" reservoir/"K1" hydrodynamic unit (modified after: **Stewart & Arnold, 2009).**

The applied separator type (**Figure 9B**) for processing of the "K" reservoir fluid, could be easily adapted for any lithologically similar Neogene reservoir in the CPBS. In such a separator, any fine-psammitic and pelitic detritus, has been deposited through a diagonal fluid flow. Solid residue is occasionally removed from the device using drains, but to prevent plugging, the entire separator needs to be cleaned periodically. Moreover, during the separation, fluids are also drained through special drainpipes; the emulsion (of oil and water) separately from the gas. Eventually, the emulsion is processed in a heat exchanger where demulsifiers are added. As a result, surface-active agents are absorbed at the oil–water interface, rupturing the tough film (skin) surrounding the water droplets, and/or displacing the emulsifying agent and forcing the emulsifying agent back into the oil phase (e.g., **Arnold and Stewart, 2008**). At the end, the fluid enters the dehydrator where the formation (field) water is separated from the inlet fluid.

By applying the previously described separation method, larger quantities (see **Table 2**) of oil (both in relative and absolute ration) were produced. Numerically, such a process made it possible to increase the oil ratio in the totally recovered fluid by approximately 25 %. Moreover, the solid particles had been efficiently removed from the processed liquid, maintaining the reinjection of processed field water. The efficiency of the "JM" field's dehydration is more than 99 %, i.e. it is the volume of the field water which is removed from the recovered oil. The process is controlled on a daily basis which proved it as a typical successful separation and dehydration method for Neogene sandstone reservoirs in the CPBS. Using such an approach, the economical production can be extended on a very late production stage of the mature fields in the CPBS (e.g., **Ivšinović and Dekanić, 2015; Ivšinović, 2016**).

Table 2: Results of the applied separation process in the gathering station of the “JM” Field

	Year						
	2009	2010	2011	2012	2013	2014	2015
Water	100*	0.96	0.94	0.96	0.95	0.91	0.93
Oil	50**	0.65	0.79	0.78	0.71	0.69	0.75
* referent relative value of produced water in the first recorded year							
** referent relative value of the produced oil in the first recorded year, also in absolute relation with water							

Such a system also reached the goal - to inject water into reservoir rock(s) without plugging or reducing permeability, which could happen because of particulates, dispersed oil, scale formation, bacterial growth or clay swelling (e.g., **Patton 1990, Bader 2007, Igunnu and Chen, 2014**). So, the formation water, after its separation from produced fluid, is distributed by a low-pressure pipeline to the injection wells. Every injection well is equipped with a reciprocating pump that ensures the pressure of the injected water be the same as the reservoir pressure (e.g., **Ivšinović, 2017**). The reciprocating pumps are constructed for working conditions under pressures higher than 200 bars and capacities up to 1000 m^3/d (**Sečen, 2006**). Such an injection well is housed in a container in order to protect the surface injection equipment, including three packers and a landing nipple for the storing of Instruments. However, the influence of each such injection well system is strongly restricted with reservoir lithology, i.e. heterogeneity. Even in the case that the injection fluid will not deteriorate reservoir petrophysics, lithological heterogeneity strongly determines the injected fluid penetration radius (see **Figure 9**).

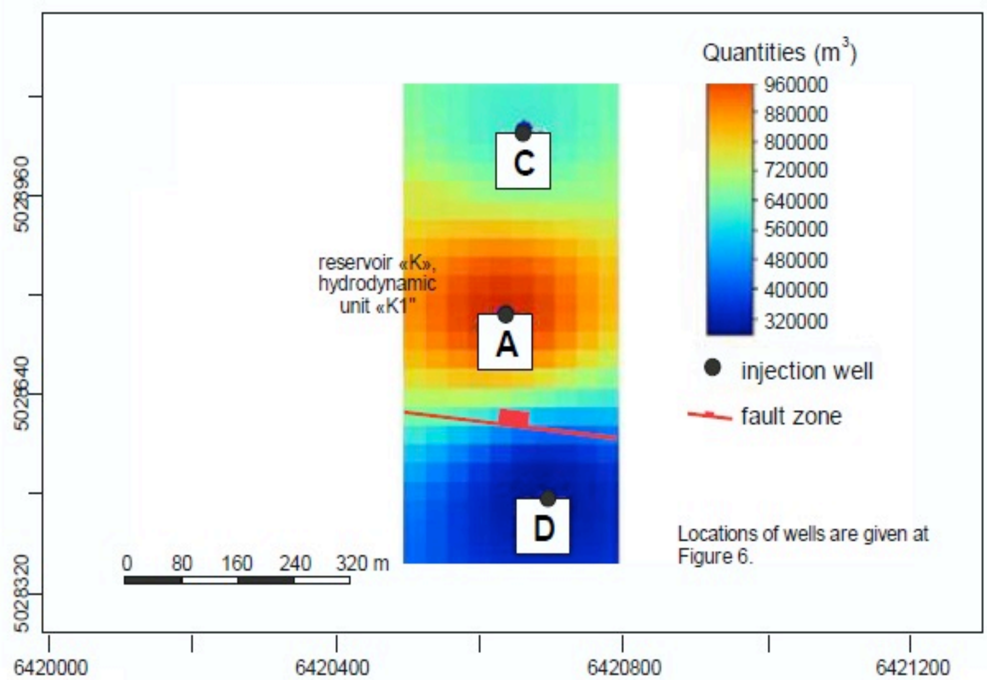

Figure 9: Injection volumes of particular wells are strongly influenced by local reservoir lithology fault zones. The map had been interpolated using the Inverse Distance Weighting method, due to polygonal methods do not consider appropriate lithology.

5. Conclusions

The presented case study, from the Sava Depression, Neogene (upper Miocene) hydrocarbon reservoir located in Northern Croatia led to the following conclusions:

• The entire area of the CPBS (Northern Croatian Upper Miocene subsurface deposits) is characterised by numerous turbiditic sandstones, where many of them are saturated with hydrocarbons.

• Due to the turbiditic origin, such reservoirs are often heterogeneous, especially in their lateral, marginal parts, where the portion of fine-grained sandstones and siltstones can be significant.

• This fact strongly affects the production from such reservoirs and, as seen from the largest “K” reservoir in the “JM” Field (Sava Depression).

• The production during the mature phase is supported with modified gravel packs, making it possible to produce even from poorly consolidates, Upper Miocene deposits, or from silty or clayey sandstones at the field margins.

• This is the reason for the application of another separation process, using special surface equipment (separator and dehydrator). Although the entire technology is well known, adaptations provided for the Neogene sandstone reservoirs in the Croatian part of the Pannonian Basin System are presented in this study.

• Lithological settings also influenced the water injection plan, i.e. the distribution of injection wells in a particular reservoir and/or hydrodynamic unit. They have cased and perforated injection intervals, which ensures the larger injection ranges into the reservoir. The application of the single injection system was especially efficient in the “JM” Field, although even there the injection radius is very local, due to lithological heterogeneity and pinch outs of reservoir beds.

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Abstract in Croatian

Odnos između taložnog okoliša pješčenjaka i sustava za utiskivanja vode, primjer ležišta ugljikovodika gornjeg miocena u sjevernoj Hrvatskoj

U Savskoj depresiji (Sjeverna Hrvatska) prisutno je tipično donjopontsko pješčenjačko ležište "K", a predmet istraživanja je hidrodinamička jedinica "K1". Litologija ležišta jako je pod utjecajem regionalnih geoloških postavki, osobito jezerskih sedimentnih okoliša s periodički aktivnim turbiditnim nanosima. Konturne karte i korelacijski profili pokazali su porast pelitnog detritusa u pješčenjaku i uz moguće progresivno isklinjavanje. Dodatno, granične zone rasjeda uzrokuju izduljene i raskomadane strukture ležišta tijekom Donjeg Ponta, koji su kasnije preokrenuti u postojeće antiklinale. Takve geološke postavke utjecale su na cijeli pridobivni sustav i opremu za utiskivanje i odvajanje vode. Odgovarajući izbor tehnologije unapredio je pridobivanje ugljikovodika u odnosu na apsolutne volumene kao i na omjer nafte i vode. Sličan pristup odabiru tehnologije je bio vrlo uspješan na duže vrijeme i na ostalim poljima u Savskoj depresiji, tj. u heterogenim pješčenjacima s velikim udjelom pelitnog detritusa.

Ključne riječi: neogen, pješčenjaci, ugljikovodici, utiskivanje fluida, dehidracija, Hrvatska

Author contribution

Josip Ivšinović done all paper.