Geologia Croatica | 65/1 | 91–101 | 5 Figs. | 4 Tabs. | Zagreb 2012

# Reservoir geology, hydrocarbon reserves and production in the Croatian part of the Pannonian Basin System

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doi: 104154/gc.2012.07

Geologia Croatica

## ABSTRACT

Approximately 104 x $10^6$ $m^3$ of oil (39 fields), 6.93 x $10^6$ $m^3$ of condensate (11 fields), and 64.92 x $10^9$ $m^3$ of gas (52 fields), were recovered in the Croatian part of the Pannonian Basin System during 64 years of exploitation (1941–2005). The production peak was attained between 1980–1989, when exploitation began in 12 new fields. Based on their cumulative production, the Croatian oil and gas fields can be divided into four groups, and the condensate fields into three groups. Such a division has been supported by analysis of recovery, number of reservoirs, porosity and permeability, age and lithology of reservoir rocks. The longest production period is assumed for the first group of fields; for oil it is approximately 55 years, for condensate 46 and gas 36 years. In the favourable first group the average number of reservoirs is 16 for oil and 11 for gas. Lithological composition is highly favourable, because reservoirs are represented mostly by sandstones of Pannonian and Pontian age with high porosities and permeabilities. A relatively homogeneous sandstone lithology, including good regional seals like marls, enables an increase in recovery through the use of secondary and tertiary recovery methods. Also, water-flooding will remain the dominant secondary-recovery method for increased production in the future.

**Keywords:** statistics, Pannonian Basin System, hydrocarbon fields, Croatia, Neogene and Pre-Neogene reservoirs, recovery, exploitation period

## 1. INTRODUCTION

This work presents a detailed overview of Croatia's oil, gas and condensate reserves. The data is derived from oil and gas fields located in the Croatian part (CPBS) of the Pannonian Basin System (PBS), and to cover the whole country's reserves, the Adriatic gas fields were also added. However, as the main topic is the CPBS, the most well know data on the evolution of the entire Pannonian Basin System are presented by way of an introduction, followed by further review of the Croatian part. These data are crucial to understand the location, age and recovery factors from all types of reservoirs as well as assumptions about future production.

The Pannonian Basin System (PBS) is a back arc basin system that belongs to an area in the past covered by the Central Paratethys, and younger brackish and fresh-water environments formed from Paratethys. PBS generation started with convergence and subduction of the Apulian Plate under the Dinarides during the Styrian orogenic phase, developing the southern (Periadriatic-Vardar lineament) and northern (Outer Carpathian) boundaries. However, the southwestern boundary of the Central Paratethys area located further to the south from the Periadriatic-Vardar lineament was represented by an array of small, fresh-water Neogene basins within the Dinarides that were never invaded during their evolution by marine transgressions in Paratethys PAVELIĆ (2002). These basins have never been considered as parts of the Mediterranean or Central Paratethys, although sediments and fauna can be correlated with some PBS characteristics.

Inside PBS, numerous basins, depressions and subdepressions were formed along dextral and sinistral strike-slip faults (Fig. 1A, modified after ROYDEN, 1988). The terms "basin, depression or subdepression" described areal geometry of opened areas. The very first extensions were initiated in the Ottnangian (ROYDEN, 1988; RÖGL, 1996, 1998), but sediments of this age were only deposited and preserved locally. The extensional period continued through the Karpathian when restricted lacustrine and fluvial sediments were deposited in the Apuseni Mts., Carpathians and Podolian Upland as well as on the margin of the Alps and the Bohemian massive (e.g., RÖGL 1996, 1998).

During the Badenian, mostly marine sedimentation and maximum extensional displacements are characteristic for the entire PBS (e.g., RÖGL, 1996, 1998), including the CPBS (e.g., VRBANAC, 1996). The real marine environment with "normal" salinity was dependent on the existence of connections with large "oceanic" areas, i.e. with the Mediterranean in the south-west and the Indo-pacific to the south-east through Trans-Tethyan trench corridors. The Lower Badenian transgression covered the entire basin, from Austria to Romania (Transylvania) and from the Carpathians to the Dinarides. The Carpathians and the Apuseni Mts., remained perhaps the two most prominent areas with island arcs. However, in the Middle Badenian, the marine environment of normal salinity was limited to the western part of Central Paratethys (i.e. parts of Poland, Hungary, Slovenia and Croatia). Elsewhere, sediments of a regional regression phase and evaporites have been proven. Deposition of thick evaporate sediments signal the Middle Badenian salinity crisis in the Transcarpathian Basin, Transylvanian Basin and Carpathian Foredeep (KOVAČ et al., 2004, 2007). The last regional flood in the PBS occurred during the Late Badenian, when the connections with the Mediterranean and Indo-pacific were interrupted (e.g., STEININGER et al., 1978). Some areas on the margins of the PBS are characterised in the Upper Badenian by evaporites, including the Carpathian Foredeep (e.g., PERYT, 1997, 1999; MĂRUNTEANU, 1999; ANDREYEVA-GRIGOROVICH et al., 1997) and the Transylvanian Basin (e.g., CHIRA, 2000).

In the CPBS, PAVELIĆ (2001) described the period of the Late Badenian as the transition between the extensional and post-extensional stages. Similarly, VRBANAC (1996) considered that Northern Croatia remained a marine environment at that time, where the present-day mountains represented islands or remarkable submarine highs.

Consequently, the next Sarmatian age is the period when a continuous marine environment began to be progressively reduced (e.g., RÖGL, 1996, 1998), resulting in isolated areas that eventually became brackish and fresh water lakes during the Late Miocene. Psammitic, and pelitic, clastic sedimentation in littoral environments, was sporadically interrupted by deposition of large quantities of coarse-grained carbonate material, originating from eroded, near-shore reefs. ROYDEN (1988) noted a major phase of extension

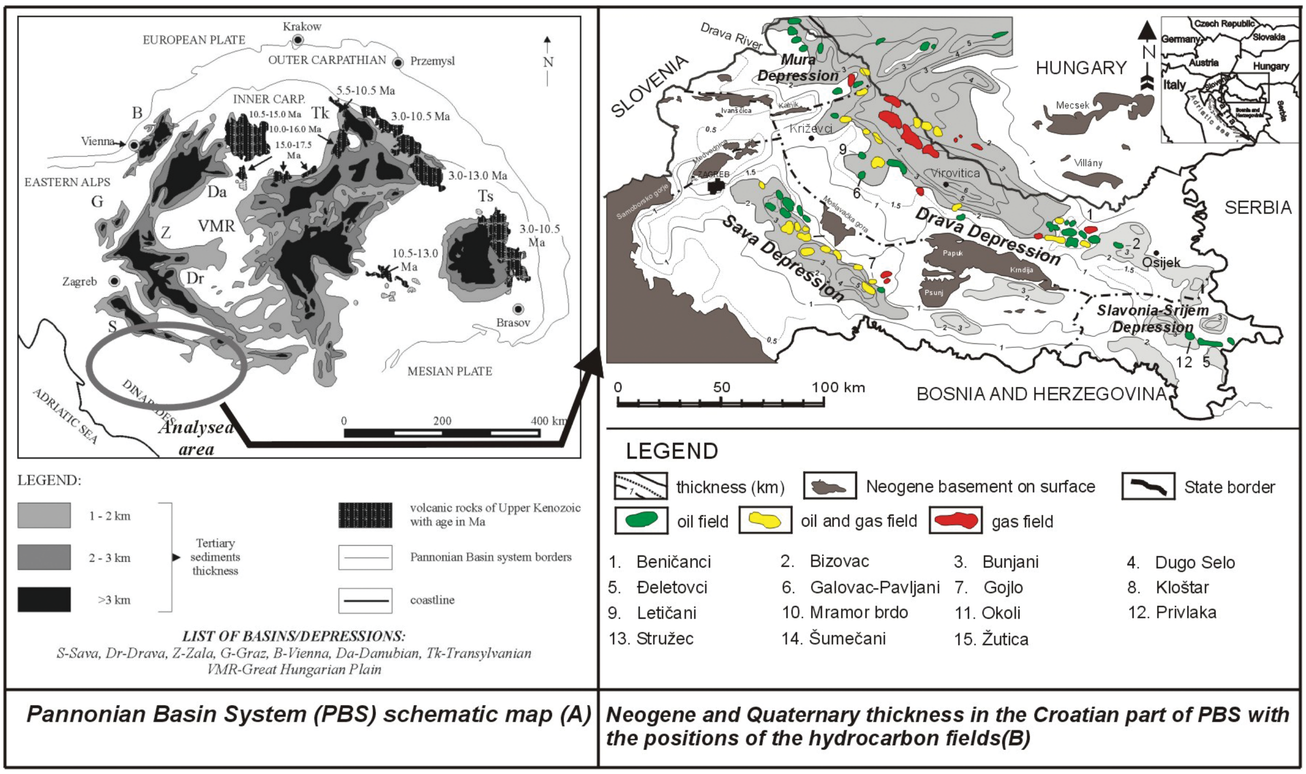


**Figure 1:** Croatian geotectonical units in Pannonian Basin System (range of depressions) and hydrocarbon fields (modified after ROYDEN, 1988; VELIĆ 2007; MALVIĆ & VELIĆ, 2010; 2011). Fields named at figure are mentioned in the text.

that finished over most of the Pannonian Basin System in the Early Pannonian. In the post-extensional phase, the generator of dynamism was thermal subsidence, triggered by cooling of the lithosphere. Subsidence was stronger in the central part of the basin system (approx. 2 km in 10 Ma), and alkali volcanic activity occurred locally. From the Early Pannonian, continuing into the Pontian, sedimentation took place in brackish and fresh water lacustrine environments (e.g., RÖGL, 1996, 1998). Sediments were transported through delta and prodelta systems, or by turbiditic mechanisms capable of moving detritus dozen of kilometres. Turbidites, as the main transport mechanism in the CPBS, were periodically activated in response to gravitational and/or tectonic instability on the structural "ramps" (e.g. MALVIĆ & VELIĆ, 2011). The Eastern Alps were the main clastic sediment source for the Croatian depressions in the Late Miocene.

Eventually, the Late Pontian, and especially the Pliocene and Quaternary were characterised by fluvial, lacustrine and marshy sedimentation along with aeolian sediments in the youngest parts of the Quaternary. These periods completed the basin infill and resulted in formation of the present-day relief. The tectonic regime was compressional, indicated by reverse faults and overthrusts (ROYDEN, 1988), and often along reactivated older fault planes with inversion of displacement as proven by the numerous relative young hydrocarbon traps. Also in the CPBS, tectonic and depositional properties were similar (e.g., VELIĆ, 2007). Interestingly, extensional and compressional phases in the PBS during the Neogene and Quaternary, and recently in the CPS, can be divided into two transtensional (Badenian and Pannonian-Early Pontian) and two transpressional (Sarmatian and Late Pontian-Quaternary) phases (in MALVIĆ & VELIĆ, 2011).

## 2. GEOLOGICAL SETTINGS AND HYDROCARBON PROPERTIES IN THE CPBS

The area of the CPBS is divided into the Drava, Sava, Mura, and Slavonija–Srijem depressions (Fig. 1B). Although each of these has their local characteristics, the general evolution of their depositional environments, transport mechanisms, tectonics and dominant lithologies is very similar, and can be described as a unique area of the PBS. The boundaries between the depressions are mountains and massifs in Northern Croatia, or their subsurface extensions, which can be recognised as uplifted structures or buried hills covered by Neogene and Quaternary sediments (VELIĆ et al. 2002; VELIĆ 2007). They are recognizable in present-day relief or in the subsurface via well or seismic data.

### 2.1. Depositional megacycles of Neogene and Quaternary systems in the CPBS

Neogene and Quaternary sedimentary systems are subdivided into three megacycles (VELIĆ et al., 2002). Neogene and older outcrops in the CPBS are rare as most of the surface is covered by Holocene sediments (VELIĆ, 2007). At the margins of the depression, the thickness of Neogene sediments varies between 500–1500 m, rising towards the centres, to 3500 m thick in Slavonia–Srijem, 5500 m in the Sava and Mura and almost 7000 m in Drava Depressions respectively (Fig. 1B; VELIĆ et al., 2002; SAFTIĆ et al., 2003). The isochore 0 m is proven along the highest mountains in Northern Croatia. These central basin zones of maximum deposit thickness are locations of thick intervals of cyclic, i.e. rhythmic deposition (FILJAK et al., 1969; ŠIMON, 1980). VELIĆ et al. (2002) described three sedimentation megacycles in the Neogene and Quaternary. These cycles consist of sequences of well defined lithostratigraphic formations. Each megacycle includes sediments deposited during cycles of relative sea level change. In the 1st part of the cycle the water level is gradually rising, and in the 2nd it is suddenly dropping (e.g., MITCHUM 1977). Generally, each megacycle is composed of a regular/ordered superposition of well defined lithologic units (formations and/or members). A particular cycle is measured in tens or hundreds of metres (e.g., MATHUR, 1981), but an entire megacycle in the CPBS can reach more than 1000 m (VELIĆ et al., 2002; VELIĆ, 2007).

The oldest, or 1st megacycle (Fig. 2), comprises Middle Miocene sediments, i.e. the Prečec Formation (Fm.) in the Sava Depression, Moslavačka Gora Fm. in the west Drava Depression, the Vukovar Fm. in the east Drava and Slavonia–Srijem Depressions and the Murska Sobota Fm. (except the formation top) in the Mura Depression. Lithologically it is a very heterogeneous sequence. It comprises coarse grained clastics (breccia, conglomerates and sandstones), fine grained clastics (clays, marls and calcareous, sandy, argillaceous marls) and carbonates (limestones and calcareous sandstones). According to ĆORIĆ et al. (2009) an initial marine transgression occurred later in the Croatian part of the Pannonian Basin – 1 Ma after the beginning of the Badenian. This was dated using Nannofossil Marker Species, especially

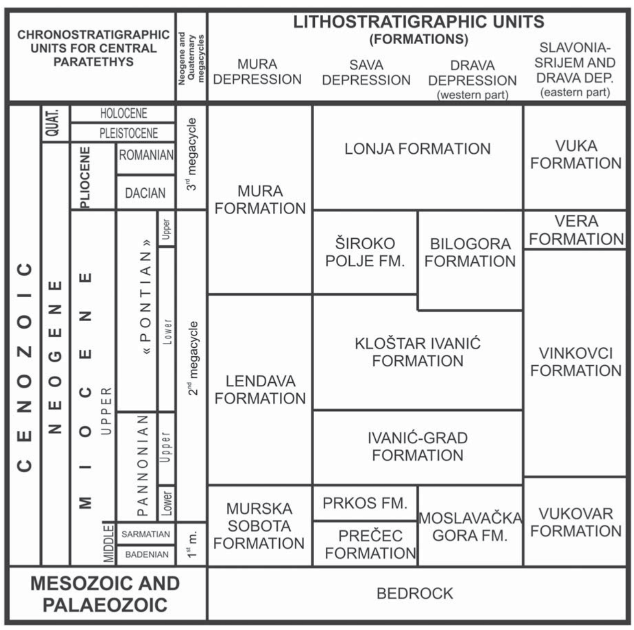


**Figure 2:** Chronostratigraphic units with lithostratigraphic units in the rank of formations valid for the Croatian part of the Pannonian Basin System (VELIĆ et al., 2002).

the nannoplankton NN5 zone, resulting in sediments previously regarded as Karpathian now being of Badenian age. All sediments that belonging to 1st megacycle but have Lower Miocene age, also are of very restricted areal extension and it is why they are excluded from this study.

The 2nd megacycle (Fig. 2), is of Late Miocene age (belonging to the Pannonian and Pontian stages). It comprises sediments of the Sava Group (Ivanić-Grad, Kloštar Ivanić and Široko Polje Formations) in the Sava Depression. In the western Drava Depression, the Bilogora Formation (Late Pontian) is equivalent to the Široko Polje Formation. In the east Drava and Slavonia–Srijem Depressions, equivalent formations are the Vinkovci and Vera Formations. Finally, in the Mura Depression, this megacycle comprises the Lendava Formation and the lower part of the Mura Formation.

The 3rd megacycle (Fig. 2), is of Pliocene, Pleistocene and Holocene age. According to the lithostratigraphic nomenclature it comprises the Lonja Formation in the Sava and the west Drava Depressions, the Vuka Formation in the east Drava and Slavonia–Srijem Depressions and the Mura Formation in the Mura Depression.

## 2.2. Hydrocarbon reserves in the CPBS

Analysis of the number of discovered and active fields (39 oil, 11 condensate and 52 gas fields) between 1941–2005 (Fig. 3) showed that the number of new fields rapidly increased in the sixties for oil, and in the eighties for gas. This period was followed by a drastic decline in new discoveries. Generally, the 30 years between1959–1989 can be described as a highly successful exploration period, when potential structural and combined traps could be discovered with the use of several easily applied methods such as gravimetric and seismic surveys. These were often discovered by the very first exploration well. Improved seismic survey methods, focused on depths greater than 2000 m, played a critical role in the discovery of the largest Croatian gas-condensate reservoirs in the Drava Depression in the eighties. Reservoirs are described as oil, condensate and gas pools.

## 2.3. Main reservoir lithofacies in the CPBS

The oldest fields are the Gojlo, Šumečani, Bunjani, Kloštar and Dugo Selo fields, (production began between 1941 and 1957). The youngest fields are Đeletovci and Privlaka (1984), Bizovac and Leticani (1989) and Galovac–Pavljani (1991). The group of "the oldest fields" is located in the Sava Depression (Fig. 1B) and includes three different reservoir lithofacies: two of them are Neogene sandstone and coarse-grained clastics while the third is in the Palaeozoic magmatic and metamorphic rocks of the crystalline basement. Almost all of these fields are of the "buried hill" type trap (Šumećani, Bunjani, Kloštar, Đeletovci, Privlaka, Galovac–Pavljani), where significant quantities of oil and gas are accumulated across an erosional unconformity between the crystalline basement and the coarse-grained Badenian sediments.

Quantitative data and conclusions from previous studies (BASSIOUNI & VELIĆ, 1996; BELOŠIĆ, 2003; DRAGAŠ et al., 1995; HERNITZ et al., 2002; MALVIĆ & VELIĆ 2010; MALVIĆ et al., 2005; JÜTTNER et al., 2001; SAFTIĆ et al., 2001; VELIĆ et al., 2002) contribute to estimation of the exploration level of hydrocarbon bearing rocks in the Croatian part of the Pannonian Basin System. These rocks were classified into two complexes with regard to their composition: (1) the rocks of Palaeozoic and Mesozoic ages represented by magmatic, metamorphic and carbonate rocks and (2) the clastics of Neogene and Quaternary ages.

Observing the volume of Neogene and Quaternary sediments explored by drilling, there is good potential for successful exploration of the remaining hydrocarbons, especially in areas among the discovered fields (VRBANAC et al., 2010). Younger sediments (upper part of the Upper Miocene, Pliocene, Pleistocene and Holocene) have not been explored at all, although the presence of gas (especially biogenic methane) has been identified in several fields and prospects. The oldest Neogene rocks, older than Lower Pannonian, probably contain significant undiscovered hydrocarbon reserves of oil and thermogenic gas, because these deposits constitute the principal sequences of Neogene source rocks (especially in the Badenian, i.e., the Middle Miocene, TRO-

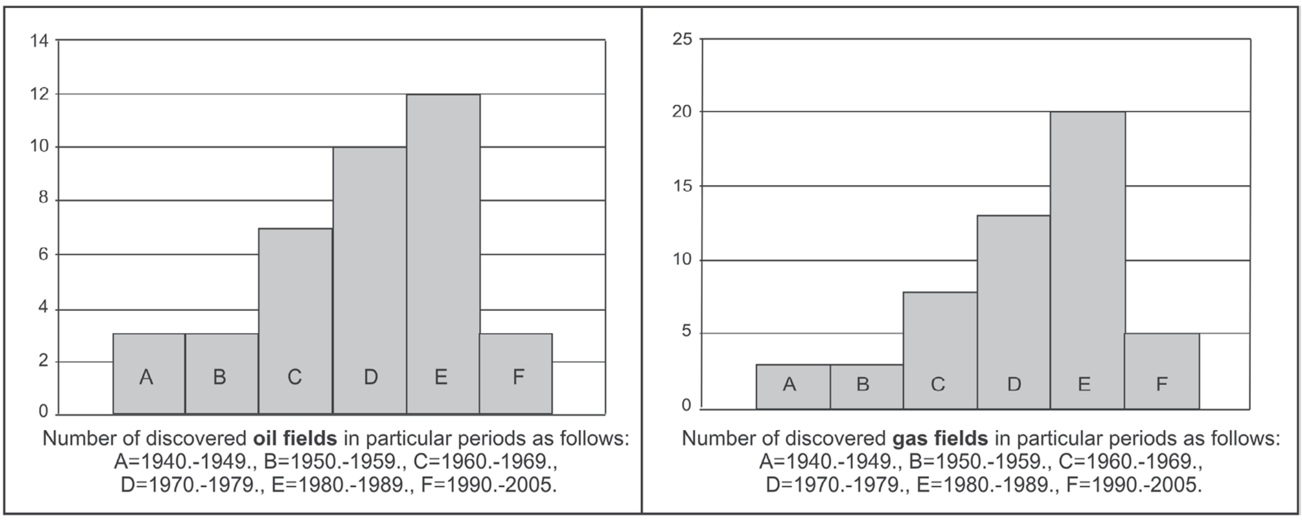


**Figure 3:** Number of discovered oil (left) and gas (right) fields during the particular time periods.

SKOT-ČORBIĆ et al., 2009; SAFTIĆ et al., 2003; VELIĆ et al., 2000; ZEČEVIĆ et al., 2010). The potential of these deposits as unconventional reservoir rocks remains to be explored.

### 2.4. Remaining recoverable and probable reserves in the CPBS

A regional study was recently published concerning exploration and production (E&P) ventures in Eastern and Central Europe, which also gave the potential of remaining recoverable hydrocarbon liquids in this area (DOBROVA et al., 2003). This study reports that *"E&P activities were particularly successful, in terms of having discovered economically viable oil and gas reserves and having achieved incremental production, in Poland, Lithuania, Hungary, the Czech Republic and Romania"*. Of course, new discoveries of hydrocarbons are small to moderate, but it is expected that they will greatly contribute to the reserves' replacement in these countries. Cited paper reveals that Croatia's resources are 6% of the total recoverable resources in Central and Eastern Europe, which places Croatia in third place along with Austria and Belarus, after Romania and Ukraine. DOBROVA et al. (2003) stated two conclusions of particular interest: (a) improved drilling success ratios were achieved mainly by state companies, since they preferred to drill appraisal and/or low risk prospects while largely reduced drilling frontier wells; and (b) current production growth will come mainly from traditional producers' activities, not from those of newcomers. This means that the decline of oil and gas production/proven reserves in Croatia may be slowed or could cease with the addition of the production from satellite reservoirs of existing fields rather than from new discoveries. MALVIĆ & RUSAN (2009) calculated the minimum size of a commercial discovery of oil in the Croatian part of the Pannonian Basin System as being of 2 x $10^5$ $m^3$ of recoverable oil. Such discoveries can be expected even in marginal areas (like the Bjelovar Subdepression) of the Drava or Sava Depression that are the largest depressions in Croatia. They calculated, that to discover one new field with an expected profit of more than 2 x $10^6$ USD (net present value, 13.52 x $10^6$ USD, and risk adjusted value of discovery 35%), approximately 50 x $10^6$ USD should be invested in exploration of the geological area where such discoveries are assumed. MALVIĆ & RUSAN (2009) also pointed out that more prospective plays for new fields would be in rocks of Lower and Middle Miocene age, or in the Mesozoic or Palaeozoic basement. It should be mentioned that between the Miocene and the Mesozoic-Palaeozoic rocks is a great tectonic and erosional unconformity, across which large secondary pore volumes in basement rocks are developed, as a result of a long period of weathering, dissolution and fracturing.

In any case, there is strong evidence that the Croatian part of the Pannonian Basin System contains significant unproven (probable & possible) hydrocarbon reserves, in existing reservoirs. It is especially valid in clastic reservoirs (breccia or sandstone). Better use of secondary or tertiary recovery methods might make it possible to recover part of these trapped or bypassed reserves as well as supporting the extended production from presently proven reserves in certain reservoirs.

## 3. BASIC RESERVOIR CHARACTERISTICS

In Croatia, about 3610 wells were drilled prior to 2002. All fields are grouped by their cumulative production, into large, medium, small and very small fields, and those currently not productive (Tables 1–4). For oil and gas, this grouping is as follows:

(a) **Large fields,** which produced more than $10^6$ $m^3$ of oil/condensate or more than $10^9$ $m^3$ of gas;

(b) **Medium fields,** which produced $10^5$–$10^6$ $m^3$ of oil/condensate or $10^8$–$10^9$ $m^3$ of gas;

(c) **Small fields,** which produced $10^4$–$10^5$ $m^3$ of oil, $<10^5$ condensate or $10^7$–$10^8$ $m^3$ of gas;

(d) **Very small fields,** which produced less than $10^4$ $m^3$ of oil or less than $10^7$ $m^3$ of gas.

As expected, the large fields (group 1) accounted for 93.07% of total oil production up to 2005, from group 2 another 6.67%, and from groups 3 and 4 the amount of production was negligible. For condensate, the reservoirs of group 1 accounted for 82.13%, and from gas reservoirs group 1 recovery was 90.75% of total production. The life-cycle of commercial production is generally long; e.g., the average production period for such fields is estimated at 55 years. Such fields characterised by an extremely long production period include the Mramor Brdo (80 years), Okoli (74 years) and Stružec (72 years). Tables 3 and 4 may indicate why fields from group 1 are more productive than others, suggesting the relevance of a higher number of reservoirs, deeper traps, higher porosity and permeability etc. Data from Tables 1 (oil), and 2 (gas and condensate) supported the classification of fields in groups by analysis of petrophysical and statistical data as well as other geological information including depression, age, lithology and trap.

### 3.1. Reservoir properties of oil reservoirs

Data are taken from 39 oil fields, 52 gas fields and from 8 fields that were never productive. Data for condensate reservoirs are from 11 active fields and 1 recently discovered field. Some earlier statistical analysis for data mostly from sandstone reservoirs of Lower Pontian age, were also included in this summary (MALVIĆ et al., 2005; SAFTIĆ et al., 2001).

For oil fields, group 1 reservoirs are sandstones of Pannonian and Pontian age, except for the Beničanci Field, where the reservoir is a Badenian breccia. Groups 2, 3 and 4 include reservoirs of heterogeneous lithology and ages: deposits in the Drava Depression consist of effusives, sandstones, breccias and conglomerates of (possible Karpathian) and Badenian ages. Other reservoirs include carbonates of Triassic, Cretaceous and Oligocene(?)-Miocene ages. In the Slavonia–Srijem Depression, reservoir rocks are represented

**Table 1:** Oil fields and reservoir groups, geological, statistical and petrophysical data.

| Variables | OILFIELDS 1st group LARGE FIELDS | 2nd group MEDIUM FIELDS | 3rd group SMALL FIELDS | 4th group VERY SMALL F. |
|---|---|---|---|---|
| | Geological data | | | |
| Depression(s) | Sava, Drava, Slavonia-Srijem | Sava, Drava, Slavonia-Srijem | Sava, Drava, Mura | Drava |
| Age | (Mostly) Pannonian and Pontian | Middle Miocene, Mesozoic, Palaeoz. | (Mostly) Middle Miocene | Upper Miocene, Pliocene |
| Reservoir lithology | (Mostly) sandstones and breccia | Coarse-grained, carbonates, metamorphic | Breccia, sandstones | Sandstones |
| Trap type | Structural, struct.-stratigraphic | Structural, struct.-stratigraphic | Struct.-stratigraphic | Structural, struct.-strati-graphic |
| | Statistical data | | | |
| Number of fields | 8 | 11 | 18 | 3 |
| Absolute depths to res. top (m) | –570 to –1700 | –310 to –2280 | –790 to –2350 | –570 to –1960 |
| Average no. of reservoirs | 13 | 5 | 5 | 2 |
| Share in total production (%) | 93.067 | 6.67 | 0.26 | 0.003 |
| Prognosis of product. (years) | 55 | 46 | 36 | 10 |
| | Petrophysical data | | | |
| Porosity (%) | 16.90–22.39 | 12.01–16.33 | 16.27–18.48 | 14.29–18.32 |
| Permeability ($10^{-15}$ m$^2$) | 3.73–384.00 | 8.16–196.60 | 2.9–92.3 | 25.17–832.96 |
| Aver. oil density (kg/m$^3$) | 847.6 | 873.6 | 857.96 | 832.96 |

by Palaeozoic granite, gneiss, schist and diabase as well as conglomerates, breccias and sandstones of Badenian age.

The oil reservoirs (Table 1) of group 1 are also characterised by high porosity, permeability, oil saturation and recovery factor (MALVIĆ et al., 2005; SAFTIĆ et al., 2001; VELIĆ et al., 2002; VELIĆ 2007). Interval porosity is greatest for group 1, with 19.9–22.4%, followed by 16.27–18.49% for group 3, 14.29–18.32% for group 4, and 12.01–16.33% for group 2. The reservoir permeability is significantly reduced in the smaller size reservoirs: It is 15.38–262.51 x $10^{-15}$ m$^2$ (median value; 2–139 x $10^{-15}$ m$^2$) in group 1 reservoirs, 6.01–174.50 x $10^{-15}$ m$^2$ (median 0.83–28.30 x $10^{-15}$ m$^2$) in group 2, 6.97–21.65 x $10^{-15}$ m$^2$ (median; 4.00–18.30 x $10^{-15}$ m$^2$) in group 3 and 14.17–25.17 x $10^{-15}$ m$^2$ (median; 6.00–26.60 x $10^{-15}$ m$^2$) in the smallest group 4 reservoirs. Median values are more valid than average ones, because the permeability input data set is characterised by many extreme values. A decline in maximum permeability is clearly observable. Consequently, recovery factors also decline from 36.47% to 24.39%, 11.33% and 8.53%, respectively.

### 3.2. Reservoir properties of gas and condensate reservoirs

The gas and condensate fields are also classified in four and three groups respectively (Table 2), regarding the statistics of geological, and petrophysical data.

The four groups of gas fields (Table 2), are based on the recovered volumes of gas. Reservoirs are in Palaeozoic and Mesozoic rocks in 10 fields, Middle Miocene rocks in 22 fields and in the Upper Miocene rocks in 20 fields. However, there is no regularity of reservoir ages in the four groups. Predicted periods of production vary between 10 and 31 years. Not counting the gas fields in the Adriatic Sea, the production periods would be between 5 and 23 years. The largest fields could have the longest production, similar to oil fields. Other parameters listed for gas fields are characterised by similar trends observed for oil fields. The condensate is added to gas field's data which mostly have the same characteristics. The main differences are in the deeper subsea depth of condensate reservoirs and number of analysed reservoirs (Table 2).

## 4. SIZE OF FIELDS, RESERVES AND PRODUCTION UNTIL 2005

The quantities of recoverable and recovered hydrocarbons in the period 1940–2005 are shown in Fig.3. The cause for a rapid production decline after 1989 is threefold: depletion of older fields, Serbian occupation of Eastern Slavonia in 1991–1995 and consequently a substantial decrease in exploration activity, resulting in no addition of reserves during this period. The maximum annual oil production was more than 3.1 x $10^6$ tons (1979–1982 and 1985–1988). Gas production reached a maximum during the periods 1987–1990 (more than 2 x $10^9$ m$^3$) and 1993 (2.05 x $10^9$ m$^3$). The total Original Hydrocarbon In Place (OHIP, sometimes also called *petroleum initially in place*), is about 740 x $10^6$ m$^3$ of equiv-

**Table 2:** Gas fields and reservoir groups, geological, statistical and petrophysical data, condensates are listed separately in italics or with additional marks* in geological data.

| Variables | GASFIELDS 1st group LARGE FIELDS | 2nd group MEDIUM FIELDS | 3rd group SMALL FIELDS | 4th group VERY SMALL F. |
|---|---|---|---|---|
| | Geological data | | | |
| Depression(s) | Drava* Sava, Northern Adriatic | Drava*, Sava* | Drava*, Sava, Slavonia–Srijem, Mura* | Drava*, Sava *Mura* |
| Age | Palaeozoic*, Mesozoic*, Miocene*, Pliocene, Quaternary | Mesozoic*, Miocene* *Pliocene* | Palaeozoic, Mesozoic, Miocene*, *Pliocene* | Palaeozoic, Miocene, Pliocene |
| Reservoir lithology | Magmatic*, metamorphic*, carbonate*, breccias*, sandstone | Carbonate*, breccias*, sandstone* | Carbonate, breccia, sandstone* | Magmatic, breccia, sandstone |
| Trap type | Structural*, struct.-stratigraphic | Structural*, struct.-stratigraphic | Structural*, struct.-stratigraphic*, stratigraphic | Structural, struct.-stratigraphic |
| | Statistical data | | | |
| Number of fields | 13 *(+2)* | 16 *(+3)* | 18 *(+6)* | 5 |
| Absolute depths to res. top (m) | –150 to –3054 *–2950 to –3050* | –240 to –3400 *–1450 to –3400* | –240 to –2230 *–710 to –1920* | –350 to –2110 |
| Aver. no. of reservoirs | 13 *1* | 6 *6* | 5 *8* | 5 |
| Share in total production (%) | 90.75 *82.13* | 7.83 *17.63* | 1.38 *0.24* | 0.04 |
| Prognosis of product. (years) | 31 *37.5* | 26 *34* | 10 *26* | N/A |
| | Petrophysical data | | | |
| Porosity (%) | 16.60–25.23 *(11.17–16.97)* | 16.39–21.96 *(16.52–21.28)* | 14.31–18.21 *(3.50)* | 12.28–15.64 |
| Permeability ($10^{-15}$ m$^2$) | 5.87–184.69 *(2.07–32.10)* | 4.96–30.51 *(14.77–20.79)* | 30.20–151.82 *(0.08–20.70)* | 2.85–13.25 |
| Relative aver. gas density (air=1) | 0.672 *(784.0 kg/m$^3$)* | 0.705 *(720.0 kg/m$^3$)* | 0.678 *(723.9 kg/m$^3$)* | N/A |

alent oil (oil, condensate, gas), with recoverable reserves of 112 x $10^6$ m$^3$ of oil, 9.5 x $10^6$ m$^3$ of condensate and 93.1 x $10^9$ m$^3$ of gas (Fig. 4) respectively. Up to 2005 a total of 179 x $10^6$ m$^3$ of equivalent oil was recovered 104 x $10^6$ m$^3$ oil from 39 fields, 6.93 x $10^6$ m$^3$ condensate from 11 fields and 64.92 x $10^9$ m$^3$ gas from 52 fields (VELIĆ et al., 2008). By 2005, 37 fields are still producing.

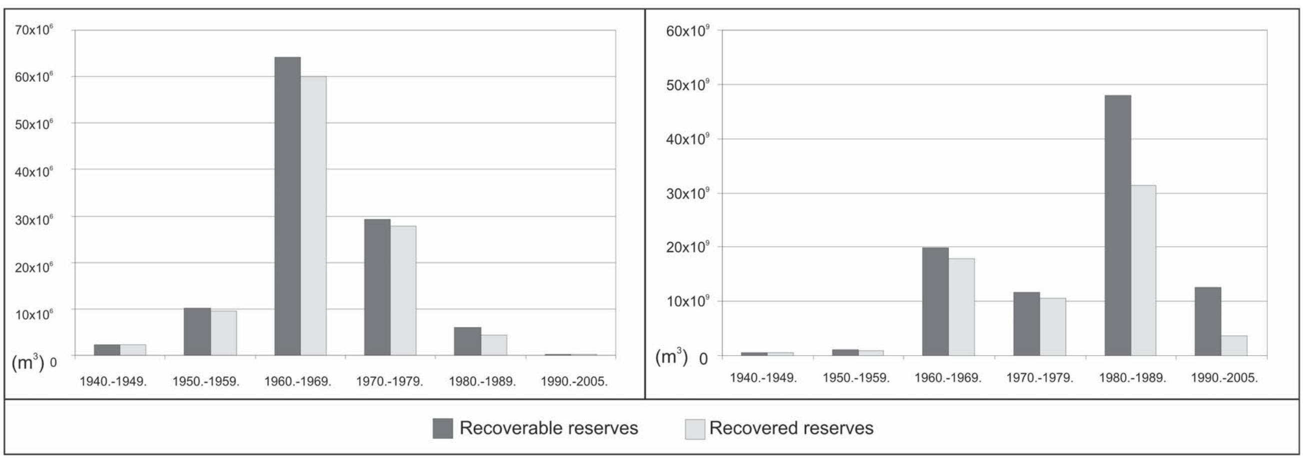


**Figure 4:** Relationships between recoverable and recovered reserves of oil (left) and gas (right) during the particular time periods.

**Table 3:** Oil reserves and production (up to 2005).

| OIL (in m³) | | | | | |
|---|---|---|---|---|---|
| Geological reserves | Recoverable reserves | Recovered reserves | Remaining reserves | Total recovery (%) | Reached rec. (%) |
| Large fields (recovered >1,000,000 m³) | | | | | |
| 269,540,224 | 103,216,280 | 96,832,281 | 6,383,999 | 36.47 | 33.55 |
| Medium fields (100,000–1,000,000 m³) | | | | | |
| 39,931,399 | 8,290,547 | 6,943,553 | 1,346,994 | 24.92 | 21.40 |
| Small fields (10,000–100,000 m³) | | | | | |
| 5,032,466 | 463,961 | 266,669 | 197,292 | 8.51 | 6.21 |
| Very small fields (<10,000 m³) | | | | | |
| 1,088,161 | 88,871 | 3,916 | 84,955 | 8.03 | 0.42 |

Table 3 gives data on production and recoveries obtained for oil, divided into groups of large, medium, small and very small fields. Table 4 gives data for production and recoveries of gas, divided into groups of large, medium and small fields as well as fields that are still not in production.

In the 1970's, when oil production peaked, recoveries by primary methods were as follows: 16– 20% (dissolved gas drive) 20–25% (gas cap drive) 30–50% (water drive). The average recovery was 25%. Considering the largest fields with sandstone reservoirs, the following recovery was achieved: 16% in the Ivanić and Žutica Fields, 31% in the Kloštar Field and 39% in the Stružec Field. A maximum of 51% has been recovered from breccia in the Beničanci Field. The average total recoveries obtained until 2005 differ for field sizes and fluids. Generally recoveries are higher from the larger reservoirs. Fields were selected in four groups for oil and gas/condensate as in Tables 3 and 4, based on production to 2005.

Three mechanisms are in use for oil production:

Artificial lift (in a narrow sense, meaning a mechanical device inside the well, i.e., hydraulic pumping for transmitting energy to the bottom of the well);

Gas lift (a widely used artificial sub-method), including injection of gas in the tubing to reduce the weight of the hydrostatic column;

**Table 4:** Gas reserves and production (up to 2005); condensates are listed separated in italic with marks*

| GAS (in m³) | | | | | |
|---|---|---|---|---|---|
| Geological reserves | Recoverable reserves | Recovered reserves | Remaining reserves | Total recov. (%) | Reached rec. (%) |
| Large fields (recovered >1,000,000,000 m³) | | | | | |
| 116,356,798,000 | 83,292,609,000 | 58,913,729,060 | 24,378,879,940 | 69.72 | 55.11 |
| **Large condensate fields (>1,000,000 m³)* | | | | | |
| 13,125,352 | 8,940,100 | 5,693,324 | 3,246,776 | 78.88 | 48.05 |
| Medium fields (100,000,000 – 1,000,000,000 m³) | | | | | |
| 7,933,806,000 | 7,702,918,960 | 5,083,771,659 | 2,619,147,301 | 62.05 | 53.28 |
| **Medium condensate fields (100,000 – 1,000,000 m³)* | | | | | |
| 3,450,332 | 1,763,313 | 1,222,079 | 541,234 | 51.10 | 35.42 |
| Small fields (10,000,000 – 100,000,000 m³) | | | | | |
| 6,021,423,000 | 3,229,932,755 | 896,153,610 | 2,333,779,145 | 47.27 | 37.06 |
| **Small condensate fields (<100,000 m³)* | | | | | |
| 40,592 | 20,475 | 16,662 | 3,813 | 50.18 | 48.58 |
| Very small fields (<10,000,000 m³) | | | | | |
| 277,400,000 | 43,890,000 | 21,848,218 | 22,041,782 | 23.83 | 14.36 |
| Never in production (gas and condensate) | | | | | |
| 12,203,694,000 | 6,417,110,000 | 0 | 6,417,110,000 | 51.92 | 0 |
| *19,251* | *11,551* | 0 | 11,551 | 60 | 0 |

Natural flow production, when oil-reservoir pressure is sufficient to transmit the hydrocarbons to the surface.

Production mechanisms used in Croatian fields were analysed with respect to field sizes. The most often used mechanisms were:

- For the largest fields, artificial lift and gas lift; for four fields, natural flow;
- For medium fields, artificial lift;
- For small fields, artificial and gas lifts;
- For very small fields, artificial lift and natural flow.

The most frequently applied secondary recovery method for many Croatian fields is water injection. Approximately half of the present Croatian production comes from water-flooded reservoirs (e.g. Žutica, Ivanić, Beničanci etc.). Recovery from these reservoirs can reach 40%, thanks to a favourable oil/water viscosity ratio. In porous reservoirs, however, tertiary recovery methods, also called unconventional, enhanced or improved oil recovery (abbr. EOR or IOR) are successfully applied, as calculated for parts of the Ivanić and Žutica Fields (e.g. SEČEN et al., 2002).

During the last 20 years, the application of $CO_2$ injection was tested for 14 Croatian fields in the INA laboratories (GORIČNIK & DOMITROVIĆ, 2003). This method was found to be applicable in 33% of reservoirs attaining a complete fluid miscibility, in 59% of reservoirs reaching a partial miscibility and in 8% of reservoirs with no fluid miscibility. The amount of total bypassed oil in the water-flooded reservoirs of the 14 fields mentioned is about 140 x $10^6$ $m^3$, which means that appropriate tertiary methods could yield another 9–24 x $10^6$ $m^3$ of liquid hydrocarbons. Gas injection (as gas lift) resulted in an approximate additional 14.5 x $10^6$ $m^3$ oil recovered until the end of 1987.

## 5. DISCUSSION

The data presented are a valid source for estimating the hydrocarbon potential of the Croatian part of the Pannonian Basin System. Listed are in-place and recoverable quantities as well as cumulative hydrocarbon production data until 2005. They are related to geological, petrophysical and statistical data about all types of reservoir lithologies in the analysed area. Such a list should be useful when determining how to increase recovery from different types of lithologies, and how to select the most appropriate secondary and tertiary methods of recovery in the analysed lithologies.

The results obtained can be viewed in context with earlier published results (DOBROVA et al., 2003) in which the authors provided a valuable review of hydrocarbon reserves and potential over a large region of Central and Eastern Europe. According to available data, they reported comprehensive exploration and production results in Romania, Hungary, Czech Republic, Poland and Lithuania, covering recent successful ventures. These authors ranked Croatia in third place according to the remaining recoverable resources in Central and Eastern Europe at the end of 2002 (Romania first, 39%; Ukraine second, 25%; and Croatia, Austria and Belarus third, 6% etc.). This is why we re-assessed our recoverable resources, cumulative production and reserves given in Table 2 of the previous report (DOBROVA et al., 2003), using 42-gallon-barrel units. The conversion of units has been accomplished using a 6.2898 barrel (USA) for 1 $m^3$ of oil.

More recent production data from Croatian hydrocarbon regions are lower, compared with data published in 2003. Even if condensate reserves are added to oil (i.e. liquid) reserves, new values of oil are still lower (122.79 vs. 141.18 x $10^6$ $m^3$), and consequently reserves in proven traps are 62.5% lower than previously published. It is also clear that remaining gas reserves are lower, at 56.6%. It is certain that new results, taken from data to 2005, are not overestimated, assuming that larger volumes can be expected only in new prospects, fields or satellite reservoirs.

## 6. CONCLUSIONS FOR FUTURE EXPLORATION AND THE STRATIGRAPHIC TARGET

Some of the remaining hydrocarbons could still be recovered from the reservoirs/fields with a long production record in the Croatian part of the Pannonian Basin System (Fig. 5).

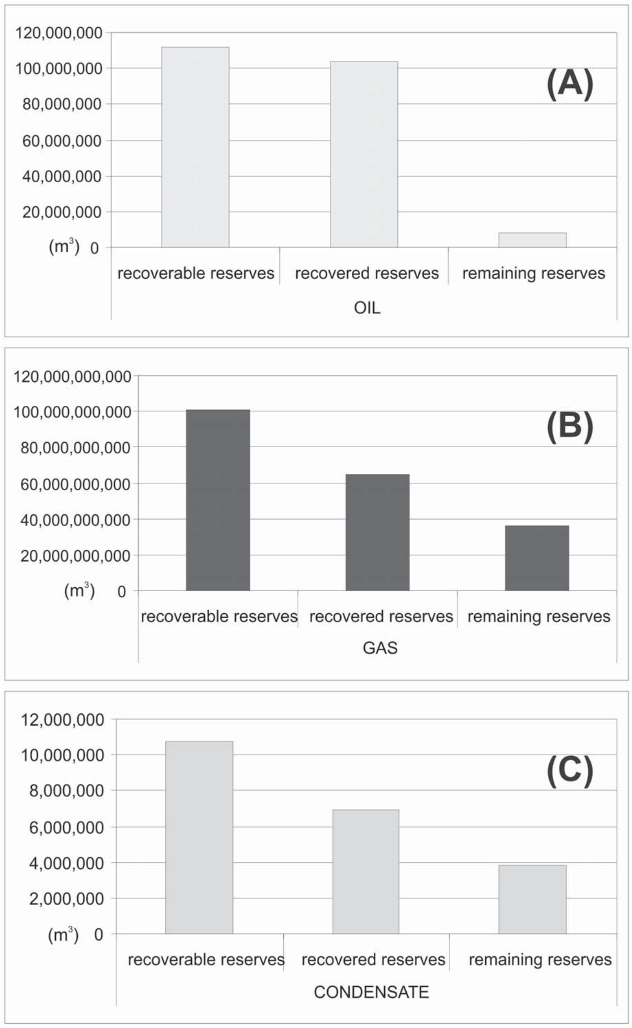


**Figure 5:** Status of the Croatian recoverable hydrocarbon reserves.

Also there are some less spectacular (“subtle”) but potentially large reservoirs; this is also supported by recovery rates given in Tables 3 and 4. Such potential petroleum resources could add to proven reserves, especially in the Drava and Sava Depressions.

“Subtle” reservoirs can be recognized using improved geological models of entire petroleum systems. Significant reservoir volumes can be expected in:

- Neogene basement rocks, along depression margins and/or uplifted palaeorelief (buried hills).
- Middle Miocene sediments, consisting of different lithofacies. These formations could be favourable for discovery of stratigraphic traps along the flanks of buried hills or at abrupt facies changes in palaeo-depositional plains.
- Typical heritage structures (or anticlines) above pre-Neogene buried hills.

Pannonian and Pontian sediments in which the main focus should be stratigraphic traps, typically along subtle or gentle anticlinal structures. Such potential traps can be observed on structural maps and especially on 3D seismic arrays by attribute analysis, searching for gradual transitions between channel sandstones and marls deposited in basinal plains. Those sediments have the most favourable petrophysical properties.

Differential compaction, which can be a significant mechanism of folding, especially in areas where depths are quite different over small lateral distances, causing “false” or “compaction” anticlines.

Sediments of all ages, for which further research needs to be undertaken for identification of possible traps along main basinal faults that influenced sedimentation. These faults had the main role in basin subsidence, but many faults also are proven migration pathways for hydrocarbons from source rocks to reservoir rocks.

Special attention should be paid to transform zones and related structural traps.

It is obvious that there is a need for renewing and/or intensifying geological and geophysical exploration and subsequent drilling in the Croatian part of the Pannonian Basin System. We believe this can be done in carefully selected areas, leading to successful prospects and plays.

## ACKNOWLEDGMENT

This work represents part of a multidisciplinary geological investigation that was performed in 2009 and 2010 within the project entitled ‘Stratigraphical and geomathematical researches of petroleum geological systems in Croatia’ (project no. 195-1951293-0237), which was financed by the Ministry of Science, Education and Sports of the Republic of Croatia.

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*Manuscript received April 04, 2011*
*Revised manuscript accepted December 27, 2011*
*Available online February 25, 2012*