Relations between Effective Thickness, Gas Production and Porosity in Heterogeneous Reservoirs: an Example from the Molve Field, Croatian Pannonian Basin

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ABSTRACT: The Molve Field is the most important gas-condensate reservoir in Croatia. This petroleum system is not typical for the Pannonian System, because it comprises several reservoir lithologies, relatively high structural closure and significant tectonic influence on the field’s compartmentalization. Strike-slip extension in the Middle Miocene and younger Late Miocene and Pliocene tectonics formed the present-day tectonic setting. Reservoir stratigraphy includes four lithofacies (from Devonian to Neogene) with a unique gas-water contact. The lithologies encompass cataclased granite, gneiss, schists, quartzites, dolomites, limestones and grainstones. Source rocks were generated in lacustrine organic facies and migration occurred in the Late Miocene to Pliocene. Reservoir gas includes 4.5–15.7% C₂+, but also non-hydrocarbon components.

Analysed porosity data were approximated with a normal-distribution curve in lithofacies I, II and III, making it possible to calculate mean and variance easily by descriptive statistics. Moreover, gas production and effective thicknesses generally can be linked through a linear trend. However, significant deviations in the expected increased production rate with regard to greater reservoir thickness are observed for particular wells. This is a result of locally abrupt changes in effective porosities and permeabilities, and the size of the drainage area along the main fault zones. These faults resulted in significant compartmentalization of the field. Furthermore, owing to significant facies variations, permeability and porosity gradually change, especially in the vertical direction.

Significant reserves of condensate (3 x 10⁶ m³) and gas (43 500 x 10⁶ m³) with a high recovery rate of 71% make this field significant for geological reservoir models. The well-established geological model for this field and its stable high pressure have maintained production rates at a present level of approximately 2900 m³ gas and 165 m³ condensate per day, thus providing a valuable example for other large heterogeneous reservoirs in the Pannonian Basin.

KEYWORDS: Molve Field, Pannonian Basin, Croatia, Palaeozoic-Cenozoic lithofacies, porosity, effective thickness, production

INTRODUCTION

This paper discusses the development of the Molve Field in the structurally complex Croatian part of the Pannonian Basin. Some of the field’s distinctive features include compartmentalization of the field by lithological variations and control by fault systems. The lithological heterogeneities make the analysed field an extraordinary example of hydrocarbon reservoirs in Croatia as well as in the Pannonian Basin as a whole. Moreover, this is one of the largest hydrocarbon reservoirs in the Drava Depression (maximal closure is almost 400 m). Because the fluid type is gas, communication is possible through most of the pore space, even in fine sandstones or silts. Moreover, secondary porosity plays an important role, especially for long-exposed unconformities or along fault zones.

Detailed analysis of the Molve Field’s hydrocarbon system can help maintain its long-term production rate. This successful result could be adapted for increasing recovery in similar fields.

Typically, in sedimentary reservoirs, the increase in porosity volume would be expected to be almost linear with net thickness. Thus, the production rate might be expected to increase. In analysing complex lithology (consisting of sedimentary, igneous and metamorphic rocks), however, such a linear relation between thickness and production rate cannot be
assumed, mostly because of different types of porosity that could be primary or secondary as a result of tectonics or diagenesis. Such an analysis is the main focus of this paper.

The Molve Field lies in the Drava Depression, an area covering about 9000 km², in the southern part of the Pannonian Basin of Croatia. This back-arc basin system was created as a result of subduction and convergence of the Apulian plate below the Dinarides that began in Ottnangian time (early Miocene series between 18.3 Ma and 17.2 Ma). Numerous pull-apart and pop-up basins and depressions were formed inside the basinal system as a result of dextral and sinistral strike-slip displacements (Fig. 1).

The Molve Field is the largest Croatian gas-condensate reservoir, located in the western part of the Drava Depression close to the Hungarian border (Fig. 2). The Molve Field, together with the adjacent smaller but geologically similar Kalinovac and Stari Gradac-Barcs Nyugat fields, accounts for 70–75% of Croatian gas-condensate production, or about 50% of Croatia's needs for gas and condensate consumption. The field was discovered in 1974, and 44 wells have been drilled to date. The field’s structure is represented as an asymmetric anticline, striking NW-SE, with dimensions of 13.0 × 4.5 km and an exploration area of 48.8 km². Reservoir depths are greater than 3000 m and the vertical closure is up to 395 m.

The total hydrocarbon reserves include 3 × 10⁶ m³ of condensate and 43500 × 10⁶ m³ of gas. The expected recovery rate of 71% classifies a large part of the reserves as proven, encouraging further activities of reservoir development and stimulation.

The reservoir is characterized by a very high initial pressure of 480 bars and a temperature range between 182°C and 190°C. Present-day reservoir pressure has been depleted to approximately 250 bars. The major portion of hydrocarbon is represented by wet gas, including 4.5–15.7% of higher hydrocarbon gases (C₂+ components). The fluid is also characterized by non-hydrocarbon aggressive and corrosive components, including mercury, CO₂, H₂S, chlorides and mercaptans. The percentage of CO₂ varies between 22.93% and 25.81%, and H₂S between 64.9 ppm and 169.7 ppm. The salinity of the reservoir water is about 26 g NaCl dm⁻³. Such peculiar characteristics also occur in the two smaller, adjacent Kalinovac and Stari Gradac-Barc Nyugat fields, which are represented by almost the same lithostratigraphic units and tectonic setting. Other Croatian gas fields contain mostly hydrocarbons, and some contain a highly increased CO₂ content, but other gases are detected only rarely.

TECTONIC AND DEPOSITIONAL HISTORY

Interpretation of 3D seismic data provides a detailed picture of the structure and stratigraphic features (Futivic & Pleić 2005). The oldest, still recognizable tectonic displacements are the results of Palaeozoic and Mesozoic orogenesis. Many Mesozoic deposits were eroded during the Palaeogene. The present-day structure of the field developed in the Miocene, with extensional tectonics that resulted in the opening of the Pannonian Basin System and uplift of the Apennines and the Dinarides (Royden 1988; Yilmaz et al. 1993; Fig. 2).

Miocene movements in the entire basin system were generally reflected in numerous extensional intra-basin strike-slip structures. The Molve anticline is such a structure (Fig. 2), connected with two adjacent anticlines (Kalinovac, Stari Gradac) in a typical strike-slip anticlinorium (Figs 3 and 4).

Royden (1988) and Rögl (1996; 1998) documented the ages of different Miocene pulses in the Pannonian area, establishing a scale used to categorize tectonic and sedimentation styles. Tectonic extension in the Pannonian Basin System started in the Ottnangian (19.0–17.2 Ma; Haq & Eysinga 1998), locally accompanied by a marine transgression and formation of strike-slip displacements. Extension continued in the Karpatian (17.2–16.4 Ma), when the Molve Field area and the entire Drava Depression were covered by marine sediments.
Maximum extension was reached in the Badenian (16.4–13.0 Ma), when strike-slip uplift was important in the structural development of the field. The major NW-SE strike-slip faults (Figs 3 and 4), which bordered the Molve structure, were created during this tectonic phase. Vrbanac (2002) described an extensive marine environment as dominant in Northern Croatia during the late Badenian, with several large mountains as islands. During extension, the surrounding basement was represented mostly by carbonate detrital sources, supported additionally by weathering of coralline reefs and briogean reefs. This material was deposited in alluvial-fan environments. Coarse-grained sediments were deposited in the proximal part, and medium- and fine-grained sandstones in the middle or outer parts of alluvial fans. This explains the gradual decrease in porosity values in Miocene facies toward the SE. Such a mechanism was proven for the adjacent Stari Gradac field by Malvić (2006). Evolution of the environment was controlled by specifics such as characteristics of the pre-Neogene basement, erosion rate, stream power and local tectonics.

The late Badenian generally represented a transition between extensional and post-extensional phases in Northern Croatia (Pavelić 2002). A series of transgressive-regressive cycles took place in the late Badenian, followed by an overall regression during the Sarmatian (13.0–11.5 Ma), typical for the Central Paratethys and the Pannonian Basin System (e.g. Rög & Steininger 1984; Kovač et al. 1997; Pavelić 2001; Vrsaljko et al. 2006). A post-extensional phase was characterized by local thermal subsidence of the base of the Pannonian Basin. Extensional tectonics (dominantly strike-slip and normal faulting) were replaced by a compressional style (mostly reverse faulting) over almost the entire Pannonian Basin System, but tectonics still controlled sedimentation locally (Royden 1988; Rög & Steininger 1984; Pavelić 2001). A new fault system in the Molve Field, striking NNW-SSE, was formed during this phase, oblique to the main strike-slip fault system and permeable for fluid flow in most of the reservoirs (Fig. 3).

The importance of alluvial fans significantly decreased in Sarmatian time, when regression started. Sea-level was lowered, salinity was reduced (a brackish environment) and, most importantly, the deep-water turbidites that originated in the Alps had been activated. These turbidites were a much more abundant source of sediments, especially from the Early Pannonian to the Late Pontian, than were the relatively small alluvial fans.

In the Early Pannonian (11.5–9.3 Ma) the last extensional and localized strike-slip tectonics took place in the entire basin system (Royden 1988). In a large lacustrine, brackish environment, characterized by depths up to several hundred of metres, salinity was continuously reduced owing to fresh-water inflow and a lack of connection with other open-sea environments (Vrsaljko et al. 2006). Such processes were the result of high-density turbidite currents active in Late Pannonian (9.3–7.1 Ma) and Pontian (7.1–5.6 Ma) time. Significant quantities of clastics were transported from the Eastern Alps through several turbidite events initiated by ramp-fault activity. Each depositional episode moved clastics over tens of kilometres, through the Mura and Drava depressions, and deposited them next to the tectonic ramp, pushing sediments to a final depositional
centre in the Molve area (Malvić et al. 2005; Fig. 1) in addition to other structurally determined areas. Successive turbidite events represented the dominant Late Miocene sedimentation mechanism in the Croatian depression (Saftić et al. 2001; Vrbanac 2002).

In the Late Pannonian and Pontian, sedimentation still took place mostly in brackish and finally in fresh lacustrine waters. This sedimentation represented periods of overall regression and reduction of the depositional area. The Pliocene (5.6–2.6 Ma) and Quaternary (2.6–0.0 Ma) were characterized by sporadically lacustrine, and mostly marsh, river and continental sediments (loess).

The Molve Field reservoir was formed through a complex series of events including strike-slip faulting and compressional uplift, and was filled by vertical and lateral migration of hydrocarbons. Charging was determined by the relative position of reservoir and source intervals, and by migration through and along fault planes. Hydrocarbons accumulated in the Molve reservoir in the Early Quaternary Period (about 2.6 Ma), after the Miocene traps had finally formed over the pre-Neogene palaeo-landscape.

Fig. 3. Structural map of the top of the Miocene reservoir in the Molve Field.

Fig. 4. Geological section shown on structural map (Fig. 3).
STRATIGRAPHIC SETTING AND SOURCE ROCKS

The stratigraphy of the reservoir rocks of the Drava Depression is highly complex (e.g. Barič et al. 1990; 1991; Baltić et al. 2005; Pikija et al. 1993). Porosity distribution is variable through different lithofacies because of the heterogeneities in the reservoir system. This reservoir parameter is especially variable in carbonate lithofacies and, therefore, porosity maps cannot provide enough geological information about drainage radius and reservoir quality. Additional comprehensive analysis of porosity, thickness and production rate from the reservoir is presented here. Reservoir evaluation, of course, has the aim of increasing future production.

Drilled intervals include rocks of Palaeozoic, Mesozoic and Cenozoic age. This entire chronostratigraphic sequence is separated by regional unconformities, but most units have retained their original superpositional relations. Reservoir rocks are classified by age and lithology into four lithofacies (Table 1) encompassing long chronostratigraphic events, several unconformities and a common gas-water contact (Fig. 4).

Table 1. Four lithofacies of reservoir rocks

<table>
<thead>
<tr>
<th>Lithofacies</th>
<th>Informal name</th>
<th>Age</th>
<th>Lithologies</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Grainstones</td>
<td>Early to Middle Miocene</td>
<td><em>Lithistitium</em> limestones composed of biocalcarenites and biocalcinites (porosity up to 20%); as well as biomicrites (porosity up to 5%)</td>
</tr>
<tr>
<td>II</td>
<td>Dolomites</td>
<td>Middle to Late Triassic</td>
<td>Early and late diagenetic dolomites, oolitic dolomites, limestones and breccia-conglomerates</td>
</tr>
<tr>
<td>III</td>
<td>Quartzites</td>
<td>Early Triassic</td>
<td>Metasandstones and quartzites, sporadic dolomites, dolomitic breccias and slates</td>
</tr>
<tr>
<td>IV</td>
<td>Diaphthorites</td>
<td>Pre-Devonian to Devonian</td>
<td>Different metamorphic and magmatic rocks, mostly cataclastized granite, gneiss and amphibibolic schists</td>
</tr>
</tbody>
</table>

The gas–water contacts in all lithofacies is at an absolute depth of −3380 m (relative depth, 3500 m) and the field has a total average reservoir porosity of 8.17%, an average effective thickness of 69.5 m and an approximate mean daily production of 2,900,000 m³ of gas and 166 m³ of condensate.

Barič et al. (1991; 1992) published an overall detailed geochemical analysis of the Molve Field and the entire Drava Depression. The investigation included source and seal rocks of Miocene age and reservoir rocks of Palaeozoic, Mesozoic and Tertiary age. Mature, organic-rich source rocks, predominantly of Ottnangian, Karpadian, Badenian and Pannonian ages, are at depths of 2800–4000 m. Accompanying seals are limestones, marly limestones and calcitic marls of Sarmatian age. The source facies of mudstones, marls and siltstones are 20–30 km NW of the Molve Field, in the northwestern part of the Drava Depression. Total organic carbon (TOC) varies from 0.45% to 1.80% (average 1.23%); the residual potential (S₂) is 3.51–10.13 mgHC g⁻¹ rock, and the hydrogen indices (HI) are 147–553 mgHC g⁻¹ TOC. According to Schoell’s (1983) genetic zonation, the gases in the Molve Field reservoir are classified as migrated thermal gases associated with condensates. These source rocks also are commonly seals, indicating lateral migration as a favourable mechanism (Barič et al. 1991).

A significant part of the non-hydrocarbon components (mercury, N₂, CO₂, H₂S, chlorides and mercaptans) in the reservoir fluid in the Molve Field can be explained by geological complexity as well as reservoir thermodynamics (Barič et al. 1998). These components are mostly aggressive and corrosive. According to Barič et al. (1991), it is believed that a small portion of the CO₂ could probably be ascribed to a magmatic origin (e.g. Tissot & Weltje 1984), but the very low negative measured values of δ¹³C in the CO₂ indicate carbonate rocks as the source.

RESERVOIR FLUID FLOW AND SEALING FAULTS

A simple view of a hydrocarbon reservoir under production can be modelled using three assumptions: isothermal (constant reservoir temperature), immiscible (no chemical fluid mixing) and three-phase fluid flow (e.g. Dake 1995; Lumley 1995; 2001). The three phases in a reservoir are water, gas and oil. During production, pore pressure decreases near oil-producing wells and increases near injection wells. Pore pressure stimulates fluid flow in three spatial dimensions of the reservoir (x) as a function of the production time (t). This fluid flow can be approximated by coupling fluid-mass conservation with Darcy’s law (Lumley 2001), which relates a gradient in pore pressure p(x,t) to the rate of fluid flow q(x,t) given the permeability k(x) and porosity ϕ(x) of the rock, and the viscosity η(x) of the fluid. The two phases of fluid flow in the MOLVE Field reservoir are coupled by the following immiscible fluid-displacement equations:

\[ \nabla \left( \frac{k}{\eta} \nabla p_x \right) - \phi_0 \xi = Q_w \]  \hspace{1cm} (1)

\[ \nabla \left( \frac{k_f}{\eta_f} \nabla p_{f} \right) - \phi \left( \rho S_g \xi \right) = \rho_f Q_g \]  \hspace{1cm} (2)

where J is the saturation of the j-th fluid component in the pore space; Q represents fluid withdrawn from a producing well or fluid addition from an injection well; p is the partial pressure for each phase of water, gas or, eventually, oil; and ρ_f is a gradient term of gas fluid density important for a compressible fluid with significant expansion and compression effects under variable pressure conditions.

There is no strong distinction between hydrodynamic pressures in the MOLVE reservoir. The entire field can be approximated as one large hydrodynamic unit, except for the very southern edge of the field, which is a second hydrodynamic unit (Fig. 3). The average reservoir pressure of the wells’ drainage radius varies mostly between 250 and 300 bars at the reservoir midpoint at an absolute depth of −3257 m.

Approximate pressure equilibrium means that most of the faults are permeable or only partially sealing (in terms of a geologically short time – i.e. they can be observed as seals through certain production periods expressed in months or years). The main partially sealing faults are the northern strike-slip and northwestern compressional faults.

Vertical communication between lithofacies exists, but, because of differences in porosity and permeability, it is not in a linear relation. This means that fluids move faster through younger parts of the reservoir, but if production is suspended over an extended period of time (weeks, months) reservoir pressure and fluid contacts can be stabilized at an approximately unique value through the entire reservoir. Such characteristics are shown indirectly in Table 2, in which daily gas
production along a 1 m average lies in a very narrow range – i.e. from 1161 m$^3$ per day in Palaeozoic ‘diaphorites’ to 1643 m$^3$ per day in Miocene ‘grainstone’ lithofacies.

STATISTICAL ANALYSIS

Statistics and geostatistics are favourable tools for analysing and explaining some production anomalies observed for different wells in the Molve Field. Well production and reservoir properties are analysed through four selected reservoir variables: production of gas ($Q$); effective thickness ($h_{ef}$); average porosity ($\phi_{mean}$) and water saturation ($S_w$). The analysed set included 6 sets of well data in lithofacies IV, 10 sets in lithofacies III, 14 sets in lithofacies II and 13 sets in lithofacies I. Reservoir parameters, averaged by lithofacies, are given in Table 1 (from Dalic´ et al. 2005). Production of gas is related to the current approximate average daily production in a selected well. Effective thickness is a term that includes total gross thickness of rocks by lithofacies for a selected well. Average porosities are calculated as arithmetic means of porosity in gross intervals, based on existing well logs. Average water saturation is average $S_w$ extrapolated for the entire lithofacies in an analysed well, extrapolated from an equation based on porosity.

Histogram analysis

Gas production, effective thickness and porosity were analysed using histograms, a normal distribution curve and Pearson’s correlation coefficient. Water saturations depend strongly on porosity and these values are no longer used in these analyses. Saturation values are calculated from Archie’s equation for formation factor as $F=1/\Phi^m$ (Archie 1942) in all four lithofacies, varying values of a cementation factor ‘$m$’ between 1.8 and 2.6 for the different lithologies. The size of the input dataset was strongly dependent on observed lithofacies.

<table>
<thead>
<tr>
<th>Lithofacies</th>
<th>Average effective thickness (m)</th>
<th>Average porosity (%)</th>
<th>Average water saturation (%)</th>
<th>Average daily gas production (in m$^3$ per day) along 1 m effective thickness of lithofacies</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>58.0</td>
<td>8.95</td>
<td>32.00</td>
<td>1643</td>
</tr>
<tr>
<td>II</td>
<td>40.6</td>
<td>5.95</td>
<td>44.20</td>
<td>1223</td>
</tr>
<tr>
<td>III</td>
<td>83.4</td>
<td>4.80</td>
<td>38.60</td>
<td>1352</td>
</tr>
<tr>
<td>IV</td>
<td>41.5</td>
<td>4.62</td>
<td>48.15</td>
<td>1161</td>
</tr>
</tbody>
</table>

Porosity histograms are approximated by normal distributions obtained in lithofacies I, II and III (Fig. 5). Lithofacies IV is characterized by insufficient data. The theoretical expectation (known also as geological axiom) is that porosity could be approximated by a normal or Gaussian distribution. Normal distributions obtained in lithofacies I, II, III indicate statistically reliable averages and variances.

Average porosity and daily production along 1 m $h_{ef}$ of lithofacies decrease in connection with the depth and age of the lithofacies (Table 2). Effective thickness ($h_{ef}$) cannot be described satisfactorily from average values per lithofacies, because it depends on palaeogeographical processes. Lithofacies III is characterized by the highest average thickness (Table 2).

Correlation

The Molve reservoir, owing to its very high heterogeneity and numerous faults, is an unfavourable area for detailed analysis of production and spatial distribution of reservoir parameters. The abrupt local changes in reservoir properties result in anomalies reflected in relationships between production rate, effective thickness and porosity. The only significant calculated correlation ($R>|0.28|$) was for the effective thickness-gas production pair ($h_{ef}$-$Q$). It was geologically expected to be normal reservoir behaviour – i.e. a larger reservoir thickness would commonly increase producible gas volume. Calculated correlations for the pair $h_{ef}$-$Q$ are $R=0.96$ in lithofacies IV, $R=0.88$ in lithofacies III, $R=0.67$ in lithofacies II and $R=0.77$ in lithofacies I.

Production anomalies can be outlined on geological maps, showing wells with the largest deviations between effective thickness and gas production trend. The positions of such wells can be additionally evaluated on the basis of porosity maps, which are the most important source of reservoir petrophysical properties.
Porosity maps

Porosity by lithofacies is presented through deterministic and probabilistic maps. Both of these maps are the result of variogram analysis and geostatistical mapping performed for the Molve Field and published by Malvić (2005). Porosity maps are interpolated by the Ordinary Kriging technique, one of the most commonly used geostatistical interpolation methods.

The reservoir was evaluated through the use of probability maps. A set of these maps was extracted from a stochastical simulation set, which included calculation of 100 porosity maps by lithofacies obtained by Sequential Gaussian Simulations (e.g. Dubrule 1998; Kelkar & Perez 2002). The zones where calculated porosity was higher than 3% were retained on the computer and overlaid on all 100 maps. The final map included maximal areal borders of zones with porosity equal to or higher than 3% per lithofacies. This value of 3% was selected as a cut-off value describing possible productive reservoir areas. Probability maps clearly describe the most favourable areas regarding higher reservoir porosity, which commonly are connected by higher permeability and drainage radius.

The presentation of only total porosity is a limitation of porosity and permeability maps. It means that we cannot distinguish the proportions of primary and secondary porosities, which is especially interesting in Mesozoic and Palaeozoic lithofacies. Some distinction between primary and secondary porosities could be made by using so-called porosity logs. However, it is more interesting to note the outline where greater secondary porosity can be expected because of palaeo-geography and palaeotectonics. Such zones lie primarily along unconformities that separate rocks of different eras, i.e. Palaeozoic/Mesozoic and Mesozoic/Cenozoic. The tops of these units had been exposed for a long time (in terms of Ma) to weathering and dissolution (especially the Mesozoic carbonates), increasing the secondary porosity and enlarging fissures and caverns. Other zones of increased pore volume lie along the main fault zones, i.e. during several episodes of tectonic activity. The main strike-slip faults, which have extended older fault lines, include movements of several decametres, which could shatter brittle rocks. Finally, the tectonic activity that formed the Molve Field is relatively young (Neogene and Pliocene), and much additional pore volume that resulted from diagenetic processes in the Palaeozoic and Mesozoic could have been subsequently cemented.

However, additional data can be obtained from the comparison of production anomalies from wells shown on geostatistical maps. Such maps show well locations with regard to the locations of higher porosities and faults, and could lead to useful conclusions about the distribution of reservoir quality.

Effective thickness and production-ratio abnormalities analysed by porosity maps

Lithofacies IV

A histogram of analysed variables ($h_{eff}$, phi-mean, $Q$) for lithofacies IV (Fig. 6) does not show any extreme irregularity in the effective thickness-gas production relationship. A production increase is associated mostly with higher effective thickness. However, it is interesting to analyse porosity in well Mol-11, where such regularity was not observed. The relatively high porosity in this well (12.7%) is not accompanied by an extraordinary production increase (Fig. 6), although the well pressure is average for the reservoir (270.7 bars). The total porosity was interpreted as high but with only a small effective porosity. The proportion of this lithofacies in relation to total production is negligible, however.

Lithofacies III

The Lithofacies III histogram in Figure 7 indicates a large increase in gas production from the Mol-37 and Mol-34 wells, respectively. These wells are not located in zones of high total porosity on porosity and probability maps in Figures 8 and 9. This again shows that zones of high total and effective porosities do not always correlate with each other (similar to lithofacies IV), and that favourable tectonics and chemical diagenesis, i.e. dissolution, especially in lithofacies I and II, including mostly carbonate or calcitic rocks – have a major influence on the effective porosity and permeability.
Porosity values in Figure 7 are measured in a relatively narrow band from 2.8% and 6.8%. The higher production obtained in the Mol-34 and -37 wells is the result of a larger drainage radius than that of other wells. The average pressure of the well-drainage radius is almost the same in both wells – 256.9 vs. 258.7 bars.

Structurally, the Mol-37 well is very close to the main extensional fault with a NW-SE strike (Figs 8, 9), which definitely has an important role in the increase in production. In fact, owing to similar well pressures in the entire block, it seems that this fault probably induced numerous fractures, increasing secondary porosity and associated permeability. Wells Mol-9 and Mol-34 are also close to the same fault (Fig. 3), and its mechanism is probably responsible for increased production from these wells. The similar well-drainage radius pressures (about 255 bars in all three wells) indicate inter-well communication in this area.

Lithofacies III is responsible for the most important play in the Molve Field. Our analysis shows that the drainage radii of wells, despite significant lithological heterogeneity, could be connected, as they show almost the same reservoir pressure over a long period of time. A few wells are measured for overpressure almost continuously. The wells with high production from this lithofacies were drilled along major transverse fault zones that played a role in tectonically increasing secondary porosity.

Lithofacies II

Three wells (Mol-15, Mol-29 and Mol-26a) are highlighted on the basis of deviation in an effective thickness/production ratio (Fig. 10). The Mol-26a well is characterized by increasing production, and the Mol-15 and Mol-29 by decreasing production.

The Mol-26a well is structurally located in the central tectonic block. This block is the most favourable play in lithofacies II as well as in the previous lithofacies. However, the pressure data for the Mol-26a well are extraordinarily high (441.7 bars) vs. an average pressure of 256 bars in Mol-29 (the pressure in Mol-15 was not measured). This indicates that production highs cannot be explained only by a well’s tectonic position, porosity values or pressure data, but probably also because of a portion of diagenetic (secondary) porosity, leading to the higher total porosity. Owing to carbonate lithology, chemical diagenesis had the largest influence on total porosity in this lithofacies. Carbonates, i.e. limestones, were strongly influenced by chemical dissolution caused by ions and pH values induced mostly by meteoric waters that filled the rocks.

A production decrease is observed for wells Mol-15 and Mol-29. The Mol-15 well is at the northwesternmost margin of the field (Fig. 11) in an area also characterized by low porosity and permeability in lithofacies III. The Mol-29 well is in the northern tectonic block. The locations of these wells indicate that these marginal tectonic blocks are mostly unfavourable areas for production stimulation. Geologically, these areas are probably characterized by smaller drainage radii and abrupt changes in petrophysical properties. Unfortunately, such porosity changes (especially from diagenetics and tectonics) in carbonate lithofacies cannot be predicted with any degree of certainty by any interpolation method.

Lithofacies I

A histogram of this Miocene lithofacies is characterized by the highest deviations of the effective thickness/porosity ratio. Also, the observed porosity ranges from 5.2% to 13.9% and is the highest.

The unusual production increase, regarding effective thickness, is observed for four wells: Mol-28a, Mol-35, Mol-1S and Mol-
Mol-27. An unexpected production decrease was observed only for the Mol-15 well.

The wells with increased production are in the central tectonic block (Mol-35 and Mol-1S wells) and in the northern block (Mol-27 and Mol-28). Their locations are shown in Figures 12 and 13. This confirms the central tectonic block as the most promising stratigraphic play for future development. However, the wells drilled in the northern tectonic block are also interesting. The well Mol-15 is characterized by increased porosity, indicating that this block is promising for additional well stimulation for the purpose of increased production (see Fig. 14).

The main transverse fault zone, striking NW-SE, is confirmed as the mechanism responsible for the production increase. Three wells, Mol-27, Mol-35 and Mol-1S, are close to or along the fault zone. A similar role for this zone is confirmed for lithofacies III of Early Triassic age.

Porosity caused by diagenesis and dissolution in a shallow-water environment was the best preserved in this, the youngest lithofacies.

The unfavourable location of the Mol-15 well was described in the section on carbonate lithofacies II. It clearly indicates that the northwestern tectonic block is geologically unfavourable for future development and reservoir stimulation.

Pressure data do not confirm the sealing properties of fault zones. The measured values in the Mol-35, Mol-28a and Mol-27 wells are similar, ranging from 254.6 to 273.5 bars.

DISCUSSION

The reservoirs of the Molve Field are geologically very complex owing to lithological heterogeneities, reservoir depth and the occurrence of numerous faults. The field encompasses only one hydrodynamic unit, but the well drainage radii are rarely interconnected, and different reservoir parts have different production quantities. Such differences are observed both laterally as well as vertically through the lithofacies.

Moreover, the major marginal faults can be classified very poorly as sealing barriers, based on pressure data. These measurements did not indicate significant differences on opposite fault blocks. Alternatively, the geological model clearly shows that major faults define the field margins and determine the gas-water contact. All these facts suggested using reservoir thickness, production and porosity in a relatively simple but useful mathematical analysis that could test for favourable production areas. The results showed where a favourable well’s drainage radius is located and why major faults can be considered as partially sealing horizontal barriers.

The main achievements for future reservoir development were reached by simple comparison of production unit thickness. Usually such data could be linked by a clear trend and, if there are any anomalies (small thickness-high production or large thickness-small production), such deviation needs to be plotted directly on the field-development map. Porosity maps are used here because production anomalies can be explained easily by increased or decreased porosity. Of course, this is not a ‘rule of thumb’ because there also could be influences from fractures or secondary porosity that might be missed in porosity-log interpretation, but this can be a highly useful methodology for available data for the Molve Field.

Pressure and production anomalies can be a useful indicator of partial fault sealing. Such anomalies were observed for two close wells, on opposite fault blocks, which clearly indicate a break in drainage radius and the sealing character of the fault. An example is shown in Figure 11 (porosity map of lithofacies II) in which data from the Mol-26a and Mol-29 wells are shown in such a trend. The reservoir in the Mol-26a in the central tectonic block, is overpressured (441.7 bars), and daily gas production is 180 000 m³. In the Mol-29 well, in the
northern tectonic block, lower production (50,000 m³) is the result of a lower pressure of 256 bars.

CONCLUSIONS

The Molve Field is a typical strike-slip anticline formed in the Pannonian Basin System during the Miocene. This reservoir is highly heterogeneous and consists of Palaeozoic, Mesozoic and Cenozoic rocks. Therefore, reservoir properties and, consequently, production rates require careful analysis. Many intra-reservoir micro-zones are present, owing to the complex tectonic and stratigraphic architecture. Each well needs to be evaluated as a possible target for future development and potential increase in hydrocarbon production. Based on the results presented in this paper, a number of conclusions can be drawn.

- The reservoir stratigraphy encompasses Palaeozoic (lithofacies IV), Mesozoic (lithofacies III, II) and Miocene (lithofacies I) rocks. This heterogeneous reservoir is characterized by petrophysical changes over small distances.
- Porosity histograms are approximated by normal distributions in lithofacies III, II, I. Lithofacies III is the most important for production because of its highest effective thickness. A positive correlation between effective thickness and production was considered to be the norm.
- Tectonic styles in the field originated in pre-Neogene and Neogene tectonic phases. These movements resulted in tectonic compartmentalization of the reservoir.
- Pressure data mostly do not indicate any different hydrodynamic units in the field. Locally, some pressure pockets can form on opposite sides of the main faults, as indicated by overpressured data. One such example is described in the section on carbonate lithofacies II, in which distribution of pore volume is mostly stochastic.
- Thus, the main faults are partial sealing barriers, but the main influence on production is the result of increased porosities and permeabilities along fault zones.
- The most promising geological area is the central tectonic block, especially for lithofacies I and III. The second promising play is the satellite, northern tectonic block, with part of the reservoir composed of lithofacies I (mostly owing to diagenesis).
- Lithofacies III is generally the most promising portion of the reservoir for further production.
- In heterogeneous reservoirs, unconformities play the most important role. If there are no sealing rocks, such interfaces are open for fluid communication and reservoir extension. Moreover, unconformities are loci for lengthy exposure at the surface. At the Molve Field these periods were very long — several millions of years — at unconformable boundaries.
- Heterogeneity and the ages of reservoir rocks, which span several geological eras, strongly emphasize diagenesis as a highly important process. Mechanical diagenesis, as a process of compaction, caused a decrease in porosity, especially in clastic rocks. However, Malvić et al. (2005) also proved that in Neogene sandstones in the Croatian part of the Pannonian Basin mechanical diagenesis makes little in the same lithostratigraphic member for a depth difference of less than 400 m. Chemical diagenesis includes several processes caused by dissolved ions, pH value, pressure and temperature. Pressure solution was a common process acting on quartz sandstones in Lower Triassic lithofacies III of the Molve Field. The dissolution of limestones from ions dissolved in water, with a characteristic pH value, was a diagenetic process important for porosity creation in carbonate lithofacies I and II of the Molve Field.
- The strike-slip fault systems played a crucial role in forming hydrocarbon fields in the Drava Depression and in the Pannonian Basin overall. These fault systems were the most important mechanism for formation of local depositional areas of reservoir rocks, which later (late Neogene and Pliocene) were inverted in positive structures (anticlines). Especially favourable places for hydrocarbon accumulation were sedimentary areas above the uplifted pre-Neogene palaeorelief.

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