

Exploration and production activities in northern Adriatic Sea (Croatia), successful joint venture INA (Croatia) and ENI (Italy)

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REVIEW

Exploration efforts in Croatian part of Northern Adriatic started in 1970 with 2D seismic acquisition and exploration drilling. Till 1995 more than 16,000 km of 2D seismic were acquired and 80 wells drilled. During early 80-s, several gas fields of significant production potential were discovered. Gas reservoirs are in unconsolidated to poor consolidated Pleistocene sands of the Po Depression (Ivana Formation in Croatia, Ravenna and Carola in Italy). Traps are structural and structural-stratigraphic, mostly formed as a result of differential compaction, also supported with folding, Mesozoic palaeorelief and lateral facies changing. Biogenic gas is trapped "in situ", composed mainly of methane with very low quantities of nitrogen. Due to the lack of infrastructure and technological problems related to the sand control, the development of the fields was postponed till 1996, when the implementation of, at that time, state-of-the-art sand control technology started. Most of the production wells were dual-completed with high rate water pack and/or "frac & pack" (FracPack) sand control technique applied. This technology was proved very efficient when developing unconsolidated reservoirs. Successful implementation of sand control increased expectations and encouraged partners (INA and ENI) to invest (via joint venture INAgip) in new exploration and production cycle. Since 1996 approximately 5,000 km² of 3D seismic were acquired, 12 new exploration wells were drilled and additional 7 gas fields discovered. INAgip developed 9 gas fields with 105 gas reservoirs, drilled more than 40 production wells, installed 19 production platforms and reached average production of approximately 30,000 boe/day.

Key words: Northern Adriatic Sea, Po Depression, Pleistocene, sands, gas, field development, Croatia

1. INTRODUCTION IN EXPLORATION HISTORY OF THE NORTHERN ADRIATIC

The history of hydrocarbon exploration in the entire Croatian area of the Adriatic Sea started in 1968, when the ship for marine seismic surveying "Vez" performed the first exploration. Today in this area exist about 45,000 km of 2D seismic lines and 6,200 km² of 3D seismic areas as well as 135 wells. The very first well Jadran-1, using French platform "Neptune", had been drilled in Dugi otok Depression in 1970. Soon, in 1973, is discovered Ivana Gas Field with Jadran-6 well in the areas of Northern Adriatic. Discovered reservoirs in Ivana Field belong to Quaternary sediment of the Po Depression. This discovery initiated investment in three Croatian platforms (named "Panon", "Zagreb" and "Labin"), which resulted in discoveries of new six gas fields in the Northern Adriatic (Ika, Ida, Annamaria, Ksenija, Koraljka and Irma) in the period between 1978-1993.

In February 1996 the work continued by forming a joint venture company between INA (Croatia) and ENI (Italy) for exploration and production of gas from the Northern Adriatic fields. The main reason was great ENI's experience in exploration and production of numerous hydrocarbon fields located in off-shore area of Ravenna, i.e. in sediments of Po River palaeodelta and existing system of pipelines constructed in the Italian part of the Po Depression (off-shore and on-shore). It resulted in successful discoveries of the next seven fields: Marica, Katarina,



Fig. 1.1. Schematic map of Croatian gas fields in Northern Adriatic

Sl. 1.1. Shematska karta hrvatskih plinskih polja u Sjevernom Jadranu

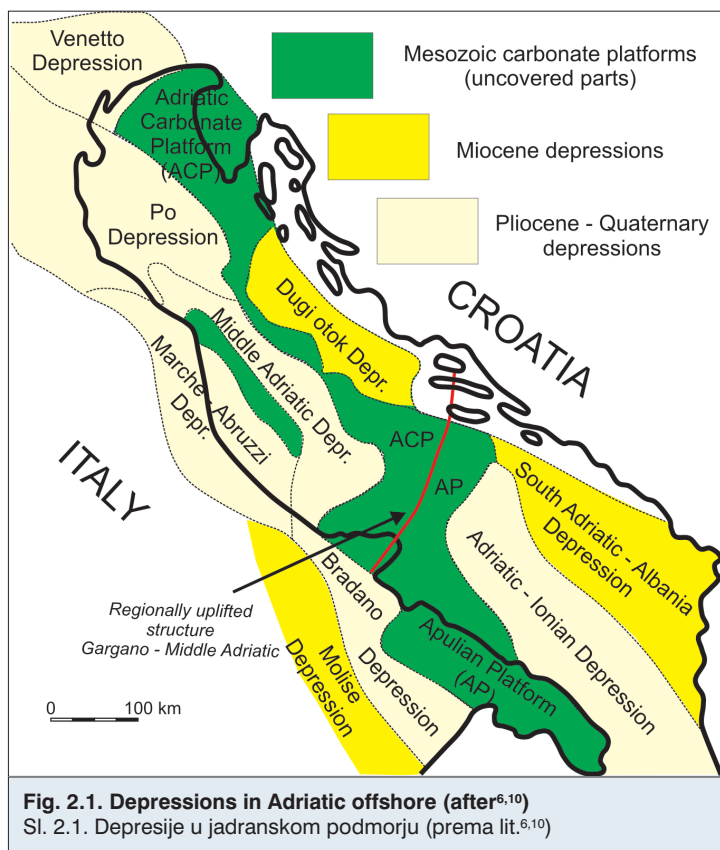


Fig. 2.1. Depressions in Adriatic offshore (after^{6,10})
 Sl. 2.1. Depresije u jadranskom podmorju (prema lit.^{6,10})

Ana, Vesna, Irina, Ika-SW, Božica after 1996, with significant reserves of hydrocarbon gas^{8,9}, even if it is compared with reservoirs located in the Croatian part of Pannonian Basin. Large quantities of proven gas reserves, numerous fields and especially reservoirs as well

as partially different depositional conditions for reservoir lithofacies in Pliocene and Pleistocene periods represented reasons for division of the Northern Adriatic into three large exploration fields named Izabela, Ivana and Marica (Figure 1.1).

2. GEOLOGICAL SETTINGS OF THE PLIOCENE AND PLEISTOCENE SEDIMENTS IN NORTHERN ADRIATIC

Adriatic Basin is divided on particular depressions that started to form in Miocene and Pliocene (Figure 2.1). Characteristic Miocene depressions are Dugi otok, South Adriatic-Albania and Molise. Later, in Pliocene, sinking of sea basin bottom caused forming of more depressions, namely Venetto, Po, Marche-Abuzzi, Middle Adriatic, Bradano and Adriatic-Ionian.⁶ Only some areas, like Istra, of the past Adriatic Carbonate Platform (AdCP) were not covered with younger (Cenozoic) sediments. The Croatian gas fields analyzed here belong to SE part of the Po Depression, which is one of the largest and youngest Adriatic depressions.

The largest part of the Po Depression today is located onshore, between Southern Alps and Apennines, but this nowadays alpine area was covered by the sea during Pliocene, spreading to margins of Istrian part of AdCP. Generally, the Po Depression is filled by sediments of Pliocene, Pleistocene and Holocene age. Siliciclastic detritus have origin from Alps and partially from Apennines.⁸ Total thickness can locally overreach 6000 m in the Italian part, but generally the depositional systems in entire part (Croatian and Italian) resulted in different facies of delta and prodelta, which interrupted hemipelagic, basin sedimentation. These facies differences resulted in different but correlative lithostratigraphic nomenclature in the Croatian and Italian parts of the Po Depression that is given in Table 2.1.

During Pliocene and Pleistocene the material in the Po Depression was mainly transported by palaeo Po River, including subsidiaries and other rivers like Adige River that still today transports detritus in the Po Depression, and possible Piave River that is a main detritus source for the Venetto Depression. In any case, all detritus transported on and along the sea bottom in the Po Depression had been deposited, with turbidites, in different lithofacies of delta and prodelta. In the Croatian part the dominant was prodelta environment, due to the distance from Po palaeodelta to Italian palaeocoast. This palaeodelta extended periodically towards SE, mostly in Quaternary glacial periods^{3,10}, when mechanisms of sea-

Table 2.1. Lithostratigraphy nomenclature in the Po Depression¹⁰

Chronostratigraphic units	Lithostratigraphic formations	
	Croatian name	Italian name
Holocene	Ivana	Ravenna
Pleistocene		Carola
Pliocene	Istra	Porto Garibaldi
		Corsini <i>(exclusive in Italian part)</i>
		Canopo <i>(exclusive in Italian part)</i>
		Santerno
Miocene	Susak	Clara
		Corinna
		Schlier
		Cavanella B
		Bisciaro
		Cavanella A
		Scaglia Cinerea
Oligocene		Scaglia
Eocene (Palaeocene?)		
Mesozoic	Dinaridi	Calcarei Del Cellina

level increasing (alocyclic process) or lateral facies migration (autocyclic process) took place in entire Northern Adriatic. Turbidites transported majority of the material in relatively shallow, hemipelagic environment, with depth up to 200 m, and alteration of turbiditic intervals and hemipelagic facies represents main property of depositional sequences in the Croatian part of the Po Depression during Pliocene and Pleistocene. In such prodelta environment fine-grained sediment indicated on turbidites of low density⁵ or currents with dominantly distal facies of Bouma sequence¹, like Tc, Td and Te. These low energy sediments are in alteration with interturbiditic, hemipelagic interval, often called as Tf⁷.

Numerous Pliocene lithofacies had been defined on locations of the Po palaeodelta slope, i.e. in Italian part of depression. This palaeoslope had been located, compared with contemporary delta around Ravenna, about 200 km W/NW and influence of turbidites created on shallow slope in Croatian part was probably very low or absent, what lasted at least to Upper Pliocene. That is why Pliocene in the Croatian part is mostly represented by basin hemipelagic clays and silts (Istra Formation), which can be easily recognized at the very southeast Croatian gas fields like Katarina and Marica Fields (Figure 1.1).

However, Pleistocene lithofacies are significantly different from Pliocene due to inter-bedding intervals of sands and silts. As Po River delta moved toward SE, more sands and silts had been transported to the Croatian part of depression. Such mostly psammitic facies can be recognized in all Croatian gas reservoirs discovered in Pleistocene sequence (i.e. in Ivana Formation), and are described, e.g., in the Ivana Field.² The total thickness of Pleistocene sediments is between 900 and 1500 m, where particular sandy gas pools can reach thickness of more than 20 m.

3. RESERVOIRS, DEVELOPMENT AND PRODUCTION ON NORTHERN ADRIATIC CROATIAN GAS FIELDS

Gas reservoirs in the Northern Adriatic had been discovered using seismic data (2D and 3D) acquired in the period 1968-2007. Seismic attribute analysis of gas saturated zones showed recognizable attribute anomalies (so called "bright spots"). It was applied in delineation and characterization of reservoirs.

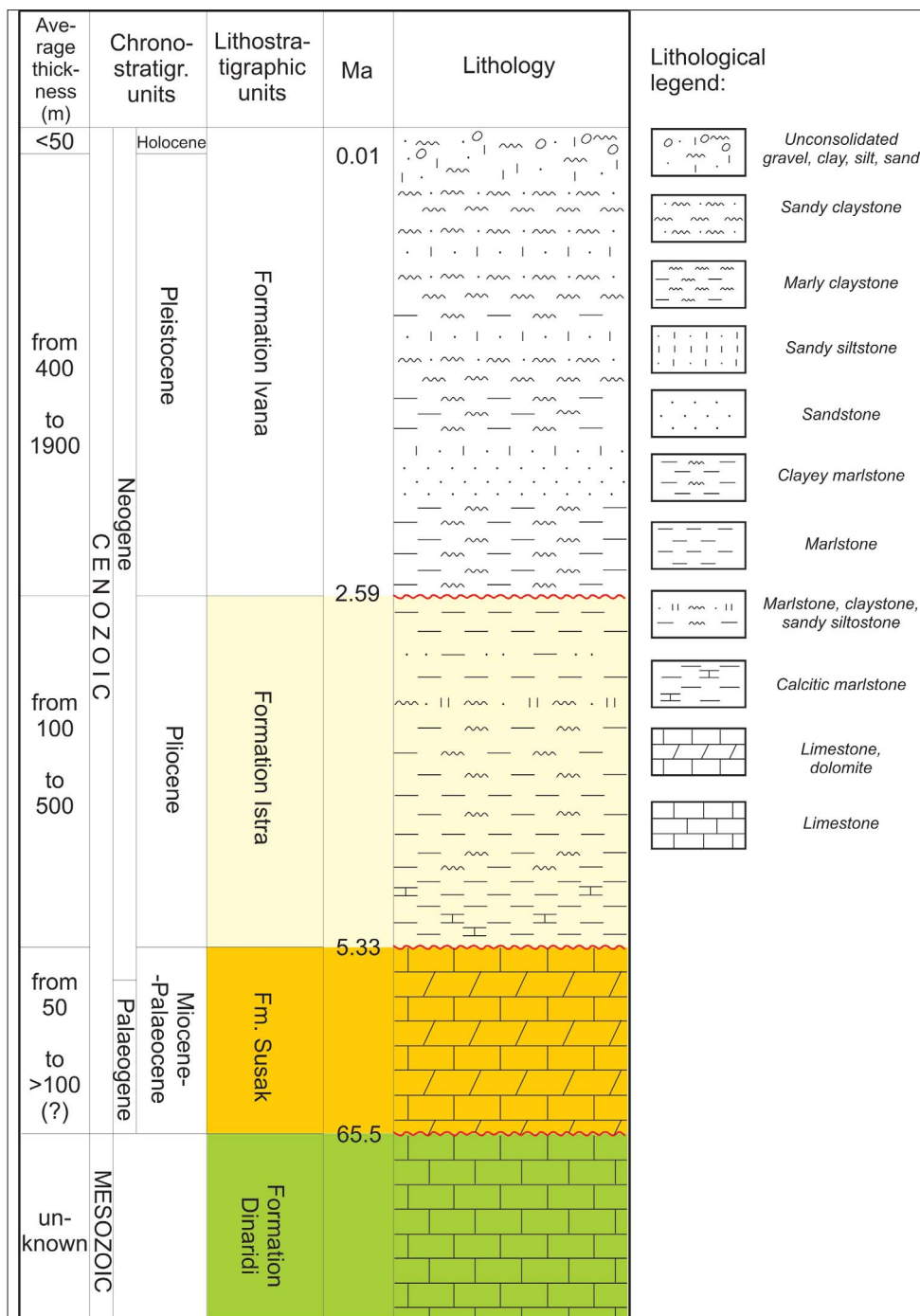


Fig. 2.2. Lithostratigraphy and lithofacies in Croatian part of Northern Adriatic (from ref.¹⁰)
Sl. 2.2. Litostratigrafija i litofacijesi u hrvatskom dijelu Sjevernog Jadrana (iz lit.¹⁰)

Development and production from those gas reservoirs in the Croatian part of the Po Depression started regularly with establishing of joint venture INAgip company in 1996. This process included several phases with spreading of number of platforms and wells through the time. Also, the significant production from this region eventually served as a trigger for planning and construction of pipeline network for supporting gas transport and consumption in southern Croatia (Figure 1.1).

3.1. Development and production

Development of gas fields started in the 1996 and continued in several phases:

- Phase 1 encompassed development of the Ivana Gas Field with four platforms (Ivana A, B, D and E) and construction of connections on pipeline on Italian side. Production started in October 1999.
- Phase 2 included development of Ika and Ida Fields using five platforms, and additional development (Ivana C) and compressor (Ivana K) platform. Moreover, the entire infrastructure for transport on Croatian land was built. All developed fields belong to the exploration field "Ivana". Moreover, this phase also included development in exploration field "Marica", where Marica and Katarina Fields started producing in 2004 and 2006, respectively. This phase ended with 13 active platforms, 34 production wells and more than 300 km of subsea gas pipeline.
- Phase 3 began with the development in 2007 and production in 2009 from the Annamaria, Ana, Vesna and Irina Fields.
- Phase 4 is currently in preparation and will include Ika-SW, Ivana-SW and Božica Fields.

All mentioned gas fields were developed on the basis of the detailed geological model, with special attention on facies distribution, because reservoir ratio of "sand/shale" content is very variable in particular fields. The reason is spatial and temporal migration of turbiditic current, resulting in different distribution of fine-grained psamitic and pelitic detritus.

It means that each field's model needs to be separately evaluated regarding the reservoir boundaries and estimation of proven or probable reserves. Such local approaches to estimation of reserves was very important especially in the areas of thin and silty reservoirs, like the one that had been discovered in Aiza-Laura contract area, i.e. exploration field "Marica" (Figure 1.1). This area extends far to southeast, on the margins of the Po Depression, and during the first stages of exploration the numerical geological risk for each prospect as the base for further development was also calculated. So Krpan et al. (ref.⁴) published such calculation of Probability of Success (POS) based on the estimation of the four geological categories: (1) generation of hydrocarbons, (2) migration, (3) trapping and (4) preservation of hydrocarbons for then named *Prospect B*. POS

reached 77%, what was base for estimation of potential OGIP (Original Gas In Place) using volumetric method, continuation of drilling and eventually discovering and development of Marica and Katarina Gas Fields.

3.2. Reservoir properties

Productive gas pools are located in unconsolidated sands on depths 600-1250 meters (Ivana Formation) and limestones on depths 1,420-1,470 m (Susak Formation). Sands are rarely replaced by poor consolidated sandstones, but only in the deepest Pleistocene reservoirs. Gas in reservoirs is almost pure methane (more than 98% CH₄ and about 1.6% N₂, 0.2% CO₂), accumulated with pressure gradient slightly higher than 1 bar/10 m, e.g. in Ivana Field 1.02-1.03 bar/10 m (ref.²). The production is currently active from 105 reservoirs.

Lithologically the reservoir sediments consist of fine to very fine grained sands. The amount of detrital matrix in reservoirs is dispersed or concentrated in thin laminae. It is described mainly as mineral smectite, like in the Ivana Field reservoirs, where portion of matrix does not exceed 7% and of carbonate cement is about 8-12%. The initial primary porosity is reduced by later mechanical compaction and chemical alteration.

Most reservoirs are defined by structural traps (Figure 3.1). Those are gentle anticlines or brachianticlines, sometimes characterized by lateral facies changes to

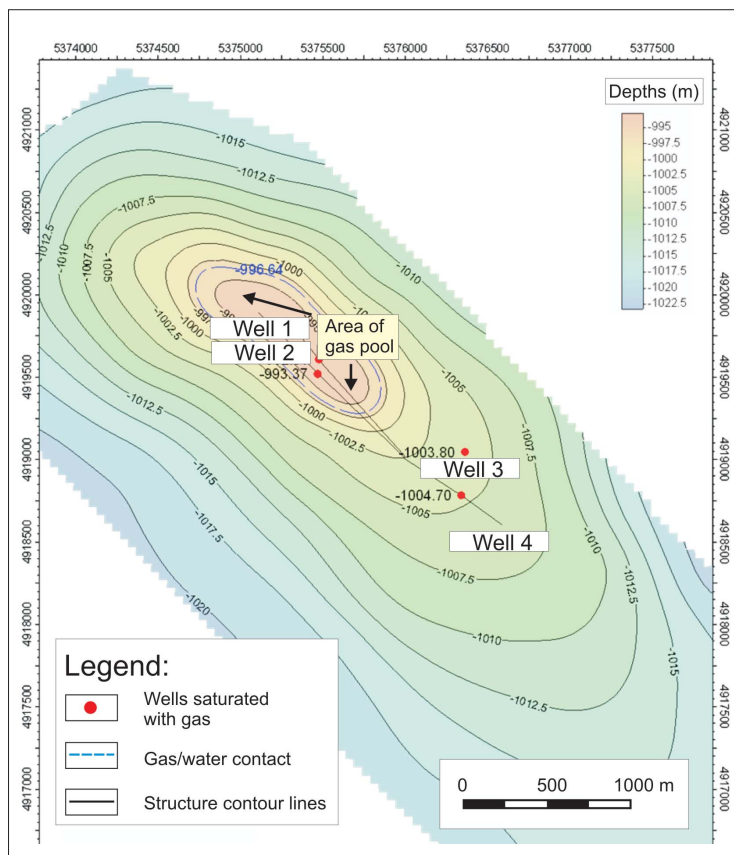


Fig. 3.1. One typical Pleistocene anticline with gas pool in the Northern Adriatic

Sl. 3.1. Tipična pleistocenska antiklinala s ležištem plina u Sjevernom Jadranu

ward deeper, impermeable or poorly permeable parts, defining such also stratigraphic traps. The main trapping mechanism had been differential compaction thanks to the large quantities of hemipelagic sediments (marls, clayey marls, and marly clays) which were periodically interrupted by depositions of sands and silts in Po prodelta. These turbiditic sequences (Tc-e) had the lower rate of compaction than completely pelitic sediments (Tf). Therefore, series of sands and silts after compaction remained as structurally shallower (uplifted) parts, forming anticlines as endpoints for gas migration. This mechanism was also supported with regular folding as results of continuous Quaternary compression in Northern Adriatic area and stress directed from SW to SE. In addition, the oldest Pleistocene reservoirs had been influenced by Mesozoic basement shapes, i.e. with "buried hills".

4. FIELDS DEVELOPMENT AND WELL COMPLETION

The main characteristics of the Northern Adriatic gas fields are set of turbiditic facies that are reservoirs with very low or not at all compaction. It means that primary (inter-granular porosity) in reservoirs range in high values, i.e. between 22-37% and accompanying permeability between 100 and 1,500 mD ($100-1,500 \times 10^{-15} \text{ m}^2$). However, absence of compaction led to very complex production conditions due to sand and sandy silt flows toward wellbore as results of production, decreasing or reservoir pressure and moving of solid particles (detritus) together with reservoir's fluid flow.

Average reservoir lithofacies consist of about 50% of sand and about 40% of silt, with water saturation between 20-50%. The drilling of such high permeable producing zones should be performed creating the lowest possible formation damage. Therefore, a water based mud had been used to form effective filter cake in order to control and stop fluid loss. Oppositely, testing of oil based mud creates a strong filtrate invasion, which the perforation with gravel pack could not cross. In such cases FracPack technique is considered as the best option for the optimized production. This technique means that a small fracture is created behind casing and the gravel is injected into fracture, also bypassing possible formation damage that could be present around the wellbore. But it could be used only in parts of pools distant from gas/water contact or in the case of pool completely saturated with gas. In other situations, i.e. perforation located close to fluid contact, there is a very high possibility that fracture would connect the well bore and water saturated part of reservoir. In any case, gravel was injected into the perforations in order to support good perforation packing and bypass infiltrated zone. However, the problem with unconsolidated reservoirs is in flow of detritus particles that is accompanied with gas production. Reservoir sand or silt can plug the screen very quickly leading to very high skin. Reservoir detritus can also erode the screen including sand or silt produced, together with gas, at the surface. Technique of gravel packing played the role for stabilizing sand and silt in the Northern Adriatic reservoirs.

It is important to point out that any damaging material, like gravel, injected into reservoir (in this case mostly sand) can reduce the well productivity. Another fine-grained or mud material could also decrease the gravel filter permeability, causing similar reduction of production rate or period. It asked for permanent reaching the maximal cleanliness of perforation and bed using appropriate tubular, tanks, lines and other. Acid pickling of the work string (except of plastic coated) and casing was recommended as cleaning techniques in the described reservoirs. Drilling fluid was continuously projected with goal of minimum invasion in the reservoir pore space.

All mentioned general problems and techniques related to well completion showed that production from unconsolidated Pleistocene reservoirs was not an easy task, especially if the goal was a long-term production with stable rate of gas. It was engineering demanding job including the planning of perforation, fracturing, drilling fluids and maintenance of borehole cleanliness.

5. CONCLUSIONS

The Croatian gas fields located in the SE part of the Po Depression are very important source of hydrocarbons and represent a significant part of the Croatian hydrocarbon gas recoverable reserves. The predictions show that production from these fields will last for the next 20 years. New large discoveries, like the Ivana Field, cannot be expected. However, there are still significant reserves in smaller satellite fields (like Ana and Vesna Fields) or in thin sandy silt layers (< 1 m) which can produce with the advanced technology.

Well completion, regarding the thickness of reservoir, location of gas/water contact and saturation, showed the production can be the easiest maintain using gravel packing or FracPack techniques. That was a demanding task with selection of drilling fluid and continuing cleaning of borehole. The next one was projecting well direction, especially for horizontal wells.

INAgip is Croatian-Italian operative joint-venture company in the Northern Adriatic, responsible for three exploration fields (concession fields) where all Croatian gas fields in the Po Depression are located. This company will put much effort, in order to:

- a) To keep the present production rate and continue the new explorations and developments;
- b) Discover new reserves in previously unexplored reservoirs or transform some of the unrecoverable into recoverable reserves.

Gas fields discovered and developed in the Croatian part of the Po Depression, i.e. in the area of the Northern Adriatic, represent the example of successful development and production from geologically very young reservoirs. These Pleistocene sediments are very demanding production target, mostly because they are unconsolidated and sometimes very thin (less than 1 meter). The first fact causes "reservoir detritus flow" toward borehole during production and solving of this sediment property was demanding task in well's completion.

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