

Croatian Pannonian Basin licence round hydrocarbon potential assessment

Karyna Rodriguez^{1*}, Neil Hodgson¹ and Howard Nicholls¹ discuss an enhanced dataset revealing deeper potential within a proven Badenian hydrocarbon system, as well as in untested tight reservoirs and fractured basement.

Introduction

With a proven hydrocarbon system, numerous discoveries and up to 59 oil, gas and condensate fields, the Pannonian basin is one of the most important hydrocarbon provinces in central Europe. Covering an area of 26,000 km, it has one of the deepest sedimentary sections and since the 1940s has produced more than 700 MMBO of oil and more than 400 MMBOE of natural gas.

The region has a long history of hydrocarbon exploration, with the first well drilled in 1855. More recently, the basin has suffered firstly from a decline in production which peaked in the early 1980s and secondly from much reduced exploration activity over the last 20 years. However, recent changes in Croatian national law are breathing new life into the basin with exploration drilling activity close to starting again as a result of the success of the 2014 First Onshore Licence Round, and now by holding the Second Onshore Licence round. This second round was opened on 7 November 2018, with seven exploration blocks being offered over the Drava, Sava and Mura Depressions and the more frontier Hrvatsko Zagorje Sub-depression (Figure 1), making it again possible for international

oil companies to explore in this proven basin with existing infrastructure and in close proximity to ever increasing energy markets.

Significant undiscovered reserves in stratigraphic/structural plays have been identified with 12,100 km of regional 2D seismic data acquired during the 1970s through to the 1990s, but, more importantly, reprocessed in 2014 through a Pre-STM sequence (Figure 1). This reprocessing project has provided a contiguous dataset, time and phase matched to a single datum and significant imaging uplift. This data is complemented by conditioned well logs, with reports translated into English, for 53 key exploration wells as well as reprocessed VSP data where available.

An evaluation carried out using the enhanced dataset has revealed deeper potential within a proven Badenian hydrocarbon system, as well as in untested tight reservoirs and fractured basement. Additional exploration opportunities have also been found in the under-explored regions on the basin margins of the Sava and Drava basins and large untested structures have been observed in the South West Sava and Hrvatsko Zagorje Basins.

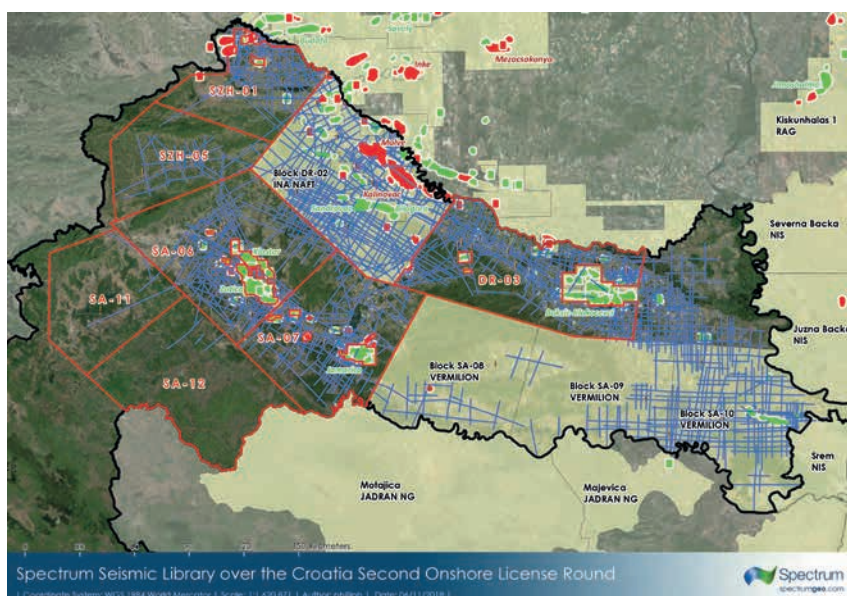


Figure 1 Spectrum Seismic Library over the Croatia Second Onshore Licence Round.

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Pannonian evolution

The structure of the Croatian area of the Pannonian is dominated by Paleozoic-Mesozoic sedimentary successions deposited on an older Palaeozoic-Precambrian metamorphic and igneous basement, subjected to sub-aerial erosion during the Maastrichtian-Palaeocene period. Subsequent deformation has taken place as Alpine orogenic uplift and thermal subsidence led to partial collapse which formed the interior depressions.

This was followed by continued subsidence through the Pleistocene Middle Miocene, with strike slip faulting leading rifts and reactivation of earlier compressional faults. Basin fill can exceed 6000 m and is comprised of mixed clastics and minor carbonates.

Most of the basin was initially starved with syn-rift Lower Miocene conglomerates forming. The region was subsequently filled by two major Upper Miocene deltaic systems prograding from the west, north and southeast, draining the Carpathian Mountains that fringed the basin. Combined thickness of the Paleozoic-Recent series can exceed more than 10,000 m. Thickness of the Neogene succession alone reaches up to 7000 m.

Hydrocarbon geology

The Croatian region of the Pannonian is roughly divided into 5 sub basins; Sava, Drava, Slavonija, Mura and Hrvatsko Zagorje. With the Drava, Sava, Mura and Hrvatsko Zagorje basins covered in the current licence round.

In the Pannonian Basin there are three main actively producing plays including the Miocene-Pliocene clastic/carbonate series, Miocene extension-related tilted fault blocks containing various reservoirs and inversion-related anticlines with various Miocene-Pliocene clastic reservoirs.

Pannonian Basin petroleum system elements

The main source rocks are Badenian mudstones, kerogen type III with dry, wet and gas condensate production and deltaic

sequences of the Pannonian, type II and III kerogen with upper gas prone lower oil prone sequences and TOC average 1–2 wt.% (up to 5 wt.%). The main reservoirs include basal Miocene conglomerates, Badenian turbidite sands, Lower Pannonian turbiditic sand lobes and Pannonian/Pontian deltaic sands. Seals are widespread and composed of fine-grained clastics, including intra-formational mudstones, generally of pro-delta and delta-top origin. In the majority of the fields, the argillaceous interval above the reservoir usually forms the sealing horizon and may even be the source rock for the next reservoir. One of the most prolific seals is the late Eocene Flysch, which can be up to 3000-m thick. The Neogene series is considered as top seal to all older reservoirs, formed mainly of silts and muds.

Major traps are generally structural, stratigraphic or combinations. Many are associated with basement highs and with positive flower structures along strike-slip faults. Minor traps are related to pinchouts, syn-depositional features, unconformities, palaeotopographic highs and internal structural traps.

There are also several underexplored plays including fractured and/or weathered basement, syn-rift-related, Miocene sandstone series truncated and sealed by post-rift mudstones and Lower Miocene unconventional reservoirs i.e. oil in limey marls/gas within tight sands.

Drava basin prospectivity

The Drava Depression, the largest and deepest in the region with a sedimentary section approaching 7000 m, covers the northern licence area. Miocene post rift sediments are actively producing with Upper Pannonian and Pontian represented with well-developed turbiditic reservoir sandstones.

Additional potential for discovery exists in three main underexplored but proven plays including buried hill structures generally composed of fractured basement rocks and carbonates; stratigraphic and structural stratigraphic traps with coarse clastic deposits of the Lower and Middle Miocene, gen-

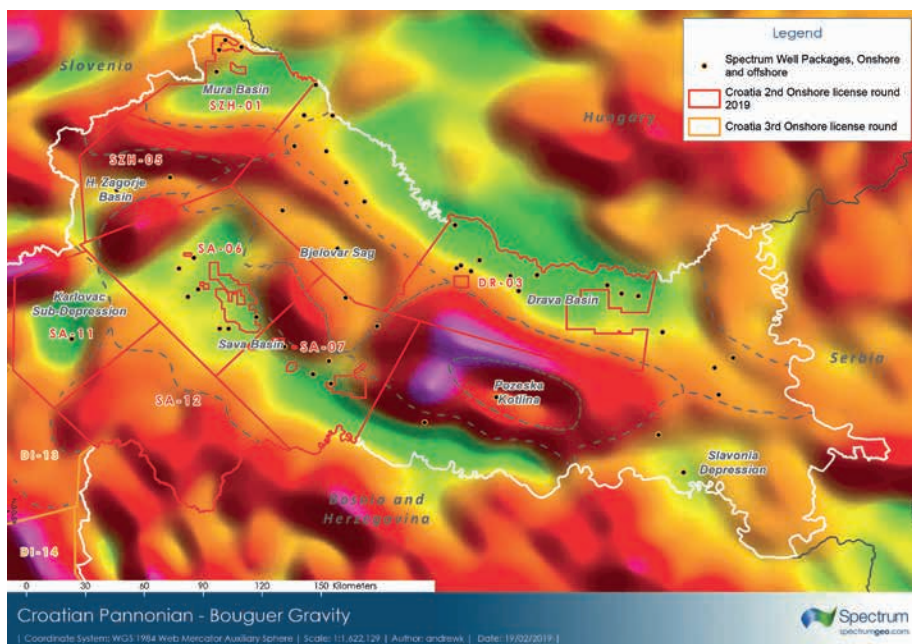


Figure 2 Bouguer Gravity Map with major sub-basins in the Pannonian Basin.

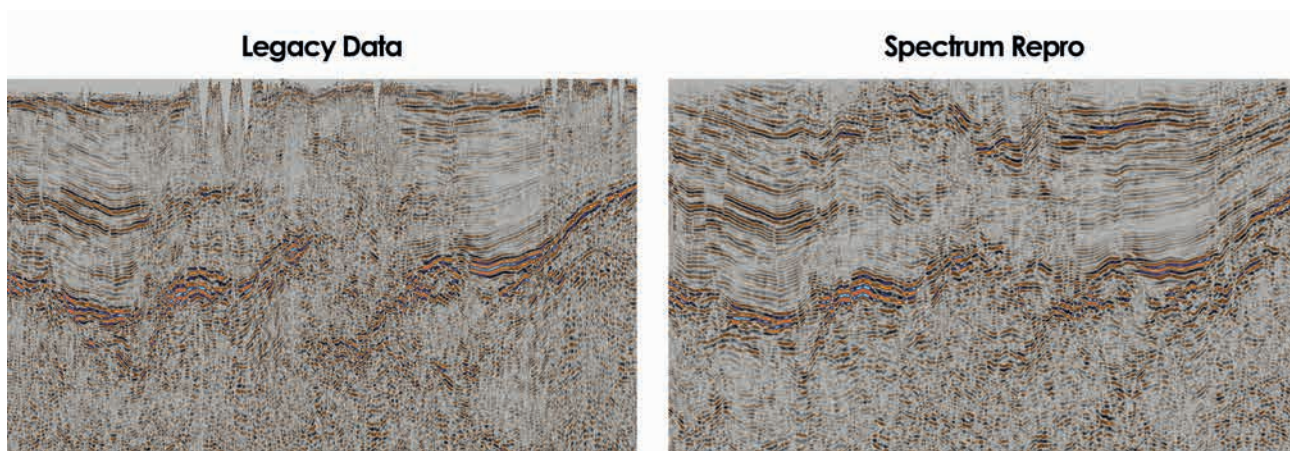


Figure 3 Legacy data compared to Spectrum 2014 reprocessed data showing significant imaging improvement.

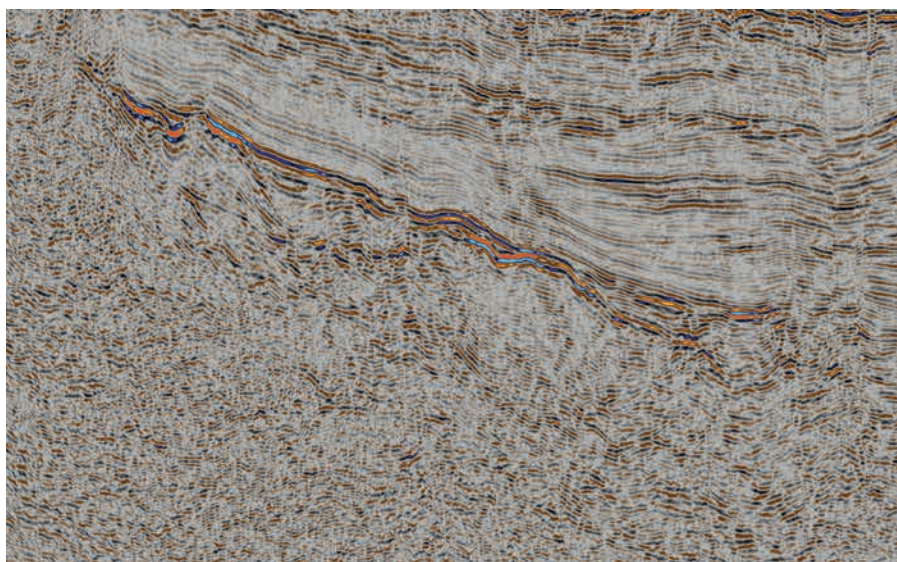


Figure 4 2014 Reprocessed seismic data showing an amplitude-supported stratigraphic trap which can be mapped over a relatively very large area in the Sava Basin.

erally alluvial plain, braided river and shore facies deposits and stratigraphic traps caused by pinch out of the Upper Miocene and Upper Pannonian turbidite sandstones, generally towards the edges of the basin and basin uplifts. Imaging uplift obtained from reprocessed seismic data (Figure 3) provides an essential tool in identifying this additional potential.

Several leads have been mapped based on interpretation of the reprocessed seismic dataset, which has been calibrated with well information in the basin. These include undrilled structural highs located along a north-east to south-west trending structural ridge; tilted basement highs on faulted terraces with Pannonian onlap and thickening of a sub cropping package, interpreted as Badenian limestone/Mosti Member conglomerates and a large sub thrust play which is imaged only on the reprocessed dataset.

Sava basin prospectivity

The Sava Basin covers the south eastern area of the round and has a well proven hydrocarbon system. There are thick synrift packages of Badenian marls with excellent oil prone source rock characteristics, TOC values between 0.5-2% and reaching the oil window from the Pliocene at a depth of 2200 m.

Multiple high-quality reservoir intervals are present in the post-rift Miocene sediments of Pannonian and Pontian age,

generally turbidite sandstones, delta front, lobes and channel fill deposits generally between 30 and 80 m thick. Primary porosity ranges from 13 to 30%, with a permeability of 0.004-0.180 μm^2 . Seal is provided by interbedded massive marls that are common in the Pontian-Pannonian section.

Remaining potential has been identified in Lower Miocene turbidite deposits, basal conglomeratic limestones of the Lower Miocene, deep Mesozoic fractured basement plays, new plays in the under-explored SW of the basin and potential stratigraphic traps on the southern basinal margin.

A large stratigraphic closure has been mapped throughout the Poljana sandstone over the southern margin of the Sava basin (Figure 4). This is undrilled and poorly mapped by the historic seismic data. Some evidence of altitudinal brightening is evident on the seismic data around this lead. Each embayment may be up to 200 km^2 .

Mura Basin prospectivity

This basin contains shallow discoveries which were among the first discovered and commercialized in Croatia. Pannonian turbidite sandstones are productive for oil and gas.

Remaining potential has been observed in multiple deeper underexplored plays including continuous resource plays, structural and stratigraphic traps with sand and Middle Miocene coarse

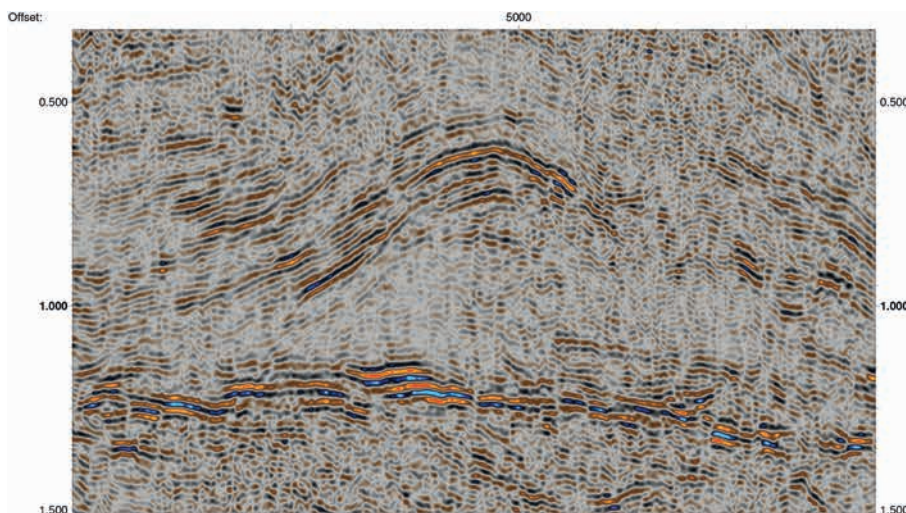


Figure 5 Untested detachment structure imaged and mapped with the 2014 reprocessed seismic data.

clastics and a Mesozoic Carbonate uplift play tested in Strmec Podravski and Vuckovec on the basin's western flank proved positive.

Leads mapped with the reprocessed seismic dataset include an untested detachment structure (Figure 5) within Pontian-Poljana Sands, with a potential analogue in producing structures to the north in the Drava basin.

There are also a series of undrilled high amplitude events in the Mursaka Sobota Fm with down dip proven gas.

Hrvatsko Zagorje Basin prospectivity

One of the most frontier regions in Croatia located a few km north of Zagreb, which has been penetrated by only three exploration wells, has 500 km of legacy 2D seismic data and has no current production.

Additional hydrocarbon potential is demonstrated by a thick source rock interval with type I, II kerogen and sapropelic components, implying it is a valid oil prone source rock, encountered in well HZ-1. Additionally, Middle Miocene sediments showed undrilled potential with two identified leads that are poorly constrained by the legacy data.

Impressive seismic imaging uplift obtained in this area (Figure 6) has allowed identification of multiple prospects within Lower and Upper Cretaceous limestones and fractured sub volcanic units that can be up to 500-m thick

and Middle Miocene sediments which show undrilled potential with an unusually high amplitude package at around 1500 m.

Additional potential

Many plays that are yet to be fully evaluated include deep/tight structures and unconventional plays. Tight overpressure sands have been formed by 'delta front' progradation towards the south-east. The main zone of interest is at around 3500-4500 m with 130 m of proven source rock, HPHT reservoir conditions (tested formation pressure — 786 bar at 4178.5 m, gp=1.88 bar/10 m and formation temperature: 1840°C at 4200 m). Expected reservoir characteristics include a dual porosity system with porosity ranging between 3.2% (matrix) and 19% associated with fractures and average permeability $k=0.12\text{mD}$ (fracture), 0.014 mD (matrix). Expected geomechanical parameters include Poisson's ratio of 0.333 and Young modulus of $3.54 \times 10^7 \text{ kN/m}^2$.

For tight Gas Sandstone and gas shale the zone of interest is between 3400 and 3971 m with > 400 m of proven source rock, HPHT reservoir conditions (tested formation pressure — 562 bar at 3414 m, gp=1.66 bar/10 m and formation temperature: 1870°C at 3504 m). Expected reservoir characteristics include a dual porosity system with porosity ranging between 3.2% (matrix) and 19% associated

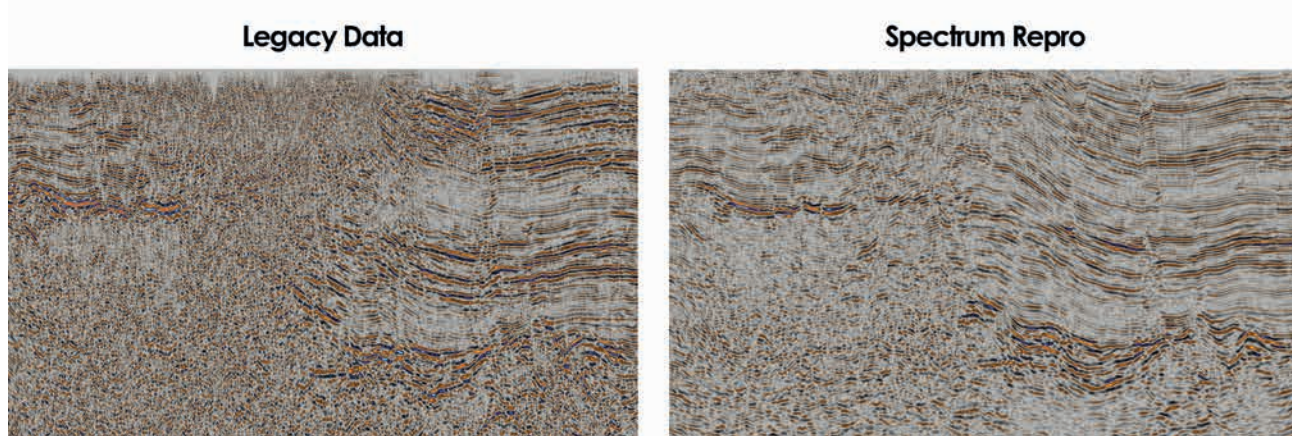


Figure 6 Impressive imaging uplift obtained in the reprocessed dataset is illustrated by the image on the right.

with fractures and average permeability: $kh=0.0017\text{mDm}$; $k=0.00017\text{ mD}$. Expected geomechanical parameters include Poisson's ratio of 0.255 and Young modulus of $3.88 \times 107\text{ kN/m}^2$.

A pilot unconventional well drilled in the Drava basin testing a tight gas sandstone proved economic (INA 2010). This was generated by 'Deltafront' progradation towards the south-east (9.6-5 my) with a huge amount of material accommodated in the available basin space and overpressure generated in the lower part of the sediments. The delta sands reservoir is believed to be perfect for stimulation. Minor shale gas potential was also encountered in Badenian mudstones.

Conclusion

Historic exploration in the Croatian Pannonian has almost exclusively been focused on the drilling of structural traps within the main Pannonian and Pontian sections of the Miocene post rift, with little exploration in stratigraphic traps that are frequently observed on the reprocessed seismic data. More recent exploration has focused on the lower Miocene coarse clastic plays and the buried hill structures of the poorly explored Mesozoic plays, but these are still very much under-explored, poorly mapped and not fully understood.

Modern exploration into these deeper and often poorly defined play types has been hindered by the quality of the legacy seismic data that has covered the basin. With seismic acquisition and data processing techniques and capabilities having been developed significantly since, Spectrum has reprocessed 12,000 km of data using a modern processing suite, which has seen the seismic data greatly uplifted, revealing the potential in deep structures with improved continuity, frequency and amplitude content. This has also encompassed a standard static elevation model that allows surveys from a variety of different vintages to tie seamlessly allowing full and comprehensive interpretation of the data set that is complemented by a reconditioned and translated key well data set covering the region.

An enhanced dataset has provided an essential evaluation tool leading to the identification of significant untapped hydrocarbon potential in the Pannonian Basin. This is a unique exploration opportunity in a basin with long-established production, a privileged location in Central Europe and a continuing licence round.



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