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New Potential in a Mature Petroleum Basin - Pannonian Basin of Northern Croatia

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Introduction

The Pannonian Basin of Northern Croatia is regarded as a mature petroleum province with a long exploration and production history extending back to the late 19th Century, with more than 1.2 billion BOE discovered to date (Velic *et al.*, 2012). However, most of the oil and gas was discovered by INA and its precursors, prior to the availability of modern exploration methodologies, and our analysis, presented here, suggest that the basins provide significant opportunities for new discoveries and re-appraisal, an opportunity encouraged by onshore licencing rounds in 2014 and 2018.

We present an integrated analysis of field outcrop, subsurface data and a wealth of public domain information that have been leveraged using play fairway-based techniques to evaluate not only the remaining conventional potential across the basin, but also the potential in tight sands and continuous resource plays. We also show how the integrated techniques can be utilised in other basins around the world to rapidly identify sweet-spots and high-grade areas for future exploration.

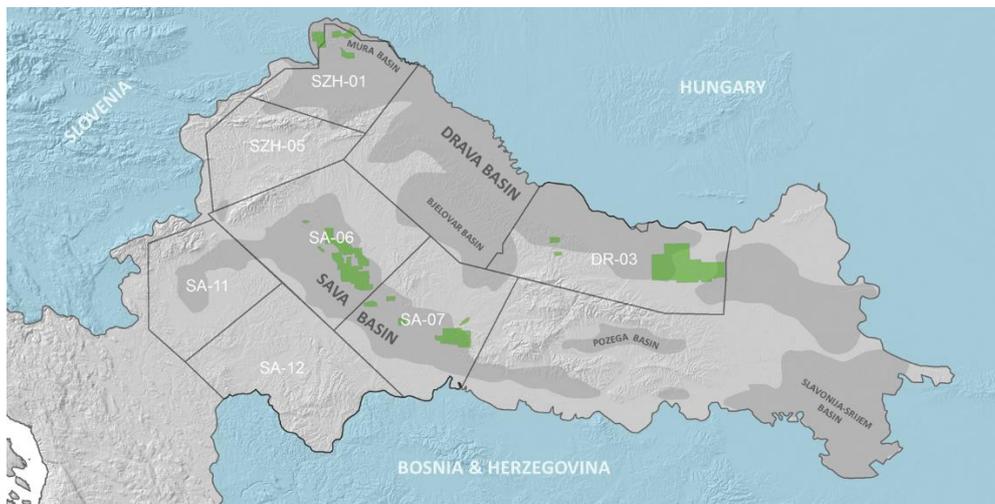


Figure 1 Map of northern Croatia showing the locations of major basins across the region (SRTM data were obtained from <https://earthexplorer.usgs.gov> and are a product of NASA)

History of Exploration in the Pannonian Basin of Northern Croatia

The history of exploration in northern Croatia can be traced back to the first oil wells drilled in 1880 and the first production in Rijeka in 1882 (Cota *et al.*, 2014). Today, the Drava and Sava Basins (and to a lesser extent the Mura and Slavonija-Srijem Basins) are mature producing provinces, with more than 1.2 billion BOE reserves discovered to date in conventional plays. However, most of these reserves were discovered in a few large fields (more than 70% of these reserves contained within 12 fields) and prior to the availability of modern exploration methodologies and techniques.

Geological Setting and Petroleum Systems of the Neogene Pannonian Basin

The Sava, Drava, Mura, Bjeilovar, Pozega & Slavonija-Srijem basins of northern Croatia represent the south-eastern extension of the Neogene Pannonian Basin of Central Europe, comprising of a series of WNW-ESE trending Miocene extensional basins, modified by Pliocene inversion tectonics. The Drava and Sava Basins are major basins today (<7km and <5km deep respectively), but, pre-inversion, the now minor Bjeilovar-Pozega and Karlovac-Glina sub-basin systems are likely to have been more significant basin trends. To the north are located the Miocene Mura-Zala Basins (which extend into Slovenia and Hungary), and associated minor Hrvatsko-Zagorje Basin, which are separated from the Sava and Drava Basins by the Mid-Hungarian Line, a major SW-NE trending Neogene sinistral strike-slip feature that partitions the entire Pannonian Basin.

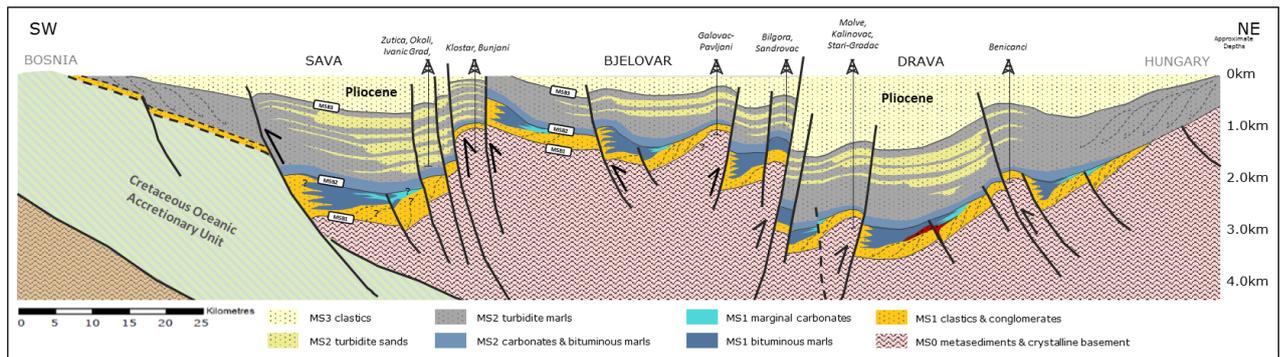


Figure 2 Schematic cross-section across the Sava, Bjelovar and Drava Basins of northern Croatia (Safic et al., 2003)

The pre-Miocene ‘basement’ predominantly comprises of Palaeozoic and Mesozoic sediments, meta-sediments and igneous bodies, and includes significant reservoirs in the Southern Pannonian Basin. Many of the prolific Lower - Middle Miocene reservoirs comprise coarse clastics and conglomerates derived directly from the local underlying ‘basement’ and the properties of these reservoirs are therefore partly a function of local ‘basement’ type.

Eight conventional plays have been proven in the basin to date, including pre- Neogene fractured basement plays, Lower to Middle Miocene syn-rift clastic and carbonate plays, and Upper Miocene sandstones plays of the Pannonian and Pontian post-rift sequences. There is a striking difference between the distribution of reserves across the basins, with most proven reserves in the Drava Basin within syn-rift (Lower & Middle Miocene) and pre-rift (Mesozoic or Palaeozoic) reservoirs, where-as production from the Sava Basin is predominantly from post-rift (Upper Miocene) reservoirs.

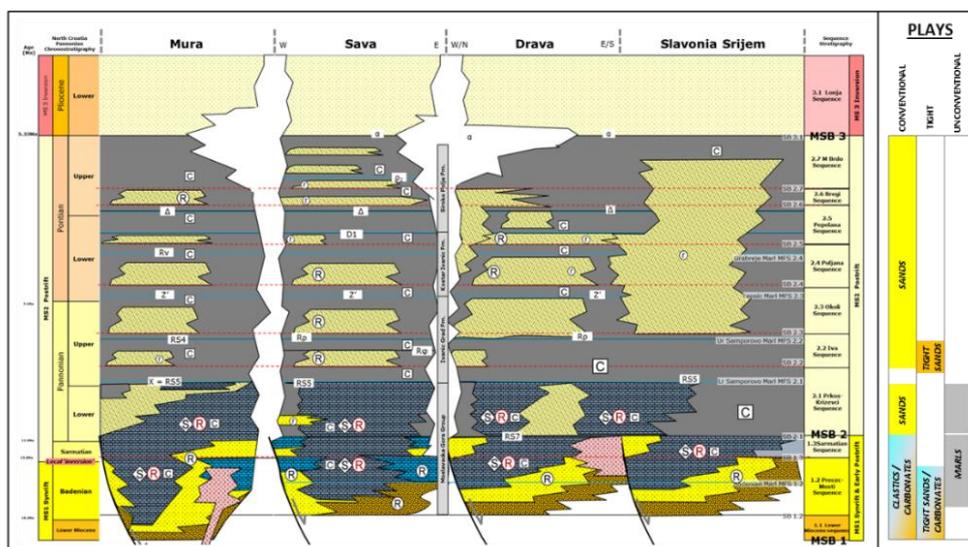


Figure 3 Schematic inter-basin sequence stratigraphic correlation for the basins of North Croatia

To date, almost all exploration across the area has focused on conventional reservoir targets trapped in structural traps (generated during Pliocene inversion), charged by organic rich marls which are present throughout the syn-rift and post-rift Miocene succession (Dolton, 2006).

Integrated Play Fairway Based Methodology

Subsurface data in Croatia is almost exclusively owned and held by the state-owned company and is typically challenging to access and therefore a critical part of the evaluation was data collation, with information gathered from a wide variety of sources. In total, the data gathered included more than 300

published papers and PhD theses that contained large amounts of maps and otherwise unavailable sub-surface data.

Following the interrogation of all available data, new structural and sequence stratigraphic frameworks were developed, to enable plays to be assessed using a play fairway approach and identify the most prospective areas for each play. The presence and effectiveness of each play element: reservoirs, charge and seals were evaluated and mapped using Common Risk Segment ('CRS') mapping techniques. The resulting CRS maps for each play element have been combined/stacked within a GIS database, to generate summary play fairway maps for use in the overall high-grading process.

Generative potential of source rocks in the study area were calculated from geochemical characteristics of the source-prone intervals, with the total volumes of hydrocarbons calculated 'reality-checked' against the volumes of discovered conventional hydrocarbons in northern Croatia (as a real-world check of the estimated source rock quality/thickness).

These results were integrated into a play and area ranking, which takes into account geological parameters and exploration risk factors, as well as specific local factors that may affect Capex/Opex (e.g. national parks, contaminants, landmines). Each play has a different volumetric potential (i.e. more hydrocarbons are capable of being present in one play versus another play) and therefore the estimated total volumetric potential of each play has been applied into the ranking through the application of a play volumetric weighting factor.

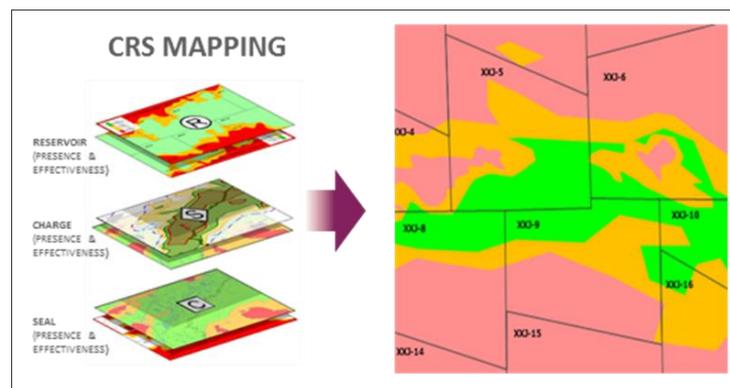


Figure 3 Common risk segment (CRS) mapping methodology utilised to high-grade sweet-spots and rank areas within conventional play fairways identified across the basins. A modified version of this methodology was utilised to evaluate continuous resource plays across the basin.

New Exploration Concepts & Sweet-spots

The new analysis has resulted in an improved understanding of the structure, sequence stratigraphy and distribution of play elements across the basins. The work has also led to the development of several new exploration concepts, including new models which better explain the distribution of hydrocarbons across the basin. The new model infers that expulsion from Miocene source rocks is mainly controlled by the pressure gradient between overpressured mature organic-rich marls and stratigraphically adjacent porous facies (at hydrostatic pressure). In the eastern Drava Basin, the Iva Sandstone is largely absent and is replaced by a thick sealing interval ('Samporovo Marls'), which a higher downward potential gradient, and thus a higher likelihood of downward/down-stratigraphy provides a thick seal over the source rocks and therefore expulsion into coeval or older carrier beds. In contrast, in the Sava Basin the Iva Sandstone is typically present above the source prone interval and thus upward and downward pressure gradients away from the source rocks are likely broadly equal, with expulsion into younger and older carrier beds. Migration then occurred up-dip through cross-sand amalgamation erosion surfaces (where inter-formational seals are absent) and along faults.

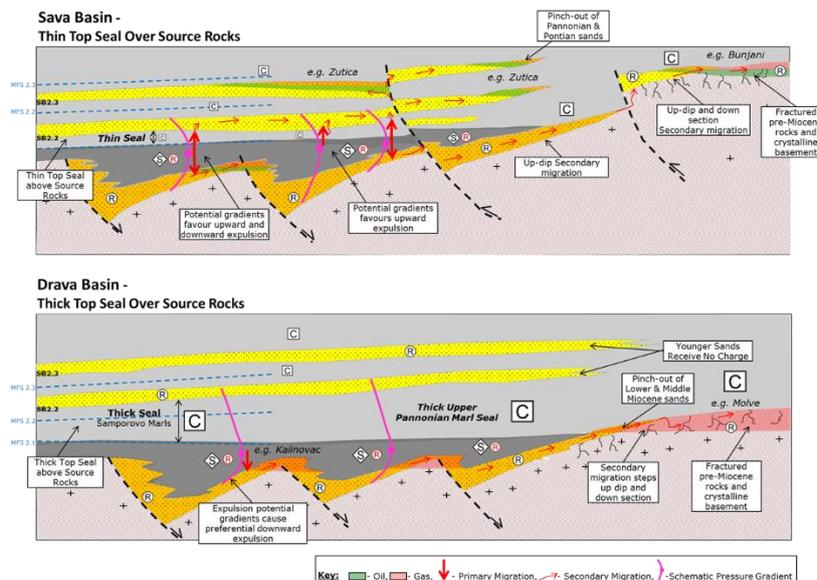


Figure 5 schematic new model for charge access and migration pathways across the Sava and Drava Basins

The play fairway analysis and ranking approach has led to the identification of multiple potential sweet-spots in conventional play fairways outside existing producing fields. Three potential tight sandstone plays and five continuous resource shale plays, which have not previously been explored for in the basin, have also been identified and these plays could be evaluated and explored for in conjunction with proven conventional plays.

Conclusions

The application of an integrated play fairway methodology has enabled the identification of new conventional and continuous resource plays, highlighted potential unexplored sweet spots outside existing producing areas and generated new insights into the controls on the distribution of play elements across the basins of northern Croatia. We believe the approach used provides a key exploration tool, which can be used not only to rapidly evaluate and high-grade new exploration sweet-spots in mature basins, but also to effectively assess more frontier exploration areas (e.g. the Dinarides to the west of the study area) where data is less extensive.

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