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Exploring the potential of deep targets in the South Adriatic Sea: insight from 2D basin modeling of the Croatian offshore

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ABSTRACT

The Croatian offshore hydrocarbon province is highly under-explored. From a total number of 128 exploration wells, 96 were drilled in the Northern Adriatic Sea, 27 in the Central Adriatic Sea and only 5 in the Southern Adriatic Sea. Most of exploration wells were drilled to test the Pliocene shallow sandstone biogenic gas play, which has been in production since the end of the twentieth century. However, the deep Mesozoic oil plays are still heavily under-explored. By interpreting regional studies, offshore well datasets and 2D seismic lines acquired by Spectrum in 2013, this study identified two new interesting explorative plays: Structural Karst play (Triassic/Jurassic); Slope Calciturbidites play (Cretaceous/Eocene). 2D petroleum system modeling was performed along a representative interpreted seismic section to define the potential and the exploration risk of the two plays. The results show that all the critical elements for a working petroleum system are present for both plays. Several fluid-saturated traps are present in the Cretaceous and Jurassic reservoirs with an indicative total depth between 3500 and 5500 m and in water depth from 500 to 1200 m. For the Structural Karst play the main uncertainties are related to the quality and efficiency of the reservoir, while for the Slope Calciturbidites play the main uncertainty is related to the sealing efficiency.

Keywords: Croatian offshore, deep target southern Adriatic Sea, petroleum system modeling, Mesozoic Carbonatic traps

1. INTRODUCTION

Hydrocarbon exploration in the Croatian offshore started with the Jadran-1 well, drilled in 1970. The first success came three years later when the Ivana gas field was discovered by the Jadran-6 well. This initial discovery was in the Pliocene shallow clastic biogenic gas play in the northern Adriatic Sea and was followed by the discovery of additional gas fields that are still in production. The hunt for oil in the central and southern Adriatic-Ionian basin, began later. The focus was the Eocene and late Cretaceous carbonate platform potential oil plays in the shelf area (BEJDIC, 2012), but a few wells encountered oil shows (e.g. Melita-1, Vlasta-1). As a consequence this area remained under-explored. In contrast, the Rovesti and Giove wells in the Italian Apulian platform margin led to interesting oil discoveries (Fig. 1). This exploration success was followed by the acquisition of a good quality seismic dataset. On the Croatian side, high quality seismic data was only obtained in 2013, when Spectrum acquired 14,700 km of long streamer 2D seismic lines (yellow lines in Fig. 1). This seismic dataset provided the opportunity to reconstruct a geological cross-section along the south Croatian offshore and to interpret potential Triassic and Jurassic source rock systems as well as multiple carbonate platforms where it is possible to distinguish changes in seismic facies and thickness from the Triassic to the Cretaceous (Fig. 2).

The aim of this study is to evaluate the efficiency of the thermogenic petroleum systems for the two newly identified and under-explored plays in the southern Croatian offshore (Fig. 2).

The Structural Karst Play (Triassic/Jurassic), formed by antiform traps in the carbonate karst of the Adriatic Carbon-

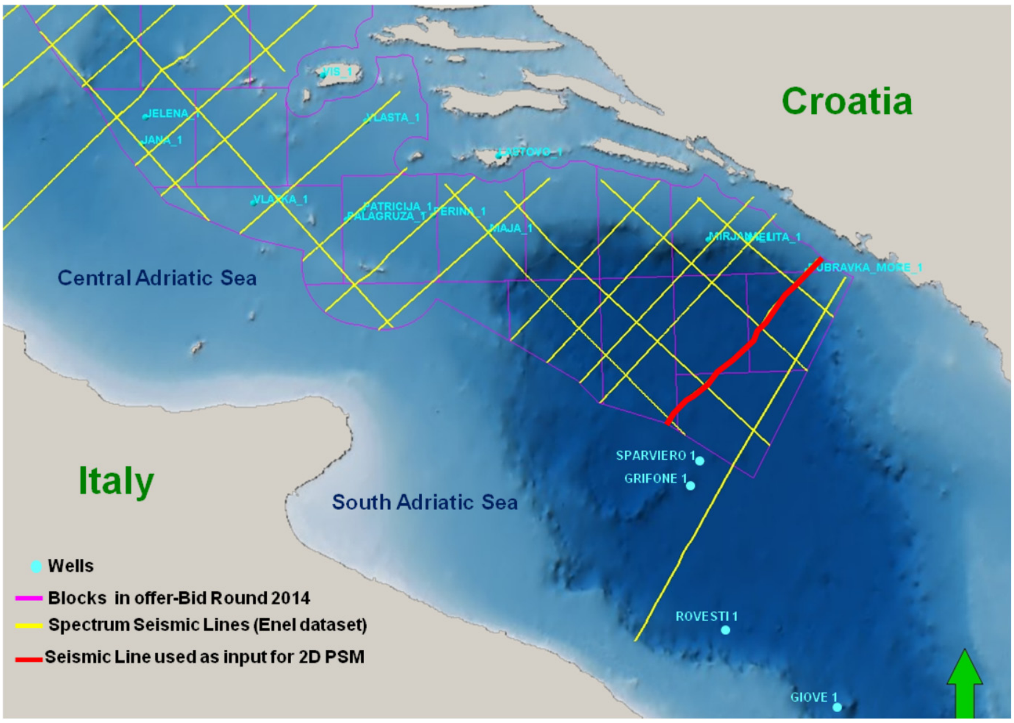

Figure 1: Location map and available data set.

ate Platform (AdCP) (VLAHOVIC et al., 2005), was created as paleo-highs from the Triassic to the Lower Jurassic and moved during the Tertiary due to transpression. The traps could be charged by hydrocarbons from Upper Triassic source rocks and sealed by deposits from the Lower Jurassic and Middle Cretaceous (Fucoidi Fm.); the Slope Calciturbidites Play consists of stratigraphic traps formed as a series of carbonate fans extended basinward and related to partial disintegration of the Upper Mesozoic AdCP during the end of the Cretaceous-Eocene period (VLAHOVIC et al., 2005). The traps could be charged by Upper Triassic and Lower Jurassic source rocks and sealed by Tertiary deposits.

2. GEOLOGICAL SETTING OF THE CROATIAN ADRIATIC OFFSHORE

The regional geology and tectonic history of the Croatian Adriatic basin is well described in the literature (CASERO et al., 2012; GRANDIC et al., 2013; SHINER et al., 2013). The Adriatic basin developed on the ‘Adria microplate’, on the stable western margin of Gondwana’s Neo-Tethys, which began to rift and subside in the Permo-Triassic. The Permian to Anisian sequences show siliciclastic beds or limestones and dolomites, interbedded by salt and gypsum deposits. The Permian is correlated to wells and outcrops of onshore Croatia (GRANDIC et al., 2004). In the Carnian-Norian period, the main lithofacies in the Periadriatic region were the Dolomia Principale/Burano formations from the extensive tidal zone to the evaporitic platform. The Burano evaporites (mainly salt and anhydrite) are present in the central and southern sectors of the Adriatic Sea (MATTAVELLI et al., 1991). The end of the Triassic and the Lower Jurassic is characterized by deposition of bituminous limestone interbedded with dolomite formations in syn-rift grabens. In the Middle Liassic, the main Tethyan rifting phase caused the break-up of the previously continuous carbonate platform (VLAHOVIC et al., 2005). As a consequence, two main pelagic domains were generated, the Umbria-Marche and South Adriatic Basins with limestone to siliciclastic sequences deposited from the Middle Jurassic until the Paleogene (CATI et al., 1987). Two different carbonate platforms remained separated: the Dalmatian-Adriatic to the east-northeast and the Apulian to the southwest. Southwest verging Dinaric compression and thrusting, similar to that affecting the Ionian basin to the south, affected the Dalmatian-Adriatic platform, developing a foredeep in the Late Eocene and Oligo-Miocene times. In a similar way, the east-vergent Apulian thrusting formed a foredeep during the Plio-Pleistocene (WRIGLEY et al., 2014). Successive deltaic sequences commenced in the Paleocene until the present day, prograding from the Po valley of Italy and the Neretva River of Croatia, with little localized sediment supply from demolition of the Dinaric thrust belt. The only exception is the evaporitic deposition during the Messinian. The effect of the Messinian salinity crisis was the generation of a clear and easily recognizable unconformity separating the Oligo-Miocene from the Plio-Pleistocene sequence.

This geological evolution favoured the development of a platform carbonate succession alternating with basin deposits, constituting the elements for efficient deep petroleum systems (Fig. 3). Bituminous limestone rocks deposited in the Upper Triassic and Early Jurassic syn-rift grabens can have high source rock potential as indicated and supported by Italian analogs.

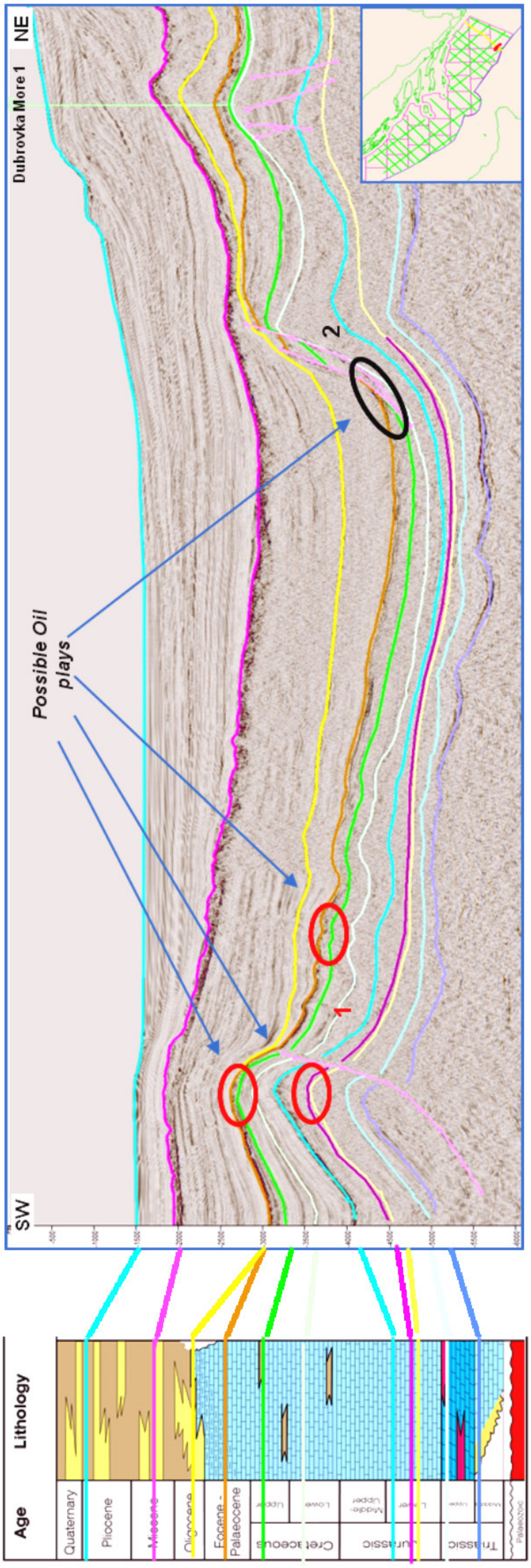

Figure 2: 2D representative interpreted seismic section considered in the present study.

The stratigraphic column representing the study area and its petroleum system elements was reconstructed from the regional geological setting, the interpretation of Croatian wells implemented with Italian well information and the interpretation of new seismic data acquired by Spectrum (Fig. 3).

The identification of Triassic evaporites has a big impact on the Mesozoic petroleum system. Within the Adriatic margin the evaporitic deposits are predominantly anhydritic to the west and a mix of anhydrite and halite to the east (GRANDIC et al., 1997). These evaporitic sequences often represent the detachment surface of major thrusts, emphasizing the "structural ejection" (development of high structure) of both compressive and strike-slip tectonics. The Apulian platform margin was remarkably stable remaining almost stationary from the Triassic to the Late Cretaceous (CASERO & BIGI, 2013). This stability is not proven for the Croatian carbonate platform edge, where the eastern platform was deposited over mobile halite (CASERO & BIGI, 2013). Salt bounded carbonate rafts and complex margins conditions can justify porosity enhancement via karstification, remobilization of carbonate and reefal build ups (WRIGLEY et al., 2014).

3. MODEL METHODOLOGY

Basin and petroleum systems modeling is an integrated multidisciplinary approach to track the evolution of a basin through time as it fills with fluids and sediments that may eventually generate or contain hydrocarbons. The modeling process consists of two main stages: model building and forward modeling. Model building involves building a structural model and identifying the chronology of deposition and physical properties of each layer. Forward modeling performs calculations on the model to simulate sediment burial, pressure and temperature changes, kerogen maturation and hydrocarbon expulsion, migration and accumulation. The calibration phase compares simulation results with independent measurements (e.g. well data) to enable refinement of the model (AL-HAJERI et al, 2009). The output model helps understanding of expulsion timing and potential migration paths existing in the system as well as the exploration risks. These processes may be examined at several levels, and complexity typically increases with spatial dimensionality. Considering the restricted available dataset in the area of interest (Fig. 1), 2D modeling along the key cross section was performed using, the PetroMod 2D (2014) software. Petromod 2D solves deterministic computations based on the discrete numerical representation of layers subdivided into grid cells with uniform properties. The software simulate physical processes that act on each cell, starting with initial conditions and progressing by selected time increments to the present day.

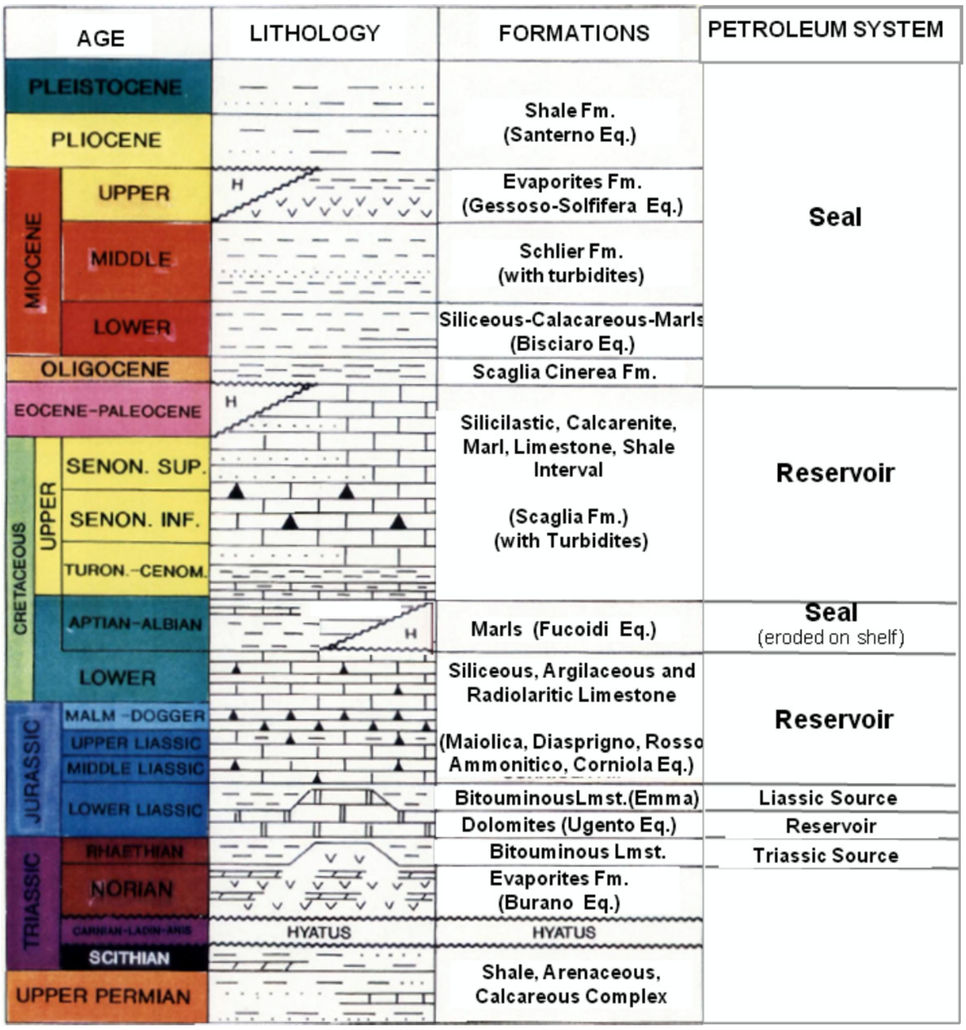

Figure 3: Reconstructed Stratigraphic Column with the main petroleum system elements.

3.1. Model Building

The depth-converted horizons coming from the key interpreted seismic line were used as input for building the 2D model. The seismic line is located in the South Adriatic Sea and extends from the Croatian coastline to the Italy-Croatia offshore border (Fig. 4). The long streamer used during the new 2D seismic survey, revealed interesting deep reflectors that probably belong to Triassic formations. These reflectors are the first acoustic impedance contrasts below the Mesozoic platform carbonates and may indeed represent low-velocity bituminous limestone deposits (Fig. 4). Oligo-Miocene and Plio-Pleistocene stratigraphic plays onlapping deeper structures are also interpreted. The Messinian unit is a characteristically strong reflector and may represent a clastic play south of the Gargano Arch.

The interpretation resulted from examination of regional geological studies, 2D seismic sections and well data on the Italian and Croatian side. The main reflectors coming from the seismic interpretation are: the Sea Bed, Top of the Miocene, Top of the Oligocene, Top of the Eocene, Top of the Fucoidi Marls (L. Cretaceous), Top of the Lias (Jurassic) and an horizon within the Triassic. Based on the wells stratigraphy and regional thickness maps, several other units have been interpreted: Near Top Cretaceous, Top Lias Source Rock, near Top Mid-Lias (Massiccio equivalent) and Near Top Triassic (Fig. 4). For the deepest reflectors, no well calibration was available. As the interpreted time horizons and the depth conversions were done on an incomplete dataset, the depth model is not accurate.

For modeling purposes, 4 main horizons were added to the model on the basis of the Italian wells (Fig. 5): the base Fucoidi Fm. (30 m below the interpreted top); the base Liassic source rock (50 m below the interpreted top); the base Trias source rock (50 m below the interpreted top); the Basement (about 1500 m below the base of the Trias source rock).

The facies model with the associated physical properties for the main petroleum system elements (sources, reservoirs and seals) was built on the basis of the evolution of the sedimentary sequence of the Dinarides, from the Paleozoic-Triassic clastic-evaporite sediments through the Mesozoic carbonate-anhydrite sequence to the Tertiary clastics (Fig. 6).

The main reservoirs were characterized as:

- Triassic (Rhaetian), Dolomite (organic lean, sandy);
- Jurassic (Lias), Dolomite (organic rich 50% and lean 50%);

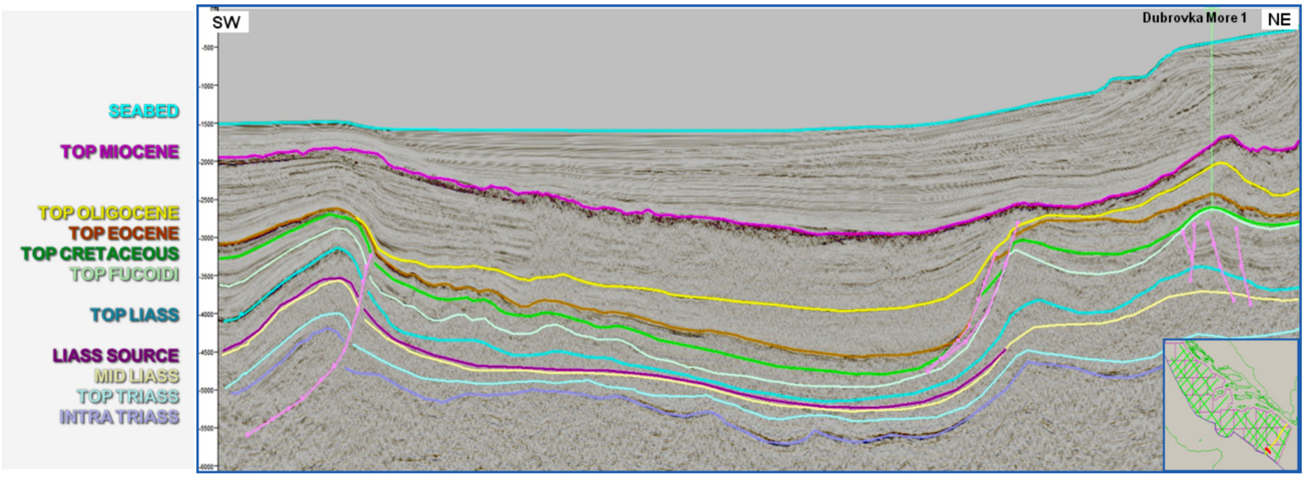

Figure 4: Interpreted horizons used as input for the 2D basin modeling.

• Jurassic (Malm), Dolomite 50% and Ooid 50%;
• Cretaceous, Limestone (ooid grainstone);
• Eocene, Limestone (ooid grainstone).

The seals were considered to be the Tertiary deposits (Marl 50% and Conglomerates 50%), the Upper Cretaceous Fucoidi (Marl) and the source rock intervals.

The Upper Triassic source rock was the bituminous Limestone inside Burano Formation (ANDRÈ & DOULCET, 1991). The second source was more speculative and mainly based on Liassic Italian analogous to the Emma Limestone formation, documented for the Grifone-1 well (MATTAVELLI et al., 1993; CASERO, 2004).

The geochemical parameters (Total Organic Carbon-TOC, Kinetics and Hydrogen Index–HI) used for the source rocks were (PEPPER&CORVI,1995):

• Trias Source: TOC 1,7%, HI 700, Kinetics Type II S;
• Lias Source: TOC 2%, HI 700, Kinetics Type II S.

Bottom Hole Temperature (BHT) data from the logs of about 10 wells were collected, corrected for equilibrium temperature and interpreted to gain understanding of the trend of the geothermal gradient. The Horner method was used. It plots the measured temperature (at a given depth) from each of several logging runs, against log(T/(t+T)). The parameter t represents the length of time that the borehole was subjected to the cooling effects of the fluid, and T represents the time after circulation that the borehole has had to partially reheat. The best fit straight line results from the plot is extrapolated to cut the temperature axis where logT/(t+T) equals zero, reflecting the true formation temperature at that particular depth. We have assumed mean surface temperature to be 7°C.

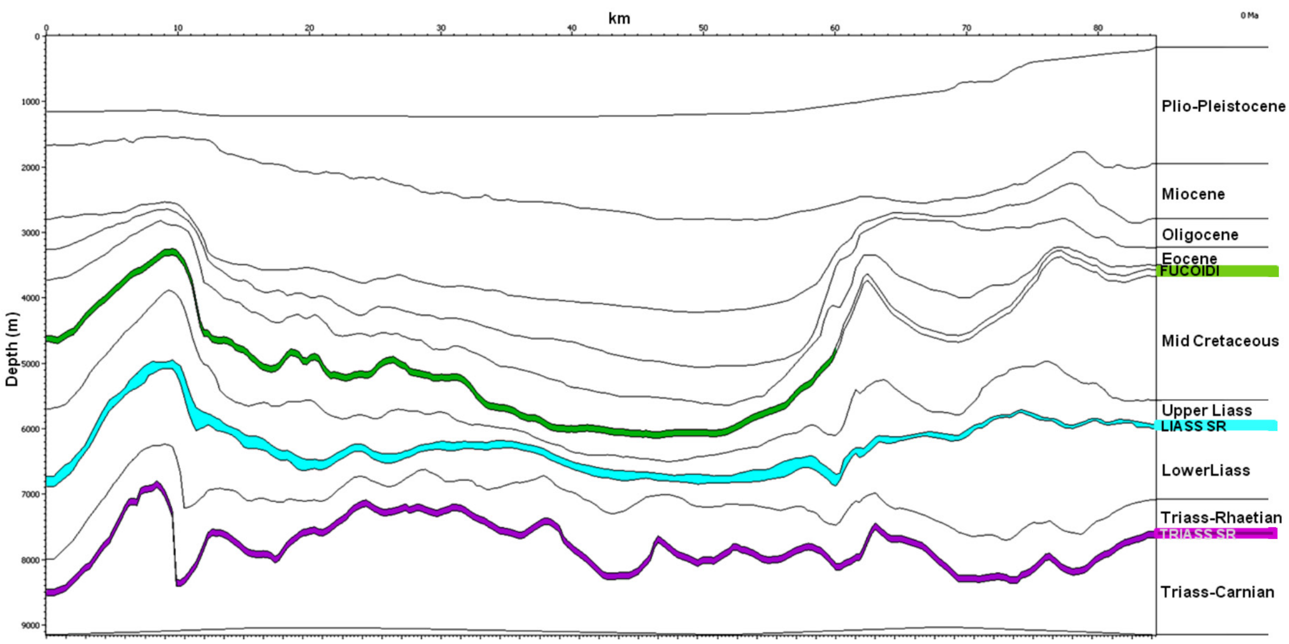

Figure 5: Seismic horizons added for 2D basin modeling purpose.

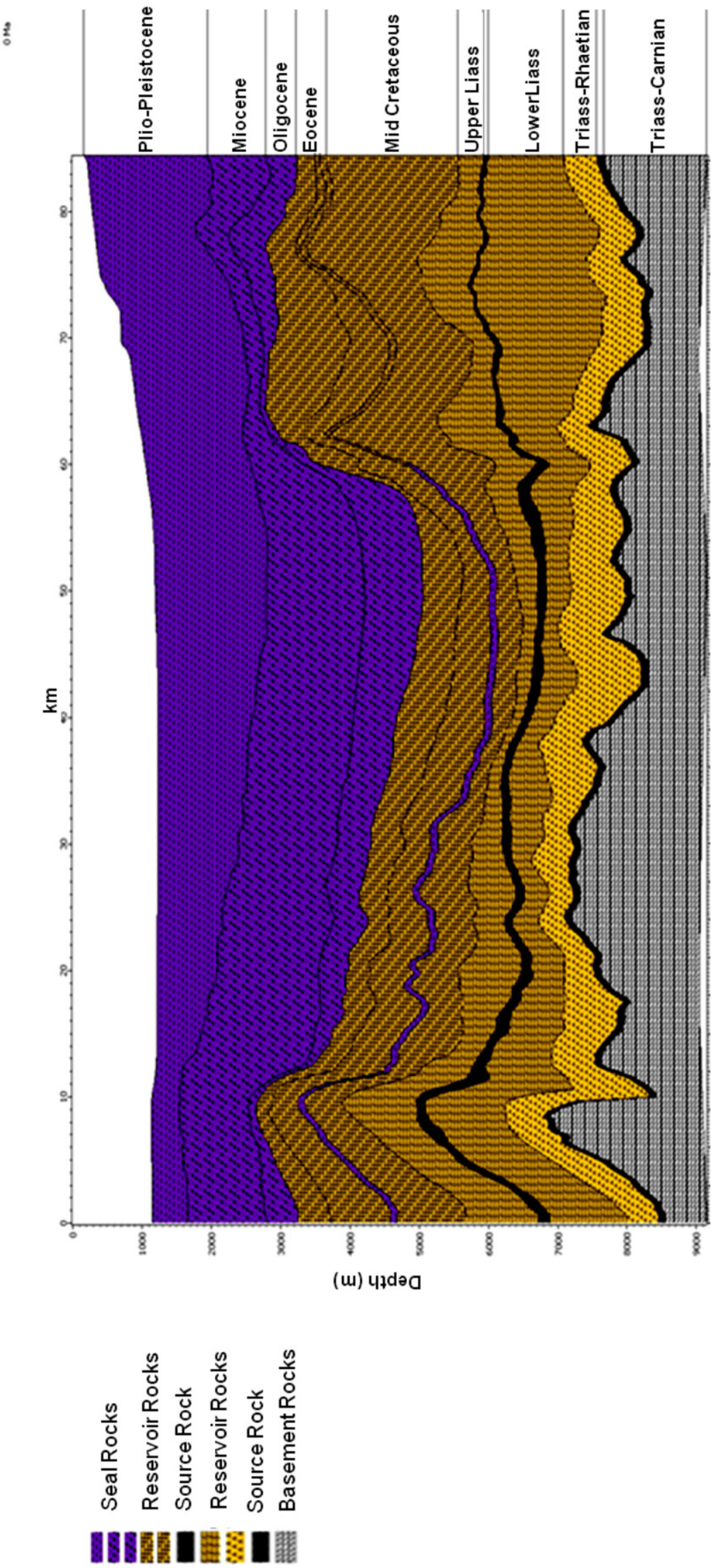

Figure 6: Facies Model with the definition of Petroleum System Elements across the studied seismic line.

The geothermal gradient of the study area varies from 10°C/km to 30°C/km and averages about 17°C/Km (Fig. 7).

3.2. Forward Modeling

To run the simulation, three important boundary conditions were defined: 1. Paleo Water Depth (PWD); 2. Sediment Water Interface Temperature (SWIT); 3. Paleo Heat Flow (HF). Two main trends were used as input to simulate the paleo-environment that defines the PWD and SWIT: one to model the geometry of a stable shelf through geological time and the second to simulate the basin conditions. For the Paleo HF history only one trend was used to simulate the effect of the Triassic rifting event and the subsequent phase of thermal subsidence (cooling). Vitrinite data for only one well was useful for calibrating the reconstructed heat flow history. Two main erosional events, during the Messinian and the Late Oligocene and one hiatus event during the end of the Cretaceous were introduced in the model. This missing overburden was reconstructed based on the well data and regional geological data (CATI et al., 1987, GRANDIC et al., 1997, WRIGLEY et al., 2014).

4. MODEL RESULTS

The starting point of this analysis was the understanding of the hydrocarbon potential and the associated exploration risks of deep Mesozoic plays.

The results can be summarized as follows:

- The risk of overmature conditions with consequent source depletion seems to be absent considering the low reconstructed geothermal gradient and related heat flow. Maturity model results confirm that both source rocks are within the oil window and that they can efficiently generate and expel hydrocarbons (Fig. 8);
- There is a significant divergence between the quantity of hydrocarbons expelled and the quantity accumulated in the reservoirs, especially during the Lower Cretaceous (Fig. 9). The main reason seems to be the timely mismatch between expulsion and the deposition and compaction of a working seal.

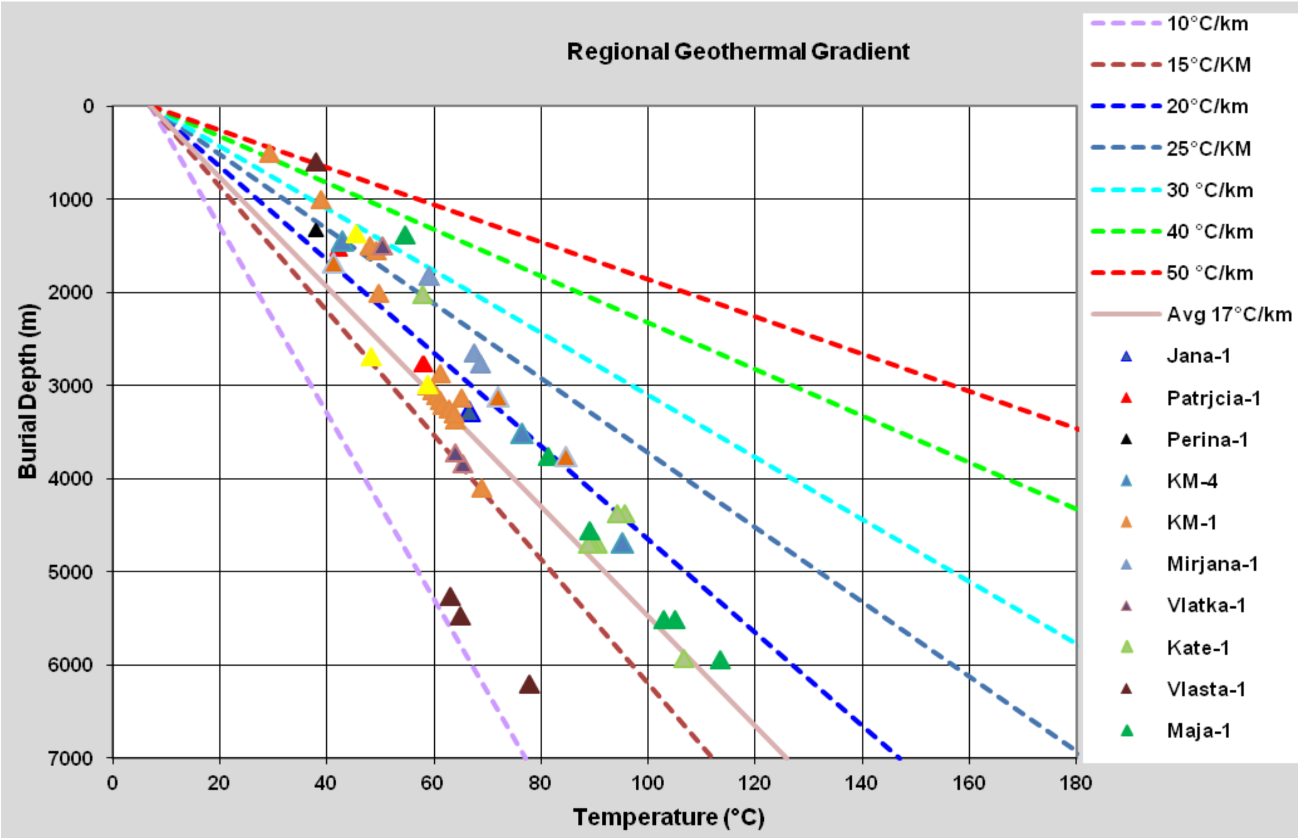

Figure 7: Geothermal gradient in the South Adriatic Croatian Offshore.

After calibrating and simulating the 2D model, the chart with all the features of the petroleum system was completed (Fig. 10). The biggest risk for the efficiency of the studied petroleum systems is the late completion of the traps for Cretaceous/Eocene reservoirs (dark blue row). The seal rock was deposited in the Oligocene and compaction is ongoing through the Miocene, when most of the hydrocarbons were expelled. A more efficient compaction can be expected in the central part of the basin, where a thicker sequence of Oligocene and Miocene sediments can be observed.

The Lower Jurassic reservoir could have the best working petroleum system assuring hydrocarbon accumulations

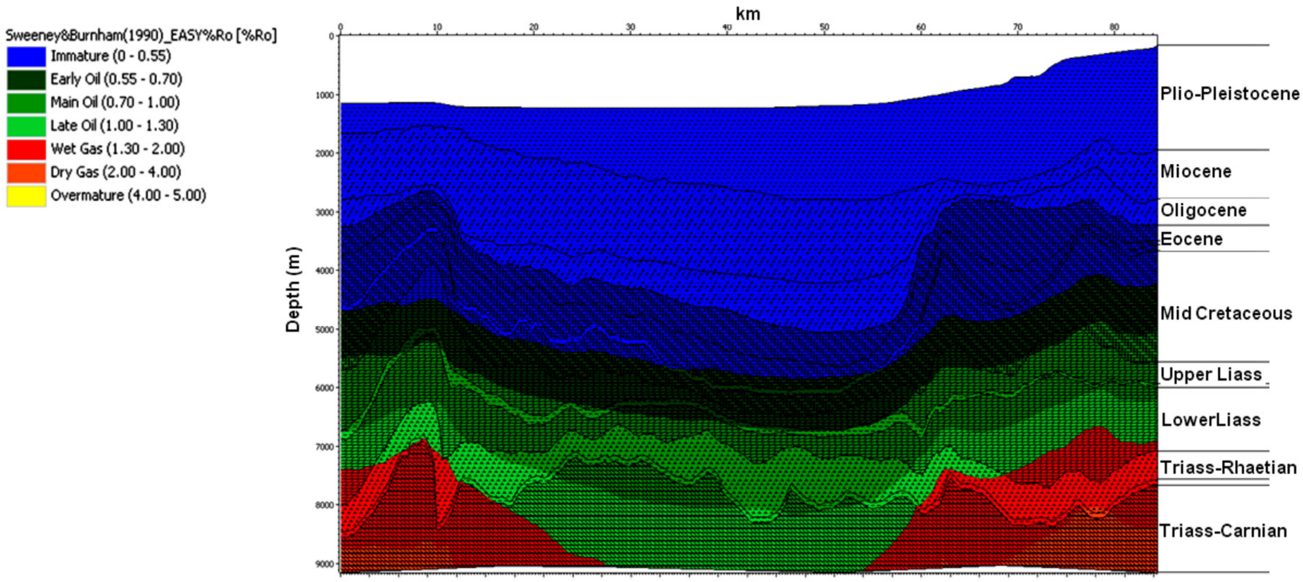

Figure 8: Maturity stage at the present day: The Lower Jurassic source is in the main oil window and the Triassic source rock is mainly in the oil window and partially in the wet gas window.

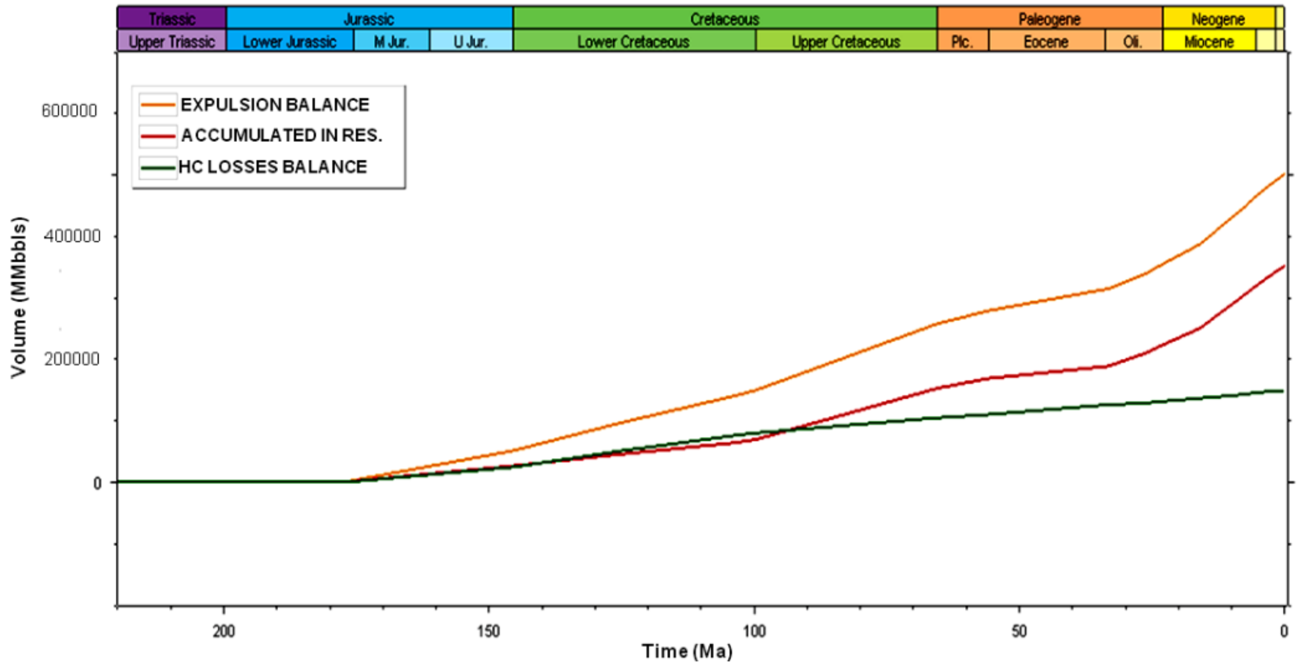

Figure 9: Graph showing the total hydrocarbons expelled (orange), accumulated (red) and lost (green) in the system.

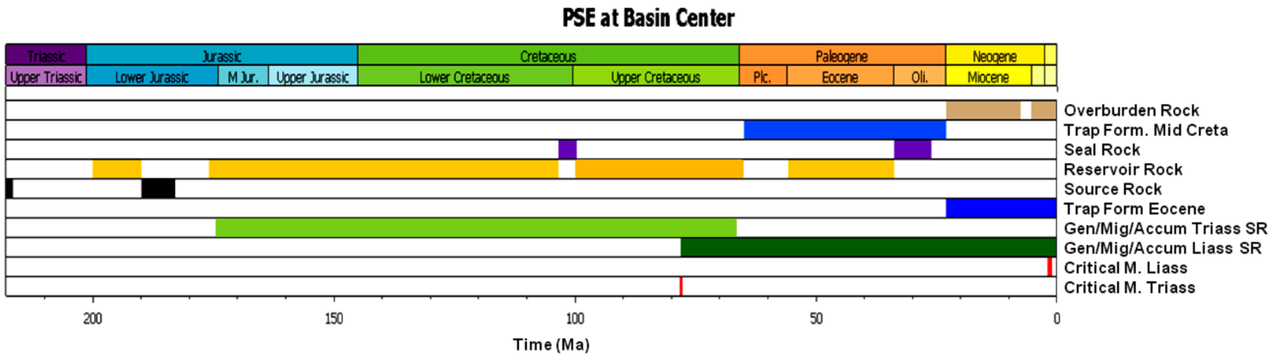

Figure 10: Petroleum Systems Elements chart derived from a pseudo-well in the central part of the 2D basin.

(Fig.10). In fact, the Triassic source rock starts to expel when the reservoir is deposited and the Lias source works as a seal.

A pseudo-well was introduced in the central part of the basin. In this area the reconstructed burial history shows that the source rocks are buried at their deepest and up-dip fluid migration, towards the highs of both structural traps, was possible. The significant difference of generation between the two source rocks is related to the slow deposition of sediments in the basin between 180 and 30 Ma (Fig. 11). The Jurassic source barely reached 50% transformation of kerogen, which explains the minor contribution to the accumulations observed in the model (Fig. 11).

The final migration model shows that fluid saturated structures are present in both plays (Fig. 12). Also, considering the actual uncertainties, the total depths of the Cretaceous traps are around 3500 m and 5500 m for Jurassic traps, in water depth between 500 and 1200 m. This reservoir depth could have a negative impact on economic viability.

5. CONCLUSIONS

All the critical elements for a working petroleum system are present in the Lower Jurassic structural carbonate karst play and in the Cretaceous slope calciturbidites play. The existence of liquid hydrocarbons coming from Triassic and Jurassic source rocks into the studied petroleum systems at the present day seems to be possible (Fig. 8 and 12).

For the Structural Karst play, which is highly under-explored, there are still uncertainties concerning reservoir quality (no porosity data) and efficiency (no well testing performed).

For the Mid-Cretaceous/Eocene platform margin, there are significant uncertainties related to the possibility of finding significant accumulation in the traps. In fact, a temporal mismatch between expulsion and the deposition and compaction of a working seal (Messinian, Top Oligocene and Top Cretaceous) could have facilitated hydrocarbon leakage to the surface.

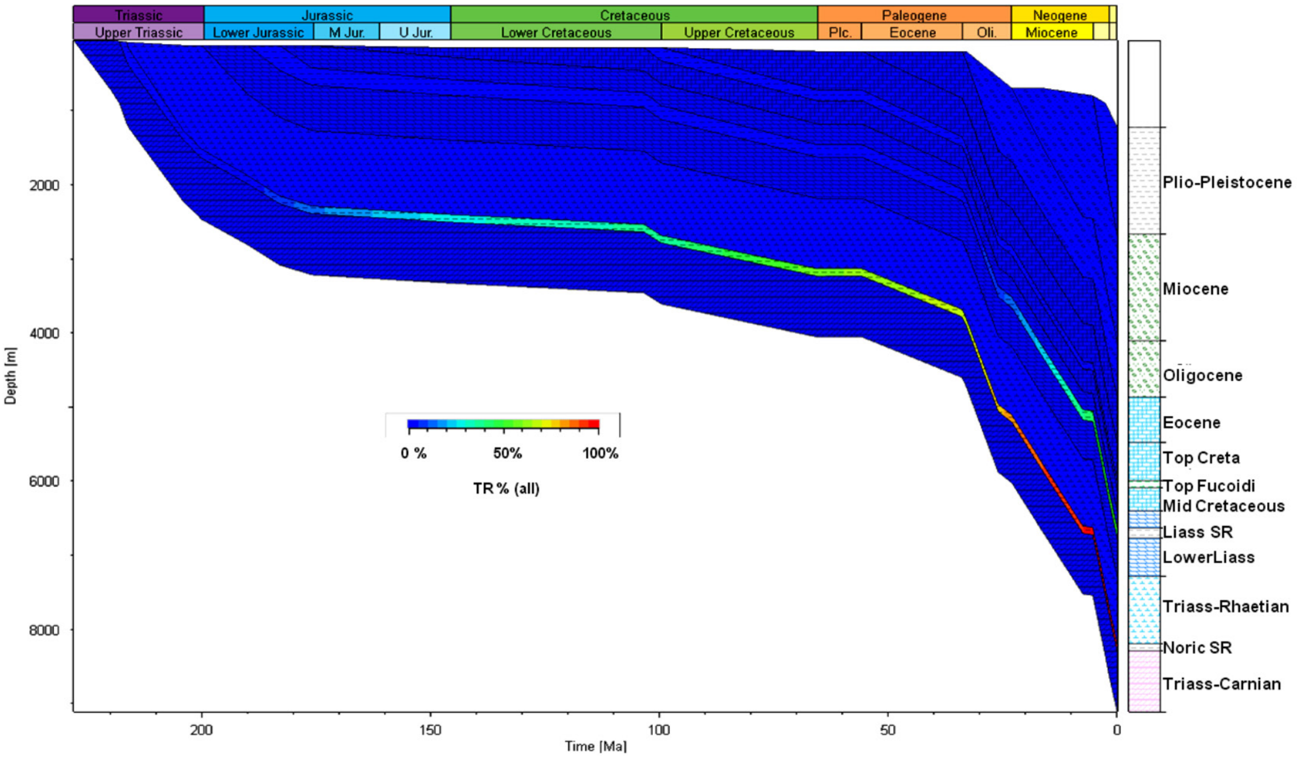

Figure 11: Transformation of hydrocarbons (%) from kerogen through time at pseudo-well location for both source rocks.

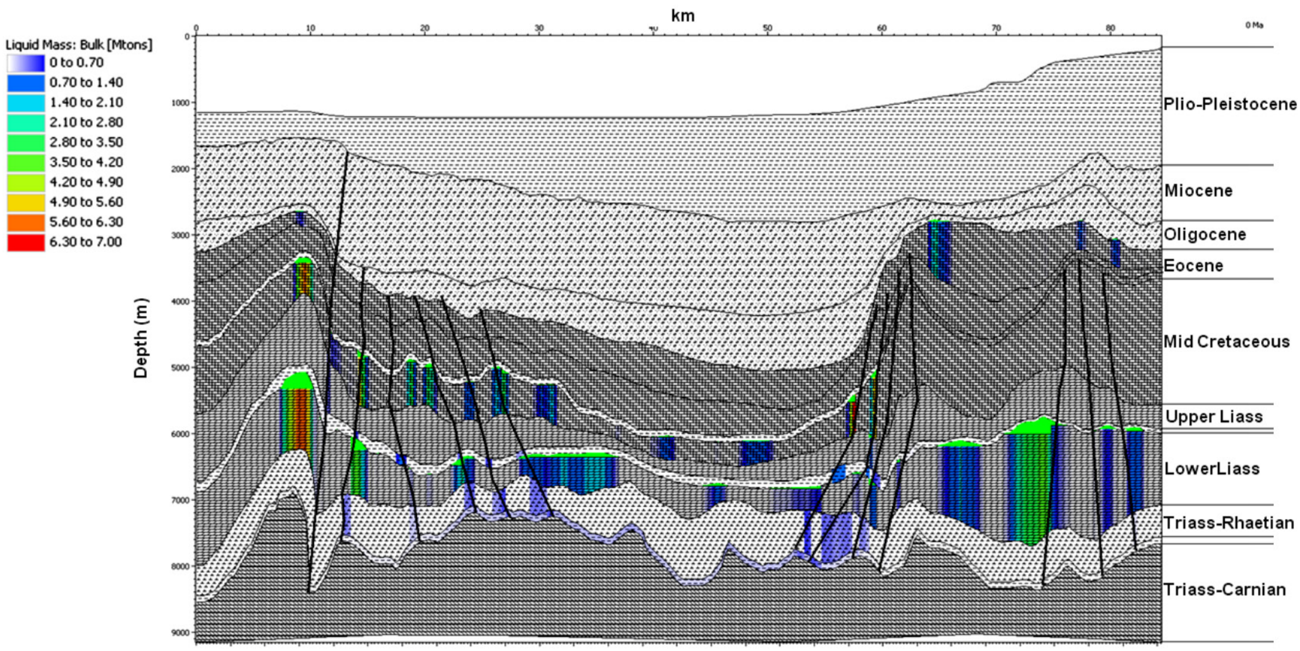

Figure 12: Potential new accumulations in Lower Jurassic and Mid Cretaceous traps.

6. DISCUSSION

At the end of this study, the following points remain open for discussion in order to reduce risk in the area:

- new ongoing exploration activities, since the last licensing round in 2014, could reduce the uncertainties related to the missing hard-dataset. This could facilitate well seismic calibration, core analyses and source rock geochemical characterization;
- build a 3D petroleum systems model, when a new 3D seismic survey is acquired, to quantify the hydrocarbons in the system passing from play to prospect analysis;

- create a detailed back stripping structural restoration model, considering Triassic salt tectonics, to better understand the structural timing of the potential traps and the associated model migration pathways.

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