Offshore Croatia – Hunting 'Big Oil' in the centre of Europe

Richard Wrigley[1], Anna Marszalek[1], Karyna Rodriguez[1] and Neil Hodgson[1*] present an exciting hydrocarbon province in the Adriatic which will soon be opening up for exploration.

The Adriatic offshore hydrocarbon province lies below the shallow waters between Italy and Croatia on the northern margin of Europe's Mediterranean Sea. Plio-Pleistocene fields in the north produce commercial biogenic gas from clastic reservoirs in both Italian and Croatian waters, while oil is produced from modest pre-Miocene carbonate fields in the Italian southern Adriatic.

The hydrocarbon play-elements required for the trapping of oil in carbonate plays offshore Croatia include the development of reservoir at carbonate platform margins, a competent top seal and the presence of mature source rock. However, until new 2D seismic data was collected in 2013, none of these factors could be reliably constrained.

Here, we demonstrate that all these play-elements (Figure 1) are indeed present and can be defined by new, long-offset seismic. Furthermore, we believe the oil play-systems offshore Croatia have potentially more robust, simpler and larger targets, and exploration risk that is more addressable by seismic methods than on the proven Italian margin.

Hydrocarbon exploration history

Hydrocarbon exploration offshore Croatia commenced with the Jadran-1 well, drilled in 1970, and two years later in 1973, the Jadran-6 well made the first discovery – the Ivana gas field. This initial success was in the shallow clastic gas play in the northern Adriatic. Since then, 135 exploration and development wells have been drilled offshore Croatia, compared to more than 1358 exploration and development wells drilled offshore Italy. Croatian exploration success continued with the discovery of eight gas fields in the northern Adriatic which are now on-stream. Exploration activity in the central and southern basins of Croatia mirrored the exploration initiatives offshore Italy and focussed on the Cretaceous carbonate platform oil play. Whilst several wells have encountered oil shows, there have been no commercial discoveries yet. However, this same carbonate platform play has been targeted successfully offshore Italy, including the discovery of the Rospo Mare, Elsa, Aquila, Rovesti and Giove oil pools.

Despite the generic similarities, the nature of the carbonate oil play offshore Croatia is significantly different from that on the Italian margin and requires high-quality seismic to successfully image the Triassic and delineate source kitchens, identify platform margin reservoirs, and support basin modelling to constrain the timing of charge. The lack of such high-quality seismic has hampered the otherwise valiant attempts to chase the Mesozoic carbonate oil play in the Croatian offshore. Therefore, in 2013 Spectrum acquired 14,700 km of long streamer 2D seismic data, which is tied to an 8000 km dataset of 2011 reprocessed Italian 2D seismic data (Figure 2).

Regional development of the Croatian margin

The regional geology and tectonic history of the Croatian Adriatic region has been well discussed in the literature. 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. This area

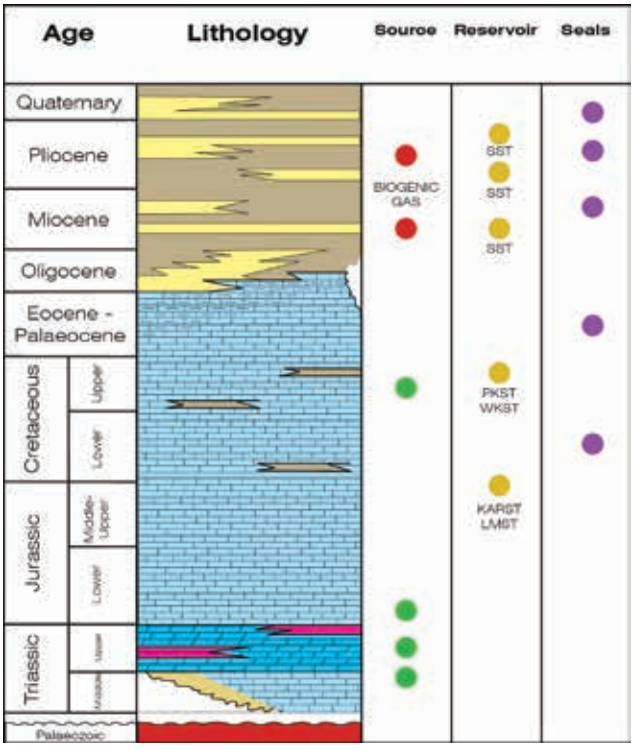

Figure 1 *Offshore Croatia stratigraphy and play elements.*

[1] *Spectrum.*

[*] *Corresponding author, E-mail: neil.hodgson@spectrumasa.com*

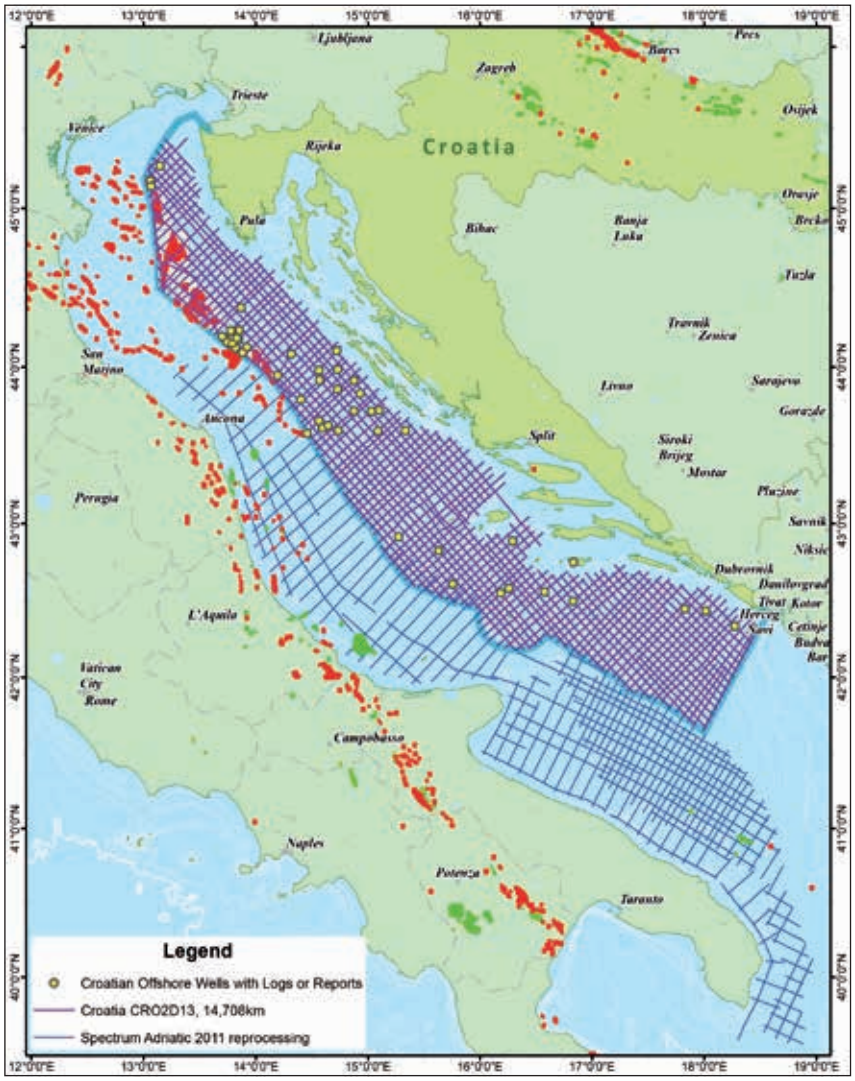

Figure 2 *Map of Adriatic with 2013 Croatia acquisition and 2011 Italian reprocessed 2D surveys.*

comprised a wide shallow-water shelf, distal from any clastic input from the Late Triassic until the Eocene. This was a perfect situation to develop platform carbonate successions and basin facies, which will prove the key to future exploration initiatives. West verging Dinaric compression and thrusting (similar to that affecting the Ionian basin to the south) affected the east of the Adriatic developing a foredeep in the Oligo-Miocene. In a similar way the east-vergent Apulian thrusting to the west formed a similar foredeep in the far north west in the Plio-Pliestocene.

The Mesozoic section

The oldest sequences penetrated by wells offshore Croatia are Triassic evaporates. Within the Adriatic margin these are predominantly anhydritic to the west and halite dominated to the east. The distribution of halite has, however been largely under-reported to the east, as lithology is rarely preserved at outcrop. In common with studies in the Ionian basin, the recognition and understanding of the distribution of mobile halite in the east reveals the controls on the structural development of the overlying carbonate platforms both onshore and offshore Croatia.

Well information (particularly Vlasta-1), outcrop studies onshore and the 2013 seismic data have confirmed the presence of a thick Triassic syn rift sequence comprising halite, sabkha carbonates and black, organic-rich shales. Deposition of source rock in Late Triassic syn-rift grabens, and within halokinetically controlled rafts, has the potential to be highly productive hydrocarbon source basins with migration routes into a range of potential traps. Such oil was recovered from Late Triassic carbonates in the deepest well drilled to date in Croatia: Vlasta-1. However, such source basins and migration pathways have hitherto been elusive, as the key reflectors were largely unimaged in legacy seismic data.

Loading of the Triassic halite by Mesozoic carbonate platform deposition created large diapiric structures which

dominate the prospectivity of the Central Adriatic. Some of these salt diapirs are imaged penetrating the current sea bed. Such features extending above the density equilibration level must be connected to a deeper halofer and it is reasonable to envisage thick salt facilitating the decollement of Dinaric thrusts.

The heterogeneities of the Triassic salt sequence will not only have determined the structural fabric of the region, but will also strongly control the subsequent Mesozoic deposition that provides the dominant prospectivity of the Croatian margin – Jurassic and Cretaceous platform carbonate margin deposits.

Mesozoic reservoir

Mesozoic and early Palaeogene sedimentation was indeed dominated by platform and ramp carbonates resulting from a complex palaeogeographic configuration of open shallow water platforms and deep marine basins (Casero and Bigi, 2013). The Italian margin however, was remarkably stable and the carbonate platform remained almost stationary from the Triassic to the Late Cretaceous. This stability is not proven for the Croatian carbonate platform edge, where the eastern platform was deposited over mobile halite. Salt bounded carbonate rafts are envisaged with complex margins and multiple opportunities for porosity enhancement via karstification, remobilization of carbonate and reefal build ups.

The extensive Jurassic and Cretaceous carbonate platform system developed across the region with extensional tectonic phases in Liassic times and early Cretaceous compressional palaeo-inversions creating large structures offshore and karst carbonates reservoir potential. This platform, perhaps reflecting pre-existing structure, was incised with a deeper water elongate basin separating the N-S trending Italian and Croatian carbonate platform margins, and what has resulted is a carbonate platform. Fascinatingly, today these platform margins run sub-parallel to the Italian and Croatian coasts control the prospectivity and these margins are the prime areas for distribution of porosity and permeability. On the Italian margin, reefs and karstic units on the shelfal side of the platform margins provide reservoirs at Giove and Medusa (reef) and Rospo Mare (karst). Slope and basin floor remobilized carbonates provide reservoirs at Elsa (slope) and Aquila and Rovesti (basin floor).

Platform margin structures are imaged and mapped clearly throughout the Croatian margin, while in the deeper-water area numerous extensional tilted fault block structures are imaged. The search in Croatian water for analogues to discoveries on the Italian margin have been devastatingly hampered until now by the poor quality of the shallow imaging of the legacy seismic data - the key tool required to identify the presence of a platform margin and subtle reef/slope/basin floor fan seismic facies.

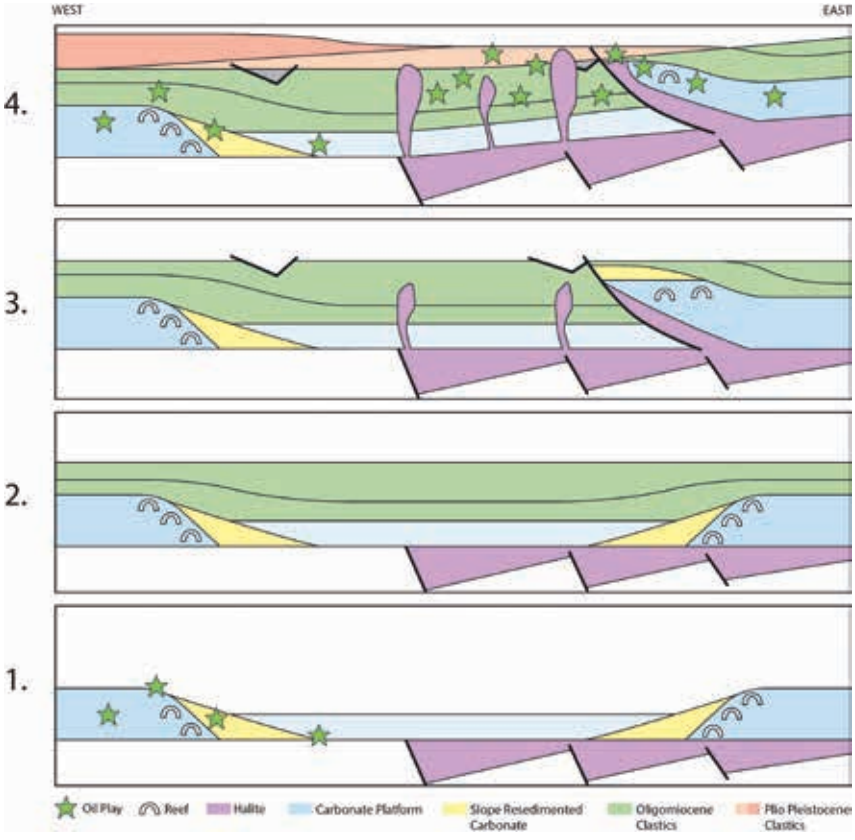

Figure 3 *Cartoon structural development of the margin: 1) Mesozoic carbonate platforms, 2) Oligo-Miocene foredeep clastics, 3) late Miocene Dinaric thrusting and halokinesis and 4) Plio-Pleistocene clastic delta loading and late charge.*

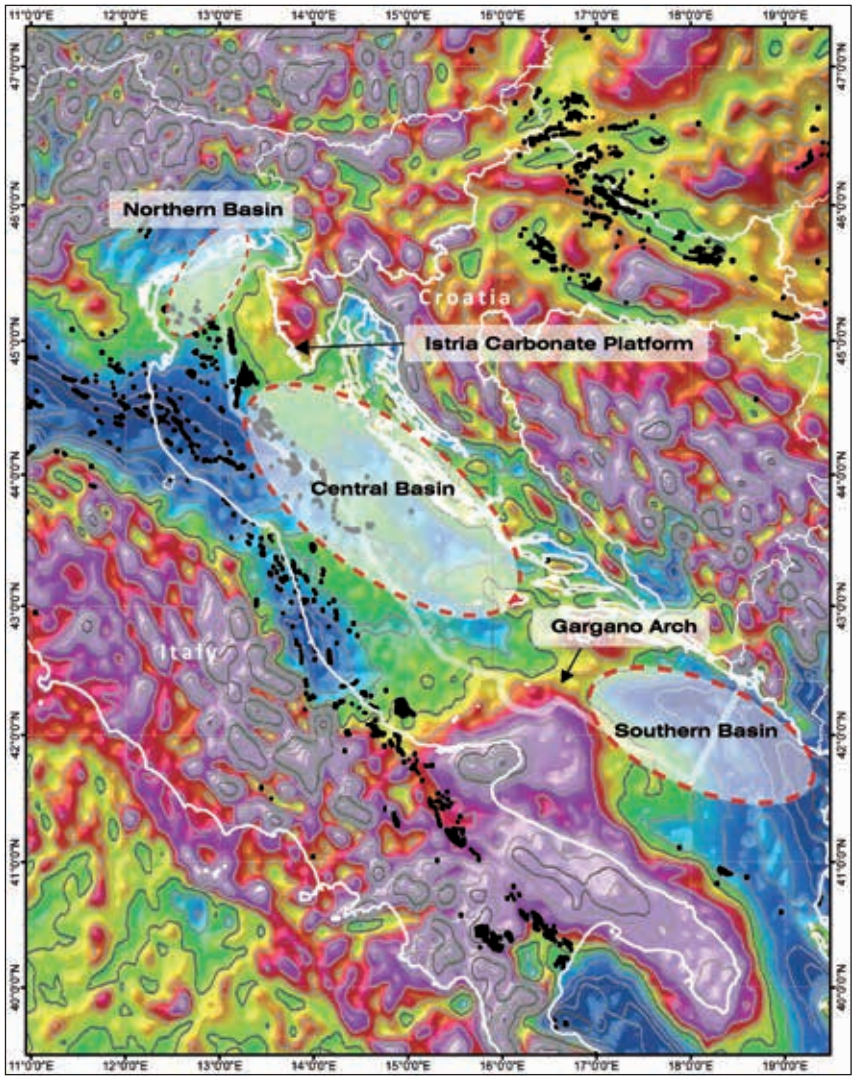

Figure 4 *Bouguer gravity and basins map.*

The post-Eocene section

At the end of the Eocene the Adria plate engaged with the southern Alps, generating the Po valley and beginning to supply coarse clastics into the previously carbonate-dominated Adriatic basin. During the Oligocene the Dinaric thrust belt was active, depressing the eastern Adriatic and creating an Oligo-Miocene flysch filled foredeep. Successive deltaic sequences have prograded from the Po valley in the north of the Adriatic, with little, localized sediment supply from the Dinaric thrust-belt. In the North these clastics have been well explored, and numerous gas fields discovered and produced. However in the central and southern regions these sediments do not appear to have been targeted despite very promising direct hydrocarbon indications being imaged on the regional 2013 seismic data.

From Middle Miocene onwards, a series of Alpine and Dinaride orogenic processes impacted the region resulting in uplift and subsidence, generating sediment supply and creating accommodation space for thick flysch deposits particularly in the north. Remarkably, there is relatively little Dinaric thrusting offshore Croatia, and the stacked thrust structures seen onshore are not observed offshore. The effect of the Messinian salinity crisis was to generate a clear and easily mappable unconformity separating the Oligo-Miocene sequence from the Plio-Pleistocene sequence. In places there is truncation at this unconformity, however, it appears more dominated by halokinetic structuration and the development of the Oligo-Miocene Dinaric fore-deep than to the creation of particularly strong incision. The Messinian unconformity appears often in wells below a thin anhydrite layer – we suspect deposited during the post-Messinian marine transgression. The Messinian thickness southwards has multiple channels developed.

Halokinesis continued during the Tertiary, creating diapir traps for turbidite and delta top sediments during the Plio-Pliestocene.

A cartoon model for the development of the Adriatic is proposed in Figure 3 which represents a very simplified model of

the basin, and in four stages, illustrates the main hydrocarbon play developing phenomena within the Adriatic basin.

Source rock presence and effectiveness

A key risk-factor for oil exploration in the Adriatic is the distribution and maturity history of the Triassic source rock offshore Croatia. The long record length of the 2013 regional seismic has allowed deep Triassic reflector(s) to be imaged, facilitating the mapping of the distribution and depth of burial of the Late Triassic source rock. These reflectors are the first acoustic impedance contrasts below the largely homogeneous lithology of the Mesozoic platform carbonates, and may indeed represent low velocity, mature source rock reflectors. Layer cake depth conversion, pre-stack depth migration and well data confirm that the Triassic has been buried to depths between 5000 and 7000 m over much of the Croatian Offshore, and that due to limited basin inversion and late Plio-Pleistocene clastic influx, these source rocks in the basin depocentres have never been buried significantly deeper than they are today. Given the relatively low geothermal gradient (20-27°C/km) recorded in offshore wells drilled in the Croatian Adriatic, the source rocks are likely to be within the oil and oil and gas generation windows. Mapping out the individual source basins and careful reconstruction of the seismic data reveals numerous deep pre-Messinian structures and traps that would have captured early charge and a second set of structures sealed by thick Plio-Pleistocene pro-deltaic mudstones.

The prospectivity of the three offshore Croatian basins

Regional gravity data indicates the presence of three basins developed offshore Croatia (Figure 4).

These basins each have a unique hydrocarbon system, with varying amounts of contribution from Dinaric thrusting, Oligocene or Plio-Pleistocene fore-deep accumulation, and halokinesis. Initial interpretation of the 2013 seismic data illustrates the impact of early Mesozoic rifting, late Mesozoic compression and Alpine earth movements on tectonic development, sedimentation and hydrocarbon prospectivity. The clear imaging of the 2013 seismic details events and sequences down to 8 sec twt (two-way time) providing a level of detail previously not seen, and helping to further understand the Mesozoic and Cenozoic basin history and the tectonic controls on prospectivity.

The 2013 seismic data confirms the presence of a Northern, Central and Southern Basin each with distinct characteristics and hydrocarbon play types. These can be seen on the NW-SE trending strike line running centrally

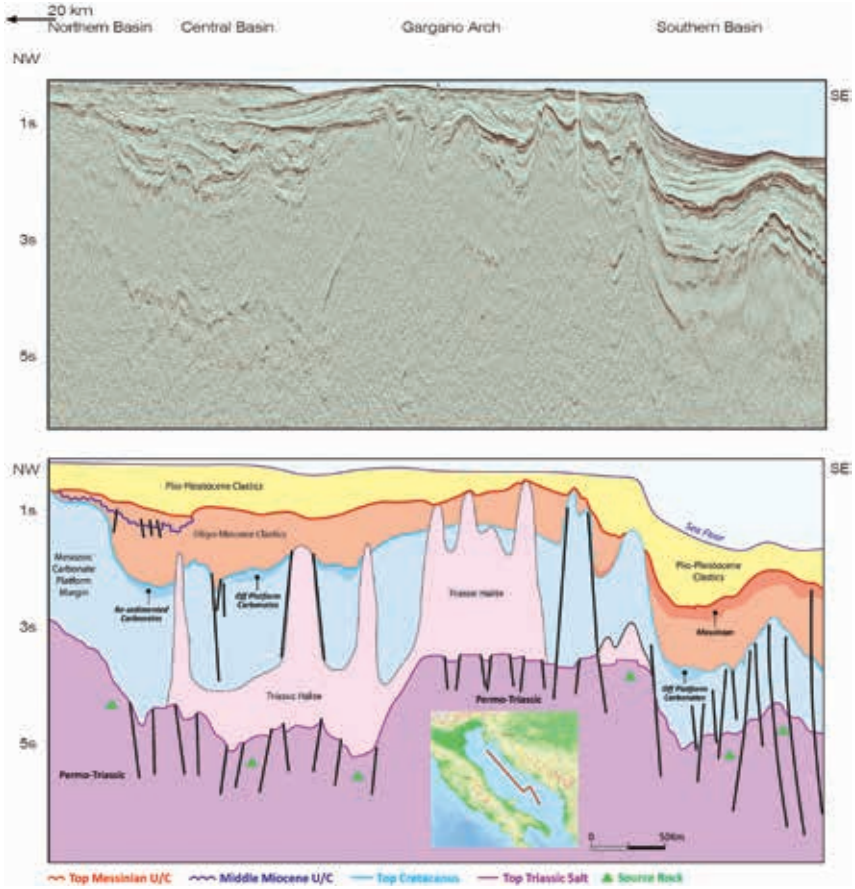

Figure 5 *Central and southern basin strike line.*

down the Adriatic (Figure 5). Note Figures 6, 7 and 8 are all dip lines running approximately orthogonally to the strike line of Figure 5, and comprise amalgamations of the eastern 2013 Croatia dataset (7 sec TWT presentation) with 2011 reprocessed legacy Italian data (5 sec twt presentation) in the West.

The Northern Basin extends southeast from the Po Depression to the Istria Platform. The basin is defined by a Pilo-Pleistocene sequence onlapping onto a thick, deformed Oligo-Miocene and Mesozoic carbonate platform sequence below the strong Messinian unconformity. The folding of this unit is considered to have occurred during the development of the Oligo-Miocene Dinaric fordeep. The onlapping Plio-Pleistocene clastics form the reservoir for the eight Croatian gas fields. The Cenozoic basin fill extends to below 2 sec twt in the deeper parts of the basin and exhibits amplitude anomalies (Figure 6). The identification of carbonate platform margin and slope offer additional prospectivity in close proximity to the hydrocarbon source basins.

The Central Basin is bounded by the Istria Carbonate Platform to the north west and the Gargano Arch to the south east, and has a different geological character to that in the north. The basin has a thicker Cretaceous and Jurassic carbonate platform and a thinner Cenozoic section (Figure 7). The basin on the east side of this line represents the Oligocene foredeep to the Dinarides, and is the earlier mirror of the Pliocene foredeep to the Apulian thrust system seen on the western side of Figure 6. The deepest reflectivity at 6 sec twt is close to (and may reflect due to acoustic impedance contrast generated by), the Triassic source rock. Several wells in the basin have encountered oil in Cretaceous and Triassic reservoirs. West of the Oligocene foredeep, the section is dominated by the presence of salt diapirs. The basin's complex tectonic history is characterised by extensional and compressional tectonics, however, it is the dominance of these halokinetic structures that is striking, as they have created several play types of varying ages. In the near shore, several islands are the result of halokinetic structures.

The depositional facies in the Jurassic and Cretaceous carbonate sequences in the Central Croatian Basin can be readily interpreted on the 2013 data, tied to the 2011 reprocessed data from Italy. This presents the opportunity to delineate the platform margin in this structurally complex area to reveal new plays and traps previously unimaged.

The deeper-water Southern Basin (Figure 8) is located south of the NE-SW trending Gargano Arch and is notably different in character to the Northern and Central Basins reflecting the basin fill. The Southern Basin extends into the Ionian Basin and includes the petroleum province offshore Albania. The asymmetry of the margin between Croatia

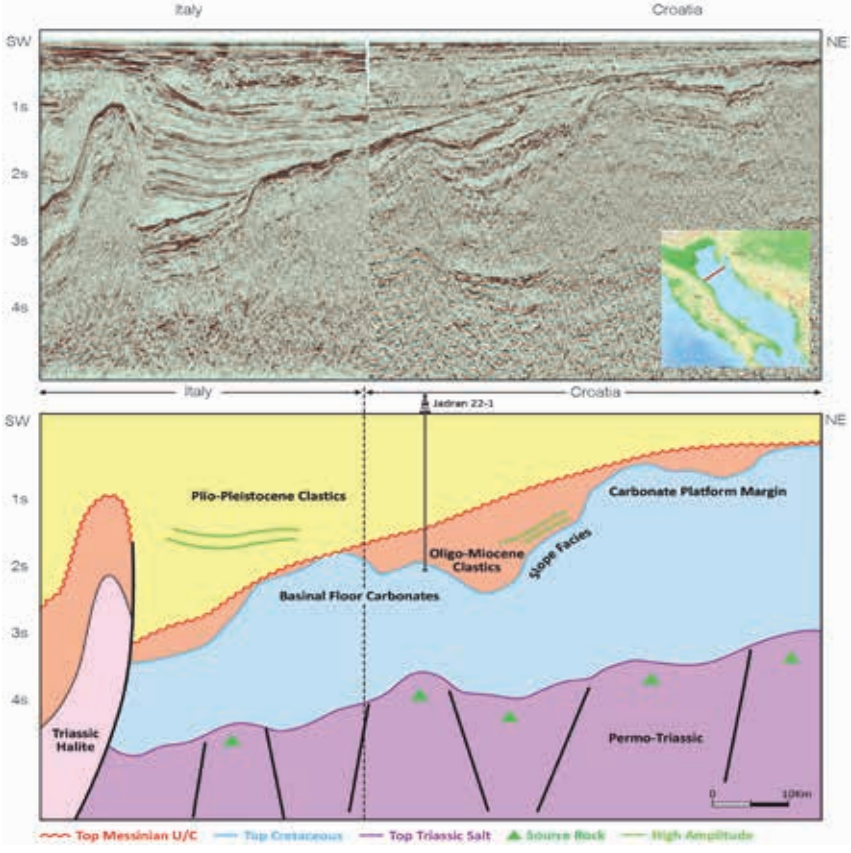

Figure 6 *Northern basin dip line.*

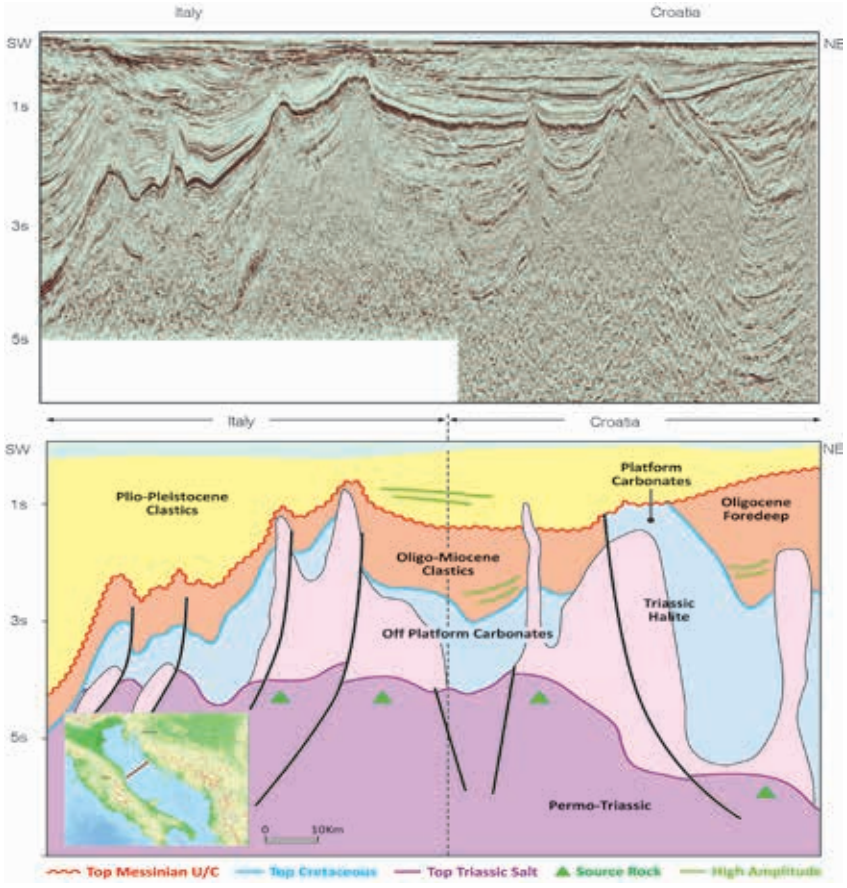

Figure 7 *Central basin dip line.*

and Italy is no less developed on Figure 8 than it is on Figures 6 and 7, however, the demonstration of a working hydrocarbon play is perhaps simpler in the Southern Basin as the carbonate oil play is clearly working in the unlikely looking shallow western margin and seems better developed in the deeper unexplored section to the east in Croatia. Here the Mesozoic carbonate platform margin is clearly distinguished by the change in seismic facies and thickness of the Triassic to top Cretaceous interval across this margin. Oligo-Miocene and Plio-Pleistocene stratigraphic plays are also interpreted in the Southern basin on-lapping deeper structures. The Messinian unit in the area is a characteristically strong reflector and may represent a clastic play south of the Gargano Arch.

Figure 8 comprises a cross-Adriatic dip line that shows both the Italian and Croatian Platform Margins, and the intervening deeper water reworked carbonate basin between them. This line clarifies the hydrocarbon system that has been proven by drilling offshore Italy. Shallow, small structures close to the Italian mainland, are fed by hydrocarbons generated in the deep Croatian basin to the east. In Croatian waters, large structures at the platform margin, show reefal build-up and possible irregular incisions (there is a potential seal level fall due to karstification events). Deep Triassic reflectors indicate that source rocks are present and will be generative at current burial depths.

Perhaps what is most striking from this section however is the relative simplicity of the hydrocarbon system and the lack of complexity from Dinaric compression. This suggests that the Southern Basin has high potential for the identification of really large, high-value traps.

Summary

Difficulties resolving key hydrocarbon play elements on legacy seismic data lead the Croatian Adriatic to represent an under explored hydrocarbon province. However, recent (2013) acquisition of regional, high-quality seismic data permits the hydrocarbon potential of the basin to be assessed for the first time. These data allow the imaging of deep, source rock-bearing basins, which inform basin modelling workflows. Multiple carbonate platforms can be imaged and accurately mapped leading to the identification of high poroperm play systems, particularly around platform carbonate margins. And finally, the surprising simplicity of the structuration in the basin can be defined by imaging the extensional, compressional and halokinetic tectonics, identifying large elegant plays and traps that have the potential for 'big oil' discoveries.

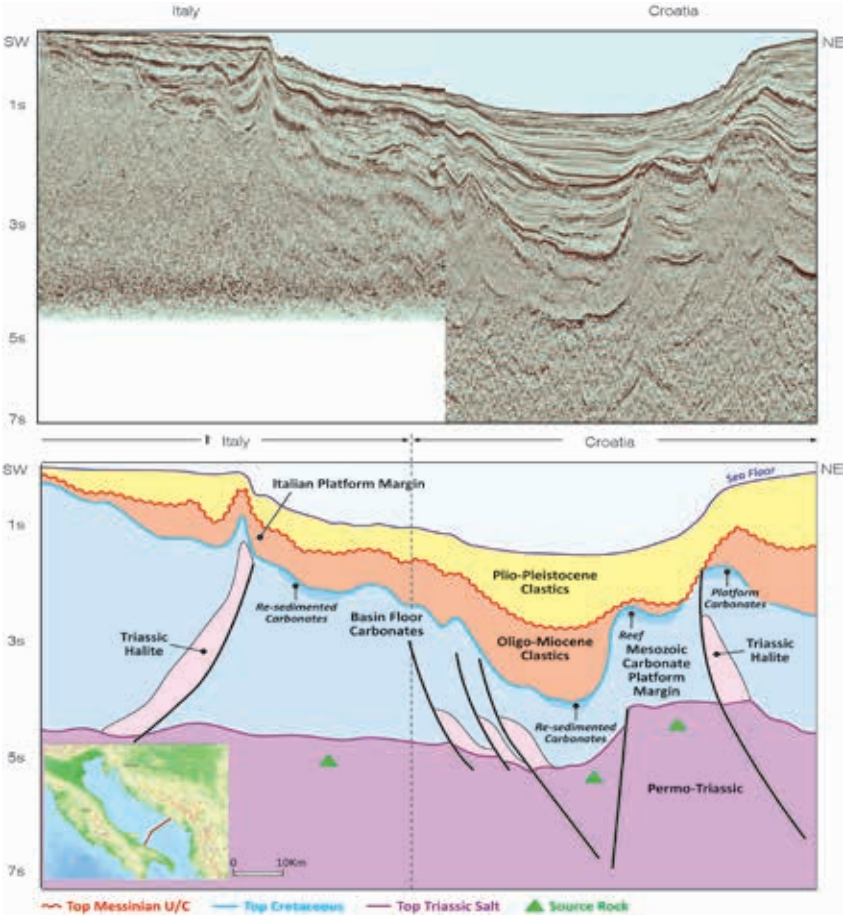

Figure 8 *Southern basin dip line.*

These new insights into the hydrocarbon plays in this basin show that although the carbonate and clastic play systems are similar to those explored on the Italian margin, the asymmetry of the Adriatic caused by the timing of the opposing thrust systems and most importantly the increased halite presence below the Mesozoic carbonates in the east, indicate that the Croatian offshore has the superior hydrocarbon system. The availability of high-quality seismic data in this region will unlock the potential of this margin to imminently develop into a much more significant oil province in the next few years.

References

Casero, P. and Bigi, S. [2013] Structural Setting of the Adriatic basin and main related petroleum exploration plays. *Marine and Petroleum Geology*, **42**, 135–147.

Grandić, S., Boromisa-Balaš, E. and Šušterčić, M. [1997] Exploration concept and characteristics of the stratigraphic and structural models of the Dinarides in Croatian offshore area. *Nafta*, **48** (8-9), 249–266.

Grandić, S., Boromisa-Balaš, E., Šušterčić, M. and Kolbah, S. [1999] Hydrocarbon possibilities in the Eastern Adriatic Slope zone of Croatian offshore area. *Nafta*, **50** (2), 51–73.

Grandić, S., Biancone, M. and Samaržija, J. [2001] Geophysical and stratigraphic evidence of the Triassic rift structuration in the Adriatic offshore area. *Nafta*, **52**, (12), 383–396.

Grandić, S., Veseli, V. and Kolbah, S. [2002] Hydrocarbon potential of Dugi Otok basin in offshore Croatia. *Nafta*, **53** (6-7), 215–224.

Malvić, T., Dureković M., *Šikonja*, Z., čogelja, T. Ilijaš, T. and Kruljac I. [2011] Exploration and production activities in northern Adriatic Sea (Croatia), successful joint venture INA (Croatia) and ENI (Italy). *Nafta*, **50** (9-10), 287–292.

Korbar, T. [2009] Orogenic evolution of the External Dinarides in the NSE Adriatic region: a model constrained by tectonostratigraphy of Upper Cretaceous to Paleogene carbonates. *Earth-Science Reviews*, **96**, 296–312.

Nicolai, C. and Gambini, R. [2007] Structural architecture of the Adria platform-and-basin system. *Italian Journal Geoscience*, Special Issue, **7**, 21–37.

Pamic, J. and Balen, D. [2005] Interaction between Perm-Triassic rifting, magmatism and initiation of the Adriatic-Dinaride carbonate platform (ADCP). *Acta Geologica Hungarica*, **48** (2), 181–204.

Underhill, J.R. [1989] Late Cenozoic deformation of the Hellenide foreland, western Greece. Geological Society of America Bulletin, 101, 613–634.