INTRODUCTION TO THE THEMATIC ISSUE

ADRIATIC AND IONIAN SEAS: PROVEN PETROLEUM SYSTEMS AND FUTURE PROSPECTS

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Fold-and-thrust belts have been extensively explored for hydrocarbons in many parts of the World and in some areas have yielded substantial reserves of oil and gas (e.g. Albania, southern Italy, Iran and Iraq, and Canada). Exploration successes in fold-and-thrust belt systems are often due to the occurrence of large-scale anticlines with which traps for hydrocarbons are associated (Nemcoc *et al*., 2005; Morley *et al*., 2011). Nevertheless, significant commercial discoveries have only been reported in relatively few fold-and-thrust belt systems, and the long-term preservation of hydrocarbons is often problematic due to factors including erosion, fault leakage, biodegradation and gas flushing (Nemcoc *et al.,* 2005). Hydrocarbons will tend to seep from all traps over time, regardless of seal quality (Miller, 1992) and are most likely to be preserved in relatively young fold-and-thrust belts (Late Mesozoic and Cenozoic). The presence of an accumulation is usually attributed to factors controlling preservation rather than to the volumes of petroleum originally present (Macgregor, 1996).

Hydrocarbon discoveries are often confined to the frontal thrusts of thin-skinned fold-and-thrust belts, or to linear zones of reactivated basement faults in inverted basins. A clustering of fields often occurs along the length of a fold-and-thrust belt due to the physical conditions which control hydrocarbon charging and entrapment and the preservation of pools (Nemcoc *et al.*, 2005).

An opportunity to examine many of the factors mentioned above is offered by the composite fold-and-thrust belt system which surrounds the Adriatic and Ionian Seas (Fig. 1) and which, together with the intervening foreland, is the focus of this Special Issue of the *Journal of Petroleum Geology*. This region has been the subject of long-standing industry interest and is a well-established hydrocarbon-producing province. In the context of increased exploration interest in the Adriatic, this brief introduction is intended to summarise past exploration activities and the proven hydrocarbon systems in the region; and to outline the area's future prospects.

REGIONAL SETTING

The Adriatic and Ionian Seas are bordered to the west by Italy and to the east by Slovenia, Croatia, Bosnia-Herzegovina, Montenegro, Albania and Greece. To the north, the area is bounded by the coastline around

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Fig. 1. General location map of the Adriatic and Ionian seas and surrounding countries. The orange box roughly delineates the area covered by papers in this issue: Italy, Croatia, Montenegro, Albania and NW Greece.

Venice, to the south and east by the Kyparisiakos Gulf, to the west by the coast of Pescara (Fig. 1).

In terms of regional structure, the Adriatic region is made up of a complex system of three fold-and-thrust belts and their associated foreland basins which developed as a result of convergence between the European Plate and the Adria (Apulia) micro-plate. Thus the Adriatic basin is surrounded by the Apennine belt to the west, the Alpine belt to the north, and the Dinarides-Albanides-Hellenides fold-and-thrust belt to the east (Lentini *et al.*, 2002; Doutsos *et al*., 2006; Fantoni and Franciosi, 2010; Peace *et al.*, 2012). This structurally complex area developed in response to the concurrent eastward displacement of thrust sheets in the Apennines, the southward migration of the Alps, and the westward motion of the Dinarides-Albanides-Hellenides. These fold-and-thrust belts were formed as a result of subduction of oceanic and thinned continental crust since the Late Cretaceous. Thus formation of the Apennines is the result of the westward subduction of the Adria micro-plate beneath the European Plate. The Alpine orogenic belt formed due to the southeastward subduction of the European Plate beneath the Adria micro-plate; and the Dinarides-Albanides-Hellenides foldbelt developed as a result of eastward subduction of the Adriatic micro-plate under the European Plate.

The Adriatic and Ionian Seas correspond to a composite system of foreland basins developed on continental crust in front of the respective fold-and-thrust belts. This foreland system subsided in response to thrust-loading with the development of discrete depozones (wedge-top, foredeep, forebulge and back-bulge). In general the study region is part of the foredeep, which can be divided into a folded region and a central foreland or carbonate high. This central foreland area covers most of the Adriatic and Ionian Seas and extends from offshore Croatia in the NE to offshore SE Italy in the SW.

Flexural subsidence and eastward motion of the Apennines created a series of depocentres with complex tectonic patterns and sedimentary fills (Peace *et al.*, 2012). In the northern and central Adriatic, the eastward thrust-front of the Apennines extends offshore into the foredeep, resulting in the formation of large-scale overthrust folds and related anticlines. The foredeep has a highly complex geometry and bathymetry; the basin succession is thick in the north

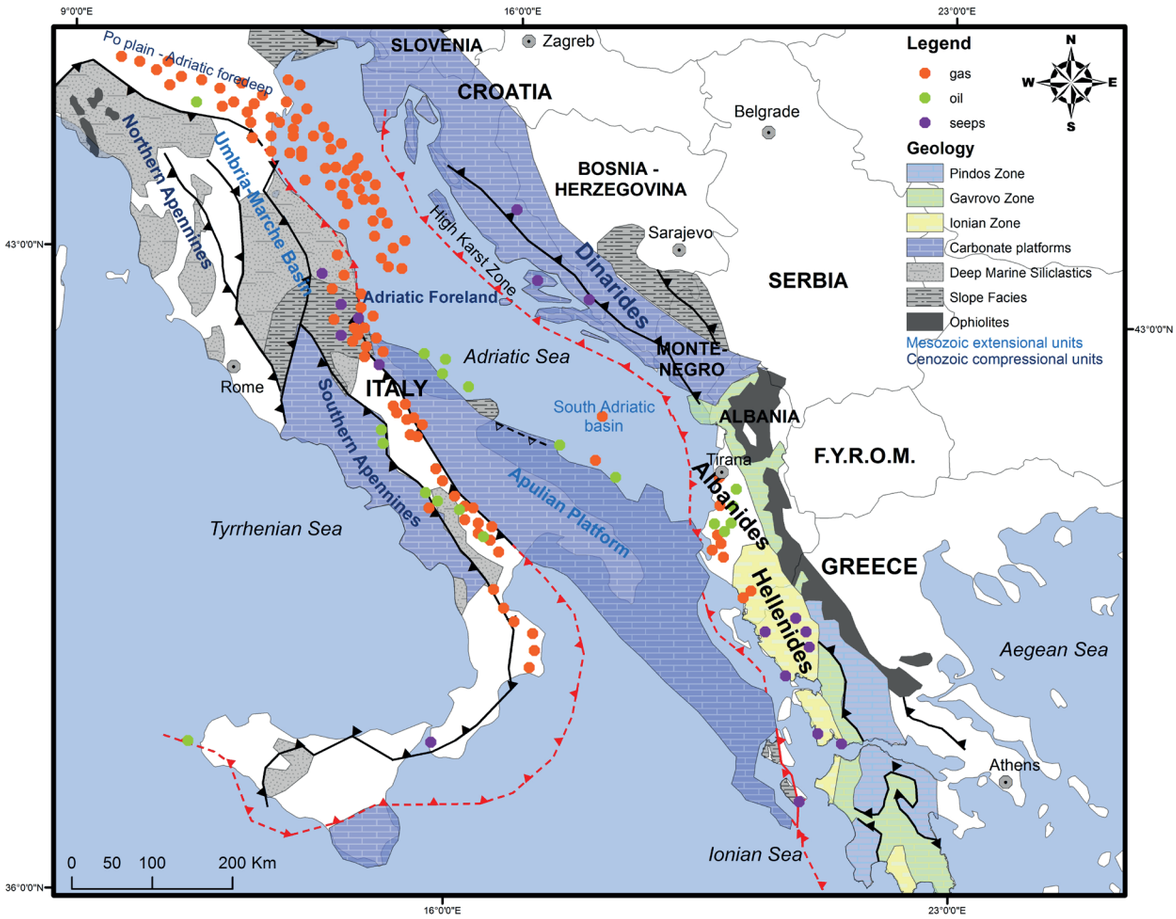

Fig.2. Generalised geological map of the Adriatic area showing oil and gas occurrences (green and red dots) and surface oil seeps (purple dots).

with clear structuring in the west; but in the east it onlaps onto the Dinarides fold-and-thrust belt. In the central area, the foredeep succession is thin on the eastern side of the Adriatic outside of Italian waters. Further south, the foredeep is not present offshore and in fact forms the onshore portion of southern Italy (around the "heel"). In this area, the Apennine fold-and-thrust belt is located onshore, significantly further to the west.

The fold-and-thrust belt system in the Balkan Peninsula is known as the external Hellenides in western Greece, the Albanides in Albania, and the Dinarides in Croatia and Montenegro. This system was established as a result of Alpine orogenic processes related to plate convergence between Apulia and Eurasia and the closure of the Mesozoic Neo-Tethyan Ocean (de Graciansky *et al.,* 1989; Doutsos *et al*., 2006). The Dinarides-Albanides-Hellenides foldbelt is made up of nappes composed of Palaeozoic, Mesozoic and Cenozoic sedimentary units (Karakitsios, 1995; Papanikolaou, 2009).

In the Hellenic domain, the thrust boundary is accompanied by intrusive evaporites indicating dominant compression during orogenesis in western Greece (Karakitsios, 1995; Zelilidis *et al.*, 2003). Detritus from the Hellenides fold-and-thrust belt was transported westwards and accumulated in a series of foreland basins systems that formed the eastern rifted margin of the Apulia micro-plate (Papanikolaou, 2009; Robertson *et al*., 1991). The Hellenides fold-and-thrust belt developed during the Tertiary after closure of the Pindos Ocean and following continent-continent collision between Apulia and Eurasia (Doutsos *et al*., 2006; Kokkalas *et al.,* 2013).

EXPLORATION HISTORY OF THE ADRIATIC AREA

The hydrocarbon potential of the Adriatic and Ionian Seas has been investigated and discussed by authors from the surrounding countries (e.g. Zelilidis *et al.*, 2003; Bertello *et al.,* 2010; Velic *et al.,* 2012; Bega, 2013; Karakitsios, 2013; Konstantopoulos *et al*., 2013; Maravelis *et al*., 2014a,b). This area is a long-established hydrocarbon province in which numerous oil and gasfields have been discovered (Fig. 2).

Commercial hydrocarbon exploration here dates back to the early 20th century, with the first drilling

operations undertaken in **Italy.** The Italian portion of the Adriatic Sea hosts major biogenic gas fields with accumulations in Pliocene reservoir units (Fig. 2). Fields such as Agostino-Porto Garibaldi, Porto Corsini mare and Barbara in the northern Adriatic have been productive for several decades. In the central Adriatic, carbonate reservoirs contain gas and heavy oil (Emilio field). Regional exploration of the southern Adriatic has been limited over the past two decades, but led to the discovery of the Aquila light oil field. The Italian exploration acreage currently available is composed of 86 permits and 195 development leases that cover an area of ~53,000 km^2.

Slovenia has limited energy resources, consisting mainly of coal, lignite and hydro-electricity. Coal is used for both heating and electricity generation. The only oil refinery in the country stopped operating in 2000, and Slovenia is a net oil importer with most imports coming from Russia. The energy demand of Slovenia is rising, highlighting the need for future, energy-related exploration activities.

Exploration efforts in the **Croatian** portion of the Adriatic Sea began in 1966 with the acquisition of 2D seismic data and (in 1970) the first exploration drilling. Over the last twenty years, ~5000 km^2 of 3D seismic lines were acquired, twelve new exploration wells were drilled and seven biogenic gas fields were discovered. Data from approximately 45,000 km of 2D seismic lines, ~6200 km^2 of 3D seismic areas and 135 wells are now available. This activity resulted in the development of nine gas fields, the drilling of more than forty production wells and the installation of nineteen production platforms. The principal gasfields in Croatia are situated in the more external sector of the Po Plain – Adriatic foredeep. Recently published assessments predict a twenty-year production from these fields. Further discoveries of the magnitude of Ivana, the largest field with reserves of 1.4 billion cu. m, are unlikely but smaller fields such as Ana and Vesna contain significant volumes of reserves.

In **Bosnia and Herzegovina,** petroleum exploration has taken place for more than 100 years but no commercial discoveries have been made. Both domestic and foreign companies have been involved in oil and gas exploration, and major projects were carried out during 1973-1992 which incorporated seismic, geophysical, geomagnetic, geochemical and magneto-telluric surveys. These surveys established the existence of a viable petroleum system (Maricic and Danilovic, 2010). Prospective areas were identified containing major structures (e.g. Trebinje, Stolac, Nevesinje, and Mostar) together with the Dreznica "mega structure". The results indicate significant oil and gas potential in the northern region at depths of 2000-4000 m and at depths of 4000-6000 m in the southern part of Bosnia (Dinarides area) (FMEMI, 2009).

In **Montenegro**, the first hydrocarbon exploration activities were conducted at the beginning of the 20th century but systematic studies were not carried out until the 1970s. Exploration was undertaken by domestic companies in cooperation with foreign companies, and included over 10,000 km of 2D seismic profiles offshore, 1250 km of 2D onshore, and 400 km^2 of 3D covering both the on- and offshore. Some 23 wells have been drilled on- and offshore. A significant but non-commercial oil discovery was made at offshore well JJ-3, drilled in 1995. The Government of Montenegro and the Ministry of Economy have recently created a legal and institutional framework to encourage development of the country's hydrocarbons, and the first bid round under the new Hydrocarbons Law was announced in 2013.

Albania was established as a hydrocarbon-bearing province in Roman times, some two thousand years ago. Commercial activities for oil and gas exploration began in 1918 as a result of the involvement of foreign companies. Exploration since the 1940s has resulted in the discovery of major oil and gas fields such as Marinza, Visoka and Ballëshi. During the 1960s, new oil discoveries were made including Gorisht-Kocul, Cakran, Amonica and Delvina. The first round of offshore licensing was held during 1989 - 1991, and five blocks of the Albanian offshore with a total surface area of 11,800 km^2 were offered. At the end of the round five petroleum-sharing agreements were signed.

Exploration activities for hydrocarbons in **Greece** began in the early 20th century, with the first drilling operations undertaken by international oil companies. Since 1960, there have been systematic onshore geological surveys and the drilling of 17 shallow wells. Subsequently, both off- and onshore, 24 exploration and production concessions have been granted. Over 73,000 km of 2D and 2,500 km^2 of 3D seismic lines were acquired and 73 exploration wells were drilled. This exploration activity led to the discovery of the Katakolo oilfield (offshore western Greece) and the Epanomi gas field, onshore northern Greece, as well as biogenic gas accumulations.

PETROLEUM SYSTEMS

Italy has the greatest hydrocarbon resources in southern Europe, with total discovered reserves (produced+remaining) of 1840 million barrels of oil and 30 trillion ft^3 of gas. At present oil production totals 43.2 million barrels per year, about 75% of which comes from the Val d'Agri field in the southern Apennines. Gas production is 340 billion ft^3 per year, mostly biogenic gas from the Po Plain – Adriatic foredeep.

Five source rock intervals have been identified and range in age from Early Mesozoic through Pleistocene.

Three of the source rocks are mainly oil-prone and were deposited during Mesozoic regional extension (Bertello *et al*., 2010) . Of these the most important source rock in the Italian Adriatic is of Late Triassic – Early Jurassic age and is composed of shaly limestones deposited in anoxic conditions in intra-platform basins. Regional seismic profiles show that this source rock probably extends eastwards to offshore Croatia (Wrigley *et al., this issue,* pp. 301-316). Hydrocarbon occurrences associated with this source rock are found in carbonate reservoir rocks from the Po Plain (Malossa field) to Sicily (e.g. Gela field) (Bertello *et al*., 2010). The system is also proven in the Adriatic sea, and includes heavy oil fields in the central sector (e.g. Emilio) and light oil in the southern sector (Aquila) (Cazzini *et al.,* 2015*, this issue,* pp. 255-279). Middle Triassic source rocks (related to the Villafortuna–Trecate oil field in the Po Plain) and Cretaceous source rocks (related to the Val d'Agri field) are not proven in the Adriatic area.

Gas-prone source rocks were deposited in foredeep areas which formed during Neogene orogenesis. The older of these source rock intervals is thermogenic gas-prone and is found in Oligo-Miocene foredeeps offshore Italy. Gas accumulations associated with this source rock occur along the northern Apennines margin (Cortemaggiore field), in Calabria (Luna field) and Sicily (e.g. Gagliano field). An overlying source rock interval produces biogenic gas and occurs in the Plio-Pleistocene succession of the Po Plain–Adriatic foredeep. This source rock produces biogenic gas at Barbara and other fields in the northern Adriatic. Hydrocarbon exploration in Italy is in general mature, especially for gas, with remaining potential estimated to be 6.0 trillion ft^3 of gas reserves and 800 million barrels.

Croatia has proven reserves in the Croatian part of the Po Plain–Adriatic foredeep (e.g. Ivana, Ana and Vesna biogenic gas fields). Reservoir rocks are unconsolidated to poorly consolidated Pleistocene sandstones (Malvic *et al*., 2011).

Major fields in **Albania** include the Patos Marinza oilfield, with production of 11,850 barrels/day; Kuçova oilfield (400 barrels/day); and Durresi oil- and gas-field, with reserves of 1960 million barrels of oil and 958×10^9 cu ft of gas. Source rock intervals occur in the Mesozoic carbonate succession and range in age from Triassic to Cretaceous. Related hydrocarbon accumulations occur within Jurassic-Eocene carbonate reservoirs in the Ionian Zone; within parts of the Albanide fold-and-thrust belt; and within upper Miocene sandstone reservoirs in the Peri-Adriatic Depression.

A working petroleum system is present in **western Greece**, as proved by the Katakolon oilfield and by a number of oil shows, seeps and gas leaks. Reserves in Katakolon are estimated at 5 million barrels of oil. Organic-rich source rocks include Triassic evaporites and Jurassic-Cretaceous pelagic mudstones, and Oligocene-Neogene siliciclastics (Karakitsios, 2013; Maravelis *et al.*, 2014a,b). Reservoir rocks are composed of Mesozoic carbonates and Cenozoic clastic sediments.

FUTURE ACTIVITIES AND PROSPECTS

The Governments of **Greece, Albania, Montenegro** and **Croatia,** have recently launched new licensing rounds to explore their offshore areas for oil and gas. **Greece** currently has open the 2nd international licensing round offering 20 offshore blocks (about 65 sq km each in the Ionian Sea and south of Crete). **Albania** launched an open door licensing round for 12 onshore blocks and one offshore block. The country is the location of continental Europe's largest onshore fields, Patos-Marinza and Kucova, both operated by Bankers Petroleum. Patos-Marinza has estimated original reserves of 5.4 billion barrels of oil; it has been recently reported that the field still holds approximately 2 billion barrels of oil. **Montenegro r**ecently closed its first offshore licensing round with 13 blocks covering a total area of 3100 sq km, and has received bids from three different groups (Marathon / OMV Montenegro; Eni / Novatek Overseas; and Energean Oil & Gas and Mediterranean Oil & Gas). **Croatia** currently has an open licensing round offering 29 offshore blocks (the licensing area covers an area of 36,823 sq. km), and companies have until early November to prepare their documentation. The fiscal regime is favourable with a royalty tax of only 10% plus license fees based on per square km areas.

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Future hydrocarbon exploration in the Adriatic area will requires a good understanding of the geodynamic setting as well as a multidisciplinary approach. The papers in the present volume therefore make use of wide-ranging multidisciplinary data-sets (including stratigraphic, structural and geophysical) to describe the development and hydrocarbon potential of the Adriatic region, with particular reference to the central and northern parts of the area.

Cazzini *et al.* (pp. 255-279) review the biogenic gas play in the Italian sector of the offshore Adriatic which is highly mature from an exploration point of view, and only very limited additional accumulations are predicted. They propose that the residual exploration potential of the Adriatic may be concentrated on the high-risk high-reward but unproven Mesozoic oil play in the north. They also describe the central and southern parts of the Adriatic, where the Mesozoic oil play is proven and has medium to low exploration potential.

Velic *et al.* (pp. 281-300) review the stratigraphy and petroleum geology of the Croatian part of the offshore Adriatic basin and the onshore Dinarides. Coastal parts of Croatia are dominated by the SW-verging Dinaric foldbelt, to the west and SW of which is the Adriatic Basin (i.e. the stable foreland). In both areas, the stratigraphic column is dominated by a thick carbonate succession ranging from Carboniferous (Middle Pennsylvanian) to Miocene. A number of organic-rich intervals with source rock potential have been identified on- and offshore Croatia. Traps and potential plays have been identified in the Dinaric belt and adjacent foreland from seismic data. Evaporites form potential regional seals, and carbonates with secondary porosity form potential reservoirs. In the northern Adriatic offshore Croatia, Pliocene hemi-pelagic marlstones and shales include source rocks which produce commercial volumes of biogenic gas. The gas is reservoired in unconsolidated sands of the Pleistocene Ivana Formation.

Wrigley *et al.* (pp 301-316) describe the petroleum geology and hydrocarbon potential of the Adriatic basin, offshore Croatia, based on recently acquired seismic data. The interpretation of this regional database points to the presence of mature source rocks, Jurassic and Cretaceous carbonate platform margins/slope talus plays, and Cenozoic clastic plays offshore Croatia. Three distinct sub-basinal areas are informally defined, each containing a variety of play types.

Bega (pp. 317-330) shows that the most important play types in Montenegro appear to be the inverted autochthonous platform carbonates (both on- and offshore) and platform margin closures (offshore). Potential source rocks for the autochthonous platform carbonate plays are of Cretaceous age and may generate economic volumes of light oils. Potential reservoirs are fractured shallow-water carbonates, sealed by deep-water shales of Oligocene age.

The paper by **Zelilidis *et al.*** (pp 331-348) focusses on the Ionian zone in NW Greece which represents the southward extension of the prolific Albanian oil- and gas-producing province. Two potential hydrocarbon systems have been identified here: an oil/gas-prone Mesozoic system, and a Tertiary biogenic gas-prone system.

A final paper in the thematic series is expected to appear in a forthcoming issue of the Journal of Petroleum Geology. This paper, based on a recently-acquired 2D seismic dataset, evaluates the petroleum potential of offshore western Greece.

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