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Review and Insights into Carbonate Plays of the Circum-Adriatic: Volume 1

1. INTRODUCTION AND OUTLINE OF REPORT

1.1. Introduction

The circum-Adriatic region is one of the most important geological provinces of the Mediterranean for the production and storage of hydrocarbons (Bigi et al., 2013; Figure 1), the majority of productive structures generally being associated with the flexure of the Adriatic/North African continental margin (Casero, 2004) and evolution of the Apennines fold and thrust belt (Casero and Bigi, 2013) (Figure 2).

Both oil and gas (biogenic and thermogenic) are reservoired in clastic and carbonate reservoirs ranging from Triassic to Neogene in age (Figure 3). Seepages are present in many countries of the circum-Adriatic, and this prompted commercial exploration to start in the mid 1800's. To date, **Italy** is by far the most prolific country in this region with respect to oil and gas discoveries, with total discovered reserves of some 1840MMBO and 30TCFG (produced and remaining reserves; Bertello et al., 2010; Figure 1). Neighbouring countries to the east of the Adriatic Sea are relatively underexplored compared to Italy. **Albania** has had exploration success since the mid 1900's, which includes discoveries such as Cakran, Visoka and Marinza. To date there have been 18 fields discovered, and the recent Shpirag discovery has prompted renewed interest in Albania. Exploration in **Greece** started in the early 1900's (Zelilidis and Maravelis, 2015), but successes to date have been modest, with the West Katakolo and Epanomi fields being the main oil producers. Petroleum exploration in the Adriatic margin of **Croatia** has been carried out for more than 50 years (Wrigley et al., 2015; Croatian Hydrocarbon Agency, 2016). This resulted in the discovery of 7 biogenic gas fields in the poorly consolidated sands of the Po Plain to Adriatic foredeep. No commercial hydrocarbon discoveries have been made in carbonate reservoirs to date, but indications for hydrocarbons were found in several wells. In **Bosnia and Herzegovina**, hydrocarbon exploration has been carried out for more than a century, but no commercial oil or gas accumulations have been found to date. **Montenegro** is underexplored compared to other areas in the region, with the First Exploration Round being announced in 2014. To date, there are no commercial oil or gas discoveries, although a non-commercial discovery was made offshore by the JJ-3

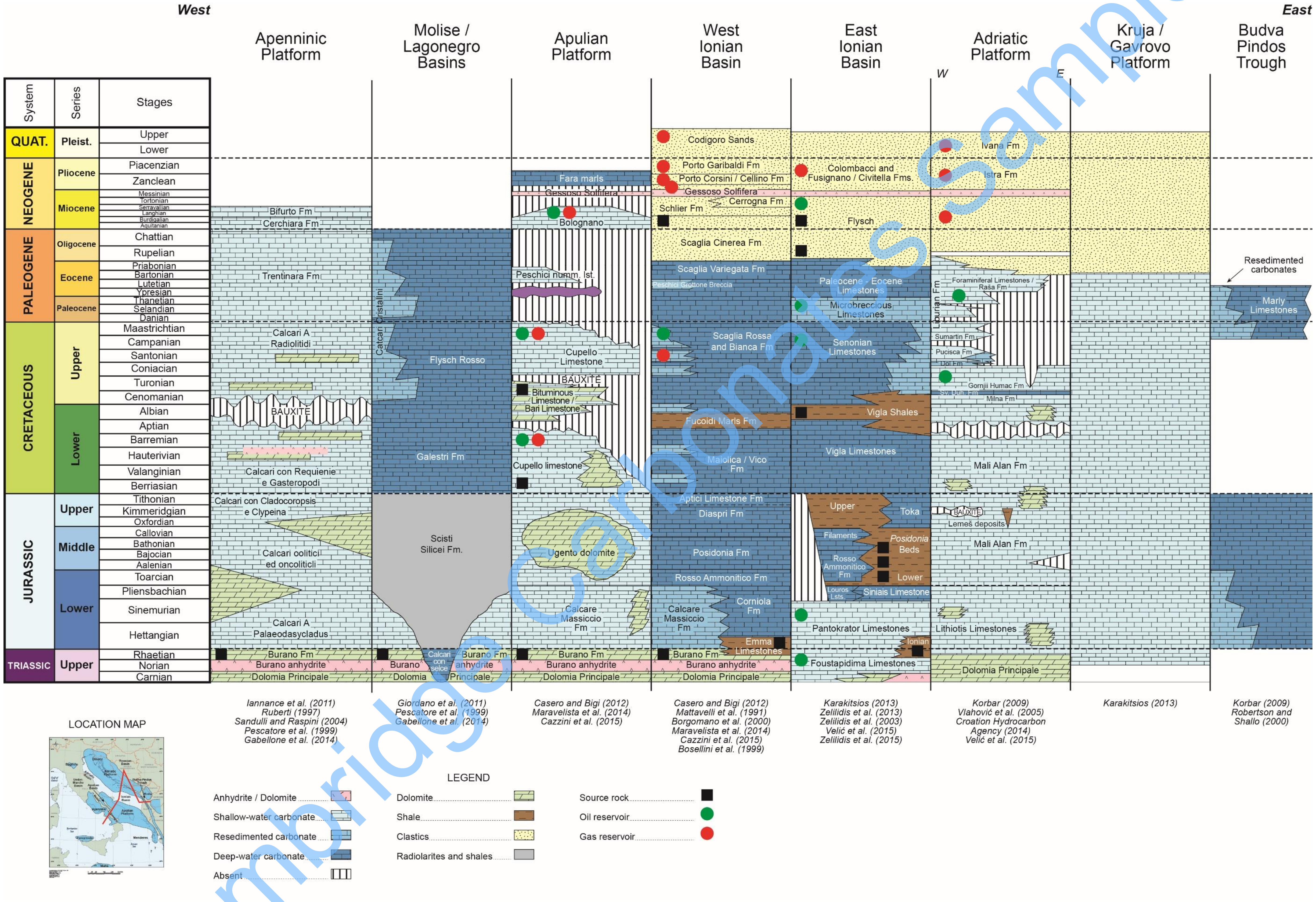

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Figure 3 Stratigraphic columns showing the regional lithostratigraphy and primary facies types. Compiled from authors above.

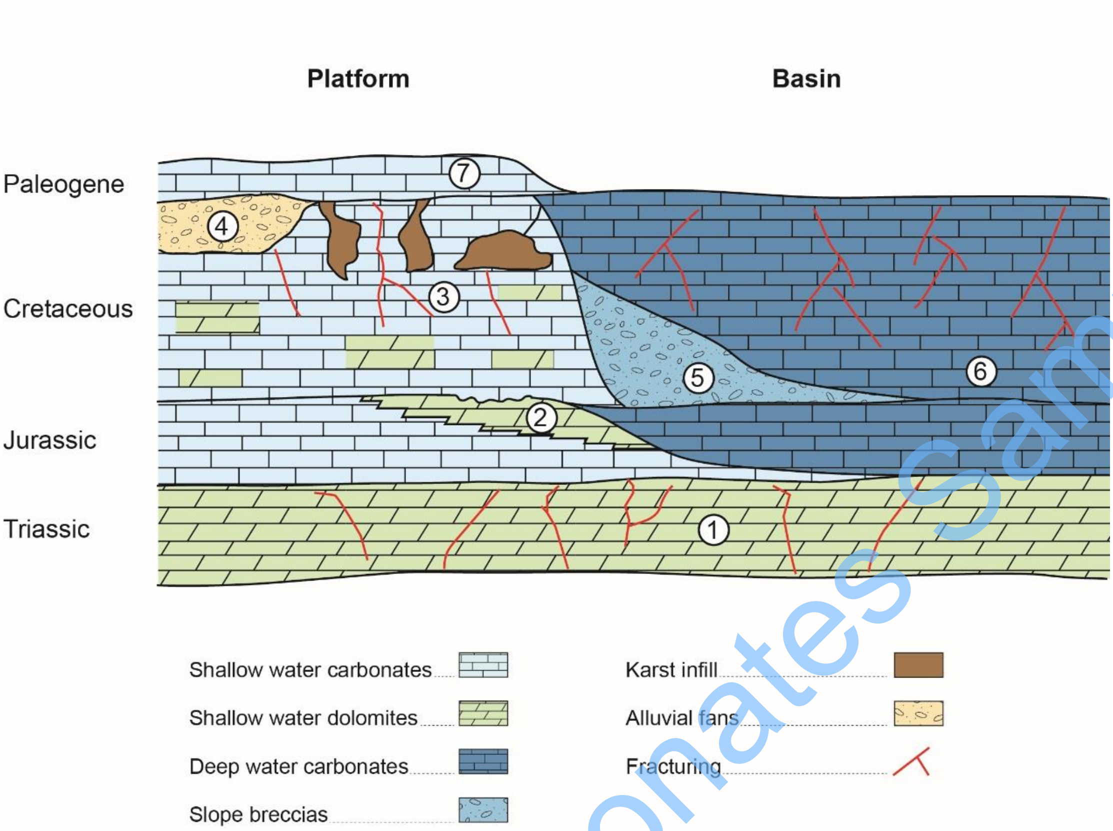


Figure 4 Schematic diagram highlighting the seven key carbonate reservoirs discussed in this report. These include (1) Triassic dolomitised peritidal reservoirs; (2) Jurassic shallow-water platform carbonate reservoirs; (3) Cretaceous karstified and fractured shallow-water carbonate reservoirs; (4) Cretaceous alluvial fans; (5) Jurassic to Eocene resedimented slope breccia reservoirs; (6) Fractured pelagic/resedimented carbonate reservoirs and (7) Paleogene shallow platform reservoirs.

2. INTRODUCTION TO THE GEOLOGY OF THE CIRCUM-ADRIATIC

2.1. Geographic and geologic setting

The circum-Adriatic, as defined in this report, is located in the central Mediterranean region. It includes the fold-and-thrust belts of the Apennines, Dinarides/ Albanides/ Hellenides and the Adriatic Sea and encompasses parts of Italy, Slovenia, Croatia, Bosnia and Herzegovina, Serbia, Montenegro, Albania and Greece (Figure 1). It is bordered by the Southern Alps to the north and two opposite vergent orogenic belts on its eastern and western margins, i.e. the Apennines to the west and the Dinarides/ Albanides/ Hellenides to the east (de Alteriis, 1995; Figure 6).

From a plate tectonic viewpoint, the circum-Adriatic region corresponds to the Adriatic Plate (also known as the Adria and Apulia (sub or micro-) plate) and structural units which developed on the African Plate in the circum-Adriatic realm and became incorporated in the fold-and-thrust belts fringing the Adriatic Sea as a result of the Alpine Orogeny. The Adriatic Plate comprises continental lithosphere that was subducted westward under the Apennines' thrust front and eastward under the Dinarides/ Albanides/ Hellenides' thrust front due to the convergence of the European and African Plates (Petricca et al., 2013) (Figure 6).

2.1. Carbonate platforms

The sedimentary units of the circum-Adriatic region are predominantly Mesozoic to Cenozoic in age and were deposited during a period of rift and drift of the Adriatic Plate. Of these deposits, Middle Triassic to Cretaceous carbonate platforms, i.e. the Apenninic, Apulian, Adriatic and Kruja Platforms (Figure 7), host the most important hydrocarbon reservoirs (Zappaterra, 1994; Vlahović et al., 2005). Time equivalent units of these geographically separated carbonate platforms consist of similar lithostratigraphic units and facies patterns (Zappaterra, 1994). As a consequence, understanding the sedimentary sequences and depositional environments of the Adriatic Platforms is of considerable help for locating reservoirs and predicting reservoir quality during exploration activities in the circum-Adriatic region. Therefore, these carbonate platforms are the focus of this report.

overthrusted by allochthonous units. In Slovenia, Croatia, Bosnia and Herzegovina and Montenegro the tectonostratigraphic units consist from east to west: Dalmatian, Budva, High Karst, pre-Karst, Bosnian Flysch and Dinaridic ophiolite (Pamić et al., 1998; Schmid et al., 2008; Figure 9). Albania and western Greece are characterised into: pre-Apulian, Ionian, Gavrovo-Tripolitza and Pindos zones (Greece) which are known respectively as the Sazani, Ionian, Kruja and Krasta-Cukali zones in Albania (Figure 10). An overview of the tectonic history and nomenclature of the different tectonic sectors in Albania and Greece are presented in Figure 11, and below.

Pre-Apulian/Sazani Zone (Albanides and Hellenides)

This uplifted foreland block lies on the Apulian Carbonate Platform to which it is bound to the west, and the Ionian zone the east (Robertson and Shallo, 2000; Sejdini et al., 1994; Figure 10). In Greece the Pre-Apulian zone is also known as the Paxos zone.

Ionian Zone (Albanides and Hellenides)

This zone forms an unbroken, elongated unit that represents a thin skinned fold-and-thrust belt with an evaporite basal décollement (Robertson and Shallo, 2000; Figure 10). It is dominated by large scale linear folds forming large anticlines and synclines cut by major high angle reverse faults (Robertson and Shallo, 2000) and is separated into Internal, Middle and External zones. According to Robertson and Shallo (2000) two major tectonic phases can be distinguished in this zone, one in the Middle Miocene and another in the Miocene-Pliocene which was related to the final thrusting of the Ionian zone southwards over the Pre-Apulian/Sazani zone. To the north the Ionian zone corresponds to the Adriatic foreland basin, which is not exposed.

Dalmatian/Kruja/Gavrovo-Tripolitza zone (Dinarides, Albanides and Hellenides)

The Dalmatian zone of the Dinarides consists of the north-eastern part of the Adriatic Platform (Schmid et al., 2008). It is considered to be equivalent to the Kruja-Gavrovo-Tripolitza zone of the Albanides/Hellenides. The latter zone is a marginal shallow-water carbonate platform that is connected to the Ionian zone by a high angle, reactivated reverse fault (Figure 10; Robertson and Shallo, 2000). In Albania it is

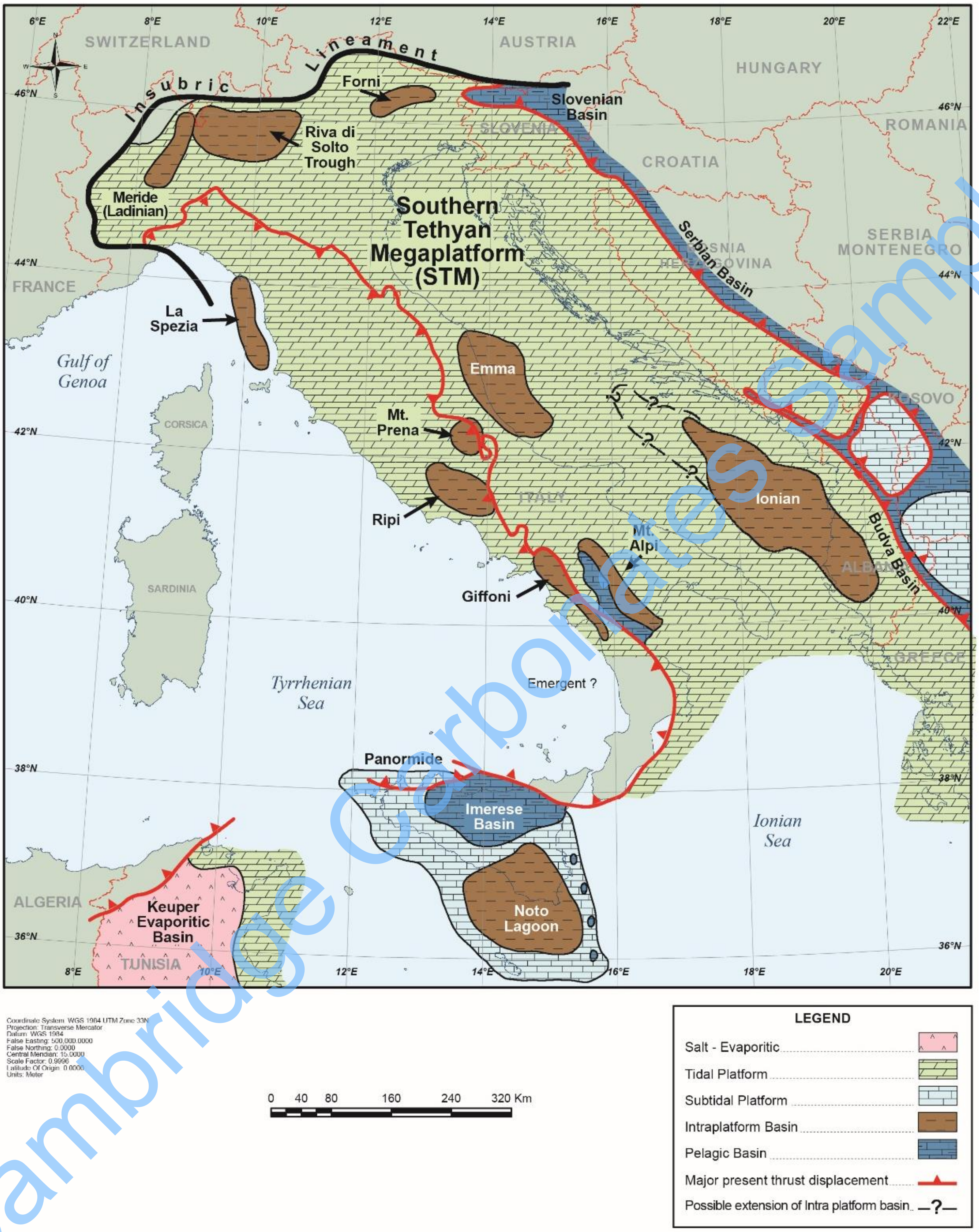


Figure 14 Late Triassic, schematic palaeogeography map. Adapted from Zappaterra (1994), Cazzini et al. (2015) and Wrigley et al. (2015).

In the Ionian Zone of western Greece, the Jurassic sequence began with deposition of shallow-water limestones of the Pantokrator Formation, which directly overlay the Foustapidima Limestones (Figure 3). Shallow-water peloid-bioclast wackestones and packstones are common, and represent probable platform interior and platform margin depositional settings during the Early Jurassic (see Section 2.7 in Volume 2 of this report for thin section photomicrographs). These facies are overprinted by calcrete textures, indicating exposure.

Syn-rift basinal sedimention associated with the formation of the Ionian Basin initiated during the Pliensbachian, with deposition of the pelagic and hemipelagic Siniais and Louros Limestones (Karakitsios, 2013; Figure 3). Significant thickness variations of the Jurassic package are a consequence of this syn-rift tectonic activity, with the deepest half grabens recording the thickest packages of shales (Posidonia Beds). The Posidonia Beds are separated into a Lower and Upper Member (Figure 3). The Lower Posidonia Beds are characterised by well-bedded pelagic laminated marls, siliceous argillites, and marly limestones. The geometry of the restricted subbasins favoured water stagnation and, consequently, the development of local euxinic conditions in the bottom waters (Karakitsios, 2013). The Callovian to Tithonian Upper Posidonia Beds exhibit an increase in radiolaria and chert compared to the Lower Posidonia Beds, with numerous horizons rich in Posidonia (Bosistra; Karakitsios, 2013). The Lower Posidonia Beds range in thickness from 10 – 150m, whilst the Upper Posidonia Beds are generally between 10 – 140m in thickness (Karakitsios, 2013). Slumped sediments found in the basin were derived both from the shallower margins of the half grabens during these extensional phases, or by halokenesis of Triassic evaporites at the base of the succession (Karakitsios, 2013).

In Central Albania, pelagic limestones are typical facies, representing basinal deposition in the eastern margins of the Ionian Basin (Zelilidis et al., 2013).

3.3.2. Adriatic Carbonate Platform and Adriatic Basin

The Jurassic of the Adriatic Platform is represented by predominantly shallow-water carbonate deposition (Figure 3; Figure 14; Figure 20). During the Toarcian, extensional tectonics resulted in the formation of the Adriatic Basin (the northern extension of the

Platform was not an isolated "Bahamian" bank, but rather more like a "Florida Peninsula".

Figure 24 Three-toed dinosaur footprints in Early Cretaceous shallow-water carbonate facies from Gargano, Italy.

with dasycladacean algae, gastropods and ostracods. Fenestral fabrics are common. Examples of these textures and microfacies are documented in Section 4 of Volume 2 of this report. Murgia et al. (2004) note that large parts of the Apulian Platform were dolomitised during burial.

The Early Cretaceous (Hauterivian to Aptian) outcrops in Greece represent platform interior facies in the eastern-most parts of the Apulian Platform. Photomicrographs presented in Section 2.6 of Volume 2 of this report show these shallow-marine inner neritic facies to be characterised by peloid, microbial and commonly pisoid-rich facies. High energy pisoid grainstones originally had excellent interparticle porosity, but this was later cemented by calcite.

Whilst spatially, the platform interior facies are the most extensive, the platform margin and transition through slope to basinal facies can be witnessed in outcrop in several areas of the Apulian Platform: at Gargano, which is the NE margin of the platform, and at Maiella, which represents the NW margin of the Apulian Platform.

Shelf margin facies in the Late Jurassic and earliest Cretaceous are typically represented by an interior oolitic belt bordered by a margin exterior bioconstructed belt. However, in the later Early Cretaceous sequences the oolitic facies belt is not present, with the shelf margin characterised by stromatoporoid boundstones, rudstones and skeletal sands (Hauterivian to Barremian) or by sponges, chaetitids, corals and rudists (Bosellini et al., 1999). Slope facies are characterised by gravity-flow deposits and slumps: breccias in proximal locations (Figure 26b), through to graded grainstones (calciturbidites) interfingering with pelagic deposits in distal settings. The true pelagic facies are represented by thin-bedded chalky limestones with cherts and locally black shales. Slumps and truncation surfaces are commonplace (Bosellini et al., 1999).

Figure 28 Outcrop examples of Eocene nummulitic facies from Gargano, Italy (Apulian Platform). (a) Nummulitic shoals form cross-bedded packages, suggestive of inner-mid ramp settings. (b) Detail of cross bedded nummulitic facies. (c) bioturbated Eocene mid-ramp carbonates with nummulites concentrated in burrows.

The Oligocene records several phases of tectonic instability along the Apulian shelf margin, with the development of small basins (grabens) between emergent areas that were locally eroded (Karakitsios, 2013). This is particularly well-developed in the Pre-Apulian zone of Greece, where spectacular slumps and turbidites are observed (Karakitsios, 2013). The reworked carbonates are characterised by pelagic carbonate mudstones interbedded with reworked intraclast-bioclast grainstones. Photomicrographs are sedimentary logs are presented in Sections 2.5, 3.1 and 3.2 of Volume 2 of this report.

In the Ionian Basin, outcrops in Greece and Albania indicate that above the Jurassic and Cretaceous pelagic carbonates lies a transitional zone of marls, which represents a change in depositional regime as Late Eocene/Early Oligocene to Early Miocene turbidites were deposited from the eastern margin of the Ionian Basin due to increased Alpine tectonic activity (Zelilidis et al., 2013).

eastward migration of the thrust front caused the progressive underplating of the Apulian platform (Pescatore et al., 1999).

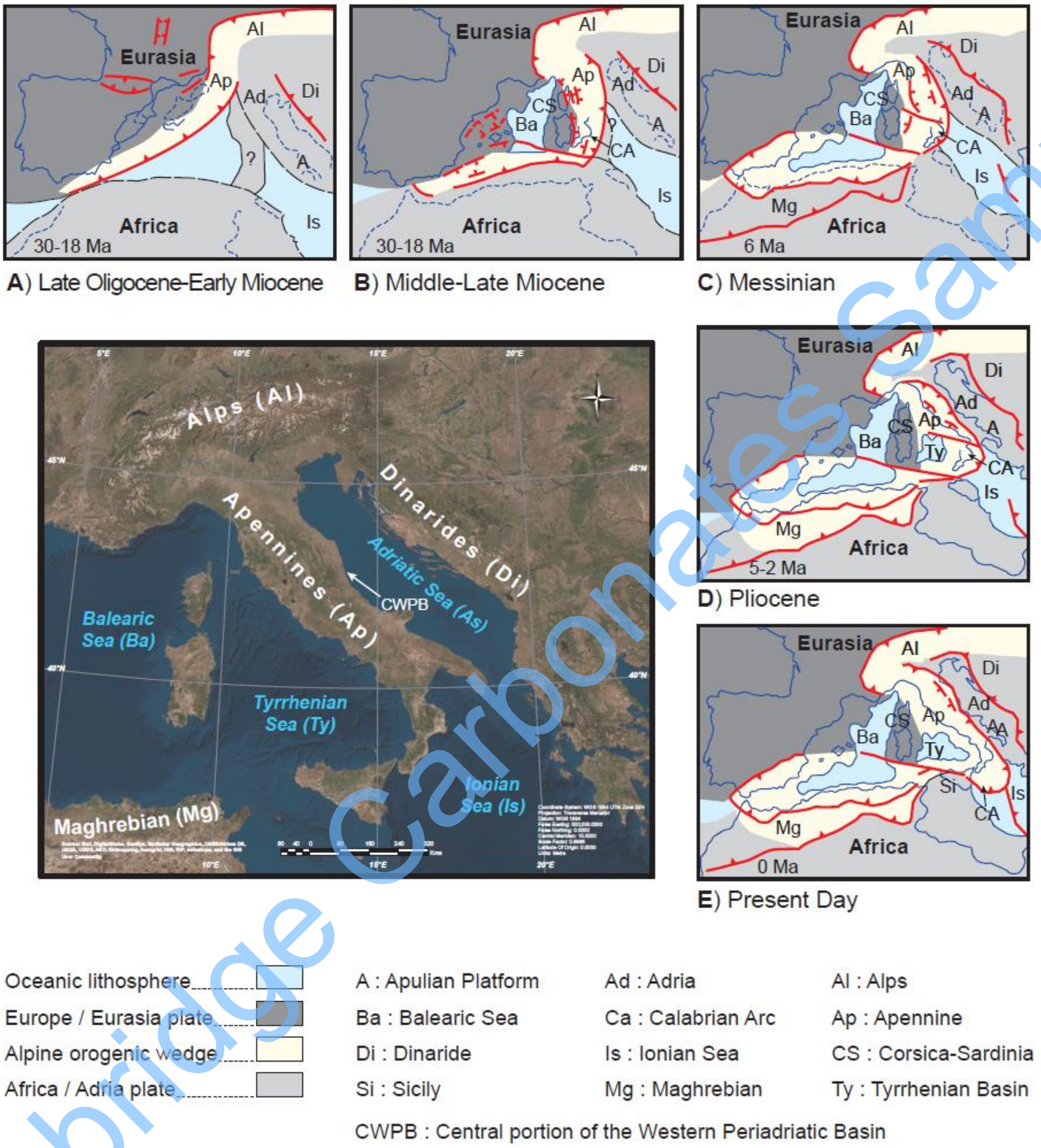


Figure 32 The Cenozoic geological evolution of the Central Mediterranean. Redrafted from Artoni, (2013).

Dinarides/Albanides/Hellenides

The Dinarides/Albanides/Hellenides consist of tectonostratigraphic nappes stacked westwards onto the Adriatic-Dinaridic Platform in the north and the Apulian Platform in the south. The tectonic evolution of this orogen (Figure 33) is thought to be influenced by a transform zone in the north of Albania - the Shkodër-Peje (Scutari-Pec)

Oils in the Sicily fields (i.e. Gela, Ragusa; Vega; Perla; Table 1) are often heavy (15 to 21°API), with studies indicating this is the result of a low thermal gradient and the early expulsion of hydrocarbons from organic rich Triassic shales (Wavetech, 1998).

Field/well	Reservoir Depth (m)	Source rock	Maturation timing	API
Gela	3300	Late Triassic Noto/Streppenosa Formation	Peak maturation/expulsion during Plio-Pleistocene	10° (biodegraded)
Val D'Agri	various	Albian-Cenomanian	Oil window during Pliocene	Wide range of gravities (7 to 46° API), mostly clustering around 32 to 37° API. Represents density segregation due to the very thick oil columns
Rospo Mare	1330	Late Triassic (Burano Formation /Emma Limestones)	Thermal maturity from Pliocene onwards	11° with 6% sulphur
Aquila	2870	Late Triassic Burano Formation	Late Cretaceous to Late Oligocene with the main expulsion during the Eocene	22° (base) to 36° (top)
Elsa	~3800	Late Triassic to Early Jurassic	Thermal maturity from Pliocene onwards	15°
Vega	2440-2750	Late Triassic to Early Jurassic	Plio-Pleistocene	15.5° to 16°
Gaggiano	4650-6200	Middle Triassic		34-42°
Castelpagano				31°
Benevento				46°
Villafortuna	4650-6200	Middle Triassic		34-42°
Ragusa		Late Triassic		19°, 2% sulphur
Malossa	4980-5800	Late Triassic	Multiple generation phases: Early Jurassic, Cretaceous and Plio-Pleistocene	47-53°
Cavone	2900	Late Triassic		20-22°; 4% sulphur

Table 1 Nature of hydrocarbons in selected fields in Italy. Data collated from Casero (2004); Bertello et al. (2010); Wavetech (1998); Mattavelli et al. (1993); Mattavelli and Margarucci (1992); Caldarelli et al. (2013); Shiner et al. (2013); Schramm and Livraga (1986); Lindquist (1999); Nardon et al., (1991).

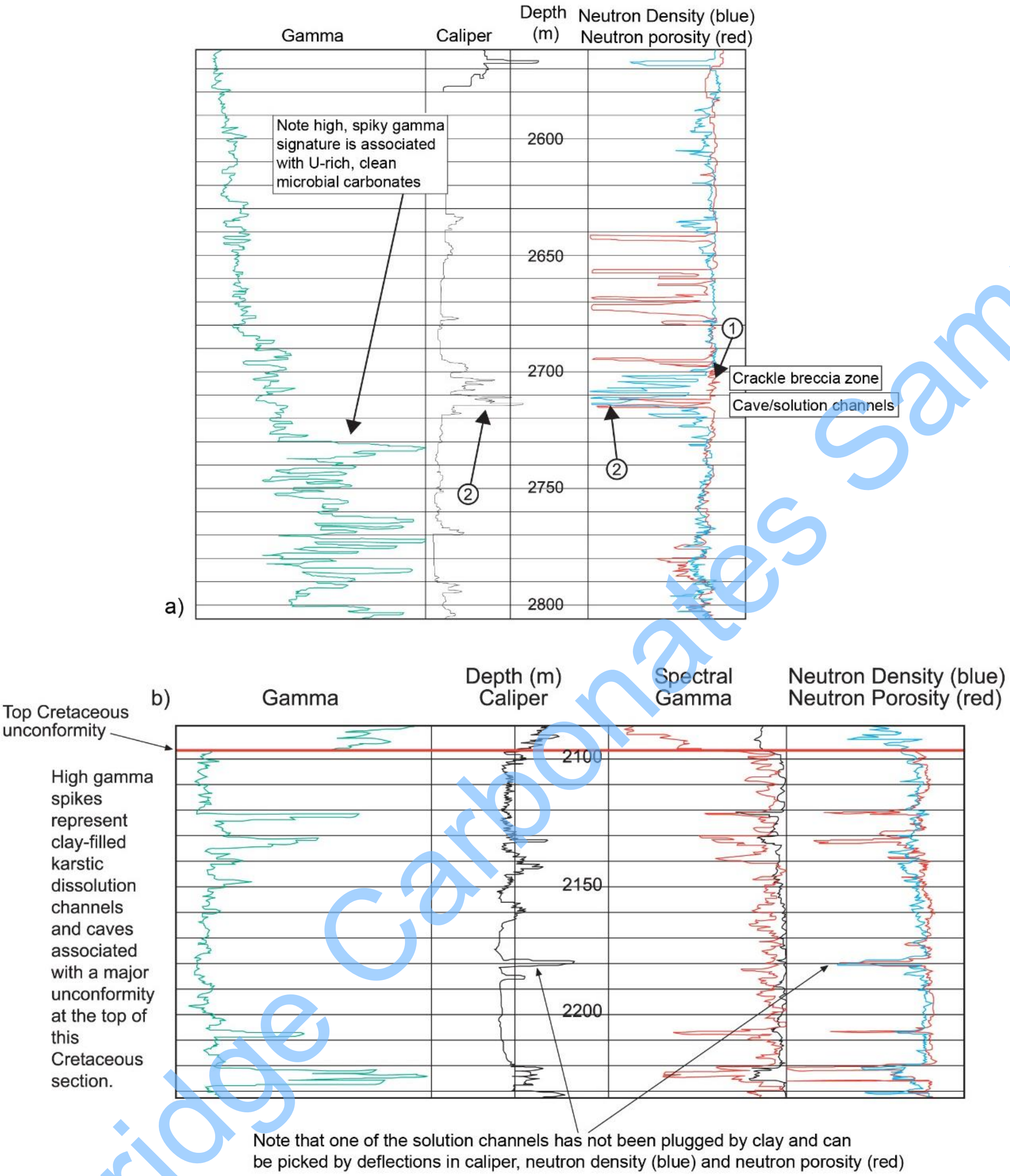
The Perla Field, also located in southern Sicily, also contains oil in Early Jurassic shelf limestones of the Siracusa Formation.

4.2.3. Cretaceous karstified and fractured shallow-water carbonate reservoirs

Shallow-water, restricted, platform-interior carbonates are particularly important in the Southern Apennines, where the Apulian platform is at depth and forms a reservoir in fields such as the Val d'Agri culminations (Costa Molina, Monte Alpi, Cerro Falcone, Monte Enoc etc.). The carbonate intervals are incredibly thick (up to 2000m), and therefore represent the evolution of the platform through the Lower Cretaceous to Miocene.

Early Cretaceous packages are characterised by shallow-water limestones and dolomitic limestones that mostly have a restricted nature (Bertello et al., 2010). These are rich in peloidal/microbial fabrics, ostracods and miliolids. In the Cenomanian, peloid/ooid/oncoidal fabrics appear more dominant, and during the latest Cretaceous, notably in the Santonian, rudist-rich facies become more common, interbedded with thick, mud-supported lagoonal carbonate mud facies (Bertello et al., 2010). Dolomitisation locally affects these inner platform facies, and is considered to be early diagenetic in origin (Giorgioni et al., 2016; Galluccio, 2009). The dolomites are typically interlayered at a metre-scale with undolomitised platform interior limestone facies. Of interest however, is that the dolomites typically exhibit better matrix porosity (averages 3.1-3.7%) compared to the host limestones (1.4%) (Giorgioni et al., 2016). Galluccio (2009) also noted the presence of fracture-related dolomites in the Southern Appenines which were precipitated from hot pore waters (130°C). These are considered to have been associated with Neogene thrusting (Galluccio, 2009).

Of importance (in a hydrocarbon production sense) is the karstification and tectonic fracturing that these low-matrix permeability reservoirs experienced. The Cretaceous was a period characterised by greenhouse conditions with low amplitude sea-level fluctuations. The influence of these sea-level fluctuations on the carbonate platform resulted in the development of metre-scale, shallowing upward cycles (Figure 26a). Periodically, at the top these of these cycles, a karst or palaeosol horizon developed



Note high, spiky gamma signature is associated with U-rich, clean microbial carbonates

High gamma spikes represent clay-filled karstic dissolution channels and caves associated with a major unconformity at the top of this Cretaceous section.

Note that one of the solution channels has not been plugged by clay and can be picked by deflections in caliper, neutron density (blue) and neutron porosity (red)

Figure 44 Example of solution channels on wireline logs from the Southern Apennines area. (a) Karst systems in Cretaceous carbonates. ① Above the solution channels (collapsed caves) deflections in caliper and neutron density but NOT neutron porosity suggest intense fracturing (crackle breccia development) in the roof of the former cave system. ② Note deflection of caliper, neutron density (blue) and neutron porosity (red) suggesting the presence of solution channels and/or caves at the base of the karstified zone. (b) Solution channels in Cretaceous carbonates.

Total gamma ray logs of wells drilled through Late Cretaceous deposits of the circum-Adriatic region may record the occurrence of clays/muds. This can reflect either the presence of clay/mud deposition in caves and palaeosols, carbonate mudstone in

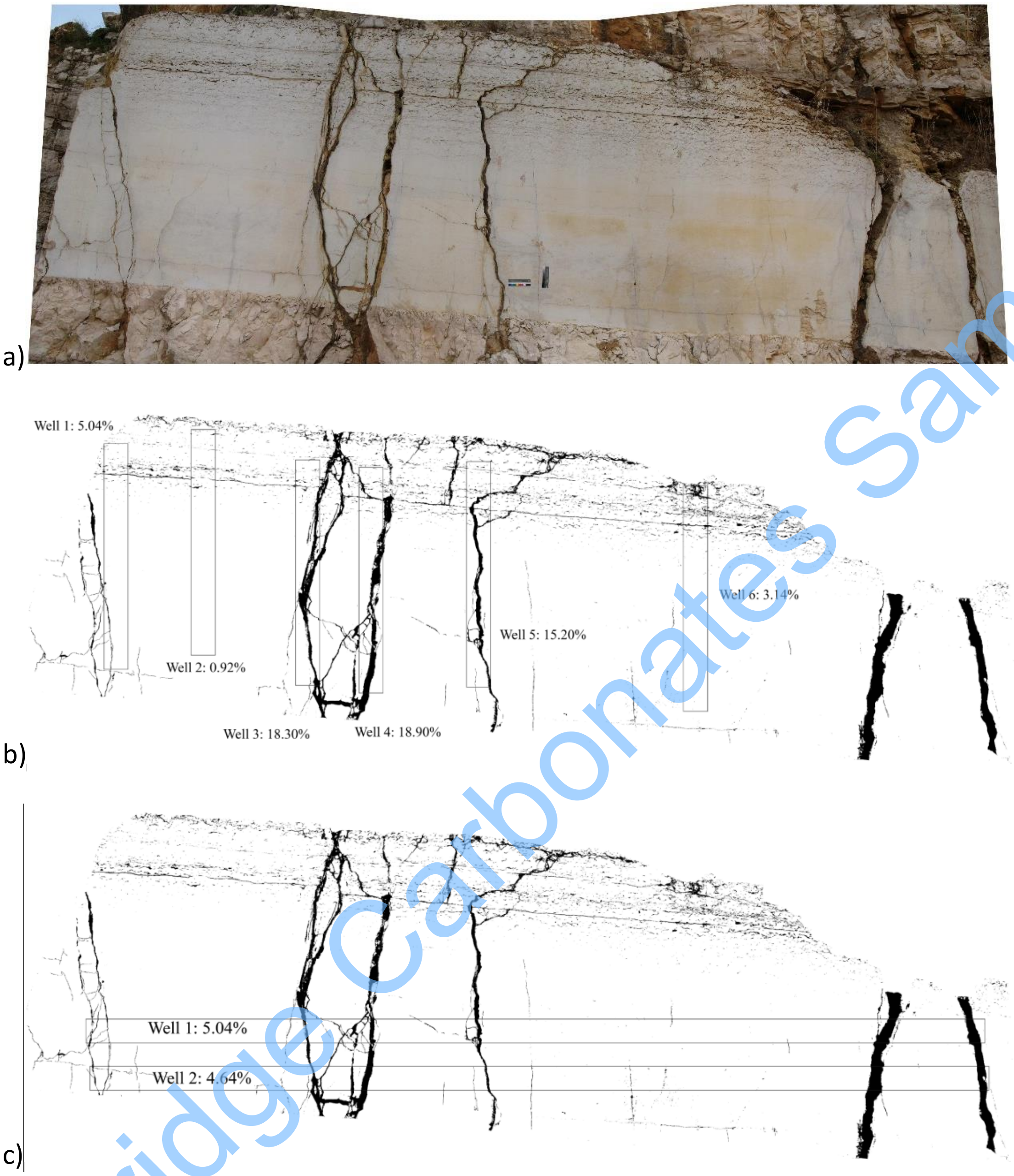


Figure 45 Early Cretaceous fractured and karstified shallow-shelf carbonates from the Gargano area. (a) Wire-cut face, cut by sub-vertical karst fissures. Total karst macroporosity if 5.01%. Field of view = 9m. (b) Karst macropore map of (a) with six randomly placed vertical "wells". (c) Karst macropore map of (a) with two randomly placed horizontal "wells".

Example: Val D'Agri fields

The Val d'Agri culminations (Monti Alpi, Cerro Falcone, Monte Enoc and Costa Molina, Calderosa) and are situated in a Cretaceous petroleum system that lies in the Mesozoic carbonate foredeep/foreland area of the thrust belt of the Southern

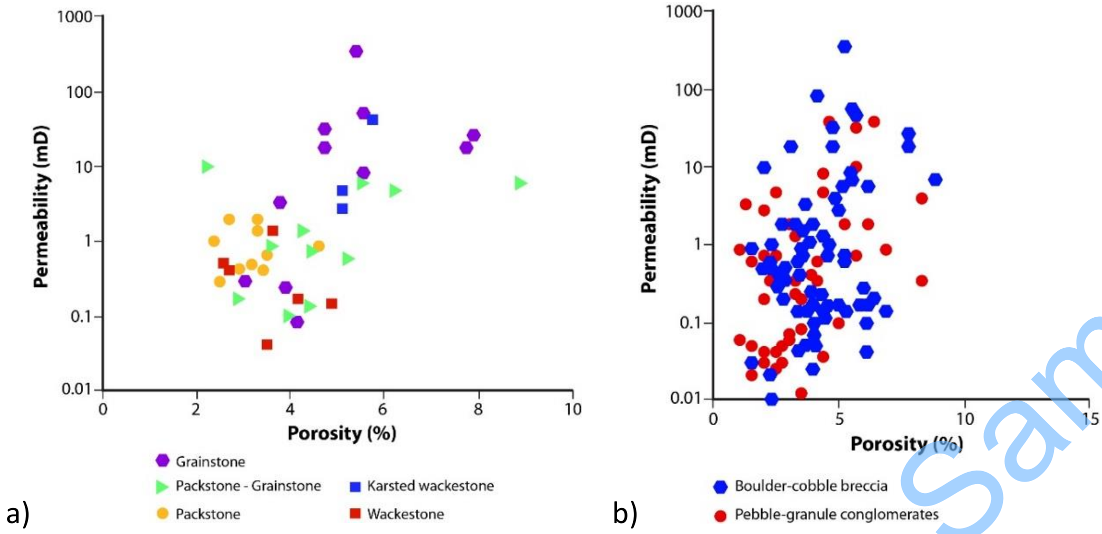


Figure 50 Influence of provenance on matrix porosity/permeability for alluvial fan deposits in the Southern Apennines example. (a) Grainstones have the best porosity and permeability properties. Wackestones have the poorest porosity/permeability properties but are improved by karstification. (b) shows the matrix poroperm properties grouped by depositional texture.

Figure 51 Subsurface example of a pebble-cobble conglomerate from a Southern Apennines field, interpreted to have been deposited from part of an alluvial fan. The conglomerate is evidently polymict and contains some angular clasts such that it is practically a breccia. The matrix sediment is relatively pale in colour, with many small fragments of clasts being visible. In the large clast at the top, an open fracture set is visible; this fracture set does not cross into the matrix.

Table 6 provides a summary of the reservoir properties for the resedimented slope breccia reservoirs.

Field/well	Lithology	Porosity (%)	Documented permeability	Comment
Aquila	Partially dolomitised	2-23% (average approx. 10%)	Up to 1800mD. Average horizontal perm ranges from 12.1-68.7mD; average vertical perm ranges from 11.5-108.4mD (depending on reservoir age)	Best reservoirs are in breccia facies
Miglianico	Partially dolomitisted	1 to 10%; averages approx. 3-4%.	Up to 100mD, locally improved by fracturing. Average horizontal perm 2-4mD; average vertical perm ranges from 17-49mD.	
Elsa-1	Limestone and dolomites	15-20%		
Emilio		Large range; Average for Senonian is 8.2%; average for Paleogene is 7.9%	Average for Senonian is 0.3mD; average for Paleogene is 0.1mD. Ranges up to approx. 15mD.	Gas reservoir

Table 6 Reservoir properties for Jurassic to Eocene resedimented slope breccia reservoirs. Data collated from Cazzini et al. (2015); Shiner et al. (2013)

4.2.6. Paleogene-Neogene shallow platform reservoirs

Paleogene shallow platform carbonates are present over much of the Apulian Platform, apart from in areas which have experienced prolonged exposure, and the Miocene sits directly upon the Early Cretaceous (i.e. in parts of the Gargano Promontory; Figure 43). In the Val D'Agri fields, Paleogene to Neogene carbonates form packages sitting above the extremely thick karstified and fractured carbonates of the Cretaceous, and are commonly considered as an "entirety" with the underlying Cretaceous section where the reservoir is described. However, the Paleogene to Miocene intervals do have different characteristics, so it is probably wise to consider them as a separate reservoir type. In the Val D'Agri fields, the Paleogene is generally thin, and still contains karstified zones. However, the Neogene carbonates are thicker, and also contain interbedded evaporites which can be considered as barriers or seals (Figure 61). Reservoirs are interbedded with these barriers, and are locally fractured or karstified.

5. PETROLEUM SYSTEMS OF ALBANIA

The main petroleum systems of Albania lie within the Ionian Zone (Graham Wall et al., 2006) and Durres Basin (Zelilidis et al., 2003) (Figure 62). To date (2016), a total of 18 oil or gas fields have been discovered in Albania (Table 7).

Figure 62 Location of the main oil and gas fields in Albania within the Durres Basin and Ionian Zone. Based on Zelilidis et al. (2003).

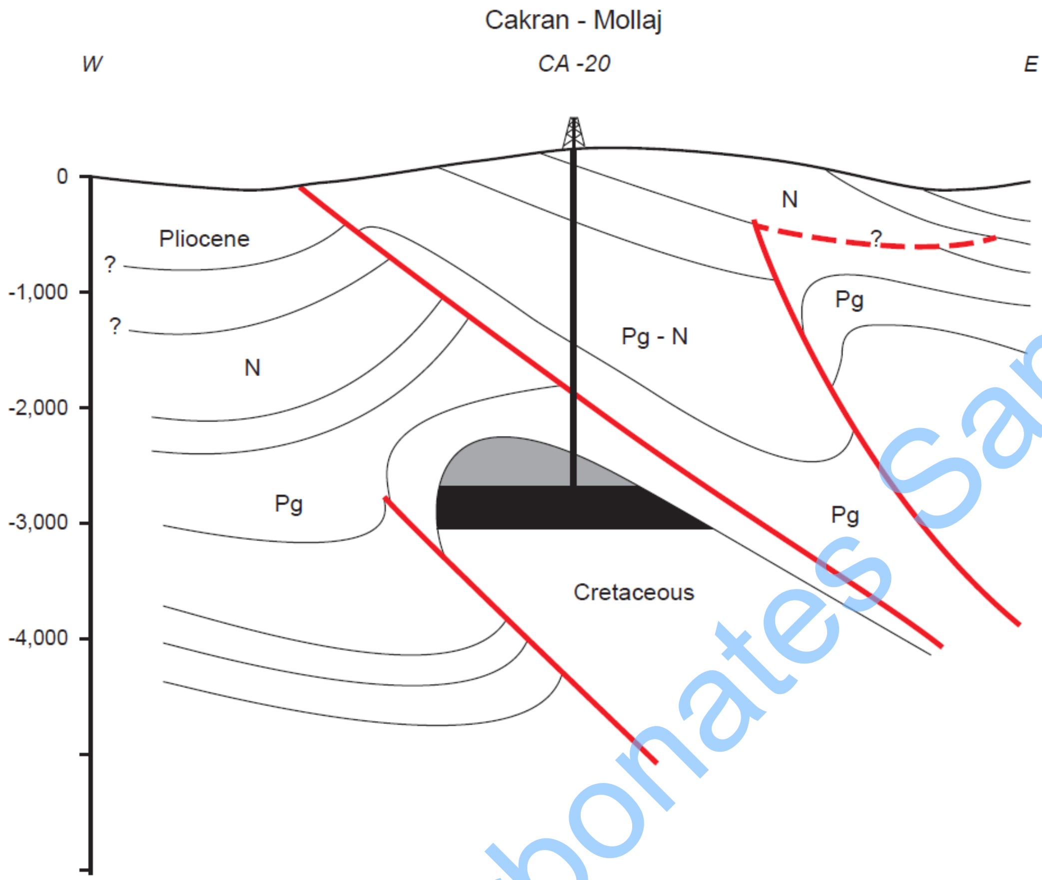


Figure 66 Simplified geological section through the Cakran-Mollaj field. Redrafted from Sejdini et al. (1994).

Example: Shpirag discovery

The Shpirag discovery is situated NE of Cakran-Mollaj (Figure 62). Two wells have been drilled on the Shpirag structure. Shpirag-1 was drilled in 2001, and Shpirag-2 in early 2014. Shpirag-3 was spudded in June 2016. All wells targeted a subthrust structural trap at a depth of approximately 5000m (Figure 68; Graham Wall et al., 2006). The reservoir is characterised by Upper Cretaceous pelagic carbonates with low matrix porosity (<2%); however, secondary porosity (about 1%) is present in the form of fractures (Graham Wall et al., 2006). Well logs from Shpirag-1 demonstrate how fractures contributed to production from the well (Figure 67). The image log was not able to record the most intensely fractured intervals as it became stuck; however, the caliper tools show distinct borehole enlargement (Graham Wall et al., 2006). Shpirag-1 flowed 35°API oil to surface.

6.1. Source and migration

In western Greece, the location and distribution of source rocks varies. This is primarily a function of the palaeogeographic evolution of the platforms and basins during the Mesozoic.

ONSHORE WESTERN GREECE (IONIAN ZONE) SOURCE ROCKS

The Ionian Zone of onshore western Greece (see Figure 35 for location) represents primarily basinal sedimentation (in the Ionian Basin) through much of the Mesozoic. The main source rocks can be compared to those of Albania (Figure 71; Figure 72; Table 8), and include (from Karakitsios, 2013; Zelilidis et al., 2003; Zelilidis et al., 2015; Figure 3):

- **Triassic to Lower Jurassic shales and evaporites**: organic-rich source rocks occur as fragments within Triassic breccias. The breccias formed due to dissolution collapse and diapirism. The TOC of the shale fragments is as much as 16.12%, with a very high petroleum potential of 8.9 to 98.8 mg HC/g of rock. The source rock is type I oil prone. Since the Triassic is deep, these shales have entered the oil zone, and are locally now in the gas zone in the Central and External Ionian zone. In the internal Ionian Zone, the source rock remains in the oil window. These entered the oil window in the Late Jurassic.

- **Toarcian lower Posidonia Beds:** these are the most important source rock in western Greece. Well-bedded, pelagic laminated marls, up to 150m in thickness depending on their location within a half graben system. TOC ranges from 1.05% to 19.12%, averaging 2.7%. The oils are type I to type II, have a petroleum potential of 4 to 125.85 mg HC/g of rock, and are mature and generating oil in western Greece (R_o % between 0.6 and 1.01). The lower Posidonia Beds probably entered the oil window during the Miocene (Serravallian).

- **Middle-Upper Jurassic upper Posidonia Beds**: bituminous cherty clays, rich in jasper beds. TOC of the upper Posidonia Beds is between 1.05% and 3.34%, and in most cases is mature in terms of oil generation.

- **Aptian-Turonian Vigla Shales:** marly limestones, shales and cherts, rich in TOC (0.94 to 5.00 wt. %). The Vigla shales are located in sub-basins, influenced by halokenetic movement. The Vigla Shales have a high petroleum potential (4.854 to 25 mg HC/g of rock). Type I to type II kerogen. The Vigla shales are early oil-mature in the central and external Ionian Zones, and in the internal zone they are oil mature. They entered the oil window after the Serravalian.

Resedimented carbonates of the Ionian Zone are encountered in Greece. These are derived from the Gavrovo Platform and deposited as megabreccias and slumps (Karakitsios, 2013), with the best reservoir quality found within the finer grained structured megabreccia units as well as the thicker, stacked and amalgamated beds towards the platform margin. Photomicrographs of these facies are documented in Sections 2.5, 2.8, 2.9, 3.1, 3.2, and 3.3 of Volume 2 of this report. These reservoirs are sourced and sealed by the surrounding pelagic carbonates. The Pindos zone of Greece also contains resedimented carbonates from the Kokkinovrakhos Formation of the Pindos Basin, which includes rudite megabreccia facies and olistoliths, in addition to pelagic limestones and radiolarian chert. Albanian resedimented carbonates of Santonian to Maastrichtian age can also be found within the Ionian Basin, derived from either the Apulian or Gavrovo/Kruja Platforms through faulted shelf breaks (Rubert et al., 2012; Le Goff et al., 2015).

6.3. Traps

The two fields with carbonate reservoirs that have been discovered to date both have thrusted, “buried hill” trapping configurations (Figure 74; Figure 73). Mesozoic-aged carbonates were thrusted and eroded, forming a trap beneath Cenozoic fine clastic sealing facies.

Thrust planes are often associated with Triassic-aged evaporites, indicating that contractional thin-skinned tectonics were the main control on development of the fold and thrust belt (Zelilidis et al., 2015). Traps related to diapiric processes are a possibility, as are potential sub-salt traps. It should be noted that WSW-ENE oriented strike slip faults were also active at the same time as the major compressional tectonism, particularly in the Pindos foreland basin (Zelilidis et al., 2015).

Other potential trapping styles have been recognised from seismic. Onshore, anticlinal structures could contribute to sub-thrust plays in areas where the sedimentary sequence is duplicated (Ionian zone); while offshore there are major buried anticlines in the Pre-Apulian zone and on the Apulian Platform (Karakitsios, 2013).

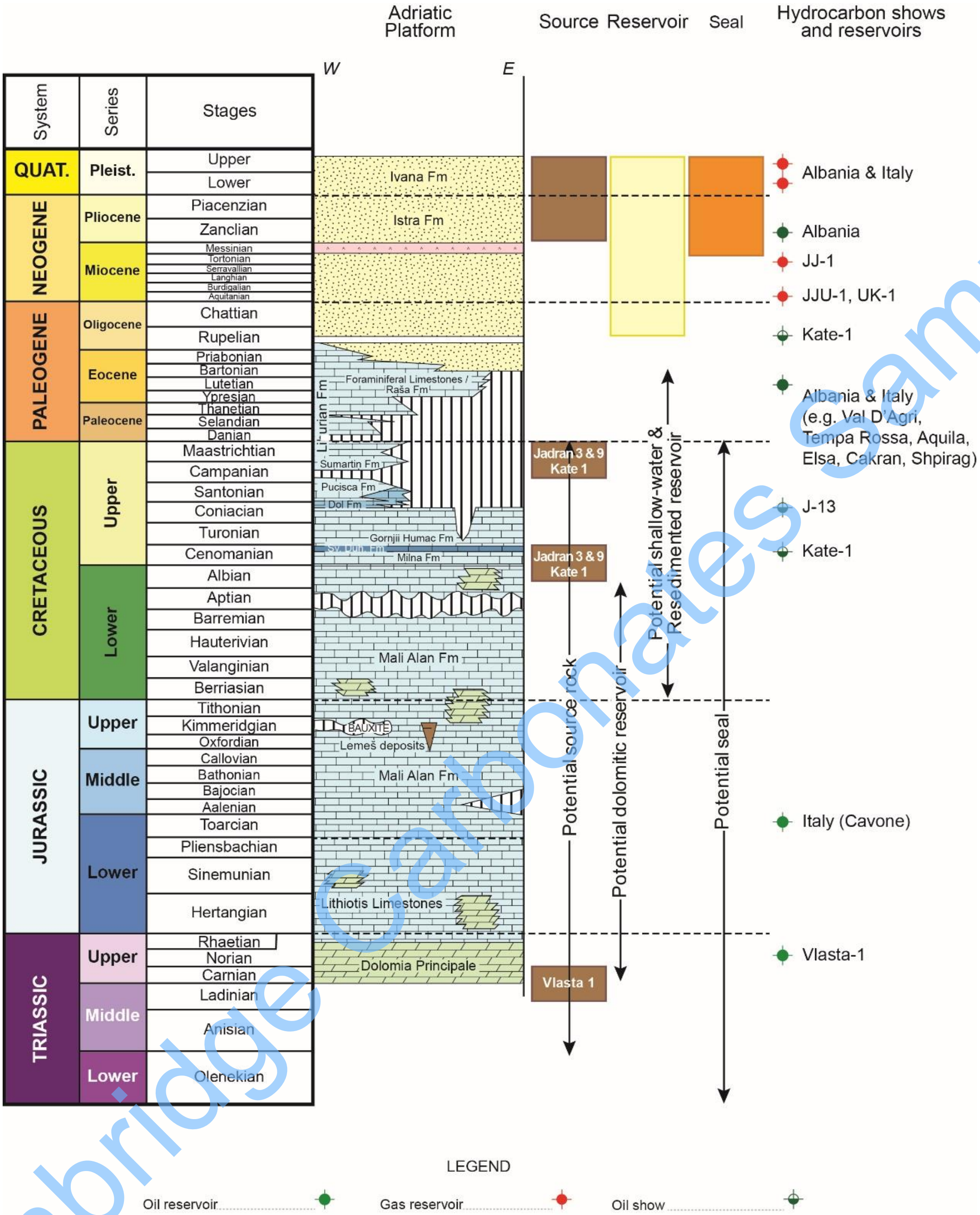


Figure 82 Stratigraphic column for the Southern Durres Basin. Adapted from Croatian Hydrocarbon Agency (2014).

9.1. Source and migration

In the northern Adriatic Sea, Pliocene-Pleistocene shales occurring both offshore Croatia and Italy represent the most prolific source rock. Biogenic gas of the Ivana, IKA, Marica and Izabela field have been sourced from these mature shales (Croatian

9.2.1. Cretaceous resedimented slope breccia reservoirs

In the central Adriatic, SE of the Kvarner Transverse Fault, a thick succession of Permian-Triassic evaporites was deposited. Halokinetic movements which were triggered by extensional tectonics during Late Jurassic rifting and flexure and shortening of the Dinaridic foreland during the Cenozoic (Wrigley et al., 2015) are interpreted to have caused instability of the Dinaridic Platform margin and deposition of a belt of resedimented carbonates, 1000m thick and 10km in width according to Grandić et al. (2010) (Figure 85). These represent potential reservoir rocks along the Dinaridic Platform margin and slope (Grandić et al., 2010; Grandić and Kolbah, 2009; Moro and Ćosović, 2013). The formation of diapirs and associated salt withdrawal in the surrounding areas as well as dissolution of salt, caused subsidence. In turn this caused back-stepping of the carbonate platform margin over time, resulting in development of several high-energy platform margins which, depending on their diagenetic history, can have good reservoir characteristics (Marszalek et al., 2015). In addition, this diapirism is very likely to have caused fracturing of the overlying carbonates and siliciclastics. In the southern Adriatic, Ionian Basin, where Triassic evaporites are thinner, no progradation/retrogradation of the platform margin has been observed.

Grandić et al. (2010; 2013) and Grandić and Kolbah (2009) also discuss the reservoir potential of proximal talus reservoirs along the margin of the Adriatic Platform which are not directly related to diapirism (Figure 85). For example, wells IM-1 and IM-3 (Istra More) have penetrated the most western portions of a potential talus slope off the margins of the Adriatic Platform. IM-3 had porosities of 14% and permeability of 45mD. However, had the well tagged the reservoir in a more proximal setting, Grandić et al. (2010; 2013) suggest that there may have been improved reservoir quality. IM-1 penetrated pelagic limestones and breccias containing fragments of shallow-water carbonates together with carbonate turbidites of Aptian to Maastrichtian age (Velić et al., 2015). Marszalek et al. (2015) also note the possibility of slumps, debris flows and turbidites based on seismic architectures, and suggest that the high amplitude seismic reflectors that are present, may indicate hydrocarbons.

11. CARBONATE RESERVOIR CLASSIFICATION

Both clastic and carbonate reservoirs host hydrocarbons in the circum-Adriatic. The carbonate reservoirs are Triassic to Miocene in age, and were deposited in response to the rifting of Gondwana, subsequent separation of Africa, Adria and Europe and the development of a passive margin. Subsequent compression relating to the formation of the Apennine and Dinarides/Albanides chains also had a significant influence on the development of reservoir quality facies.

Synthesis of published and in-house data has enabled us to classify seven key carbonate reservoir types which provide a framework for evaluation of underexplored areas (Figure 4; Figure 5;Table 10):

11.1. Late Triassic dolomitised peritidal reservoirs

To date, these reservoirs are only productive in Italy, in the Po and Ragusa Basins (i.e. Gela, Malossa and Gaggiano fields). Reservoir facies are characterised by fractured and vuggy dolomites which have experienced early meteoric diagenesis, and several phases of dolomitisation. Fractures are critical to production. Generally, matrix permeabilities are low.

Although these facies have only proven to be reservoirs to date in Italy and Sicily, given the considerable areal distribution of the Late Triassic dolomites (Figure 14), these could prove to be reservoirs in many other areas of the circum-Adriatic.

11.2. Jurassic shallow-water platform carbonate reservoirs.

Jurassic, shallow-water carbonates produce effective reservoirs, particularly to the north of Italy in the Po Basin (i.e. Cavone field) and in southern Sicily (i.e. Vega field). Jurassic reservoirs that have been discovered to date are Early Jurassic in age; however, there is potential for Middle and Late Jurassic facies having reservoir quality as well. Early Jurassic reservoirs are characterised by cyclic ooid grainstones and tidal flat facies, with good interparticle porosity and localised vuggy porosity. Early meteoric diagenesis (dissolution/karstification) is commonplace, and fault-controlled dolomitisation is locally critical to creating reservoir-quality facies (i.e. Vega field).

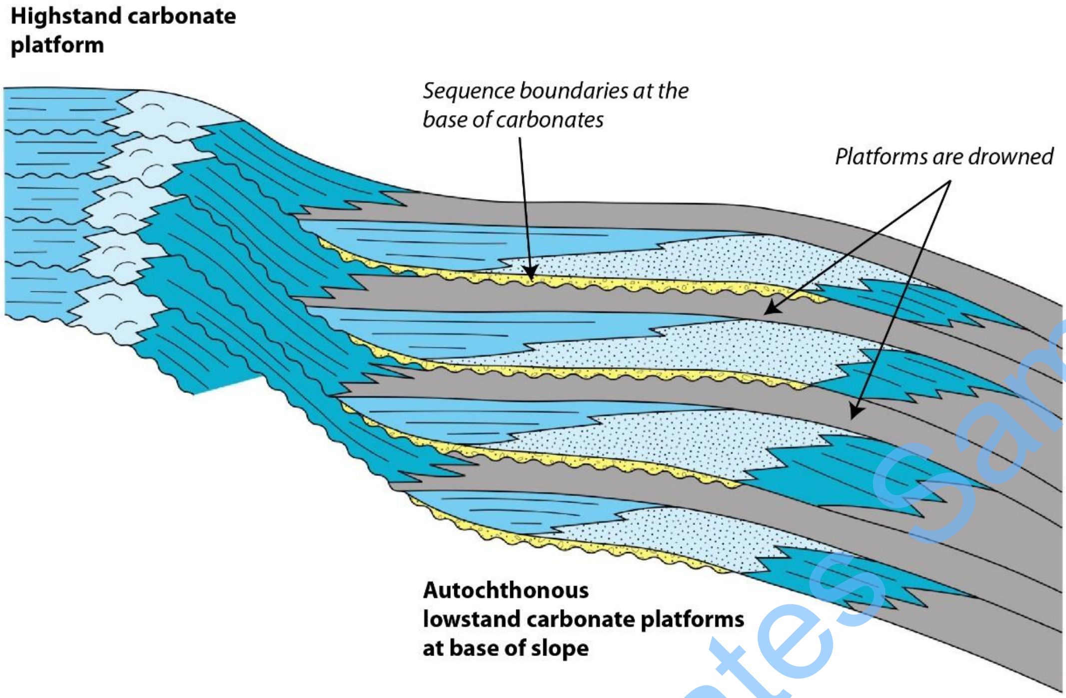


Figure 88 Schematic diagram illustrating the development of autochthonous carbonate platforms in a base of slope setting during periods of sea level lowstand.

Whilst authochthonous carbonate platforms could potentially develop in the basin during periods of sea level lowstand, another play-concept yet to be proven in the Adriatic, is the possibility of pinnacle reefs developed in "basinal" settings during periods of sea-level rise (transgressions). These shallow-water platforms develop as a response to sea-level rise, and as such have steep margins and can reach great thicknesses (many 100s m). However, they are typically surrounded by deep-water mudstone facies, and as such have an integral lateral and top seal. These structures are commonly easy to recognise on seismic (Figure 89).

12. WORLDWIDE ANALOGUES OF CARBONATE RESERVOIRS

Choosing an appropriate analogue is important when evaluating underexplored plays. For much of the eastern parts of the Adriatic, the carbonate reservoirs remain relatively underexplored. Whilst the Italian side of the margin exhibits many of the potential reservoirs (as described within this report) and these should be used as regional analogues where they can, a wealth of additional data from very mature basins can also be beneficial. Analogues from mature basins provide insights into production data (flow rates etc) and techniques for achieving the best exploitation of a reservoir. These analogues also provide important data on geometries of reservoir bodies, particularly for those reservoirs that are depositionally controlled.

Worldwide analogues have been provided for key play types where additional data from within the basin may be lacking. For example, in resedimented breccia reservoirs, examples from the USA and SE Asia provide data on the significance of the sequence stratigraphic context of the breccias (lowstand vs highstand etc). The Cretaceous "slope" carbonates of Mexico are commonly used as an analogue for resedimented breccias in Italy; however, in this report we discuss how this may not be a wholly appropriate analogue, as more needs to be learnt about how these sediments were deposited in Mexico.

Analogues of fractured carbonates are present in Section 12.2. The analogues from the Zagros fold-and-thrust belt are of particular importance for the fractured reservoirs of Albania for example, as these are in a similar tectonic setting. In fact, the Italian side of the Adriatic does not provide ANY suitable analogues to this specific play, since these have also undergone karstification to varying degrees.

Another key area for the use of analogues is in reservoirs that have undergone karstification (Section 12.3). Examples are presented from China, the USA and offshore Spain. Karstification is a critical process that modifies reservoir quality in many of the Southern Apennine fields, and for this reason the use of analogues is important for production and exploitation insights.

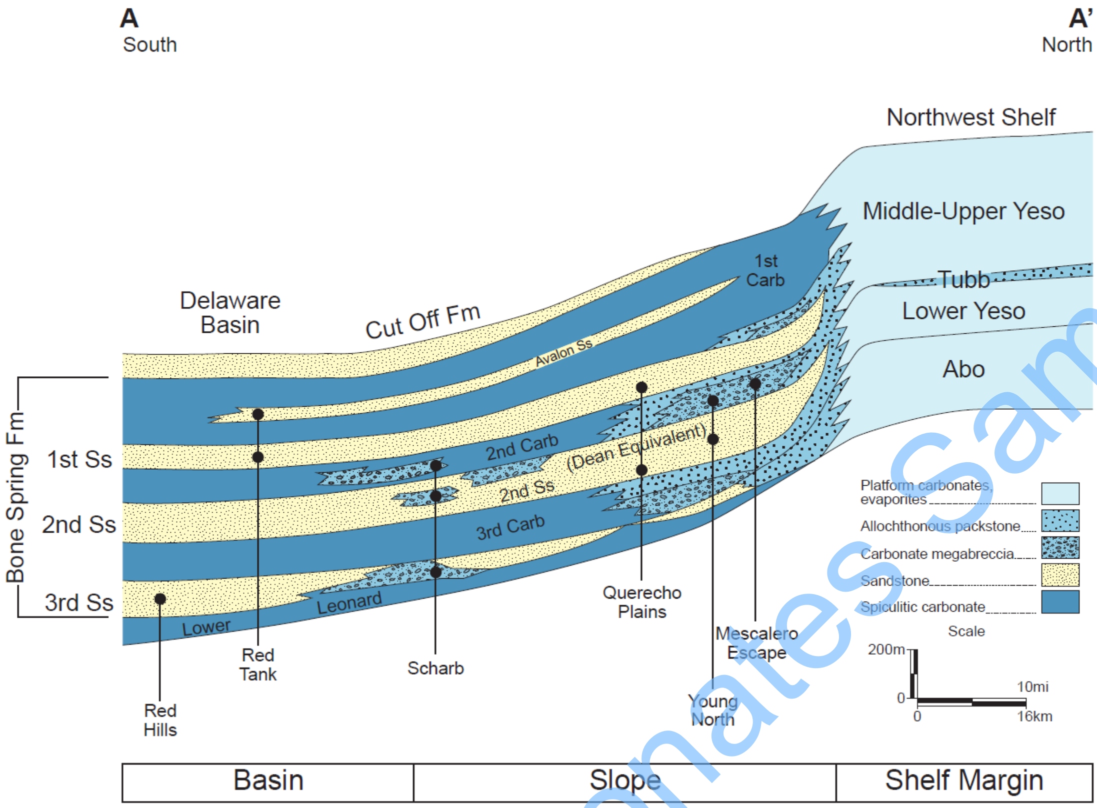


Figure 92 Schematic overview of the shelf and equivalent basin deposits of the north Delaware Basin. Redrafted from Montgomery (1997).

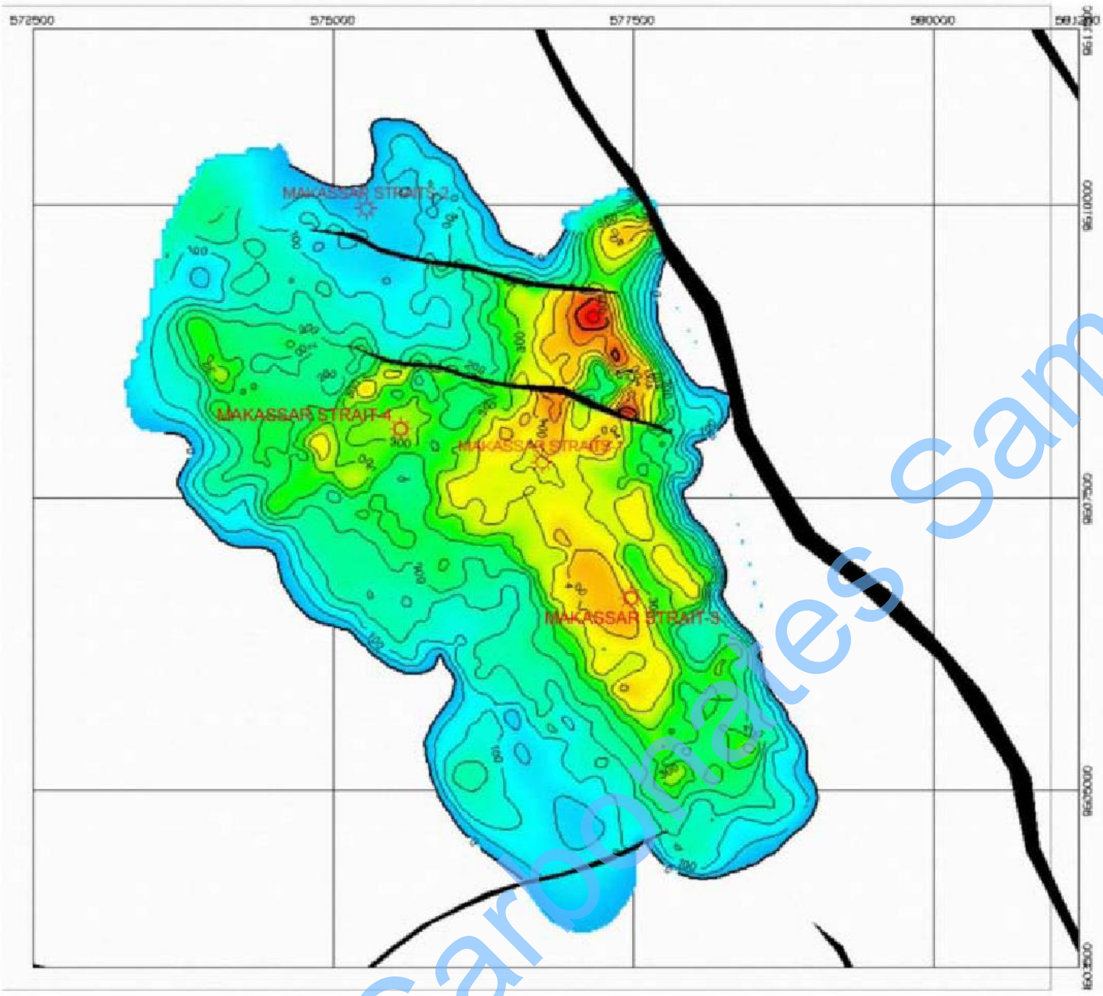


Figure 99 Isopach map of the Ruby field showing the fan lobe structure of the Berai deposits. Reproduced with permission from Pireno et al. (2009).

The debris flows consist of pebble to boulder size clasts enveloped by a matrix of micrite and abraded bioclasts. The clasts, mainly pack- and wackestones, contain bioclasts originating from shallow-water, mixed reef and back-reef environments, such as red algae, mollusc fragments, echinoderm plates, miliolid and both small and large rotaliid foraminifera as well as coral fragments. The degree of lithification of the clasts prior to erosion and transportation is variable. In fact, since similar bioclasts are found in the matrix of the resedimented carbonates, they are believed to have formed partially by the disaggregation of poorly indurated clasts during transportation. The degree of lithification of the clasts is believed to be indicative of the duration of transportation. The occurrence of mainly well-lithified clasts would indicate less transportation, compared to the occurrence of poorly lithified clasts, which would have disintegrated if transported over large distances (Pireno et al., 2009).

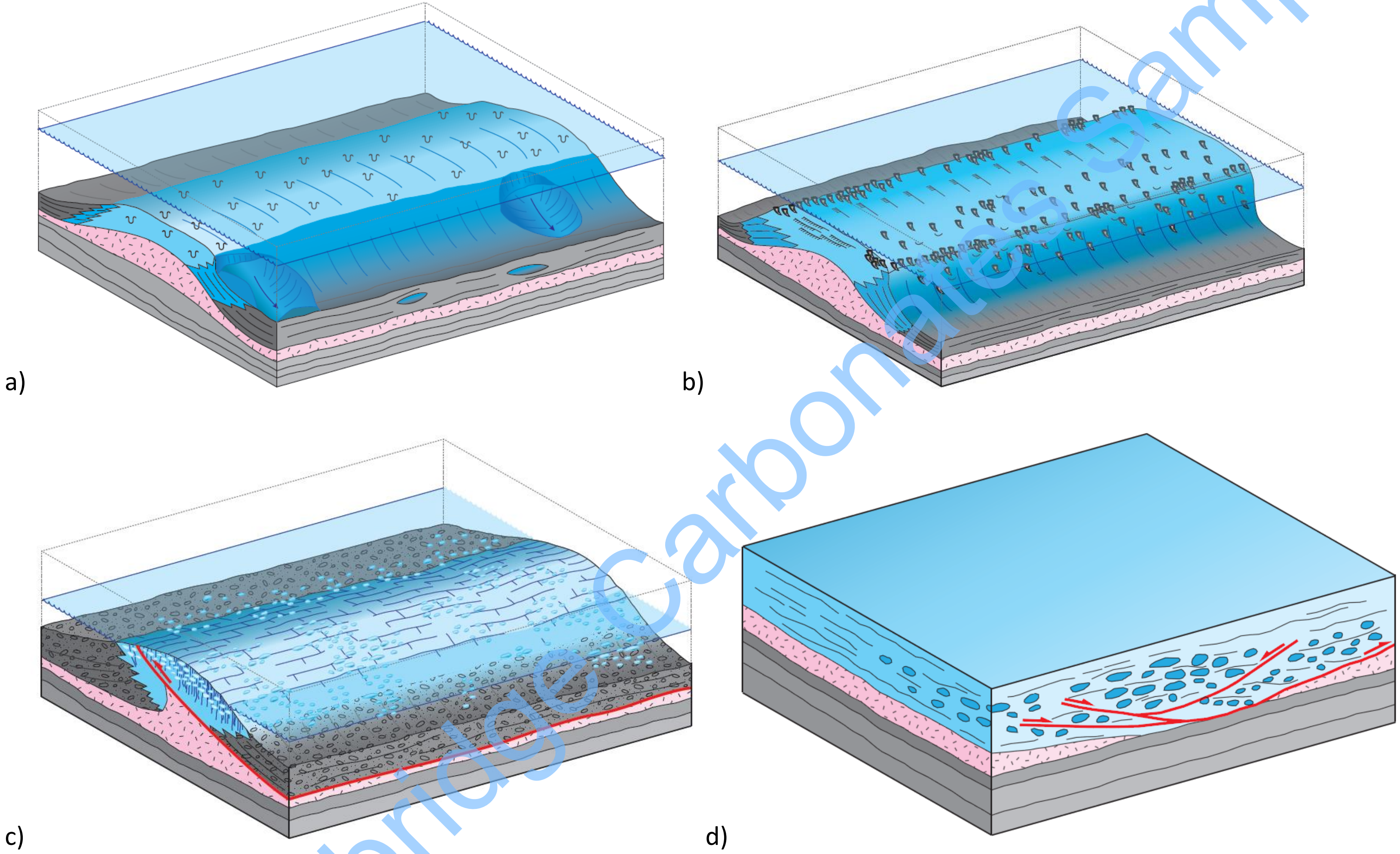


Figure 106 Breccia models: A. Salt roller with oolite shoal developing on top (Jurassic). Resulting breccia fragments consist of oolite breccia fragments. B. Salt roller with rudist reef (Cretaceous). C. Salt moving to the seabed carrying fragments to the surface on its way up. D. Collapsed (brecciated) platform due to salt withdrawal.

is therefore important to not only be able to predict fractures in carbonates, but also to understand their impact on production.

Fractures can impact on reservoir quality and producibility in many different ways, and it should not be presumed that this is always positive. Nelson (2001) characterised the impact of fractures into four key groups: where fractures provide reservoir porosity and permeability (Type 1), where fractures provide the key reservoir permeability (Type 2), where fractures assist permeability in an already producible reservoir (Type 3) and where fractures inhibit porosity and permeability (Type 4).

The type of fracture network present will have a big impact on how the reservoir will perform. For example if fractures are predicted to provide all reservoir porosity and permeability with little or no contribution from matrix, one might expect early water break-through if offtake was too fast and a development strategy would be designed to avoid this. If, however, the reservoir has a significant matrix component to storage and production, as well as a natural fracture system, the reservoir would be developed in quite a different way.

It is important to understand the impact of fractures at every stage of field life, from exploration through to production (Table 12).

Stage of field life	Impact of fractures
Exploration stage	Presence or absence of fractures will undoubtedly affect the commerciality of a prospect
Development stage	Understanding the contribution of fractures will impact on the design of the facilities and maximum flow-rates
Production stage	The type of fracture system present will influence the secondary recovery methods adopted (e.g. water-flood viability).

Table 12 Impact of fractures during field life.

The analogues provided in this report aim to highlight the varying impact of fractures in carbonate reservoirs.

Many reservoirs of the circum-Adriatic region are characterised by enhanced secondary porosity as a result of fracture development, e.g. the Val d’Agri, Aquila, Epanomi, Katakolon West, Cakran, Shpirag and IKA fields (this report). Salt tectonics with halokinetic mechanisms possibly activated by strike-slip and normal faults are

Meillon (Lower Kimmeridgian-Oxfordian) dolomite, which are separated by the non-productive Lons and Cagnotte Formations that consist mostly of thick micritic beds (Figure 113) (Bez et al., 1996). Communication between both reservoirs exists in the western part of the field, whereas it is absent in the eastern part of the field. Both reservoirs are ~200 m thick and are characterised by matrix porosities of 1-2% (Mano dolomite) and 3-5% (up to 8% where vuggy pores occur) (Meillon dolomite) and matrix permeabilities below 1mD (Golaz et al., 1990). Fracture permeability is inferred to be in the order of tens of mD. The Meillon dolomite is considered as the main reservoir unit of the field. The structural setting of the gas field is complex as it is overridden by the Pau anticline, which forms the trap of the reservoirs (Figure 113). This anticline formed as a result of thrusting along the northern Pyrenean front that propagated to the north by bedding-plane slip within Albian-Aptian flysch deposits, but deflected upwards and "popped up" due to a facies change to thick limestone beds and the presence of rigid Jurassic carbonates (Haller and Hamon, 1993). Fractures developed in the Meillon field are related to these deformation stresses.

The field produced gas over ~10 years through wells placed in culminations of the field, known as the Saint Faust, Pant D'As, Mazère, Baysère and Meillon, before water breakthrough led to the re-evaluation of the field and its geology and subsequent drilling of additional wells. Water breakthrough is related to the heterogeneous distribution of fractures and the occurrence of "megafractures", generally known as fracture swarms, which are highly fractured zones related to faults (Golaz et al., 1990). Fractures in the Meillon fields play an important role, but result in moderate permeabilities only, as a large fraction are not interconnected (Haller and Hamon, 1993). Haller and Hamon (1993) state that no productivity will be obtained from vertical wells in the Meillon field if fracture swarms are not crossed by wells. This represents a major challenge for this type of reservoir as defining and locating megafractures is difficult because these features are below seismic resolution and are characterised by large spacing (Haller and Hamon, 1993).

generally developed in thrust-belt or syn-rift carbonate successions draped by post-tectonic sediments. Reserves are moderate e.g. offshore Spain, southern Italy.

3rd/4+th order exposure:

- The host limestone has not undergone burial diagenesis or tectonism prior to karstification. In these cases, karst reservoirs tend to be more layered and may have significant amounts of remnant primary/ early secondary matrix porosity.
- Factors applicable to describing the karst reservoir include allogenic vs. autogenic meteoric recharge on attached or isolated carbonate platforms, duration of exposure and the development of flank-margin caves.

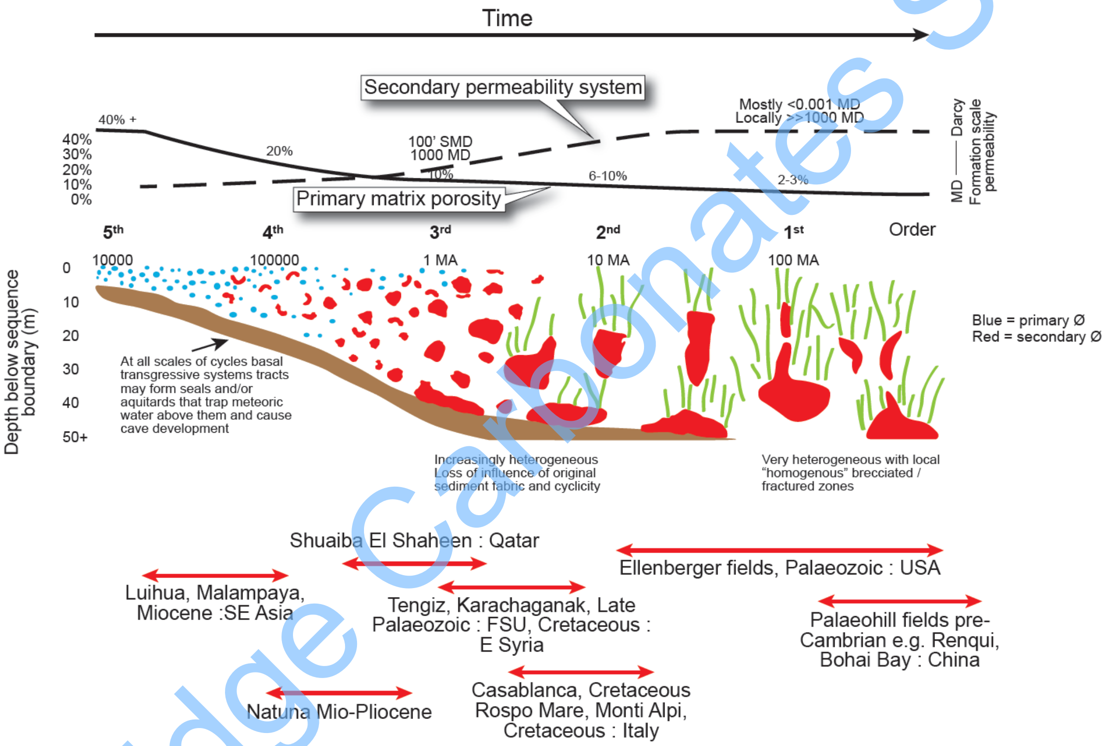


Figure 114 Relation of lowstand order to matrix pore types, macropore structure, reservoir thickness and development of internal seal.

Karstification in the circum-Adriatic

The Cretaceous was a period characterised by greenhouse conditions with low amplitude 4th/5th order sea level fluctuations. The influence of these eustatic sea level fluctuations on the carbonate platforms of the circum-Adriatic region is reflected in the depositional patterns that are characterised by shallowing-upward cycles. Occasionally, at the top of such shallowing-upward cycles a karst or palaeosol horizon modified by further Paleocene and Neogene karst episodes. Sub-Paleozoic karst shows a considerable karst relief with dolines 30m deep and conglomerate-filled channels up to 250m deep. Major karst features exploit seismically mappable faults. Karstic exposure during the Middle Ordovician to Middle Carboniferous resulted in the formation of bauxites. Paleocene and Neogene peneplained surfaces do not have any associated karst reservoir quality. Reservoir quality is also present in non-carbonate rocks associated with these unconformities. Internal baffles and barriers to flow may be present; the reservoir quality in some palaeohills may be restricted to a relatively thin permeable layer.

Dolomite contains the best matrix porosity of 2 to 3%; limestones have <2% matrix porosity. The Upper Proterozoic and Lower Paleozoic carbonate sequences are strongly cyclic with layered intraplatform karst. The macropore system includes highly fractured dolomite and limestone; these fractures have often been enlarged by dissolution. In addition, large caverns are present, as identified by significant bit drops and lost circulation (Figure 116).

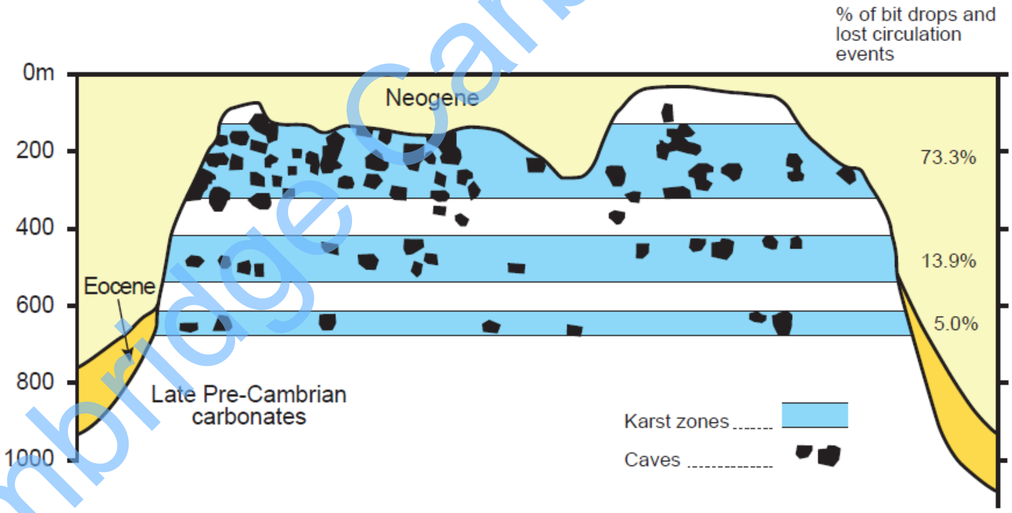


Figure 116 Distribution of bit drops and multi-layered karst reservoir of the Precambrian Renqiu field. Adapted from Qi and Xie-Pie (1984).

The initial flow rate was 700 BOPD from discovery well Ren-4. A further 7000 BOPD was obtained after acidisation. Daily output of production wells was 1400 to 1900 BOPD. Even if single palaeohills contain separate oil pools, there is a unified pressure enlarged fractures. Indicative flow rates and reserves from various fields are as follows:

Emerald Field: Discovery well flowed at 520 BOPD from an 18m interval with minor intercrystal porosity in dolomite with karst fractures.

Buckwheat Field: Cumulative production of 672,636BO from 3 wells over a period of 3 years. Initial production from one well was 302 BOPD. It has a dual pore system with moderate intercrystal matrix porosity in dolomite and crackle and interclast pores in breakdown breccia.

Crittenden Field: 90m fault-bounded anticlinal closure in karsted Silurian dolomites contains cavernous and interclast porosity in breccia with common lost circulation zones and bit drops. Discovery well flowed at 238,683 MCFGPD.

Lower Paleozoic carbonates in the ***Appalachian Basin*** of eastern USA Lower Ordovician (Ellenberger/Arbuckle equivalents) locally contain karsted and fracture porosity. Karst reservoirs are a combination of 4th order karst that cap glacioeustatic cycles with superimposed lower-order karst associated with a Middle Ordovician 2nd order unconformity (Montanez, 1992; Wilson et al., 1993). Matrix porosity is moderate to good in dolomites. MVT (Mississippi Valley Type) ore deposits are also common suggesting that the pore system was modified during burial diagenesis.

Michigan Basin: contains production from Middle Ordovician carbonates and Silurian reefal carbonates overlain by evaporites. The main dual porosity reservoirs are found in Devonian carbonates that contain lower order karst systems formed by subaerial leaching. The top Ordovician carbonates have large dolines (10skm across x 50m deep) infilled by overlying 'Brazos Shale' (Nardon and Smith, 1992; Kruger, 1992).

Late Paleozoic mid-continental Basins (USA): The Late Paleozoic transcontinental Arch is surrounded by a number of intracratonic basins. A foreland basin associated with the Marathon-Ouachita fold belt is present along the southern margin of the Transcontinental Arch and some basins along the western margin (e.g. the Western Overthrust belt) were later deformed during the Cenozoic Laramide Orogeny. A number of dual porosity plays and reservoirs are present in these basins:

- Note that the standard processing of FMI logs for bedding and fracture types often underestimates the presence of karst macropores that are best revealed by a qualitative examination of the FMI.

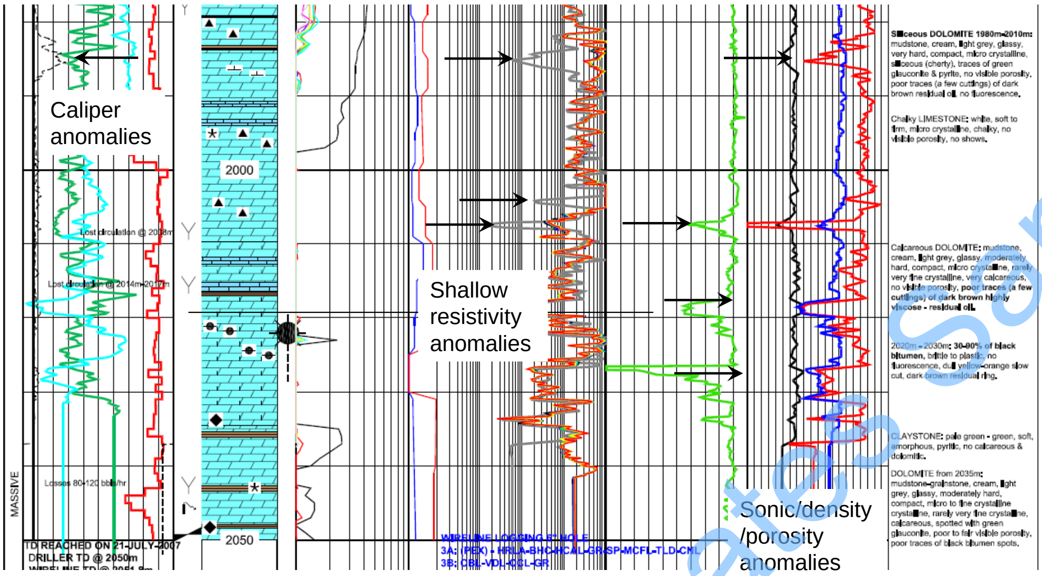


Figure 117 Log response of inferred karst intervals in Cretaceous carbonates, Middle East.

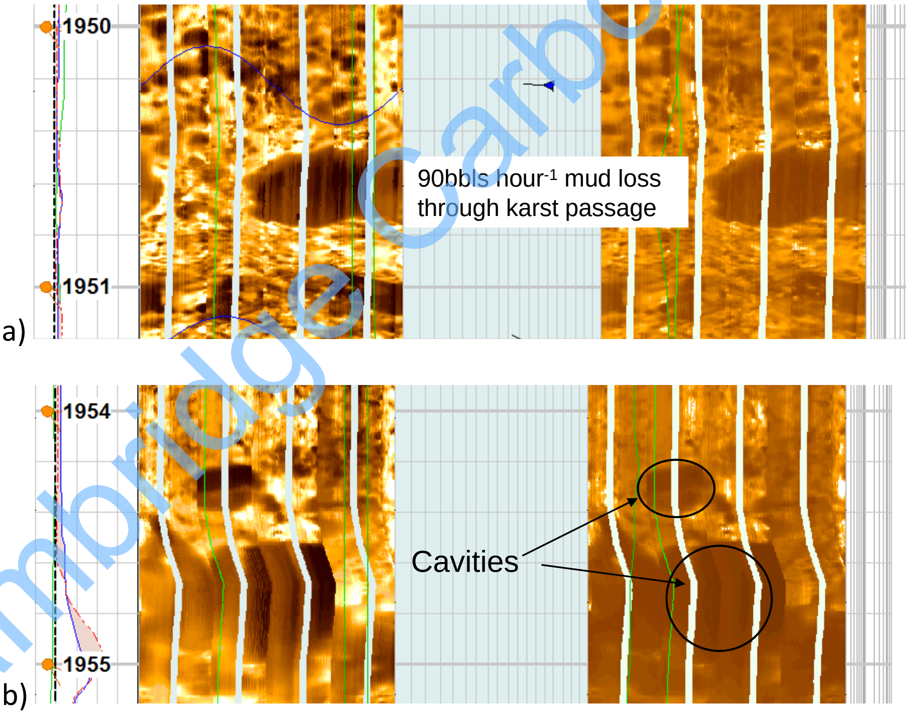


Figure 118 (a) Large karst cavity 0.25m in diameter; high mud loss implies a high volume karst passage. (b) Empty cavities associated with caliper, density/porosity, shallow resistivity and sonic anomalies Cretaceous carbonates, Middle East.

this unit have an average porosity of 27%, with contributions from vuggy and interparticle and intraparticle porosity.

Base: Basal transition zone. It consists of algal-foraminiferal packstones (operculinids, rotalids, planktonic foraminifera), with relatively low porosity. Approximately 35m thick.

The entire package is partially dolomitised. Reservoir quality is typically a function of periodic emergence and meteoric dissolution creating mouldic porosity. Measured permeabilities range from 2-200mD, averaging approximately 26mD.

Production data for Intisar A is presented in Table 20.

	Intisar A field
Reservoir fluids	Oil, 45°API, GOR of 1336 SCF/STB, undersaturated
Number of producers	18
Number of water injectors	29
Initial production	100,000 BOPD (from 2 producers), increased to 548,000 BOPD (from 17 producers)
Cumulative production	719MMBO (1996). STOOIP 1875MMBO and 1.6TCFG.

Table 20 Reservoir performance data for Intisar A. From DesBrisay and Daniel (1972), Terry and Williams (1969) and Hallett (2002).

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