Petroleum Systems of Lebanon : an update and review

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Abstract

Extensive 3D seismic data offshore Lebanon together with new investigations of the onshore domain have resulted in a considerable wealth of information on the regional geology and petroleum prospectivity. This article presents a new interpretation of the Levant margin offshore Lebanon with an up-to-date review of the geology of Lebanon and a new comprehensive insight on the petroleum systems along the Eastern Mediterranean sector. The Lebanese onshore and offshore territories are separated in this study into four different domains: the deep basin, the Lattakia Ridge, the Levant margin and the onshore. Each of these domains is marked by a general structural style and various stratigraphic architectures, resulting in different source-reservoir-trap configurations. The new subdivision impacts exploration as it highlights specific geographic areas having distinct petroleum systems. This study takes into account all previously published geological knowledge and provides new results from stratigraphic,

structural and geochemical investigations to propose a summary of the potential petroleum systems for each domain, on the eve of Lebanon first offshore licensing round.

Introduction

Lebanon, part of the larger Levant region, is located in the NW part of the Arabian plate along its western active boundary with Africa (fig. 1). This area is marked by the passage of the Levant Fracture System (LFS), the fold and thrust belt of the Palmyrides ranges to the east and the stable foreland Levant basin to the west. Lebanon and its offshore are considered as a promising petroleum province as a result of more than 70 tcf of proven natural gas reserves in nearby countries, following the discovery of Tamar, Leviathan, Aphrodites and Zohr between 2006 and 2015 (fig. 2). Onshore, recoverable reserves of Syria are estimated at about 2.5 billion bbl of oil and about 8.5 TCF of gas, with productive fields in the Palmyrides, the Euphrates graben and the Sinjar high (Barrier *et al.*, 2014).

The latest petroleum activities in the Levant and the promising potential of Lebanon have prompted the Lebanese government to acquire an extensive amount of multiclient 3D seismic data to aid exploration offshore. Improved knowledge of the geology of the Levant region was achieved by using this unprecedented wealth of information and seismic data coverage and by attracting considerable academic and industrial research projects, referenced herein. A new model for the stratigraphic setting and filling of the basin has been suggested based on seismic data and extensive fieldwork (Hawie *et al.*, 2015).

The structural framework of the Levant basin and margin has been described on the light of new 3D reflection seismic data interpretation, and modelling (Ghalayini *et al.,* 2014; and references therein). A new geochemical assessment of source rock potential based on extensive sampling onshore Lebanon has also been completed (Bou Daher *et al.*, 2014; Bou Daher *et al.*, 2015). This has resulted in the development of a new basin model for Lebanon and its offshore based on an integration of all the newly acquired knowledge, providing an updated picture of the hydrocarbon potential of Lebanon (Bou Daher *et al.*, 2016). In addition, a refined model for the crustal structure of the Levant Basin was proposed (Inati *et al.*, 2016), which directly impacts the petroleum systems and the source rock maturity.

This article summarizes the results of the latest geological and petroleum investigations in Lebanon and adds new up-to-date data – especially with regard to potential petroleum systems. First, it presents new interpretation of the Levant margin offshore Lebanon since the carbonate prospects have attracted major attention following the Zohr discovery in carbonate reservoirs offshore Egypt. Second, it subdivides the region into geological domains based on multitude of stratigraphic, structural and geochemical data. Third, it discusses the various petroleum aspects of each domain (potential source rocks, reservoirs, and traps) and points out new objectives based on recent data and neighboring discoveries. These results serve as a basis for the understanding of the petroleum potential of Lebanon and provide a good case study on exploration effectiveness and strategy at a critical time as the first offshore licensing round has been set.

Exploration history

Petroleum exploration in Lebanon started with the first legal decree issued in 1933 and amended in 1936. Twelve companies were actively involved in exploration in Lebanon among which the 'Compagnie Libanaise des Pétroles' (CLP) and the 'Syria Petroleum Company' (SPC) were the largest (Wetzel, 1974). The SPC, which was a subsidiary of the Iraq Petroleum Company, drilled the first well in Terbol in 1947 and failed to reach economic accumulations. It has since relinquished all its concessions in Lebanon and concentrated its activity in Syria. The CLP drilled five wells in the Bekaa between 1953 and 1964, four of which with foreign partners, but without any commercial result. The CLP was the only company to hold concessions amounting to 5200 Km^2. Exploration was not only undertaken onshore, as Shaheen-Oxoco had offshore permits next to Tripoli. In 1970, the first seismic data was acquired by Oxoco offshore north Lebanon and in 1971 Delta acquired 320 km of 2D seismic lines in addition to a gravity survey on the Shaheen permit.

The acquisition of several regional 2D seismic reflection surveys by Spectrum and TGS in 2000 and 2002 respectively, led to mapping of several promising leads in the subsalt units. Between 2006 and 2012 PGS acquired 9700 Km^2 of multiclient 3D seismic data followed by Spectrum who also acquired additional 5172 km^2 of multiclient 3D seismic data between 2012 and 2013 in the deep-water offshore Lebanon resulting in an exceptional wealth of information for the offshore basin. The new data has indicated a promising hydrocarbon potential

for Lebanon (Roberts and Peace, 2007) prompting the government to issue new decrees in 2017 to regulate the offshore exploration.

Tectonic and crustal setting

The present-day tectonic framework is the result of the complex geodynamic evolution of the region through geologic time. Two large structures are dominating the geological landscape: (1) the LFS, and (2) the Lattakia Ridge System. The LFS is a sinistral transform fault system linking rifting in the Red Sea with collision in the Taurus (Freund *et al.*, 1970) (fig. 1). Lebanon is located along the LFS on the plate boundary between Africa and Arabia. To the west of the LFS, the area is marked by the stable foreland Levant basin, which was formed synchronously with the Palmyra Basin during the polyphase Mesozoic rifting event (Gardosh *et al.*, 2010).

Bordering the Levant Basin at its NW boundary is the Lattakia Ridge. This Late Cretaceous structure was established as a result of the subduction of Africa beneath Eurasia starting in the Maastrichtian (Frizon de Lamotte *et al.*, 2011; Stampfli and Hochard, 2009). Continuous compression has marked the region till modern days with an accelerated rollback of the subduction zone along the Hellenic-Cyprus arc during the Tortonian (Le Pichon and Kreamer, 2010) which led to renewed fold-thrust activity in the middle–upper Miocene along the Lattakia Ridge (Hall *et al.*, 2005; Robertson *et al.*, 1996). A regional geodynamic event was witnessed in the Messinian and Pliocene causing a westward tectonic escape of the Anatolian microplate with a component of anticlockwise rotation

(Le Pichon and Kreamer, 2010; Sengor and Yilmaz, 1981). It has directly affected the Lattakia Ridge which was reactivated into a sinistral strike-slip motion (Hall *et al.*, 2005). These geodynamic events were marked in both the Levant Basin and onshore Lebanon by reactivation of structures, and a decrease in the lateral motion of the LFS (Freund *et al.*, 1970; Ghalayini *et al.*, 2014; Le Pichon and Gaulier, 1988; Quennell, 1984). It is also at this time, that the accelerated uplift of the pre-existing Lebanese structures took place (Walley, 1998; Ghalayini *et al.*, 2017; Beydoun, 1999).

The thickness of the crust gradually decreases westward from the Palmyrides to the Levant Basin, with 44 km in the SW Palmyrides, 35 km beneath the anti-Lebanon ranges and 27 km beneath Mount Lebanon (Brew *et al.*, 2001; Khair *et al.*, 1993). This westward thinning of the crust beneath Syria and Lebanon indicates a transition between a crust of continental type east of the Levant margin, transitioning to a thinned continental crust of 8-10 km thickness beneath the Levant Basin as evidenced by modern gravity inversion (Inati *et al.*, 2016) and refraction seismic profiles (Ben-Avraham *et al.*, 2002; Makris *et al.*, 1983; Netzeband *et al.*, 2006). This gradual, smooth thickness transition is the result of the Permo-Jurassic rifting of Pangea, causing the break-off of continental blocks from the Afro-Arabian plate to form the Neo-Tethys ocean (Garfunkel, 1998; Robertson, 1998) and pointing to successive regimes of extension that did not reach a real break up stage.

Methods and data

Interpretation of three seismic lines along the margin offshore north and south Lebanon were performed (figs 3 to 6). The data used consist of pre-stack depth migrated 3D seismic cube acquired in 2012 by PGS. Streamer length was 7050m long at a spacing of 12.5m and 25m shot point intervals. The interpretation was performed on depth-converted sections. Because no well data were available, time to depth conversion was done using a velocity model built from stacking velocities.

Levant Margin north of Lebanon

Observations

11 horizons were identified in seismic data based on impedance contrast variations and following the interpretation of Hawie *et al. (*2014) (fig. 3). Horizon RN1 separates non-continuous and low amplitude reflectors from the overlying semi-continuous and relatively brighter package. The latter is exhibiting growth strata and fanning geometries. RN2 is a continuous very bright reflector with a strong impedance contrast. Toward the deep basin, it separates a set of bright and stacked continuous reflectors package from non-continuous and dim reflectors. RN3 marks the top of a series of three stacked reflectors package in the east. To the west of the line, it forms an angular unconformity surface in which the underlying unit is truncated. The overlying reflectors also exhibit relatively lower amplitudes. RN4 exhibits a strong impedance contrast and separate chaotic reflectors above from the stacked and bright reflectors below. RN5 is a continuous horizon with a strong impedance contrast marking the top of the low amplitude unit to the east from more continuous and bright reflectors

above. It continues westward to the deep basin in which it is still marked by a strong impedance contrast. Horizons RN6 to RN11 were picked up based on the interpretation of Hawie *et al. (*2014).

The unit between RN2 and RN3 exhibits significant seismic facies variation toward the deep basin in which continuous semi-bright reflectors appear to be transitioning to chaotic reflectors in the middle. Further west, the unit is dominated by a series of stacked and bright reflectors. Similar observations can be made on the unit between RN3 and RN5 to the east in which the reflectors become chaotic in the centre of the line and the overall unit adopts a wedge shape geometry.

Interpretation

The fan-shaped geometry of reflectors between RN1 and RN2 point to the presence of growth strata suggesting that normal faults are present at this depth. The latter are NE trending parallel to the coastline and are dipping to the NW. Similar extensional structures are documented in the southern Levant and believed to have nucleated during the Triassic as a result of Tethyan rifting (e.g. Gardosh et al. 2010). Therefore, units below RN1 are likely the pre-rift package while units between RN1 and RN2 are the syn-rift package. This could be attributed to the Permian and Triassic-Lower Jurassic units respectively. As RN2 is not displaced by faulting and separates deformed units below from non-deformed units above, it could correspond to the break-up unconformity of mid-Jurassic age (Hawie *et al.*, 2014). RN2 therefore marks the initiation of tectonic

quiescence and gentle subsidence of the Levant region starting the mid to late Jurassic. The seismic package between RN2 and RN3 likely represents the Jurassic unit composed of shallow-water, inner to middle shelf carbonates. Its thickness of 1 – 1.5 km is in coherence with the thickness of the Jurassic in north Lebanon (Nader *et al.*, 2016; Dubertret, 1955) and is conformable with the seismic facies interpretation of Hawie *et al.* (2014). Therefore, RN3 could refer to the Late Jurassic-Early Cretaceous sequence boundary. The seismic facies transition from continuous to chaotic reflectors indicate mass transport or talus deposits originating from the Jurassic carbonate platform and deposited at the distal end of the margin over a slope. The abrupt facies variation into high amplitude bright reflectors toward the distal basin could point to the presence of Jurassic clastic units away from the margin.

The unit between RN3 and RN4 exhibit a set of stacked high amplitude reflectors indicating different facies than the adjacent carbonates. They are likely representing thick bedding which alludes to sand packages of a possibly Lower Cretaceous age. Therefore, this unit could be analogous to the onshore Hauterivian Chouf formation, and RN4 could likely represent the top Hauterivian. The overlying wedge-shape of the unit and the chaotic reflectors associated could represent mass transport deposits or carbonate talus originating from the Cretaceous carbonate succession along the margin and onshore (Hawie *et al.*, 2014). RN5 horizon corresponds to a major marine onlapping surface and therefore could represent the Senonian unconformity horizon (Hawie *et al.*, 2014; Gardosh *et al.*, 2011). On top of the Senonian unconformity, the high amplitude package should be Tertiary in age as it overlies

the Cretaceous unit. This unit displays high amplitude reflectors with similar seismic facies to the underlying carbonates unit. Therefore, it could represent Eocene to Miocene carbonate successions. The presence of such Tertiary carbonate units along the Levant margin has been discussed by Hawie *et al.* (2014).

Levant Margin south of Lebanon

Observations

The southern Levant margin offshore Lebanon is marked by a specific structural element termed the Saida-Tyr plateau (STP) which is a 2500 km^2 elevated Mesozoic plateau as observed in the Senonian unconformity depth map (fig. 4). It is differentiated from the deep Levant basin by large crustal faults to is north and west (figs. 5-6) and is characterized by a thinner Cenozoic unit thickness relative to the remainder of the basin (Hawie *et al.*, 2014).

13 horizons were identified in seismic data based on the interpretation of Hawie *et al. (*2014) and through correlation with the Adloun well, located 5 km east of the seismic line (fig. 5). It was drilled to a depth of 2150 m and reaches the Upper Jurassic unit (Beydoun, 1977). Horizon RS1 separates chaotic non-continuous horizons from a set of semi-continuous thick and bright horizons above. RS2 exhibits a strong impedance contrast separating the overlying chaotic and dim horizons from bright and underlying semi-continuous horizons. It is challenging to assess the continuity of RS1 and RS2 horizons to the west in the deep basin. Horizons RS3 to RS8 are extrapolated from well data and consist of stacked high

amplitude set of reflectors, with occasional dimming. Horizon RS8 marks the boundary between stacked high amplitude bright reflectors to the east, and stacked continuous medium to high amplitude reflectors to the west. The latter package is pinching out and exhibits onlap on RS8. Horizons RS9 to RS13 are picked up based on the interpretation of Hawie *et al. (*2014).

The seismic units between horizon RS2 and RS3, and horizons RS4 and RS5 are thinning to the west and disappear. Their seismic facies change abruptly from stacked bright horizons to chaotic. On top of horizon RS2, pinnacle shape buildups are observed. They cover an area of about 200 Km^2.

Large vertical displacement related to vertical faults is observed north and west of the plateau. The northern bounding fault displaces RS8 horizon 2 km upward and locally forms a mini-basin along RS12 (fig. 5). The faults to the west have positive-flower geometries with two anticlines observed along their strike (fig. 6). ENE-WSW to ESE-WNW normal faults are observed at the easternmost STP (fig. 5) having a displacement of few hundred meters and extend between RS1 and RS8 horizons. Their strike is ENE-WSW to ESE-WSW.

Interpretation

From correlation with well data, horizons RS3 to RS7 correspond to Top Jurassic, Top Hauterivian, Top Aptian, Top Albian and Top Cennomanian. As RS8 horizon is truncating the Turonian and Senonian units as well as deeper units to the west, it is believed to be the Senonian unconformity horizon (e.g. Hawie *et al.*, 2013).

The thickness between RS3 and RS2 is 1.5 to 2 Km, slightly higher than the total expected thickness of the Jurassic unit south of Lebanon (Nader *et al.*, 2016; Dubertret, 1955). Horizon RS2 exhibits a strong impedance contrast, probably indicating a transition between primarily dolomite succession to evaporites. Therefore, RS2 is likely the top of the mid Triassic. The thickness between RS2 and RS1 is 1 to 1.5 km in accordance with the expected thickness of the Triassic in Lebanon (Nader *et al.*, 2016; Beydoun and Habib, 1995) and therefore RS1 is likely the base Triassic. This interpretation points to an extension of the broad geometries observed onshore to the Levant margin offshore with possible lateral facies changes expected away from the coast.

The interpretation of the Tertiary units is adopted from Hawie *et al.* (2014) in which horizons RS9 to RS13 correspond to the Eocene Unconformity, Base Miocene, Base mid Miocene, Base Messinian and Base Pliocene respectively. These units are overlying the Mesozoic units found eastward and are onlapping on the Senonian Unconformity horizon, while to east and closer to the shoreline, the Mesozoic is directly overlain by the Pliocene and the Messinian unit is not observed in seismic data. This likely indicates an existing topographic high prior to the deposition of the Tertiary unit. The westward seismic facies variation observed in the Jurassic and Cretaceous units could be interpreted as talus deposits originating from the carbonate platform in the East. Overlying the RS2 horizon, the pinnacle shape geometries could consist of local build-ups or isolated carbonate mounds, though it is challenging to assess their true nature from seismic data alone.

The large vertical displacement observed on the ENE trending northern bounding fault, referred to as the Saida fault, is likely related to an old Mesozoic extensional regime. Ghalayini *et al.* (2014) argues that this fault is reactivated into a dextral strike-slip in the Late Miocene due to the en-echelon anticlines observed in the upper Miocene unit. Onshore, the Saida fault is correlated with the passage of the Damour fault zone, which consists of a deformation zone of multiple ENE-WSW faults, separating Mount-Lebanon into two different compartments. It has been suggested that both the Saida and the Damour faults are the westward continuation of the Jhar fault in Syria due to the similar trend, evolution history and crustal configuration north and south of these faults (Ghalayini *et al.*, 2017). Therefore, it is likely that the STP also marks a crustal transition and could be underlain by a continental crust (e.g. Ghalayini *et al.*, 2014). The western bounding faults displace vertically the Mesozoic unit for more than 2 km, also suggesting an older extensional episode prior to the Cenozoic. The positive flower structures and the folding in the Tertiary units might indicate a transpressive regime starting in the Late Miocene times. The ENE-WSW to ESE-WNW normal faults documented at the easternmost STP (fig. 5) are similar to faults well documented in southern Mount Lebanon (Homberg *et al.*, 2009; Homberg *et al.*, 2010). It is very likely that these faults belong to the same fault family as the ones documented onshore and therefore were active during the Cretaceous times (e.g. Homberg et al. 2009)

Main geological domains

Based on the available geological data and on the new interpretation of the margin, the Lebanese onshore/offshore area is differentiated into four geological domains, having distinct sedimentological and structural features: (1) the distal, deeper basin, (2) The Lattakia Ridge, (3) the Levant Margin and (3) the onshore (fig. 7). The following sub-sections describe the main geological features of these domains and are as such a review of the available literature. The lithostragraphic column of the Levant region summarizes the stratigraphy, structures and expected petroleum systems (fig. 8).

The Deep Basin

It has formed on an attenuated crust (Inati *et al.*, 2016) during the Triassic and Jurassic when the Neo-Tethys has opened up following the rifting of Pangea. It is characterised by a thick Cenozoic sedimentary cover reaching over 8 km thickness, overlying a Mesozoic succession (Gardosh and Druckman, 2006; Hawie et al., 2013; Roberts and Peace, 2007). The main structural features prevalent in this domain are the normal faults and the NE trending anticlines.

Stratigraphic setting

Nine horizons were identified in the Levant basin offshore Lebanon in seismic data and correlated with nearby wells (Hawie *et al.*, 2013). They are believed to correspond to the Mid Jurassic, Jurassic-Cretaceous boundary, Senonian unconformity, Eocene unconformity, Base Miocene, Base mid Miocene, Base

Messinian and Base Pliocene. The seismic packages are defined by their large-scale reflection configurations, impedance contrasts, specific stratigraphic contacts with their lower and upper bounding surfaces, stratal terminations and overall seismic facies. As the pre-Tertiary units in the deep basin were not drilled elsewhere in the Levant basin, it is very challenging to separate and seismically characterize the Mesozoic strata in this domain. The Cenozoic units, such as the Eocene, Oligocene-Miocene, Messinian and Pliocene, possess higher certainty and are laterally continuous throughout the Levant basin.

A mixed carbonate-siliciclastic system characterizes the stratigraphy of the deep basin. The documented units consist of Mesozoic rocks, possibly deep-water carbonates or clastics, below the Senonian unconformity. The overlying Cenozoic consists of several units starting with the undercompacted shales of Paleogene age (Montadert *et al.*, 2014). The Oligo-Miocene units consist of siliciclastic materials deposited as a result of marginal uplift and sea-level lowstands during the late Eocene and Oligocene (Haq and Al-qahtani, 2005) which have led to erosion on the margin and clastic deposition in the basin (Gardosh *et al.*, 2008). Hawie *et al.* (2013) documented the presence of canyons incising the margin within the middle-upper Miocene offshore northern Lebanon, together with various characteristics of deep-water sedimentary environments such as channels, levees and sheeted turbidite lobes towards the distal basin.

The thick Oligo-Miocene succession in the Levant Basin can be explained by considerable sedimentary flux originating from a proto Nile (Steinberg *et al.*, 2011) in which distal turbidites and basin floor fans could extend as far as the

offshore Lebanon (Dolson *et al.*, 2005; Hawie *et al.*, 2013). However, it was shown that a multi-source system better describes the filling of the basin based on forward stratigraphic modelling constrained by seismic, well and field data (Hawie *et al.*, 2015). Therefore, it is most likely that the filling was also accomplished by erosion from the eastern margin together with provenance of sediments from the north, mainly from the Lattakia region in Syria. Overlying the Oligo-Miocene, the Messinian unit is a ~1.7 km thick evaporitic sequence deposited as a result of the sequestration of the Mediterranean Sea at the end of the Miocene and contains mass transport complexes at the base, clastic materials intercalations and halite (Gorini *et al.*, 2015). A return to a pelagic/hemi-pelagic sedimentation is attested during the Pliocene with the deposition of deep-water turbidites in the basin (Hawie *et al.*, 2013).

Structural setting

NE trending anticlines are documented in the deep basin and are 5 to 15 km long structures deforming the Oligo-Miocene units only and detaching in the Eocene unit (fig. 9). Ghalayini *et al.* (2014) argues that these anticlines were folded immediately prior to, or at the onset of the Messinian salinity crisis due to absence of growth strata in the pre-Messinian units, and erosion of the anticlinal crest along the base Messinian horizon. They were formed due to regional geodynamics caused by the collision and suturing of Arabia with Eurasia. In the southern Levant, similar trending anticlines were formed and are overlying deep-seated Mesozoic extensional structures (Gardosh and Druckman, 2006). It is not clear if the anticlines offshore Lebanon are overlying deeper reactivated

structures, but thickness variations below the ones found closer to the margin strongly suggest so (Ghalayini *et al.*, 2014).

The normal faults are layer bound, found ubiquitously in the Oligo-Miocene units in the deep basin. The faults are regularly spaced with a dip of 60° either to the NE or SW. At depth, all the faults consistently die out at the same intra-Eocene detachment level (fig. 10), which has been interpreted to have a regionally developed shale sequence acting as the basal detachment surface for these faults (Montadert *et al.*, 2014; Hawie *et al.*, 2013; Kosi *et al.*, 2012). As there is no NE-SW extension documented in the basin during the Oligo-Miocene, an exclusive tectonic origin for their formation or a nucleation model in relation to the Messinian Salinity Crisis (MSC) has been refuted (Ghalayini *et al.*, 2016). Detailed analysis of the fault growth and evolution have showed that they have nucleated during the Early Miocene and remained syn-sedimentary till the Late Miocene (Ghalayini *et al.*, 2016). A likely nucleation mechanism for these faults could be related to diagenetic reactions in the Oligo-Miocene units leading to volumetric contraction of the host rock and causing intra-formational normal faulting (e.g. Cartwright 2011, Davies *et al.* 2009, Wrona *et al.* 2015).

The Lattakia Ridge

The Lattakia Ridge is a prominent structure that is found at the NW part of the Levant basin offshore Lebanon. It is part of the Cyprus Arc system and stretches from the Syrian region in the NE to offshore southern Cyprus. It is characterized by a strong topographic high observed at the seafloor.

Stratigraphic setting

The stratigraphy in this domain is similar to the rest of the Levant basin, albeit with different thicknesses of units, especially to the west of the ridge itself. The same horizons in the deep basin are also documented along the Lattakia Ridge. The Late Cretaceous convergence has resulted in a depocenter in the lower Tertiary in this region evidenced by thicker Eocene and Oligocene units south and south-east of the Lattakia Ridge (Hawie *et al.*, 2013). The Miocene unit, however, is thinning considerably and reaches up to 1 km in total thickness. It is suggested that the proximity to a northern sedimentary source, i.e. from Syria, could result in coarser sediment and more clastic material in the Oligo-Miocene unit of this domain, possibly pointing to better reservoir qualities (Hawie *et al.*, 2015).

Structural setting

The Latakia Ridge consists of a series of south-east verging thrusts forming prominent NE trending narrow structures and having a profound bathymetric expression (fig. 11). Several anticlines are found adjacent to the Lattakia ridge. These are symmetrical NE-trending structures, which in the Oligo-Miocene units appear very similar to compressional anticlines, while in the deeper Eocene and Mesozoic unit they consist of deep-seated SE verging thrusts with steep SE limbs (fig. 11). Back thrusts are documented along this ridge and are believed to have

been initiated during the Pliocene as a result of transpression (Hall *et al.*, 2005; Symeou *et al.,* in review). This complex structural style of the Lattakia Ridge is a result of the geodynamic setting of the Eastern Mediterranean region discussed above.

The Levant margin

The Levant margin domain covers the area adjacent to the Lebanese shoreline and comprises the Saida-Tyr plateau, a small narrow strip in front of Beirut, and a larger platform north of Lebanon (fig. 7). It is differentiated from the Cenozoic deeper basin by its thick Mesozoic carbonate succession on top of which the Cenozoic units are pinching out and onlapping. It is generally acknowledged that the Levant margin encompasses the onshore domain in Lebanon, including Mount Lebanon (Nader 2011). However, for the purpose of this paper, we differentiate the Levant margin from the inner onshore domain (i.e. Mount Lebanon and the Bekaa Valley) as the depositional setting and associated petroleum systems are expected to be different (Hawie *et al.*, 2014; Bou Daher *et al.*, 2016; Bou Daher *et al.*, 2015; Nader, 2014).

Stratigraphic setting

Interpretation of the stratigraphy along the Levant margin is provided by Hawie *et al.* (2013), in which they correlate the units identified in seismic data to those documented onshore (Dubertret, 1955; Hawie *et al.*, 2014; Nader, 2011). An

updated interpretation of the expected stratigraphy of Levant margin is provided in the previous section of this manuscript.

Structural setting

The structures of the southern Levant margin were described in the previous section. They show an analogy with those described by Ghalayini *et al.* (2014) on the strike-slip faults, and those of Homberg *et al.* (2009) regarding the normal faults in southern Lebanon. From south to north, the structural setting of the Levant margin offshore Lebanon is markedly different. At the latitude of Beirut, a narrow strip is documented in which the Mesozoic carbonate platform is considerably narrow or absent. It is correlated with very steeply dipping Cretaceous strata onshore adjacent to this location (Dubertret, 1955), in contrast with the broad plateau documented along the southern margin (Homberg *et al.*, 2010; Hancock and Atiya, 1979). In the north, the Tertiary units gently onlap the Mesozoic succession and the overall margin is cross-cut by E-W trending dextral strike-slip faults. En-echelon anticlines, oriented NE-SW, are documented in the Upper Miocene unit along the strike of these strike-slip faults. Several NNE trending Mesozoic normal faults are documented in the Permo-Triassic units and could be related to the Mesozoic rifting event (Hawie *et al.*, 2013).

The onshore domain

The onshore domain comprises the prominent Lebanese ranges including Mount Lebanon, Anti-Lebanon and the Bekaa Valley in between (fig. 1). It is located at

the margins of the Levant and the Palmyra Basins, which have similar ages and tectonic histories (Ghalayini *et al.*, 2017; Nader, 2014). Therefore, it has been stated that the Lebanese ranges are part of the Palmyra Basin due to the large resemblance between the structural features, the similar crustal configuration and the analogous stratigraphic intervals (Ghalayini *et al.*, 2017; Beydoun and Habib, 1995; Nader, 2014), yet the Lebanese ranges have been further affected by the passage of the LFS in the Late Miocene and Pliocene. The main folding phase of the Palmyrides and the initial uplift of Mount Lebanon, took place during the Late Oligocene or Early Miocene (Brew *et al.*, 2001; Sawaf *et al.*, 2001; Chaimov *et al.*, 1992; Beydoun, 1999; Hawie *et al.*, 2014; Ghalayini *et al.*, 2017).

Stratigraphic setting

The documented units observed in outcrops range from the mid-Jurassic to the Upper Cretaceous in Mount Lebanon, with Paleogene and Neogene sediments closer to the shoreline and in the Bekaa valley. Pre-Jurassic units are not exposed onshore. Nevertheless, correlation with the geology of the Syrian Palmyra basin allowed suggesting that the Triassic sequence is expected to extend westward and is thicker in Lebanon (Beydoun and Habib, 1995). This is based on extensive deep exploration wells and seismic data in Syria (Sawaf *et al.*, 2001; Chaimov *et al.*, 1993; Brew *et al.*, 2001) as well as an old electro-resistivity survey that indicated the presence of a conductive unit located at 650m below the oldest outcropping Jurassic outcrop (Renouard, 1955) which was attributed to a potential Triassic evaporate layer (Beydoun, 1977; Beydoun and Habib, 1995). Therefore, it is likely that the Triassic in Lebanon is analogous to Syria, which has

also been proposed based on interpretation of reflection seismic data onshore northern Lebanon (Nader *et al.*, 2016). The Triassic unit in the Palmyrides is documented to consist of a Lower Triassic Amanus shale formation and a middle to Upper Triassic Kurrachine formation. The latter is subdivided into two units, a dolomite and an overlying anhydrite sequence. Equivalent units are identified in Jordan (Luning and Kuss, 2014) and in the southern Levant margin (Gardosh and Tannenbaum, 2014).

The Jurassic sequence in Lebanon is approximately 1,700 m thick, and could reach 2,700 m thick in the Mount Hermon region of the southern Anti-Lebanon ranges (Dubertret, 1955). The Lower Jurassic consists of a dark and thick dolomite sequence termed the Chouane Dolomites. It is overlain by the mid to late Jurassic Kesrouane Limestone Formation deposited during a period of post-rift subsidence in shallow water environment. Above the Kesrouane formation, lies the Kimmeridgian Bhannes volcanic unit which consists of a mixture of carbonates, marls, lavas and pyroclastics. It is distinctive in some location by its red soils and hard basalts, with occasional pillow lavas. The thickness of this unit decreases southward and is in average around 80-100m thick. Overlying the Bhannes volcanics, is a 60-80 m thick cliff-forming formation termed the Bikfaya formation. It consists of massive bedded limestone deposited in a period of sea level rise. The end of the Jurassic is marked by a return to shallow water sedimentation with deposition of ferruginous oolitic limestone of the Salima formation.

The Cretaceous sedimentary cycle starts with deposition of the Hauterivian Chouf sandstone formation (Maksoud *et al.*, 2014; Walley, 1997). This unit is between 5-300 m thick across Lebanon and thins northward reflecting possible clastic provenance from the southeast. It consists of ferruginous brown to white sandstone with clays, coaly shales and volcanics. It was deposited under a fluvial to deltaic littoral environment. The overlying Barremian Abieh formation varies between fossiliferous limestone, marls and sandstones and represents a transition between the fluvial Chouf and the overlying shallow marine late Barremian to Aptian units. The latter is a conspicuous cliff-forming formation clearly visible throughout all of Lebanon, with a thickness of about 50 m (Maksoud *et al.*, 2014). It consists of a single massive grey limestone. Small scale rudist and stromatoporoidal reef buildups are visible in some locations. It represents a sequence of shallow marine transgressive carbonate facies linked to early Aptian eustatic rise. The overlying Albian corresponds to thin bedded carbonates, marls and terrigenous sand. It represents a brief return to terrigenous clastic deposition, in a general marine setting, before sea levels caused renewed carbonate deposition.

The upper part of the Cretaceous and early Paleogene is almost entirely composed of carbonate. The Cennomanian Sannine formation is 600 m thick and consists of medium to thick bedded shallow water limestones and marly limestone. This sequence thickens to the west with increasing thin bedded chalk and cherty pelagic sediments along the coast. It is possible that these lateral facies change and thickness increase could point to a shift from shallow water deposition in the east, to deeper environments westward dominated by

carbonate turbidite deposits (Hawie *et al.*, 2014). The overlying Turonian unit is 200-300 m thick and represents a continuation of the carbonate deposition of the Cennomanian and is characterized by thin finely bedded, chalky micrites and cherts with abundance of Hippurite fossils. The Senonian/Campanian-Maastrichtian Chekka formation consists of very dark grey to white sequence of chalks and marly limestone units. Its thickness ranges from 100 to 500 m with the thickest succession documented in the southern Bekaa valley and is made of chalk and marly limestone. It has a very good source rock potential as it contains organic rich argillaceous limestone with TOC values between 2 and 10% (Bou Daher *et al.*, 2014; Bou Daher *et al.*, 2015).

The overlying Paleocene units are 300 m thick and consist of chalky limestones and marls. Nummulitic middle Eocene limestone have been documented in the Bekaa (Dubertret, 1955) where they reach up to 900 m in thickness (Hawie *et al.*, 2014) and in south of Lebanon. The upper Eocene and Oligocene units are absent in all of Lebanon due to uplift and erosion of the margin during the Early Miocene compressive folding event (Walley, 1998), except of one outcrop south of Lebanon (Müller *et al.*, 2010). The middle Miocene is outcropping and consists of continental lacustrine facies in the Bekaa in contrast with the Miocene open marine facies along the margin (Hawie *et al.*, 2014; Dubertret, 1955). The Pliocene in this area is referred to as the Zahle formation (Nader *et al.*, 2016) and corresponds to clastic deposits, breccias, silt, marl and lacustrine limestone, overlain by alluvial fan conglomerates (Dubertret, 1955).

Structural setting

Mount Lebanon is a NNE trending structure. It exhibits two different structural styles, similar to the Palmyrides ranges (Brew *et al.*, 2001), separated by a deep crustal fault that forms the westward extension of the Jhar fault in the Palmyrides (Ghalayini *et al.*, 2017; Walley, 1998). Northern Mount Lebanon consists of a broad and symmetric box-fold anticline, (Renouard, 1955; Beydoun and Habib, 1995), while southern Mount Lebanon is topographically lower and the deformation zone includes several shorter wavelength folds including a tight SE verging overfold termed the Niha-Barouk anticline (Dubertret, 1955; Walley, 1998). Anti-Lebanon is an anticlinal structure very similar to Mount Lebanon located more inland and merges topographically with the Syrian Palmyrides ranges in the south. The Bekaa valley, which is dominated by a thick Tertiary to recent continental succession, separates the two mountain ranges. The valley is narrow in the south in the Hasbaya area and widens northward into the Homs Plain in Syria.

The Yammouneh Fault passes through Mount Lebanon and forms a continuation of the plate boundary between Arabia and Africa that stretches from Aqaba in the south to Taurus in the North. In Lebanon, it reaches 160 km length and bounds the eastern side of southern Mount Lebanon, while it cuts through its northern counterpart. It is believed to be an ancient fault system from pre-Cambrian times (Butler *et al.*, 1998). The LFS effect in Lebanon is mostly tranpsressive resulting in a restraining bend and causing large uplift of the existing structures during the Pliocene. Since the late Quaternary, it is believed to

accommodate principally strike-slip movements (Daëron *et al.*, 2004; Gomez *et al.*, 2006). Transpression and strike-slip tectonics are mainly accommodated by several faults including the Roum and Serghaya Faults. They are major sinistral strike-slip faults branching from the southern LFS in the Golan Heights and accommodate part of the displacement along the LFS (Gomez *et al.*, 2001; Butler *et al.*, 1998).

Several ENE-WSW, currently active, dextral strike-slip faults are documented along Mount Lebanon (Gedeon, 1999) and extend to the Levant margin offshore (Ghalayini et al. 2014). These faults have most likely nucleated during the Mesozoic as normal faults during the breakup of Pangaea and were subsequently reactivated during the Neogene compression (Collin et al. 2010; Ghalayini et al. 2014). Similar faults are also found in the Palmyra basin further east.

Petroleum Systems

Source rocks and maturity

Potential source rocks are thought to exist in units between the Permian to Pliocene based on regional stratigraphic correlation, field investigations and geochemical analysis. The major potential source rocks are described here below.

The deep basin and Lattakia Ridge

Geochemical analysis of gas samples from Middle Jurassic to Pliocene reservoirs along the southeastern margin of the Levant Basin proved the presence of five thermogenic and biogenic sources (Feinstein *et al.*, 2002). Offshore Lebanon, the Permian and Triassic thermogenic sources – if present – are believed to generate petroleum between 90 and 34 Ma in the deep basin (Bou Daher *et al.*, 2016). The Upper Jurassic Kimmeridgian thermogenic source rocks have most probably generated oil between the Late Cretaceous and the Late Miocene. The Upper Cretaceous Campanian might constitute good thermogenic source rocks which have produced hydrocarbons between 34 and 16 Ma. However, it is expected that in the deep basin, the Campanian source rock quality and TOC content would decline (Bou Daher *et al.*, 2015). Paleocene and Eocene thermogenic source rocks have probably produced hydrocarbons during the Oligocene and are still active in some parts of the basin.

The Oligocene unit might constitute potential thermogenic source rocks which have started to generate hydrocarbons at around 6 Ma and are in the maturity window at the present day. In addition, the Oligocene is believed to contain a promising biogenic potential in the deep basin in which generation of biogenic gas might have occurred between 18.5 and 6 Ma, while on the Lattakia Ridge and in the more proximal basinal realm it might still be ongoing (Bou Daher et al., 2016) as the units are thinner and located at shallower intervals. In fact, the most productive biogenic source rocks in the southern Levant are thought to be within the Oligocene sequence (Gardosh and Tannenbaum, 2014) and these are expected to extend northward to Lebanon (Hawie *et al.*, 2013; Nader, 2014). Other biogenic source rocks include the lower and middle Miocene from which

methane is believed to have been expelled during the Messinian and is currently ongoing (Bou Daher et al., 2016). Based on thermal history modelling, Bou Daher *et al* (2016) predicted that a thickness of 700 to 1500m of sub-Messinian Miocene succession is within the biogenic zone at present day. Detailed information on source rock kinetics, maps of source rock maturation and transformation ratios are presented in Bou Daher *et al*. (2016).

The Levant margin and onshore

Permian and Triassic source rocks – if present – would have generated hydrocarbon between 75 Ma to present day along the margin and onshore (Bou Daher *et al.*, 2016). In Syria, the upper Permian/Lower Triassic Amanus dolomites are very good source rocks for Triassic Reservoirs in the Palmyrides (Barrier *et al.*, 2014) and might therefore be as good in the Levant margin and onshore. Similarly, the Upper Jurassic Kimmeridgian source rocks most probably generated oil between the Oligocene to the present day along the margin (Bou Daher *et al.*, 2016) with minor amount on the onshore in the Late Miocene which were most probably washed out by meteoric waters (Nader and Swennen, 2004a). However, in the deeply buried Jurassic under the Bekaa Valley, the Kimmeridgian source rocks are in the oil window today.

The Campanian source rocks appears not to have been buried deep enough in Mount Lebanon to generate hydrocarbon. In the Bekaa valley and along the margin, however, the Campanian is in the maturity window and minor generation might have occurred (Bou Daher *et al.*, 2015). Geochemical data

suggest that the these source rocks are rich in organic sulphur at high TOC (Bou Daher *et al.*, 2014; Bou Daher *et al.*, 2015) leading to hydrocarbon generation at earlier stages of thermal maturity (Bou Daher *et al.* 2016). Large amounts of immature solid bitumen are found in caves and along fault planes in the Bekaa which are typical for early stages of hydrocarbon generation from type IIS kerogen (Bou Daher *et al.*, 2015).

Reservoirs

The main reservoirs in the deep basin are found in the Oligo-Miocene unit and consist of sand deposited in deep-water turbidite systems (Gardosh *et al.*, 2008; Hawie *et al.*, 2013). In the lower Miocene unit, the Tamar sand is considered as the best reservoir interval, consisting of sand with high net-to-gross and high porosity/permeability in the range of 20-27% and 500-1000 md respectively (Gardosh and Tannenbaum, 2014). The fact that the Cenozoic unit in the deep basin offshore Lebanon is much thicker than its southern counterpart may suggest that the equivalent potential reservoirs might also be thicker. Investigation of the normal fault system offshore Lebanon has revealed that the growth of faults has been affected by mechanical stratigraphy caused by a strong competent lower Miocene unit with faults nucleating in incompetent fine grained sediments. The competent interval is interpreted to consist of a ~100m thick sandy unit equivalent of the Tamar sand in the south (Ghalayini *et al.*, 2016) or could correspond to another lithology that is mechanically more resistant to faulting.

In the northernmost part of the deep basin and in the Lattakia Ridge domain, seismic facies interpretation (Hawie *et al.*, 2013) point that the main reservoirs are possibly located in the upper Miocene and suggest an increased sand content at the base Oligocene. The fact that the normal faults have smaller heights and displacement in this area point that there is a barrier to vertical fault propagation (Ghalayini *et al.*, 2014). As the faults do not propagate to the upper Miocene and lower Oligocene units, it is likely that the latter units consist of incompetent lithologies which might be attributed to coarse clastics or sand. The provenance of clastic material in this area is most likely from a northerly source, probably from the Lattakia region in Syria. In addition, the erosion of Cretaceous to Miocene carbonate platforms contemporaneously with Mount Lebanon's accelerated uplift in the Late Miocene/Pliocene, could lead to more conglomeratic material from the northern Lebanese ranges (Hawie *et al.*, 2015; Hawie *et al.*, 2013).

Along the Levant margin, the Jurassic carbonate platform is far from meteoric influence prevalent onshore (Nader and Swennen, 2004a). This fact, together with the predicted presence of fracture-associated hydrothermal dolomites could form effective reservoirs in the Jurassic carbonate platforms. The Lower Cretaceous Chouf sandstones are correlated to the Rutbah formation in Syria, which constitutes the principal reservoir in the Euphrates Graben (Barrier *et al.*, 2014; Sawaf *et al.*, 2001), and to the Helez formation in the southern Levant, which constitutes the reservoir for the Helez field (Shenhav, 1971). Therefore, the Chouf sandstone might form good reservoirs in the margin offshore. Other units in the Cretaceous, such as the Albian and the Aptian, could form good

reservoirs consisting of isolated reefal buildups similar to the Eratoshtenes margin (Hawie *et al.*, 2013; Montadert *et al.*, 2014; Esestime *et al.*, 2016). Younger reservoirs along the Levant margin consist of the lateral ends of the Oligo-Miocene clastic units onlapping on the Mesozoic carbonate platforms. These reservoirs are believed to be of good quality due to their proximity to the Mount Lebanon sedimentary source than their deep basin's equivalent. Miocene reefs are also documented on paleo-highs along the northern margin and could provide good reservoirs (Hawie *et al.*, 2013; Hawie *et al.*, 2014).

In the onshore domain below Mount Lebanon, the expected reservoirs are pre-Jurassic. All exposed units are subject to severe weathering and influx of meteoric waters, strongly deteriorating the reservoir quality (Nader and Swennen, 2004a). Good reservoirs could belong to the Permian to lower Triassic Amanus sand formation consisting of shales interbedded with channel sandstones and siltstone beds together with the lower to mid Triassic Kurrachine unit consisting of dolomite and sandy intervals. These units are important oil and gas reservoirs in the Palmyrides (Barrier *et al.*, 2014) and in the southern Levant's as they are equivalent to the Mihilla formation (Gardosh and Tannenbaum, 2014). In the Bekaa region, the reservoirs are believed to be Jurassic limestones protected from meteoric invasion, Lower Cretaceous sandstone of the Chouf formation, Upper Cretaceous Senonian fractured carbonates and Eocene nummulitic limestone.

Seal

In the deep basin, the Paleocene/Eocene package is believed to form a strong impermeable unit sealing the deeper reservoirs and preventing vertical hydrocarbon migration from deeper intervals. The consistent detachment of normal faults on the Eocene unconformity horizon (fig. 10) together with the chaotic seismic facies and weak amplitudes observed in the Paleocene/Eocene unit point that the latter is likely constituted by shales (Kosi *et al.*, 2012) and highly overpressured rocks (Montadert *et al.*, 2014). In the Oligo-Miocene unit, intra-formational shale or clay may constitute good seals for Miocene reservoirs similar to the Tamar and other fields in the south (Gardosh *et al.*, 2008). In this unit, the normal faults could either form good lateral seals at present day or act as conduits to hydrocarbon migration. In fact, the maximum documented displacement on these faults is around 350 m, causing a large offset of reservoir against seal lithologies, increasing the likelihood of impermeability along fault planes. In contrast, the same faults are observed to cross-cut the Tamar, Aphrodite and Leviathan fields in the southern Levant basin but they do not seem to affect the continuity of the reservoirs (Gardosh and Tannenbaum, 2014). Therefore, this juxtaposition relationship still needs to be checked during drilling. The shallowest cap rocks in the basin are the Messinian salts forming up to 1500 m of evaporites and are as such considered to be an optimal seal if underlying reservoirs are present.

The cap-rocks in the Lattakia Ridge are the same as the ones in the deep basin. In this area, the complex deformation and extensive fracturation has most probably affected the sealing potential of all units. This effect is most pronounced at the Lattakia ridge itself and diminishes south-eastward toward the deep basin. In

addition, the Messinian unit is absent on top of the ridge while thinning considerably in the adjacent areas. Gas chimneys are frequently observed in the area where the Messinian is absent and/or thinning on top of anticlines SE of the Lattakia Ridge. In one particular example, gas accumulations in the shallow upper Miocene reservoirs were possibly leaked out when the seal was thinning and absent, as evidenced by the chimneys documented only in the absence of the salt (fig. 12).

Along the Levant margin, potential cap rocks are the Lower Triassic evaporites of the Kurrachine formation that are probably extending to the offshore carbonate platform. The Kimmeridgian volcanic formation might also constitute a good seal for deeper reservoirs, even though this unit is not laterally homogenous (Dubertret, 1955) with expected facies change toward the basin. Cretaceous clays, marls, and basalts could represent good cap rocks for the underlying reservoirs. The Messinian unit in the Levant margin is either considerably thinning in some locations (fig. 3) or is absent in others (fig. 5) which could diminish the Messinian seal quality in this location.

Onshore, the expected thick Upper Triassic evaporites of the Kurrachine Formation seal the underlying dolomitic reservoirs and protect them from meteoric influence since the uplift of Mount Lebanon (Nader, 2011).They are well documented to provide a regional seal in the Palmyrides (Barrier *et al.*, 2014; Sawaf *et al.*, 2001) and in the southern Levant with the equivalent Saharonim and Mihilla Formations (Gardosh and Tannenbaum, 2014). In the Bekaa, intra-formational volcanic, marly and shaly units of Jurassic and

Cretaceous age could seal the Jurassic and Cretaceous reservoirs. The Paleocene calcareous shales might form a good seal as well as a protection to meteoric infiltration in the Bekaa.

Traps and migration

Trap formation in the deep basin offshore Lebanon is mostly related to structural processes in sub-salt units. The structural traps consist of (1) NE trending anticlines in the Oligo-Miocene, detaching on the Eocene unconformity horizon and folded immediately prior to, or at the onset of the Messinian salinity crisis; (2) NE trending transpressive anticlines and positive flower structures found primarily in the south west of the STP and formed during the Late Miocene and (3) Oligo-Miocene tilted fault blocks that nucleated during the lower Miocene and active during Miocene time. Migration of hydrocarbon from biogenic source rocks may have been aided by the intense faulting and fracturing of the Oligo-Miocene unit. As discussed earlier, the faults may constitute a good seal at present day and provide 3-way closures. Their nucleation time during the early Miocene and their continuous activity throughout the Miocene time (Ghalayini *et al.*, 2016) make these faults permeable throughout the Miocene. Therefore, any petroleum migration after the Oligocene could result in charging the reservoirs in the Oligo-Miocene unit.

In the Lattakia Ridge domain, the trap type is mostly structural with symmetrical anticlines in the Cenozoic unit underlain by deep-seated SE verging thrust faults,

providing excellent four-way closures. These anticlines are found surrounding the Lattakia Ridge as of the Late Cretaceous time, but the ridge itself is a poor trap due to the lack of closure as a result of intense uplift and erosion of the Cenozoic units. Migration of hydrocarbons from source to reservoirs must have happened through the numerous faults and fractures associated with the intense deformation of the Lattakia ridge since the Late Cretaceous times. Deformation continued till modern day indicating that several faults are still active and implying that they could form effective migration pathways.

Along the Levant Margin, trap mechanism is mostly stratigraphic within the Mesozoic carbonate platform. Other stratigraphic traps include pinchout of the Early Cretaceous sand sealed by Cretaceous carbonates in addition to pinchout of Oligo-Miocene sandy units onto shallower Mesozoic strata and sealed by intra-Miocene shale. Structural traps include inversion structures, such as reactivated ENE-WSW strike-slip faults (e.g. Ghalayini et al. 2014) forming 4-way dip closures below the Messinian. Along the margin, pre-existing and inverted faults may have played an important role in hydrocarbon migration from the deep Mesozoic source rocks to shallower reservoirs. As these faults were active throughout much of the geological time, they might have been permeable during the Mesozoic and Cenozoic times.

Onshore, the traps are mostly of structural type, consisting of 4-way dip closure anticlines formed by the transpression along the LFS (Nader, 2014; Nader *et al.*, 2016). Potential large traps are the Qartaba anticline (Nader, 2014; Nader, 2011) together with other large structures, such as the Sir-Ed-Denie, Barouk-Niha and

Jezzine, which might form a good trap geometry in the subsurface similar to the Qartaba anticline, and could be potential prospects (Beydoun and Habib, 1995; Beydoun, 1977). They might have formed in the Late Miocene in association with the activity of the LFS. In the Bekaa valley, potential traps might be structures located beneath the quaternary cover (e.g. Nader *et al.*, 2016).

Overall Discussion

Based on 3D seismic data, a new interpretation of the Levant margin offshore Lebanon is proposed. In the southern margin, the seismic horizons were tied to nearby well which resulted in updated stratigraphic subdivisions of the Saida-Tyr plateau. The Triassic unit is likely present based on the predicted unit thicknesses in Lebanon (Beydoun and Habib, 1995). This is conformable with the finding of Nader *et al.* (2016) onshore in which they suggest the presence of high amplitude seismic horizons which they interpret as the Top Triassic based on regional thicknesses. The high impedance contrasts along this horizon in the southern margin could be related to the presence of evaporites within the Triassic but this still needs to be checked by drilling.

Recently, the discovery of Zohr in carbonate reservoirs around the Eratosthenes seamount has opened new play concepts in the basin and attracted attention to the carbonate potential (e.g. Esestime et al., 2016; Montadert et al., 2014). The presented interpretation along the margin refines our understanding of the expected carbonate sequences which could open up new play concepts. The Mesozoic carbonates are considered to have good porosity from correlation with

onshore analogues in Lebanon (Nader and Swennen, 2004a; Nader and Swennen, 2004b) and Syria (Barrier *et al.*, 2014). As they are sealed from meteoric invasion, they are very likely not affected by flushing and so are good reservoirs (e.g. Nader and Swennen 2004a). Hawie *et al.* (2013) demonstrate the presence of reefal buildups onshore Lebanon based on extensive field observations and analysis and suggest the likely continuity of such buildups to the margin offshore. This could make the potential reservoir within the Levant carbonate sequence equivalent to the Eratosthenes ones and therefore provide effective analogues for the Zohr (e.g. Esestime et al. 2016). An attractive aspect of the Levant margin is the strong thermogenic potential in this domain which could invoke liquid hydrocarbon accumulations.

This new interpretation of the margin reduces risk in exploration as it provides new elements for the petroleum system and hence new potential prospects. The Lower Cretaceous sandstone is identified in the northern margin, stratigraphically trapped between the Jurassic and Cretaceous carbonate talus. This unit offshore appears to be thicker than its equivalent onshore (e.g. Dubertret, 1955; Bellos, 2008). This could be related to an established basin/margin differentiation since at least the Early Cretaceous in which a larger accommodation space is available for the Nubian sand to be deposited offshore. Hawie *et al.* (2013) indeed argues for a general westward facies variation in Mesozoic sequences caused by a transition to deeper basinal environments.

The relatively good reservoir properties of the Lower Cretaceous sandstone unit onshore Lebanon and Syria (e.g. Bellos, 2008) and the hydrocarbon production

from this same unit in the southern Levant (Shenhav, 1971; Gardosh and Tannenbaum, 2014), suggest that similar prospective plays might well exist offshore Lebanon. In fact, DHI's such as bright spots and a potential flat-spot is observed in seismic data (fig. 13) which invoke hydrocarbon accumulations, originating from thermogenic source rocks. This unit extends along the entire margin offshore Lebanon and therefore could be associated to large prospects. The challenge, however, is the depth of this play being around 8 km in some locations, resulting in potentially high pressure reservoirs.

Additional DHI's, such as flat spots, can also be observed within the Oligocene unit along the Levant margin (fig. 14). With the relatively better reservoir quality expected in this location (Hawie *et al.*, 2015), it is very likely that Oligo-Miocene pinchout prospects could also be promising. As the flat spot is located below the Base Miocene horizon, this indicates that the seal might be around the Base Miocene. This could point that towards the margin, the base Miocene is probably be associated with shaly/marly or fine grained facies and transitions to coarser grains or sandy facies toward the basin.

Significance of geological domains

This contribution aims at updating the general knowledge on the potential petroleum systems of Lebanon ahead to the first Lebanese offshore licensing round. Based on a comprehensive review of previously published and achieved integrated research work (geodynamics, stratigraphy, structural geology and geochemistry) together with the interpretation of two key seismic profiles, we

provide here an original subdivision of the Lebanon onshore/offshore into four distinct geological domains.

This subdivision is more adequate when assessing the petroleum potential of Lebanon as every domain is characterized by a variable petroleum system. This is due to different geological characteristics of each domain resulting in different source-reservoir-trap configurations, and hence different petroleum plays. Therefore, this subdivision becomes very beneficial during exploration as it focuses attention to specific plays which are a unique to each domain.

Previous studies have grouped the Lattakia Ridge and the deep basin into one domain termed the 'offshore' in which a similar petroleum system is expected (Nader and Swennen, 2004b). More detailed analysis, however, suggests otherwise. The source rocks charging the reservoirs in the Lattakia Ridge are supposed to be both thermogenic and biogenic, while in the deep basin the biogenic ones are dominant (Bou Daher *et al.*, 2016). In addition, the traps are of Late Cretaceous age and the reservoirs intervals are unlikely to consist of the Tamar sands but could belong to other intervals (Ghalayini *et al.*, 2014; Ghalayini *et al.*, 2016; Hawie *et al.*, 2015). Such geological variations necessitate to associate the Lattakia Ridge to an independent domain of the deep basin.

The onshore domain have been discussed abundantly and the expected petroleum system is well described from regional correlations and field studies (e.g. Beydoun, 1977; Beydoun and Habib, 1995; Nader and Swennen, 2004b; Nader, 2014; Hawie *et al.*, 2014). Although the expected source-reservoir

configurations differ between the Bekaa valley and Mount Lebanon, they have been grouped into one domain. They both are believed to contain a good thermogenic system (Bou Daher *et al.*, 2016) in which the Triassic petroleum system is dominant. In the Bekaa, a working Cretaceous petroleum system might also be effective beneath the quaternary cover (e.g. Nader, 2014; Beydoun, 1977).

Four petroleum system charts have been compiled for the Lattakia, deep basin, margin and onshore domains (figs. 15-16). They show the variable petroleum system elements expected in each. The reservoirs, seals, traps and source rock maturity have been discussed in previous sections and are summarized in each chart. In the Lattakia ridge domain and the Levant margin, a mixed thermogenic/biogenic charge is feeding the reservoirs as of the Late Cretaceous to modern time, while in the deep basin a dominantly biogenic system is expected. Onshore, only thermogenic sources are active and charging the reservoirs as of the late Tertiary.

Regional analogues

Comparison between structures and facies documented both offshore and onshore Lebanon draws similarities between the structural style and reservoirs of nearby discoveries and therefore decreases uncertainty. Numerous analogue studies are expected to be carried out in the Levant region in order to bring further knowledge on such an under-drilled and less known basin. Here, we

provide a few insights on the similarities between onshore and probably similar offshore structures.

The anticlines offshore Beirut (fig. 9) are interpreted to have thin-skinned deformation in which the Eocene unconformity horizon acts as a detachment surface (Ghalayini *et al.*, 2014; Kosi *et al.*, 2012). In the southern Palmyrides, the Triassic salt sequence acts as an effective detachment surface for some of the anticlines in Syria (Brew *et al.*, 2001). One particular example is the Cheriffe anticline (Chaimov *et al.*, 1992) which shows a similar structural style to the offshore Lebanese ones. In addition, some of the anticlines in the Palmyrides have a box-fold geometry, based on subsurface data and surface expression (Searle, 1994) drawing analogies to the Qartaba anticline onshore. The latter has very steep to overturned flanks locally with a gently westward dipping top. This suggests that the Qartaba anticline is not simply a horst as it was commonly referred to (Dubertret, 1955) but a compressional structure with possible fault-propagation folding and/or detachment faulting in which the middle Triassic evaporates could have acted as a decoupling horizon. In fact, Nader *et al.* (2016) identified in 2D seismic profiles a deepest horizon in north Lebanon possibly representing the Triassic evaporites and suggested a continuity of the Qartaba structure at depth.

Although the effect of the Triassic detachment layer is not observed offshore, the Eocene unconformity could possess a similar decoupling effect. Therefore, the thin-skinned anticlines of the Palmyrides are very likely structural analogues for the offshore anticlines. In addition, both the offshore and Qartaba anticlines are

cross-cut by the same ENE trending dextral strike-slip faults documented along the Levant margin (Ghalayini *et al.*, 2017). This increases the structural similarities of these anticlines and insinuates a similar timing, being in the Late Miocene prior to the effect of the strike-slip faults (e.g. Ghalayini *et al.*, 2014).

The exploration implications on the structural style of the anticlines is profound as it affects the subsurface closures and location of faults. The uncertainties are probably less offshore with the availability of 3D seismic data, but the challenges persist for onshore anticlines. The adopted structural style helps predicting the likely location of subsurface traps and directly affects the proper positioning of the wells during exploration. Therefore, using analogues to help exploration offshore and onshore Lebanon could be of a great value and would reduce uncertainty significantly.

Lessons learnt from exploration onshore

In the onshore domain, exploration wells have been drilled with total depths ranging from 1,421 m to 3,065 m (Beydoun and Habib, 1995). The deepest formations reached range in age from Late Cretaceous to mid-Jurassic. In most of these wells, the main reservoirs were water-flushed due to erosion leading to bad and ineffective seals, direct communication with elevated meteoric recharge areas in the high Lebanon and Anti-Lebanon Mountains, or their proximity to major faults (Nader and Swennen, 2004a; Beydoun and Habib, 1995). Therefore, it is clear that prospective units must be pre-Jurassic with petroleum system

elements similar to the Palmyrides with a probable exception of the Bekaa in which the Jurassic and some Cretaceous strata are buried deeper and could be well sealed.

Some of the important lessons acquired for future explorers of the onshore Lebanon are the followings: (i) most importantly, the wells must reach the most promising units, being the Lower Triassic reservoirs that are proven in the Palmyrides and (2) analogues must be used to aid exploration – since no adequate drilling is available to date. Still hydrocarbon shows were noted in shallow wells, indicating that a working petroleum system exists. This has also been observed offshore with the numerous DHI's, gas chimneys and working petroleum system elements, which are all encouraging additional exploration.

To minimise the risk, it is primordial to use modern techniques to properly characterise the prospects and choose the best drilling location. These involve (1) reliable seismic data aided by other geophysical data such as gravity, magnetic and electrical surveys to image the subsurface at depth, (2) usage of satellite imagery and remote sensing to carefully map the structure at surface and draw new geological and facies maps over each prospect, and (3) usage of new modelling techniques in order to visualise and reconstruct the structure at depth. These techniques will substantially reduce the risk of the petroleum prospects in the onshore domain. Promising discoveries can be made if new play concepts are developed and deeper units are targeted in drilling.

Conclusions

Interpretations of key seismic reflection profiles along the Levant margin offshore Lebanon together with a comprehensive overview based on recently achieved integrated research projects have resulted inan improved understanding of the geology of this area and of its petroleum exploration potential. Four geological domains have been identified, and petroleum system charts were compiled for each summarizing the main source rocks, reservoirs, seals and traps:

- The deep basin: characterised by predominantly clastic reservoirs and dominated by Oligo-Miocene biogenic source rocks. The structural traps might be late Miocene four-way dip closures and early Miocene tilted fault blocks,

- The Lattakia Ridge: characterised by dominantly Oligo-Miocene clastic reservoirs and with a mixed biogenic-thermogenic source rock potential. The traps are Late Cretaceous four-way dip closures.

- The Levant Margin: characterised by Mesozoic carbonate reservoirs together with Early Cretaceous and Oligo-Miocene clastics, with predominantly thermogenic source rocks with possibility of lateral migration from biogenic source rocks. The traps are mostly stratigraphic.

- The onshore: Characterised by Triassic dolomitic, Jurassic and Cretaceous carbonate reservoirs with thermogenic source rocks in the Lower Triassic, Kimmeridgian and Campanian. The traps are mostly four-way dip closures.

Working petroleum systems are very likely present in Lebanon and should be encouraging to undertake additional exploration and drilling within these four domains. Several lessons can be taken from the wells onshore, which can be used to better focus future exploration. Nearby discoveries could provide good analogue examples for the Lebanese prospects and could help in reducing uncertainties, namely onshore. Such analogues are likely found in the Palmyrides, and if considered, could positively impact exploration success.

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Figures

Fig1: Main structural elements of Lebanon, the Levant Basin and part of Syria. Map compiled from Barrier et al. 2014; Ghalayini et al. 2016; Ghalayini et al. 2014; Brew et al. 2001.

fig. 2: Creaming curve for both the Oligo-Miocene 4-way dip closures and the Mesozoic carbonate plays in the Levant Basin.

Fig. 3: Geo-seismic line showing the Levant margin off the coast of northern Lebanon consisting mainly of a carbonate succession. The Triassic contains extensional normal faults in relation to the Triassic breakup of Pangea and the Early Cretaceous clastics are pinching out on the Jurassic carbonate talus deposits.

Fig. 4: Structural map of the Saida-Tyr plateau offshore and the onshore Tyr-Nabatieh plateau. The depth map offshore corresponds to the Senonian unconformity horizon. The en-echelon anticlines along the Saida fault are only observed at the Base Messinian horizon and not at the level of the Senonian unconformity.

Fig. 5: Geo-seismic line showing the Levant margin off the coast of southern

Lebanon. The broad Mesozoic platform in this area is referred to as the Saida-Tyr Plateau (Ghalayini et al. 2014). The seismic data was tied to the nearby Adloun well and shows the complete Jurassic to Cretaceous succession found onshore. The strong reflectors below the Jurassic are believed to represent the Triassic. For location, see figure 4.

Fig. 6: Geoseismic line across the western edge of the Saida-Tyr plateau showing the transgressive anticlines separating the deep basin from the Mesozoic plateau. For location, see figure 4.

Fig 7: The geological domains of Lebanon together with the nearby hydrocarbon discoveries

Fig. 8: Petroleum potential, stratigraphy and tectonic events for Lebanon and its offshore

Fig. 9: An example of a NE trending anticline in the deep basin domain offshore Lebanon. The structural style suggests detachment folding on an intra-Eocene horizon. The anticlines were folded in the Late Miocene prior to the Messinian event (Ghalayini *et al.* 2014).

Fig 10: Seismic section showing the titled fault blocks in the deep basin domain. The depth map of the base mid Miocene horizon shows the geometry of the associated traps at present day

Fig. 11: Geo-seismic line showing the Latakia Ridge north of the Levant Basin

FIg. 12: gas chimneys on top of a Miocene anticline observed only when the Messinian seal thins or is absent. The overlying Pliocene exhibits numerous bright spots and DHI's pointing to entrapment of the leaked gas into Pliocene reservoirs in structural closures.

Fig. 13: Geoseismic line showing a bright spot and a potential flat spot in the Lower Cretaceous unit pinching out along the Levant margin and trapped between Mesozoic carbonates.

Fig. 14: Geoseismic line showing a potential flat spot in the Oligocene unit observed along the Levant margin. The lateral Oligo-Miocene units are pinching out on the margin forming classical stratigraphic traps.

Fig. 15: Petroleum system charts for the deep basin and Latakia Ridge domains.

Fig. 16: Petroleum system charts for the Levant margin and onshore domains.

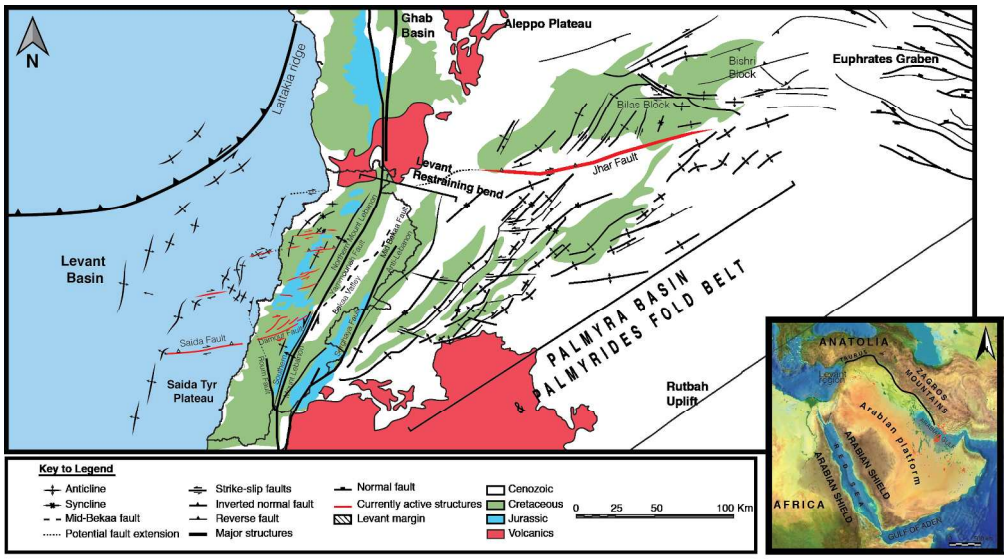


Figure 1

Main structural elements of Lebanon, the Levant Basin and part of Syria. Map compiled from Barrier et al. 2014; Ghalayini et al. 2016; Ghalayini et al. 2014; Brew et al. 2001.

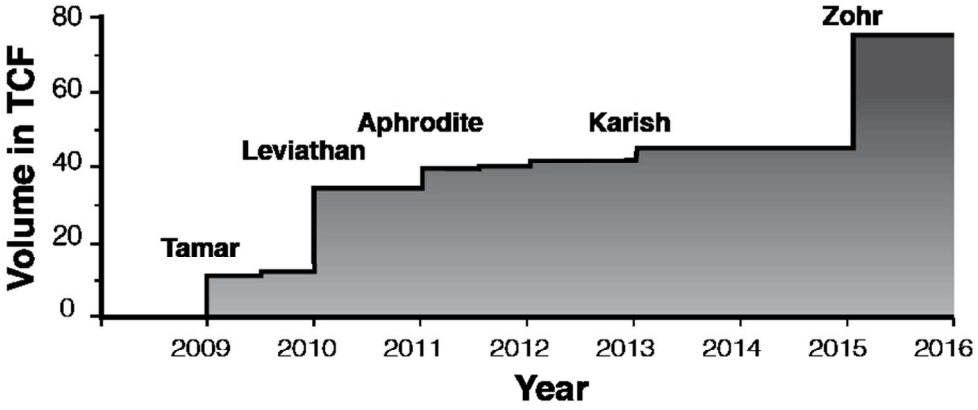


Figure 2

Creaming curve for both the Oligo-Miocene 4-way dip closures and the Mesozoic carbonate plays in the Levant Basin.

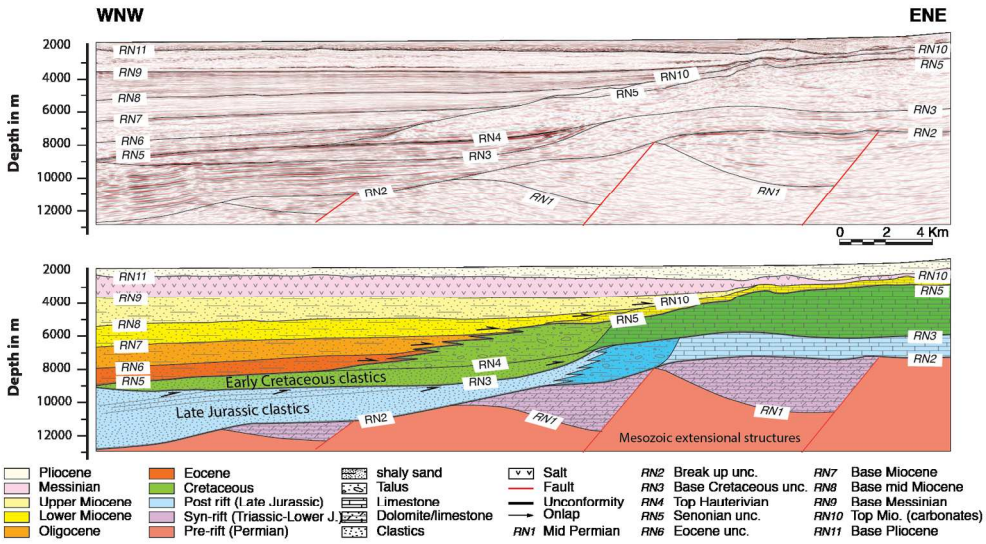


Figure 3

Geo-seismic line showing the Levant margin off the coast of northern Lebanon consisting mainly of a carbonate succession. The Triassic contains extensional normal faults in relation to the Triassic breakup of Pangea and the Early Cretaceous clastics are pinching out on the Jurassic carbonate talus deposits.

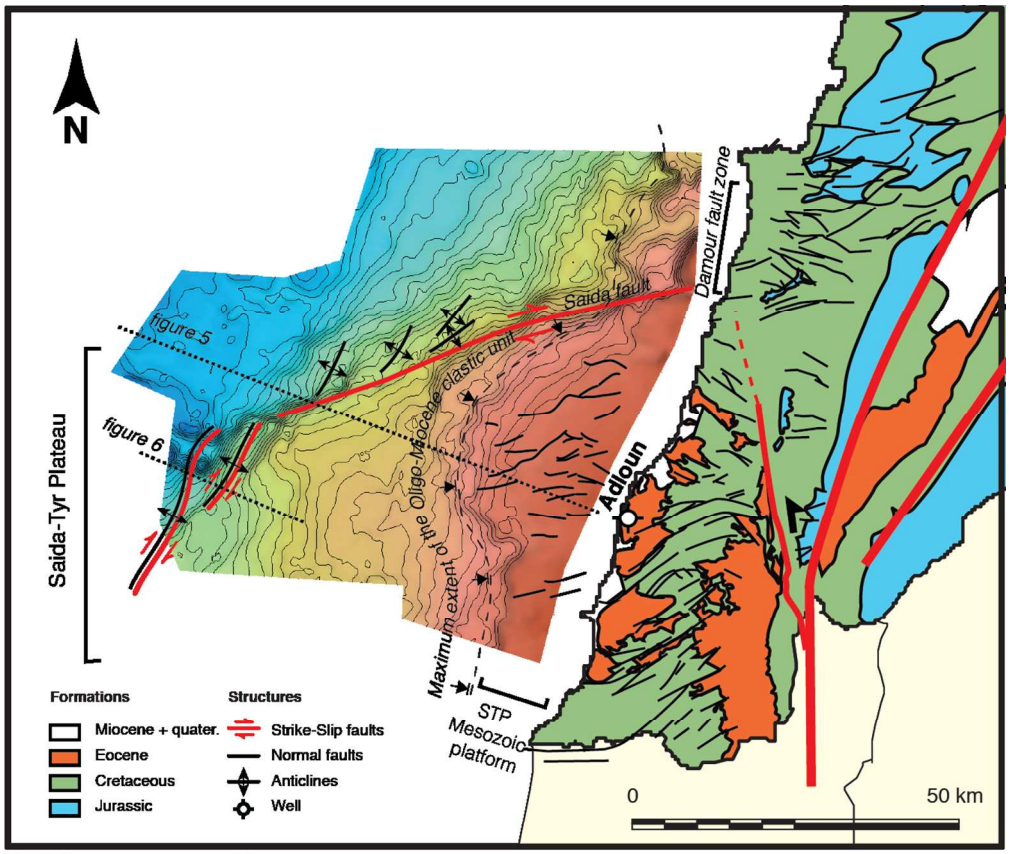


Figure 4

Structural map of the Saida-Tyr plateau offshore and the onshore Tyr-Nabatieh plateau. The depth map offshore corresponds to the Senonian unconformity horizon. The en-echelon anticlines along the Saida fault are only observed at the Base Messinian horizon and not at the level of the Senonian unconformity.

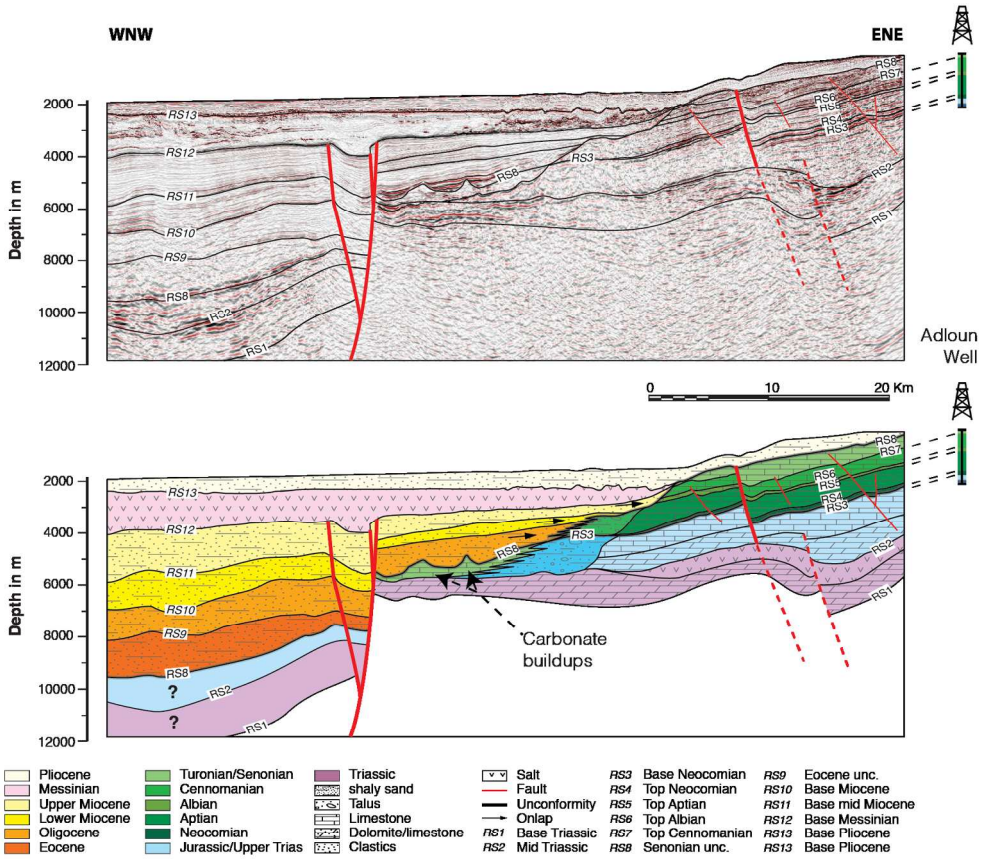


Figure 5

Geo-seismic line showing the Levant margin off the coast of southern Lebanon. The broad Mesozoic platform in this area is referred to as the Saida-Tyr Plateau (Ghalayini et al. 2014). The seismic data was tied to the nearby Adloun well and shows the complete Jurassic to Cretaceous succession found onshore. The strong reflectors below the Jurassic are believed to represent the Triassic. For location, see figure 4.

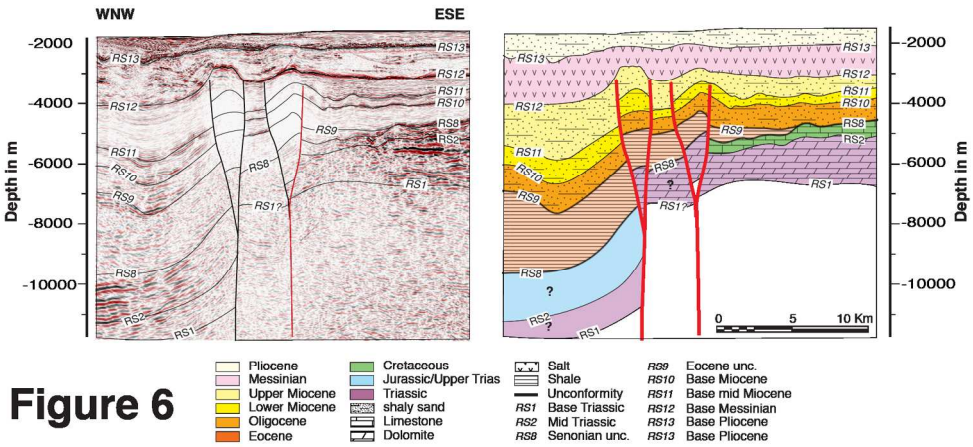
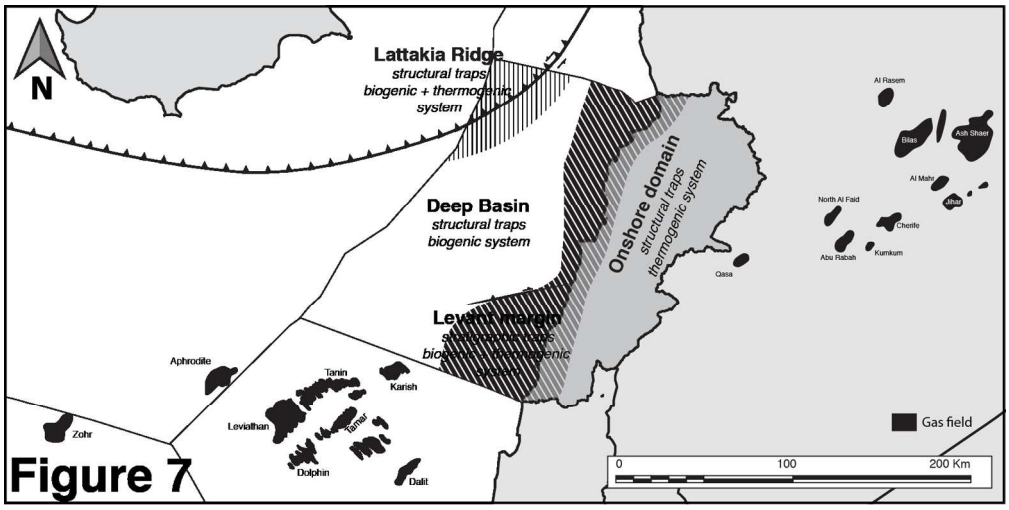


Figure 6

Geoseismic line across the western edge of the Saida-Tyr plateau showing the transgressive anticlines separating the deep basin from the Mesozoic plateau. For location, see figure 4.



The geological domains of Lebanon together with the nearby hydrocarbon discoveries.

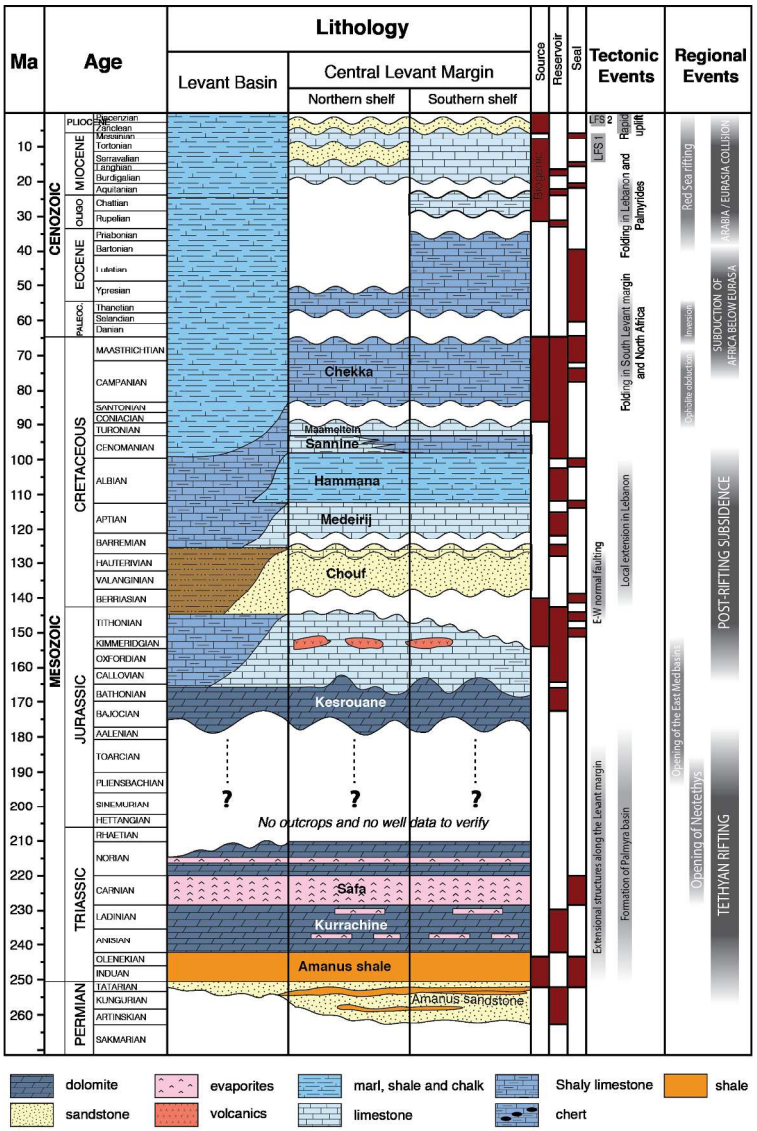


Figure 8

Petroleum potential, stratigraphy and tectonic events for Lebanon and its offshore.

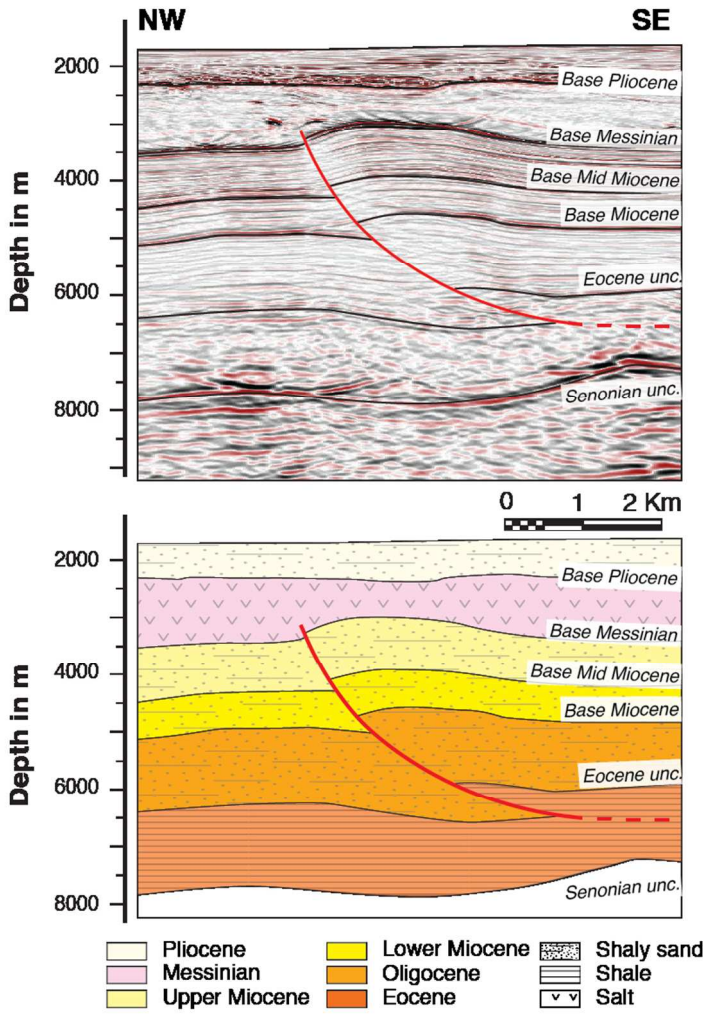


Figure 9

An example of a NE trending anticline in the deep basin domain offshore Lebanon. The structural style suggests detachment folding on an intra-Eocene horizon. The anticlines were folded in the Late Miocene prior to the Messinian event (Ghalayini et al. 2014).

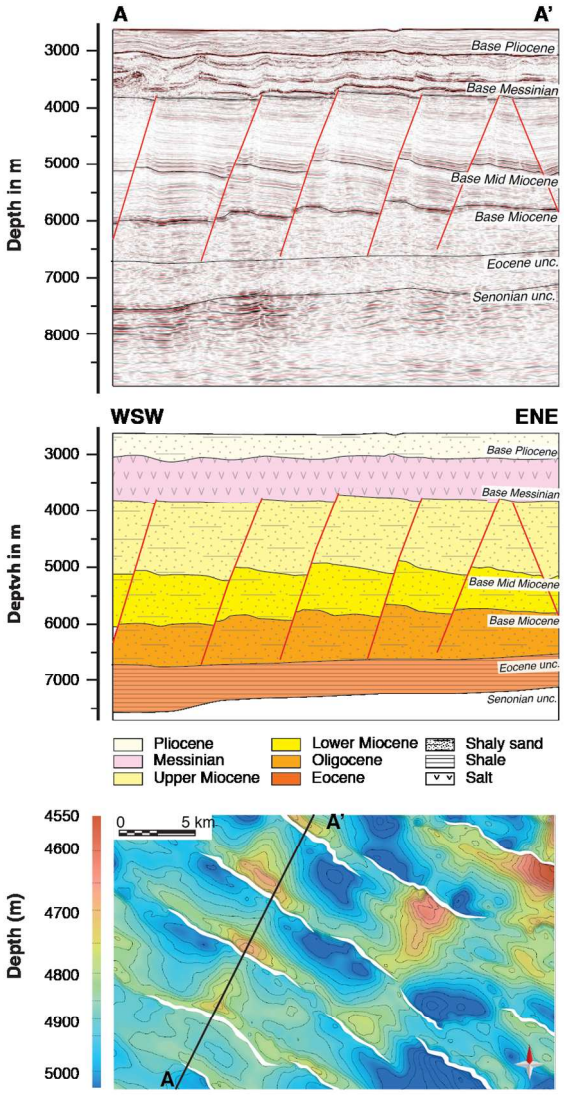


Figure 10

Seismic section showing the titled fault blocks in the deep basin domain. The depth map of the base mid Miocene horizon shows the geometry of the associated traps at present day.

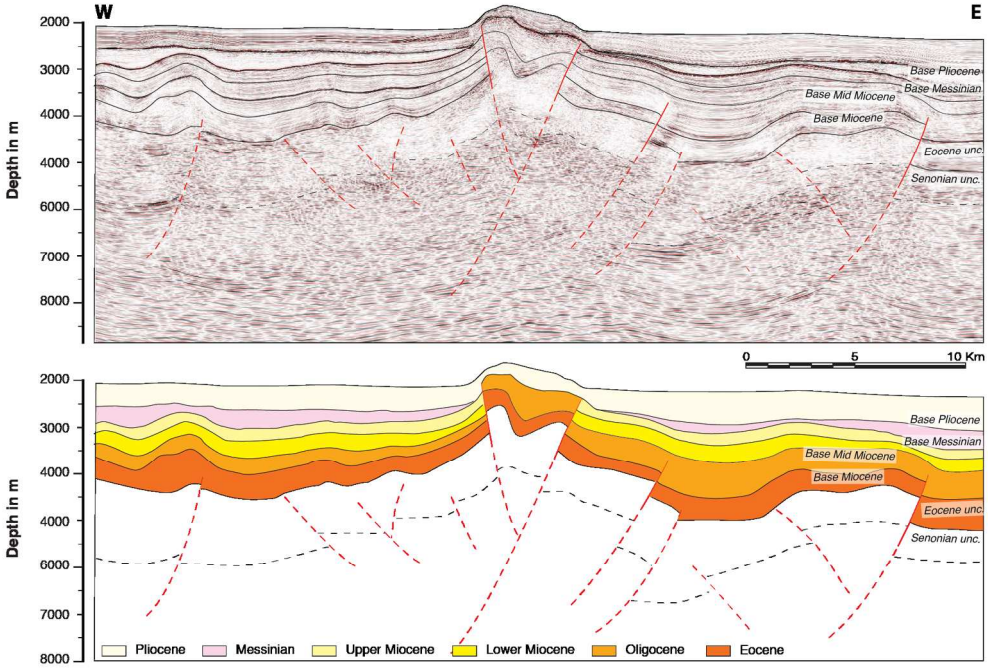


Figure 11

Geo-seismic line showing the Latakia Ridge north of the Levant Basin

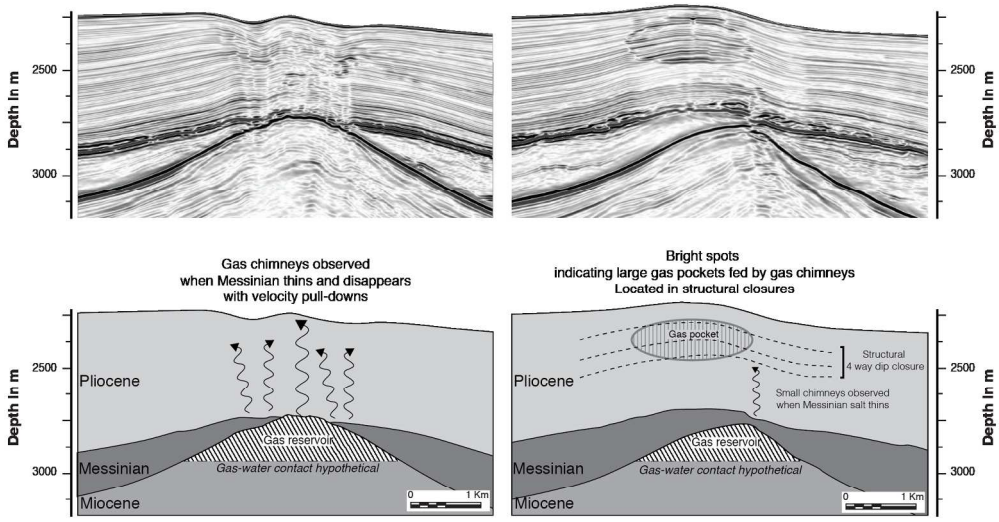


Figure 12

gas chimneys on top of a Miocene anticline observed only when the Messinian seal thins or is absent. The overlying Pliocene exhibits numerous bright spots and DHI's pointing to entrapment of the leaked gas into Pliocene reservoirs in structural closures.

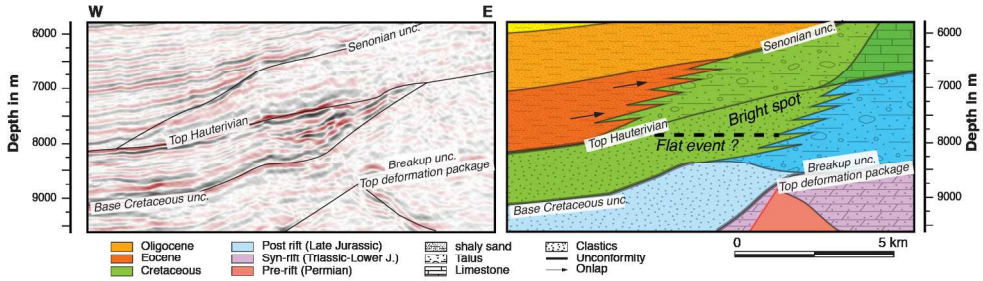


Figure 13

Geoseismic line showing a bright spot and a potential flat spot in the Lower Cretaceous unit pinching out along the Levant margin and trapped between Mesozoic carbonates.

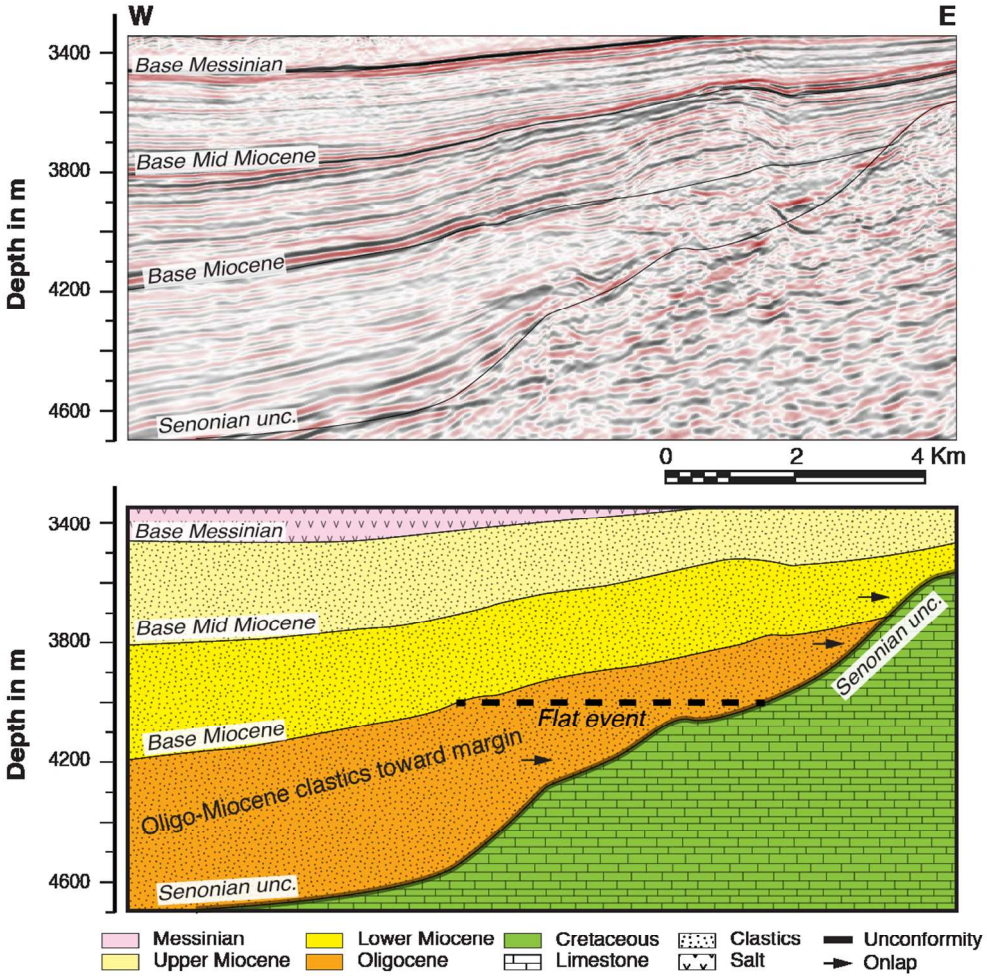


Figure 14

Geoseismic line showing a potential flat spot in the Oligocene unit observed along the Levant margin. The lateral Oligo-Miocene units are pinching out on the margin forming classical stratigraphic traps.

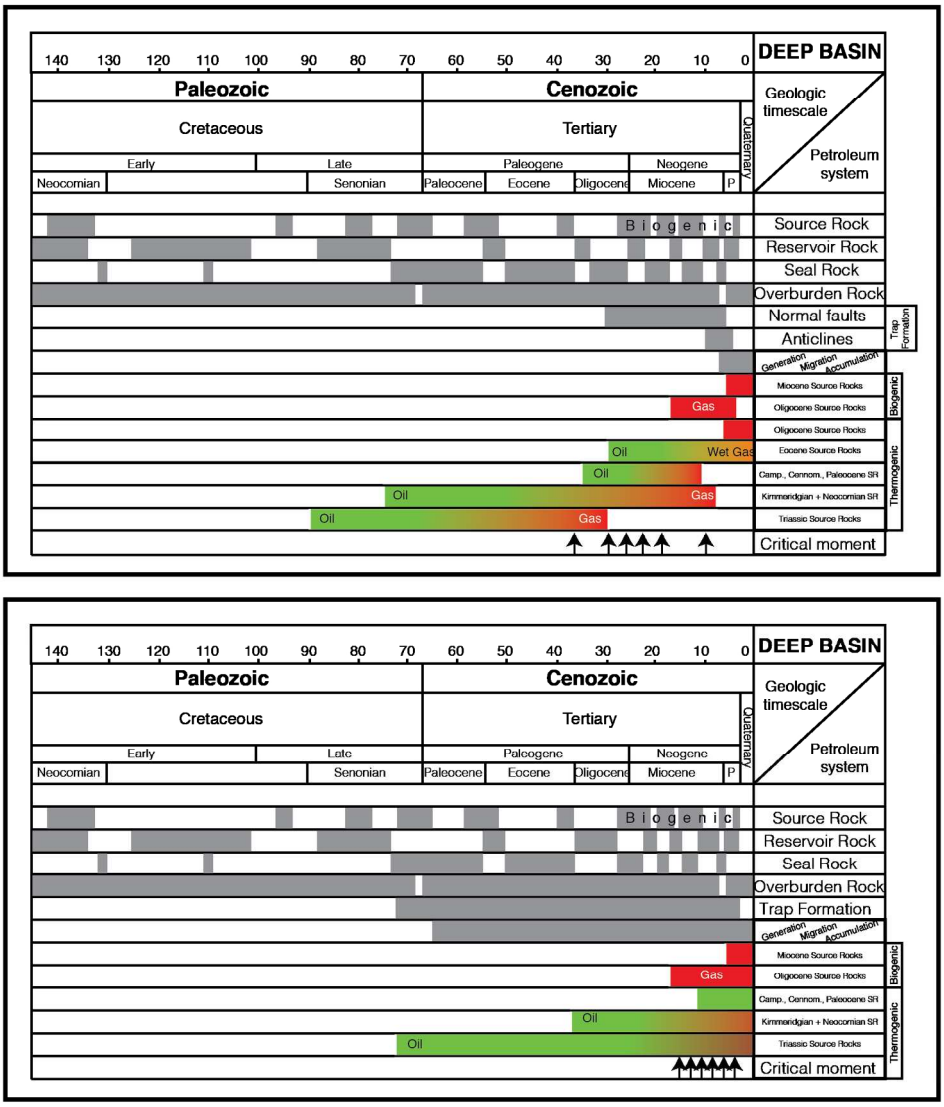


Figure 15

Petroleum system charts for the deep basin and Latakia Ridge domains.

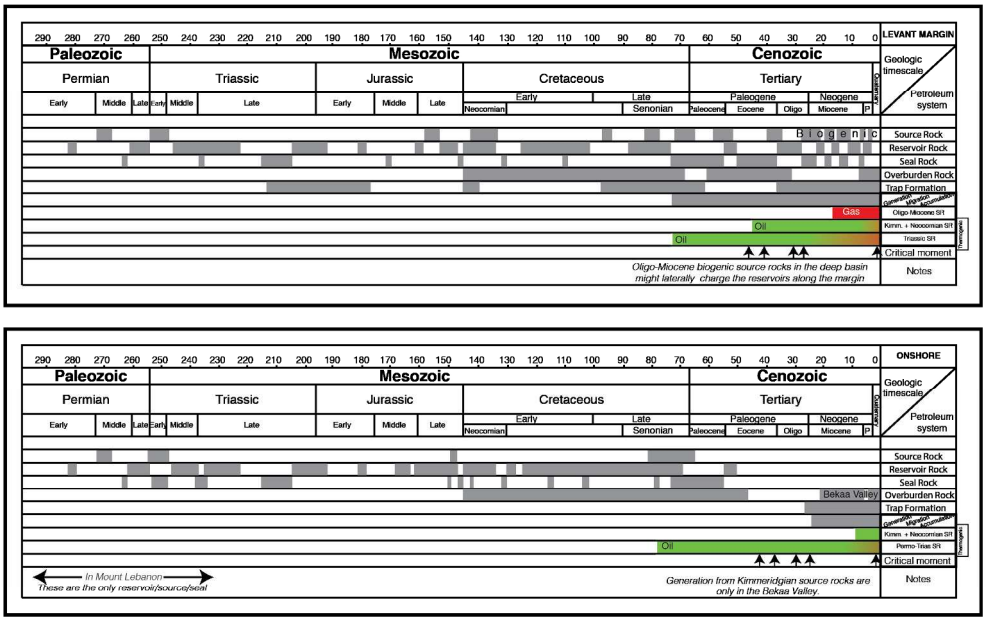


Figure 16

Petroleum system charts for the Levant margin and onshore domains.