PETROLEUM SYSTEMS OF LEBANON: AN UPDATE AND REVIEW

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This paper presents a new interpretation of the Levant margin, offshore Lebanon, with a review of Lebanese onshore geology and a new evaluation of the petroleum systems of the Eastern Mediterranean. Here, we divide the Lebanese onshore and offshore into four domains: the distal Levant Basin, the Lattakia Ridge, the Levant margin, and the onshore. Each domain is characterised by a particular structural style and stratigraphic architecture, resulting in different source-reservoir-trap configurations. This new division draws attention to specific areas of exploration interest in which there are distinct petroleum systems. Following a review of previously published data, this study presents new results from stratigraphic, structural and geochemical investigations. The results include a new interpretation of the Levant margin, focussing on the carbonate-dominated stratigraphy of this area and its petroleum potential. New petroleum systems charts are presented for each of the four domains to refine and summarize the updated geological knowledge.

INTRODUCTION

Lebanon, part of the greater Levant region, is located on the active NW margin of the Arabian plate, the margin being largely defined by the left-lateral Levant Fracture System (LFS) (Fig. 1) (Nader, 2014 a,b). To the east is the petroliferous Palmyride fold-and-thrust belt and to the west the stable foreland of the Levant Basin. Lebanon and the adjacent offshore are considered to have significant exploration potential. This is based on the discovery of more than 70 TCF of proven natural gas reserves in nearby parts of the Levant Basin between 2006 and 2015; fields include Tamar, Leviathan, Aphrodite and Zohr (Fig. 2). Onshore, in Syria, recoverable reserves are estimated at about 2.5 billion (B) brl of oil and about 8.5 TCF of gas, with fields located in the Palmyrides, the Euphrates graben, and the Sinjar high (Barrier *et al*., 2014).

Recent exploration successes in the Levant region have prompted the Lebanese government to acquire an extensive volume of multi-client 3D seismic data to aid offshore exploration. An improved understanding

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Key words: Levant Basin, Palmyra Basin, Lebanon, petroleum system, Eastern Mediterranean.

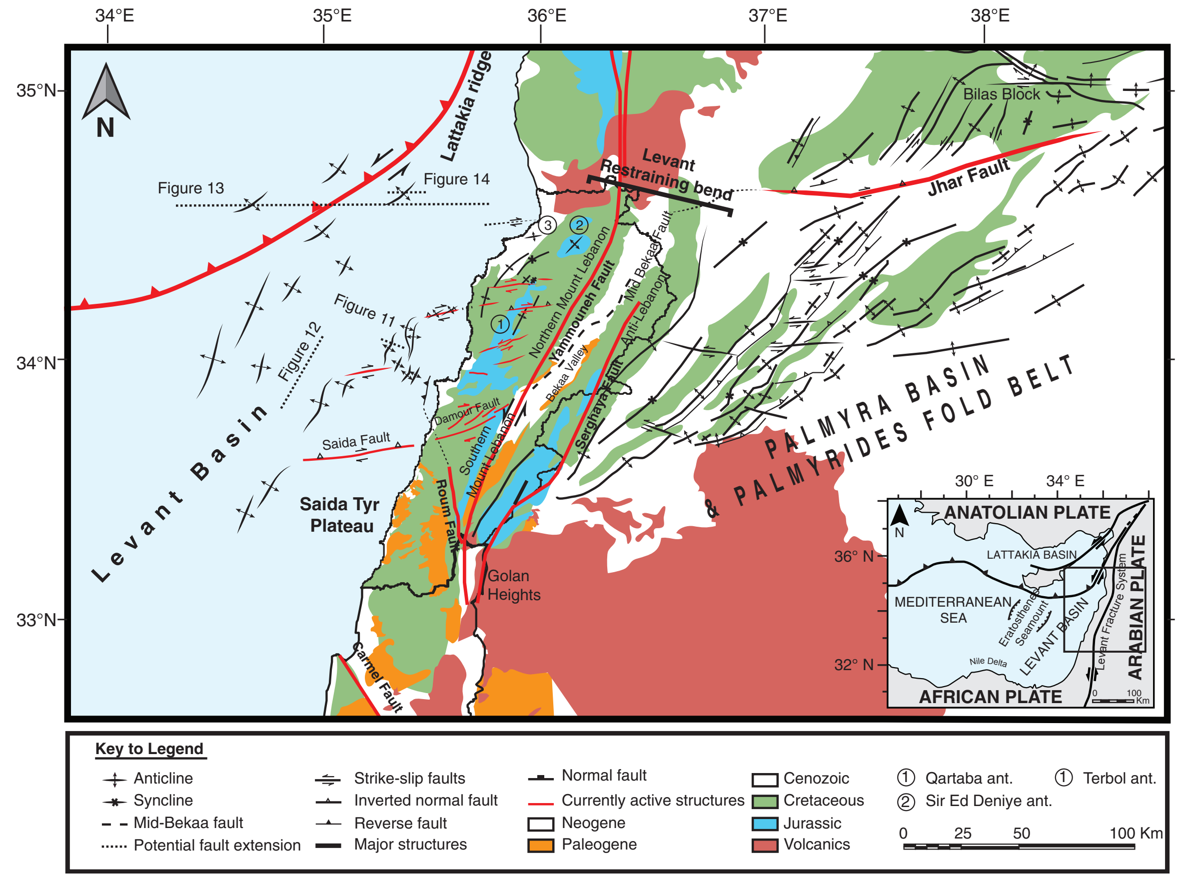

Fig. 1. Main structural elements of Lebanon, the Levant Basin and part of Syria. Map compiled from Barrier *et al.*, 2014; Ghalayini *et al.*, 2014; Ghalayini *et al.*, 2016; and Brew *et al.*, 2001.

of the geology of the Levant region has been acquired from interpretations of this data-set by academic and industrial research partners. The results of these studies include: (i) a new stratigraphic model for the Levant Basin based on seismic data, extensive fieldwork, and forward modelling (Hawie *et al.*, 2013, 2014, 2015); (ii) a more detailed structural framework for the Levant Basin and margin based on new 3D seismic data interpretation and analogue modelling (Ghalayini *et al.*, 2014, 2016, 2017); (iii) a thorough geochemical assessment of source rock potential supported by extensive sampling onshore and regional basin modelling, providing an updated evaluation of the hydrocarbon potential of Lebanon (Bou Daher *et al.*, 2014, 2016); and (iv) an improved model of the crustal structure of the Levant Basin confirmed by deep seismic and gravity modelling (Inati *et al.*, 2016).

The purpose of this paper is to summarize the results of recent geological and petroleum-related investigations in Lebanon, and to interpret new seismic lines located off the northern and southern parts of the country. A new interpretation of the Levant margin (offshore Lebanon) is presented with a focus on carbonate-related prospects, reflecting the fact that associated plays have attracted major attention following the recent Zohr discovery in offshore Egypt (Fig. 2). The Levant region is divided into geological domains based on stratigraphic, structural and geochemical data (Fig. 2). Aspects of the petroleum geology of each domain (potential source rocks, reservoirs and traps) are discussed, and new exploration objectives are tentatively identified. These results serve as a basis for an improved understanding of the petroleum potential of on- and offshore Lebanon.

Exploration history

Petroleum exploration in Lebanon began in the 1930s (Wetzel 1974; Nader, 2014a). Twelve companies were actively involved in exploration in the country, among which the Compagnie Libanaise des Pétroles (CLP) and the Syria Petroleum Company (SPC) were the largest (Wetzel, 1974). The SPC, a subsidiary of the Iraq Petroleum Company, drilled the first well (at Terbol: location in Fig. 2) in 1947 but failed to find economic accumulations of hydrocarbons. The company has since relinquished its concessions in Lebanon. The CLP drilled five wells in the Bekaa valley between 1953 and 1964, four with foreign partners, but without any commercial success, and held concessions covering about 5200 km^2. In 1970, the first offshore seismic data was acquired by Oxoco off north Lebanon, and in 1971 Delta acquired 320 km of 2D seismic lines in addition to a gravity survey on the Shaheen permit.

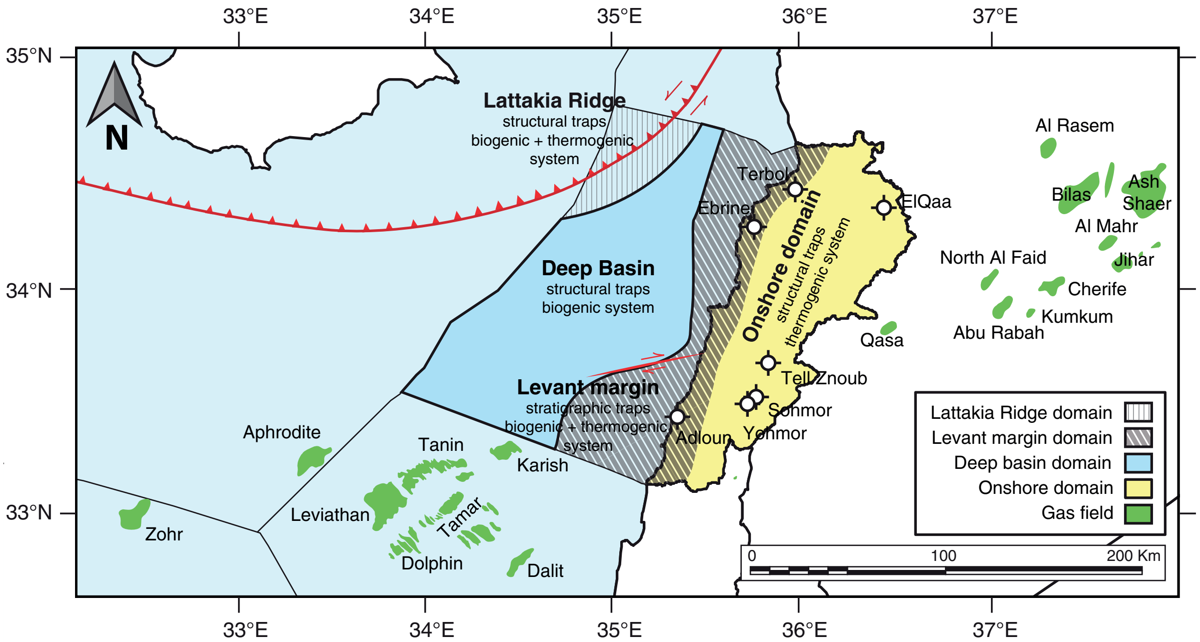

Fig. 2. Map showing the geological domains of Lebanon as discussed in this study, together with hydrocarbon discoveries in nearby countries.

The acquisition of regional 2D seismic reflection surveys by Spectrum and TGS in 2000 and 2002, respectively, led to the mapping of several promising leads in sub-Messinian units. Between 2006 and 2012, PGS then acquired 9700 km^2 of 3D seismic data; Spectrum acquired an additional 5172 km^2 of 3D data between 2012 and 2013 in the deep-water offshore. These new data have indicated that Lebanon has promising hydrocarbon potential (Roberts and Peace, 2007), and the Lebanese Government recently (2017) issued a series of decrees to regulate future offshore exploration activities. A joint venture of three companies, Total, ENI and Novatek, was awarded exploration licenses by the Lebanese Government in January 2018 for two blocks offshore south and central Lebanon, respectively.

Tectonic and crustal setting

The present structural framework of on- and offshore Lebanon is dominated by the Levant Fracture System (LFS) and the Lattakia Ridge System (Fig. 1). The LFS is a sinistral transform fault system linking extension in the Red Sea with compression in the Tauride fold belt to the north (Freund *et al.*, 1970). To the west of the LFS is the Levant Basin, which was formed synchronously with the Palmyra Basin during polyphase Mesozoic rifting (Gardosh *et al.*, 2010).

The Lattakia Ridge bounds the NW margin of the Levant Basin (Fig. 1). This structure formed as a result of the subduction of the African plate beneath the southern margin of Eurasia, starting in the Maastrichtian (Frizon de Lamotte *et al.*, 2011; Stampfli and Hochard, 2009). Continuous compression has characterised the Africa-Eurasia margin from the Late Cretaceous until the present day. Accelerated roll-back of the subduction zone along the Hellenic-Cyprus arc occurred during the Tortonian (Le Pichon and Kreamer, 2010), which resulted in renewed fold-thrust activity in the mid–Late Miocene along the Lattakia Ridge (Hall *et al.*, 2005; Robertson *et al.*, 1996). Westward tectonic escape of the Anatolian microplate took place in the Messinian – Pliocene, with a component of anticlockwise rotation (Le Pichon and Kreamer, 2010; Sengor and Yilmaz, 1981) resulting in reactivation of the Lattakia Ridge with sinistral strike-slip motion (Hall *et al.*, 2005). These regional-scale geodynamic events were marked in both the Levant Basin and in onshore Lebanon by post-Oligocene reactivation of structures, and by a decrease in strike-slip activity on the LFS (Freund *et al.*, 1970; Ghalayini *et al.*, 2014; Le Pichon and Gaulier, 1988; Quennell, 1984). Accelerated uplift of pre-existing structures such as Mount Lebanon has taken place from the Late Miocene to the present day (Walley, 1998; Ghalayini *et al.*, 2017; Beydoun, 1999).

The thickness of the crust gradually decreases westwards from the Palmyrides foldbelt to the Levant Basin, from 44 km in the SW Palmyrides to 35 km beneath the Anti-Lebanon ranges and 27 km beneath Mount Lebanon (Brew *et al.*, 2001; Khair *et al.*, 1993). This westward crustal thinning beneath Syria and Lebanon indicates a transition between continental crust to the east of the Levant margin, to thinned continental crust (8-10 km thick) beneath the offshore Levant Basin, as indicated by gravity inversion (Inati *et al.*, 2016) and refraction seismic profiles (Ben-Avraham *et al.*, 2002; Makris *et al.*, 1983; Netzeband *et al.*, 2006).

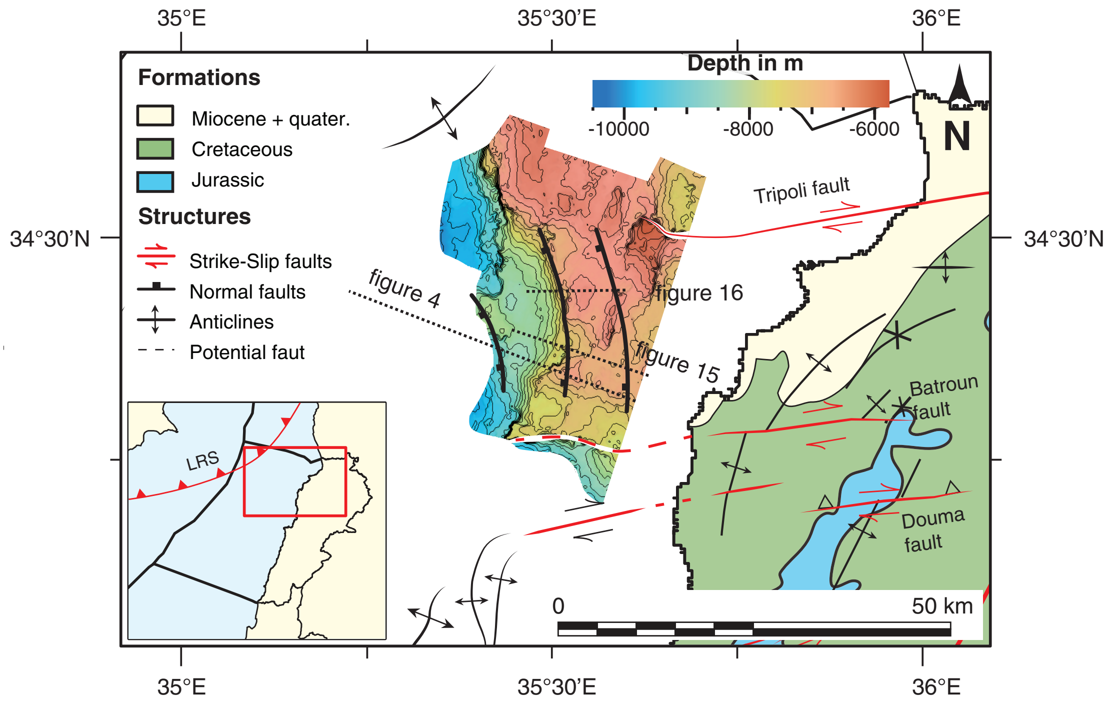

Fig. 3. Map of the offshore margin of northern Lebanon, with depth map of the the RN2 horizon which is interpreted as the mid-Jurassic break-up unconformity (see text for details). The horizon is not displaced by the NNW-SSE striking normal faults observed in the underlying succession (seismic units NU1, NU2), which is interpretd to be Permian-Triassic. The profiles of the sections in Figs 4, 15 and 16 are marked.

METHODS AND DATA

Five seismic lines along the margin offshore north and south Lebanon were interpreted; the lines are presented in Figs 4, 15 and 16 (offshore northern Lebanon, Fig. 3); and in Figs 6 and 8 (offshore southern Lebanon, Fig. 5). The data consist of a pre-stack depth-migrated 3D seismic cube acquired in 2012 by PGS. Streamer length was 7050 m at a spacing of 12.5 m, with 25 m shot-point intervals. The interpretation was performed on depth-converted sections. Time-to-depth conversion was done using a velocity model built from stacking velocities. All interpretations and stratigraphic subdivisions in the basin presented in this contribution, and in previous published literature, are entirely based on seismic facies interpretation and regional correlation with nearby countries since no wells have been drilled to-date offshore Lebanon. The interpretation of Tertiary units in this contribution is based on the seismic-stratigraphic framework interpretations of Hawie *et al.* (2014). The Tertiary is represented by horizons RN5 to RN11 in the northern margin, and RS9 to RS13 in the southern margin. The latter correspond to the Eocene Unconformity, Base Miocene, Base mid-Miocene, Base Messinian and Base Pliocene, respectively.

THE LEVANT MARGIN OFFSHORE NORTHERN LEBANON

The Levant margin offshore northern Lebanon consists of an extensive carbonate platform (Jurassic – Cretaceous) with extensional structures in the underlying pre-Jurassic seismic interval (Fig. 4). Eleven horizons referred to as RN1 (oldest) to RN11 (youngest) were identified in an ESE-WNW profile off the coast of northern Lebanon based on impedance contrast variations (Fig. 4). Seismic packages ("NUs") are defined by their seismic facies and reflection configurations, and are bounded by the identified horizons (Fig. 4). Only horizons RN1 to RN5 and units NU1 to NU6 will be considered in this study in order to discuss the Mesozoic stratigraphic divisions.

Units NU1-NU2

Description

The deepest-lying Horizon, RN1, separates non-continuous and low-amplitude reflections of unit NU1 from the overlying semi-continuous, and relatively higher amplitude package of unit NU2, which exhibits growth strata and fanning geometries against faults in the eastern part of the profile in Fig. 4. The faults trend NNW-SSE and dip to the WSW as seen in 3D seismic data. These faults have a normal displacement and are perpendicular to present-day structures along the Levant margin including roughly east-west trending strike-slip faults (Fig. 3).

Interpretation

The fan-shaped geometry of reflections in unit NU2 suggest the presence of growth strata, indicating that synsedimentary normal faults are present at this depth (Fig. 3). Palaeomagnetic studies indicated that

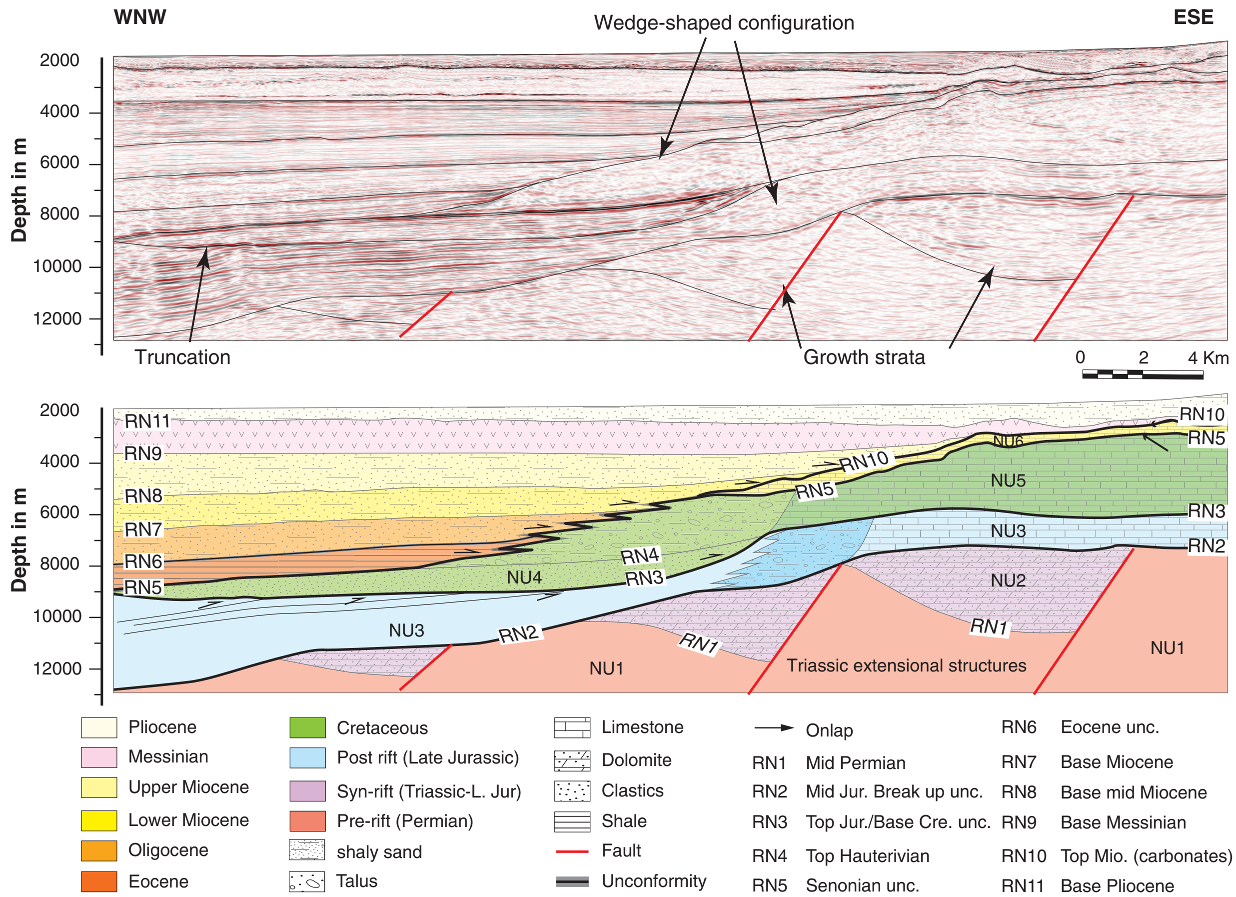

Fig. 4. Geo-seismic line showing the Levant margin off the coast of northern Lebanon which consists mainly of a carbonate succession. The Triassic contains extensional normal faults related to the Triassic break-up of Pangea, and the Early Cretaceous NU4 pinches out on the Jurassic carbonate talus deposits. Overlying the Cretaceous strata, Eocene to Miocene carbonate build-ups are believed to occur. For location, see Fig. 3.

Lebanon underwent a regional counter-clockwise rotation of 55° to 70° since the Jurassic (Van Dongen *et al.*, 1967; Gregor *et al.*, 1974). When this rotation is restored along these faults, their strike becomes NNE-SSW, similar to the strike of extensional structures in the southern Levant. The latter are believed to have developed during the Triassic as a result of Tethyan rifting (e.g. Gardosh *et al.*, 2010). Therefore, the faults probably developed during the Triassic, and NU1 is interpreted as a pre-rift package, while NU2 is syn-rift; the packages may be attributed to the Permian and Triassic – Lower Jurassic, respectively (Fig. 4).

Unit NU3

Description

RN2 is a continuous, high amplitude reflection that, towards the deep Levant Basin, separates a package of high amplitude and stacked continuous reflections in unit NU3 from the discontinuous and relatively lower amplitude reflections of units NU1 and NU2. The reflection is not displaced by the Triassic faults observed in unit NU1 (Fig. 4). NU3 exhibits significant seismic facies variations towards the deep basin, whereby continuous semi-bright reflections in the east appear to pass into chaotic reflections at the centre of the profile. Further west, the unit is dominated by a series of stacked and high amplitude reflections (Fig. 4).

Interpretation

As RN2 is not displaced by faulting and separates deformed units below from non-deformed units above, it is interpreted to correspond to the mid-Jurassic break-up unconformity (Hawie *et al.*, 2014). RN2 therefore marks the initiation of gentle post-rift subsidence in the Levant region, starting in the mid- to Late Jurassic, and NU3 could consist of Middle to Upper Jurassic units. It has a thickness of 1–1.5 km, consistent with that of similar Jurassic strata in onshore north Lebanon (Nader *et al.*, 2016; Dubertret, 1955). It is challenging to determine the lithology of unit NU3 based on seismic data alone, but it is possible that closer to the margin, NU3 consists of shallow-water, inner to middle shelf carbonates similar to the onshore (Dubertret, 1955). Lateral facies changes could explain the different seismic character of unit NU3 to the west, with uncertainties regarding its composition. The seismic facies transition from continuous to chaotic reflections could indicate mass transport or talus deposits derived from the Jurassic carbonate platform and deposited at the distal end of the slope margin. The talus deposits may have originated from the erosion of significant amounts of carbonate during the Late Jurassic, and its subsequent deposition in the basin during a major sea-level lowstand with the emergence of Lebanon during the Late Jurassic/Early Cretaceous (Dubertret, 1955; Homberg *et al.*, 2009). Another interpretation could be that the chaotic unit in the centre represents a Jurassic reef, while the units to east and west represent back-reef and fore-reef deposits respectively. We favour the first interpretation, on the basis that the gentle uplift of Lebanon in the Jurassic resulted in mass transport and talus deposits, which most likely accumulated at the slope margin. Such interpretations require confirmation when well data becomes available.

Unit NU4

Description

RN3 marks the top of a low amplitude series with semi-continuous reflections in the east of the profile in Fig. 4. It can be followed west of the profile to mark the top of a truncated series of bright, high amplitude, and continuous reflections. An angular unconformity surface is observed at this level. The overlying reflections exhibit similar seismic facies with high amplitude, continuous reflections in the west. Unit NU4 pinches out on RN3 (Fig. 4).

Interpretation

RN3 may correspond to the top of the Jurassic, marked by an Upper Jurassic – Lower Cretaceous sequence boundary (c. f Haq *et al.*, 1988). Unit NU4 exhibits a set of stacked, high-amplitude reflections, indicating the presence of facies different from those in the adjacent Jurassic carbonates to the east, which are marked by chaotic seismic facies. The different seismic facies could represent a transition to thick-bedded strata in the west, but it is challenging to accurately interpret their nature without well data. As unit NU4 overlies the Upper Jurassic unit, it might belong to the Lower Cretaceous and therefore could be analogous to the Neocomian/Hauterivian Chouf Formation known onshore (Nader, 2014a) (*see below*). Therefore, the high amplitude units may represent clastic material similar to that in the Chouf Sandstone Formation onshore. RN4 may therefore correspond to the top-Hauterivian. This interpretation requires confirmation when well data becomes available.

Unit NU5

Description

RN4 exhibits a large impedance contrast and separates the chaotic reflection package in unit NU5 from the stacked and high amplitude reflection package of unit NU4 in the centre of the profile (Fig. 4). RN4 onlaps on RN3 and is truncated by RN5 in the west. Unit NU5 is characterised by an overall low-amplitude non-continuous reflections, while in the shallower units, the reflections become more continuous. In the centre of the profile, reflections become chaotic and the overall unit adopts a wedge-shaped configuration (Fig. 4).

Interpretation

NU5 probably corresponds to the Cretaceous as it overlies the Upper Jurassic NU3 and Lower Cretaceous NU4. The uniform seismic character of unit NU5 suggests that it may be composed of homogenous lithologies, which could form the offshore extension of the Cretaceous carbonate platforms observed onshore Lebanon (Dubertret, 1955). The wedge-shape of the unit towards the basin and the chaotic associated reflections may represent mass transport deposits or carbonate talus originating from the Cretaceous carbonate succession along the margin and onshore. RN5 corresponds to a major marine onlap surface and may therefore represent the Senonian unconformity (Hawie *et al*., 2014; Gardosh *et al*., 2011).

Unit NU6

Description

RN5 is a continuous seismic horizon with a strong impedance contrast representing an onlapping surface throughout the margin and the basin. It is overlain by a thin package of continuous and high amplitude reflections of unit NU6. Toward the basin in the west, NU6 exhibits chaotic and low amplitude reflections, very similar to those in the underlying NU5 (Fig. 4).

Description

RN5 represents the Senonian unconformity horizon which is observed throughout the Levant Basin (Gardosh and Druckman, 2006; Hawie *et al.*, 2013). The high amplitude package on top of the Senonian unconformity is interpreted to be Tertiary. This unit displays high amplitude reflections with similar seismic facies to those in the underlying carbonate unit, and is therefore interpreted to represent an Eocene to Miocene carbonate succession. Such units are observed onshore northern Lebanon and could extend to the margin offshore. The presence of Tertiary carbonate units along the Levant margin has been discussed by Hawie *et al*. (2014).

THE LEVANT MARGIN OFFSHORE SOUTHERN LEBANON

The Levant margin offshore southern Lebanon includes a structural element termed the Saida – Tyr plateau (STP), which is an elevated Mesozoic feature as observed in the Senonian unconformity depth map (Fig. 5). It is separated from the deep Levant

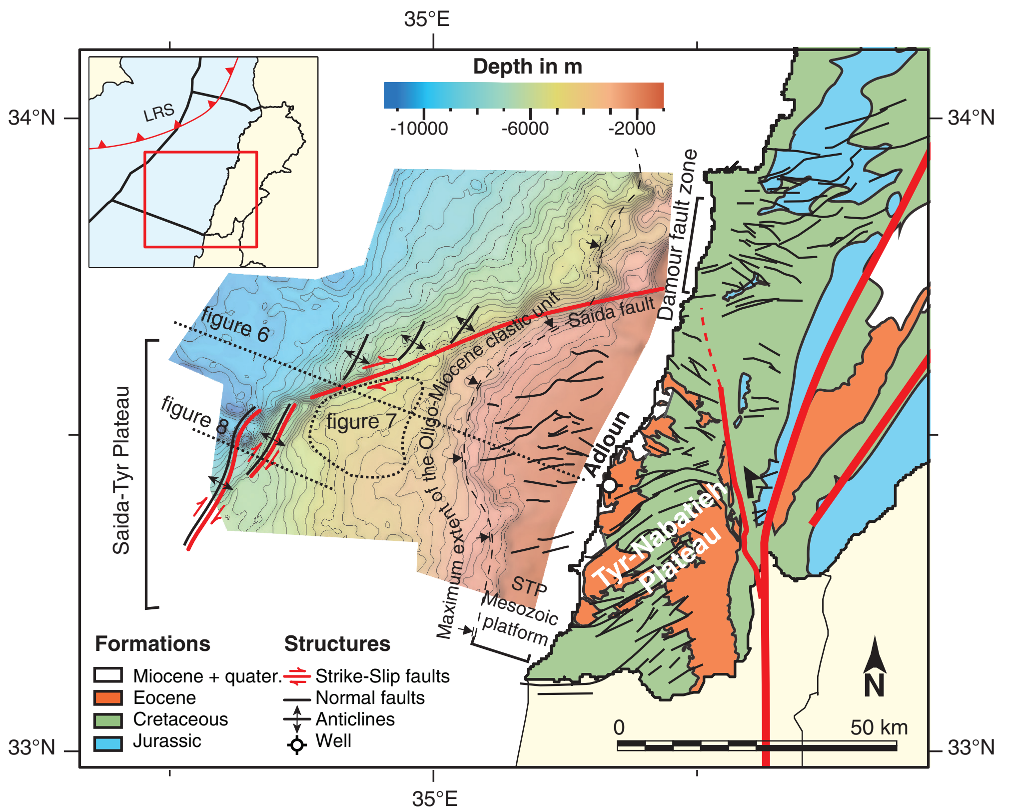

Fig. 5. Structural map of the Saida-Tyr plateau (STP) offshore southern Lebanon and the adjacent onshore Tyr-Nabatieh plateau. The depth map offshore corresponds to RS8, the Senonian unconformity horizon. The *en échelon* anticlines along the Saida fault are only observed at the Base Messinian horizon and not at the level of the Senonian unconformity, and may indicate dextral strike-slip movement of the Saida fault. A series of transpressive anticlines limit the STP to the west, and ENE-trending normal faults occur to the east of the plateau close to the margin.

Basin by major faults to the north and west, and is characterized by a thinner Cenozoic succession relative to the rest of the basin (Hawie *et al.*, 2014). A total of thirteen horizons (RS1 to RS13) were identified in a NW-SE seismic profile across the STP (Fig. 6) and the Levant margin offshore southern Lebanon. Only horizons RS1 to RS8 will be discussed here. The seismic line presented in Fig. 6 was correlated with the Adloun well, located 5 km to the east (location in Fig. 5). This well was drilled to a depth of 2150 m and reaches the Upper Jurassic (Fig. 6) (Beydoun, 1977). From well correlation, horizons RS3 to RS7 are interpreted to correspond to the Top Jurassic, Top Neocomian/Hauterivian, Top Aptian, Top Albian and Top Cenomanian, respectively. As horizon RS8 truncates the Turonian and Senonian units as well as deeper units to the west, it is interpreted to correspond to the Senonian unconformity (e.g. Hawie *et al.*, 2013) (Fig. 5). Further to the east and closer to the coastline, the Mesozoic is directly overlain by the Pliocene, indicating the presence of a topographic high prior to the deposition of the Tertiary succession.

A series of seismic packages or units in the southern Lebanon margin ("SUs", Fig. 6) were defined by their seismic facies characteristics and are bounded by the observed reflections.

Units SU1-SU2

Description

RS1 separates chaotic low amplitude non-continuous reflections from a set of semi-continuous thick and high amplitude reflections in unit SU1 (Fig. 6). The latter is composed of a configuration of parallel reflections, which in the centre of the profile become high amplitude and continuous. RS2 exhibits an impedance contrast and is overlain by low amplitude semi-continuous reflections of unit SU2. This unit exhibits lateral facies changes in which chaotic, low amplitude seismic facies are observed towards the west and a wedge-shaped configuration is observed, similar to the northern Levant margin discussed above. Unit SU2 is 1.5-2 km thick and is truncated westward toward the centre of the profile by RS8. Both RS1 and RS2 extend towards the west and are cross-cut by a large vertical fault. However, it is challenging to assess the continuity of the horizons in the deep basin. A cross-fault horizon correlation was attempted by restoration and backstripping of the succession, and indicated the probable continuity of units SU1 and SU2 into the deep basin (Fig. 6).

Interpretation

The RS3 horizon is correlated with the top-Jurassic in the Adloun well, and therefore the underlying SU2 unit

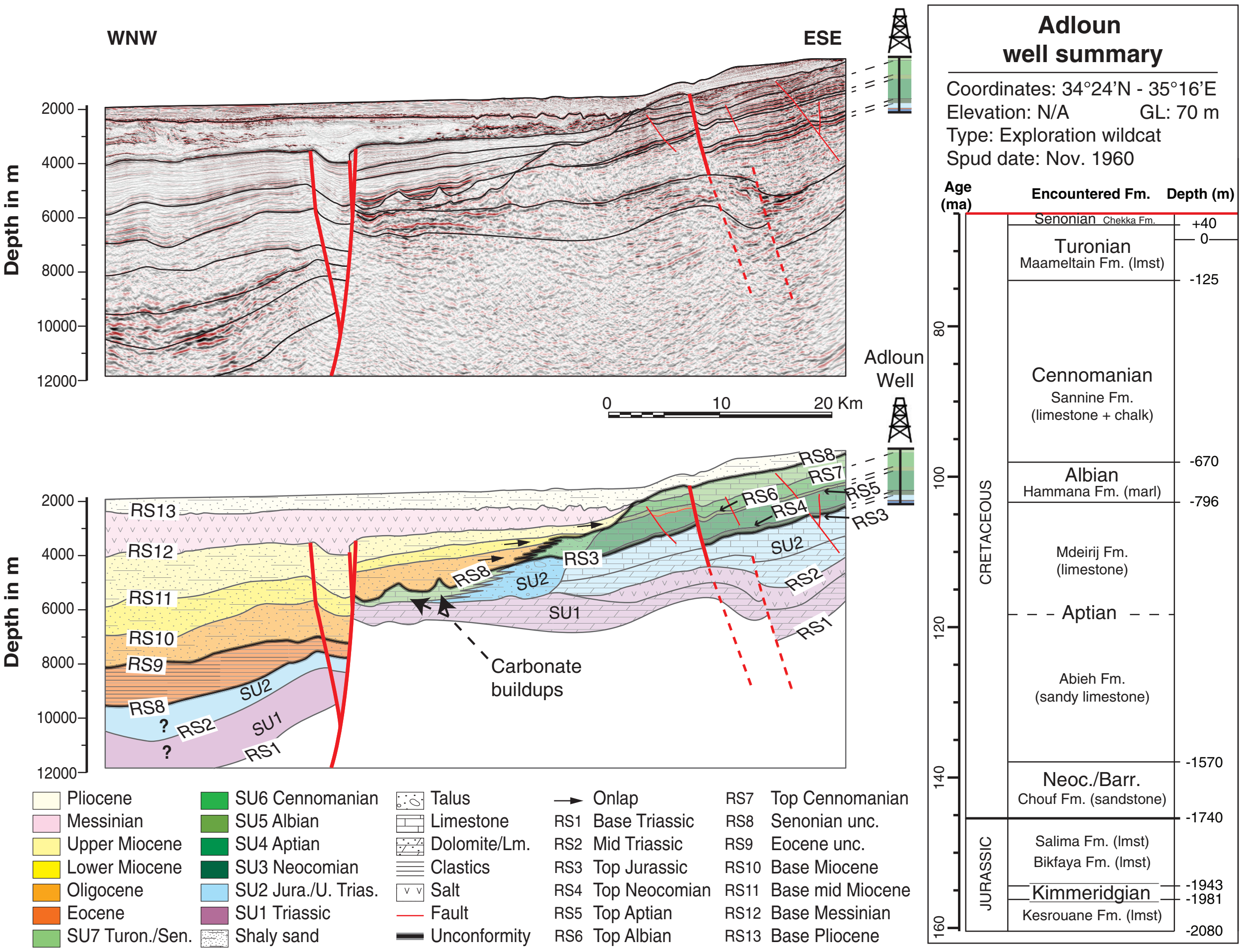

Fig. 6. Geo-seismic line showing the Levant margin off the coast of southern Lebanon. The seismic data was tied to the nearby Adloun well and shows the complete Jurassic to Cretaceous succession found onshore (modified from Beydoun, 1977). Below the Jurassic unit SU2, Triassic strata are believed to occur. At the centre of the profile, pinnacle-shaped structures are interpreted as carbonate build-ups or mounds. For location, see Fig. 5.

should include the Jurassic. The RS2 horizon exhibits a strong impedance contrast, probably indicating a transition between mostly dolomite lithologies and evaporites in unit SU1, as documented in the Triassic in Palmyra (Barrier *et al.*, 2014). Therefore, RS2 is probably the top of the mid-Triassic evaporite unit, and unit SU2 corresponds to both the Jurassic and top-Triassic unit. The thickness of unit SU2 is 1.5 to 2 km, slightly greater than the thickness recorded for the Jurassic in the south of Lebanon (Nader, 2014a; Nader *et al.*, 2016; Dubertret, 1955), which could be expected bearing in mind that unit SU2 also encompasses the Upper Triassic. The latter is also formed of dolomitic facies similar to the Lower Jurassic unit observed onshore (Nader and Swennen, 2004a; Beydoun and Habib, 1995). The westward variation of seismic facies and overall wedge-shaped configuration observed in unit SU2 may be interpreted to indicate the presence of talus deposits originating from the carbonate platform in the east, similar to the northern Levant margin. The thickness of unit SU1 is 1 to 1.5 km, consistent with the expected thickness of the Triassic in Lebanon (Nader *et al.*, 2016; Beydoun and Habib, 1995); therefore, RS1 is likely the base-Triassic. This interpretation points to an extension of the broad-scale geometries observed onshore to the Levant margin offshore, but it is challenging to map deeper units or to assess the lateral facies changes in the offshore based on seismic data.

Units SU3-SU7

Description

RS3 is characterised by a strong impedance contrast in which high amplitude and continuous reflections characterise the overlying SU3 to SU7 units. Horizons RS3 to RS8 are extrapolated from well data and consist of a stacked, high amplitude reflection set, with occasional dimming. Unit SU4 exhibits some lateral facies changes from high amplitude, stacked and parallel reflections to low amplitude and chaotic ones to the west, resembling those of Unit SU2 and those of the northern margin discussed above. Horizon RS8 marks the boundary between high amplitude and continuous reflections to the east and stacked, continuous, low to medium amplitude reflections of the Tertiary units to the west. The latter package pinches out and exhibits

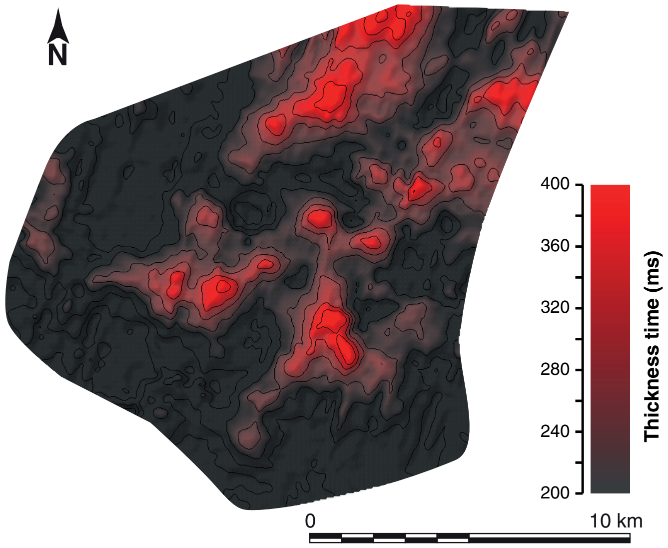

Fig. 7. Isochron map of the Cretaceous mounds observed on the Saida – Tyr plateau. Note that the mounds cluster in a specific area covering about 200 km^2. For location, see Fig. 5.

onlap on RS8. Below horizon RS8 in the centre of the profile, pinnacle-shape build-ups are observed (Fig. 6) and cover an area of about 200 km^2. They occur as a localised cluster of build-ups which have a maximum twt thickness of about 500 ms (Fig. 7).

Interpretation

SU3 to SU7 most likely belong to the Cretaceous series encompassing the Neocomian to Senonian succession, similar to that penetrated by the Adloun well (Fig. 6). The stacked seismic facies may represent the clastic unit of the base Cretaceous (SU3), which is overlain by carbonate and marl successions (SU4 and SU5), and calci-turbidites in the Cenomian and Turonian (SU6 and SU7). These lithologies are documented onshore and therefore may extend to the near-margin offshore (Hawie *et al.*, 2014). The westward variation of seismic facies observed in the Cretaceous units (SU4) may be interpreted to indicate the presence of talus deposits originating from the carbonate platform in the east, similar to unit SU2 and the northern Lebanese margin. The pinnacle-shaped geometries at the RS8 horizon may correspond to local carbonate build-ups or isolated mounds, similar to those observed around the Mediterranean in ramp or foreslope settings (Monty *et al.*, 2009). Their occurrence in a cluster, or group, suggests that their formation was environmentally mediated, which is typical of deep-water mud mounds (Fig. 7) (Wood, 2001). An alternative explanation was suggested by Hawie *et al.* (2015) in which these pinnacle-shaped bodies could represent the cinder cones of Late Jurassic to Early Cretaceous volcanoes, since evidence of volcanism has been observed at this time onshore Lebanon (Dubertret, 1955).

Structure of the Saida – Tyr plateau

Description

Large vertical displacements related to near-vertical faults are observed to both north and west of the Saida-Tyr plateau. The northern bounding fault displaces the RS8 horizon by about 2 km downwards and locally forms a mini-basin along RS12 (Fig. 6). The faults to the west exhibit a vertical and deep deformation zone in which anticlines resembling positive flower geometries are observed in the Tertiary units (Fig. 8). Poor seismic imaging within the core of the anticlines makes it difficult to interpret the horizons. The Upper Miocene units, however, can be mapped and are truncated by RS12, the Base Messinian horizon. ENE-WSW to ESE-WNW oriented normal faults are observed in the easternmost part of the plateau and have a displacement of a few hundred metres. They extend between the RS1 and RS8 horizons and are overlain by an undeformed Pliocene unit (Fig. 8).

Interpretation

The large vertical displacement observed on the ENE-trending northern bounding fault, referred to as the Saida fault (Fig. 6), is likely caused by an extensional component of the fault. Ghalayini *et al.* (2014) proposed that this structure is a pre-existing Mesozoic normal fault, reactivated with dextral strike-slip offset in the Late Miocene, as evidenced by the *en échelon* anticlines in the Upper Miocene interval (Fig. 5). The offshore Saida fault can be correlated with the onshore Damour fault zone (Fig. 5), and it has been suggested that these faults are the westward continuation of the Jhar fault in Syria (Fig. 1) due to their similar trend and evolutionary history, and the similarity of the crustal configuration to the north and south of the faults (Walley, 1998; Brew *et al.*, 2001; Ghalayini *et al.*, 2017). The fault separates the Saida-Tyr plateau which is possibly underlain by normal continental crust, from the deep Levant Basin which is likely characterised by thinned continental crust (Inati *et al.*, 2016).

The bounding faults at the western margin of the Saida-Tyr plateau vertically displace the Mesozoic succession by more than 2 km, suggesting a previous

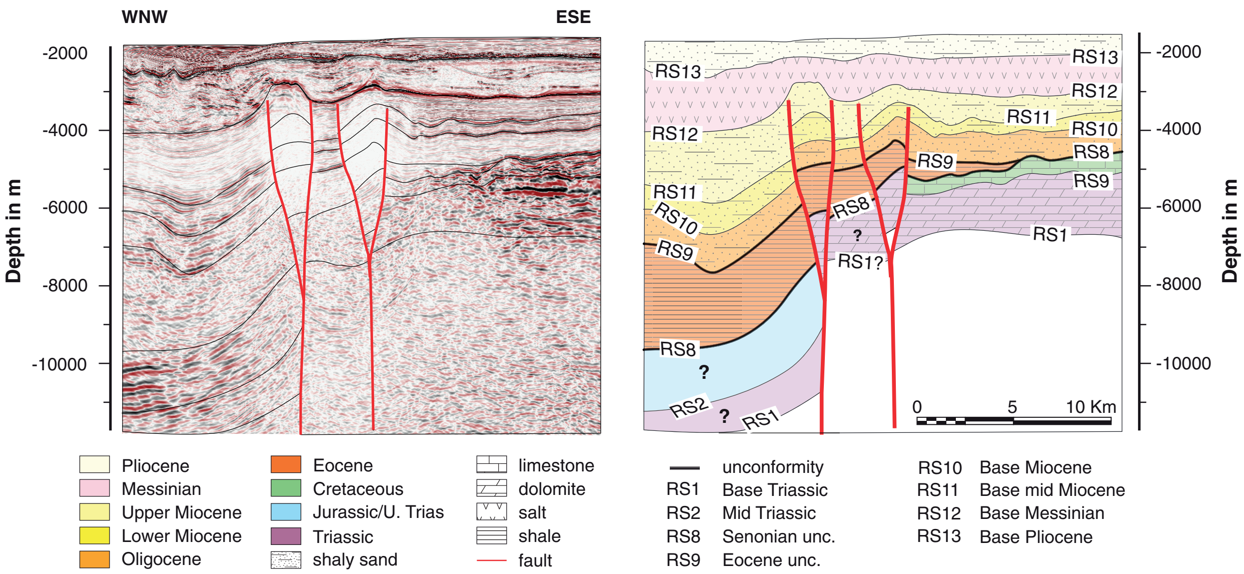

Fig. 8. Geoseismic line across the western edge of the Saida-Tyr plateau showing the transpressive anticlines separating the deep basin from the Mesozoic plateau. These anticlines may consist of pre-existing structures which were reactivated in the Late Miocene. For location, see Fig. 5.

extensional episode prior to the Cenozoic (Fig. 8). The internal horizons at the core of the anticline were built by extrapolating the adjacent horizons, and were verified by backstripping and restoration. The vertical and deep deformation zone point to the presence of deep strike-slip faults, although it is challenging to determine the motion direction. It is possible that they also possess a transpressive component, as evidenced by the presence of positive flower structures in the Tertiary units. The erosion and truncation of the shallower parts of the Upper Miocene indicate that this movement and folding started in the Late Miocene, and most probably reactivated previously-formed, deeper extensional structures.

The ENE-WSW to ESE-WNW striking normal faults documented in the easternmost part of the Saida -Tyr plateau are similar to the well-documented faults in southern Mount Lebanon (Fig. 5) (Homberg *et al.*, 2009, 2010). It is likely that the former faults belong to the same fault family as those documented onshore and were therefore active during the Cretaceous (e.g. Homberg *et al.*, 2009).

GEOLOGICAL DOMAINS ON- AND OFFSHORE LEBANON

Based on the available geological data and our new interpretation of the Levant margin, the Lebanese onshore/offshore area can be differentiated into four geological domains that have distinct sedimentological and structural features: (i) the distal Levant Basin; (ii) the Lattakia Ridge; (iii) the Levant Margin; and (iv) the Lebanese onshore (Fig. 2). The following sections describe the main geological features of these domains. A lithostragraphic column for the Levant region summarizes the stratigraphy, structures and potential petroleum system elements (Fig. 9).

(i) The distal Levant Basin

The Levant Basin formed on attenuated continental crust (Gardosh *et al.* 2006, 2010; Inati *et al.*, 2016) during the Triassic and Jurassic as a result of Neo-Tethyan rifting. The basin is characterised by a thick Cenozoic sedimentary cover (over 8 km thick) overlying a Mesozoic succession (Gardosh and Druckman, 2006; Hawie *et al.*, 2013; Roberts and Peace, 2007). Structural features include layer-bound NW-SE trending normal faults and NE-SW trending anticlines in the supra-Eocene interval (Fig. 1).

Stratigraphy

Nine horizons have been identified in seismic data in the deep Levant Basin offshore Lebanon and have been correlated with wells in nearby countries (Hawie *et al.*, 2013); these horizons 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. As pre-Tertiary units have not been drilled in the Levant Basin, it is difficult to distinguish and identify the Mesozoic units. However, Cenozoic units such as the Eocene, Oligocene-Miocene, Messinian and Pliocene are interpreted with greater certainty and are laterally continuous throughout the basin (Fig. 4).

A mixed carbonate-siliciclastic system characterizes the stratigraphy of the deep Levant Basin. Mesozoic deposits, possibly deep-water carbonates or clastics, are interpreted to occur below the Senonian unconformity. The overlying Cenozoic consists of a number of units starting with undercompacted shales of Paleogene

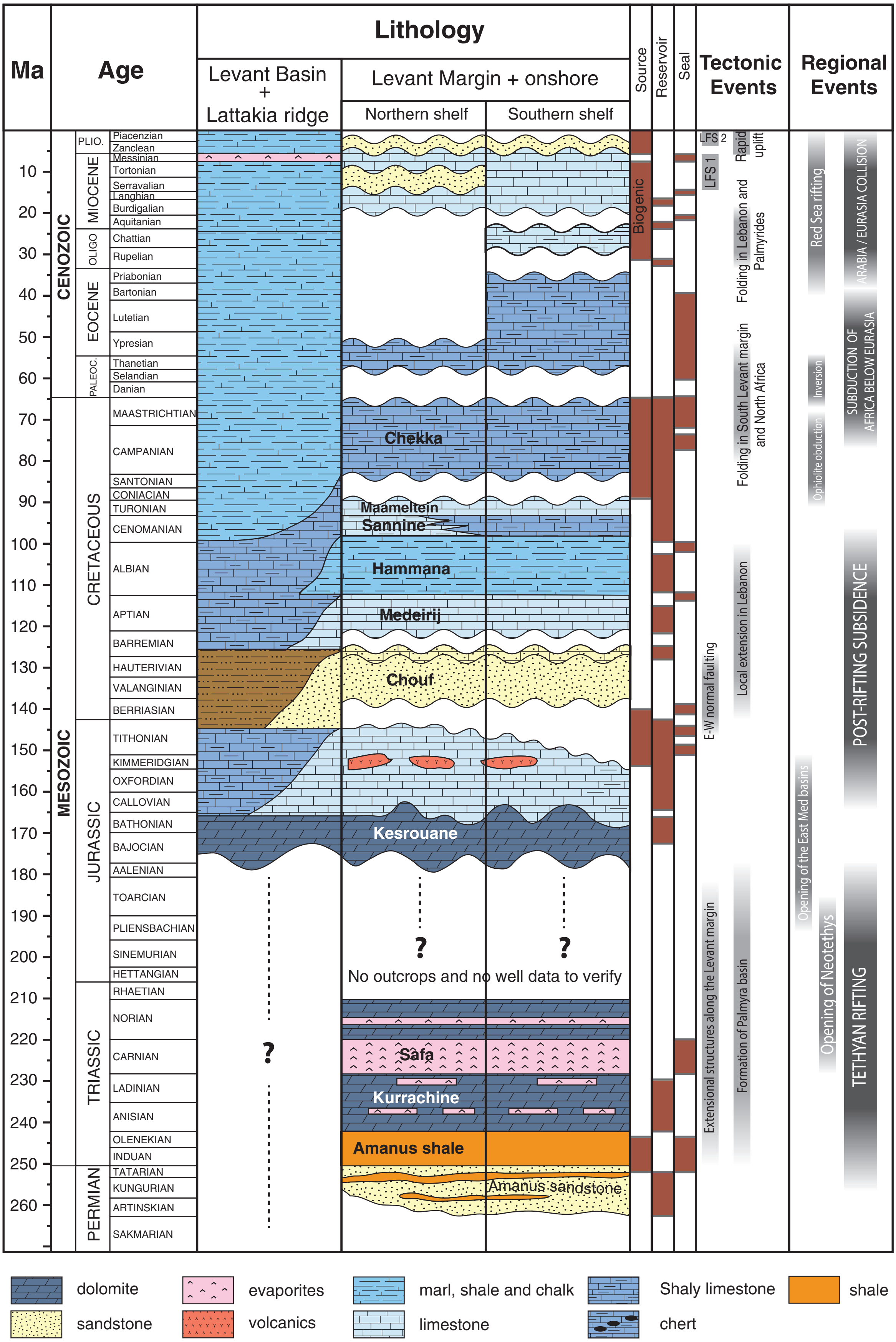

Fig. 9. Chronostratigraphic chart of the four domains identified on- and offshore Lebanon, depicting the expected sedimentary facies from correlation with outcrop and well data onshore. The major geological events are shown together with the expected source, reservoir and seal intervals. Modified from Hawie *et al.* (2013), Barrier *et al.* (2014) and Ghalayini *et al.* (2017).

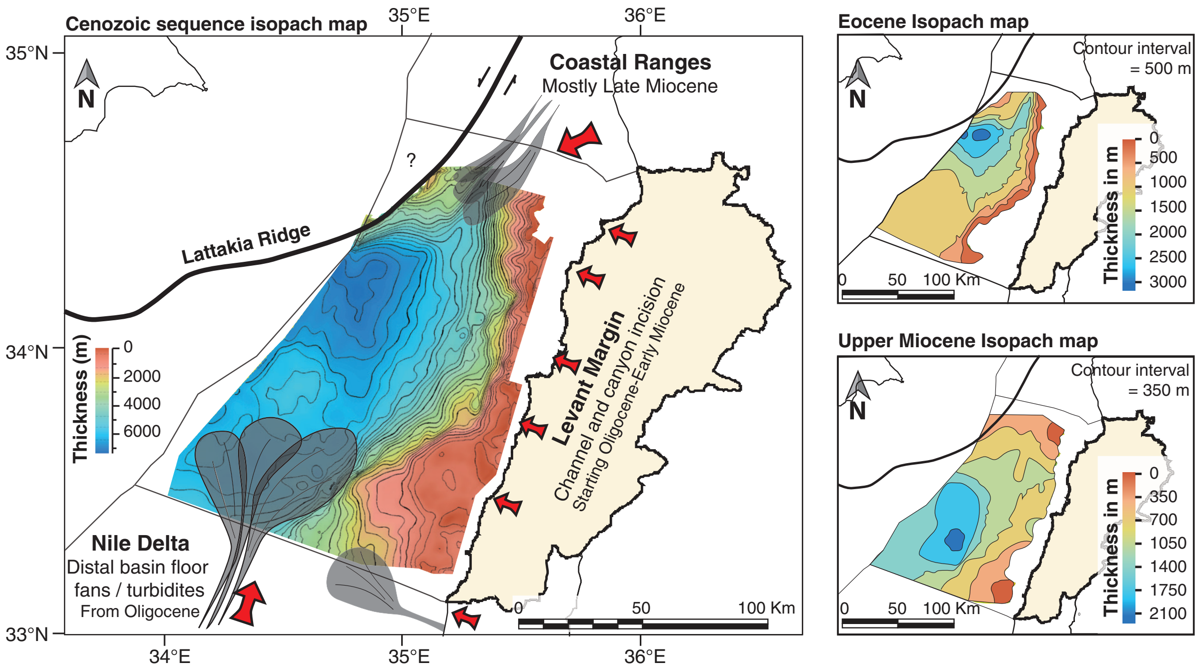

Fig. 10. Isopach maps showing the thickness of the entire Cenozoic, the Eocene, and the Upper Miocene units in the Levant basin offshore Lebanon. Note that the Eocene depocenter is located close to the Lattakia Ridge, while the Upper Miocene depocenter has shifted southwards. The isopach maps have been constructed based on 3D seismic data covering >80% of the Lebanese offshore. No isopachs have been shown NW of the Lattakia Ridge due to uncertainty in horizon interpretation, as no well data is available for calibration. The sedimentary input sources for the Cenozoic units are from Hawie *et al.* (2013, 2015).

age and is up to 7 km thick (Fig. 10) (Montadert *et al*., 2014). The Oligo-Miocene consists of siliciclastic material deposited during margin uplift and sea-level lowstand during the late Eocene and Oligocene (Haq and Al-qahtani, 2005), which resulted in 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 mid-Upper Miocene succession offshore northern Lebanon, together with deep-water sedimentary features such as channels, levees and turbidite lobes towards the distal part of the basin.

The thick Oligo-Miocene succession in the deep Levant Basin can be explained by an influx of considerable volumes of detrital material originating from the proto Nile (Steinberg *et al*., 2011), from which distal turbidites and basin floor fans may extend as far north as offshore Lebanon (Dolson *et al*., 2005; Hawie *et al*., 2013). However, forward stratigraphic modelling indicates that a multi-source system may better explain the basin fill (Fig. 10) (Hawie *et al*., 2015). Thus, deposition was likely accompanied by erosion from the eastern (Levant) margin as well as sediment transport from the north, mainly from the Lattakia region in coastal Syria.

Overlying the Oligo-Miocene is a ~1.7 km thick sequence of Messinian evaporites which was deposited as a result of the isolation of the Mediterranean Sea. The Messinian succession contains mass transport complexes at the base, together with intercalations of clastic material and halite (Gorini *et al*., 2015). A return to pelagic/hemi-pelagic clastic-dominated sedimentation occurred during the Pliocene with the deposition of deep-water clastics (Hawie *et al*., 2013).

Structural setting

NE-SW trending anticlines have been documented in the deep Levant Basin. These are 5 to 15 km long, deform the Oligo-Miocene, and detach downward within the Eocene unit (Fig. 11). The absence of growth strata in the pre-Messinian section and the erosion of the anticlinal crests along the base-Messinian horizon indicate that these anticlines developed immediately prior to, or at the onset of, the Messinian Salinity Crisis (Ghalayini *et al.*, 2014). The anticlines formed as a result of regional-scale compression caused by the convergence and suturing of Arabia with Eurasia. In the southern Levant, anticlines with a similar trend are documented and overlie deep-seated Mesozoic extensional structures (Gardosh and Druckman, 2006). It is not clear if the anticlines offshore Lebanon also overlie deeper reactivated structures, but thickness variations below the anticlines found closer to the margin strongly suggest that this is the case (Ghalayini *et al*., 2014).

Layer-bound normal faults are common in the Oligo-Miocene section in the deep Levant Basin. The faults are regularly spaced with a dip of 60° either to NE or SW, making it difficult to refer to them as "piano key" faults as has been done previously (Kosi *et al*.,

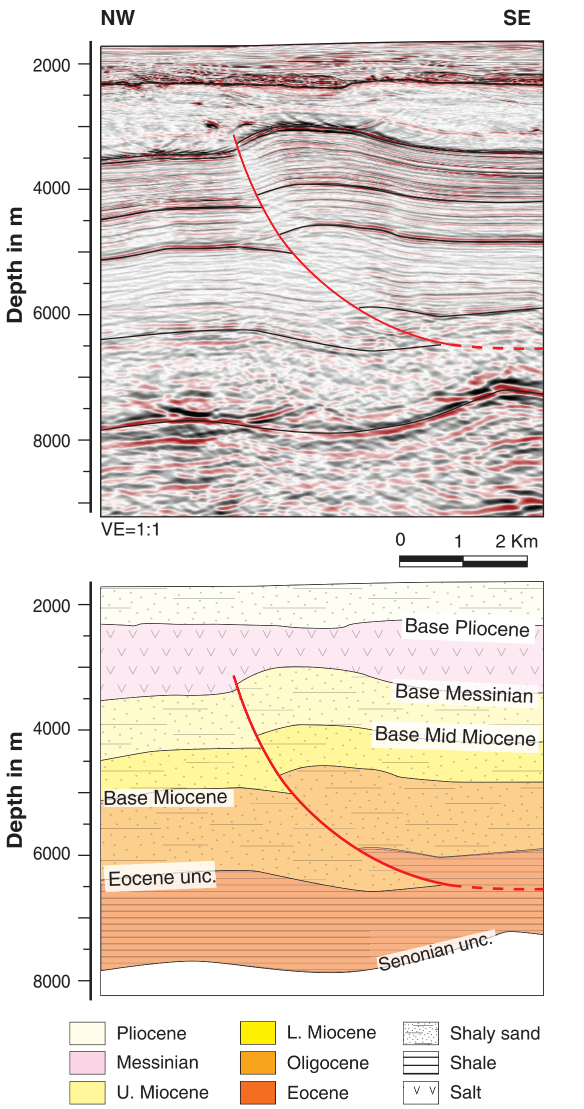

Fig. 11. Geo-seismic line showing an example of a NE-trending anticline in the deep basin domain offshore Lebanon. The structural style suggests detachment folding on an intra-Eocene horizon. The anticlines were folded in the Late Miocene prior to the Messinian event (Ghalayini *et al.*, 2014). For location, see Fig. 1.

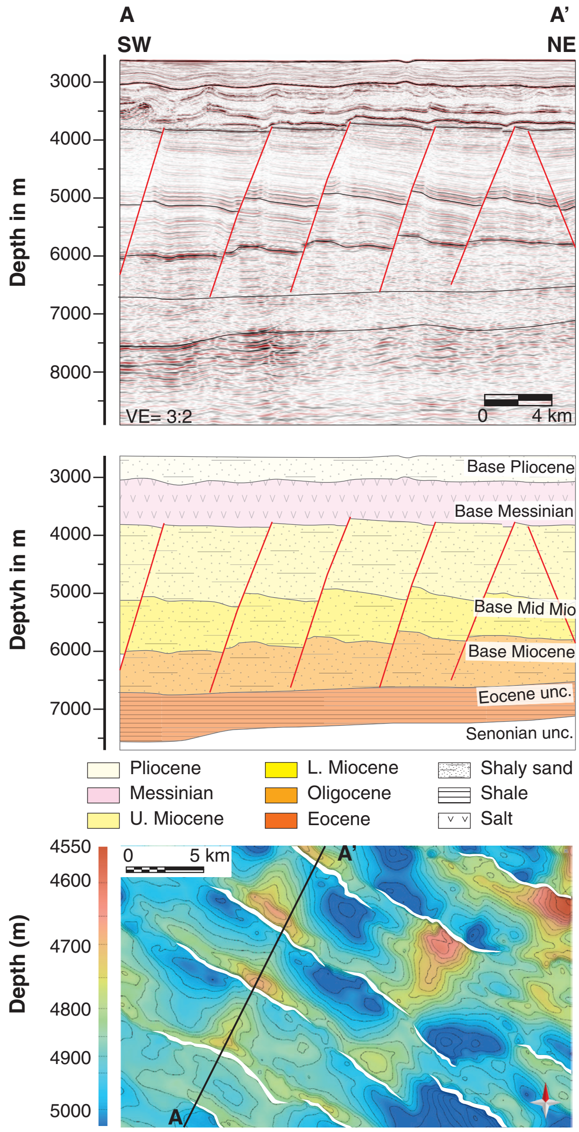

Fig. 12. Geo-seismic line (above) showing tilted fault blocks in the deep basin domain. The depth map of the base mid-Miocene horizon (below) shows the geometry of the strata in hanging wall blocks, which could form closed traps at the present day. For location, see Fig. 1.

2012) since they do not share a single dip direction. At depth, all the faults consistently die out at the same intra-Eocene detachment level, which has been interpreted as a regionally developed shale (Fig. 12) (Montadert *et al.*, 2014; Hawie *et al.*, 2013; Kosi *et al.*, 2012). As no NE-SW extension is documented to have occurred in the basin during the Oligo-Miocene, a solely tectonic origin for their formation or an origin related to the Messinian Salinity Crisis has been refuted (Ghalayini *et al.*, 2016). Detailed analyses of the faults' growth and evolution has shown that they developed during the Early Miocene and remained syn-sedimentary until the Late Miocene (Ghalayini *et al.*, 2016). A possible nucleation mechanism for these faults may be related to diagenetic reactions within the Oligo-Miocene section which led to volumetric contraction of the host rock, causing intra-formational normal faulting (c.f. Cartwright, 2011; Wrona *et al.*, 2017).

(ii)The Lattakia Ridge

The Lattakia Ridge in the NW of the Levant Basin offshore Lebanon is part of the Cyprus Arc system, extending from the coast of Syria in the NE to offshore southern Cyprus (Fig. 1). The Lattakia Ridge domain includes the ridge itself and the areas to both north and south.

Stratigraphy

The stratigraphy in this domain is similar to that elsewhere in the Levant Basin, albeit with different unit thicknesses, especially to the west of the ridge

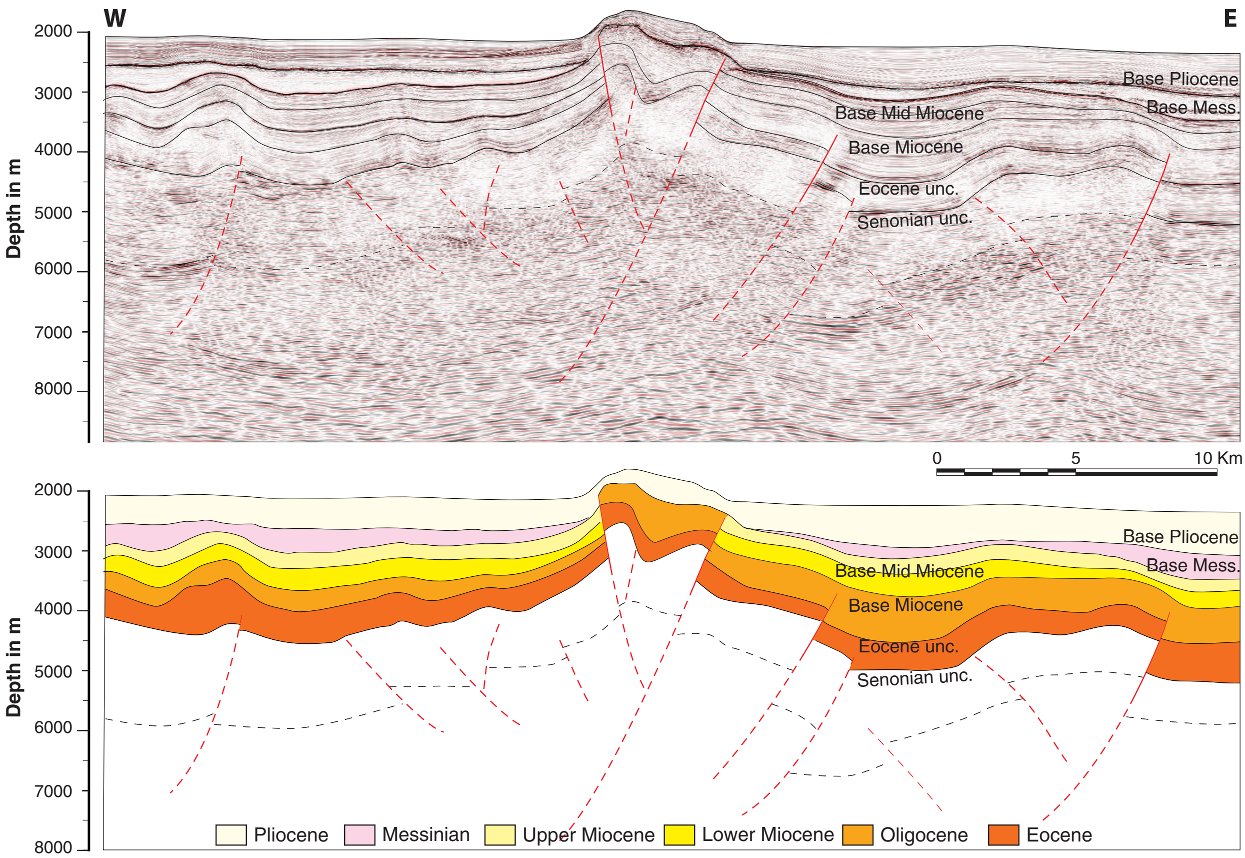

Fig. 13. Geo-seismic line showing the Latakia Ridge north of the Levant Basin. The structures in this area consist of reverse, thrust and back-thrust faults which are related to the movement of the African plate relative to the Arabian plate. Note the thinning of the Tertiary units in this area relative to the deep basin. For location, see Fig. 1.

where the Tertiary is believed to thin. Due to the lack of wells to the west of the Lattakia Ridge, it is challenging to accurately date the seismic horizons. Late Cretaceous convergence of Afro-Arabia and Eurasia resulted in formation of an Early Tertiary depocentre, as indicated by the presence of relatively thick Eocene and Oligocene units to the south and SE of the Ridge (Fig. 10) (Hawie *et al.*, 2013). The Miocene, however, thins considerably but is up to 1 km thick SE of the ridge. Proximity to a northerly sediment source (i.e. Syria and Turkey) may have resulted in coarser clastic material in the Oligo-Miocene unit in this domain, possibly resulting in improved reservoir qualities (Fig. 10) (Hawie *et al.*, 2015). Ghalayini *et al.* (2016) drew atention to the likely presence of coarser-grained material in the Oligocene and Upper Miocene, based both on the normal fault distribution and a geomechanical assessment.

Structural framework

The Lattakia Ridge consists of a series of SE-verging thrusts forming prominent but narrow, NE-SW trending structures that have a profound bathymetric expression (Fig. 13). Several symmetrical, NE-trending anticlines are observed adjacent to the ridge. In the deeper intervals, i.e. Eocene and Mesozoic, the anticlines are cut by SE-verging thrusts along their SE limbs. The thrusts disappear in shallower intervals, i.e. the Oligo-Miocene, and the anticlines resemble compressional structures without any observed reverse faulting (Fig. 13). Back thrusts are also documented along the Lattakia Ridge itself and are believed to have been initiated during the Pliocene as a result of transpression (Hall *et al.*, 2005; Symeou *et al.*, 2018).

(iii) The Levant Margin

The Levant margin domain covers the area adjacent to the Lebanese coastline and comprises the Saida-Tyr plateau together with a narrow strip offshore Beirut and a larger platform to the north (Fig. 2). In previous reviews, the Levant margin was included with onshore Lebanon (e.g. Nader, 2011); however, for the purpose of this paper, the Levant margin is differentiated from the onshore domain as the depositional settings are somewhat different (Hawie *et al.*, 2014; Bou Daher *et al.*, 2015; Bou Daher *et al.*, 2016; Nader, 2014b).

Stratigraphy

The margin is distinguished from distal parts of the Levant Basin by the presence of a thick Mesozoic carbonate succession, above which the Cenozoic pinches-out and onlaps (Figs 4, 5, 6). Hawie *et al*. (2013) interpreted the stratigraphy along the Levant margin and correlated the units identified in seismic data to those documented onshore (Dubertret, 1955; Hawie *et al*., 2014; Nader, 2011). Cenozoic units are similar to those expected to occur in the distal basin and include the Eocene, Oligo-Miocene, Messinian and Pliocene (Figs 4, 6, 9). However, they thin towards the margin and pinch out against the adjacent Mesozoic units (Fig. 10). The expected Mesozoic stratigraphy and structures of the Levant margin were discussed above.

Structural framework

The structural setting of the Levant margin offshore Lebanon is markedly different from south to north. At the latitude of Beirut, offshore south-central Lebanon, the Mesozoic carbonate platform is narrow (or absent) and can be correlated with steeply-dipping Cenomanian units in the adjacent onshore (Dubertret, 1955; Nader, 2014a); by contrast, a broad plateau is documented along the margin to the south (Fig. 5) (Ghalayini *et al.*, 2014). From south to north, the margin is frequently cross-cut by vertical, east-west trending, dextral strike-slip faults (Fig. 3). *En échelon* anticlines, oriented NE-SW, are documented in the Upper Miocene interval along the strike of these faults, suggesting a dextral strike-slip motion (Ghalayini *et al*., 2014). A number of NNW-SSE striking Mesozoic normal faults are documented in this study in the Permo-Triassic succession and may be related to Triassic rifting (Figs 3, 4).

(iv) The Lebanese onshore domain

The onshore domain comprises Mount Lebanon, Anti-Lebanon, and the intervening Bekaa Valley (Fig. 1) (Nader, 2014a). Onshore Lebanon is located at the margins of the Levant and Palmyra Basins, which have similar ages and tectonic histories (Ghalayini *et al*., 2017; Nader, 2014b). The Lebanese onshore can be considered as part of the Palmyra Basin due to the similar crustal configuration and the analogous stratigraphy (Beydoun and Habib, 1995; Walley 1998; Nader, 2014b; Ghalayini *et al*., 2017). However, the Lebanese mountain ranges have been influenced by activity on the Levant Fracture System in the Late Miocene and Pliocene. The main folding phase in the Palmyrides foldbelt and the initial uplift of Mount Lebanon took place earlier, 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 stratigraphic units documented in the onshore domain range between the Lower- to mid-Jurassic and the Upper Miocene and consist predominantly of carbonate successions. Mid-Jurassic to Upper Cretaceous rocks are exposed in Mount Lebanon, and Paleogene and Neogene sediments occur at outcrop closer to the shoreline and in the Bekaa valley (see the review by Nader, 2014a). Pre-Jurassic units are not exposed onshore. Nevertheless, correlations with the Palmyra Basin suggest Triassic rocks are expected to extend westwards and to be thicker in Lebanon (Beydoun and Habib, 1995). This is based on deep exploration wells and seismic data in Syria (Sawaf *et al*., 2001; Chaimov *et al*., 1993; Brew *et al*., 2001) and seismic data interpretation onshore northern Lebanon (Nader *et al*., 2016). It is likely that the Triassic in Lebanon is analogous to that in Syria, making it promising for hydrocarbon exploration. The Triassic consists of the Lower Triassic Amanus Shale Formation which may have source rock potential, and the mid- to Upper Triassic Kurrachine Formation, both of which have an average TOC content of 1% (Barrier *et al.*, 2014). The latter is divided into a dolomite unit, which could act as a reservoir, and an overlying anhydrite unit, possibly forming a seal. Equivalent units are identified in Jordan (Luning and Kuss, 2014) and in the southern Levant margin (Gardosh and Tannenbaum, 2014).

The Jurassic succession in Lebanon is in general approximately 1700 m thick and is dominated by monotonous carbonates (Nader and Swennen, 2004). The Kimmeridgian Bhannes Formation, however, consists of a mixture of carbonates, marls, lavas and pyroclastics (Dubertret, 1955). Marly intervals in this 80-100 m thick unit have high TOC contents and may have source rock potential (Bou Daher *et al.,* 2016).

The Cretaceous succession includes the 5-300 m thick Neocomian/Hauterivian Chouf Sandstone Formation (Maksoud *et al*., 2014; Walley, 1997). The formation was deposited in a fluvial to deltaic setting and may have both reservoir and source rock potential where buried to adequate depths.

The majority of the remaining Cretaceous interval is composed of a ~1000 m thick limestone and marl succession deposited in shallow-water conditions which may have some reservoir potential; marl interbeds could form seals. The Senonian/Campanian–Maastrichtian Chekka Formation consists of dark grey to white chalks and marly limestones. Its thickness ranges from 100 to 500 m, with the thickest succession documented in the southern Bekaa valley. The formation has some source rock potential where it contains organic-rich argillaceous limestones with TOC values between 2 and 10%, with higher values in South Lebanon in Hasbaya (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 valley (Dubertret, 1955) where they are up to 900 m thick (Hawie *et al*., 2014), and in south Lebanon. Upper Eocene and Oligocene units are absent from the whole of onshore Lebanon due to uplift and erosion of the Levant margin during Early Miocene compression (Walley, 1998), except for one local outcrop in the south of Lebanon (Müller *et al*., 2010). The middle Miocene at outcrop consists of continental lacustrine facies in the Bekaa valley and, by contrast, of open-marine facies along the margin (Dubertret, 1955) including isolated reef structures (Hawie *et al*., 2014).

Structural setting

Onshore Lebanon is dominated topographically by the NE-trending Mount Lebanon and Anti-Lebanon mountains and the intervening Bekaa valley (Fig. 1; Nader 2014a; Dubertret 1955). Northern Mount Lebanon consists of a broad, symmetrical 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 (Dubertret, 1955; Walley, 1998). These two structural zones are separated by a deep-seated fault which forms the westward extension of the Jhar Fault of the Palmyrides (Ghalayini *et al*., 2017; Walley, 1998) (Fig. 1). Anti-Lebanon has an anticlinal structure similar to that of Mount Lebanon, and merges topographically with the Syrian Palmyrides ranges to the north. The Bekaa valley, in which there is a thick Tertiary to Recent continental succession, separates the two mountain ranges. The valley is narrow in the south and widens northwards towards Syria (Fig. 1).

The 160 km long Yammouneh Fault, part of the Levant Fracture System (LFS), bounds the eastern side of southern Mount Lebanon and cuts through northern Mount Lebanon (Fig. 1). The fault may have been active since the Precambrian (Butler *et al*., 1998). Displacement on the LFS in Lebanon was in general transpressional during the Pliocene, resulting in the formation of a restraining bend (Fig. 1), and causing uplift of pre-existing structures. Since the late Quaternary, the fault has accommodated mainly sinistral strike-slip displacement (Daëron *et al*., 2004; Gomez *et al*., 2006). Transpression and strike-slip tectonics are also accommodated by the sinistral strike-slip Roum and Serghaya Faults which branch from the southern LFS in the Golan Heights (Gomez *et al*., 2001; Butler *et al*., 1998) (Fig. 1).

A number of ENE-WSW, currently active, dextral strike-slip faults occur along Mount Lebanon (Gedeon, 1999) and extend into the Levant margin offshore (Ghalayini *et al*., 2014). These faults most likely developed during the Mesozoic as normal faults during the break-up of Pangea and were subsequently reactivated during Neogene compression (Collin *et al*., 2010; Ghalayini *et al*. 2014). Similar faults are also found in the Palmyra Basin to the east.

PETROLEUM SYSTEMS

Source rocks and maturity

Potential source rocks are thought to occur in units between the Permian and the Pliocene based on regional stratigraphic correlations, field investigations and geochemical analysis. Potential source rocks intervals are summarised below.

The distal Levant Basin and Lattakia Ridge

Geochemical analyses of gas samples from Middle Jurassic to Pliocene reservoir rocks along the SE margin of the Levant Basin to the south of Lebanon indicate the presence of five thermogenic and biogenic sources belonging to different genetic groups (Feinstein *et al*., 2002). Source rock information for the offshore and distal margin is mostly conjectural based on extrapolation from the onshore where source rocks may include: (i) Silurian shales; (ii) Triassic and Lower Jurassic organic-rich strata (Saharonim and Mohilla Formations) with 0.5-1.4% TOC; (iii) the mid- Jurassic Barnea Limestone, which contains Type II kerogen with 2.6% TOC; (iv) Type IIS Senonian marls and chalks (Mount Scopus Group) with up to 10% TOC expected in the offshore; and (v) Oligo-Miocene units which may potentially produce biogenic gas. These source rocks belong to different petroleum systems which are identified in the southern Levant as the Meged, the coastal plain (or Helez), the continental margin (Yam and Mango) and the inland Dead Sea systems, together with the Tamar system in the deep basin (Feinstein *et al*., 2002; Dolson *et al*., 2005; Gardosh *et al*., 2014). TOC contents in source rocks in the offshore may be less than those recorded onshore.

Offshore Lebanon, potential source rocks for thermogenic petroleum may occur in the Permian-Triassic, Upper Jurassic, Upper Cretaceous, Paleocene-Eocene and Oligocene. The thermal maturation of these potential source rocks was modelled by Bou Daher *et al.* (2016) and results are summarised as follows. Permian and Triassic thermogenic source rocks may have generated petroleum between 90 and 34 Ma in the Levant Basin, and Upper Jurassic (Kimmeridgian) source rocks may have generated thermogenic oil between the Late Cretaceous and Late Miocene. The Upper Cretaceous (Campanian) was modelled to have generated hydrocarbons between 34 and 16 Ma. However, Campanian source rock quality and TOC content may decline in the distal part of the Levant Basin (Bou Daher *et al*., 2015). Paleocene and Eocene source rocks may have generated hydrocarbons during the Oligocene and may still be active in some parts of the basin. Oligocene source rocks are modelled to have begun generating thermogenic hydrocarbons at around 6 Ma and are in the maturity window at the present day.

In addition to a thermogenic potential, the Oligocene is believed to contain potential biogenic source rocks in the Levant Basin. Generation of biogenic gas may have occurred between 18.5 and 6 Ma; while on the Lattakia Ridge and in the more proximal basinal realm, it may still be ongoing as the units are thinner and located at shallower depths (Bou Daher *et al*., 2016). In fact, the most productive biogenic source rocks in the southern Levant are thought to be within the Oligocene succession (Gardosh and Tannenbaum, 2014), and these are expected to extend northwards into Lebanon (Hawie *et al*., 2013; Nader, 2014b). Other biogenic source rocks include the Lower and Middle Miocene from which methane is believed to have been expelled from the Messinian to the present day (Bou Daher *et al*., 2016). Based on thermal history modelling, Bou Daher *et al*. (2016) predicted that a thickness of 700 to 1500m of the sub-Messinian Miocene succession is currently within the biogenic zone.

The Levant margin and onshore

In Syria, the Upper Permian/Lower Triassic Amanus dolomites are source rocks for the oil in Triassic reservoirs in the Palmyrides (Barrier *et al*., 2014) and may also be promising in the Levant margin and onshore. Potential Permian and Triassic source rocks are modelled to have generated hydrocarbons between 75 Ma and the present day along the margin and onshore (Bou Daher *et al*., 2016). Similarly, Kimmeridgian source rocks are modelled to have generated oil between the Oligocene and the present day (Bou Daher *et al*., 2016). Where deeply buried beneath the Bekaa valley, Kimmeridgian source rocks are currently in the oil window. Campanian source rocks appear not to have been buried sufficiently deeply in Mount Lebanon to generate hydrocarbons. In the Bekaa valley and along the Levant margin however, the Campanian (10-20% TOC) is currently in the maturity window and minor generation may have occurred (Bou Daher *et al*., 2015).

Reservoir rocks

The distal Levant Basin

Potential reservoir rocks in the distal part of the Levant Basin occur in the Oligo-Miocene succession and consist of deep-water sandstones (Gardosh *et al*., 2008; Hawie *et al*., 2013). Offshore the southern Levant, the lower Miocene Tamar Sand is considered to have the best reservoir characteristics, with high net-to-gross and high porosity/permeability (20-27% and 500-1000 mD respectively) (Gardosh and Tannenbaum, 2014). The Cenozoic interval in the Levant Basin offshore Lebanon is much thicker than that to the south, and the corresponding Lower Miocene package is three times as thick as its counterpart in the southern Levant (Hodgson, 2012). This suggests that the Lower Miocene reservoir unit offshore Lebanon is thicker than that encountered in Tamar (c.f. Gardosh and Tannenbaum, 2014). However this hypothesis is based only on the strong impedance contrast of horizons within the Miocene unit offshore Lebanon, but these horizons are not observed with the same clarity in the southern Levant (Hodgson, 2012).

Studies of the normal fault system offshore Lebanon (Ghalayini *et al*., 2016) have shown that the fault growth has been affected by mechanical stratigraphy and the presence of a competent Lower Miocene unit, with faults nucleating in incompetent fine-grained sediments. The competent interval is interpreted to consist of a ~100 m thick sandstone unit equivalent to the Tamar Sand (Ghalayini *et al*., 2016), or may correspond to another lithology which is mechanically resistant to faulting. Using a polygonal fault distribution to map deep-water reservoirs and lithological variations across an area has been used in other frontier basins to aid exploration (Jackson *et al.,* 2014; Turrini *et al*., 2017).

The Lattakia Ridge

In the northernmost part of the deep Levant Basin and in the Lattakia Ridge domain, seismic facies interpretations (Hawie *et al*., 2013) suggest that potential reservoirs may be located in the Upper Miocene, and suggest an increased sand content in the base-Oligocene. The fact that the normal faults have smaller vertical extents and displacements in this area suggests that there is a barrier to vertical fault propagation (Ghalayini *et al*., 2014). As the faults do not propagate to Upper Miocene and Lower Oligocene intervals, it is likely that the latter units consist of incompetent lithologies which may correspond to coarse grained material, possibly sand. Clastic material in this area is most likely derived from a northerly source, probably from the Lattakia region in coastal Syria (Fig. 10). In addition, the erosion of Cretaceous to Miocene platform carbonates contemporaneously with the accelerated uplift of Mount Lebanon in the Late Miocene/Pliocene may have resulted in an influx of conglomeratic material from northern Lebanon (Hawie *et al*., 2015; Hawie *et al*., 2013).

Levant margin

Along the Levant margin, deeply-buried Jurassic platform carbonates are protected from meteoric influence (Nader and Swennen, 2004a) and, together with fracture-associated hydrothermal dolomites, may form effective reservoir rocks.

The Lower Cretaceous Chouf sandstones can be correlated with the Rutbah Formation in Syria, which

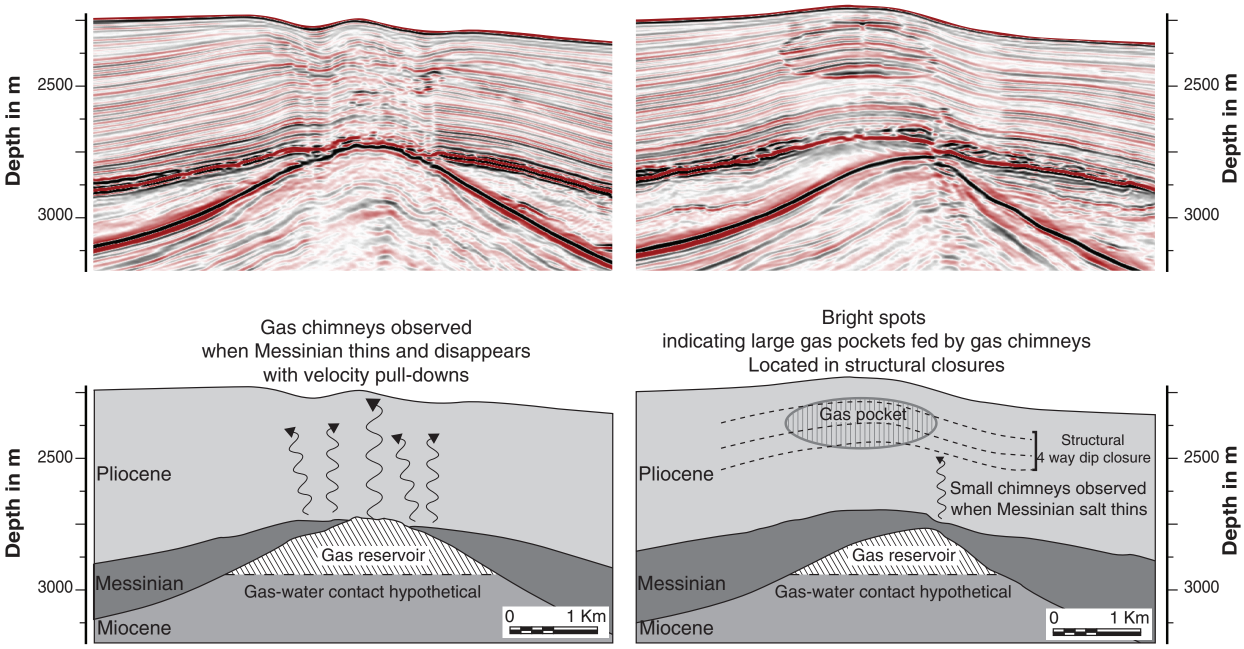

Fig. 14. Geo-seismic lines showing gas chimneys on top of a Miocene anticline in the Lattakia Ridge domain observed only when the Messinian seal thins or is absent. The overlying Pliocene exhibits numerous bright spots and DHIs, suggesting the entrapment of the leaked gas in Pliocene reservoirs in structural closures. For location, see Fig. 1.

constitutes the principal reservoir in the Euphrates Graben (Barrier *et al*., 2014; Sawaf *et al*., 2001); and with the Helez Formation in the southern Levant, which is the reservoir at the Helez field (Shenhav, 1971). Therefore, Lower Cretaceous sandstones may form reservoirs in the Levant margin offshore. Within the Albian and Aptian, potential reservoirs may consist of isolated reefal build-ups, similar to the Eratosthenes margin (Hawie *et al*., 2013; Montadert *et al*., 2014; Esestime *et al*., 2016).

Overlying reservoirs along the Levant margin may consist of Oligo-Miocene clastics that onlap the Mesozoic carbonates. These reservoir rocks may be of better quality than their equivalents in the distal Levant Basin due to their proximity to the Mount Lebanon sedimentary source. The Miocene reefal carbonates documented on palaeo-highs along the northern margin may also have good reservoir characteristics (Hawie *et al*., 2013; Hawie *et al*., 2014).

Onshore

Onshore, in the subsurface of Mount Lebanon, potential reservoirs are present in the pre-Jurassic succession. Near the surface, Jurassic and younger strata have undergone severe weathering and the influx of meteoric waters has reduced reservoir quality (Nader and Swennen, 2004a). Effective reservoirs may occur in the Permian to Lower Triassic Amanus Formation, which consists of shales interbedded with sandstones and siltstones, and in the Lower to mid-Triassic Kurrachine Formation, which consists of dolomites and sandstones. These units are important reservoirs for oil and gas in the Palmyrides (Barrier *et al*., 2014), and are equivalent to the Mihilla Formation in the southern Levant (Gardosh and Tannenbaum, 2014).

Potential reservoirs in the Bekaa region may include Jurassic limestones protected from meteoric invasion, Lower Cretaceous sandstones of the Chouf Formation, Upper Cretaceous Senonian fractured carbonates, and Eocene nummulitic limestones.

Seal

The distal Levant Basin

The consistent detachment of normal faults on the Eocene unconformity horizon (Fig. 12), together with the chaotic seismic facies and weak amplitudes observed in the Paleocene/Eocene, suggest that the latter is probably composed of shales (Kosi *et al*., 2012) and other highly overpressured deposits (Montadert *et al*., 2014). Therefore, it is likely that the Paleocene/Eocene package forms an impermeable unit which could seal the underlying reservoirs and prevent vertical hydrocarbon migration in the distal Levant Basin. Oligo-Miocene intraformational shales or claystones may constitute good seals for Miocene reservoirs, as in the Tamar and other fields to the south (Gardosh *et al*., 2008). The shallowest cap rocks in the basin are the up to 1500 m thick Messinian evaporites, which could form a very efficient seal for underlying reservoirs.

In the Oligo-Miocene unit, normal faults may either form lateral seals at the present day or act as conduits for hydrocarbon migration. In fact, normal faults are observed to cross-cut the Tamar, Aphrodite and Leviathan fields in the southern Levant Basin but do not seem to affect reservoir continuity (Gardosh and Tannenbaum, 2014). However low transmissibility across the normal faults in the deep basin offshore Lebanon is suggested by: (i) the 350 m of maximum documented displacement on the faults, which results in the juxtaposition of reservoirs against sealing units; and (ii) the fact that faults are developed in predominantly fine-grained lithologies, although some sand units may also be present (Ghalayini *et al.*, 2016), resulting in the production of large amounts of shale gouge in the fault zone. It is difficult, however, to determine the fault permeability in the absence of wells, V_{shale} and pressure data.

Lattakia Ridge
Cap rocks in the Lattakia Ridge domain are the same as those in the distal Levant Basin, but the complex deformation and extensive fracturing in the former area has probably affected the sealing potential. This effect is most pronounced near the ridge itself and diminishes to the SE into the basin. In addition, Messinian salt is absent above the ridge and thins considerably in adjacent areas, which deteriorates the top-seal strength. In fact, gas chimneys are frequently observed in some locations where the Messinian evaporites are absent or thin above anticlines to the SE of the ridge (Fig. 14).

Levant margin
Along the Levant margin, potential cap rocks include Lower Triassic evaporites of the Kurrachine Formation, which probably extend offshore. Kimmeridgian volcanics may constitute a good seal for deeper-lying reservoirs, even though this unit is not laterally homogenous (Dubertret, 1955), with facies changes expected towards the Levant Basin. Cretaceous claystones, marls, and basalts may also form good cap rocks. The Messinian salt unit in the Levant margin is thin in some locations (Fig. 4) to absent (Fig. 6), diminishing its seal potential.

Onshore
Onshore, thick Upper Triassic evaporites of the Kurrachine Formation could seal underlying dolomitic reservoirs and protect them from meteoric influence (Nader, 2011). The evaporites provide a regional seal in the Palmyrides (Barrier *et al*., 2014; Sawaf *et al*., 2001) and the equivalent Saharonim and Mihilla Formations provide a seal in the southern Levant (Gardosh and Tannenbaum, 2014). In the Bekaa, intra-formational volcanic, marly and shaly units of Jurassic and Cretaceous ages may provide a seal for Jurassic and Cretaceous reservoir units. Paleocene calcareous shales may form a good seal as well as a barrier to meteoric infiltration.

Traps and migration

Deep basin
Potential sub-salt traps in the distal Levant Basin offshore Lebanon consist of: (i) NE-SW trending anticlines in the Oligo-Miocene, detaching on the Eocene unconformity and folded immediately prior to, or at the onset of, the Messinian Salinity Crisis; (ii) NE-SW trending Late Miocene transpressional anticlines and positive flower structures found mostly to the SW of the Saida-Tyr plateau; and (iii) Oligo-Miocene tilted fault blocks, which developed during the Early Miocene. Migration of hydrocarbon from biogenic source rocks may have been aided by the intense faulting and fracturing of the Oligo-Miocene interval. As discussed above, the faults may constitute a good seal at the present day; but since they were active, synsedimentary and continuously growing between the Early and Late Miocene, it is likely that they were permeable during the Miocene (Ghalayini *et al*., 2016). Therefore, petroleum migration after the Oligocene could result in charging of Oligo-Miocene reservoirs.

Lattakia Ridge
In the Lattakia Ridge domain, potential traps include symmetrical anticlines in the Cenozoic interval underlain by deep-seated SE-verging thrust faults providing four-way closures. These anticlines surround the Lattakia Ridge, but the ridge itself has poor trap potential due to the lack of closure as a result of intense Cenozoic uplift and erosion. Deformation has continued until the present day, suggesting that several faults are still active and may therefore form migration pathways.

Levant margin
Along the Levant margin, potential stratigraphic traps may occur within the Mesozoic platform carbonates. Other stratigraphic traps include pinch-outs of the Early Cretaceous sands sealed by Cretaceous carbonates (Fig. 15), and pinch-outs of Oligo-Miocene clastic units onto underlying Mesozoic strata, and sealed by intra-Miocene shales (Fig. 16). Structural traps include inversion structures such as reactivated ENE-WSW strike-slip faults (e.g. Ghalayini *et al*., 2014) which may form four-way dip closures below the Messinian. Along the margin, pre-existing and reactivated faults may have permitted hydrocarbon migration to occur from deep Mesozoic source rocks to shallower reservoirs.

Onshore
Onshore, potential traps include four-way dip-closed anticlines adjacent to the Levant Fracture System (Nader, 2014b; Nader *et al*., 2016). Structures with the most promising exploration potential include the

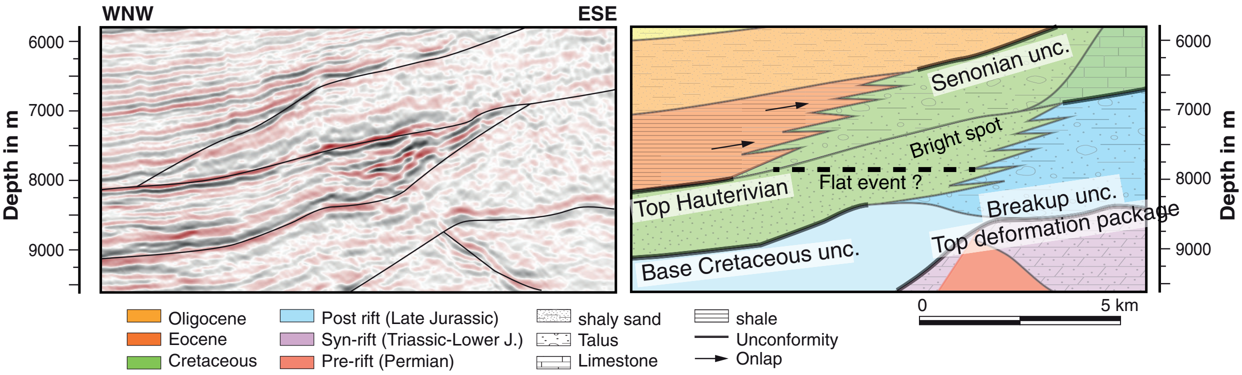

Fig. 15. Geo-seismic line along the Levant margin offshore northern Lebanon, showing a bright spot and a potential flat spot in the Lower Cretaceous unit pinching-out and trapped between Mesozoic carbonates. For location, see Fig. 3.

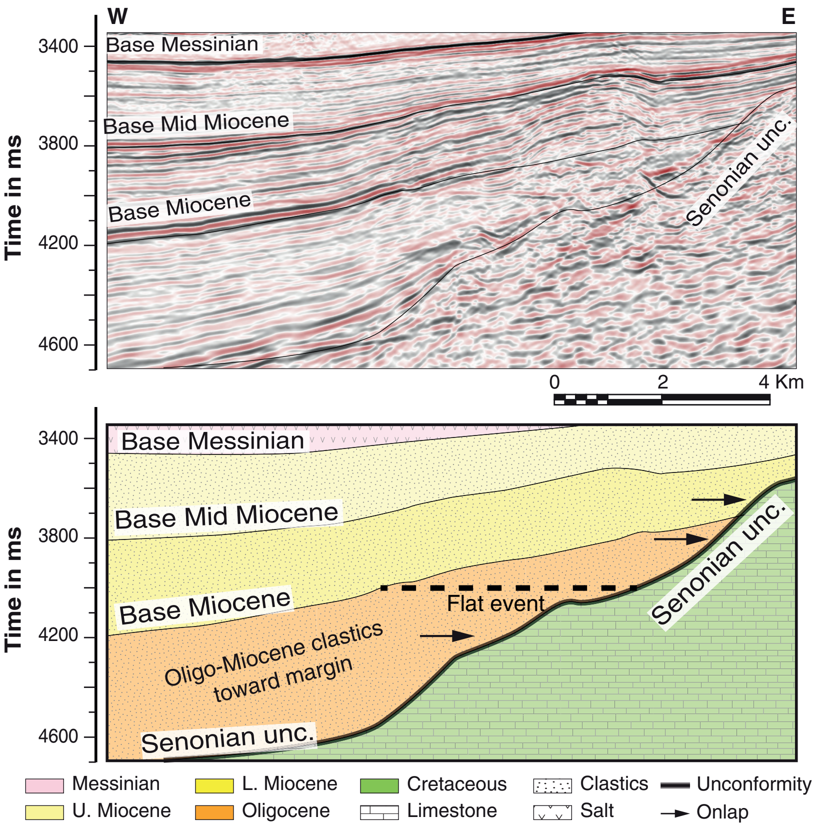

Fig. 16. Geo-seismic line on the Levant margin offshore northern Lebanon, showing the pinch-out of the Oligocene-Miocene units forming stratigraphic traps. A potential flat spot in the Oligocene unit is observed. It is possible that the Oligocene unit contains more clastic material close to the margin, which could enhance reservoir quality. Location in Fig. 3.

Qartaba anticline (Nader, 2014 a,b; Nader, 2011). The Sir-Ed-Denie and Terbol anticlines, whose subsurface geometries may be similar to that at Qartaba, may also be prospective (locations in Fig. 1) (Beydoun and Habib, 1995; Beydoun, 1977). The onshore structures may have formed in the Late Miocene in association with activity on the LFS. In the Bekaa valley, potential structural traps may be located beneath the Quaternary cover (e.g. Nader *et al*., 2016).

DISCUSSION

A new interpretation of the Levant margin offshore Lebanon is proposed in this paper, based on recently-acquired 3D seismic data. In the southern margin, seismic horizons were tied to a nearby well which resulted in an updated Mesozoic stratigraphic division of the Saida-Tyr plateau. A thick Triassic interval is likely to be present in the south based on predicted unit thicknesses in onshore Lebanon (Beydoun and Habib, 1995). This is consistent with data in Nader *et al*. (2016), who identified a high amplitude horizon in onshore seismic profiles which was interpreted as the Top Triassic. The high impedance contrasts along this horizon in the southern Levant margin may be related to the presence of evaporites within the Triassic, but this needs to be confirmed by drilling. In the north, a Permian pre-rift unit, Triassic syn-rift unit and Jurassic post-rift unit have been identified based on the presence of deep extensional normal faults in the Permo-Triassic, which are believed to be remnants of the Triassic rifting event. The overlying units in

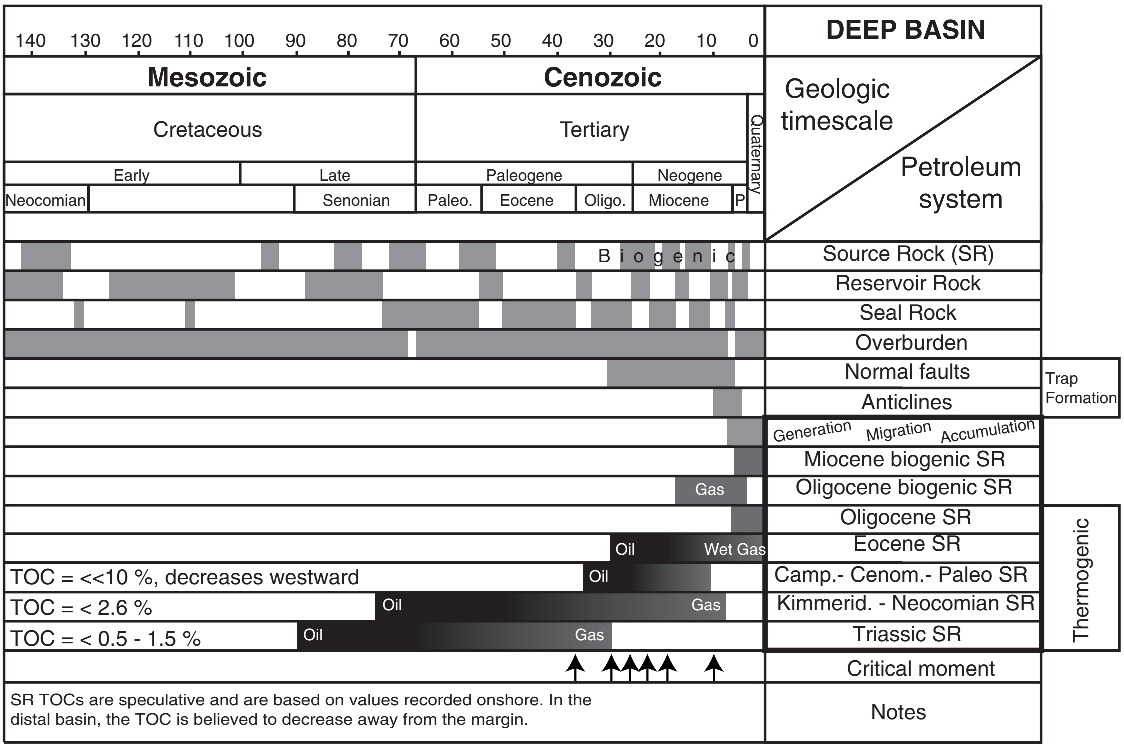

Fig. 17. Petroleum systems chart for the distal Levant Basin domain. Note that the source rock TOC in the deep basin is conjectural and is based on data from nearby countries, and may therefore change once well data becomes available. The chart is compiled from data in Hawie *et al.*, 2013; Ghalayini *et al.*, 2014; and Bou Daher *et al.*, 2016.

the north are interpreted based only on the reflector configuration and impedance contrasts.

The recent discovery of the Zohr field in carbonate reservoir rocks near the Eratosthenes seamount has opened a new play concept in the Levant Basin (e.g. Esestime *et al*., 2016; Montadert *et al*., 2014). Mesozoic carbonates are considered to have good porosity by correlation with analogues in onshore Lebanon (Nader and Swennen, 2004a; Nader and Swennen, 2004b) and Syria (Barrier *et al*., 2014) which are sealed from meteoric invasion (e.g. Nader and Swennen 2004a). Hawie *et al*. (2013) recorded the presence of reefal build-ups onshore Lebanon and suggested their possible continuation offshore, providing potential analogues for Zohr (e.g. Esestime *et al*., 2016).

In the northern Levant margin, Lower Cretaceous sandstones occur between the Jurassic and Cretaceous carbonates. This unit offshore appears to be thicker than its equivalent onshore (e.g. Dubertret, 1955; Bellos, 2008), possibly due to a basin/margin differentiation developed since at least the Early Cretaceous with more accommodation offshore. Hawie *et al*. (2013) proposed a general westward facies variation during the Mesozoic caused by a transition to deeper basinal depositional environments.

The relatively good reservoir properties of the Lower Cretaceous sandstone unit onshore Lebanon and Syria (e.g. Bellos, 2008), and the continuing hydrocarbon production from this same unit in the southern Levant (Shenhav, 1971; Gardosh and Tannenbaum, 2014), suggest that it may also be prospective offshore Lebanon. In fact, DHIs including bright spots and a potential flat-spot are observed in seismic data and may correspond to thermogenic hydrocarbon accumulations (Fig. 15). This unit likely extends along the entire margin offshore Lebanon. However, it is located at depths of up to 8 km in some locations, and potential reservoirs will therefore be highly pressured.

Additional DHIs, such as gas chimneys above anticlines in the deep basin and flat spots, have also been observed. The latter are noted within the Oligocene interval along the Levant margin (Fig. 16). As reservoir quality in this location may be relatively good (Hawie *et al*., 2015), Oligo-Miocene pinch-outs may be a promising target. As the flat spot is located below the Base Miocene horizon, the seal may also be at this level. This suggests that towards the margin, the base-Miocene is probably associated with shaly/marly or fine-grained facies, but a transition to coarser or sandy facies is expected to occur westwards, towards the basin (Fig. 16).

Significance of the geological domains

In this paper, the Lebanese onshore/offshore is divided into four distinct domains in order to draw attention to specific plays which are unique to each area. The subdivision highlights the geological variability of the domains and of their petroleum systems. Petroleum

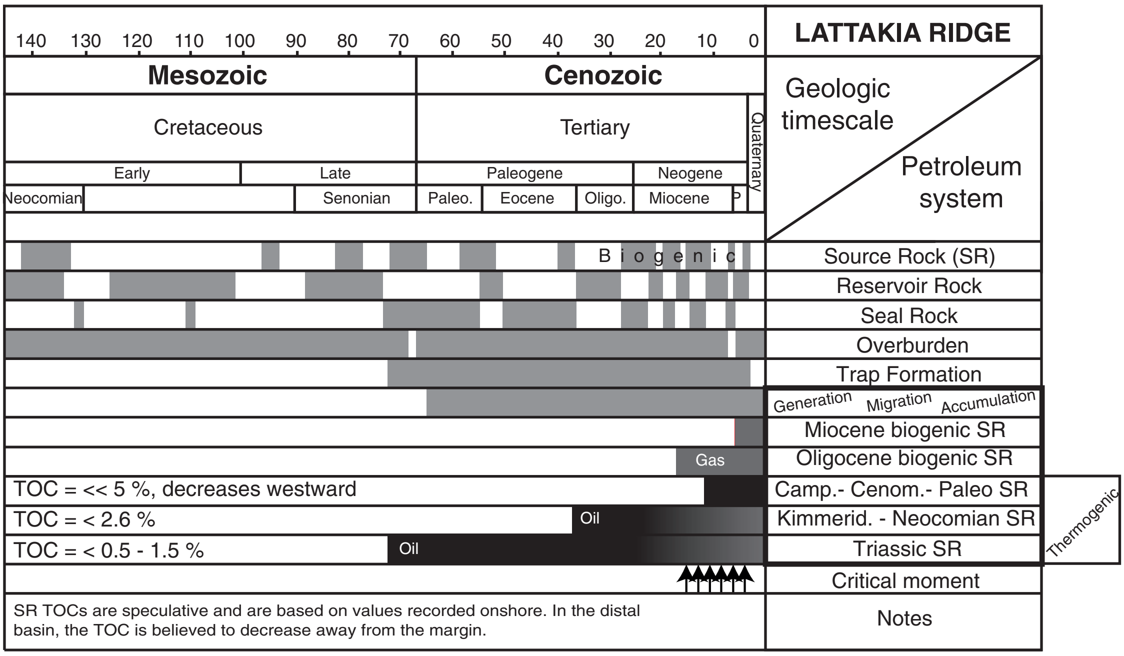

Fig. 18. Petroleum systems chart for the Lattakia Ridge domain. Note that the source rock TOC is conjectural and is based on data from nearby countries, and is therefore likely to change once well data become available. The chart is compiled from data in Hawie *et al.*, 2013; Ghalayini *et al.*, 2014; and Bou Daher *et al.*, 2016.

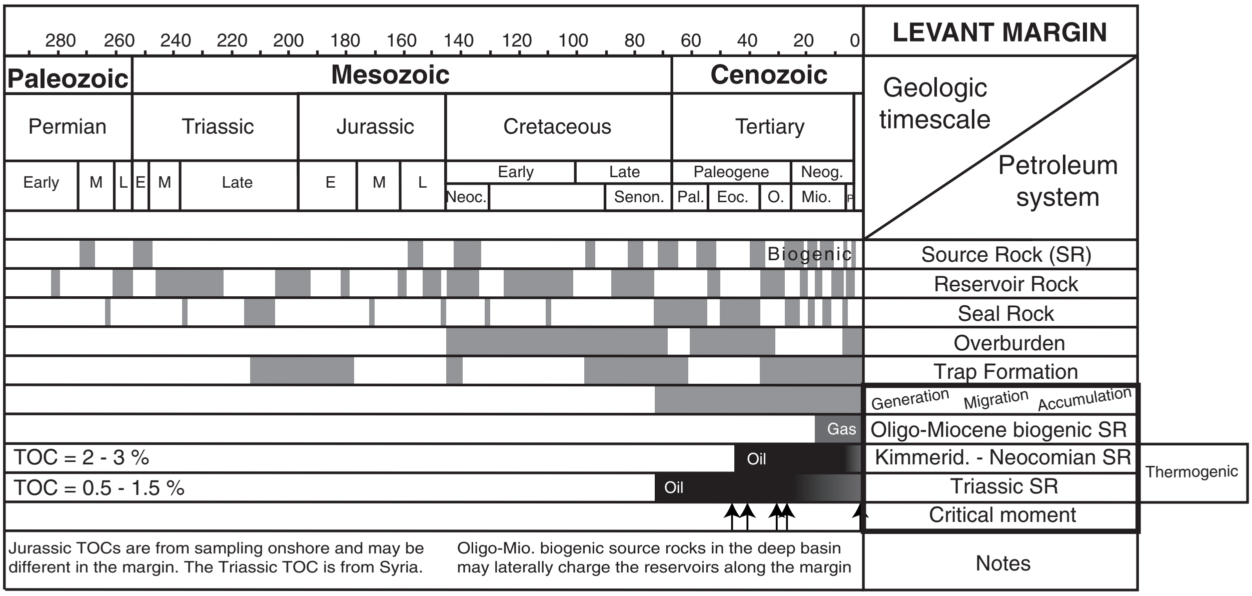

Fig. 19. Petroleum system chart for the Levant margin domain. Note that the source rock TOC in the Levant margin is conjectural and is based on data from onshore Lebanon, and may therefore change once well data become available. The chart is compiled from data in Hawie *et al.*, 2013; Ghalayini *et al.*, 2014; and Bou Daher *et al.*, 2016.

system charts have been compiled for the Lattakia Ridge, the distal Levant Basin, the Levant margin and the Lebanese onshore, and are presented in Figs 17-20. Reservoirs, seals, traps and source rock maturity are summarized in each chart. In the Lattakia ridge and the Levant margin domains, a mixed thermogenic/biogenic charge may have supplied reservoir units between the Late Cretaceous and the present day (Figs 18, 19); while in the distal Levant Basin, a mainly biogenic system is expected to occur with a possible contribution from thermogenic sources (Fig. 17). Onshore, only thermogenic source rocks are active, possibly charging reservoirs since the Late Tertiary (Fig. 20).

To better understand the petroleum system present in each domain, analogues must be used to reduce uncertainty. Sructures in the Palmyrides are of particular importance as they may be analogues for anticlines both on- and offshore Lebanon. For example the Cheriffe anticline (Chaimov *et al.*, 1992) has a similar structural style to anticlines in the Lebanese offshore. In addition, some of the anticlines in the Palmyrides have a box-fold geometry (Searle,

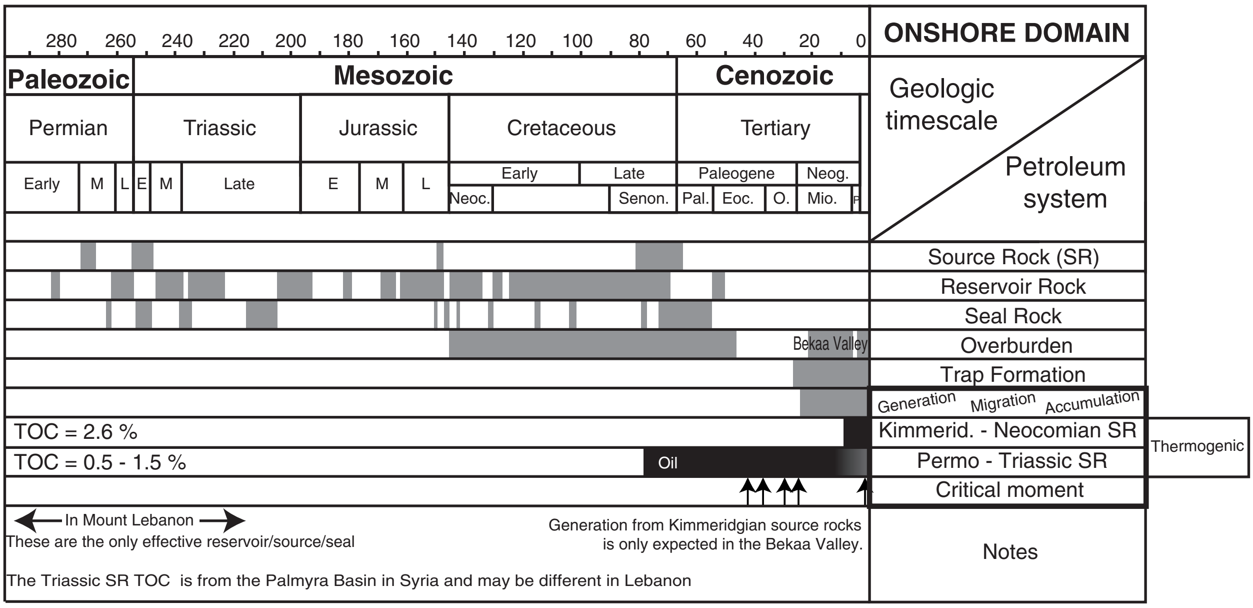

Fig. 20. Petroleum systems chart for the onshore domain. Note that the source rock TOC in the onshore is conjectural and is based on data from the Syrian fields in Palmyra, and may therefore change once well data become available onshore Lebanon. The chart is compiled from data in Hawie *et al.*, 2013; Ghalayini *et al.*, 2014; and Bou Daher *et al.*, 2016.

1994), similar to that of the Qartaba anticline onshore Lebanon (Beydoun, 1995; Nader, 2014a, 2016). Such an approach, which is based on the study of regional analogues and the subdivision of on- and offshore Lebanon into four distinct geographical domains, could help with the assessment of the petroleum systems in each domain and thereby decrease exploration risk.

CONCLUSIONS

The interpretation of recently-acquired seismic reflection profiles along the undrilled Levant margin offshore Lebanon, together with an overview of recently completed academic and industry research projects, has resulted in an improved understanding of the geology and petroleum exploration potential of this area. On- and offshore Lebanon is divided in this paper into four geological domains: the Lattakia Ridge; the distal Levant Basin; the Levant margin; and the Lebanese onshore. Petroleum systems charts were compiled for each domain and summarize potential petroleum system elements and traps:

• The *distal Levant Basin* offshore Lebanon is characterised by Oligocene-Miocene siliciclastic units which have reservoir potential. Time-equivalent sandstones are proven reservoir rocks for natural gas to the south. The domain is in general dominated by Oligo-Miocene biogenic source rocks, with a possible contribution from deeper-lying, thermogenic source rocks. Potential structural traps include Upper Miocene four-way dip closures and Lower Miocene tilted fault blocks,

• In the *Lattakia Ridge,* potential reservoir rocks are mainly composed of Oligo-Miocene siliciclastics, and there is a mixed biogenic-thermogenic source rock potential. Potential traps are Upper Cretaceous four-way dip closures.

• The *Levant Margin*: potential reservoirs include Mesozoic carbonates together with Lower Cretaceous and Oligocene-Miocene siliciclastics. Potential source rocks along the margin are predominantly thermogenic, and there is the possibility of lateral migration from kitchens in the deep offshore. Potential traps are in general stratigraphic.

• In the *Lebanese onshore,* Triassic dolomites and Jurassic and Cretaceous carbonates have reservoir potential, and thermogenic source rocks may be present in the Lower Triassic, Kimmeridgian and Campanian. Potential traps include four-way dip closures.

Working petroleum systems are likely to be present in Lebanon, encouraging future exploration within the four domains identified. Lessons can be learned from previous exploration campaigns onshore and can be used to focus future activity. Discoveries in nearby countries could provide good analogues for Lebanese prospects and could help to reduce exploration uncertainty. In particular, the study of potential analogues in the Palmyrides could have a positive impact on future exploration in Lebanon.

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