

Petroleum Systems of Lebanon: an update and review

R. Ghalayini, F. Nader, S. Bou Daher, N. Hawie, W. Chbat

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Title: Petroleum Systems of Lebanon
 Authors: Ghalayini, R.⁽¹⁾, Nader, F.H. ⁽²⁾, Bou Daher, S. ⁽³⁾, Hawie, N. ⁽⁴⁾ & Chbat,
 W.E. ⁽¹⁾

4 **Institutions**:

5 ⁽¹⁾Lebanese Petroleum Administration, Georges Akouri Street, Beirut, Lebanon

6 ⁽²⁾ Geology Department, Geosciences Division IFP Energies Nouvelles, 1 & 4 Av.

7 de Bois-Préau, 92852 Rueil-Malmaison, France.

8 ⁽³⁾ Department of Geosciences and Natural Resource Management, University of

9 Copenhagen, Øster Volgade 10, 1350 Copenhagen, Denmark.

10 ⁽⁴⁾ BeicipFranlab, 232 Av. de Bois-Préau, 92502 Rueil-Malmaison, France.

11 Abstract

12 Extensive 3D seismic data offshore Lebanon together with new investigations of 13 the onshore domain have resulted in a considerable wealth of information on the 14 regional geology and petroleum prospectivity. This article presents a new 15 interpretation of the Levant margin offshore Lebanon with an up-to-date review 16 of the geology of Lebanon and a new comprehensive insight on the petroleum 17 systems along the Eastern Mediterranean sector. The Lebanese onshore and 18 offshore territories are separated in this study into four different domains: the 19 deep basin, the Lattakia Ridge, the Levant margin and the onshore. Each of these 20 domains is marked by a general structural style and various stratigraphic 21 architectures, resulting in different source-reservoir-trap configurations. The 22 new subdivision impacts exploration as it highlights specific geographic areas 23 having distinct petroleum systems. This study takes into account all previously 24 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.

28 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).

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49	The structural framework of the Levant basin and margin has been described on
50	the light of new 3D reflection seismic data interpretation, and modelling
51	(Ghalayini et al., 2014; and references therein). A new geochemical assessment
52	of source rock potential based on extensive sampling onshore Lebanon has also
53	been completed (Bou Daher <i>et al.</i> , 2014; Bou Daher <i>et al.</i> , 2015). This has
54	resulted in the development of a new basin model for Lebanon and its offshore
55	based on an integration of all the newly acquired knowledge, providing an
56	updated picture of the hydrocarbon potential of Lebanon (Bou Daher et al.,
57	2016). In addition, a refined model for the crustal structure of the Levant Basin
58	was proposed (Inati et al., 2016), which directly impacts the petroleum systems
59	and the source rock maturity.
60	
61	This article summarizes the results of the latest geological and petroleum
62	investigations in Lebanon and adds new up-to-date data – especially with regard
63	to potential petroleum systems. First, it presents new interpretation of the

64 Levant margin offshore Lebanon since the carbonate prospects have attracted

65 major attention following the Zohr discovery in carbonate reservoirs offshore

66 Egypt. Second, it subdivides the region into geological domains based on

67 multitude of stratigraphic, structural and geochemical data. Third, it discusses

68 the various petroleum aspects of each domain (potential source rocks,

69 reservoirs, and traps) and points out new objectives based on recent data and

70 neighboring discoveries. These results serve as a basis for the understanding of

the petroleum potential of Lebanon and provide a good case study on

72 exploration effectiveness and strategy at a critical time as the first offshore

73 licensing round has been set.

74 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 relinguished 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 Km². 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 Km² of
multiclient 3D seismic data followed by Spectrum who also acquired additional
5172 km² of multiclient 3D seismic data between 2012 and 2013 in the deepwater offshore Lebanon resulting in an exceptional wealth of information for the
offshore basin. The new data has indicated a promising hydrocarbon potential

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

100 Tectonic and crustal setting

101

102 The present-day tectonic framework is the result of the complex geodynamic 103 evolution of the region through geologic time. Two large structures are 104 dominating the geological landscape: (1) the LFS, and (2) the Lattakia Ridge 105 System. The LFS is a sinistral transform fault system linking rifting in the Red Sea 106 with collision in the Taurus (Freund *et al.*, 1970) (fig. 1). Lebanon is located 107 along the LFS on the plate boundary between Africa and Arabia. To the west of 108 the LFS, the area is marked by the stable foreland Levant basin, which was 109 formed synchronously with the Palmyra Basin during the polyphase Mesozoic 110 rifting event (Gardosh et al., 2010). 111

112 Bordering the Levant Basin at its NW boundary is the Lattakia Ridge. This Late 113 Cretaceous structure was established as a result of the subduction of Africa beneath Eurasia starting in the Maastrichtian (Frizon de Lamotte *et al.*, 2011; 114 115 Stampfli and Hochard, 2009). Continuous compression has marked the region till 116 modern days with an accelerated rollback of the subduction zone along the 117 Hellenic-Cyprus arc during the Tortonian (Le Pichon and Kreamer, 2010) which 118 led to renewed fold-thrust activity in the middle-upper Miocene along the 119 Lattakia Ridge (Hall *et al.*, 2005; Robertson *et al.*, 1996). A regional geodynamic 120 event was witnessed in the Messinian and Pliocene causing a westward tectonic 121 escape of the Anatolian microplate with a component of anticlockwise rotation

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122	(Le Pichon and Kreamer, 2010; Sengor and Yilmaz, 1981). It has directly affected
123	the Lattakia Ridge which was reactivated into a sinistral strike-slip motion (Hall
124	et al., 2005). These geodynamic events were marked in both the Levant Basin
125	and onshore Lebanon by reactivation of structures, and a decrease in the lateral
126	motion of the LFS (Freund et al., 1970; Ghalayini et al., 2014; Le Pichon and
127	Gaulier, 1988; Quennell, 1984). It is also at this time, that the accelerated uplift of
128	the pre-existing Lebanese structures took place (Walley, 1998; Ghalayini et al.,
129	2017; Beydoun, 1999).
130	
131	The thickness of the crust gradually decreases westward from the Palmyrides to
132	the Levant Basin, with 44 km in the SW Palmyrides, 35 km beneath the anti-
133	Lebanon ranges and 27 km beneath Mount Lebanon (Brew et al., 2001; Khair et
134	al., 1993). This westward thinning of the crust beneath Syria and Lebanon
135	indicates a transition between a crust of continental type east of the Levant
136	margin, transitioning to a thinned continental crust of 8-10 km thickness
137	beneath the Levant Basin as evidenced by modern gravity inversion (Inati et al.,
138	2016) and refraction seismic profiles (Ben-Avraham et al., 2002; Makris et al.,
139	1983; Netzeband <i>et al.</i> , 2006). This gradual, smooth thickness transition is the
140	result of the Permo-Jurassic rifting of Pangea, causing the break-off of
141	continental blocks from the Afro-Arabian plate to form the Neo-Tethys ocean
142	(Garfunkel, 1998; Robertson, 1998) and pointing to successive regimes of
143	extension that did not reach a real break up stage.

144 Methods and data

145

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

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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).

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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.

181

- 182 Interpretation
- 183

184 The fan-shaped geometry of reflectors between RN1 and RN2 point to the 185 presence of growth strata suggesting that normal faults are present at this depth. 186 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 187 188 believed to have nucleated during the Triassic as a result of Tethyan rifting (e.g. 189 Gardosh et al. 2010). Therefore, units below RN1 are likely the pre-rift package 190 while units between RN1 and RN2 are the syn-rift package. This could be 191 attributed to the Permian and Triassic-Lower Jurassic units respectively. As RN2 192 is not displaced by faulting and separates deformed units below from non-193 deformed units above, it could correspond to the break-up unconformity of mid-194 Jurassic age (Hawie et al., 2014). RN2 therefore marks the initiation of tectonic

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195	quiescence and gentle subsidence of the Levant region starting the mid to late
196	Jurassic. The seismic package between RN2 and RN3 likely represents the
197	Jurassic unit composed of shallow-water, inner to middle shelf carbonates. Its
198	thickness of 1 – 1.5 km is in coherence with the thickness of the Jurassic in north
199	Lebanon (Nader et al., 2016; Dubertret, 1955) and is conformable with the
200	seismic facies interpretation of Hawie et al. (2014). Therefore, RN3 could refer to
201	the Late Jurassic-Early Cretaceous sequence boundary. The seismic facies
202	transition from continuous to chaotic reflectors indicate mass transport or talus
203	deposits originating from the Jurassic carbonate platform and deposited at the
204	distal end of the margin over a slope. The abrupt facies variation into high
205	amplitude bright reflectors toward the distal basin could point to the presence of
206	Jurassic clastic units away from the margin.
207	
208	The unit between RN3 and RN4 exhibit a set of stacked high amplitude reflectors
209	indicating different facies than the adjacent carbonates. They are likely

210 representing thick bedding which alludes to sand packages of a possibly Lower

211 Cretaceous age. Therefore, this unit could be analogous to the onshore

212 Hauterivian Chouf formation, and RN4 could likely represent the top

213 Hauterivian. The overlying wedge-shape of the unit and the chaotic reflectors

214 associated could represent mass transport deposits or carbonate talus

215 originating from the Cretaceous carbonate succession along the margin and

- 216 onshore (Hawie *et al.*, 2014). RN5 horizon corresponds to a major marine
- 217 onlapping surface and therefore could represent the Senonian unconformity
- 218 horizon (Hawie *et al.*, 2014; Gardosh *et al.*, 2011). On top of the Senonian
 - 219 unconformity, the high amplitude package should be Tertiary in age as it overlies

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> 220 the Cretaceous unit. This unit displays high amplitude reflectors with similar 221 seismic facies to the underlying carbonates unit. Therefore, it could represent 222 Eocene to Miocene carbonate successions. The presence of such Tertiary 223 carbonate units along the Levant margin has been discussed by Hawie *et al.* 224 (2014). 225 **Levant Margin south of Lebanon** 226 Observations 227 228 The southern Levant margin offshore Lebanon is marked by a specific structural 229 element termed the Saida-Tyr plateau (STP) which is a 2500 km² elevated 230 Mesozoic plateau as observed in the Senonian unconformity depth map (fig. 4). It 231 is differentiated from the deep Levant basin by large crustal faults to is north and 232 west (figs. 5-6) and is characterized by a thinner Cenozoic unit thickness relative 233 to the remainder of the basin (Hawie *et al.*, 2014). 234 235 13 horizons were identified in seismic data based on the interpretation of Hawie 236 et al. (2014) and through correlation with the Adloun well, located 5 km east of 237 the seismic line (fig. 5). It was drilled to a depth of 2150 m and reaches the Upper 238 Jurassic unit (Beydoun, 1977). Horizon RS1 separates chaotic non-continuous 239 horizons from a set of semi-continuous thick and bright horizons above. RS2 240 exhibits a strong impedance contrast separating the overlying chaotic and dim 241 horizons from bright and underlying semi-continuous horizons. It is challenging 242 to assess the continuity of RS1 and RS2 horizons to the west in the deep basin.

243 Horizons RS3 to RS8 are extrapolated from well data and consist of stacked high

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3 4	244	amplitude set of reflectors, with occasional dimming. Horizon RS8 marks the	
5 6 7	245	boundary between stacked high amplitude bright reflectors to the east, and	
8 9	246	stacked continuous medium to high amplitude reflectors to the west. The latter	
10 11	247	package is pinching out and exhibits onlap on RS8. Horizons RS9 to RS13 are	
12 13 14	248	picked up based on the interpretation of Hawie et al. (2014).	
15 16	249		
17 18 10	250	The seismic units between horizon RS2 and RS3, and horizons RS4 and RS5 are	
20 21	251	thinning to the west and disappear. Their seismic facies change abruptly from	
22 23	252	stacked bright horizons to chaotic. On top of horizon RS2, pinnacle shape	
24 25 26	253	buildups are observed. They cover an area of about 200 Km ² .	
27 28	254		
29 30 31	255	Large vertical displacement related to vertical faults is observed north and west	
32 33	256	of the plateau. The northern bounding fault displaces RS8 horizon 2 km upward	
34 35 36	257	and locally forms a mini-basin along RS12 (fig. 5). The faults to the west have	
37 38	258	positive-flower geometries with two anticlines observed along their strike (fig.	
39 40	259	6). ENE-WSW to ESE-WNW normal faults are observed at the easternmost STP	
41 42 43	260	(fig. 5) having a displacement of few hundred meters and extend between RS1	
44 45	261	and RS8 horizons. Their strike is ENE-WSW to ESE-WSW.	
46 47 48	262		
49 50	263	Interpretation	
51 52 52	264		
53 54 55	265	From correlation with well data, horizons RS3 to RS7 correspond to Top Jurassic,	
56 57	266	Top Hauterivian, Top Aptian, Top Albian and Top Cennomanian. As RS8 horizon	
วช 59 60	267	is truncating the Turonian and Senonian units as well as deeper units to the west,	
-	268	it is believed to be the Senonian unconformity horizon (e.g. Hawie <i>et al.</i> , 2013).	
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269	The thickness between RS3 and RS2 is 1.5 to 2 Km, slightly higher than the total
270	expected thickness of the Jurassic unit south of Lebanon (Nader et al., 2016;
271	Dubertret, 1955). Horizon RS2 exhibits a strong impedance contrast, probably
272	indicating a transition between primarily dolomite succession to evaporites.
273	Therefore, RS2 is likely the top of the mid Triassic. The thickness between RS2
274	and RS1 is 1 to 1.5 km in accordance with the expected thickness of the Triassic
275	in Lebanon (Nader <i>et al.</i> , 2016; Beydoun and Habib, 1995) and therefore RS1 is
276	likely the base Triassic. This interpretation points to an extension of the broad
277	geometries observed onshore to the Levant margin offshore with possible lateral
278	facies changes expected away from the coast.
279	
280	The interpretation of the Tertiary units is adopted from Hawie <i>et al.</i> (2014) in

281 which horizons RS9 to RS13 correspond to the Eocene Unconformity, Base 282 Miocene, Base mid Miocene, Base Messinian and Base Pliocene respectively. 283 These units are overlying the Mesozoic units found eastward and are onlapping 284 on the Senonian Unconformity horizon, while to east and closer to the shoreline, 285 the Mesozoic is directly overlain by the Pliocene and the Messinian unit is not 286 observed in seismic data. This likely indicates an existing topographic high prior 287 to the deposition of the Tertiary unit. The westward seismic facies variation 288 observed in the Jurassic and Cretaceous units could be interpreted as talus 289 deposits originating from the carbonate platform in the East. Overlying the RS2 290 horizon, the pinnacle shape geometries could consist of local build-ups or 291 isolated carbonate mounds, though it is challenging to assess their true nature 292 from seismic data alone.

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294	The large vertical displacement observed on the ENE trending northern
295	bounding fault, referred to as the Saida fault, is likely related to an old Mesozoic
296	extensional regime. Ghalayini et al. (2014) argues that this fault is reactivated
297	into a dextral strike-slip in the Late Miocene due to the en-echelon anticlines
298	observed in the upper Miocene unit. Onshore, the Saida fault is correlated with
299	the passage of the Damour fault zone, which consists of a deformation zone of
300	multiple ENE-WSW faults, separating Mount-Lebanon into two different
301	compartments. It has been suggested that both the Saida and the Damour faults
302	are the westward continuation of the Jhar fault in Syria due to the similar trend,
303	evolution history and crustal configuration north and south of these faults
304	(Ghalayini <i>et al.</i> , 2017). Therefore, it is likely that the STP also marks a crustal
305	transition and could be underlain by a continental crust (e.g. Ghalayini et al.,
306	2014). The western bounding faults displace vertically the Mesozoic unit for
307	more than 2 km, also suggesting an older extensional episode prior to the
308	Cenozoic. The positive flower structures and the folding in the Tertiary units
309	might indicate a transpressive regime starting in the Late Miocene times. The
310	ENE-WSW to ESE-WNW normal faults documented at the easternmost STP (fig.
311	5) are similar to faults well documented in southern Mount Lebanon (Homberg
312	et al., 2009; Homberg et al., 2010). It is very likely that these faults belong to the
313	same fault family as the ones documented onshore and therefore were active
314	during the Cretaceous times (e.g. Homberg et al. 2009)

- 315 Main geological domains
- 316

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317	Based on the available geological data and on the new interpretation of the
318	margin, the Lebanese onshore/offshore area is differentiated into four geological
319	domains, having distinct sedimentological and structural features: (1) the distal,
320	deeper basin, (2) The Lattakia Ridge, (3) the Levant Margin and (3) the onshore
321	(fig. 7). The following sub-sections describe the main geological features of these
322	domains and are as such a review of the available literature. The lithostragraphic
323	column of the Levant region summarizes the stratigraphy, structures and
324	expected petroleum systems (fig. 8).
325	
326	The Deep Basin
327	
328	It has formed on an attenuated crust (Inati et al., 2016) during the Triassic and
329	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

331 thickness, overlying a Mesozoic succession (Gardosh and Druckman, 2006;

Hawie et al., 2013; Roberts and Peace, 2007). The main structural features 332

prevalent in this domain are the normal faults and the NE trending anticlines. 333

334

335

330

Stratigraphic setting

336

337 Nine horizons were identified in the Levant basin offshore Lebanon in seismic

338 data and correlated with nearby wells (Hawie et al., 2013). They are believed to

339 correspond to the Mid Jurassic, Jurassic-Cretaceous boundary, Senonian

340 unconformity, Eocene unconformity, Base Miocene, Base mid Miocene, Base

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341	Messinian and Base Pliocene. The seismic packages are defined by their large-
342	scale reflection configurations, impedance contrasts, specific stratigraphic
343	contacts with their lower and upper bounding surfaces, stratal terminations and
344	overall seismic facies. As the pre-Tertiary units in the deep basin were not drilled
345	elsewhere in the Levant basin, it is very challenging to separate and seismically
346	characterize the Mesozoic strata in this domain. The Cenozoic units, such as the
347	Eocene, Oligocene-Miocene, Messinian and Pliocene, possess higher certainty
348	and are laterally continuous throughout the Levant basin.
349	
350	A mixed carbonate-siliciclastic system characterizes the stratigraphy of the deep
351	basin. The documented units consist of Mesozoic rocks, possibly deep-water
352	carbonates or clastics, below the Senonian unconformity. The overlying Cenozoic
353	consists of several units starting with the undercompacted shales of Paleogene
354	age (Montadert et al., 2014). The Oligo-Miocene units consist of siliciclastic
355	materials deposited as a result of marginal uplift and sea-level lowstands during
356	the late Eocene and Oligocene (Haq and Al-qahtani, 2005) which have led to
357	erosion on the margin and clastic deposition in the basin (Gardosh et al., 2008).
358	Hawie et al. (2013) documented the presence of canyons incising the margin
359	within the middle-upper Miocene offshore northern Lebanon, together with
360	various characteristics of deep-water sedimentary environments such as
361	channels, levees and sheeted turbidite lobes towards the distal basin.
362	

363 The thick Oligo-Miocene succession in the Levant Basin can be explained by364 considerable sedimentary flux originating from a proto Nile (Steinberg *et al.*,

365 2011) in which distal turbidites and basin floor fans could extend as far as the

366	offshore Lebanon (Dolson <i>et al.</i> , 2005; Hawie <i>et al.</i> , 2013). However, it was
367	shown that a multi-source system better describes the filling of the basin based
368	on forward stratigraphic modelling constrained by seismic, well and field data
369	(Hawie et al., 2015). Therefore, it is most likely that the filling was also
370	accomplished by erosion from the eastern margin together with provenance of
371	sediments from the north, mainly from the Lattakia region in Syria. Overlying the
372	Oligo-Miocene, the Messinian unit is a ${\sim}1.7$ km thick evaporitic sequence
373	deposited as a result of the sequestration of the Mediterranean Sea at the end of
374	the Miocene and contains mass transport complexes at the base, clastic materials
375	intercalations and halite (Gorini <i>et al.</i> , 2015). A return to a pelagic/hemi-pelagic
376	sedimentation is attested during the Pliocene with the deposition of deep-water
377	turbidites in the basin (Hawie <i>et al.</i> , 2013).
378	
379	Structural setting
380	
381	NE trending anticlines are documented in the deep basin and are 5 to 15 km long
382	structures deforming the Oligo-Miocene units only and detaching in the Eocene
383	unit (fig. 9). Ghalayini <i>et al.</i> (2014) argues that these anticlines were folded
384	immediately prior to, or at the onset of the Messinian salinity crisis due to
385	absence of growth strata in the pre-Messinian units, and erosion of the anticlinal
386	crest along the base Messinian horizon. They were formed due to regional
387	geodynamics caused by the collision and suturing of Arabia with Eurasia. In the
388	southern Levant, similar trending anticlines were formed and are overlying
389	deep-seated Mesozoic extensional structures (Gardosh and Druckman, 2006). It
390	is not clear if the anticlines offshore Lebanon are overlying deeper reactivated

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391 structures, but thickness variations below the ones found closer to the margin
392 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 (Ghalavini 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).

409 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.

415	
416	Stratigraphic setting
417	
418	The stratigraphy in this domain is similar to the rest of the Levant basin, albeit
419	with different thicknesses of units, especially to the west of the ridge itself. The
420	same horizons in the deep basin are also documented along the Lattakia Ridge.
421	The Late Cretaceous convergence has resulted in a depocenter in the lower
422	Tertiary in this region evidenced by thicker Eocene and Oligocene units south
423	and south-east of the Lattakia Ridge (Hawie <i>et al.</i> , 2013). The Miocene unit,
424	however, is thinning considerably and reaches up to 1 km in total thickness. It is
425	suggested that the proximity to a northern sedimentary source, i.e. from Syria,
426	could result in coarser sediment and more clastic material in the Oligo-Miocene
427	unit of this domain, possibly pointing to better reservoir qualities (Hawie et al.,
428	2015).
429	
430	
431	Structural setting
432	
433	The Latakia Ridge consists of a series of south-east verging thrusts forming
434	prominent NE trending narrow structures and having a profound bathymetric
435	expression (fig. 11). Several anticlines are found adjacent to the Lattakia ridge.
436	These are symmetrical NE-trending structures, which in the Oligo-Miocene units
437	appear very similar to compressional anticlines, while in the deeper Eocene and
438	Mesozoic unit they consist of deep-seated SE verging thrusts with steep SE limbs
439	(fig. 11). Back thrusts are documented along this ridge and are believed to have

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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.

444 The Levant margin

445

446 The Levant margin domain covers the area adjacent to the Lebanese shoreline 447 and comprises the Saida-Tyr plateau, a small narrow strip in front of Beirut, and 448 a larger platform north of Lebanon (fig. 7). It is differentiated from the Cenozoic 449 deeper basin by its thick Mesozoic carbonate succession on top of which the 450 Cenozoic units are pinching out and onlapping. It is generally acknowledged that 451 the Levant margin encompasses the onshore domain in Lebanon, including 452 Mount Lebanon (Nader 2011). However, for the purpose of this paper, we 453 differentiate the Levant margin from the inner onshore domain (i.e. Mount 454 Lebanon and the Bekaa Valley) as the depositional setting and associated 455 petroleum systems are expected to be different (Hawie et al., 2014; Bou Daher et 456 al., 2016; Bou Daher et al., 2015; Nader, 2014). 457 458 Stratigraphic setting 459

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

463 updated interpretation of the expected stratigraphy of Levant margin is provided464 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 Ghalavini *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).

483 The onshore domain

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

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487	the margins of the Levant and the Palmyra Basins, which have similar ages and
488	tectonic histories (Ghalayini <i>et al.</i> , 2017; Nader, 2014). Therefore, it has been
489	stated that the Lebanese ranges are part of the Palmyra Basin due to the large
490	resemblance between the structural features, the similar crustal configuration
491	and the analogous stratigraphic intervals (Ghalayini et al., 2017; Beydoun and
492	Habib, 1995; Nader, 2014), yet the Lebanese ranges have been further affected
493	by the passage of the LFS in the Late Miocene and Pliocene. The main folding
494	phase of the Palmyrides and the initial uplift of Mount Lebanon, took place
495	during the Late Oligocene or Early Miocene (Brew <i>et al.</i> , 2001; Sawaf <i>et al.</i> , 2001;
496	Chaimov <i>et al.</i> , 1992; Beydoun, 1999; Hawie <i>et al.</i> , 2014; Ghalayini <i>et al.</i> , 2017).
497	
498	Stratigraphic setting
499	
500	The documented units observed in outcrops range from the mid-Jurassic to the
501	Upper Cretaceous in Mount Lebanon, with Paleogene and Neogene sediments
502	closer to the shoreline and in the Bekaa valley. Pre-Jurassic units are not exposed
503	onshore. Nevertheless, correlation with the geology of the Syrian Palmyra basin
504	allowed suggesting that the Triassic sequence is expected to extend westward
505	and is thicker in Lebanon (Beydoun and Habib, 1995). This is based on extensive
506	deep exploration wells and seismic data in Syria (Sawaf <i>et al.</i> , 2001; Chaimov <i>et</i>
507	<i>al.</i> , 1993; Brew <i>et al.</i> , 2001) as well as an old electro-resistivity survey that
508	indicated the presence of a conductive unit located at 650m below the oldest
509	outcropping Jurassic outcrop (Renouard, 1955) which was attributed to a
510	potential Triassic evaporate layer (Beydoun, 1977; Beydoun and Habib, 1995).
511	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.

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536	The Cretaceous sedimentary cycle starts with deposition of the Hauterivian
537	Chouf sandstone formation (Maksoud <i>et al.</i> , 2014; Walley, 1997). This unit is
538	between 5-300 m thick across Lebanon and thins northward reflecting possible
539	clastic provenance from the southeast. It consists of ferruginous brown to white
540	sandstone with clays, coaly shales and volcanics. It was deposited under a fluvial
541	to deltaic littoral environment. The overlying Barremian Abieh formation varies
542	between fossiliferous limestone, marls and sandstones and represents a
543	transition between the fluvial Chouf and the overlying shallow marine late
544	Barremian to Aptian units. The latter is a conspicuous cliff-forming formation
545	clearly visible throughout all of Lebanon, with a thickness of about 50 m
546	(Maksoud <i>et al.</i> , 2014). It consists of a single massive grey limestone. Small scale
547	rudist and stromatoporoidal reef buildups are visible in some locations. It
548	represents a sequence of shallow marine transgressive carbonate facies linked to
549	early Aptian eustatic rise. The overlying Albian corresponds to thin bedded
550	carbonates, marls and terrigenous sand. It represents a brief return to
551	terrigenous clastic deposition, in a general marine setting, before sea levels
552	caused renewed carbonate deposition.
553	
554	The upper part of the Cretaceous and early Paleogene is almost entirely
555	composed of carbonate. The Cennomanian Sannine formation is 600 m thick and
556	consists of medium to thick bedded shallow water limestones and marly
557	limestone. This sequence thickens to the west with increasing thin bedded chalk
558	and cherty pelagic sediments along the coast. It is possible that these lateral

- 559 facies change and thickness increase could point to a shift from shallow water
- 560 deposition in the east, to deeper environments westward dominated by

561	carbonate turbidite deposits (Hawie <i>et al.</i> , 2014). The overlying Turonian unit is
562	200-300 m thick and represents a continuation of the carbonate deposition of
563	the Cennomanian and is characterized by thin finely bedded, chalky micrites and
564	cherts with abundance of Hippurite fossils. The Senonian/Campanian-
565	Maastrichtian Chekka formation consists of very dark grey to white sequence of
566	chalks and marly limestone units. Its thickness ranges from 100 to 500 m with
567	the thickest succession documented in the southern Bekaa valley and is made of
568	chalk and marly limestone. It has a very good source rock potential as it contains
569	organic rich argillaceous limestone with TOC values between 2 and 10% (Bou
570	Daher <i>et al.</i> , 2014; Bou Daher <i>et al.</i> , 2015).
571	
572	The overlying Paleocene units are 300 m thick and consist of chalky limestones
573	and marls. Nummulitic middle Eocene limestone have been documented in the
574	Bekaa (Dubertret, 1955) where they reach up to 900 m in thickness (Hawie <i>et al.</i> ,
575	2014) and in south of Lebanon. The upper Eocene and Oligocene units are absent
576	in all of Lebanon due to uplift and erosion of the margin during the Early
577	Miocene compressive folding event (Walley, 1998), except of one outcrop south
578	of Lebanon (Müller et al., 2010). The middle Miocene is outcropping and consists
579	of continental lacustrine facies in the Bekaa in contrast with the Miocene open
580	marine facies along the margin (Hawie <i>et al.</i> , 2014; Dubertret, 1955). The
581	Pliocene in this area is referred to as the Zahle formation (Nader et al., 2016) and
582	corresponds to clastic deposits, breccias, silt, marl and lacustrine limestone,
583	overlain by alluvial fan conglomerates (Dubertret, 1955).
584	

Structural	setting
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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 lhar 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

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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).

616

617 Several ENE-WSW, currently active, dextral strike-slip faults are documented

618 along Mount Lebanon (Gedeon, 1999) and extend to the Levant margin offshore

619 (Ghalayini et al. 2014). These faults have most likely nucleated during the

620 Mesozoic as normal faults during the breakup of Pangaea and were subsequently

621 reactivated during the Neogene compression (Collin et al. 2010; Ghalayini et al.

622 2014). Similar faults are also found in the Palmyra basin further east.

623 Petroleum Systems

624 Source rocks and maturity

625

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.

631 The deep basin and Lattakia Ridge

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633	Geochemical analysis of gas samples from Middle Jurassic to Pliocene reservoirs
634	along the southeastern margin of the Levant Basin proved the presence of five
635	thermogenic and biogenic sources (Feinstein et al., 2002). Offshore Lebanon, the
636	Permian and Triassic thermogenic sources – if present – are believed to generate
637	petroleum between 90 and 34 Ma in the deep basin (Bou Daher et al., 2016). The
638	Upper Jurassic Kimmeridgian thermogenic source rocks have most probably
639	generated oil between the Late Cretaceous and the Late Miocene. The Upper
640	Cretaceous Campanian might constitute good thermogenic source rocks which
641	have produced hydrocarbons between 34 and 16 Ma. However, it is expected
642	that in the deep basin, the Campanian source rock quality and TOC content
643	would decline (Bou Daher <i>et al.</i> , 2015). Paleocene and Eocene thermogenic
644	source rocks have probably produced hydrocarbons during the Oligocene and
645	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

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658	methane is believed to have been expelled during the Messinian and is currently
659	ongoing (Bou Daher et al., 2016). Based on thermal history modelling, Bou Daher
660	et al (2016) predicted that a thickness of 700 to 1500m of sub-Messinian
661	Miocene succession is within the biogenic zone at present day. Detailed
662	information on source rock kinetics, maps of source rock maturation and
663	transformation ratios are presented in Bou Daher et al. (2016).
664	
665	The Levant margin and onshore
666	
667	Permian and Triassic source rocks – if present – would have generated
668	hydrocarbon between 75 Ma to present day along the margin and onshore (Bou
669	Daher et al., 2016). In Syria, the upper Permian/Lower Triassic Amanus
670	dolomites are very good source rocks for Triassic Reservoirs in the Palmyrides
671	(Barrier et al., 2014) and might therefore be as good in the Levant margin and
672	onshore. Similarly, the Upper Jurassic Kimmeridgian source rocks most probably
673	generated oil between the Oligocene to the present day along the margin (Bou
674	Daher et al., 2016) with minor amount on the onshore in the Late Miocene which
675	were most probably washed out by meteoric waters (Nader and Swennen,
676	2004a). However, in the deeply buried Jurassic under the Bekaa Valley, the
677	Kimmeridgian source rocks are in the oil window today.
678	
679	The Campanian source rocks appears not to have been buried deep enough in
680	Mount Lebanon to generate hydrocarbon. In the Bekaa valley and along the
681	margin, however, the Campanian is in the maturity window and minor

682 generation might have occurred (Bou Daher *et al.*, 2015). Geochemical data

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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 \sim 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.

707	In the northernmost part of the deep basin and in the Lattakia Ridge domain,
708	seismic facies interpretation (Hawie <i>et al.,</i> 2013) point that the main reservoirs
709	are possibly located in the upper Miocene and suggest an increased sand content
710	at the base Oligocene. The fact that the normal faults have smaller heights and
711	displacement in this area point that there is a barrier to vertical fault
712	propagation (Ghalayini et al., 2014). As the faults do not propagate to the upper
713	Miocene and lower Oligocene units, it is likely that the latter units consist of
714	incompetent lithologies which might be attributed to coarse clastics or sand. The
715	provenance of clastic material in this area is most likely from a northerly source,
716	probably from the Lattakia region in Syria. In addition, the erosion of Cretaceous
717	to Miocene carbonate platforms contemporaneously with Mount Lebanon's
718	accelerated uplift in the Late Miocene/Pliocene, could lead to more
719	conglomeratic material from the northern Lebanese ranges (Hawie et al., 2015;
720	Hawie <i>et al.</i> , 2013).
721	
722	Along the Levant margin, the Jurassic carbonate platform is far from meteoric
723	influence prevalent onshore (Nader and Swennen, 2004a). This fact, together
724	with the predicted presence of fracture-associated hydrothermal dolomites
725	could form effective reservoirs in the Jurassic carbonate platforms. The Lower
726	Cretaceous Chouf sandstones are correlated to the Rutbah formation in Syria,
727	which constitutes the principal reservoir in the Euphrates Graben (Barrier et al.,
728	2014; Sawaf et al., 2001), and to the Helez formation in the southern Levant,
729	which constitutes the reservoir for the Helez field (Shenhav, 1971). Therefore,

- the Chouf sandstone might form good reservoirs in the margin offshore. Other
- via the Cretaceous, such as the Albian and the Aptian, could form good

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732	reservoirs consisting of isolated reefal buildups similar to the Eratoshtenes
733	margin (Hawie <i>et al.,</i> 2013; Montadert <i>et al.,</i> 2014; Esestime <i>et al.,</i> 2016).
734	Younger reservoirs along the Levant margin consist of the lateral ends of the
735	Oligo-Miocene clastic units onlapping on the Mesozoic carbonate platforms.
736	These reservoirs are believed to be of good quality due to their proximity to the
737	Mount Lebanon sedimentary source than their deep basin's equivalent. Miocene
738	reefs are also documented on paleo-highs along the northern margin and could
739	provide good reservoirs (Hawie <i>et al.,</i> 2013; Hawie <i>et al.,</i> 2014).
740	
741	In the onshore domain below Mount Lebanon, the expected reservoirs are pre-
742	Jurassic. All exposed units are subject to severe weathering and influx of
743	meteoric waters, strongly deteriorating the reservoir quality (Nader and
744	Swennen, 2004a). Good reservoirs could belong to the Permian to lower Triassic
745	Amanus sand formation consisting of shales interbedded with channel
746	sandstones and siltstone beds together with the lower to mid Triassic
747	Kurrachine unit consisting of dolomite and sandy intervals. These units are
748	important oil and gas reservoirs in the Palmyrides (Barrier et al., 2014) and in
749	the southern Levant's as they are equivalent to the Mihilla formation (Gardosh
750	and Tannenbaum, 2014). In the Bekaa region, the reservoirs are believed to be
751	Jurassic limestones protected from meteoric invasion, Lower Cretaceous
752	sandstone of the Chouf formation, Upper Cretaceous Senonian fractured
753	carbonates and Eocene nummulitic limestone.
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756	In the deep basin, the Paleocene/Eocene package is believed to form a strong
757	impermeable unit sealing the deeper reservoirs and preventing vertical
758	hydrocarbon migration from deeper intervals. The consistent detachment of
759	normal faults on the Eocene unconformity horizon (fig. 10) together with the
760	chaotic seismic facies and weak amplitudes observed in the Paleocene/Eocene
761	unit point that the latter is likely constituted by shales (Kosi et al., 2012) and
762	highly overpressured rocks (Montadert et al., 2014). In the Oligo-Miocene unit,
763	intra-formational shale or clay may constitute good seals for Miocene reservoirs
764	similar to the Tamar and other fields in the south (Gardosh <i>et al.</i> , 2008). In this
765	unit, the normal faults could either form good lateral seals at present day or act
766	as conduits to hydrocarbon migration. In fact, the maximum documented
767	displacement on these faults is around 350 m, causing a large offset of reservoir
768	against seal lithologies, increasing the likelihood of impermeability along fault
769	planes. In contrast, the same faults are observed to cross-cut the Tamar,
770	Aphrodite and Leviathan fields in the southern Levant basin but they do not
771	seem to affect the continuity of the reservoirs (Gardosh and Tannenbaum, 2014).
772	Therefore, this juxtaposition relationship still needs to be checked during
773	drilling. The shallowest cap rocks in the basin are the Messinian salts forming up
774	to 1500 m of evaporites and are as such considered to be an optimal seal if
775	underlying reservoirs are present.
776	
777	The cap-rocks in the Lattakia Ridge are the same as the ones in the deep basin. In
778	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
- 780 Lattakia ridge itself and diminishes south-eastward toward the deep basin. In

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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

801 meteoric influence since the uplift of Mount Lebanon (Nader, 2011). They are

802 well documented to provide a regional seal in the Palmyrides (Barrier *et al.*,

803 2014; Sawaf *et al.*, 2001) and in the southern Levant with the equivalent

804 Saharonim and Mihilla Formations (Gardosh and Tannenbaum, 2014). In the

805 Bekaa, intra-formational volcanic, marly and shaly units of Jurassic and

806 Cretaceous age could seal the Jurassic and Cretaceous reservoirs. The Paleocene
807 calcareous shales might form a good seal as well as a protection to meteoric
808 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.

828 In the Lattakia Ridge domain, the trap type is mostly structural with symmetrical829 anticlines in the Cenozoic unit underlain by deep-seated SE verging thrust faults,

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830	providing excellent four-way closures. These anticlines are found surrounding
831	the Lattakia Ridge as of the Late Cretaceous time, but the ridge itself is a poor
832	trap due to the lack of closure as a result of intense uplift and erosion of the
833	Cenozoic units. Migration of hydrocarbons from source to reservoirs must have
834	happened through the numerous faults and fractures associated with the intense
835	deformation of the Lattakia ridge since the Late Cretaceous times. Deformation
836	continued till modern day indicating that several faults are still active and
837	implying that they could form effective migration pathways.
838	
839	Along the Levant Margin, trap mechanism is mostly stratigraphic within the
840	Mesozoic carbonate platform. Other stratigraphic traps include pinchout of the
841	Early Cretaceous sand sealed by Cretaceous carbonates in addition to pinchout of
842	Oligo-Miocene sandy units onto shallower Mesozoic strata and sealed by intra-
843	Miocene shale. Structural traps include inversion structures, such as reactivated
844	ENE-WSW strike-slip faults (e.g. Ghalayini et al. 2014) forming 4-way dip
845	closures below the Messinian. Along the margin, pre-existing and inverted faults
846	may have played an important role in hydrocarbon migration from the deep
847	Mesozoic source rocks to shallower reservoirs. As these faults were active
848	throughout much of the geological time, they might have been permeable during
849	the Mesozoic and Cenozoic times.
850	
851	Onshore, the traps are mostly of structural type, consisting of 4-way dip closure
852	anticlines formed by the transpression along the LFS (Nader, 2014; Nader et al.,
853	2016). Potential large traps are the Qartaba anticline (Nader, 2014; Nader, 2011)
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together with other large structures, such as the Sir-Ed-Denie, Barouk-Niha and 854

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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

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879	onshore analogues in Lebanon (Nader and Swennen, 2004a; Nader and Swennen,
880	2004b) and Syria (Barrier et al., 2014). As they are sealed from meteoric
881	invasion, they are very likely not affected by flushing and so are good reservoirs
882	(e.g. Nader and Swennen 2004a). Hawie <i>et al.</i> (2013) demonstrate the presence
883	of reefal buildups onshore Lebanon based on extensive field observations and
884	analysis and suggest the likely continuity of such buildups to the margin
885	offshore. This could make the potential reservoir within the Levant carbonate
886	sequence equivalent to the Eratosthenes ones and therefore provide effective
887	analogues for the Zohr (e.g. Esestime et al. 2016). An attractive aspect of the
888	Levant margin is the strong thermogenic potential in this domain which could
889	invoke liquid hydrocarbon accumulations.
890	
891	This new interpretation of the margin reduces risk in exploration as it provides
892	new elements for the petroleum system and hence new potential prospects. The
893	Lower Cretaceous sandstone is identified in the northern margin,
894	stratigraphically trapped between the Jurassic and Cretaceous carbonate talus.
895	This unit offshore appears to be thicker than its equivalent onshore (e.g.
896	Dubertret, 1955; Bellos, 2008). This could be related to an established
897	basin/margin differentiation since at least the Early Cretaceous in which a larger
898	accommodation space is available for the Nubian sand to be deposited offshore.
899	Hawie et al. (2013) indeed argues for a general westward facies variation in
900	Mesozoic sequences caused by a transition to deeper basinal environments.
900 901	Mesozoic sequences caused by a transition to deeper basinal environments.

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> 904 from this same unit in the southern Levant (Shenhav, 1971; Gardosh and 905 Tannenbaum, 2014), suggest that similar prospective plays might well exist 906 offshore Lebanon. In fact, DHI's such as bright spots and a potential flat-spot is 907 observed in seismic data (fig. 13) which invoke hydrocarbon accumulations, 908 originating from thermogenic source rocks. This unit extends along the entire 909 margin offshore Lebanon and therefore could be associated to large prospects. 910 The challenge, however, is the depth of this play being around 8 km in some 911 locations, resulting in potentially high pressure reservoirs.

912

913 Additional DHI's, such as flat spots, can also be observed within the Oligocene 914 unit along the Levant margin (fig. 14). With the relatively better reservoir quality 915 expected in this location (Hawie *et al.*, 2015), it is very likely that Oligo-Miocene 916 pinchout prospects could also be promising. As the flat spot is located below the 917 Base Miocene horizon, this indicates that the seal might be around the Base 918 Miocene. This could point that towards the margin, the base Miocene is probably 919 be associated with shaly/marly or fine grained facies and transitions to coarser 920 grains or sandy facies toward the basin.

921 Significance of geological domains

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

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928 provide here an original subdivision of the Lebanon onshore/offshore into four929 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.

938 Previous studies have grouped the Lattakia Ridge and the deep basin into one 939 domain termed the 'offshore' in which a similar petroleum system is expected 940 (Nader and Swennen, 2004b). More detailed analysis, however, suggests 941 otherwise. The source rocks charging the reservoirs in the Lattakia Ridge are 942 supposed to be both thermogenic and biogenic, while in the deep basin the 943 biogenic ones are dominant (Bou Daher et al., 2016). In addition, the traps are of 944 Late Cretaceous age and the reservoirs intervals are unlikely to consist of the 945 Tamar sands but could belong to other intervals (Ghalayini et al., 2014; Ghalayini 946 et al., 2016; Hawie et al., 2015). Such geological variations necessitate to 947 associate the Lattakia Ridge to an independent domain of the deep basin. 948 949 The onshore domain have been discussed abundantly and the expected 950 petroleum system is well described from regional correlations and field studies (e.g. Beydoun, 1977; Beydoun and Habib, 1995; Nader and Swennen, 2004b; 951

Nader, 2014; Hawie *et al.*, 2014). Although the expected source-reservoir

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953 configurations differ between the Bekaa valley and Mount Lebanon, they have 954 been grouped into one domain. They both are believed to contain a good 955 thermogenic system (Bou Daher et al., 2016) in which the Triassic petroleum 956 system is dominant. In the Bekaa, a working Cretaceous petroleum system might 957 also be effective beneath the quaternary cover (e.g. Nader, 2014; Beydoun, 958 1977). 959 960 Four petroleum system charts have been compiled for the Lattakia, deep basin, 961 margin and onshore domains (figs. 15-16). They show the variable petroleum 962 system elements expected in each. The reservoirs, seals, traps and source rock 963 maturity have been discussed in previous sections and are summarized in each 964 chart. In the Lattakia ridge domain and the Levant margin, a mixed 965 thermogenic/biogenic charge is feeding the reservoirs as of the Late Cretaceous 966 to modern time, while in the deep basin a dominantly biogenic system is 967 expected. Onshore, only thermogenic sources are active and charging the reservoirs as of the late Tertiary. 968

- 969 Regional analogues
- 970

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

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976 provide a few insights on the similarities between onshore and probably similar977 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 Oartaba 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.

997 Although the effect of the Triassic detachment layer is not observed offshore, the
998 Eocene unconformity could possess a similar decoupling effect. Therefore, the
999 thin-skinned anticlines of the Palmyrides are very likely structural analogues for
1000 the offshore anticlines. In addition, both the offshore and Qartaba anticlines are

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1001	cross-cut by the same ENE trending dextral strike-slip faults documented along
1002	the Levant margin (Ghalayini et al., 2017). This increases the structural
1003	similarities of these anticlines and insinuates a similar timing, being in the Late
1004	Miocene prior to the effect of the strike-slip faults (e.g. Ghalayini et al., 2014).
1005	
1006	The exploration implications on the structural style of the anticlines is profound
1007	as it affects the subsurface closures and location of faults. The uncertainties are
1008	probably less offshore with the availability of 3D seismic data, but the challenges
1009	persist for onshore anticlines. The adopted structural style helps predicting the
1010	likely location of subsurface traps and directly affects the proper positioning of
1011	the wells during exploration. Therefore, using analogues to help exploration
1012	offshore and onshore Lebanon could be of a great value and would reduce
1013	uncertainty significantly.
1014	
1015	Lessons learnt from exploration onshore
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1010	In the onshore domain, evoloration wells have been drilled with total denths
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1018	ranging from 1,421 m to 3,065 m (Beydoun and Habib, 1995). The deepest
1019	formations reached range in age from Late Cretaceous to mid-Jurassic. In most of

- 1020 these wells, the main reservoirs were water-flushed due to erosion leading to
- 1021 bad and ineffective seals, direct communication with elevated meteoric recharge
- 1022 areas in the high Lebanon and Anti-Lebanon Mountains, or their proximity to
- 1023 major faults (Nader and Swennen, 2004a; Beydoun and Habib, 1995). Therefore,
- 1024 it is clear that prospective units must be pre-Jurassic with petroleum system

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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.

1029 Some of the important lessons acquired for future explorers of the onshore 1030 Lebanon are the followings: (i) most importantly, the wells must reach the most 1031 promising units, being the Lower Triassic reservoirs that are proven in the 1032 Palmyrides and (2) analogues must be used to aid exploration – since no 1033 adequate drilling is available to date. Still hydrocarbon shows were noted in 1034 shallow wells, indicating that a working petroleum system exists. This has also 1035 been observed offshore with the numerous DHI's, gas chimneys and working petroleum system elements, which are all encouraging additional exploration. 1036 1037 1038 To minimise the risk, it is primordial to use modern techniques to properly 1039 characterise the prospects and choose the best drilling location. These involve

1040 (1) reliable seismic data aided by other geophysical data such as gravity,

1041 magnetic and electrical surveys to image the subsurface at depth, (2) usage of
1042 satellite imagery and remote sensing to carefully map the structure at surface
1043 and draw new geological and facies maps over each prospect, and (3) usage of
1044 new modelling techniques in order to visualise and reconstruct the structure at
1045 depth. These techniques will substantially reduce the risk of the petroleum
1046 prospects in the onshore domain. Promising discoveries can be made if new play
1047 concepts are developed and deeper units are targeted in drilling.

Conclusions 1048

1 2 3		
4 5	1048	Conclusions
6 7 8	1049	
9 10	1050	Interpretations of key seismic reflection profiles along the Levant margin
11 12 13	1051	offshore Lebanon together with a comprehensive overview based on recently
14 15	1052	achieved integrated research projects have resulted inan improved
16 17 19	1053	understanding of the geology of this area and of its petroleum exploration
19 20	1054	potential. Four geological domains have been identified, and petroleum system
21 22	1055	charts were compiled for each summarizing the main source rocks, reservoirs,
23 24 25	1056	seals and traps:
26 27	1057	
28 29 30 31 32	1058	• The deep basin: characterised by predominantly clastic reservoirs and
	1059	dominated by Oligo-Miocene biogenic source rocks. The structural traps
33 34 35	1060	might be late Miocene four-way dip closures and early Miocene tilted fault
36 37	1061	blocks,
38 39	1062	
40 41 42	1063	• The Lattakia Ridge: characterised by dominantly Oligo-Miocene clastic
43 44	1064	reservoirs and with a mixed biogenic-thermogenic source rock potential.
45 46 47	1065	The traps are Late Cretaceous four-way dip closures.
48 49	1066	
50 51	1067	• The Levant Margin: characterised by Mesozoic carbonate reservoirs
52 53 54	1068	together with Early Cretaceous and Oligo-Miocene clastics, with
55 56	1069	predominantly thermogenic source rocks with possibility of lateral
57 58 59	1070	migration from biogenic source rocks. The traps are mostly stratigraphic.
60	1071	

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3 4	1072	• The onshore: Characterised by Triassic dolomitic, Jurassic and Cretaceous
5 6 7	1073	carbonate reservoirs with thermogenic source rocks in the Lower
8 9	1074	Triassic, Kimmeridgian and Campanian. The traps are mostly four-way
10 11	1075	dip closures.
12 13 14	1076	
15 16	1077	Working petroleum systems are very likely present in Lebanon and should be
17 18 10	1078	encouraging to undertake additional exploration and drilling within these four
20 21	1079	domains. Several lessons can be taken from the wells onshore, which can be used
22 23	1080	to better focus future exploration. Nearby discoveries could provide good
24 25 26	1081	analogue examples for the Lebanese prospects and could help in reducing
27 28	1082	uncertainties, namely onshore. Such analogues are likely found in the
29 30 31	1083	Palmyrides, and if considered, could positively impact exploration success.
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56 57 58 59	1092	References
60	1093	

2		
3 4	1094	BARRIER, É., MACHHOUR, L., and BLAIZOT, M., 2014. Petroleum systems of Syria.
5 6 7 8 9	1095	In L. MARLOW, C. KENDALL, and L. YOSE (Eds.), Petroleum systems of the
	1096	Tethyan region, AAPG Memoir 106, 335–378.
10 11	1097	http://doi.org/10.1036/13431862M1063612
12 13 14	1098	
15 16	1099	BELLOS, G.S., 2008. Sedimentology and diagenesis of some neocomian-
17 18 10	1100	Barremian rocks (Chouf Formation) southern Lebanon. M.S. thesis, American
20 21	1101	University of Beirut, Beirut, Lebanon.
22 23	1102	
24 25 26	1103	BEN-AVRAHAM, Z., GINZBURG, A., MAKRIS, J., and EPPELBAUM, L., 2002. Crustal
27 28 29 30 31 32 33 34 35 36 37 38	1104	structure of the Levant Basin, eastern Mediterranean. <i>Tectonophysics</i> , 346 (1–2),
	1105	23-43. <u>http://doi.org/10.1016/S0040-1951(01)00226-8</u>
	1106	
	1107	BEYDOUN, Z. R., 1977. Petroleum Prospects of Lebanon: Reevaluation. AAPG
	1108	Bulletin, 61 (I), 43–64. <u>http://doi.org/10.1306/C1EA3BF4-16C9-11D7-</u>
39 40	1109	<u>8645000102C1865D</u>
41 42 43	1110	
44 45	1111	BEYDOUN, Z. R., and HABIB, J. G. 1995. Lebanon revisited: new insights into
46 47 48 49 50	1112	Triassic hyrocarbon prospects. <i>Journal of Petroleum Geology</i> , 18 (1), 75–90.
	1113	
51 52 53	1114	BEYDOUN, Z.R., 1999. Evolution and development of the Levant (Dead Sea Rift)
53 54 55	1115	transform system: a historical- chronological review of a structural controversy.
56 57	1116	In: MacNiocaill, C., Ryan, P.D. (Eds.), Continental Tectonics. Geol. Soc. Lond., Spec.
58 59 60	1117	<i>Publ.</i> , 164, 239-255 <u>http://doi.org/10.1144/GSL.SP.1999.164.01.12</u>
	1118	

1		
2 3 4	1119	
5 6 7 8 9	1120	BOU DAHER, S., DUCROS, M., MICHEL, P., NADER, F. H., and LITTKE, R., 2016. 3D
	1121	thermal history and maturity modelling of the Levant Basin and Margin. Arabian
10 11	1122	Journal of Geosciences, 17 , 3161. http://doi.org/10.1007/s12517-016-2455-1
12 13 14	1123	
15 16	1124	BOU DAHER, S., NADER, F. H., MÜLLER, C., and LITTKE, R., 2015. Geochemical
17 18 19	1125	and petrographic characterization of Campanian – Lower Maastrichtian
20 21	1126	calcareous petroleum source rocks of Hasbayya, South Lebanon. Marine and
22 23 24	1127	<i>Petroleum Geology</i> , 64 , 304–323.
25 26 27 28 29 30 31 32 33 34 35 36	1128	http://doi.org/10.1016/j.marpetgeo.2015.03.009
	1129	
	1130	BOU DAHER, S., NADER, F. H., STRAUSS, H., and LITTKE, R., 2014. Depositional
	1131	environment and source-rock characterisation of organic-matter rich Upper
	1132	Santonian-Upper Campanian carbonates, northern Lebanon. Journal of Petroleum
37 38	1133	<i>Geology</i> , 37 , 5–24.
39 40 41	1134	
41 42 43	1135	BREW, G. E., BARAZANGI, M., AL-MALEH, A. K., and SAWAF, T., 2001. Tectonic
44 45 46	1136	and Geologic Evolution of Syria. <i>GeoArabia</i> , 6 (4), 573–616.
40 47 48	1137	
49 50	1138	BUTLER, R. W. H., SPENCER, S., and GRIFFITHS, H. M., 1998. The structural
51 52 53	1139	response to evolving plate kinematics during transpression: evolution of the
54 55	1140	Lebanese restraining bend of the Dead Sea Transform. In Holdsworth, R.E.,
56 57 58	1141	Strachan, R.A., Dewey, J.F. (Eds.), Continental transpressional and transtensional
59 60	1142	tectonics, <i>Geol. Soc. Lond., Spec. Publ.</i> 135 , 81–106.
	1143	(doi.org/10.1144/GSL.SP.1998.135.01.06)

1		
3	1144	
4 5	1111	
6 7	1145	CARTWRIGHT, J. A., 2011. Diagenetically induced shear failure of fine-grained
8 9	1146	sediments and the development of polygonal fault systems. Marine and
10 11 12	1147	Petroleum Geology, 28 (9), 1593–1610.
12 13 14	1148	(<u>http://doi.org/10.1016/j.marpetgeo.2011.06.004)</u>
15 16	1149	
17 18 19	1150	CHAIMOV, T. A., BARAZANGI, M., AL-SAAD, D., SAWAF, T., and GEBRAN, A., 1992.
20 21	1151	Mesozoic and Cenozoic deformation inferred from seismic stratigraphy in the
22 23	1152	southwestern intracontinental Palmyride fold-thrust belt, Syria. Geological
24 25 26	1153	Society of America Bulletin, 104 (6), 704–715
27 28	1154	(doi.org/10.1130/0016-7606(1992)104<0704:MACDIF>2.3.CO;2)
29 30 31	1155	
32 33	1156	CHAIMOV, T. A., BARAZANGI, M., AL-SAAD, D., SAWAF, T., and KHADDOUR, M.
34 35 36	1157	(1993). Seismic fabric and 3-D structure of the southwestern intracontinental
37 38	1158	Palmyride fold belt, Syria. AAPG Bulletin, 77 (12), 2032–2047.
39 40	1159	
41 42 43	1160	DAËRON, M., BENEDETTI, L., TAPPONNIER, P., SURSOCK, A. and FINKEL, R.C.,
44 45	1161	2004. Constraints on the post \sim 25-ka slip rate of the Yammoûneh fault
46 47 48	1162	(Lebanon) using in situ cosmogenic 36Cl dating of offset limestone-clast fans:
49 50	1163	Earth and Planetary Science Letters, 227 , 105–119.
51 52 53	1164	(doi:10.1016/j.epsl.2004.07.014)
54 55	1165	
56 57	1166	DAVIES, R. J., IRELAND, M. T., and CARTWRIGHT, J. A., 2009. Differential
ох 59 60	1167	compaction due to the irregular topology of a diagenetic reaction boundary : a
	1168	new mechanism for the formation of polygonal faults. <i>Basin Research</i> , 21 , 354–

1		
2 3 4	1169	359. (doi.org/10.1111/j.1365-2117.2008.00389.x)
5 6 7	1170	
8 9	1171	DOLSON, J. C., BOUCHER, P. J., SIOK, J., and HEPPARD, P. D., 2005. Key Challenges
10 11 12	1172	to realizing full potential in an emerging giant gas province: Nile
13 14	1173	Delta/Mediterranean offshore, deep water, Egypt. In Doré, A. G., Vining, B.A.
15 16 17 18 19 20 21	1174	(Eds.), Petroleum Geology: North-West Europe and Global Perspectives -
	1175	Proceedings of the 6th Petroleum geology conference, Petroleum Geology
	1176	Conferences, 607–624. (doi.org/897.553)
22 23 24	1177	
24 25 26 27 28 29 30 31	1178	DUBERTRET, L., 1955. Carte géologique du Liban au 1/200000 avec notice
	1179	explicative: Beirut, République Libanaise, Ministère des Travaux Publiques, 74
	1180	pp.
32 33	1181	
34 35 36 37 38 39 40 41 42 43	1182	ESESTIME, P., HEWITT, A., and HODGSON, N., 2016. Zohr – A newborn carbonate
	1183	play in the Levantine Basin, East-Mediterranean. <i>First Break</i> , 34 , 87–93.
	1184	
	1185	FEINSTEIN, S., AIZENSHTAT, Z., MILOSLAVSKI, I., GERLING, P., SLAGER, J., and
44 45	1186	MCQUILKEN, J., 2002. Genetic characterization of gas shows in the east
46 47 48	1187	Mediterranean offshore of southwestern Israel. Organic Geochemistry, 33 (12),
49 50	1188	1401–1413. (doi.org/10.1016/S0146-6380(02)00184-5)
51 52	1189	
53 54 55	1190	FREUND, R., GARFUNKEL, Z., ZAK, I., GOLDBERG, M., WEISSBROD, T., DERIN, B.,
56 57	1191	GIRDLER, R. W. (1970). The Shear along the Dead Sea Rift [and Discussion].
58 59 60	1192	Philosophical Transactions of the Royal Society A: Mathematical, Physical and
	1193	Engineering Sciences, 267 (1181), 107–130. (doi.org/10.1098/rsta.1970.0027)

1		
2 3 4 5 6 7 8 9	1194	
	1195	FRIZON DE LAMOTTE, D., RAULIN, C., MOUCHOT, N., CHRISTOPHE, J., DAVEAU,
	1196	W., BLANPIED, C., and RINGENBACH, J. C. (2011). The southernmost margin of
10 11 12	1197	the Tethys realm during the Mesozoic and Cenozoic : Initial geometry and timing
12 13 14	1198	of the inversion processes. <i>Tectonics</i> , 30 , 1–22.
15 16	1199	(doi.org/10.1029/2010TC002691)
17 18 10	1200	
19 20 21 22 23	1201	GARDOSH, M. and DRUCKMAN, Y., 2006. Seismic strati- graphy, structure and
22 23 24	1202	tectonic evolution of the Levantine basin, offshore Israel. In: A.H.F. Robertson
24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43	1203	and D. Mountrakis, (Eds.), Geol. Soc. Lond., Spec. Publ., 260, 201 – 227.
	1204	
	1205	GARDOSH, M., DRUCKMAN, Y., BUCHBINDER, B. and CALVO, R., 2008. The Oligo-
	1206	Miocene deepwater system of the Levant Basin. Geological survey of Israel, 33, 1-
	1207	73.
	1208	
	1209	GARDOSH, M. A., GARFUNKEL, Z., DRUCKMAN, Y. and BUCHBINDER, B., 2010.
	1210	Tethyan rifting in the Levant Region and its role in Early Mesozoic crustal
44 45	1211	evolution. In: Homberg C. and Bachmann M. (Eds), Evolution of the Levant
46 47 48	1212	Margin and Western Arabia Platform since the Mesozoic. Geol. Soc. Lond., Spec.
49 50	1213	<i>Publ.</i> , 341 , 9 – 36.
51 52 53	1214	
54 55	1215	GARDOSH, M., WEIMER, P., and FLEXER, A., 2011. The sequence stratigraphy of
56 57 58	1216	Mesozoic successions in the Levant margin, southwestern Israel: A model for the
58 59 60	1217	evolution of southern Tethys margins. AAPG Bulletin, 95 (10), 1763–1793.
	1218	(doi.org/10.1306/02081109135)

1		
2 3 4	1219	
5 6 7	1220	GARDOSH, M., and TANNENBAUM, E., 2014. Petroleum systems of Israel. In L.
8 9	1221	MARLOW, C. KENDALL, and L. YOSE (Eds.), Petroleum systems of the Tethyan
10 11	1222	region, <i>AAPG Memoir 106</i> , 179–216.
12 13 14	1223	
15 16	1224	
17 18 19	1225	GARFUNKEL, Z., 1998. Constrains on the origin and history of the Eastern
20 21	1226	Mediterranean basin. <i>Tectonophysics</i> , 298 (1–3), 5–35. (doi.org/10.1016/S0040-
22 23 24	1227	1951(98)00176-0)
25 26	1228	
27 28 20	1229	GEDEON, M., 1999. Structural analysis of latitudinal faults in the Mount Lebanon
30 31	1230	north of Beirut: their kinematic and their role in the tectonic evolution of
32 33	1231	Lebanon. Master's thesis, American University of Beirut, Beirut, Lebanon.
34 35 36	1232	
37 38	1233	GHALAYINI, R., DANIEL, JM., HOMBERG, C., NADER, F. H., and COMSTOCK, J. E.,
39 40 41	1234	2014. Impact of Cenozoic strike-slip tectonics on the evolution of the northern
42 43	1235	Levant Basin (offshore Lebanon). <i>Tectonics</i> , 33 (11), 2121–2142.
44 45 46	1236	(doi.org/10.1002/2014TC003574)
47 48	1237	
49 50 51	1238	GHALAYINI, R., HOMBERG, C., DANIEL, JM., and NADER, F. H., 2016. Growth of
51 52 53	1239	layer-bound normal faults under a regional anisotropic stress field. In Childs, c.,
54 55	1240	Holdsworth, R.E., Jackson, C.A.L, Manzocchi, T., Walsh, J.J., Yielding, G. The
วช 57 58	1241	Geometry an Growth of normal faults. <i>Geol. Soc. Lond., Spec. Publ.</i> 439.
59 60	1242	(doi.org/10.1144/SP439.13)
	1243	

2		
3 4	1244	GHALAYINI, R., DANIEL, J., HOMBERG, C., NADER, F. H., DARNAULT, R., MENGUS,
5 6 7	1245	J., and BARRIER, E., 2017. The effect of the Palmyra trough and Mesozoic
8 9	1246	structures on the Levant margin and on the evolution of the Levant Restraining
10 11	1247	bend. In Roure, F., Amin, A., Khomsi, S., Al-Garni, M.A.M. (Eds.), Lithosphere
12 13 14	1248	dynamics and sedimentary basins of the Arabian plate and surrounding areas,
15 16	1249	Springer, 149–172. (doi.org/10.1007/978-3-319-44726-1)
17 18 10	1250	
20 21	1251	GOMEZ, F., KHAWLIE, M., TABET, C., DARKAL, A. N., KHAIR, K., and BARAZANGI,
22 23	1252	M., 2006. Late Cenozoic uplift along the northern Dead Sea transform in Lebanon
24 25 26	1253	and Syria. Earth and Planetary Science Letters, 241 (3–4), 913–931.
27 28	1254	(doi.org/10.1016/j.epsl.2005.10.029)
29 30 31 32 33 34 35 36 37 38	1255	
	1256	GOMEZ, F., MEGHRAOUI, M., DARKAL, A. N., SBEINATI, R., DARAWCHEH, R.,
	1257	TABET, C., KHAIR, K. and BARAZANGI, M., 2001. Coseismic displacements along
	1258	the Serghaya fault: an active branch of the Dead Sea fault system in Syria and
39 40	1259	Lebanon. Journal of the Geological Society, 158 , 405–408.
41 42 43	1260	
43 44 45	1261	GORINI, C., MONTADERT, L., and RABINEAU, M., 2015. New imaging of the
46 47	1262	salinity crisis: Dual Messinian lowstand megasequences recorded in the deep
48 49 50	1263	basin of both the eastern and western Mediterranean. Marine and Petroleum
51 52	1264	<i>Geology</i> , 1–17. (doi.org/10.1016/j.marpetgeo.2015.01.009)
53 54 55	1265	
56 57	1266	HALL, J. T., CALON, T. J., AKSU, A. E., and MEADE, S. R., 2005. Structural evolution
58 59	1267	of the Latakia Ridge and Cyprus Basin at the front of the Cyprus Arc , Eastern
Ю	1268	Mediterranean Sea. <i>Marine Geology, 221,</i> 261–297.

1 2		
-345678910	1269	(doi.org/10.1016/j.margeo.2005.03.007)
	1270	
	1271	HANCOCK, P. L., and ATIYA, M. S., 1979. Tectonic significance of mesofracture
10 11 12	1272	systems associated with the Lebanese segment of the Dead Sea transform fault.
13 14	1273	Journal of Structural Geology, 1 (2), 143–153. (doi.org/10.1016/0191-
15 16 17	1274	8141(79)90051-8)
17 18 19	1275	
20 21	1276	HAQ, B. U., and AL-QAHTANI, A. M., 2005. Phanerozoic cycles of sea-level change
22 23 24	1277	on the Arabian Platform Rationale for an Arabian Platform Cycle Chart.
25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45	1278	GeoArabia, 10 (2), 127–160.
	1279	
	1280	HAWIE, N., GORINI, C., DESCHAMPS, R., NADER, F.H., MONTADERT, L.,
	1281	GRANJEON, D., and BAUDIN, F., 2013. Tectono-stratigraphic evolution of the
	1282	northern Levant Basin (offshore Lebanon). Mar. Pet. Geo., (doi: 10.1016:j.
	1283	marpetgeo.2013.08.004)
	1284	
	1285	HAWIE, N., DESCHAMPS, R., NADER, F.H., GORINI, C., MÜLLER, C., DESMARES, D.,
	1286	HOTEIT, A., GRANJEON, D., MONTADERT, L. and BAUDIN, F., 2014.
40 47 48	1287	Sedimentologic and stratigraphic evolution of northern Lebanon since the Late
49 50 51 52	1288	Cretaceous: implications on the Levant margin and basin. Arabian Journal of
	1289	Geosciences (DOI: 10.1007/s12517-013-0914-5)
54 55	1290	
56 57	1291	HAWIE, N., DESCHAMPS, R., GRANJEON, D., NADER, F.H., GORINI, C., MULLER, C.,
58 59 60	1292	MONTADERT, L. and BAUDIN, F., 2015. Multi-scale constraints of sediment
	1293	source to sink systems in frontier basins: a forward stratigraphic modeling case

1 2		
3	1294	study of the Levant region. <i>Basin Research</i> 1–28, doi: 10.1111/bre.12156
5 6 7	1295	
8 9	1296	HOMBERG, C., BARRIER, É., MROUEH, M., HAMDAN, W., and HIGAZI, F., 2009.
10 11	1297	Basin tectonics during the Early Cretaceous in the Levant margin, Lebanon.
12 13 14	1298	Journal of Geodynamics, 47 (4), 218–223. (doi.org/10.1016/j.jog.2008.09.002)
15 16	1299	
17 18 19	1300	HOMBERG, C., BARRIER, É., MROUEH, M., MÜLLER, C., HAMDAN, W., and HIGAZI,
20 21	1301	F., 2010. Tectonic evolution of the central Levant domain (Lebanon) since
22 23	1302	Mesozoic time. In Homberg, C. and Bachmann, M. (Eds.), Evolution of the Levant
24 25 26	1303	margin and western Arabia platform since the Mesozoic, Geol. Soc. Lond., Spec.
27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43	1304	<i>Publ.</i> , 341 , 245–268. (doi.org/10.1144/SP341.12)
	1305	
	1306	INATI, L., ZEYEN, H., NADER, F. H., ADELINET, M., SURSOCK, A., ELIE, M., and
	1307	ROURE, F., 2016. Lithospheric architecture of the Levant Basin (Eastern
	1308	Mediterranean region): A 2D modeling approach. <i>Tectonophysics</i> , 693 , 143–156.
	1309	(doi.org/10.1016/j.tecto.2016.10.030)
	1310	
43 44 45	1311	KHAIR, K., KHAWLIE, M., HADDAD, F., BARAZANGI, M., SEBER, D., and CHAIMOV,
46 47 48	1312	T. A., 1993. Bouguer gravity and crustal structure of the Dead Sea transform fault
48 49 50	1313	and adjacent mountain belts in Lebanon. <i>Geology</i> , 21 , 739–742.
51 52	1314	
53 54 55	1315	KOSI, W., TARI, G., NADER, F. H., SKIPLE, C., TRUDGILL, B. D., and LAZAR, D.,
56 57	1316	2012. Structural analogy between the "piano key faults" of deep-water Lebanon
58 59 60	1317	and the extensional faults of the Canyonlands grabens, Utah, United States. <i>The</i>
00	1318	<i>Leading Edge</i> , (July), 824–830.

1		
2 3 4 5 6 7 8 9 10 11 12 13 14 15	1319	
	1320	LE PICHON, X., and GAULIER, J. M., 1988. The rotation of Arabia and the Levant
	1321	fault system. <i>Tectonophysics</i> , 153 (1–4), 271–294. (doi.org/10.1016/0040-
	1322	1951(88)90020-0)
	1323	
15 16 17	1324	LE PICHON, X., and KREAMER, C., 2010. The Miocene-to-Present Kinematic
17 18 19 20 21 22 23 24 25 26 27	1325	Evolution of the Eastern Mediterranean and Middle East and Its Implications for
	1326	Dynamics. Annual Review of Earth and Planetary Science, 38 , 323–351.
	1327	(doi.org/10.1146/annurev-earth-040809-152419)
	1328	
27 28 29	1329	LUNING, S., and KUSS, J., 2014. Petroleum Geology of Jordan. In L. MARLOW, C.
29 30 31 32 33 34	1330	KENDALL, and L. YOSE (Eds.), Petroleum systems of the Tethyan region, AAPG
	1331	Memoir 106, 149-172.
34 35 36	1332	
37 38	1333	MAKRIS, J., BEN-AVRAHAM, Z., BEHLE, A., GINZBURG, A., GIESE, P., STEINMETZ,
39 40 41	1334	L., ELEFTHERIOU, S., 1983. Seismic refraction profiles between Cyprus and
42 43	1335	Israel and their interpretation. <i>Geophysical Journal International</i> , 75 , 575–591.
44 45 46	1336	
40 47 48	1337	MAKSOUD, S., RANIER, B.G., AZAR, D., GEZE, R., PAICHELER, J.P. and MORENO-
49 50 51 52 53	1338	BEDMAR, J., 2014. Revision of ' Falaise de B LANCHE ' (Lower Cretaceous) in
	1339	Lebanon , with the definition of a Jezzinian Regional Stage: Carnets de Geologie,
54 55	1340	14 , 401–427.
56 57 58	1341	
59 60	1342	MONTADERT, L., NICOLAIDES, S., SEMB, P. H., and LIE, O. (2014). Petroleum
	1343	Systems offshore Cyprus. In L. MARLOW, C. KENDALL, and L. YOSE (Eds.),

1 2		
3 4 5 6 7	1344	Petroleum systems of the Tethyan region, AAPG Memoir 106, 301–334.
	1345	MONTADERT, L., SEMB, P. H., LIE, O., and KASSINIS, S., 2010. New seismic may
8 9	1346	put offshore Cyprus hydrocarbon prospects in the spotlight. First Break, $oldsymbol{28}$
10 11 12	1347	(April), 91–101.
12 13 14	1348	
15 16	1349	MÜLLER, C., HIGAZI, F., HAMDAN, W., and MROUEH, M., 2010. Revised
17 18 19	1350	stratigraphy of the Upper Cretaceous and Cenozoic series of Lebanon based on
20 21	1351	nannofossils. In Homberg, C. and Bachmann, M. (Eds.), Evolution of the Levant
22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43	1352	margin and western Arabia platform since the Mesozoic, Geol. Soc. Lond., Spec.
	1353	<i>Publ.</i> , 341 , 287–303. (doi.org/10.1144/SP341.14)
	1354	
	1355	NADER, F. H., and SWENNEN, R., 2004a. Petroleum prospects of Lebanon: some
	1356	remarks from sedimentological and diagenetic studies of Jurassic carbonates.
	1357	Marine and Petroleum Geology, 21 (4), 427–441. (doi.org/10.1016/S0264-
	1358	8172(03)00095-3)
	1359	
	1360	NADER, F. H., and SWENNEN, R., 2004b. The hydrocarbon potential of Lebanon:
44 45	1361	new insights from regional correlations and studies of Jurassic dolimitization.
46 47 48	1362	Journal of Petroleum Geology, 27 (3), 253–275.
49 50	1363	
51 52	1364	NADER, F. H., 2011. The petroleum prospectivity of Lebanon: an overview.
53 54 55	1365	Journal of Petroleum Geology, 34 , 135–156.
56 57	1366	
58 59 60	1367	NADER, F. H., 2014. Insights into the petroleum prospectivity of Lebanon. In L.
00	1368	MARLOW, C. KENDALL, and L. YOSE (Eds.), Petroleum systems of the Tethyan

1 2		
3 4 5 6 7	1369	region, AAPG Memoir 106, 241–278. <u>(doi.org/10.1036/13431859M1063609</u>)
	1370	
8 9	1371	NADER, F. H., BROWNING-STAMP, P., and LECOMTE, J. C., 2016. Geological
10 11 12	1372	intepretation of 2D seismic reflection profiles onshore Lebanon: implications for
13 14	1373	petroleum exploration. <i>Journal of Petroleum Geology</i> , 39 , 333–356.
15 16 17	1374	
18 19	1375	NETZEBAND, G., GOHL, K., HÜBSCHER, C., BEN-AVRAHAM, Z., DEHGHANI, G. A.,
20 21	1376	GAJEWSKI, D., and LIERSCH, P., 2006. The Levantine Basin—crustal structure
22 23 24	1377	and origin. <i>Tectonophysics</i> , 418 (3-4), 167–188.
25 26 27 28 29 30 31 32 33 34 35 36 37 38	1378	(doi.org/10.1016/j.tecto.2006.01.001)
	1379	
	1380	QUENNELL, A. M., 1984. The Western Arabia rift system. In R. J. Dixon, R.J.,
	1381	Robertson, A.H.F. (Eds.), The geological evolution of the Eastern Mediterranean,
	1382	Geol. Soc. Lond., Spec. Publ., 17, 775–788.
	1383	(doi.org/10.1144/GSL.SP.1984.017.01.62)
39 40	1384	
41 42 43 44 45	1385	RENOUARD, G., 1955. Oil prospects of Lebanon. AAPG Bulletin, 39 (11), 2125-
	1386	2169.
46 47 48	1387	
49 50	1388	ROBERTS, G., and PEACE, D., 2007. Hydrocarbon plays and prospectivity of the
51 52	1389	Levantine Basin , offshore Lebanon and Syria from modern seismic data.
53 54 55	1390	GeoArabia, 12 (3).
56 57	1391	
58 59	1392	ROBERTSON, A. H. F., 1998. Tectonic significance of the Eratosthenes Seamount:
	1393	a continental fragment in the process of collision with a subduction zone in the

1 2		
3 4	1394	eastern Mediterranean (Ocean Drilling Program Leg 160). Tectonophysics, 298
5 6 7	1395	(1–3), 63–82. (doi.org/10.1016/S0040-1951(98)00178-4)
8 9	1396	
10 11 12	1397	ROBERTSON, A. H. F., DIXON, J. E., BROWN, S., COLLINS, A., MORRIS, A. P.,
12 13 14	1398	PICKETT, E., USTAOMER, T., 1996. Alternative tectonic models for the Late
15 16	1399	Palaeozoic-Early Tertiary development of Tethys in the Eastern Mediterranean
17 18 19	1400	region. In Morris, A., Tarling, D.H. (Eds.), Palaeomagnetism and tectonics of the
20 21	1401	Mediterranean region. <i>Geol. Soc. Lond., Spec. Publ.</i> , 105, 239–263.
22 23	1402	(doi.org/10.1144/GSL.SP.1996.105.01.22)
24 25 26	1403	
27 28	1404	SAWAF, T., BREW, G. E., LITAK, R. K., and BARAZANGI, M., 2001. Geologic
29 30 31 32 33 34 35 36 37 38 39 40	1405	evolution of the intraplate palmyride basin and euphrates fault system syria. In
	1406	P. A. Ziegler, P.A, Cavazza, W., Robertson, A.H.F., Crasquin-Soleau, S. (Eds.), Peri-
	1407	Tethys Memoir 6: Peri-Tethyan rift/Wrench basins and passive margins,
	1408	Memoire du Museum national d'histoire naturelle, Paris,, 441–467).
	1409	SEARLE, M.P., 1994. Structure of the intraplate eastern Palmyride fold belt, Syria:
41 42 43	1410	Geological Society of America Bulletin, 106 , 1332–1350. (doi: 10.1130/0016-
44 45	1411	7606(1994)106<1332)
46 47 48	1412	
40 49 50	1413	SENGOR, A. M. C., and YILMAZ, Y., 1981. Tethyan evolution of Turkey: a plate
51 52	1414	tectonic approach. <i>Tectonophysics</i> , 75 , 181–241.
53 54 55	1415	
56 57	1416	SHENHAV, H., 1971. Lower Cretaceous Sandstone Reservoirs, Israel:
58 59	1417	Petrography, Porosity, Permeability. AAPG Bulletin, 55 (12), 2194–2224.
00	1418	(doi.org/10.1306/819A3E30-16C5-11D7-8645000102C1865D)

1		
2 3 4	1419	
5 6 7 8 9 10 11 12	1420	STAMPFLI, G. M., and HOCHARD, C., 2009. Plate tectonics of the Alpine realm. In
	1421	Murphy, J.B., Keppie, J.D., Hynes, A.J. (Eds.), Ancient orogens and modern
	1422	analogues, <i>Geol. Soc. Lond., Spec. Publ.</i> 327 , 89–111(doi.org/10.1144/SP327.6)
13 14	1423	
15 16 17	1424	STEINBERG, J., GVIRTZMAN, Z., FOLKMAN, Y., and GARFUNKEL, Z., 2011. Origin
17 18 19	1425	and nature of the rapid late Tertiary filling of the Levant Basin. <i>Geology</i> , 39 (4),
20 21 22	1426	355–358. (doi.org/10.1130/G31615.1)
22 23 24	1427	
25 26	1428	SYMEOU, V., HOMBERG, C., NADER, F.H., DARNAULT, R., LECOMTE, J.C. &
27 28 29	1429	PAPADIMITRIOU, N. In review. Longitudinal and temporal evolution of the
30 31	1430	tectonic style along the Cyprus Arc system, assessed through 2D reflection
32 33 34	1431	seismic interpretation.
35 36	1432	
37 38 20	1433	WALLEY, C.D., 1997. The lithostratigraphy of Lebanon: a Review. Lebanese
40 41	1434	Scientific Bulletin, 10, 81-108
42 43	1435	
44 45 46	1436	WALLEY, C.D., 1998. Some outstanding issues in the geology of Lebanon and
47 48	1437	their importance in the tectonic evolution of the Levantine region.
49 50 51	1438	Tectonophysics, 298, 37-62.
52 53	1439	
54 55 56	1440	WETZEL, R., 1974. Etapes de la prospection petroliere en Syrie et au Liban
57 58	1441	(Notes et mémoires). <i>Compagnie Francaise des Petroles,</i> Paris.
59 60	1442	
	1443	WRONA, T., JACKSON, C. A., HUUSE, M., and TAYLOR, K. G., 2015. Silica diagenesis

Journal of Petroleum Geology

3 4 5 6 7 8 9 10 1 12 3 4 5 6 7 8 9 10 1 12 3 4 5 6 7 8 9 10 1 12 3 4 5 6 7 8 9 10 1 12 3 4 5 6 7 8 9 10 1 2 2 2 2 2 2 2 2 2 2 2 2 2 3 3 3 2 3 3 3 3 3 3 3 4 4 2 3 4 4 5 6 7 8 9 0 1 2 2 3 4 5 6 7 8 9 0 1 2 2 3 4 5 6 7 8 9 0 1 2 3 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 1 2 3 4 4 5 6 7 8 9 0 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1	1444	in Cenozoic mudstones of the NorthViking Graben : physical properties and basin
	1445	modelling. <i>Basin Research</i> , 1–20. <u>(doi.org/10.1111/bre.12168</u>)
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	1448	Figures
	1449	
	1450	Fig1: Main structural elements of Lebanon, the Levant Basin and part of Syria. Map
	1451	compiled from Barrier et al. 2014; Ghalayini et al. 2016; Ghalayini et al. 2014; Brew
	1452	et al. 2001.
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	1454	fig. 2: Creaming curve for both the Oligo-Miocene 4-way dip closures and the
	1455	Mesozoic carbonate plays in the Levant Basin.
	1456	
	1457	Fig. 3: Geo-seismic line showing the Levant margin off the coast of northern Lebanon
	1458	consisting mainly of a carbonate succession. The Triassic contains extensional
	1459	normal faults in relation to the Triassic breakup of Pangea and the Early Cretaceous
	1460	clastics are pinching out on the Jurassic carbonate talus deposits.
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	1462	Fig. 4: Structural map of the Saida-Tyr plateau offshore and the onshore Tyr-
	1463	Nabatieh plateau. The depth map offshore corresponds to the Senonian
	1464	unconformity horizon. The en-echelon anticlines along the Saida fault are only
	1465	observed at the Base Messinian horizon and not at the level of the Senonian
	1466	unconformity.
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	1468	Fig. 5: Geo-seismic line showing the Levant margin off the coast of southern

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3 4 5 6 7 8 9 10 11 2 3 4 15 6 7 18 9 02 12 23 24 25 6 7 28 9 00 11 20 12 20 22 20 20 10 10 10 10 10 10 10 10 10 10 10 10 10	1469	Lebanon. The broad Mesozoic platform in this area is referred to as the Saida-Tyr
	1470	Plateau (Ghalayini et al. 2014). The seismic data was tied to the nearby Adloun well
	1471	and shows the complete Jurassic to Cretaceous succession found onshore. The
	1472	strong reflectors below the Jurassic are believed to represent the Triassic. For
	1473	location, see figure 4.
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	1475	Fig. 6: Geoseismic line across the western edge of the Saida-Tyr plateau showing
	1476	the transgressive anticlines separating the deep basin from the Mesozoic plateau.
	1477	For location, see figure 4.
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	1480	discoveries
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	1483	offshore
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	1486	Lebanon. The structural style suggests detachment folding on an intra-Eocene
	1487	horizon. The anticlines were folded in the Late Miocene prior to the Messinian event
	1488	(Ghalayini <i>et al.</i> 2014).
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	1490	Fig 10: Seismic section showing the titled fault blocks in the deep basin domain. The
	1491	depth map of the base mid Miocene horizon shows the geometry of the associated
	1492	traps at present day
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	1494	Fig. 11: Geo-seismic line showing the Latakia Ridge north of the Levant Basin

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	1496	Flg. 12: gas chimneys on top of a Miocene anticline observed only when the
	1497	Messinian seal thins or is absent. The overlying Pliocene exhibits numerous bright
	1498	spots and DHI's pointing to entrapment of the leaked gas into Pliocene reservoirs in
	1499	structural closures.
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	1501	Fig. 13: Geoseismic line showing a bright spot and a potential flat spot in the Lower
	1502	Cretaceous unit pinching out along the Levant margin and trapped between
	1503	Mesozoic carbonates.
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	1505	Fig. 14: Geoseismic line showing a potential flat spot in the Oligocene unit observed
	1506	along the Levant margin. The lateral Oligo-Miocene units are pinching out on the
	1507	margin forming classical stratigraphic traps.
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	1509	Fig. 15: Petroleum system charts for the deep basin and Latakia Ridge domains.
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	1511	Fig. 16: Petroleum system charts for the Levant margin and onshore domains.
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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.



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





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.



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.





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.





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).
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Base Pliocene

Base Mid Miocen

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Senonian unc

ENE

Base Plioce

Base Mid Mioce

Base Mioce

Eocene une

Lower Miocene Shaly sand Oligocene Shale Eocene Salt

Oligocene Eocene



For review only





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



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.



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.





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.



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Paleozoic			Mesozoic															Cenozoic						Geologic			
Permian			Triassic				Jurassic					Cretaceous							Tertiary						timescale		
Early	Middle	ate Eart	Middle		Late	6		Early		Middle		Late	Neoco	mian	Early			La	ate enonian	Pal	eocene	Eocen	ene e C	ligo	Neoge	e P	Petrole
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Figure 16

Petroleum system charts for the Levant margin and onshore domains.