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THE PETROLEUM PROSPECTIVITY OF LEBANON: AN OVERVIEW

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This paper presents an updated review of the petroleum prospectivity of Lebanon. It is based on a re-assessment of the tectono-stratigraphic succession in Lebanon, correlation with nearby countries and the results of a recent offshore seismic survey. A generalized model illustrating potential petroleum system(s) in Lebanon is presented with data on Palaeozoic, Mesozoic and Cenozoic plays. Major lithological units are described with respect to their source, reservoir and cap-rock potential.

Based on a general review of previous studies and existing data, Lebanese exploration prospects may comprise on- and offshore as well as coastal (margin) targets. They include potential Triassic reservoirs in onshore central-northern Lebanon including those at the Qartaba structure. Offshore plays are discussed with reference to recent seismic profiles; potential offshore targets comprise Oligo-Miocene reservoirs sealed by Messinian evaporites as well as deeper Mesozoic reservoirs.

INTRODUCTION

There has been renewed interest in petroleum exploration on- and offshore Lebanon following the recent disclosure of new offshore seismic data and new discoveries offshore Israel and the Levantine margin. The results of recent studies indicating that the sedimentary succession offshore Lebanon may include source and reservoirs rocks similar to those in neighbouring countries have been discussed at recent international conferences and in professional publications (e.g. Breman, 2006; Roberts and Peace, 2007; Gardosh *et al*., 2009; Lie and Trayfoot, 2009; Montadert *et al*., 2010). Discoveries offshore Israel (e.g. *Noa*, *Mari-B, Tamar, Dalit* and *Leviathan*) have confirmed the presence of gas accumulations in Pliocene, Miocene and Oligocene sandstones (see *www.nobleenergyinc.com*).

To date, there has been no commercial development of oil or natural gas in Lebanon. Little exploration has taken place for the past four decades and earlier exploration efforts were unsuccessful. Only seven exploration wells have been drilled in Lebanon, between 1947 and 1967; these failed to encounter oil or gas in commercial volumes, or to penetrate rocks older than the Jurassic Kesrouane Formation which is the oldest unit exposed at the surface.

Indications of petroleum, however, have been found both at outcrop and in wells (Dubertret, 1955; Renouard, 1955; Ukla, 1970; Beydoun, 1977a, 1981). The Upper Cretaceous Chekka Formation, which consists of organic-rich mudstones and is well exposed in southern Lebanon, includes two types of asphalt. The first is related to *in situ* maturation of organic matter; the second is fracture-related and is interpreted to have migrated from a deeper source rock (Al Haddad, 2007). The deeply-buried Triassic succession may possess good source (and reservoir) characteristics, and may also contain evaporitic cap-rocks equivalent to those in Syria (Nader and Swennen, 2004b). Recent seismic surveys have drawn attention to the significant potential for hydrocarbon

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accumulations offshore the northern Lebanese coast (Breman, 2006; Montadert *et al*., 2010).

This paper is intended to reassess the petroleum prospectivity of Lebanon and to update the petroleum model proposed by Nader and Swennen (2004b). It includes data gathered during early onshore exploration (e.g. Renouard, 1955; Beydoun, 1977a and 1981), more recent studies involving regional correlation and diagenesis (Nader, 2003; Nader and Swennen, 2004a, b) and studies of potential reservoirs and source-rocks (e.g. Doummar, 2005; Al Haddad, 2007). The Upper Cretaceous and Cenozoic rock successions, which have been relatively little studied in the past, were recently subjected to a nannofossil-based stratigraphic investigation which has permitted more precise dating of the structural evolution of Mount Lebanon (Müller *et al*., 2010). Also discussed are the results of recent offshore seismic surveys (Breman, 2006; Roberts and Peace, 2007; Gardosh *et al*., 2008, 2009; Montadert *et al*., 2010).

GEOLOGIC SETTING

Lebanon extends along the eastern coast of the Mediterranean Sea ("Levantine margin") and covers a surface area of 10,450 sq. km. Onshore Lebanon lies within the same Mesozoic basinal area in which major oil- and gasfields have been found in the Eastern Mediterranean and northern Arabia; whereas the offshore Eastern Mediterranean has been targeted for Cenozoic gas reservoirs (Fig. 1).

The topography of Lebanon is dominated by three major structural features (Fig. 2): Mount Lebanon, the Bekaa Valley and Mount Anti-Lebanon. Regional-scale folds include the Anti-Lebanon, Coastal/Western Lebanon, Qartaba and Barouk/Niha flexures. The NE-SW trending Yamouneh Fault, which comprises part of the Levant Fault System, has multiple splays (Fig. 2).

The total thickness of Jurassic to Recent strata exposed at the surface is about 5800 m (Nader and Swennen, 2004a; Fig. 3). Using seismic and other geophysical studies, Roberts and Peace (2007) suggested that the Mesozoic and Cenozoic successions offshore Lebanon comprise at least 10,000 m of sedimentary rocks deposited above a rifted Triassic – Early Jurassic terrain, including up to 1500 m of Messinian evaporites.

Regional-scale tectonic elements in Lebanon include the Palmyride Basin, Levantine Margin, Syrian Arc fold belt, and the Levant Fault System. These elements have played an important role in defining the present-day structural and stratigraphic setting of the country. The elements are discussed briefly in turn in the following paragraphs.

The Palmyride Basin

Most Mesozoic rocks in Lebanon were deposited in the intraplate Palmyride Basin which extends from NE Egypt northwards through Israel, Lebanon and Syria to NW Iraq. Subsidence of the Palmyride Basin began in the Late Permian and was probably associated with the opening of Neo-Tethys (Lovelock, 1984; Sengor *et al*., 1988). However, Lower Silurian shales are present within an elongate depocentre roughly along the trend of the present-day Palmyrides; thus, Brew *et al*. (2001) proposed an Early Silurian initiation for a larger-scale Palmyride-Sinjar Basin. Late Silurian and Devonian sequences are absent, and Early Silurian shales were significantly eroded, as elsewhere throughout the Arabian Plate, during the Late Carboniferous ("Hercynian") orogenic phase (Sharland et al., 2001).

Brew *et al*. (2001) suggested that the Palmyride trough continued to be a depocentre in Syria until the Late Cretaceous. The Palmyride Basin appears to have been shallow-marine during the Cretaceous until a Cenomanian transgression. Hundreds of metres of fluvio-deltaic to shallow-marine sandstones, probably derived from the Hamad Uplift (Fig. 4), were deposited on the northern Arabian Platform (Caron and Mouty, 2007). Inversion of pre-existing structures started in the Santonian-Campanian (Ponikarov, 1967; Chaimov *et al*., 1990) or possibly Late Maastrichtian (Brew *et al*., 2001) during the first phase of Syrian Arc deformation. Local syntectonic deposition continued during this inversion event (Chaimov *et al*., 1993), which is believed to represent a far-field stress effect of the formation of the peri-Arabian ophiolitic belt (Ricou, 1971; Parrot, 1977) including its NW extension referred to as the Cyprus Arc (Robertson and Dixon, 1984).

The Levantine Margin

Stratigraphic correlations based on well data show that the Jurassic and Cretaceous sequences, and probably also the Triassic, thicken towards the present-day (coastal) Levantine margin (Nader and Swennen, 2004a) which probably coincides with a regional Mesozoic depocentre. Gravity data demonstrate a westward thinning of the continental crust beneath onshore Lebanon and Syria (Beydoun, 1977b; Khair *et al*., 1997) and seismic refraction data show a similar trend westwards and in Israel (Ginzburg and Folkman, 1980; Makris *et al*., 1983; Netzeband *et al*., 2006). Bathymetric mapping, the relatively narrow coastal plain and the NNW-SSE alignment of the major structural features in Lebanon, all point to the regional significance of the Levantine margin. Garfunkel (1989) suggested a Liassic to Bajocian age for rifting along this margin, while Walley (2001) favored a Late Triassic – Early Jurassic age.

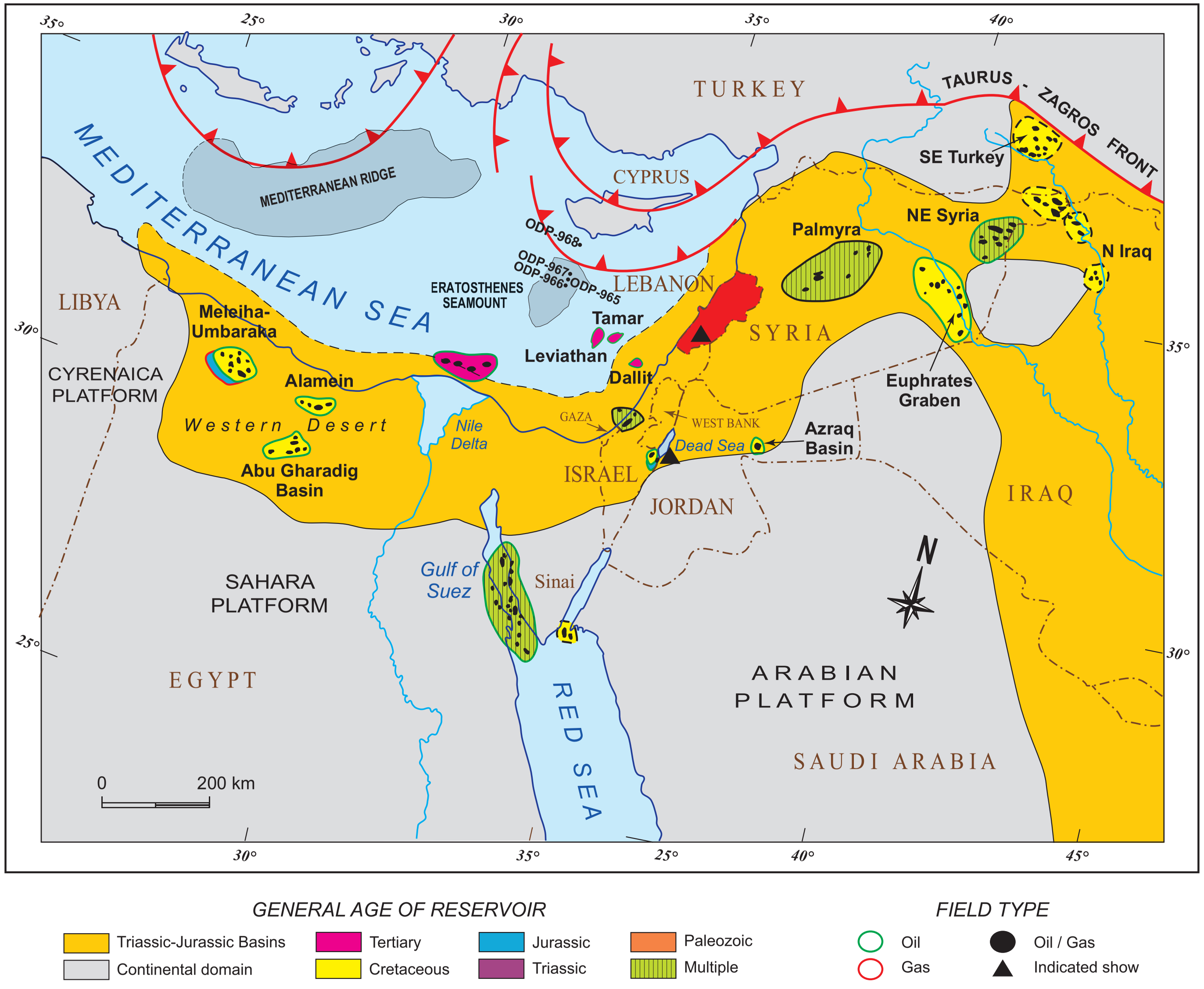


Fig. 1. Simplified map showing the Eastern Mediterranean and North Arabian regions and the extent of the area where Triassic-Jurassic basins as well as major oilfields are found. Lebanon is marked by the red area. Map updated from May (1991), Abou Shagar (2000) and references in text.

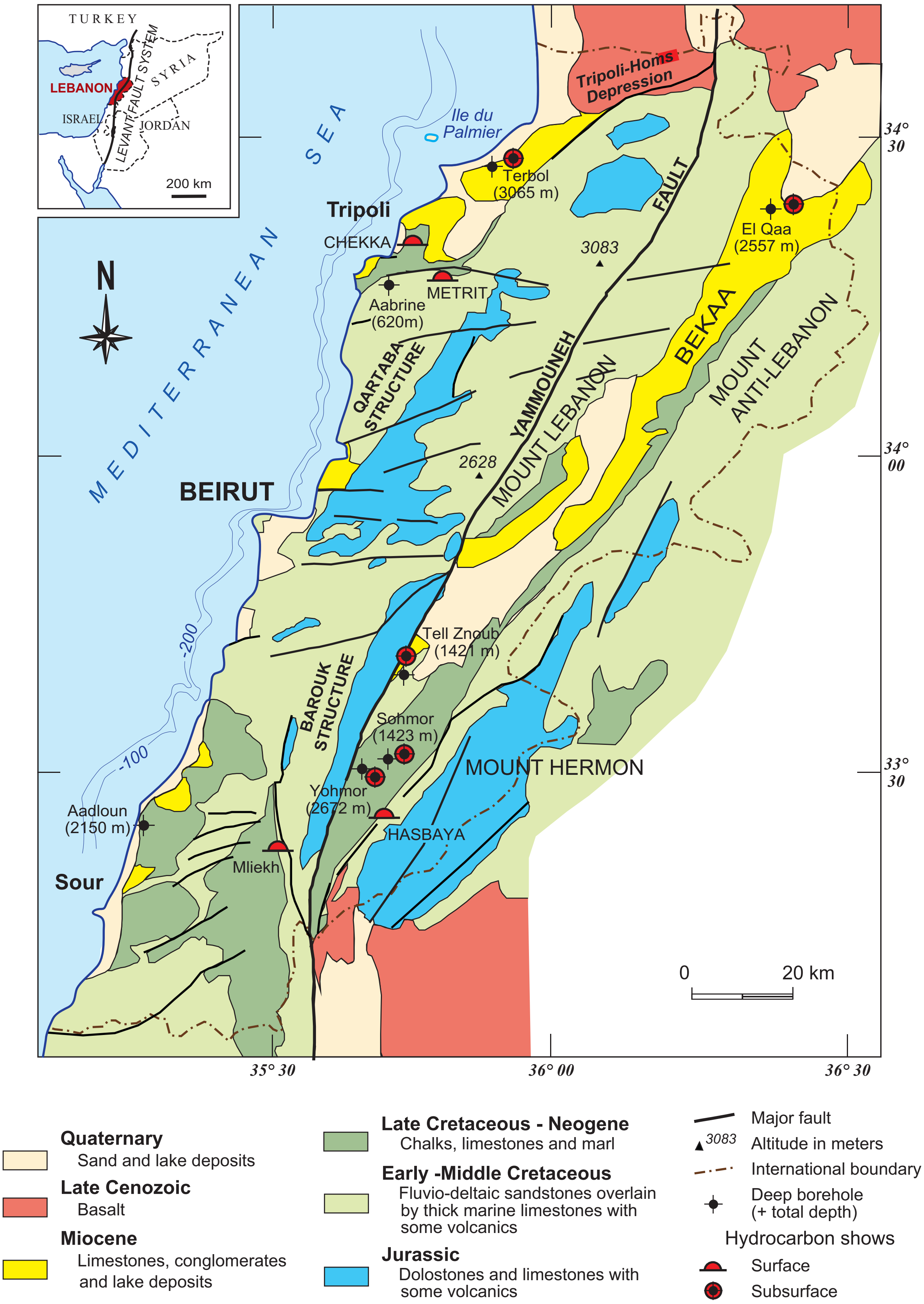


Fig. 2. Simplified geological map of Lebanon. Map shows the locations of the seven exploration wells so far drilled in Lebanon and of the reported hydrocarbon shows, and also the location of the Qartaba structure. Compiled from Dubertret (1955), Ukla (1970) and Beydoun and Habib (1995).

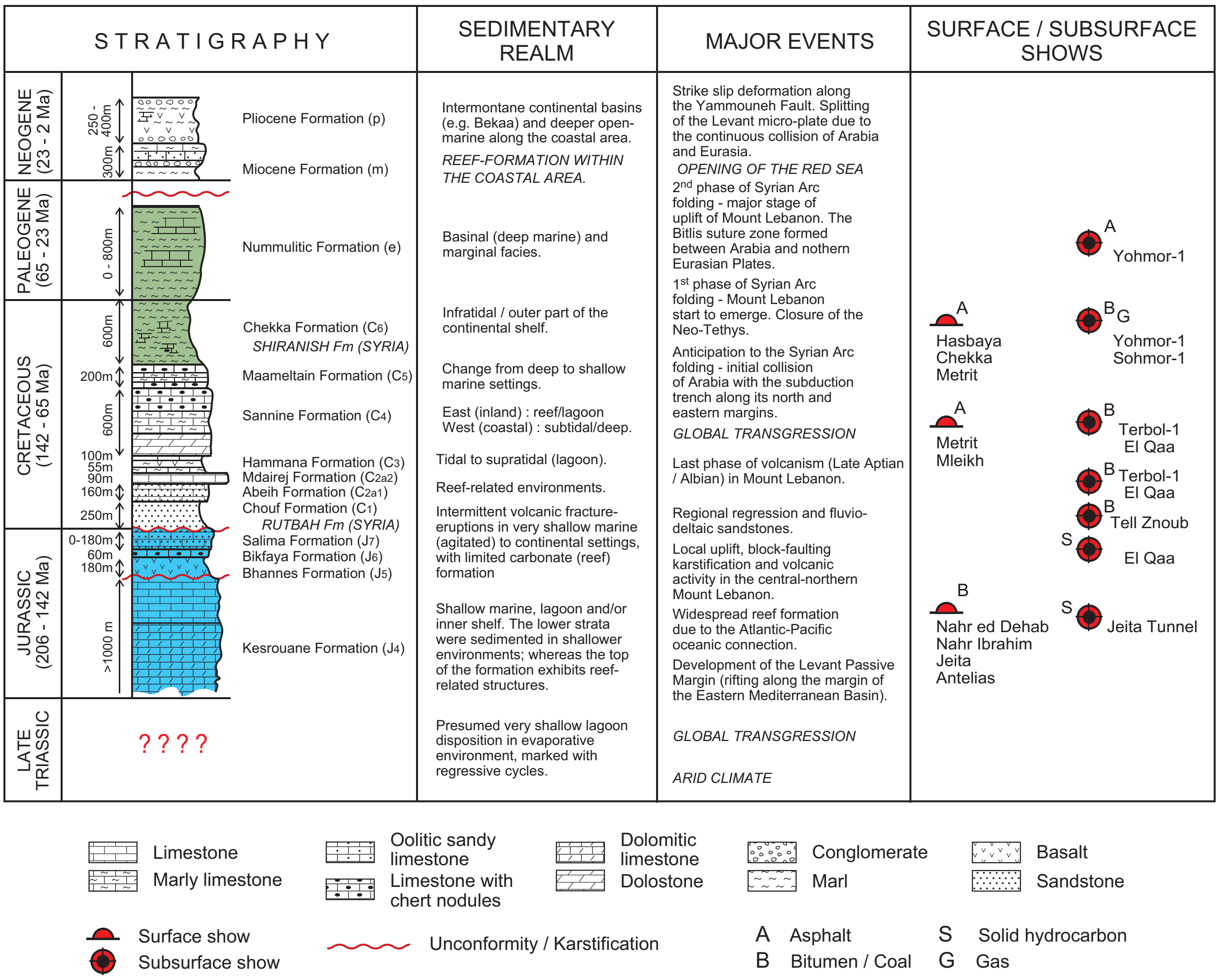


Fig. 3. General tectono-stratigraphic column for Lebanon with the interpreted depositional environments of the various rock-units and the corresponding surface and subsurface shows of hydrocarbons (compiled from many authors cited in the text).

Recent deep seismic sections from offshore Lebanon show the presence of a Triassic rifted terrain but no sign of oceanic crust (Roberts and Peace, 2007). The Levantine Margin constitutes an important feature which is clearly observed on seismic sections offshore Lebanon, and which has evolved as a Jurassic-Cretaceous (predominantly carbonate) shelf-edge and slope.

Syrian Arc fold belt

The Syrian Arc is a sigmoidal fold belt extending from western Egypt through Sinai, Israel and Lebanon into the Palmyrides in Syria (Fig. 4). Krenkel (1924) considered the major structures in Lebanon (e.g. the Lebanese mountains and the Bekaa valley) to be related to this fold belt (see also Wolfart, 1967). These structures are aligned NNE-SSW, matching the central segment of the Arc (see index map in Fig. 4).

In general, the Arc structures are thin-skinned open flexures and folds, frequently associated with strike-slip and reverse faulting (Walley, 1998; Abd El-Motaal and Kusky, 2003). Freund *et al.* (1975) and Reches *et al.* (1981) proposed that these structures result from inversion of pre-existing extensional faults. According to these authors, the Hebron Monocline in Israel (a NNE-SSW trending, 35 km long, doubly-plunging monocline) is fault-cored and the normal fault that was later reactiated preceded the monoclinal fold. Reches *et al.* (1981) proposed that steeply-dipping norml faults appear to have been active during the Triassic-Jurassic and were reactivated in reverse motion in the Late Cretaceous to form the monocline. This model is consistent with a proposed Late Triassic to Early Jurassic phase of extension in the Levant region (Freund *et al.*, 1975). The western and eastern segments of the Syrian Arc (Fig. 4) probably resulted from inversion along older extensional SW-NE faults (Late Permian – Early Triassic).

Walley (1998) identified two main episodes of Syrian Arc folding: Early Senonian and Late Eocene - Late Oligocene. Sawaf *et al.* (2001) described three episodes for the inversion and compression of the

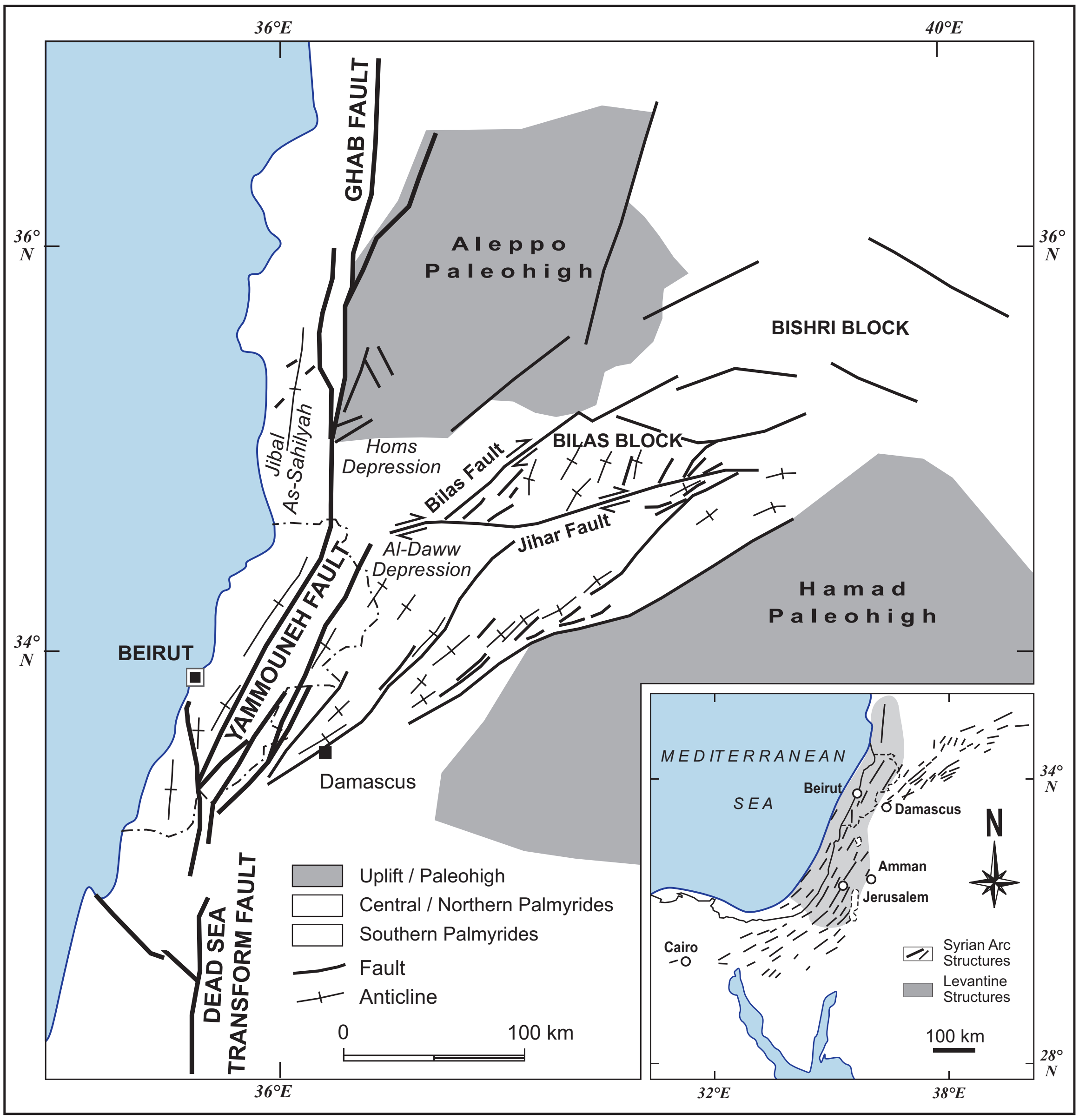


Fig. 4. Simplified maps showing the Palmyride Basin (as well as the Palmyrides fold and thrust belt), the extent of the Syrian Arc fold structures and the Levant Fault System in Lebanon and adjacent countries (modified from Walley, 1998).

Syrian Palmyrides (latest Cretaceous, Middle Eocene and Miocene-to-present). It seems that such deformation continued along the eastern segment of the arc (inland Syria) slightly later than elsewhere. The magnitude of the folding increased with time so that the final phase seems to have been responsible for most of the uplift (Ponikarov, 1967; Walley, 1998, Sawaf *et al.*, 2001).

The latest phase of deformation identified by Sawaf *et al.* (2001) was masked by activity on the Levant Fault System. Here, deformation takes the form of motion along the splays of the Levant fault (Fig. 4) and transpressional neo-tectonism affecting Mount Lebanon (e.g. Gedeon, 1999; Nemer, 1999; Elias *et al.*, 2007) (see below).

Levant Fault System

The Levant Fault System extends about 1000 km from the Red Sea (Gulf of Aqaba) to the Taurus Mountains in Turkey and currently forms the western edge of the Arabian Plate. The fault system has a broadly north-south alignment that changes to NNE-SSW in Lebanon. Hancock and Atiya (1979) divided the fault system into as many as seven segments, but a three-fold division is common (e.g. Walley, 1998) comprising from south to north the Dead Sea Transform Fault, the NNE-SSW Yammouneh Fault (the Lebanese segment) and the south-north Ghab Fault (Dubertret, 1966) (Fig. 4).

Left-lateral displacement has been proposed for the entire Levant Fault System (Quennel, 1958;

Freund, 1965), although this is not observed along the Yammouneh fault (opposed by Dubertret, 1975). Quennel (1958) and Freund *et al*. (1970) proposed that sinistral offset of 60-65 km occurred along the Dead Sea fault from the latest Oligocene to the Early Miocene, with an additional 40 km during the last 5 Ma.

Motion on the fault system is related to the opening of the Red Sea. An early phase of Red Sea rifting started between 25 to 20 Ma with extension through the Gulf of Suez. Activity on the Dead Sea fault started during a later phase of rifting affecting the Gulf of Aqaba about 14 Ma ago (Bayer *et al*., 1988; Makris and Rihm, 1991), with a second episode of activity from 6-5 Ma to the present day, accompanied by extensive magmatism (Garfunkel, 1989) and the onset of transpression in Lebanon (Walley, 1998). A structural element recently observed offshore Lebanon was referred to as the "offshore Mount Lebanon thrust" by Elias *et al*. (2007), who interpreted it to be part of the Levant Fault System and to have controlled the growth of Mount Lebanon since the Late Miocene.

Different amounts of offset have also been postulated for the northernmost segment of the Levant fault system (i.e. the Ghab fault; Fig. 4). Displacement of ophiolites cut by the fault in Turkey was used by Freund *et al*. (1970) to identify some 70 km of sinistral offset, but this has been disputed (e.g. Quennel, 1984). Chaimov *et al*. (1990) proposed a total of 40 to 45km of displacement (Pliocene to present-day), in accordance with the second episode of displacement identified by Quennel (1958) for the southern portion of the Levant Fault System. Of this 40-45 km, shortening of the Palmyride fold-and-thrust belt may have accommodated some 20 km of sinistral movement so that strike-slip offset along the Ghab Fault totalled some 20-25 km. This is demonstrable by offsets of Pliocene basalts (Quennel, 1984), Quaternary alluvial fans and perhaps Mesozoic ophiolites (Brew *et al*., 2001).

DEPOSITIONAL HISTORY

The oldest rock-unit known in Lebanon (at outcrop and in the subsurface) is the Lower Jurassic dolostone (Fig. 2). The nature and extent of underlying older rocks can be extrapolated from surrounding countries.

A number of unconformities are present within the Devonian to Upper Jurassic – Lower Cretaceous succession of the northern Arabian Plate (Fig. 5). Many of these unconformities have been correlated with the boundaries of the Arabian Plate megasequences identified by Sharland *et al*. (2001), and correspond to boundaries of second-order cycles with fining-upward sequences (e.g. within the Palmyride Basin: Wood, 2001). The unconformities coincide with major eustatic cycles (Haq *et al*., 1988) and are time-equivalent to phases of magmatic activity (Wood, 2001).

Palaeozoic

In Syria, Cambrian rocks include arkosic sandstones (probably derived from a granitic basement in the south), together with siltstone and shales. The widespread Early to Middle Cambrian Burj Limestone Formation (Fig. 5; Brew *et al*., 2001) is the deepest continuous seismic reflector in subsurface Syria and northern Jordan (McBride *et al*., 1990; Best *et al*., 1990). Cambrian rocks are exposed at Al Burj in the southern Jordan Valley (Wetzel and Morton, 1959).

Ordovician strata increase in thickness southeastwards from Aleppo to Rutbah and Jordan (1.6 to 3.5km). Sandstones pass into siltstones and shales (Brew *et al*., 2001); such facies and thickness variations indicate open-marine conditions to the east during Ordovician times. An end-Ordovician regional unconformity is associated with uplift in western Saudi Arabia (Sharland *et al*., 2001).

In the Early Silurian, much of Arabia was flooded due to deglaciation and important organic-rich source rocks (Upper Ordovician – Lower Silurian "hot shales") were deposited regionally (Beydoun, 1991). In Syria, these deposits comprise the Tanf Formation which consists of graptolitic shales whose original thickness may range between 500 and 1000 m (Fig. 5; Brew *et al*., 2001). Loydell *et al*. (2009) demonstrated that there are a number of different Lower Silurian "hot shales" in Jordan (thus forming thicker potential source rock intervals), some of which could have been deposited during an interval of lowered eustatic sea-level, regression and rapid burial of organic matter. Upper Ordovician – Lower Silurian "hot shales" in Iraq were re-assessed by Aqrawi *et al*. (2010).

Late Silurian and Devonian rocks are generally absent in Arabia, as the Tanf Formation (or its equivalent) is unconformably overlain directly by Carboniferous siliciclastics which form important reservoir rocks (e.g. Husseini, 1992; Kohn *et al*., 1992; Stampfli *et al*., 2001). In Carboniferous times, the Palmyride Basin, together with the eastern Sinjar extension, flanked to the NW by the Aleppo High and to the SE by the Rutbah High (Figs 4, 5), formed the main depocentre in Syria (and most probably Lebanon), until the onset of Syrian Arc folding in the Late Cretaceous. The Carboniferous succession, whose thickness exceeds 1700 m in the Palmyride Basin, is mainly composed of sandstones and sandy shales, together with some minor carbonates (Brew *et al*., 2001).

Transgressive sedimentation dominates the Early Permian succession in Syria, suggesting little tectonic activity at this time (Wood, 2001). The configuration of the Palmyride Basin persisted

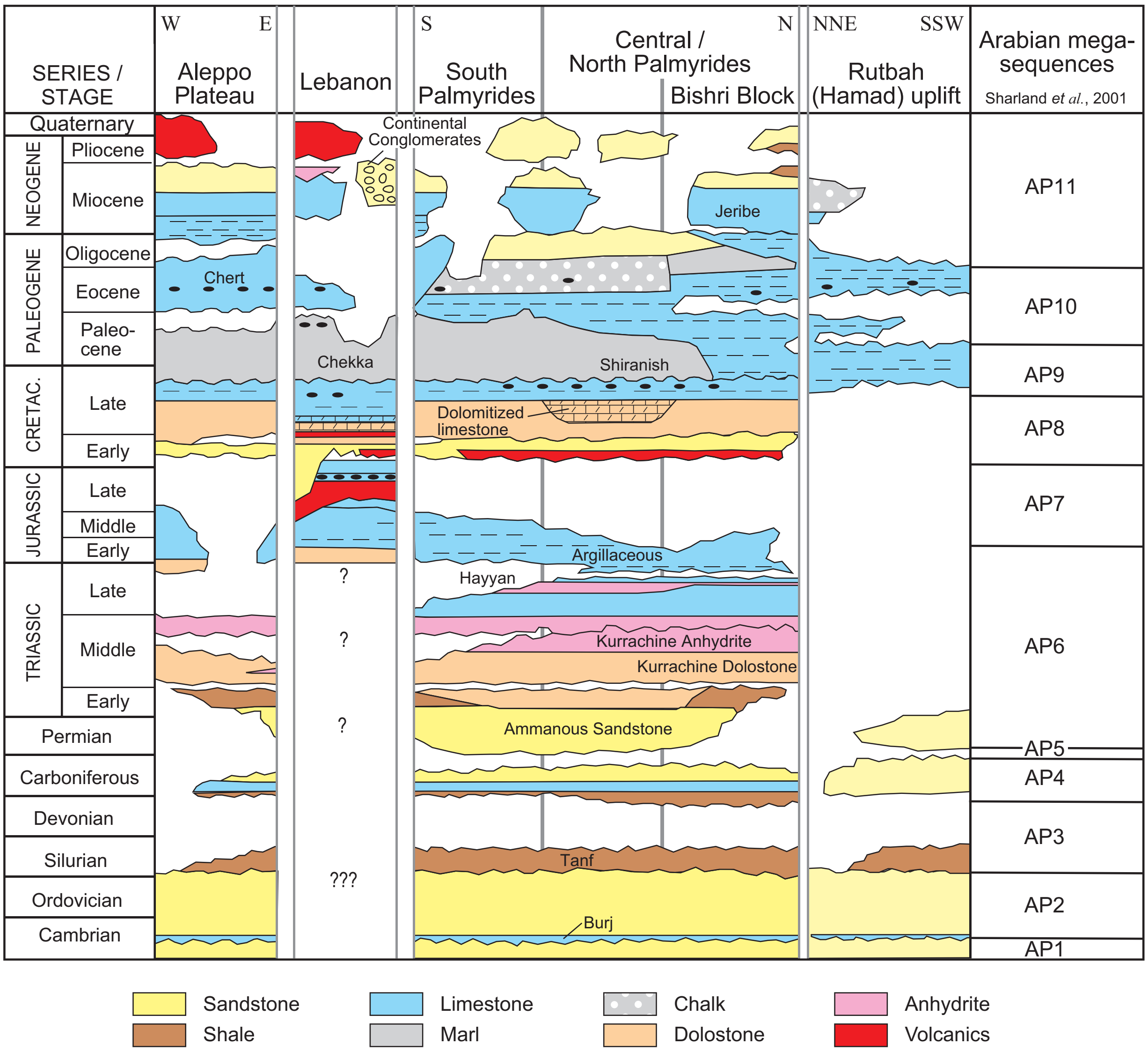


Fig. 5. Generalized lithostratigraphic chart showing the Palmyride rock sequence in Syria (from Brew *et al.*, 2001) and Lebanon. Both Aleppo and Rutbah palaeohighs are represented by a major hiatus spanning most of the Mesozoic (until the inversion phase which affected the Palmyride Basin). The lithostratigraphic scheme of Lebanon matches well with that of the Palmyride Basin. Arabian Plate megasequences (from Sharland *et al.*, 2001) are also presented.

throughout most of the Permian (similarly to the Yemen-Oman and central-northern Saudi Arabia basins), with an eastwards or SEward basinal marine connection. Permian-Triassic siliciclastics (exceeding 1000 m of thickness; Amanous Formation) are preserved within the Palmyride/Sinjar Basin and include both source and reservoir rocks (Brew *et al.*, 2001; Fig. 5). The Aleppo and Rutbah Highs were emergent throughout the Permian (Figs. 4 and 5). In the subsurface of Israel, the Upper Permian consists of marine sandstones, shales and carbonates up to 500 m thick, with a probable hiatus near the Permo-Triassic boundary (Hirsch, 1991).

Mesozoic (pre-Cretaceous)

The Triassic rock sequence has a thickness ranging between 500 and 1100 m, including open/shallow and restricted hypersaline carbonates (and evaporites) as well as continental clastics, in Israel and Jordan (Benjamini *et al.*, 1993). The Early Triassic is composed of cyclical trans- and regressive deposits (Hirsch, 1991). In subsurface Syria, the Lower Triassic within the Palmyride Basin is a continuation of the Permian sandstones and shales. The Permian to Lower Triassic Amanous Formation forms the basal unit (Fig. 5). Shales become dominant towards the top of this formation with dolomites and dolomitic limestones in the central Palmyride trough.

The top of the Amanous Formation marks either a halt in rifting (Brew *et al.*, 2001), a decrease in accommodation space within the Palmyride Basin and/or a phase of tectonic inversion (Wood, 2001). Extremely low sea levels prevailed in the Early Triassic (Haq *et al.*, 1988) and contributed to an extensive unconformity recognized in Israel (Gvirtzman and Weissbrod, 1984; Hirsch, 1991), in Jordan (Wood, 2001), in interior Syria (Brew *et al*., 2001) and elsewhere in the Arabian region (Beydoun, 1991). Areas where the unconformity is absent were depocentres which remained submerged – e.g. central Palmyrides, where the Amanous Formation passes gradationally into the overlying Kurrachine Dolomite (Fig. 5). The Middle Triassic Kurrachine Dolomite (or Mulussa B) in Syria directly overlies Permian, Carboniferous and sometimes even Silurian strata (Brew *et al*., 2001). Dolostones with reservoir potential dominate the formation in the Palmyrides and in the northern Syrian regions. Source potential may be associated with local deep-marine limestones. The inner Palmyride Basin hosts increasingly more evaporitic deposits (Fig. 5; Wood, 2001).

The overlying Kurrachine Anhydrite (or Mulussa C), which forms an excellent seal for the underlying reservoir and source rock units, was probably deposited within the Palmyride Basin when the marine connection was temporarily lost (Wood, 2001). The anhydrites, found in the subsurface, covered the Aleppo High and the Syrian Coastal Ranges (Sawaf *et al*., 2001). The Late Triassic Mulussa D and E are characterized by a return to limestones interbedded with anhydrites and dolomites and are restricted to the Palmyride/Sinjar basins. In Israel, the equivalent Early Carnian Mohilla Formation consists of a thick dolostone and evaporite sequence (reaching 210 m; Druckman and Magaritz, 1991; Benjamini *et al*., 1993). This coincided with a fall in eustatic sea-level and the global "Saharan" event at 231 Ma (Hirsch, 1991).

An extensive latest Triassic unconformity was followed by a regional transgression which did not affect the Aleppo and Hamad/Rutbah Highs bounding the Palmyride Basin (Brew *et al*., 2001). Early Jurassic (Liassic) sedimentary rocks in the Levantine region have similar lithological characteristics to the underlying Triassic succession and consist of cyclically-deposited sub- and supratidal carbonates, evaporites and continental clastics (Benjamini *et al*. 1993; Buchbinder and Le Roux, 1993).

Jurassic strata are surface-exposed in several locations in the Levant. In Sinai and the Negev, the Late Liassic to Kimmeridgian succession, made up of carbonates, marl/shale, sandstones and volcanics, is over 2000 m thick (Hirsch *et al*., 1998). At Mount Hermon (SW margin of Anti-Lebanon; Fig. 2), alternating massive and thin-bedded carbonates of Liassic to Kimmeridgian age are more than 1200 m thick (Mouty and Zaninetti, 1998). The lower boundary of the Jurassic sequence is still not accurately defined in Mount Lebanon but previous studies have considered the oldest dolostones exposed in the Nahr Ibrahim valley to be Liassic (Renouard, 1951; Dubertret, 1955; Nader, 2003). In this case, the Jurassic sequence in Mount Lebanon would be about 1420 m thick (Fig. 3). In the Palmyrides of internal Syria, these rocks were intensively eroded during the Late Jurassic – Early Cretaceous, and Upper Jurassic rocks are absent. The total thickness of the remaining Lower-Middle Jurassic varies between tens and a few hundreds of metres (Mouty, 1997; Mouty and Zaninetti, 1998). There is no clear evidence for the presence of Tithonian strata in Lebanon, Syria, Jordan and west Iraq (Mouty, 2000).

Early Jurassic strata are characterized in Lebanon and Syria by shallow-marine facies, mostly carbonates. Within the Palmyride Basin, the Lower Jurassic is not distinct from the Upper Triassic as the transgression that started in the latest Triassic continued through the Early Jurassic and covered most of Syria and probably all of Lebanon. The resulting deposits generally consist of grey, fine to medium crystalline dolostone (locally anhydritic) together with intervals of limestone and marl (Fig. 5; Renouard, 1955; Mouty, 2000; Wood, 2001). The lagoonal-evaporitic depositional environment that prevailed throughout most of the Triassic (e.g. Hayyan Gypsum in Syria) passed progressively into deeper-marine conditions, hence the dominance of mudstones, wackestones and packstones with rare anhydrite (e.g. Renouard, 1955; Walley, 1997; Brew *et al*., 2001; Wood, 2001) in the Lower Jurassic succession.

The Middle Jurassic (Aalenian to Oxfordian) succession is represented by undifferentiated dolomicrites over 1000 m thick in subsurface Israel (Haifa Formation; Hirsch *et al*., 1998). A south-north facies change (i.e. continental passing into shallow-marine) observed for the Early Jurassic was generally repeated during the Middle Jurassic. The Bqaasem Limestone (Dubertret, 1960) exposed in Mount Hermon (cf. Fig. 3), consisting of 150 m of oolitic bioclastic limestones, is Bajocian-Bathonian (Mouty and Zaninetti, 1998). These oolitic facies result from a regression at the start of the Bathonian. The Callovian generally marks a return to micritic limestones with undifferentiated shallow-marine carbonates in Mount Lebanon (Bajocian to Oxfordian; Dubertret, 1955).

Uppermost Jurassic rocks cropping out in Mount Hermon and Anti-Lebanon consist of massive limestones (Oxfordian-Kimmeridgian; 15 m thick), overlain by a bed, less than a metre thick, of oolitic limestones of Kimmeridgian age with marl and basalt intercalations (Mouty and Zaninetti, 1998). A similar pattern is observed in Mount Lebanon but the two units are much thicker. In the Syrian Coastal Ranges, Oxfordian-Kimmeridgian reefal carbonates (Nasirah Formation) unconformably underlie Early Cretaceous sandstones (Mouty, 1997).

Significant erosion occurred by the beginning of the Kimmeridgian as the sea retreated westwards and most of Syria and Lebanon became subaerially exposed by the end-Kimmeridgian (Mouty, 2000). This could have been also associated with tectonic movements in Lebanon (especially in the northern part of the country; Dubertret, 1955; Renouard, 1955; Saint-Marc, 1980; Picard and Hirsch, 1987; Noujaim Clark and Boudagher-Fadel, 2001; Walley, 2001). Most of the post-Callovian to Early Albian succession is absent in interior Syria. In addition, Oxfordian-Kimmeridgian alkaline volcanism (which continued intermittently through the Early Cretaceous) occurred in Mount Lebanon (Bhannes Formation; Fig. 3), Anti-Lebanon, the Syrian Coastal Ranges and the Palmyrides (Mouty *et al*., 1992). Wilson (1992) and Garfunkel (1992) suggested mantle plume activity centred in the Levant region throughout the Late Jurassic – Early Cretaceous. Nader and Swennen (2004a) discussed the influence of an early phase of karstification (ca. Late Jurassic to Early Cretaceous) of the Jurassic carbonates on their reservoir properties, associated with local uplift in central-northern Mount Lebanon. The overlying Upper Jurassic basalts and claystones, as well as Lower Cretaceous shales, marls and basalts, may form efficient seals.

Mesozoic (post-Jurassic)

Volcanic activity together with associated uplift, emergence and erosion continued into the Early Cretaceous (Noujaim Clark and Boudagher-Fadel, 2001). Contemporaneous block-faulting and fault-reactivation probably related to this volcanism led to locally enhanced sediment deposition in the Palmyride Basin (Brew *et al*., 2001). Robertson and Dixon (1984) associated this faulting with accelerated spreading in the Eastern Mediterranean Basin. Nader *et al*. (2004, 2007) investigated hydrothermal dolomitisation associated with the Late Jurassic – Early Cretaceous faulting and volcanism in central and nothern Lebanon. They demonstrated that fault-associated strata-discordant dolomite bodies enhance the reservoir potential of the Jurassic succession (Nader and Swennen, 2004a, b).

After a sedimentary hiatus lasting some 25 Ma, widespread distribution of fluvio-deltaic sandstones and shallow-marine shales (up to hundreds of metres thick) occurred in the Early Cretaceous (Litak *et al*., 1998; Brew *et al*., 2001; Wood, 2001) with local volcanics (Dubertret, 1955). These sandstones include the Chouf Formation in Lebanon, Palmyra/Rutbah sandstone in Syria, and Kurnub sandstone in Jordan. They are generally dated as Neocomian to Barremian and form a strong seismic and electrical log marker (Wood, 2001). The Hamad and Rutbah Highs remained emergent at this time and until the Late Cretaceous (cf. Figs. 4 and 5; Brew *et al*., 2001). The Cretaceous sandstones are believed have been derived locally from Carboniferous and Permian sandstones. This provenance is also suggested by the fact that the sandstones become more shaly and carbonaceous to the north, reflecting increasing distances from the Hamad and Rutbah Highs. In northern Mount Lebanon, there is local thinning of the sandstones (Chouf Formation); the thickness varies from 300 m in central Lebanon to tens of metres in the Qadisha area in the north (cf. Figs. 2 and 3). This is probably due to local uplift before and during the deposition of the Chouf Formation.

The sandstones pass gradationally up into Late Barremian - Early Aptian nearshore carbonates (oolitic, sandy; e.g. Abeih Formation, Lebanon) and reefal carbonates (Mdairej Formation, Lebanon) (cf. Figs. 3 and 5). The surface-exposed Albian Hammana Formation in Lebanon indicates a brief, local return to near-shore, supra-tidal conditions (Noujaim, 1977; Doummar, 2005) and/or terrigenous clastic deposition (Walley, 2001), before a sea-level rise in the Late Albian. In general, slow subsidence and the stability of the relatively low sea-level (Haq *et al*., 1988) combined to result in Albian-Turonian carbonate platform deposition across most of Syria and Lebanon, e.g. the Sannine and Maameltain Formations in Lebanon and the Judea Formation in Syria (Mouty and Al-Maleh, 1983) (Fig. 5). The palaeogeographic configuration of shallow to deeper environments along westwards and SW trends was maintained. Clear east-west facies changes are observed across Mount Lebanon (e.g. Sannine Formation; stratigraphic thickness reaching 600 m), corresponding to supratidal - peritidal environments as well as reefal and lagoon settings and deeper-water pelagic carbonate realms (Ja'ouni, 1971; Walley, 1997; Nader *et al*., 2006). Thin-bedded, chalky and cherty sediments as well as slump and scour features characterize the Sannine Formation in its coastal (western) facies (Nader, 2000; Nader, 2003; Nader *et al*., 2006).

In Lebanon, the Turonian Maameltain Formation (Fig. 3) has an average thickness of 200 to 300 m. Lithologic and diagenetic features indicate a change from deep to shallow-marine conditions during sedimentation (Noujaim, 1977; Nader, 2000). Wood (2001) proposed an unconformity marking the Turonian-Senonian boundary within the Palmyride Basin. Müller *et al*. (2010) confirmed a similar regional unconformity in Mount Lebanon, based on biostratigraphic data, spanning the Coniacian to Early Santonian time interval. As a result of ophiolite obduction and other tectonic factors, northern Arabia underwent renewed subsidence throughout the Senonian; the Chekka Formation in Lebanon may reach

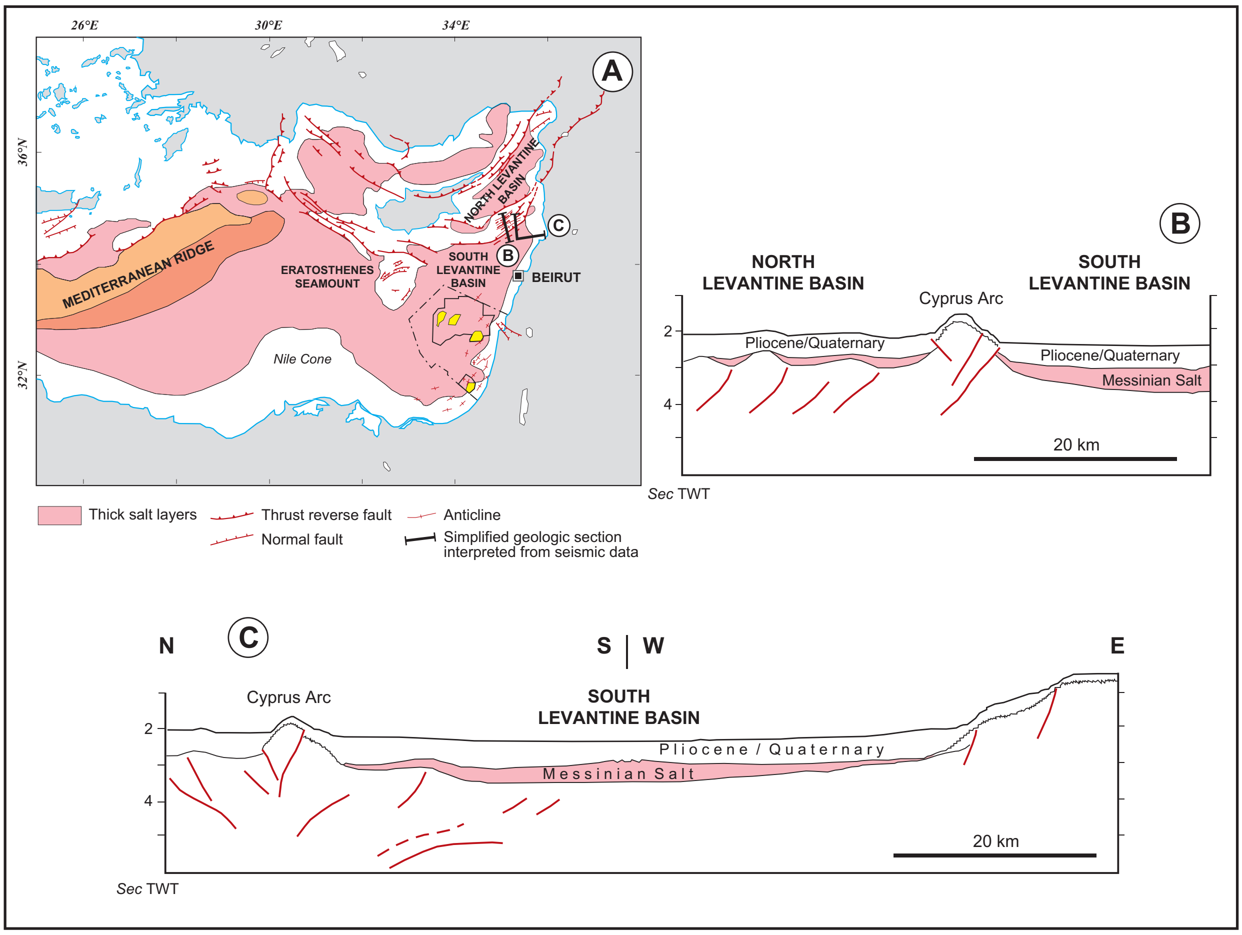


Fig. 6. Structural configuration of the Eastern Mediterranean Basin (A) and simplified geologic sections (B, C) which were interpreted from seismic sections oriented south-north and east-west, respectively. Map and seismic data from Sage and Letouzey (1990). The locations of the *Leviathan, Tamar, Dallit* and *Mari-B* discoveries are indicated by yellow ovals on the map.

600 m in thickness (cf. Fig. 6). Sedimentary facies point to increasing water depths after Turonian times in the Palmyrides (Brew *et al*., 2001) and in Lebanon (Nader, 2000). The very finely-grained biomicrites (Nader, 2000) represents high sea-level conditions on the outer part of a continental platform, with pelagic chalk deposition (Walley, 1997). Nevertheless, shallower conditions and even partially emergent zones occurred locally until the Late Senonian (Dubertret, 1955; Mouty and Al-Maleh, 1983). Phosphatic limestones are also present within this sequence, mainly in the lower Senonian (Dubertret, 1955). Their location was controlled by palaeogeographic factors (Al-Maleh and Mouty, 1994).

Maastrichtian to Early Eocene strata (e.g. Shiranish and Bardeh Formation in Syria) are characterized by an increase in marl content with planktonic and benthonic foraminifera, indicating greater water depths in a low-energy open-marine environment, with the thickest strata occurring in the central areas of the Palmyride Basin (Al-Maleh and Mouty, 1988). A tectonic-induced change in palaeogeography in interior Syria is indicated by the Paleocene limestone which sharply overlies the Maastrichtian Shiranish marls (Wood, 2001). In Lebanon, marine deposition in isolated depocentres persisted until the Middle Eocene (Dubertret, 1955). A major phase of tectonism occurred in the Late Eocene through Late Oligocene, culminating in much of the present-day uplift of Mount Lebanon during a second phase of Syrian Arc folding.

Cenozoic

In the Neogene, the opening of the Red Sea and activity on the Dead Sea Transform Fault and the Levant Fault System accentuated the uplift of Mount Lebanon and resulted in the regional-scale present-day topographic structure. Based on geophysical data from the 2003 Shalimar offshore survey, Elias *et al*. (2007) suggested that the uplift of Mount Lebanon was chiefly driven, since the Late Miocene, by activity on a 160 km long east-dipping thrust system (the Mount Lebanon Thrust) located about 20 km offshore the Lebanese coastline.

During the Paleogene, most of the northern Arabian platform remained under marine conditions with extensive pelagic deposition (mudstone/wackestone).

The Early Eocene Arak Formation (carbonate and siliciclastic facies) was deposited in shallower waters. Chalk, chalky limestones and marls rich in microfossils and nannofossils characterize the low-energy pelagic carbonate deposits of the Middle Eocene (Fig. 5). For most of the Late Eocene and Oligocene, the Palmyrides region was covered by nummulitic sandy limestones and sandstones with major lateral changes which indicate tectonic uplift (Yzbek, 1998). Equivalent strata were either not deposited or eroded in Lebanon.

The second phase of Syrian Arc folding occurred in the Late Eocene (Guiraud and Bosworth, 1997) including uplift of the Syrian Coastal Ranges (Brew *et al.*, 2001). The associated stratigraphic gap in onshore Lebanon spans the Late Eocene and Oligocene. The Lebanese meso-scale structures also developed at this time. This major uplift was accompanied by a global sea level fall (Haq *et al.*, 1988). A period of non-deposition and/or erosion in Lebanon continued until the mid-Miocene (Figs 3, 5).

Paleogene strata have not yet been properly classified in Lebanon, with the exception of the recent biostratigraphic work of Müller *et al.* (2010). Surface-exposed Paleocene rocks have been included within the Chekka Formation. The Eocene Formation is divided into early and middle units (Dubertret, 1975; Walley, 1997). The former is composed of marls and chalky limestones with chert in southern Lebanon and the Bekaa (cf. Fig. 2). The latter is made up of nummulitic limestone. The total thickness of these strata reaches 900 m in southern Bekaa (Fig. 2). According to Müller *et al*. (2010), a number of regional hiatuses can be recognized in the Cenozoic rock successions exposed in Lebanon. These are: (i) the topmost Maastrichtian to lowermost Paleocene, (ii) Lower Oligocene, and (iii) lowermost Miocene (Aquitanian to lowermost Burdigalian).

By Middle Miocene times, Mount Lebanon and the Anti-Lebanon were uplifted, and sedimentation was henceforth restricted mainly to the coast and the inland Bekaa basin. Miocene deposits therefore have two distinct facies. Coastal facies are exposed in the Nahr el Kalb region (central Lebanon) and Jebel Terbol (northern Lebanon; Fig. 2). At Nahr El Kalb, sediments consist of littoral limestones containing corals, algae and bivalves, passing into conglomerates and beach rocks (Dubertret, 1955; Walley, 1997). At Jebel Terbol, Miocene rocks are composed of creamy limestones overlain by well-cemented conglomerates of continental origin (Middle to Late Miocene; Müller *et al*., 2010). The Miocene section has a stratigraphic thickness ranging between 200 and 300 m (Dubertret, 1975; Walley, 1997). In the Bekaa basin, Miocene deposits are composed of alluvial fan and lacustrine clastics up to 1.5 km thick (Walley, 1997).

A final transition to continental conditions throughout Syria and interior Lebanon occurred during the Miocene. Deposition of the Senonian – Late Oligocene sequence across Syria and Jordan was terminated by uplift and marine regression (Wood, 2001). Subsequently, local uplift and erosion created intramontane basins including the Bekaa basin. To the NW and west of Mount Lebanon, deeper open-marine conditions prevailed during the Miocene and Pliocene.

Volcanic activity is indicated by Middle Miocene basalts. Further marine regressions occurred in Late Miocene times as evidenced by hiatuses and deposition of evaporites correlative with the Messinian “salinity crisis”. The Pliocene sequence (up to 450m thick) shows a progression towards continental deposition with some basaltic volcanism (Brew *et al*., 2001). Volcanic rocks were extruded from 24 to 16 Ma throughout western Syria with the exception of the Coastal Ranges. This period approximately coincides with advanced stages of Arabia-Eurasia plate convergence (Mouty *et al*., 1992). The absence of volcanism from about 16 to 8 Ma roughly corresponds to an interval when there was little Red Sea spreading and no movement on the Dead Sea Fault (Hempton, 1987).

In Lebanon, the basal Pliocene is marked by an important transgression (Müller *et al*.; 2010). Inland, Miocene rocks are overlain unconformably by fluvial and lacustrine sediments of Pliocene to Pleistocene age. These sediments predominate in the Bekaa and Akkar areas (northern Lebanon; Fig. 2) and have a variable thickness that may reach 500 m (Dubertret, 1975). Volcanism in southern and northern Lebanon is represented by basalts and volcanic plumes (Abdel Rahman and Nassar, 2004).

Roberts and Peace (2007) discussed the stratigraphy of the Levantine Basin, offshore Lebanon based on seismic data. They suggested that the shallow-water platform present in coastal Lebanon passes into a relatively deep basin to the west. While highstand systems tracts within the Levantine Basin are believed to consist of aggrading and back-stepping carbonate platforms, the lowstand systems tracts may correspond to siliciclastics and deep-water carbonate turbidite systems (Gardosh and Druckman, 2006). These are generally sealed by Tertiary shales and Messinian evaporites. The latter appears to be locally breached by deep-seated faults (observed on seismic lines), especially close to the coastline.

POTENTIAL OFFSHORE AND ONSHORE PLAYS

Hydrocarbon shows in Lebanon were outlined by Nader and Swennen (2004a, and references therein); their locations and nature are illustrated in Figs. 2 and

3. Since no hydrocarbon production takes place in Lebanon, such hydrocarbon shows are the only direct evidence for the petroleum potential of onshore Lebanon and the coastal margin. Five out of the seven drilled wells intercepted major shows (Fig. 2): these were *Terbol* (TD: 3065 m), *El Qaa* (TD: 2557 m), *Yohmor* (TD: 2672 m), *Sohmor* (TD: 1423 m), and *Tell Znoub* (TD: 1421 m). In addition, Jurassic and Cretaceous rock formations include shows in the form of asphalt, bitumen/coal, solid hydrocarbons and natural gas (Fig. 3).

According to Renouard (1955), some hydrocarbon shows in Lebanon are characterized by the presence of authigenic quartz (e.g. Metrit, Chekka, south Bekaa; Figs. 2 and 3). He demonstrated the association of such hydrocarbons with quartz cement, invoking the circulation of hydrothermal fluids oversaturated with silica and asphalt along faults and fractures. Aqueous inclusions trapped within the quartz crystals indicate homogenization temperatures of about 150°C, which could imply an origin from Triassic or deeper units on the basis of regional and stratigraphic considerations. The Hasbaya heavy oil seeps (Fig. 2), known since prehistoric times, may indicate active migration (in a liquid state) at the present-day from a possible deep reservoir (Al Haddad, 2007). However, both the mode of occurrence and geochemical analyses (Renouard, 1955) tend to support an allochthonous origin for the hydrocarbons. This is also consistent with the suggestion by Horowitz and Langoskey (1965) that the Late Jurassic and Early Cretaceous oil reservoirs (and asphalt seeps) in Israel are derived from pre-Jurassic rocks (probably Triassic), based on studies of the palynological remains in hydrocarbons. Beydoun (1977a) speculated (based on regional geology) that Triassic and Palaeozoic units may act as source and reservoir rocks in Lebanon.

Offshore Potential Plays

The initial development of the Eastern Mediterranean Basin has been related to the opening of the Neo-Tethys at the beginning of the Mesozoic. During the collision of the Afro-Arabian and Eurasian plates in the Late Cretaceous, the Eastern Mediterranean basin was cut off from its eastern extension. Sage and Letouzey (1990) divided this basin, based on structural studies, into three areas (Fig. 6A): (i) to the north, a "thrust belt" – part of the Alpine orogen and including the North Levantine Basin; (ii) in the south, a stable foreland, including the Herodotus Abyssal Plain, the (South) Levantine Basin, the Eratosthenes Plateau and the Nile Cone; and (iii) an intermediate central area consisting of the deformation front (Cyprus Arc, the Florence Ridge and the Mediterranean Ridge).

The Lebanese offshore covers parts of the southern and northern Levantine basins as well as the Cyprus Arc. Messinian evaporites are in general thinner in the northern than the southern Levantine basin (Fig. 6B). A seismic line trending east-west and terminating close to the Syrian shoreline (Fig. 6C) shows westward thinning of sub-salt (Jurassic and Cretaceous) units and the erosional surface below the Pliocene-Quaternary section. The thick sub-salt series to the south of the Cyprus Arc thins in the direction of the continental margin (Sage and Letouzey, 1990). In the area of the Arc, these rock units are affected by folds, thrusts and backthrusts which were synchronous with Messinian evaporite deposition. At the deformation front, the faults were still active in the Plio-Quaternary (Fig. 6). Based on sesimic analyses, Sage and Letouzey (1990) suggested that a major compressive phase offshore Cyprus preceded the deposition of the Messinian series. Compressive structures are also believed to be present in the Upper Miocene, but most of the shortening is supposed to be pre-Messinian and the salt does not represent a major *décollement*. Sage and Letouzey (1990) thought that Cretaceous nappes and ophiolites constituted a likely *décollement* level. Briais *et al*. (2004), based on geophysical data produced during the offshore 2003 Shalimar survey, described Plio-Quaternary turbidites detached above Messinian evaporites and folded some 30 km offshore Lebanon. The regional compressional regime that is believed to have begun by the end of the Cretaceous (Syrian Arc folding) seems therefore to have been continuously active to the present-day, although with varying rates. Alternatively, the post-Messinian, Plio-Pleistocene successions appear relatively undeformed except where the underlying Messinian salt underwent deformation (mainly at major collision zones and/or near the basin margins).

Roberts and Peace (2007) recognized and illustrated 13 potential hydrocarbon plays ranging in age from Triassic to Neogene-Pliocene in the (South) Levantine Basin, offshore Lebanon. These include karst-associated plays, carbonate build-ups, anticlines and inversion structures, onlaps and Messinian-related (sub-, intra- and post-salt) plays. For instance, folds and faults trending SW-NE appear to affect Cretaceous and Cenozoic strata on the seismic sections. This general tectonic trend is parallel to the orientation of structures interpreted to result from Syrian Arc deformation with which they may therefore be related. Messinian evaporites (up to 1500 m thick in the Levantine Basin) are considered to be an effective seal; underlying sediments, if shown to have good reservoir characteristics, could therefore provide promising exploration targets (Roberts and Peace, 2007). The recent discoveries of gas accumulations in the *Tamar, Dalit* and *Leviathan* wells offshore Israel (Fig. 6A) encountered important payzones in sub-salt Oligocene and Miocene sandstones probably capped by intra-Miocene shales (*www.nobleenergyinc.com*).

Two interpreted 3D seismic lines (Fig. 7), with no precise coordinates, were kindly provided by PGS; their detailed interpretation has been discussed at international conferences (e.g. Geo2010: Sortemos *et al*., 2010). The lines confirm most of the potential play types which were proposed by Roberts and Peace (2007).

The first line was shot over the (South) Levantine Basin, parallel to the coast about 50 km offshore Beirut (Fig. 7A). The second line (Fig. 7B) was shot with an east-west orientation, starting 70 km offshore Tripoli, passing over the Latakia Ridge (part of the deformation front separating the southern and northern Levantine Basins) and crossing into offshore Cyprus. As indicated by the *Tamar* well offshore Israel and recent 3D seismic data acquisition, the thickness of the Cenozoic package, previously estimated from seismic character, has been revised (Roberts, GGS-Spectrum, *pers. comm*., 2010; Semb, *pers. comm.* 2010), and is now believed to be thicker than previously thought (up to 6 km).

In the North Levantine Basin (west of the Latakia Ridge), the Messinian evaporites appear to be shallower than those to the east of the Ridge, probably due to further compression and uplift to the west and north of the ridge with respect to the South Levantine Basin. Faulting clearly affects the eastern flank of the Latakia ridge (Fig. 7B). Deformation within the southern Levantine Basin appears to have been active at least until the deposition of the Messinian evaporites. According to the recent PGS data, Oligocene deposits are present in the (South) Levantine Basin (Fig. 7B) and show similar seismic attributes to the Oligocene-Miocene reservoirs recently discovered offshore Israel. Taking into account the major uplift and erosion occurring onshore at the equivalent time (no Oligocene deposits are found onshore Lebanon), these deposits could be attractive for further exploration as they may have originated from the erosion of the platform rocks adjacent to the Eastern Mediterranean basin. This could also suggest that the same Oligocene sandstones which are being targeted offshore Israel may extend northwards.

2D seismic data from offshore Lebanon has indicated probable siliciclastic systems in the sub-salt Oligo-Miocene succession, including channel systems and possible sandbodies (Semb, *pers. comm.* 2010). Gardosh *et al*. (2008) suggested two depositional regimes for the Oligo-Miocene gravity-flow sandstones offshore Israel (Fig. 8): channel fills confined to intra-slope canyons and unconfined sand sheets and lobes at distal slope locations and on the basin floor.

Potential source rocks present in the offshore Levantine Basin are believed to include Senonian-Eocene black shales and marls (Gardosh *et al*., 2006) and Lower Miocene shales (Dolsen *et al*., 2005; Gardosh *et al*., 2006). Miocene deep-marine clastics, turbidites and channel fill sands may form reservoir rocks (Semb, *pers. comm*. 2008, 2010). According to recent seismic data, potential structures offshore Lebanon may have closures exceeding 50 sq. km and some exceeding 100 sq. km.

Continental Margin Potential Plays

Miocene rocks exposed in the Lebanese coastal region and on the Tripoli Islands (Fig. 3) are composed of shallow-marine limestones (with corals, algae and bivalves) that pass landwards into conglomerates and beach rocks. The transition from conglomerate to reefal carbonates is at the scale of a few kilometres and is not continuous along the eastern Mediterranean coastline (Fig. 3), implying that reefs could have been formed offshore on local palaeo-highs. Miocene reefal carbonates onshore Lebanon have cavernous porosity; the Hab Cave in Dahr Al Ain, near Tripoli City, is more than 1500 m in length. Underlying uppermost Cretaceous successions may include source rocks and the overlying thick Messinian evaporites may act as a regional seal (Fig. 7). The Miocene carbonates may therefore form good reservoir targets. However, it is not clear if oil migration occurred before or after sealing. If oil migration occurred during the compression that preceded deposition of the Messinian evaporites, major oil accumulations are unlikely to have formed. However, if migration occurred after deformation of the Messinian evaporites – and where the Messinian seals were not breached by deep-seated faults commonly found near the coastline – then the underlying Miocene may include interesting plays.

Other exploration targets along the continental margin may include Upper Cretaceous reefal carbonates; the Lower Cretaceous Chouf sandstones, equivalent to the Rutbah sandstones in Syria which form reservoirs in the Euphrates Graben; Jurassic platform and reefal carbonates influenced by fracture-associated hydrothermal dolomitisation; and Triassic dolomites which may also have source potential. Fig. 10 shows swuch potential reservoirs which could be charged by Triassic and/or older source rocks

Onshore Potential Plays

Seismic surveys offshore Tripoli in 1970 and 1971 located the compressional Ile du Palmier structure (Fig. 2) (Beydoun, 1977a). A later seismic survey (1993) pointed to the presence of pre-Jurassic salt in the core of this structure (Beydoun and Habib, 1995), although the extent of diapirism was not clear due to the poor quality of the seismic data (Nader and

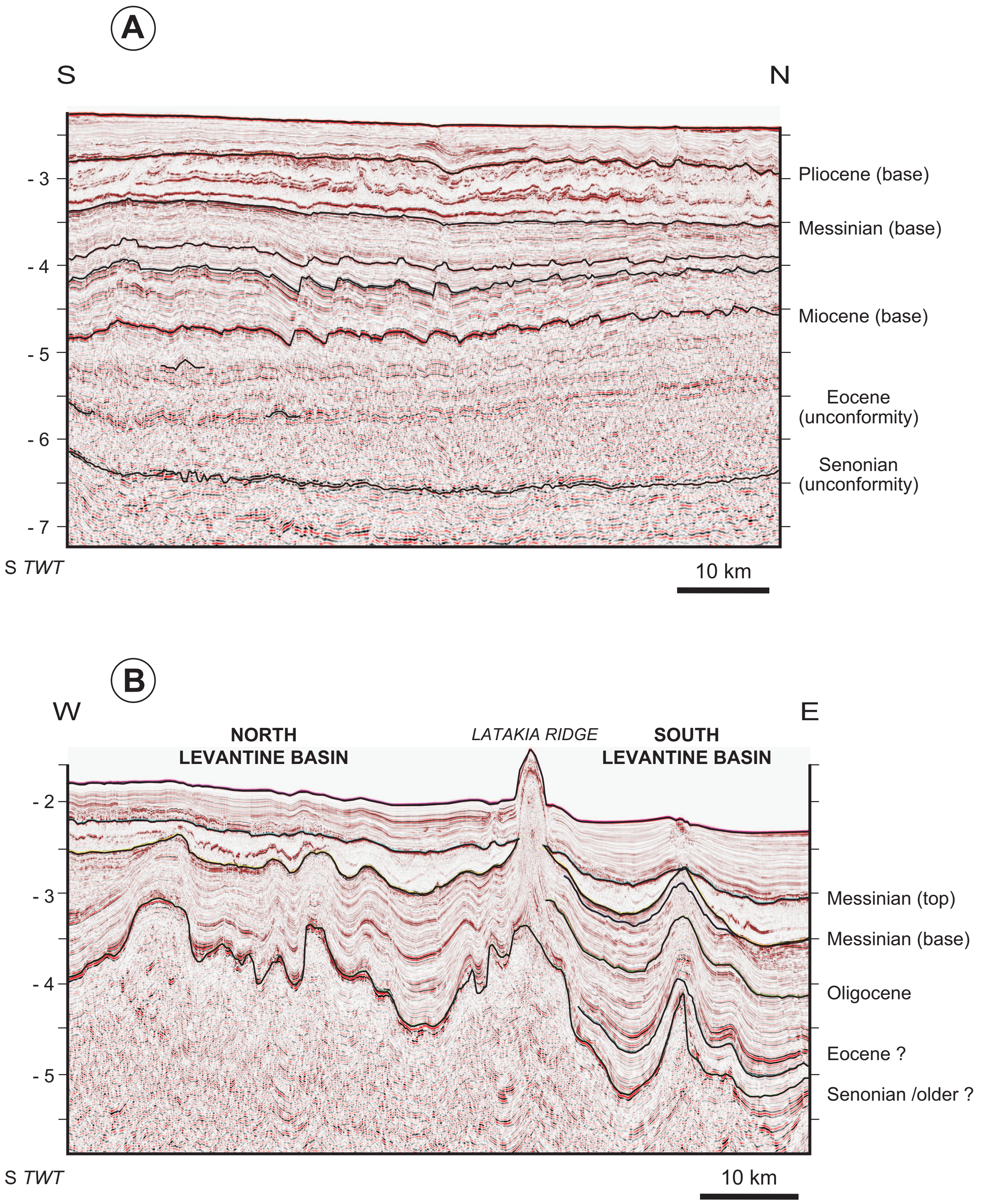


Fig. 7. Seismic lines from offshore Lebanon (reproduced courtesy of PGS); (A) sourth-north line from the Levantine Basin in water depths of ~1700 m; (B) west-east seismic line offshore Lebanon and Cyprus in water depths of ~1500m, traversing the Latakia Ridge.

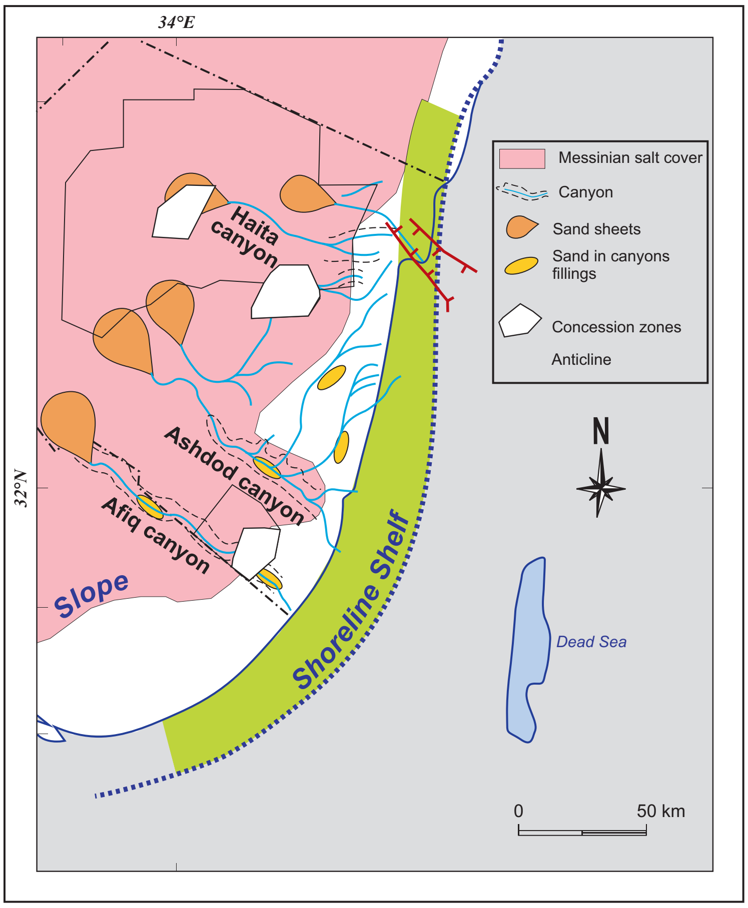


Fig. 8. Schematic map after Gardosh *et al.* (2009) of offshore Israel/Palestine with suggested distribution of Oligo-Miocene gravity-flow sands (channel filling confined in intra-slope canyons and sand sheets and lobes on distal basin floor) based on seismic and well data. The Tamar concession area is shown.

Swennen, 2004b). However, the box-fold structure may overlie a basal detachment (Late Triassic – Early Jurassic) and the salt may therefore be comparable to the Kurrachine salt of the Palmyrides (Beydoun and Habib, 1995).

A geo-electrical survey in the Nahr Ibrahim valley (central Lebanon: location in Fig.8) indicated the presence of a conductive horizon (interpreted to be evaporitic) at 650 m below the oldest-exposed Jurassic rocks (Renouard, 1955). These inferred evaporites may be an extension of the Late Triassic evaporites which are widespread in Syria (Beydoun and Habib, 1995; Brew *et al.*, 2001) and southern Israel (Druckman, 1974). If evaporites are present in the Mount Lebanon area, the Triassic succession here would be sealed and protected from the meteoric waters which invaded the overlying Jurassic carbonates (Nader and Swennen, 2004a). The pre-Jurassic succession may therefore have exploration potential in northern Mount Lebanon, particularly at the Qartaba "horst" structure (Nader and Swennen, 2004b) which formed before the end of the Jurassic.

The Qartaba structure (~20 km long, ~5 to 10km wide) is bounded by two SW-NE trending flexures (Fig. 9A). The flexures are combined with minor faults which maybe why Dubertret (1955) and Renouard (1955) described the structure as a horst. From structure-contour mapping, Renouard (1967, unpublished report) showed that in the subsurface the structure may reach a length of 75 km and a width of 10-25km, with a maximum closure height of 1000 m. The eastern limb of the local anticline dips more steeply (up to 55°; see Fig. 9B, C) than the western limb, which has an average dip of 20°.

Beydoun (1977a) also investigated the Qartaba structure and estimated the depth of potential Triassic reservoirs. He chose a location at Qornet al Aaliyeh and determined the thicknesses of the underlying rock units from regional stratigraphic correlations. He estimated that the boundary between the Permian and the Triassic at this location was at 1952 m and that the Carboniferous began at around 2952 m. Renouard (1967, unpublished report) tentatively identified three sites for exploration well locations at this structure.

DISCUSSION

Potential source rocks in Lebanon correspond to those recognized in adjacent countries and include Ordovician and Silurian (e.g. Tanf "hot shales"), Permo-Triassic, Lower/Middle Jurassic (Kesrouane Formation) and Upper Cretaceous (Chekka Formation) units. According to regional correlations, Cambrian (Burj limestones), Ordovician, Carboniferous, Permo-Triassic (Kurrachine-equivalent), Jurassic, Cretaceous (Chouf sandstone,

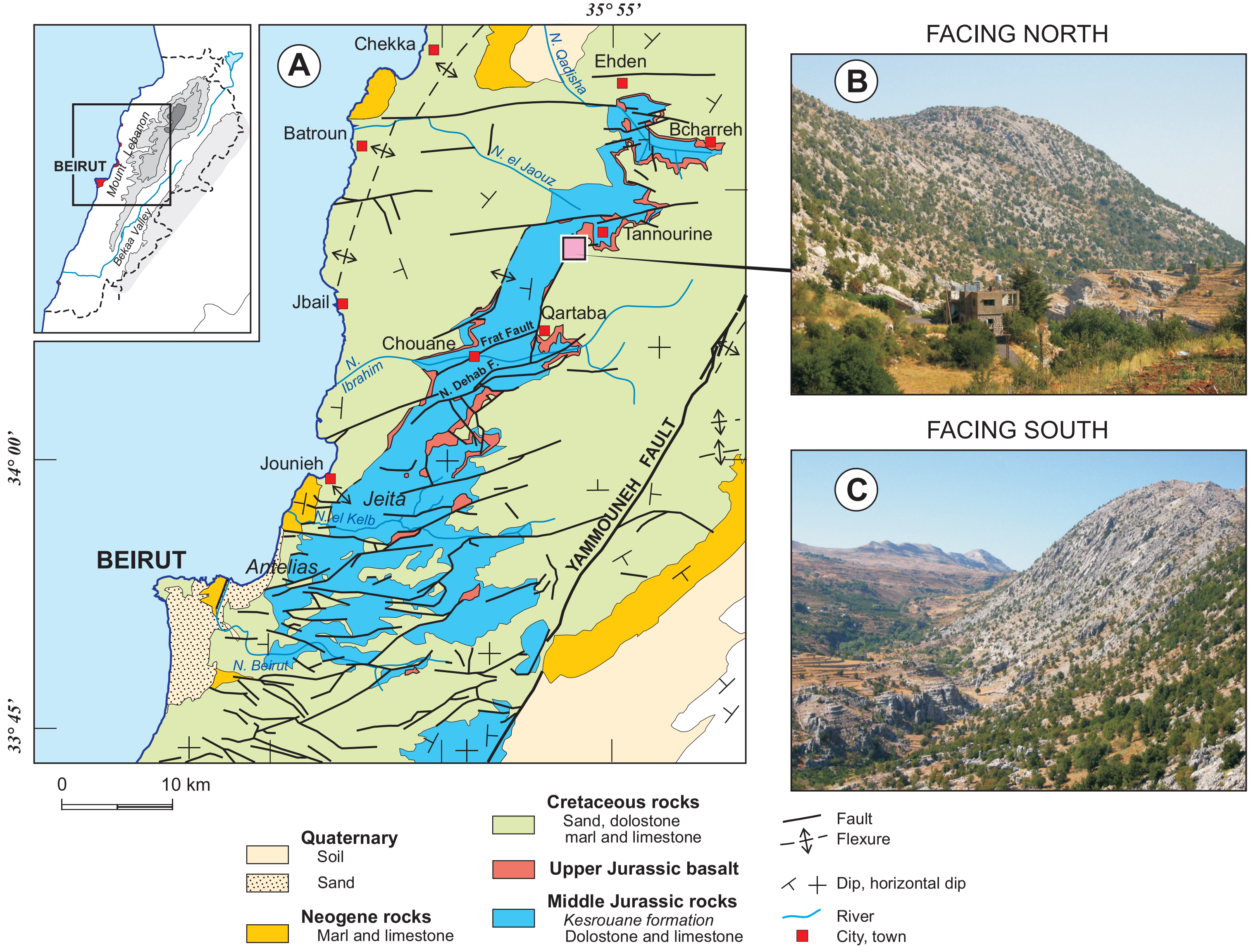


Fig. 9. Major outcrop characteristics of the Qartaba structure. (A) Geological map of central-northern Lebanon showing the extent of the Qartaba structure (after Dubertret, 1955); (B) Photograph of the eastern flexure (facing north); (C) photograph of the eastern flexure (facing south).

Sannine and Chekka carbonates) as well as Oligo-Miocene carbonates and siliciclatsics may provide potential reservoir rocks. The Kurrachine evaporites (Middle/Upper Triassic), the Bhannes volcanics (Upper Jurassic), the Hammana marls (Albian), the Chekka marls (Senonian) and the Messinian evaporites (offshore) may form efficient seals. Potential traps may relate to Syrian Arc folding (post-Late Cretaceous); local traps may also have been formed during Late Jurassic / Early Cretaceous uplift of northern Mount Lebanon and Early Mesozoic rifting.

A schematic model of plays on- and offshore Lebanon is presented in Fig. 10. The model is based on regional facies correlations and geological history, the few known hydrocarbon indications and shows, an interpretation of available seismic lines and comparison with nearby countries.

The onshore Qartaba structure constitutes one potential structural trap (Fig. 9). Within this structure, the Triassic Kurrachine evaporites may form an efficient seal which has protected underlying Triassic reservoirs from degradation by meteoric waters. Hydrocarbons may have been generated by Triassic or underlying source rocks (e.g. Carboniferous, Ordovician/Silurian). In the Palmyride Basin, Syria, analogous source rocks underwent deep burial and generated mostly gas; this may have migrated and accumulated within the Qartaba structure since the Late Jurassic. Similar anticlinal structures are known in Lebanon (on- and offshore) and include the Ile du Palmier structure near Tripoli.

The shallow-water continental margin offshore Lebanon may have a "layer-cake" stratigraphic architecture in which Triassic, Jurassic, Cretaceous and Oligo-Miocene strata including reservoir and source rock intervals are separated by evaporites (occurring between Triassic and Jurassic sequences), as well as by volcanics, clays and marls (occurring at the Jurassic/Cretaceous and Cretaceous/Paleogene boundaries) (Fig. 10). Messinian evaporites are also present (Figs. 6A, 10). Hydrocarbons originating in Triassic source rocks may have remained *in situ* or migrated into relatively small-scale traps (e.g. the Ile du Palmier structure) sealed by Triassic evaporites. Lower-Middle Jurassic source rocks may have generated hydrocarbons, by analogy with Syria, which were sealed by Upper Jurassic – Lower Cretaceous volcanics, marls and clays. Lower Cretaceous sandstones and Cenomanian-Turonian carbonates may also include source and reservoir rocks, as validated by Turonian fossil-fish beds at outcrop and shows in various wells, provided that they are properly sealed (e.g. by Upper Cretaceous shales or Messininan evaporites)

The maturity of generated hydrocarbons depends on the overburden thickness and the presence or absence of Oligocene deposits. Fig. 7B shows interpreted Oligocene strata present near the Latakia Ridge. Offshore Tripoli, potential source rocks in the Chekka Formation are believed to underlie a succession about 1500 m thick. Generated hydrocarbons may have migrated into overlying Cretaceous reservoir rocks. For example, in the *Terbol-1* well in Tripoli City, hydrocarbon shows were reported throughout the Cenomanian succession (limestones and dolostones). Senonian hydrocarbons may also have migrated into overlying Miocene reservoirs, assuming that sealing lithologies (similar to those in Syria) are present. Based on the burial history and on regional correlation, Senonian source rocks are believed to be oil-prone, whereas Jurassic and (definitely) Triassic source rocks are believed to yield gas (cf. Feinstein *et al*., 2002).

The offshore (South) Levant Basin formed a depocentre for Mesozoic and Cenozoic potential source and reservoir rocks overlain by thick Messinian evaporites (Roberts and Peace, 2007). Sub-salt Oligocene and Miocene strata include high-quality sandstone reservoir rocks which have been confirmed by the recent *Tamar*, *Dallit* and *Leviathan* discoveries (locations on Figs. 6A and 8). Other plays suggested by Roberts and Peace (2007) to exist in the Levant Basin are also plausible. In addition to turbidite sandstones, local platform carbonates in the Middle Miocene were identified on seismic lines offshore northern Lebanon (Semb, *pers. comm*., 2010). These carbonates may have cavernous porosity, similar to equivalent rocks exposed onshore, due to early karstification.

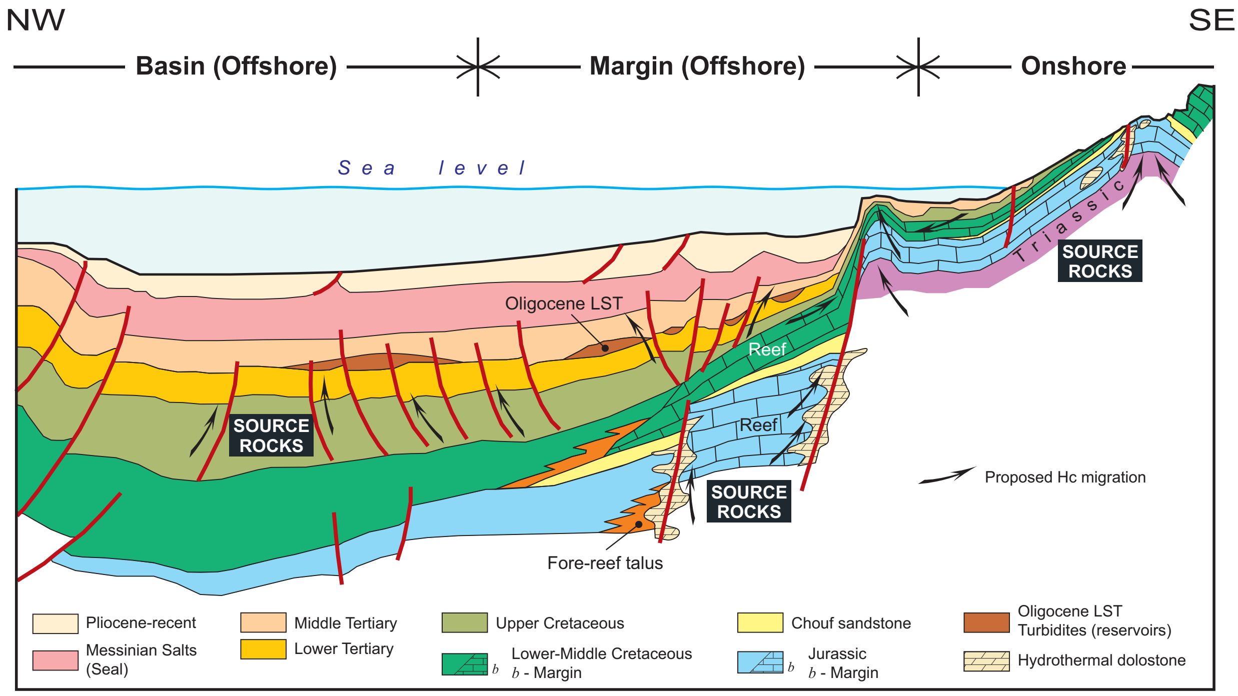
CONCLUSIONS

A schematic model for potential plays in Lebanon is presented and describes onshore, marginal and offshore areas:

Onshore plays include the Qartaba structure in northern Mount Lebanon, which may have a maximum length of 75 km and a width ranging between 10 and 25km; and the Ile du Palmier structure offshore Tripoli.

Triassic, Jurassic, Cretaceous and Oligo-Miocene reservoir rocks along the Lebanese coastline may be separated by sealing evaporites, volcanics, clays and marls and overlain by Messinian evaporites. Fracture-related and hydrothermal dolomitisation may enhance the reservoir properties and vertical connectivity of these potential Mesozoic plays. Local carbonate platforms of Miocene age may provide attractive targets if capped by Messinian evaporites.

Offshore, turbidite sandstones of Oligocene and Miocene ages (sub- Messinian salt) in the southern Levant Basin have reservoir potential. Underlying



(Not to scale)

Fig. 10. Schematic petroleum system model for Lebanon, with possible plays offshore, in the continental margin and onshore. Potential source rocks (e.g. Upper Cretaceous strata, (pre-)Triassic rocks), reservoirs (e.g. Oligocene LST sandstones, Triassic dolostones) and seals (e.g. Cenozoic shales and evaporites) are indicated. Proposed hydrocarbon migrations paths are indicated by arrows.

Mesozoic formations could provide suitable source and reservoir rocks. Potential reservoirs are sealed by the overlying Tertiary shales and Messinian evaporites.

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