Architecture, geodynamic evolution and sedimentary filling of the levant basin : a 3D quantitative approach based on seismic data

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Architecture, Geodynamic Evolution and Sedimentary Filling of the Levant Basin:

A 3D quantitative approach based on seismic data

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I dedicate this work to Norma, Gaby and Alex

"The best and most beautiful things in this world cannot be seen or even heard, but must be felt with the heart."

Helen Keller

"Imagination is more important than knowledge. Knowledge is limited. Imagination encircles the world."

Albert Einstein

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“Let us be grateful to people who make us happy, they are the charming gardeners who make our souls blossom” Marcel Proust

To Alexandra, Tina, Halim & Joseph

EXTENDED SUMMARY

The Levant Basin is located in the eastern Mediterranean region. It is bound by the Cyprus Larnaca thrust zone to the north, the Eratosthenes Seamount to the west, the Nile Delta deep sea fan to the south, and by the eastern Mediterranean coast. Recent 2D and 3D seismic data sets and major hydrocarbon discoveries, make out of this basin an interesting region for academic research and industrial exploration purposes.

Sedimentological and stratigraphic investigations onshore Lebanon as well as interpretations of eight offshore 2D seismic profiles were achieved *(Courtesy of the Petroleum GeoServices PGS and the Lebanese Ministry of Energy and Water MEW)* in order to investigate the impact of major geodynamic events on the architectural evolution and sedimentary infill of the northern part of the Levant margin and basin.

Fieldwork conducted in northern, central and southern Lebanon permitted to review the Upper Mesozoic and Cenozoic stratigraphic units by means of sedimentary facies analysis as well as nannofossil and foraminifer biostratigraphy (about 6500 m of sedimentary logs). Hiatuses from the Late Turonian to Late Santonian, Late Maastrichtian to Early Paleocene, and Early/Late Eocene to Late Burdigalian have been identified. They correlate well with the timing of major geodynamic events affecting the Levant region.

The surface-exposed Upper Mesozoic and Cenozoic rock column of Lebanon (~5000m thick) is mainly composed of carbonate rocks. A siliciclastic unit of Lower Cretaceous age (Chouf Fm) deposited in a fluvial to aeolian setting is absent in northernmost Lebanon and thickens southwards to reach more than 300 m in the Jezzine area (south of Beirut). This southward thickening is believed to be the consequence of early onshore deformations since the Triassic (i.e., Palmyride Basin evolution). Such north-south onshore structuration has also induced a facies differentiation in the Cenomanian-Turonian where shallower settings are seen in northern Lebanon compared to deeper marine settings around Beirut and the southern coastal area.

An angular unconformity was observed in northern Lebanon (Ras Chekka, Balamand, Amioun) and the Bekaa Valley (Zahleh) between the Ypresian/Lutetian and Late Burdigalian rock units proving the occurrence of a pre-Burdigalian and post Ypresian deformation phase onshore Lebanon. The Middle Miocene rocks of northern Lebanon were deposited in a euphotic to oligotrophic rhodalgal realm. This is contrasted near Beirut and southern Lebanon by prevailing slope to basinal settings during the equivalent Middle Miocene time. Thus, the impact of the inherited Palmyridian Mesozoic architecture on the sedimentary facies spatial configuration is apparent onshore Lebanon.

Continued plate collision between Afro-Arabia and Eurasia (through the Cenozoic) led to additional local deformations with paleotopographic highs separating the coastal Middle-Miocene marine facies from their age equivalent lacustrine facies in Zahleh (hinterland, Bekaa valley). The fast uplift of Mount Lebanon is marked by a rapid shedding of conglomeratic material in shallow marine to continental settings as a consequence of the propagation of the Levant Fracture System northwards in the late Miocene.

Seismic stratigraphic concepts and seismic facies analysis were used to interpret regional 2D reflection profiles offshore Lebanon. This allowed to pin-point the different phases of basin evolution and to define eight distinct seismic packages. Rifting appears to end in the Middle Jurassic. It is followed by a post-rift phase in the Late Jurassic to Early Cretaceous with the initiation of deep marine settings in the basin. A foreland basin at the front of the Latakia Ridge in the northernmost sector of the Levant Basin formed since the Turonian. It is associated with the Afro-Arabian and Eurasian plate-convergence. A

southward shift of depocenter location in the Early Miocene resulted from the continuous plate convergence and flexural basin advance. A set of strike-slip faults affecting the whole pre-Messinian evaporite succession have been observed in the northern Levant Basin where more than 10 km of Cenozoic sediments reside. Note that onshore Lebanon a maximum of 1.5 km of Cenozoic sediments have been preserved.

Several sources and pathways contribute to the infill of the northern Levant Basin offshore Lebanon in the Oligo-Miocene: (i) local sources (Levant margin) providing sediments into the basin through channels and canyon systems and (ii) regional drainage systems as the Nile and the Latakia that transport sediments from more distant sources. An onshore-offshore stratigraphic model was accordingly built using the interpreted data set as well as a wide compilation of regional and local isopach maps. It was used to conduct forward stratigraphic simulations of the Middle and Upper Miocene source to sink system using Dionisos (IFPEN) a deterministic "process-based" modeling tool. Source volume estimations as well as sediment transport parameters and observed depositional patterns prove that the carbonate rich Lebanese onshore is unlikely to represent the main sediment source for the northern Levant Basin. The modeling also discredits the possibility of having a unique source providing sediments solely from coastal Syria, Lebanon Arabia and the Nile into the Levant Basin.

A multi-source system is thus proposed honoring (1) the periods of contribution of each source to the sink infill, (2) the volumes of basinal infill as well as (3) the observed and interpreted onshore/offshore sedimentary and seismic facies.

These results open further discussions related to the impact of the varied sources and pathways on the expected petroleum systems of the frontier northern Levant Basin.

RESUMÉ ÉTENDU

Situé en Méditerranée orientale, le bassin du Levant est délimité par l'arc de Chypre au Nord, le mont sous-marin Eratosthène à l'Ouest, l'extension profonde du delta du Nil au Sud, et par la côte est méditerranéenne. L'acquisition de nouvelles données sismiques (2D et 3D) suivies d'importantes découvertes d'hydrocarbures dans la région ont généré ces dernières années un intérêt scientifique et industriel croissant pour ce bassin.

Les études sédimentologiques et stratigraphiques entreprises au Liban ainsi que l'interprétation de huit profils sismiques 2D en mer (autorisation de PGS et du Ministère Libanais de l'Energie et de l'Eau) ont permis une meilleure compréhension de l'impact des événements géodynamiques majeurs sur l'évolution architecturale et le remplissage sédimentaire de la marge levantine et de son bassin.

Le travail de terrain effectué dans le nord, centre et sud du Liban a permis d'examiner les unités stratigraphiques du Mésozoïque supérieur et du Cénozoïque. Une analyse approfondie des faciès sédimentaires a donc été entreprise sur plus de 6500 m de logs sédimentaires et soutenue par des études bio-stratigraphiques (nannofossiles et foraminifères).

Différents hiatus ont ainsi été identifiés datant du Turonien supérieur au Santonien supérieur, du Maastrichtien au Paléocène, de l'Éocène inférieur/supérieur et Burdigalien supérieur. Ils représentent la conséquence de la déformation continue de la marge levantine soumise à des événements géodynamiques majeurs.

La section mésozoïque et cénozoïque du Liban (~ 5000m d'épaisseur) est principalement composée de roches carbonatées. Une unité silicoclastique datant du Crétacé inférieur (Chouf Fm) a été déposée dans un environnement fluviatile et éolien. Un changement drastique de l'épaisseur de cette unité a lieu entre le Nord de Beyrouth (0-25m) et le Sud ou plus de 300 m de sable ont été déposés dans la région de Jezzine. Cet épaississement est considéré comme la conséquence des déformations affectant la marge depuis le début du Trias (l'évolution du bassin des Palmyrides). Cette structuration Nord-Sud à terre a induit une différenciation de faciès pendant le Cénomanien et Turonien où des environnements de dépôts peu profonds ont été identifiés dans le nord contrastant avec des environnements marins profonds autour de Beyrouth et la région côtière sud libanaise.

Une discordance angulaire a été observée au nord du Liban (Ras Chekka, Balamand, Amioun) et dans vallée de la Bekaa (Zahlé) séparant des unités yprésiennes/lutétiennes de celles burdigaliennes. Ceci prouve la présence d'une phase de déformation post Yprésien et pré-Budigalien à terre.

Les roches du Miocène moyen du Nord du Liban ont été déposées dans un système rhodalgal euphotique à oligotrophe. Aux alentours de Beyrouth et du Sud Liban le Miocène moyen représente des environnements de dépôts de pente et de bassin profond soulignant ainsi l'impact de l'architecture héritée depuis le Mésozoïque sur la repartition spatiale des faciès sédimentaires.

Suite à la collision des plaques afro-arabe et eurasiatique pendant le Cénozoïque, des déformations locales supplémentaires ont mené à une différenciation E-W des faciès sédimentaire pendant le Miocène moyen. Un faciès marin a été décrit le long de la côte libanaise et un faciès lacustre dans l'arrière-pays (vallée de la Bekaa à proximité de Zahlé).

Le soulèvement rapide du Mont Liban est causé par la propagation de la Faille du Levant vers le Nord de la marge levantine. Une importante érosion des plateformes carbonatées anté-Miocène est suivie par un dépôt de fan conglomératique dans les régions adjacentes.

L'utilisation des concepts de la stratigraphie sismique et de l'analyse des faciès ont permis une interprétation détaillée des profils 2D régionaux au large du Liban. Huit paquets sismiques distincts ont été identifiés permettant la reconstitution de l'évolution tectono-stratigraphique du Bassin du Levant.

Le rifting semble s'achever dans la période du Jurassique moyen. Une phase de post-rift s'initie à la fin du Jurassique suivi de dépôts marins profonds dans le bassin. Un bassin flexural à l'avant de la ride de Lattaquié dans le secteur nord du bassin du Levant se développe depuis le Turonien suite à la subduction de l'Afro-Arabie sous l'Eurasie. Un déplacement de dépocentre vers le Sud de l'offshore libanais dans le Miocène inférieur résulte de l'avancée continue de ce bassin flexural.

Un ensemble de décrochements affectant l'ensemble de la succession anté-evaporites messiniennes a été observé dans le secteur nord du bassin du Levant où plus de 10 km de sédiments cénozoïques sont déposés, alors qu'à terre 1,5 km seulement ont été conservés.

Pendant l'Oligo-Miocène, plusieurs sources et systèmes de drainages contribuent au remplissage du bassin nord levantin au large du Liban: (i) des sources locales (marge levantine) fournissant des sédiments dans le bassin à travers des systèmes de canyons incisant la marge ainsi qu'à travers des chenaux turbiditiques et (ii) des systèmes de drainages régionaux comme le Nil et Lattaquié transportant des sédiments de sources plus lointaines.

Un modèle stratigraphique terre-mer a donc été construit en utilisant l'ensemble des données interprétées ainsi que d'une large compilation de cartes isopaques régionales et locales. Ce modèle a été incorporé dans le logiciel Dionisos (IFPEN), un outil de modélisation déterministe, permettant de simuler différents scénarios de remplissage de bassin pour la section miocène.

Les estimations du volume des sources ainsi que les paramètres de transport des sédiments prouvent que la marge libanaise ne peut représenter la principale source de sédiments remplissant le bassin nord levantin. La modélisation stratigraphique discrédite également la possibilité d'un système de « source isolée » fournissant des sédiments uniquement à partir du Nil, de l'Arabie, ou de la côte syrienne. Un système « multi source » permet donc de restituer (1) les périodes d'activité de chaque source (2) les volumes de remplissage de bassin ainsi que (3) l'évolution sédimentaire onshore/offshore.

Ces résultats ouvrent de nouvelles discussions en relation avec l'impact des sources et des systèmes de transport sur les systèmes pétroliers du bassin frontalier nord levantin.

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INTRODUCTION

"Sedimentary basins" represent regions where relatively fast subsidence induces accommodation of sedimentary rocks (Allen & Allen, 2008). Several classification schemes are proposed depending on the basin's type of lithospheric sub-stratum, its position with regards to plate boundaries as well as the mode of plate motion nearest to it (e.g. Buck, 1991; Allen & Allen, 2005). The extensive work on focal mechanisms of large earthquakes, their epicenters as well as magnetic lineation along the oceans have permitted to support the relative plate motion concept linked with the earth's deep dynamics (Minster & Jordan, 1978). The continuous use of GPS measurements led to a better constrain of the velocities of plate motions and their directions (Allen & Allen, 2005). Three main plate movement patterns consequently impact on the formation and evolution of sedimentary basins. They are referred to as divergent (i.e., rifting), convergent (i.e., subduction and collision) and conservative boundaries (i.e., strike-slip).

Recent applications of geophysical techniques (e.g., seismic refraction and reflection, tomography) provide a better imaging of the subsurface and thus a clearer insight into the deeper basin's architecture, the type of crust that floors it (oceanic versus continental) as well as the geometries of its infill with relation to global sea level changes (Mitchum et al., 1997; Vail et al., 1977). Reduced noise geophysical reflection data allow more accurate seismic stratigraphic interpretations in frontier provinces with sparse well control (Mitchum et al., 1977; Sheriff, 1977). Through the use of seismic stratigraphic techniques it is possible to propose reflection correlations, genetic unit thicknesses, depositional environment assessment and burial history as well as an understanding of paleo-relief and topography. However the main limiting factor behind this application is the inability to determine lithofacies and rock types from the reflection geometries without the use of other available geologic data (e.g. wells, outcrops) (Mitchum et al., 1977; Vail et al., 1977).

Multi-disciplinary approaches referred to as "source to sink studies" have thus been used since the 1970's to unravel the history of landscapes and sedimentary basins evolution through time (Meade, 1972; 1982; Dickinson, 1997; Allen, 2008; Sømme et al., 2009a,b; Martinsen et al., 2010; Macgregor, 2012; amongst others). These studies focus on the integration of geological, geomorphologic and oceanographic data as well as their associated physical, chemical and biological processes. Two main controlling factors impact on landscape erosion rates: relief and climate (Allen; 1997, Hay; 1998; Hay et al., 2002). The quantification of sediment erosion, transport and accumulation with regards to tectonic deformation is being constrained using wide sets of methodologies and techniques (e.g. field work, biostratigraphy, thermo-chronology).

In order to represent the sedimentary source to sink systems in carbonate and/or siliciclastic domains numerical modeling tools have been developed over the last decade, mostly based on empirical data gathered from current day geomorphologic and hydrological systems (e.g. Granjeon & Joseph, 1999; Syvitski et al., 2003; Syvitski & Milliman, 2007). The shift from applications of numerical modeling using geometric aspects (all space below sea level consequently infilled by sediments; Schlische, 1991) into diffusion based models (e.g. Jordan & Flemings, 1991; Granjeon & Joseph, 1999) have permitted to better mimic and assess the sediment transport and deposition through time.

Apart from the academic advances in source to sink studies, the hydrocarbon exploration community has expressed a growing interest in these geological, geophysical and modeling applications (e.g. Norwegian margin: Sømme et al., 2009b, Martinsen et al., 2010; Gulf of Mexico: Alzaga-Ruiz et al., 2009; Gulf of Lion: Rabineau et al., 2005, Brazil: Pinheiro-Moreira, 2000; Nile Delta: Dolson et al., 2005; Macgregor, 2012). The major improvement in subsurface data acquisition quality allowed uncertainty reduction in the exploration of oil and gas resources leading to the discovery of new hydrocarbon prone provinces such as the Levant Basin (e.g. Gardosh et al., 2006; 2008). The northern sector of the Levant Basin (i.e., offshore Lebanon) remain a frontier area where scientific breakthrough should bring further insights into its geological history as well as its hydrocarbon potential (Nader, 2011).

Lebanon is located at the junction of the Arabian and African plates and has been affected by successive deformations from the Early Triassic onwards. Rifting followed by convergence, collision and strike slip deformation from the Early Mesozoic until the Late Tertiary impacted on the architecture of the northern Levant margin and basin and thus on its infill. Yet, assessing the effect of tectonic deformation on the associated sedimentary environments using refined ages subdivisions is still unachieved and partly hindered by the lack of borehole data in the northern sector of the basin and its margin.

The objectives of this PhD project entitled "Architecture, geodynamic evolution and sedimentary filling of the Levant Basin" are to propose an integrated approach in order to provide an adequate comprehension of the interactions between geodynamic and surface processes during the Late Mesozoic and Cenozoic along the Levant margin and basin. This investigation aims to propose a 3D onshore offshore geologic model of the northern Levant region (Lebanon) permitting to test scenarios of sedimentary accumulations in the basin and their expected sources.

This PhD thesis is subdivided into seven main chapters:

The Chapter 1 presents an overview of the geodynamic and tectono-stratigraphic framework of the Eastern Mediterranean region with a focus on Lebanon.

The Chapter 2 highlights the methodology followed in order to achieve this study using field investigations (i.e., sedimentary logging, facies analysis and biostratigraphic studies), 2D seismic interpretations of the northern Levant Basin and forward stratigraphic modeling.

The Chapter 3 consists of the fieldwork results conducted along northern Lebanon with the following associated article: Hawie et al., 2013a: "Sedimentological and stratigraphic evolution of northern Lebanon since the Late Cretaceous: implications for the Levant margin and basin",

The Chapter 4 exposes the outcropping rock units in northern, central and southern Lebanon for the Upper Jurassic to the Upper Miocene units. The article entitled "The Miocene of Lebanon: a revisited geological model" will be submitted to Terra Nova.

The Chapter 5 provides an integration of offshore and onshore data sets permitting to propose an updated tectono-stratigraphic framework of the northern Levant margin and basin. The basin infill is discussed in a source to sink perspective. Two associated articles are presented: (1) Hawie et al., 2013b: "Tectono-stratigraphic evolution of the northern Levant Basin (offshore Lebanon)" and (2) Fürstenau et al., 2013: "Aspects of the depositional history of the depositional history of the Levant Basin, offshore Cyrpus and Lebanon".

The Chapter 6 is focalized on the stratigraphic modeling and testing of the several scenarios of basin infill proposed for the northern Levant Basin.

The Chapter 7 presents a synthesized and integrated discussion around the presented results and interpretations focused on the importance of source to sink studies in understanding basin infill of frontier regions.

Finally concluding remarks and recommendations for future studies are proposed.

CHAPTER I

Geologic Setting

I. Geodynamic framework of the eastern Mediterranean

New explanations to mantle geodynamic processes associated with rifting, convergence, subduction and collision of continental lithospheric bodies have been recently proposed for the eastern Mediterranean region. A variety of data has been used in order to assess the geodynamic evolution of three major interacting plates (i.e., the African, Arabian and Eurasian Plates; Fig.1.1) and a micro-plate referred to as the Anatolian continental block (e.g., Hempton, 1987; Dewey *et al*., 1986; Stampfli *et al*., 1991; Robertson, 1998; amongst others). The modern Anatolian- African plate boundary is floored by a northward dipping subduction zone part of a regional plate convergence domain between Afro-Arabia and Eurasia since the Late Mesozoic (Faccenna *et al*., 2003; Jolivet and Brun, 2008).

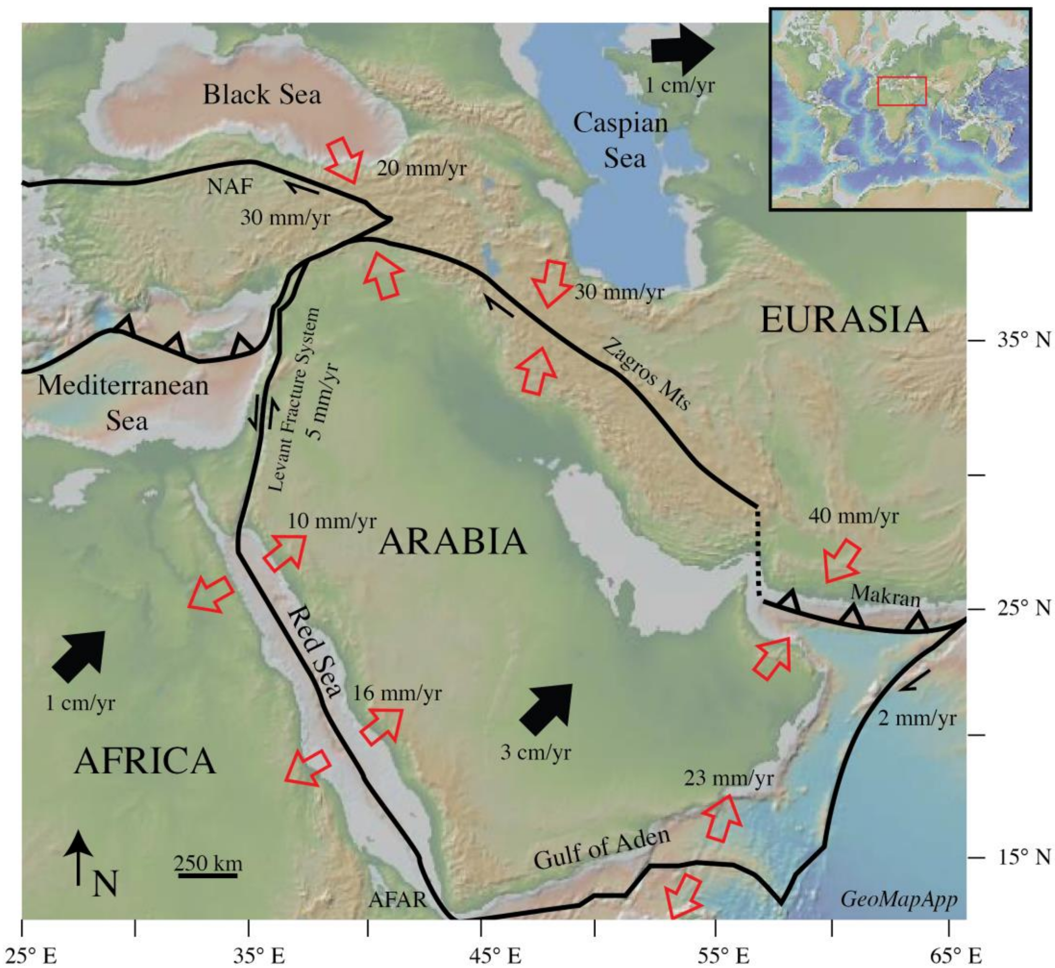


Fig1.1 Tectonic framework of the eastern Mediterranean region showing the major plate interactions. Directions and values of absolute velocities (black arrows) are gathered from Argus & Gordon (1991). Relative velocities (red arrows) of (1) the Levant Fracture System (LFS) are from Daeron *et al*. (2004), Westaway (2004), Gomez *et al* (2006), (2) northern convergent zone from Reilinger *et al*. (1997) et Allen *et al*. (2001), (3) Red Sea from Le Pichon & Gaulier (1988) and Chu & Gordon (1998), (4) Gulf of Aden from Jestin *et al.* (1994).

I.1 Early Mesozoic extension in the eastern Mediterranean

Extensive work along the plates' boundaries using ocean floor magnetic anomaly data and stratigraphic investigations lead to the development of palinspatic and paleogeographic reconstructions of the eastern Mediterranean (e.g., Dercourt *et al*. 1986; Dewey *et al*. 1989a; Garfunkel 1998; Stampfli & Borel 2002; Robertson *et al*. 2004) (Fig.1.2).

Successive evidence from the eastern Mediterranean pointed out to the extent of a wide Mesozoic to Early Tertiary Tethyan ocean separating Africa from Eurasia (Dercourt *et al.,* 1986; 1993; 2000). Continental collision marking the closure of the PaleoTethys Ocean in the Early Mesozoic time was followed by the opening of the NeoTethys in the Early Triassic and the separation of the Cimmerian block from Gondwana (Fig.1.2) (Stampfli Robertson & Mountrakis, 2006). Around that period the extension attested along the eastern Mediterranean region (i.e., Palmyride and Levant Basins) could have been linked to both intra-continental rifting and/or back-arc basin extension related to continued northward subduction. However, new studies focused on the Palmyride and Levant Basins using field and seismic data sets support the Early Mesozoic rifting framework model unrelated to subduction (e.g. Brew et al., 2001; Gardosh, 2010).

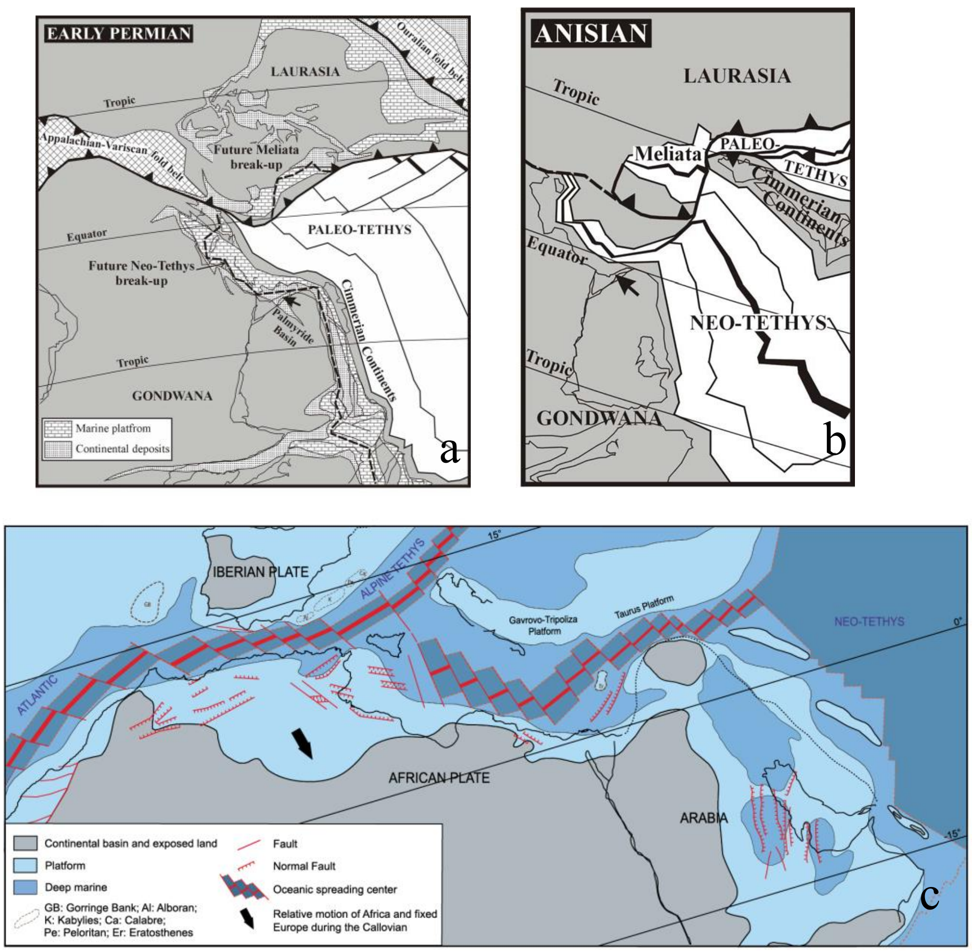


Fig1.2. Paleogeographic reconstruction of the Tethys region during the (a) Early Permian, (b) Middle Triassic (Anisian) (modified from Stampfli & al., 2001) and (c) Middle Jurassic (callovian) (Frizon et al., 2011). The black arrows in a,b point to the Levant region.

The use of gravity, magnetic and seismic data allowed to propose a new model for the Levant Basin evolution (Gardosh *et al*., 2010; Montadert *et al.,* in press). This model tackles the understanding of a feature that has been omitted in past studies: the Eratosthenes Continental Block (ECB). The splitting of the ECB (continental crust) from Arabia in the Early Mesozoic to Middle Jurassic was caused by a NNW-SSE extension accommodated by a set of NW-SE transfer-transform faults in the southern offshore section of Cyprus cutting obliquely the northern African margin. These new arguments refute the northward separation of the ECB from Africa accommodated by a N-S transform fault running across the eastern margin of the Levant Basin (as proposed in Dewey *et al.*, 1973; Bein & Gvirtzman, 1977; Robertson & Dixon, 1984; Stampfli & Borel, 2002).

The convergence of Afro-Arabia with Eurasia starting from the Late Cretaceous caused the initiation of the Alpine Orogeny and to the ophiolite obduction seen across the eastern Mediterranean region and more specifically in Greece, Turkey, Cyprus and Syria (Fig.1.3) supporting a northward dipping subduction zone (refer to Smith *et al*., 1975; Robertson & Woodcock, 1979; Garfunkel & Derin, 1984; Dercourt *et al*., 1986; Dewey *et al*., 1989).

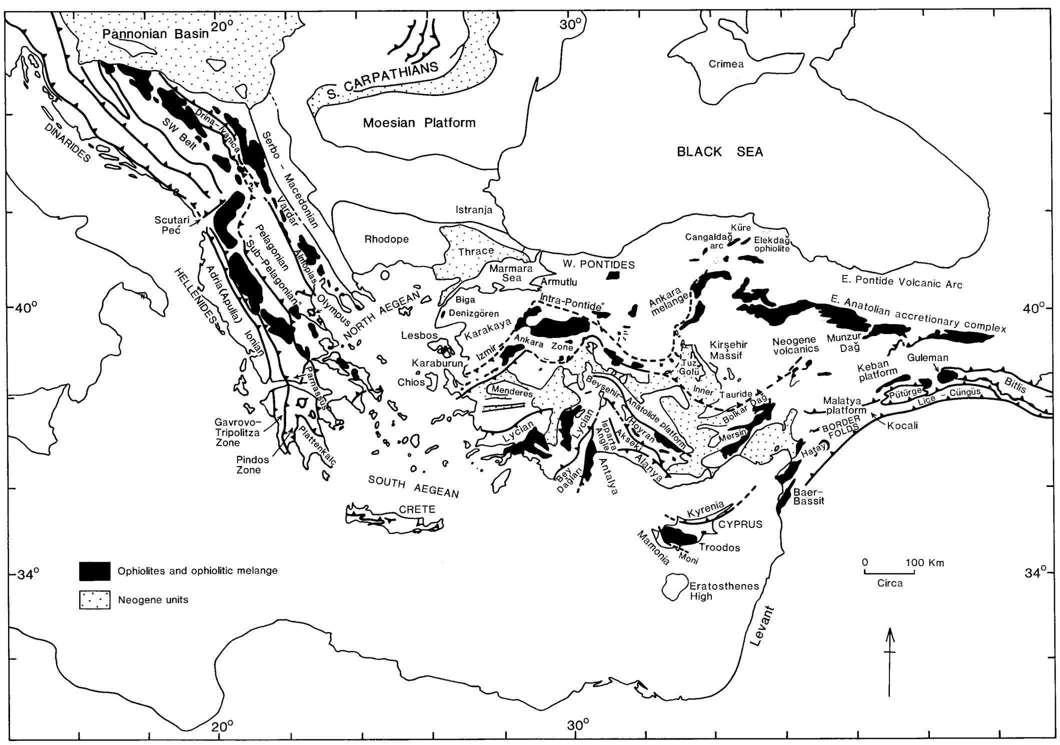


Fig1.3. Outline tectonic map of the eastern Mediterranean region showing the ophiolite locations as well as the major Neogene rock units (from Robertson et al., 1998).

II. 2 Cenozoic Period

I.2.1 Mediterranean subduction and back-arc extension

Extensional events are noted around the western and central Mediterranean since 30-25 Ma contemporaneously with the slowing pace of the absolute motion of Afro-Arabia after its collision with Eurasia in the Eocene-Oligocene (Dewey *et al.,* 1989; Dercourt *et al* 1986; 1993; Jolivet & Faccenna, 2000; Fig.1.4). The Mediterranean extension has been observed along five regions from the west to the east respectively: Alboran Sea (Lonergan an White, 1997), Liguro Provinçal Basin (Burrus, 1984; Malinverno & Ryan, 1986), The Tyrrhenian Sea (Royden, 1993; Faccenna *et al*., 1996), Aegean Sea (Le Pichon & Angelier, 1981) and Pannonian Basin (Linzer, 1996).

Models linked with slab retreat or rollback of subduction zones were proposed to explain this extension in the Mediterranean referred to as "back-arc extension". The latter is most likely to occur when the slab velocity retreat overcomes the absolute velocity of the overriding plate (Dewey, 1980). Geochemical investigations of subducted slab/mantle relationships from young volcanism supported by upper mantle seismic tomography and shear wave anisotropy focused on the western Mediterranean support the presence of a cold and dense slabs at depth controlling the mantle dynamics (e.g. Spakman *et al*. 1988; 1993; Csontos 1995; Turner *et al.* 1996; Kosarev *et al*. 1999; Wortel & Spakman 2000; Schiano *et al.* 2001; Faccenna et al. 2003).

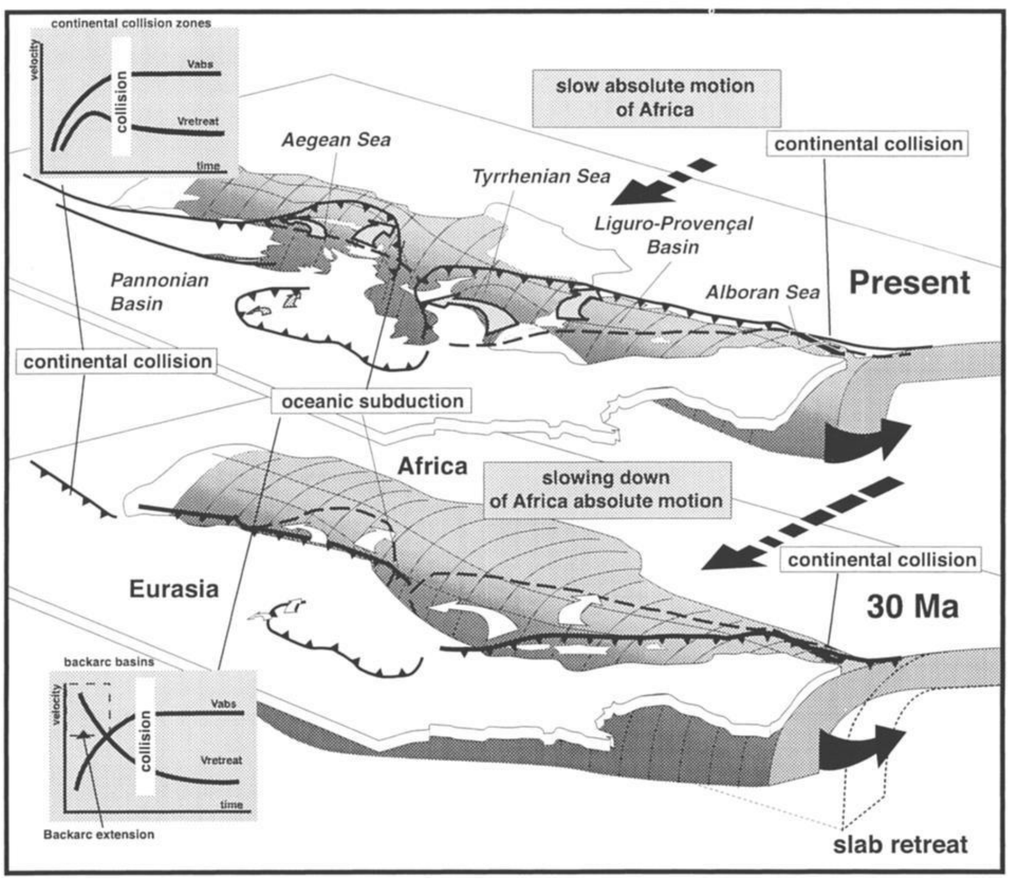


Fig1.4. Schematic representations (Jolivet & Faccenna, 2000) showing the fast slab retreat in the Mediterranean. The diagrams reflect the evolution of the velocity of retreat of the subducting slab and the absolute plate velocity in two cases: (1) the velocity of slab retreat progressively increases during continuous subduction of oceanic lithosphere (e.g., Faccenna et al., 1996) and (2) the velocity of slab decreases after the inception of continental subduction.

The very sudden and drastic changes in the Mediterranean tectonic regime in the Cenozoic alludes to a more complex subduction/ slab retreat system (Jolivet & Facenna, 2000) with a decrease of the absolute velocity of Africa to less than 3cm/yr around 35 Ma (Jolivet & Faccenna, 2000) followed by an increase at 30 Ma and later by a decrease around 20 Ma (from about 1.5 to 0.5 cm/yr; e.g., Dewey *et al*., 1989; Ricou, 1994; Muller and Roest, 1992). The convergence direction between the two major plates (i.e, Africa and Eurasia; Fig.1.5) trends N-S during the Cenozoic and changes in the last 10 Ma (imposed by a rotation pole) from a NNW-SSE in the eastern Mediterranean sector to WNW-ESE in the western Mediterranean (Le Pichon & Kreemer, 2010).

I.2.2 Collision of Afro-Arabia with Eurasia

The collision of Afro-Arabia with Eurasia impacted on the eastern Mediterranean region (i.e., north Africa and Levant) that witnessed drastic changes in the stress regimes starting from 30 Ma followed by important volcanic events (Ebinger & Sleeep, 1998; Kenea *et al*., 2001; Fig.1.5) and leading to the fragmentation of the African plate (extension in Gulf of Aden, Afar triple junction and Red Sea) and the formation of the Arabian Plate as two separate entities. Several reasons have been proposed to explain the extension and rifting seen on the Afro-Arabian Plate at this period: (1) far-field extensional stresses due to slab pull force along the Zagros subduction, (2) Excess of potential energy due to the Afar mantle plume (e.g. Zeyen *et al*., 1997).

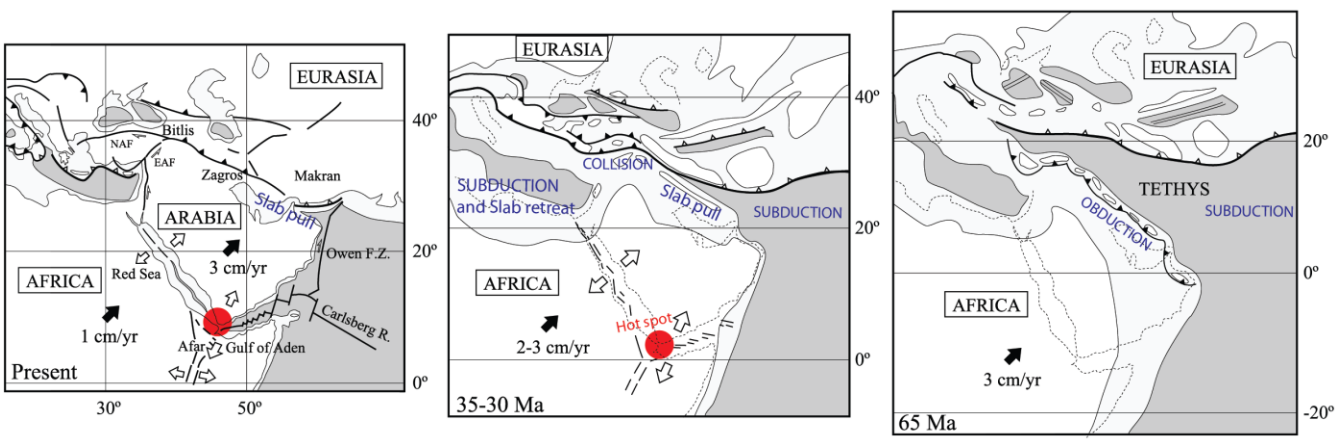


Fig1.5. Tectonic reconstructions of the eastern Mediterranean based on Dercourt *et al*. (1973), Jolivet & Faccenna (2000), Bellahsen *et al*. (2003). Absolute velocities are from Argus & Gordon (1991). Note that the white color represents continents; light gray stand for the continental platforms and the darker gray corresponds to the oceans.

Analogue modeling techniques shed light on the role of subduction in the Cenozoic breakup of Africa (i.e., Gulf of Aden and Red Sea rifts) and on the understanding of the westward migration of the Anatolian continental block (refer to models of Bellahsen *et al*., 2003 and Mart, 2013). Experiments show that the rifting process along the African plate is caused by the plate collision and trench locking, soon after the onset of the Afro-Arabian collision with Eurasia in Turkey (around 40 Ma). The stress field and slab pull generated by the active Makran trench (subduction still in process today) could reveal to be an important rifting factor (Bellahsen *et al*., 2003). The anti-clockwise rotation of Arabia due to the rifting on its southern sector (i.e., Red Sea) led to the transition from a subduction domain into a collisional one along the Zagros front in the Mid-Miocene (Bellahsen *et al*., 2003).

Another proposed factor for the extension in the Gulf of Aden and Red Sea is the resumption of spreading ridge of the NW Indian Ocean leading to a change in the direction of its propagation from NNW to WSW. This induced rifting along weakness zones between Arabia and Somalia (refer to the discussions around the impact of Oligocene Ethiopian hotspot/Afar plume on Afro-Arabian separation and lithospheric weakness; e.g., White & McKenzie, 1989; Schillin *et al*., 1992; Baker *et al*., 1996; Zeyen *et al*., 1997; George *et al*., 1998; Bosworth *et al*., 2005; Mart, 2013; amongst others; Fig.1.5).

I.2.3 The Levant Fracture System (LFS)

The Levant Fracture System (Beydoun, 1999; Brew *et al.,* 2001; Fig.1.6) represents a set of strike-slip faults (i.e., Dead Sea Transform, the Yammouneh Fault and the Ghab Fault) connecting the Red Sea domain in the south to the East Anatolian Fault in the north (Daeron *et al*., 2004). The southern part of the system (Dead Sea Transform) is expected to have initiated around the Middle Miocene (Garfunkel & Ben Avraham, 2001) and later propagated northwards in the Late Miocene to Pliocene (e.g., Beydoun, 1999, Gomez *et al*., 2006)

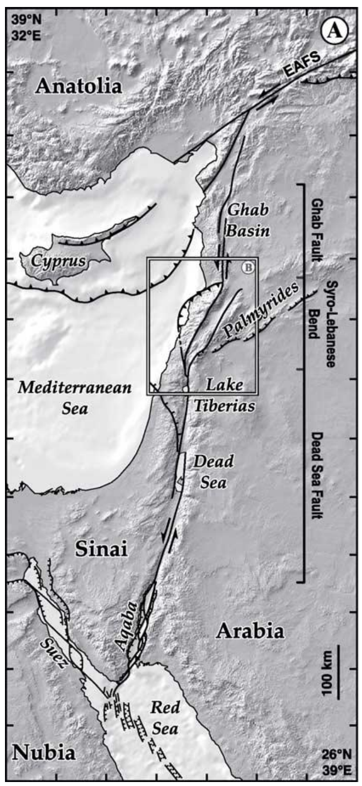


Fig1.6. Structural framework of the Levant Fracture System subdivided into 3 segments: Dead Sea Fault, Syrian and Lebanese Bend (or Yammouneh Fault) and the Ghab Fault (from Daeron *et al*., 2004)

Important marginal uplifts (3-5 km) are attested (1) towards the southern Levant rift-sector (i.e., southern Dead Sea domain) that constitute the northern Arabian-Nubian Shield as well as (2) towards the eastern side of the rift shoulder (Garfunkel, 1981). GPS measurements refer to 5 mm/yr of sinistral offset along the Dead Sea Transform (Al Tarazi *et al*., 2011) while the Yammouneh sector presents offset values ranging between 3 and 5 mm/yr (Daeron *et al*., 2004; Westaway, 2004; Gomez *et al*, 2006).

After the continued collision of Arabia with Eurasia an uplift of the convergent zones to 1-2 km was noted in Anatolia (Hempton, 1987). The term "escape tectonism" has been used in the literature in order to represent the westward motion of the Anatolian micro-Plate over subducting African oceanic lithosphere at the Hellenic Trench (e.g., McKenzie, 1972; Dewey & Sengor, 1979). The movement was accommodated along numerous intersecting strike-slip faults. The two largest faults are the North and East Anatolian (NAF and EAF on Figs.1.1 and 1.6) faults that initiated between the late Miocene and early Pliocene (refer to Hempton and *S*engör, 1980; *S*engör et al., 2005). Old interpretations referred to a rigid plate tectonic explanation to the Anatolian continental block extrusion that initiated towards the Late Miocene (e.g., McKenzie, 1970; 1972).

A recent investigation proposed by Le Pichon & Kreemer (2010) based on wide GPS measurements brought new tentative explanations to the extrusion of the micro-Anatolian Plate westwards (Fig.1.7). The increased rotational velocities from the Levant to Aegea and the extension observed in Anatolia have been linked to a post-Mid Miocene toroidal flow along the eastern African slab that is witnessing subduction rollback. The initiation of the North Anatolian Fault (NAF on Fig.1.1) as well as the volcanism and associated uplift of eastern Anatolia could thus be enhanced by this mantle dynamics.

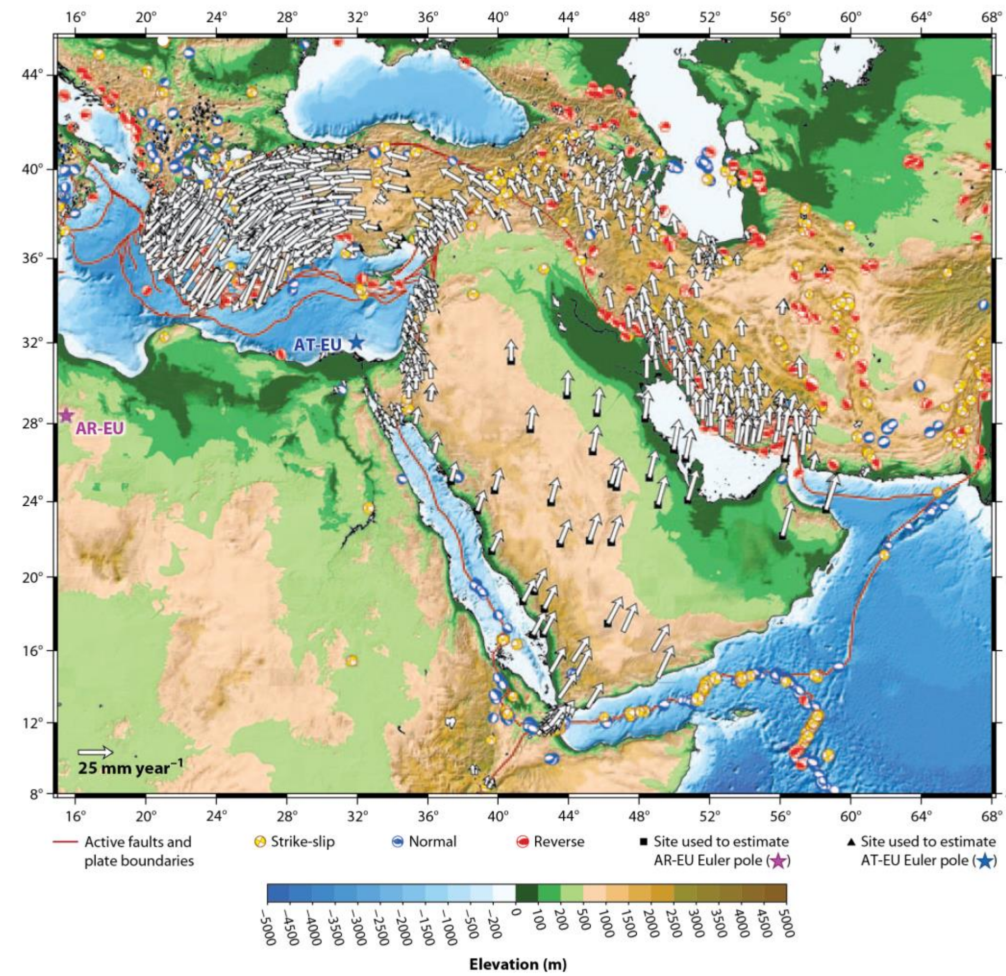


Fig1.7. Regional GPS velocities data relative to Eurasia (refer to Le Pichon & Kreemer, 2010). Note the counter-clockwise rotation between Arabia, Eurasia and the Anatoian micro-Plate. Focal mechanisms are from the Centroid Moment Tensor catalog. Length of white arrows shows the intensity and direction of velocities of moving blocks.

I.3 The present state of Mediterranean

The present-state of the Mediterranean system has been referred to as "landlocked" as subduction is wholly enclosed in between two bordering continental masses (e.g. Le Pichon 1982; Jolivet & Faccenna 2000). Products of this system represent the wide orogenic belts seen along the northern sector of the Mediterranean from the Betics to the west passing by the Apennines and Alps and reaching the Zagros to the east. Oceanic lithosphere remnants are still being consumed around the central Mediterranean (Jolivet & Faccenna, 2000).

The seismicity along the Mediterranean region (refer to Edwards & Grasemann, 2009) clearly points to the retreating slab (Fig.1.8). Moderate depth hypocenters have been identified along the collisional zones (from 0- 90 km) while much deeper activity is noted along the expected subduction zone (i.e., mainly around the Hellenic arc, Calabria and Kabylies) where the slab is still being consumed in the deeper asthenosphere (hypocenters reach high values –between 100 and 600 km along the suspected Wadati-Benioff zone) (Jolivet & Faccenna, 2000; Edwards & Grasemann, 2009)

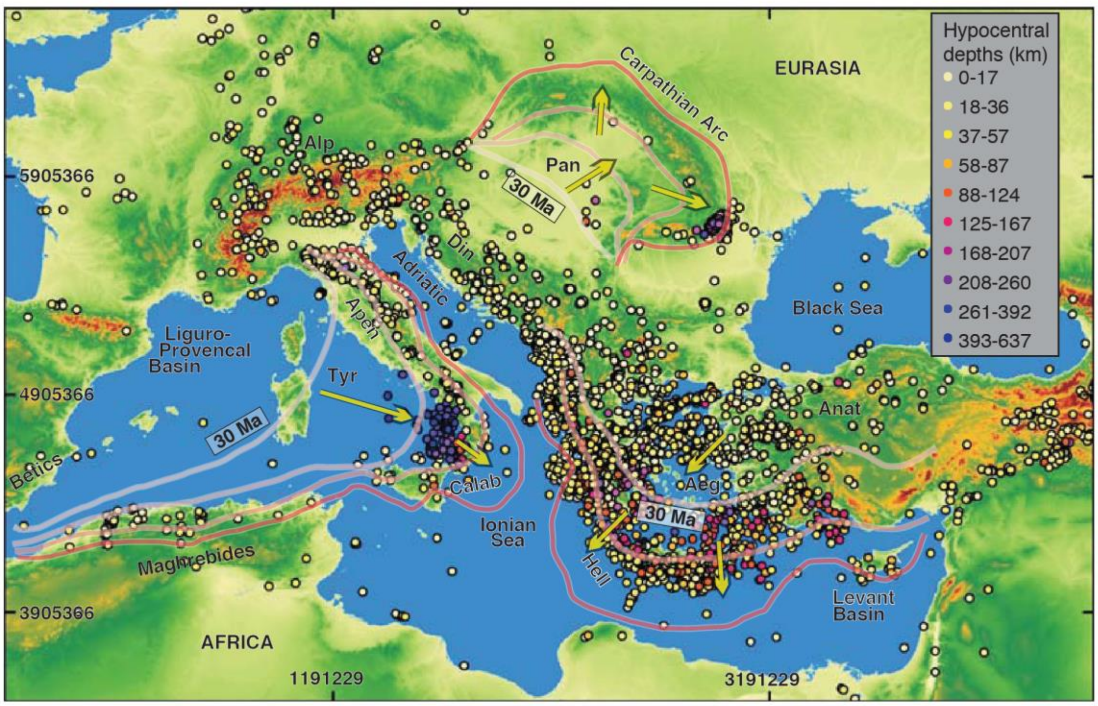


Fig1.8. Retreating slab geodynamics in the Mediterranean identified through seismicity data (hypocenters) from Edwards & Grasemann (2009). Tyr: Tyrrhenian Sea; Cal: Calabria; Apen: Apennines; Alp: Alphides; Pan: Pannonian Basin; Din: Dinarides; Hell: Hellenides; Aeg: Aegean; Anat: Anatolia. Selected earthquakes, data coutesy: http//neic.usgs.gov/neis/epic (Earthquake Hazarads Program, National Earthquake Information Center of the USA Geological Survey) and Russian public domain catalogue (Moscow 1994) corrected after Engdahl *et al*. (1998).

II. Tectono-stratigraphic evolution of the Levant region

II.1 Mesozoic period

The break-up of the Gondwana supercontinent initiated in the Late Carboniferous and led to the formation of the Neotethys (Stampfli *et al*., 1991). The NE-SW fault trends and graben structures investigated along the eastern Mediterranean region proved the presence of a Late Paleozoic/Early Mesozoic extensive rift system that persisted until the Jurassic and that affected mainly the Palmyrides and the Levant Basin domains (Gardosh *et al*., 2006; 2008; 2010; Moustafa, 2010; Yousef *et al.,* 2010; Figs.1.9a; 1.10; 1.11). The Palmyrides region (Fig.1.6, 1.9) represented at that time a local depocenter where a restricted shallow marine environment with evaporites was noted (Sawaf *et al*., 2001). The nearby Euphrates region is thought to have been in a relatively uplifted position shown through the reduced thickness of the Upper Triassic and the absence of the Jurassic unit (Best *et al*., 1993; Al-Saad *et al*., 1992; Alsdorf *et al*., 1995; Fig.1.11). The lack of most of Mesozoic section in the Rutbah and the northern Aleppo plateau proves that these two structures were elevated at that time (Brew *et al*., 2001; Wood, 2001). Important subsidence in the Levant Basin occurred in the Early Jurassic (Druckman, 1977; Derin & Gerry, 1986a; Alsharhan & Salah, 1996; Hirsch *et al*., 1998) followed by the deposition of pyroclastics and volcanics along the Levant margin (i.e. Asher Basin in Israel).

Rifting activity ceased and a gradual initiation of a passive margin in the Late Jurassic was characterized by a continuous calm shelf-edge carbonate deposition on the Levant margin. A western deepening slope witnessed marine carbonate as well as deepwater silicilastics deposition (Cohen, 1976; Bein & Gvirtzman, 1977; Gardosh, 2002; Roberts & Peace, 2007; Fig.1.9b). During the Late Oxfordian to Early Kimmeridgian alkaline basaltic volcanics occurred in Lebanon and south Egypt and has been linked to continued marginal rifting (Schandelmeier *et al.,* 1987; Laws & Wilson, 1997; Walley, 1999; Fig.1.11). A regional regressional trend marked the Early Cretaceous. Fluvio-deltaic and shallow marine environments persisted along northeastern Africa and Arabia (Bosworth, 1992; Litak *et al.,* 1998; Brew *et al*., 2001) and were followed by marine transgression in the Middle Aptian along the Levant margin (Walley, 1997; Guiraud & Bosworth, 1999).

The Late Cretaceous to Early Eocene period represents a global sea level highstand associated with warm climates and important thermal subsidence noted along the central African plate (Guiraud *et al.,* 1992; Fig.1.9c,d). Following the convergence of the African and Eurasian plates the obduction of the ophiolites in Late Cretaceous (Maastrichtian) onto the Arabian platform led to the exposure of this rock unit in NW Syria and Cyprus, causing the flexure of the northern Arabian plate under the ophiolitic overload (Homberg & Bachmann, 2010; Al Abdalla *et al*., 2010). A major folding stage and basin inversion (known as the "Syrian Arc Folding" e.g Picard, 1959; Freund et al., 1975; Neev & Ben-Avraham, 1977; Eyal, 1996; Buchbinder & Zilberman, 1997; Garfunkel, 1998; Walley, 2001; amongst others) caused an inversion of major normal faults previously formed in the Early Mesozoic into sets of asymmetric folds present near the Levant margin and further inland (Walley, 2001). The onshore deformation intensified by the Maastrichtian Paleocene transition resulting in an angular unconformity between the Paleocene and older rock units along the northern African and Arabian margins (Ponikarov, 1966; Guiraud & Bosworth, 1999).

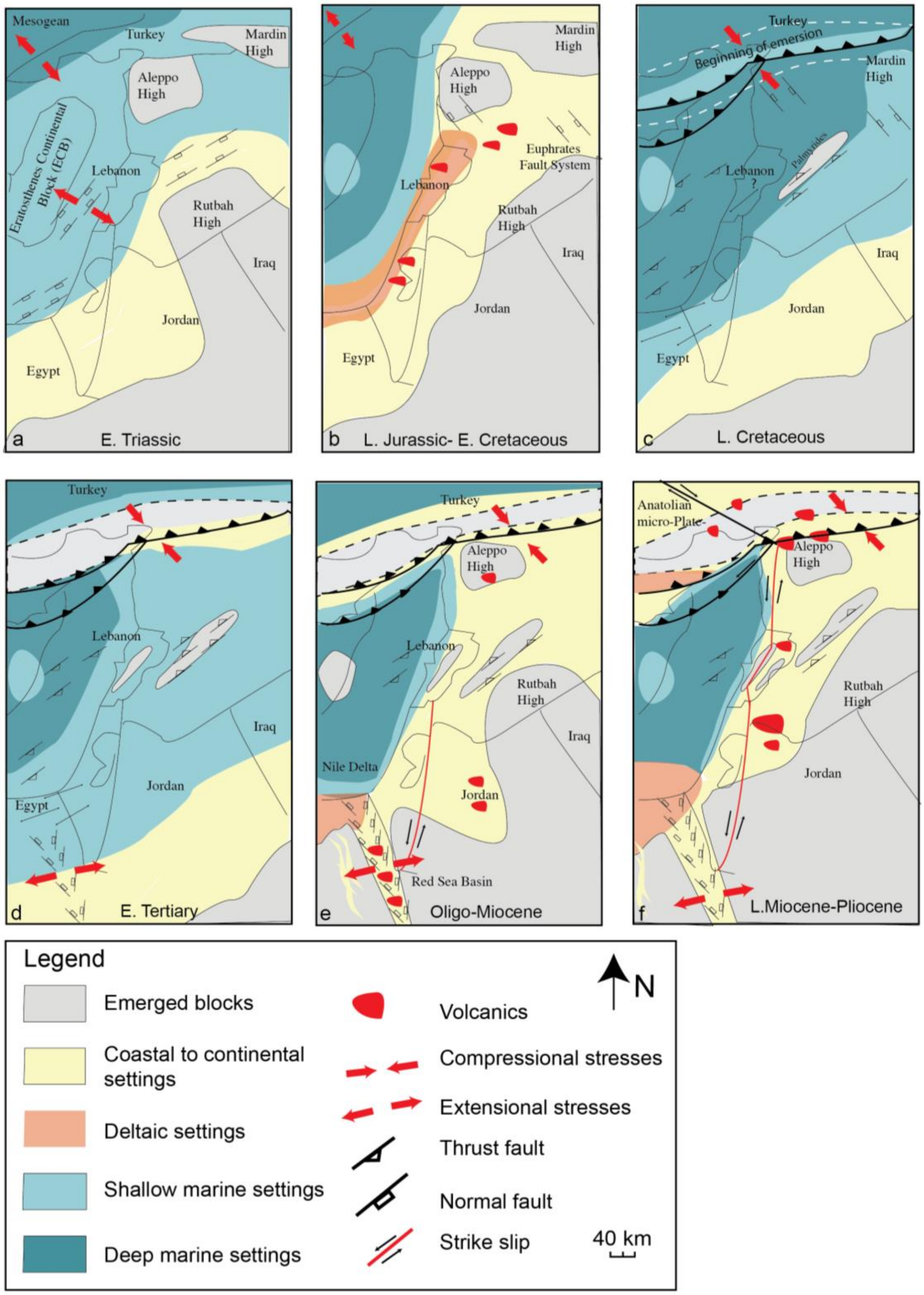


Fig1.9. Paleogeographic reconstructions showing the different environments prevailing along the Levant region as well as the main geodynamic events shaping the Levant margin and the basin (compiled and modified from Dercourt *et al*., 1993; Brew *et al*., 2001; Barrier and Vrielynck, 2008 and references in text)

II.2 Cenozoic period

During the Early Tertiary (Bartonian-Priabonian), a 2nd phase of deformation linked with the continued convergence and collision of Afro-Arabia with Eurasia was characterized by low amplitude folds throughout the basin as well as marginal uplift (Robertson 1998a,b; Guiraud and Bosworth, 1999; Walley, 2001; Fig.1.9d). From the Late Eocene onwards, marginal uplift might also be a direct consequence of the up-doming Afar plume region in Ethiopia and Yemen (White & McKenzie, 1989; Schillin *et al*., 1992; Baker *et al*., 1996; Hofmann *et al*., 1997; Zeyen *et al*., 1997; George *et al*., 1998). At that period a westward sea retreat of hundreds of kilometers (Dercourt *et al*., 1992; Ziegler, 2001) exposed the Arabian carbonate platform (Steinberg *et al*., 2011). Extensive marginal erosion and wide spread canyon incisions on the Levant slope directed Tertiary clastic sediments into the Levant Basin (Gardosh *et al*., 2006; 2008).

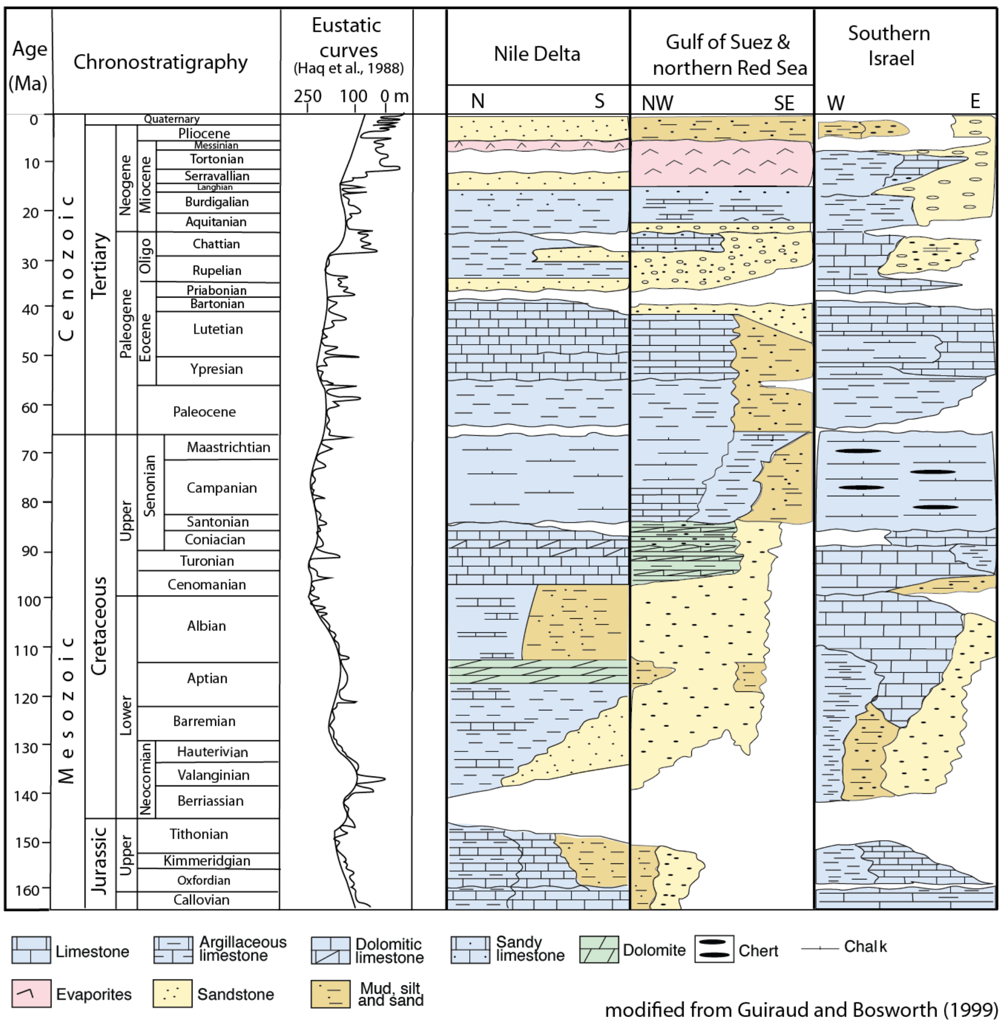


Fig1.10. Regional onshore chronostratigraphic chart of the southern Levant margin showing the major lithologies observed from Jurassic till Present as well as the main hiatuses (modified from Guiraud and Bosworth, 1999).

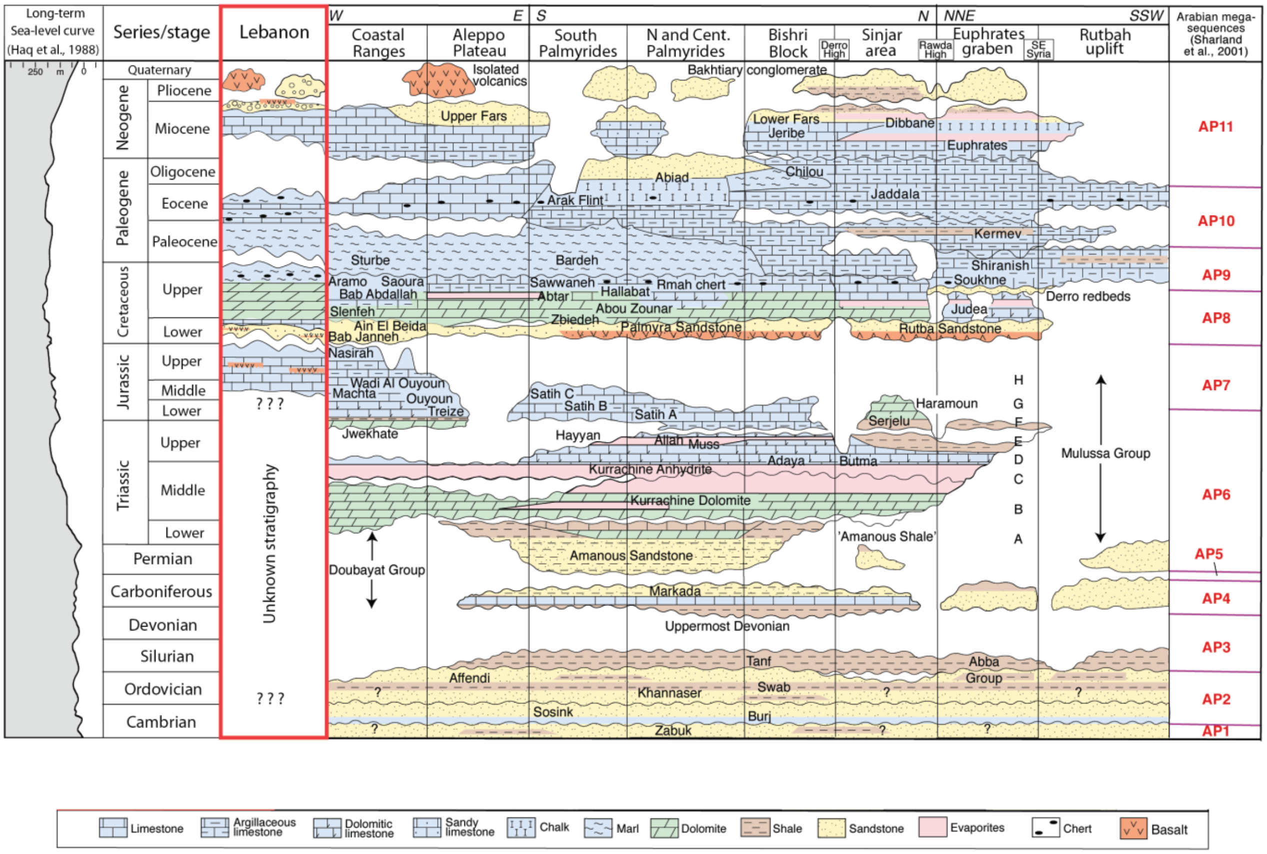
A major unconformity is attested at the boundary between Late Eocene and Early Oligocene, which could have been related to an interaction between eustatic sea level fall (Haq *et al*., 1988; Miller *et al*.,

2005) and wide spread marginal uplift also noted along the Gulf of Suez and in the Red Sea domain (34 Ma; Omar & Steckler, 1995).

The extension in the Red Sea starting from the Late Eocene initiated the separation between Arabia and Africa with pull-apart basins rapidly filled with fluvial sediments (Bohannon, 1986; Figs.1.9e). A transgression initiated in the Latest Eocene followed by the development of mixed and/or carbonate platforms on the northern African margin and Levant area. The Lower Oligocene sediments are commonly apparent in wells along the eastern Mediterranean coast as well as offshore and consist of pelagic deep-water marly chalks. The Middle and Late Oligocene are successively marked by slumped blocks and debris flows, overlain by '*in situ* large foraminiferal limestone' which is representative of a lowstand prograding wedge identified in the coastal plain area (i.e. Ashdod wells in Israel) (Gardosh *et al*., 2008).

During the Early Miocene, rifting continued along the Gulf of Suez and Red Sea succeeded by rift-shoulders uplift of large domains (i.e., south central Egypt, western Arabian Shield) (Buck, 1991; Guiraud & Bosworth, 1999; Fig.1.10). The Levant area was further uplifted as a consequence of the continued collision of Afro-Arabia with Eurasia (Buchbinder & Zilberman, 1997). Strong magmatic activity has been observed in the Burdigalian in Saudi Arabia and the Sinai region (Guiraud & Bosworth, 1999). The Arabian Plate separated from the African Plate in Mid to Late Miocene along the "Levant Fracture System" (Hempton, 1987; Walley, 1998; Beydoun, 1999; Brew *et al*., 2001; Fig.1.9e). The end of the Miocene period is marked by the isolation of the Mediterranean Sea from the Atlantic, known as the 'Messinian Crisis' (Hsu *et al*., 1973). Intense erosion on the basin margin (incision of deep canyons and valleys) followed by thick evaporitic deposition (reaching more than 2000m in the Levant Basin), have shaped the eastern Mediterranean (e.g. Gvirtzman & Buchbinder 1978; Cita & Ryan, 1978; Druckman *et al.*, 1995).

The Early Pliocene was marked by an inundation of the Levant Basin (Fig.1.9f). At that time Arabia resumed its independent movement from Africa with extrusions of crustal wedges in the convergent zone marking a faster 2nd episode of separation supported by extension in the Red Sea area (Hempton, 1987). The Pliocene (to present) section –unlike older units– is thinner in the basin and thicker on the continental margin and makes up the Nile Delta with a thickness of about 4km (Said, 1981; Segev *et al.*, 2006; Fig.1.10). Deposition of hemi-pelagic marl and sandy turbidites (gas-bearing) in a basin floor or lower slope environment has been noted (Druckman, 2001; Oats, 2001).



modified from Walley (1997) and Brew et al. (2001)

Fig1.11. Regional onshore chronostratigraphic chart of the northern Levant margin (Syria and Lebanon) showing the major lithologies observed from the Cambrian till Present as well as the main hiatuses. Note that the pre-Jurassic stratigraphy of Lebanon is still unknown (refer to section III.2 for a detailed assessment of the sedimentology and stratigraphy of Lebanon).

III. Lebanon

Lebanon is located in the central part of the Levant region, at the boundary between the Arabian and African plates. Since the 1950s, a number of studies have focused on the structural and stratigraphic evolution of Lebanon from the Mesozoic onwards (refer to Dubertret 1975; Beydoun 1977; Saint-Marc 1972, 1974; Beydoun & Habib 1995; Walley 1997, 2001; Nader 2000; Nader and Swennen 2004). The generation of geological maps (Fig.1.12) was mainly based on macrofossil dating and lithological studies. In a published stratigraphic overview, Walley (1997) noted out a need for further geologic investigations in order to better understand ages subdivisions of some outcropping formations (i.e. Upper Cretaceous and Cenozoic) allowing to unravel missing clues of the tectono-stratigraphic evolution of Lebanon.

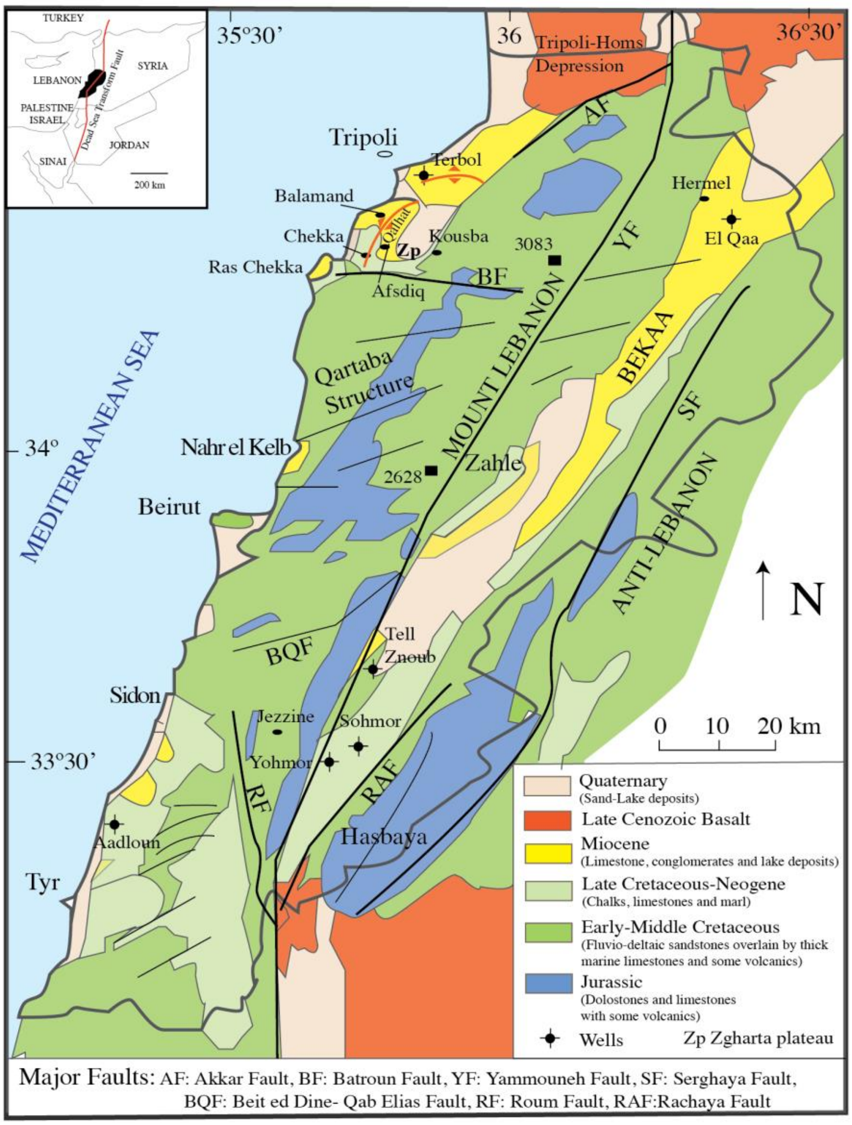


Fig1.12. Simplified geologic map of Lebanon showing the major outcropping rock units as well as the major structural features (modified from Dubertret, 1955).

III.1 Structural evolution

Lebanon is composed of major meso-structures resulting from the successive onshore tectonic deformation (refer to Fig.1.13 for the following descriptions). The Lebanese coastal area is bound to the east by a NNE-SSW trending mountain chain known as "Mount Lebanon". The culminating point reaches an elevation of about 3088 m in northern Lebanon while towards the south the relief is much less prominent. Mount Lebanon is separated from the eastern "Anti-Lebanon" chain by a Neogene-infilled valley referred to as the "Bekaa valley". The southern part of the Anti-Lebanon represent a 2814 m high Jurassic cored structure the "Mount Hermon" (Dubertret, 1975).

III.1.1 Levant Fracture splays

A set of faults dissects the Lebanese territory. The NNE–SSW trending Yammouneh Fault runs along the eastern flank of Mount Lebanon along the entire length of the country. It links the Dead Sea Fault (Israel) to the south with the Ghab Fault System to the north (Syria). A number of sub-parallel and divergent fault splay of the major Yammouneh Fault accommodating some of the Miocene-Present strike slip motion (Walley, 1988) expected to reach 105 km in Israel (Quennell, 1958; Freund *et al*., 1970; Garfunkel, 1981).

The Roum Fault splays with a NW-SE direction from the Yammouneh Fault at the southern Lebanese border with a total length of about 35. The Roum Fault is a sinistral strike-slip fault characterized by a decreasing amount of displacement northward, from 7-9km in its southern segment (Butler *et al*., 1997; Griffiths *et al*., 2000) to 0.2km in its northern extremity (Griffiths *et al.,* 2000). This fault is thought to have been active since Miocene (Girdler 1990; Butler *et al.* 1998). The Roum fault offsets the Litani and Zahrani rivers cutting across the Tyr–Nabatieh plateau showing left lateral displacement in the past 5 Ma (Walley 1988). Nemer (1999) suggested that the Roum Fault is dominantly a normal fault with about 1200 m of throw terminating in a diffuse fault system expressed on the surface as folds. Other interpretations link the Roum Fault to an offshore thrust system parallel to the northern Lebanese coastline (Fig.1.6) (e.g. Elias *et al*., 2007; Carton *et al*., 2009)

The Serghaya Fault branches out from the southern Levant Fracture System around the Golan Heights area and is traced approximately 125 km through the Anti-Lebanon to the eastern edge of the Bekaa Valley. Studies in the western Palmyride region underlined a 20-30 km shortening induced by the sinistral motion of the Serghaya Fault (Chaimov *et al*., 1990; Khair *et al*., 1993). The fault is still active today with slip rates of about of 1-2 mm per year (Gomez et al., 2001)

The Rachaya fault is located in between the Yammouneh and the Serghaya Faults branching of the eastern border of the Dead Sea rift, with a NNE-SSW trend. The Rachaya Fault presents a 600 m throw towards the east (Renouard, 1955), and about 1km of sinistral offset (Heimann & Ron, 1987) with a total length of 45 km.

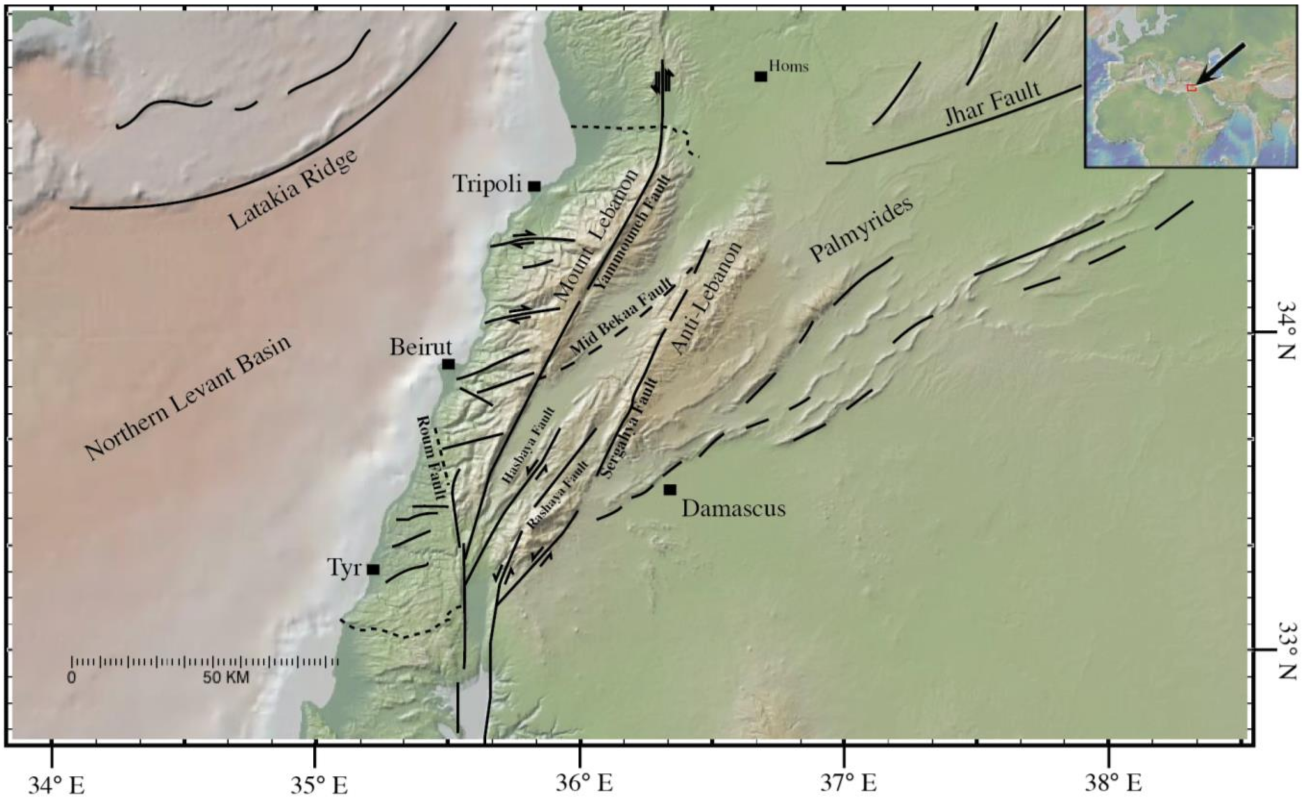


Fig1.13. Structural map of Lebanon and the Palmyrides showing the major faults trends and structures. Refer to the description of these features in the text. (topographic and bathymetric data from GeoMapApp).

III.1.2 Other faults

Along northern Mount Lebanon a set of ENE-WSW as well as E-W faults are apparent. They seem to be offsetting Mount Lebanon's core presenting a dextral motion (Dubertret, 1975; Hancock & Atiya, 1979). Homberg *et al.* (2010) refers to some of these faults as being induced by an Early Cretaceous (from Hauterivian (maybe earlier) to Albian times) NNE-SSW extension retaken by counter clockwise rotations in Lebanon leading to dextral strike slip motions along them (Gedeon 1999; Walley 1988).

Along southern Lebanon a set of ENE-WSW faults is observed across the coastal southern Lebanon (i.e., Tyr-Nabatieh plateau) and are still not well understood. Some authors suggested a dip slip component linking them to a potential extensional regime (Hancock & Atiya, 1979; Griffiths *et al.,* 2000) while Butler *et al.* (1997) discussed the strike-slip component of these faults. Lately Homberg et al. (2010) argued that some of the faults present in southern Lebanon are extensional and present growth features affecting the Middle Eocene section suggesting further extensional stresses in the Eocene.

III.1.3 Onshore deformation summary

Several phases of tectonic deformations have been observed onshore Lebanon. Since the convergence between Afro-Arabia and Eurasia in the Turonian, gentle folding resulted from the inversion of inherited old fault systems (Dubertret, 1975; Walley, 1998). Several arguments have been proposed to justify this deformation phase timing:

(1) The NNE–SSW trend of the main Lebanon structures is consistent with the regional Syrian Arc trend.

(2) Stratigraphic investigations supported by thickness changes in the Upper Cretaaceous (i.e., Senonian) rock unit.

(3) The identical trend and similarities in structural style between both the Mount Lebanon and the Anti-Lebanon, which are more easily explained by the impact of a regional compressional regime on their formation rather than by a transpressive one.

(4) A number of fundamental structures in Lebanon are offset by the motion on the Yammouneh Fault System and must therefore pre-date it. For example, the maximum fold deformation seen in the zone immediately west of the Yammouneh Fault is at Jebel Niha on the western flanks of the Barouk–Niha Uplift

Continuous folding of the Lebanese ranges should have persisted in the Oligocene and Early Miocene (Walley, 1998; Homberg *et al*., 2010) probably linked to the continuous collision of Afro-Arabia with Eurasia. The major phase of Mount Lebanon's deformation was dated back to the Late Miocene onwards and has been linked to the transpression over the central LFS (Butler et al., 1998; Walley, 1998; Beydoun, 1999; Gomez *et al*., 2006; Homberg *et al*., 2010; among others).

III.2 Sedimentological and stratigraphic framework

During the Mesozoic, the Lebanese carbonate platform was deposited in the intraplate Palmyride Basin formed in the Late Paleozoic and that extends along the whole Levantine margin from northern Egypt passing by Israel, Lebanon, Syria and NW Iraq (Walley, 1998). No information is available on the Triassic in Lebanon. It is thought that this unit has been deposited in a quite similar environment with that of the Early Jurassic consisting of carbonates, clastics and evaporites (Benjamini *et al*., 1993; Buchbinder & Le Roux, 1993; Nader & Swennen, 2004). After rifting episodes that led to the thinning of the crust, a large carbonate shelf extending from the Coastal Ranges of Syria to the Coastal Chains and Galilee in northern Israel prevailed in the Middle to Late Jurassic. An epicontinental shelf dominated the Lebanese territory from the end of the Bathonian to the Kimmeridgian (Kesrouane Fm: about 1000m thick; refer to Fig.1.14 for the following stratigraphic descriptions) (Collin *et al*., 2010).

A global relative sea level fall followed by continental volcanism linked with Late Jurassic rifting (Abdel-Rahman, 2002; Laws & Wilson, 1997) led to the deposition of the Bhannes Fm (thickness ranges between 50-150m; made of volcanic and basaltic flows as well as rare intercalation of limestone beds; Walley, 1997). The main part of the Bhannes Fm has been dated on paleontological grounds as being of a Late Oxfordian to early (possibly mid) Kimmeridgian (Dubertret, 1955; Saint-Marc, 1980). The limited K-Ar dating analyses of Laws & Wilson (1997) resulted in approximate volcanic ages of about 148 Ma, coinciding well with biostratigraphic dating.

Following a marine transgression, a shallow carbonate platform unit (Bikfaya Fm and Salima Fm) dominated the uppermost Kimmeridgian-Tithonian? attesting of a warm climate. The Bikfaya Fm is a cliff-forming unit with thicknesses reaching a maximum of 60 m, and thins northwards (e.g. Nahr

Ibrahim: 30 to 40m; Qadisha: completely missing- eroded or not deposited). The limestones are mainly of micritic texture with some porcellanitic splintery fractures reflecting a return to marine (reef) environments over the subaerial Bhannes Fm (Walley, 1997). The Bikfaya Fm was previously considered of a Late Kimmeridgian to Tithonian age (Dubertret, 1955; Walley, 1997) and the age was lately confirmed using benthic foraminifera and calcareous algae biostratigraphy (Collin *et al*., 2010).

The Salima Fm has a variable thickness ranging between 0 and 200 m (Dubertret, 1955) probably deposited on an already faulted terrain and affected by Early Cretaceous erosion (Dubertret, 1955; Walley, 1997). The Salima Fm is thin/missing in northern Mount Lebanon while in the vicinities of Beirut the formation attains a considerable thickness. It consists of a series of ochre brown-yellow ferruginous oolitic, sandy limestones with marl, clay, and sand intercalations. The age of the Salima Formation has been a controversial issue. Dubertret (1955) assigned a Late Portlandian age for this formation while the presence of ammonite Berriasella richteri, in the upper beds may characterize the upper Tithonian (Hirsch and Picard, 1988). Noujaim Clark and Boudagher-Fadel (2001) as well as Ferry *et al*. (2007) proposed a Berriasian-Valanginian age for the Salima Fm.

A loss of accommodation as a consequence of regression and exposure marked the Jurassic Cretaceous boundary and is observed over the Levant margin (Walley, 1998; Collin *et al*., 2010). The Early Cretaceous is marked by a regional NNE-SSW extensional phase that started in the Valanginian or slightly later. This direction of extension in the Early Cretaceous is approximately orthogonal to that of the previous rifting events seen offshore. The Chouf area represented at that time a depocenter with thickest sedimentary succession (about 400 m) of ferruginous brown to white quartz sandstone (Walley, 1998; Homberg *et al*., 2010). These terrigenous clastics might have been provided from the erosion of uplifted basement rocks as well as Paleozoic sandstones located in Saudi Arabia, northeastern Jordan and south of Syria (Walley, 1998). The northern Mount Lebanon displays a local thinning of these sandstones, which could be explained or by local uplift in northern Mount Lebanon, before and during the deposition of the Chouf Fm or by subsidence in central and southern Lebanon associated with rifting (Dubertret, 1975; Walley, 1997).

Marine conditions directed the Aptian; where massive clay forming limestone units (Mdairej Fm) (Nader & Swennen, 2004) have been described by Walley (1998) as being representative of a shallow marine shelf environment. The end of this epoch was marked by a return to terrigenous clastic sedimentation with the presence of clay material that might be representative of a restricted tidal to supratidal (lagoon) environment (Hammana Fm). Volcanism episodes were brought to an end. A major transgression dating from the Cenomanian followed, leading to a 600 m deposition of a pale grey thinly bedded limestone (Sannine Fm) in 2 types of environments: (1) East (inland): reef/lagoon; (2) West (coastal): subtidal to deep. The top of the Sannine Fm along the coastal area presents marly limestone facies however Dubertret (1975) dated the Turonian based on biostratigraphic criteria of the appearance of either Turonian *Ammonites* or the rudist bivalve *Hippurites*. This unit is apparently about 200-300 m thick (Dubertret, 1975). The Turonian rock unit is referred to as the Maameltain Fm (Dubertret, 1975; Walley, 1997).

The term "Senonian" has been used in the literature in order to refer to the Coniacian to Maastrichtian. Recent investigations done by Müller *et al*. (2010) have allowed to better revise the Upper Cretaceous stratigraphy (known as the Chekka Fm marly and chalky limestone). Hiatuses have been identified dating from the Coniacian to Santonian hiatus as well from the Upper Maastrichtian to Lower Paleocene. The Paleocene to Early Middle Eocene units in Lebanon represent a continuation of the Cretaceous marine conditions, consisting of thinly-bedded argillaceous marls overlain by compact marly units as well as an alternation of marls, limestone with the local presence of chert bands or nodules (Walley, 1998; Müller *et al*., 2010). This sequence corresponds to a global sea-level highstand (Hardenbol *et al*., 1998).

The Upper Eocene to Upper Oligocene strata were thought to be missing from the Lebanese stratigraphy and thus representing a major hiatus (Dubertret, 1975). However, these rock units have been identified widely in southern Lebanon by Müller *et al*. (2010), which permitted to review more thoroughly the Cenozoic stratigraphy.

More restricted towards the coastal areas, the Neogene series was subdivided into the "Vindobonian" and "Pontian", old terms that refer respectively to the Middle and Late Miocene (Dubertret, 1975). A Lower Miocene regional hiatus has been noted along the Levant region including Lebanon. The Burdigalian is the first transgressive sequence attested onshore Lebanon followed by the more extensive Langhian transgression capping strata of variable ages as Campanian, Late Paleocene, Early-Late Eocene and Late Oligocene. This unconformity, as well as the intense reworking of the Langhian series, indicates a possible tectonic event within the uppermost Burdigalian (Müller *et al*., 2010). Rhodalgal banks have been identified dating from the Serravallian to Tortono-Messinian in northern Lebanon by (BouDagher-Fadel & Clark, 2006). Continental sedimentation was attributed to the Middle to Late Miocene epoch mainly found inland east of Tripoli (Jebel Turbol) as well as the Bekaa valley with thicknesses reaching hundreds of meters and consisting of marl and algal pisolites with intercalation of conglomeratic and fresh water carbonates (200-800 m thick) overlain by 500-600 m of alluvial fan conglomerates.

An important transgression marks the Early Pliocene with sea invasion of coastal areas of Lebanon leading to silt and sandy silt deposition rich in nannofossils. Marine Lower Pliocene sediments overly unconformably continental deposits of Late Miocene in Tripoli, while fluvial and lacustrine environment persisted in the Bekaa region into the Holocene (Fig.1.12) (Elias, 2006; Druckman *et al*., 1995; Gardosh *et al*., 2008; 2010; Müller *et al*., 2010).

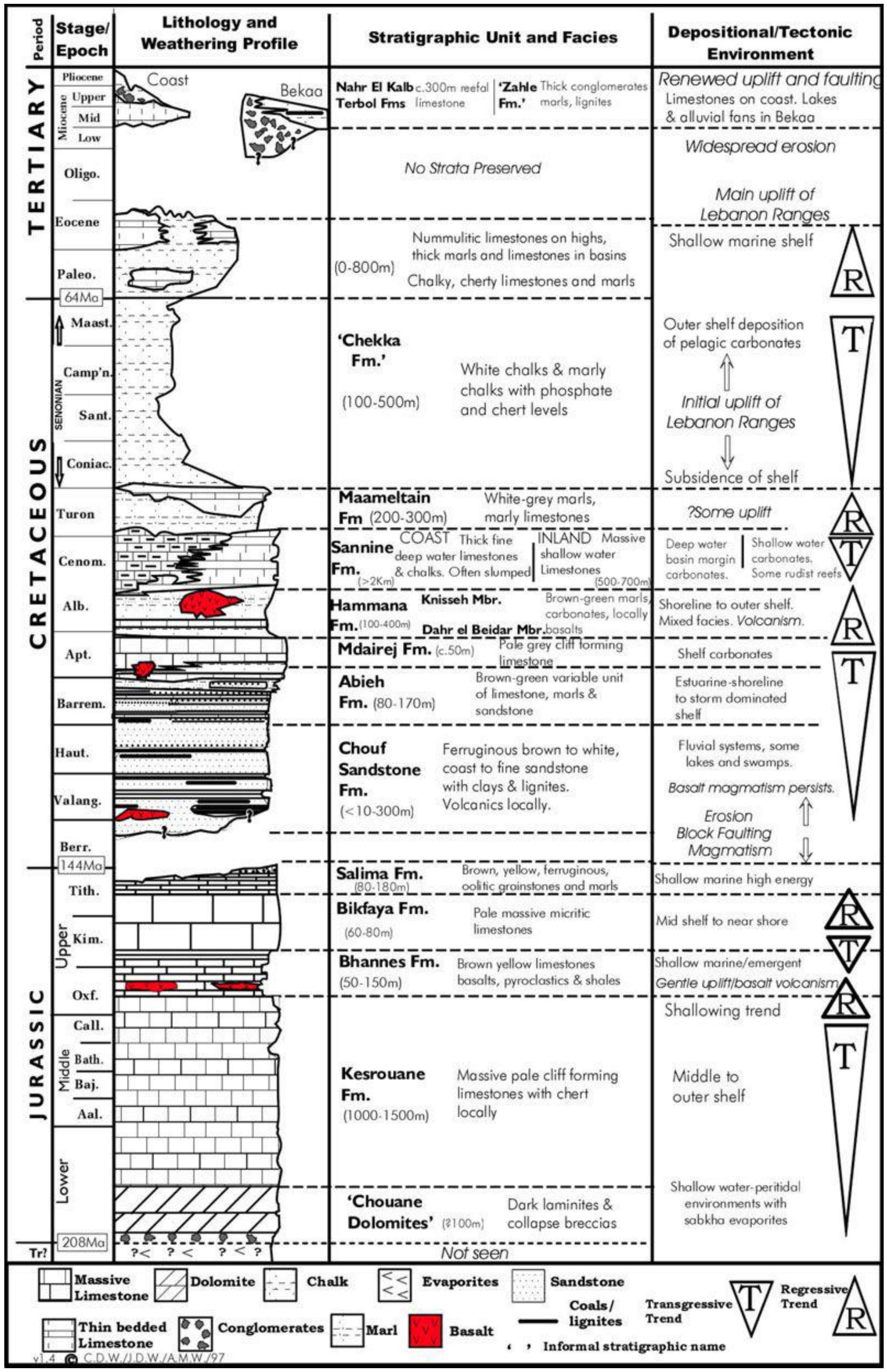


Fig1.14. Simplified chronostratigraphic chart of Lebanon from the Jurassic to the Pliocene (Walley, 1997).

CHAPTER II

Data & Methodology

This chapter highlights the methodology used in order to assess the architecture and sedimentary infill of the northern Levant margin and basin (onshore-offshore Lebanon). The chapter is divided into three sections each focused on a set of data: (1) acquired through fieldwork; (2) provided by the Petroleum Geo-Services (PGS) and the Lebanese Ministry of Energy and Water (i.e., seismic and well data) or (3) gathered and synthesized from the literature. Note that further details linked with the principles behind the seismic interpretation and forward stratigraphic modeling can be found in the chapter 3 of the manuscript.

I. Fieldwork (Facies analysis, sedimentary logs, biostratigraphy)

Six fieldwork campaigns have been conducted to better constrain the ages subdivisions of the Upper Cretaceous to Upper Miocene outcropping rock units as well as to assess the potential depositional environments prevailing in each period studied. Several field visits consisted of sedimentological, structural and stratigraphic observations and documentations around four main locations: northern, central and southern coastal Lebanon as well as on the eastern flank of central Mount Lebanon. The locations have been thoroughly chosen based on their accessibility, importance in allowing to understand the complete Upper Cretaceous to Cenozoic rock succession, and on the variability of facies attested for the same age unit in each of the different sites (Fig.2.1).

I.1 Biostratigraphy

The use of nannofossil and foraminifer biostratigraphy (benthic and mainly planktonic) respectively by Dr. Carla Müller (independent consultant) and by Dr. Delphine Desmares (University of Pierre and Marie Curie- UPMC) permitted the dating of the several studied rock units. In addition a master project was achieved at IFP Energies Nouvelles by Nemo Crognier who also provided important age constraints for the sedimentological sections studied in northern and central Lebanon using foraminifer stratigraphy (master thesis in french entitled: Études sédimentologiques et biostratigraphiques de la série Turono-Miocène du Nord Liban: Contraintes pour la modélisations stratigraphique sur DIONISOS)

The calcareous nannofossils were studied in smear slices under polarizing microscope at 1,250 magnification. The Cretaceous biozonation follows Thierstein (1976), Sissingh (1977) and Perch-Nielsen (1985); the Cenozoic biozonation used is based on Martini (1971) and Martini and Müller (1986). The planktonic foraminifers were studied based on material from washed samples (calcareous shales) and in thin sections (carbonates). For calcareous shales, bulk samples were soaked in a weak peroxide solution and rinsed with tap water over sieves of 1 mm and 63 μm mesh width. Residues were ovendried at 40 °C. The planktonic foraminifers zonation used follows those of Caron (1985), Toumarkine and Luterbacher (1985), Premoli Silva and Sliter (1995), and Robaszynski and Caron (1995).

Two sampling approaches have been followed: (1) a high resolution sampling (every 0.5 m); mainly for the subdivision of the Upper Cretaceous "Senonian" rock succession at the Chekka quarry type-section and (2) a lower resolution sampling (variable) aimed at dating stratigraphic contacts and major hiatuses as well as allocating refined ages to sedimentological facies attested on the field.

I.2 Sites investigations and sedimentologic logging

The major outputs of the fieldwork proposed are the high-resolution sedimentary logs covering strata from the Upper Jurassic till the Upper Miocene. Macro-facies investigations were supported by micro-facies analysis under polarizing light microscope. The typical proposed sedimentary log presents the overall bed lithology, the grain size/sedimentary texture, the sedimentary features attested as well as the biological and fossil content identified. Depositional environments and age constraints are also featured on the logs. Field investigations in surrounding locations help provide additional hard data for a better three-dimensional understanding of the studied structures, the continuity of stratigraphic contacts and the sedimentary facies extent (Figs.2.1, 2.2).

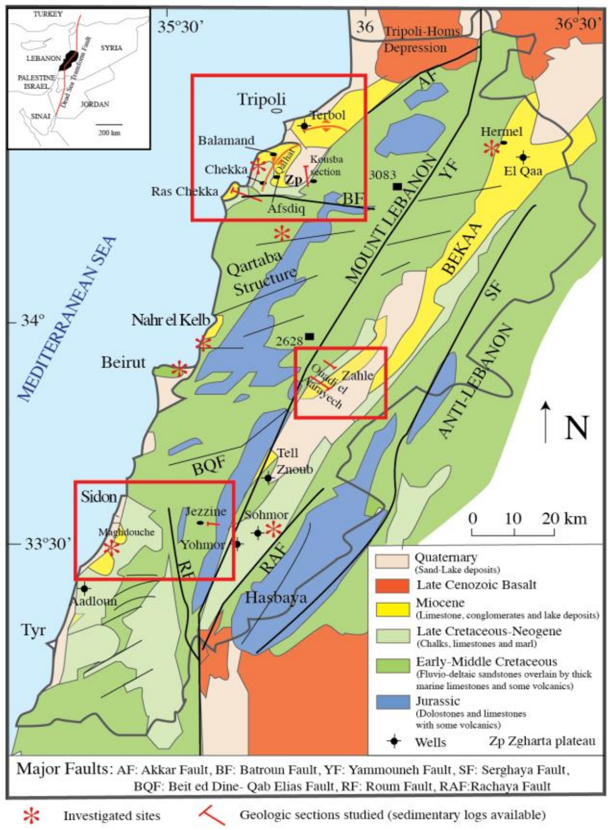


Fig2.1. Geologic map showing the major outcrops and sections investigated along this project.

A total of about 6560 m of high-resolution sedimentary logs are presented below (Fig.2.1) and discussed in further details in the chapters 3 and 4 under the onshore results section.

<u>Northern Lebanon:</u>

- At the Kousba locality a 1860 m thick Turonian to Upper Miocene section was sedimentologically logged along the Nahr Abou Ali River (between 34°18′27.54″N; 35°51'48.00″E and 34°19′47.81″N; 35°51′ 37.97″E).

- Five wells (BH-3, BH-8, BH13, BH-26, and BH-27) as well as one, 45-m-thick outcrop section were described in order to provide a composite log of the complete Chekka Formation (Coniacian–Paleocene).

- At the Deir Billa locality (N 34°14'38.40"; E 35°48'39.06") a log of about 320 m was completed for the Turonian to Senonian transition

- At the Ras Chekka locality (N 34°17'57.00"; E 35°42'24.12") a log of 304 m covers the Senonian to Middle Miocene rock units.
- The surrounding locations of Amioun, Afsdiq, Balamand were visited in order to better constrain the facies changes and extent as well as to study stratigraphic contacts.
- Samples have been gathered for micro facies analysis and dating.

Central Lebanon:

- At the Ouadi el Aarayech (Zahle) a composite sedimentary log (1720 m) has been completed for the Upper Cretaceous to Upper Miocene rock succession (composite section: between 33°51’54.001”N; 035°53’18.0”E and 33°50’29.0”N; 035°54’32.9”)
- A geologic section running north of Ouadi el Aarayech was also conducted and covers the extension of the Zahle anticlinal feature.
- Towards the central coastal area, the Miocene unit was described in Beirut (Charles Helou station- 33°53'46.45"N; 35°30'57.76"E).
- Samples have been gathered from both Zahle section and Beirut outcrop for dating purposes as well as for micro-facies analysis.

Southern Lebanon:

- A 1520 m sedimentary log was completed for the Jezzine area comprising the Upper Jurassic to Cenomanian rock units.
- A Focus on the Lower Cretaceous Chouf Sandstone in Jezzine (main onshore depocenter) brought forward views on the depositional environments affecting Lebanon at that period.
- The sedimentary facies of the Eocene to Miocene were studied along the Tyr-Nabatieh plateau and compared to the previously studied locations providing answers to the impact of onshore structural deformation on sedimentary facies evolution.
- Samples have been gathered in order to conduct micro-facies studies and dating, permitting to constrain the stratigraphy of southern Lebanon

Source rock characterization was accomplished using RockEval6 at IFP Energies Nouvelles for the Jurassic to Upper Cretaceous rock units. Forty samples from varied locations onshore Lebanon were acquired and assessed. The aim of this campaign is to set ground for upcoming detailed source rock characterization investigations (refer to the PhD of Samer Boudaher -Aachen University- entitled “Source rock maturation and petroleum generation and migration modeling of the Levantine Basin, offshore Lebanon: an integrated approach”).

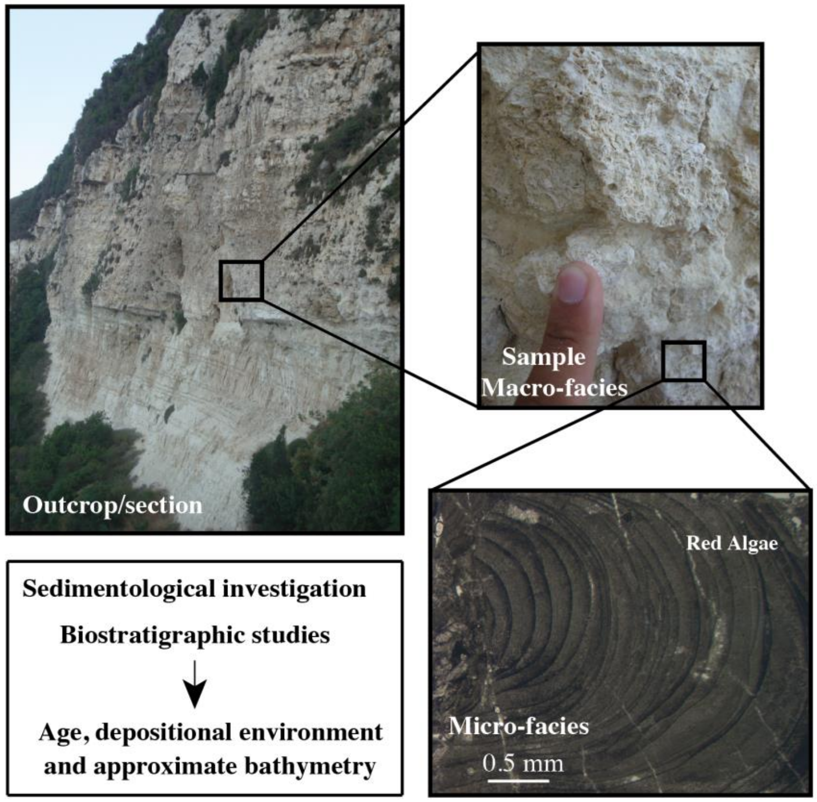


Fig2.2 Pictures showing the fieldwork approach conducted along this thesis: a coupling between varied scales investigations leading to an in-depth assessment of the sedimentology, stratigraphy and depositional environments prevailing from the Upper Mesozoic onwards.

II. Seismic and well data set

II.1 Seismic interpretation

The Levant Basin offshore Lebanon covers an area of about 25 000 km^2. About 960 km of regional 2D seismic profiles were gathered and interpreted from the MC2D LEB 2008 PGS multi-client survey. Additional 100 km of 2D seismic profiles from the Geco-Prakla 1993 database (*courtesy of the MEW*) covering the shallow marine section of northern Lebanon (around the offshore Tripoli region) have been seen and discussed in this study (Fig.2.3). The latter allow investigating more closely the onshore-offshore platform extension into the northernmost Levant Basin. The KINGDOM suite software (SMT) was used for the seismic interpretation section of this PhD thesis.

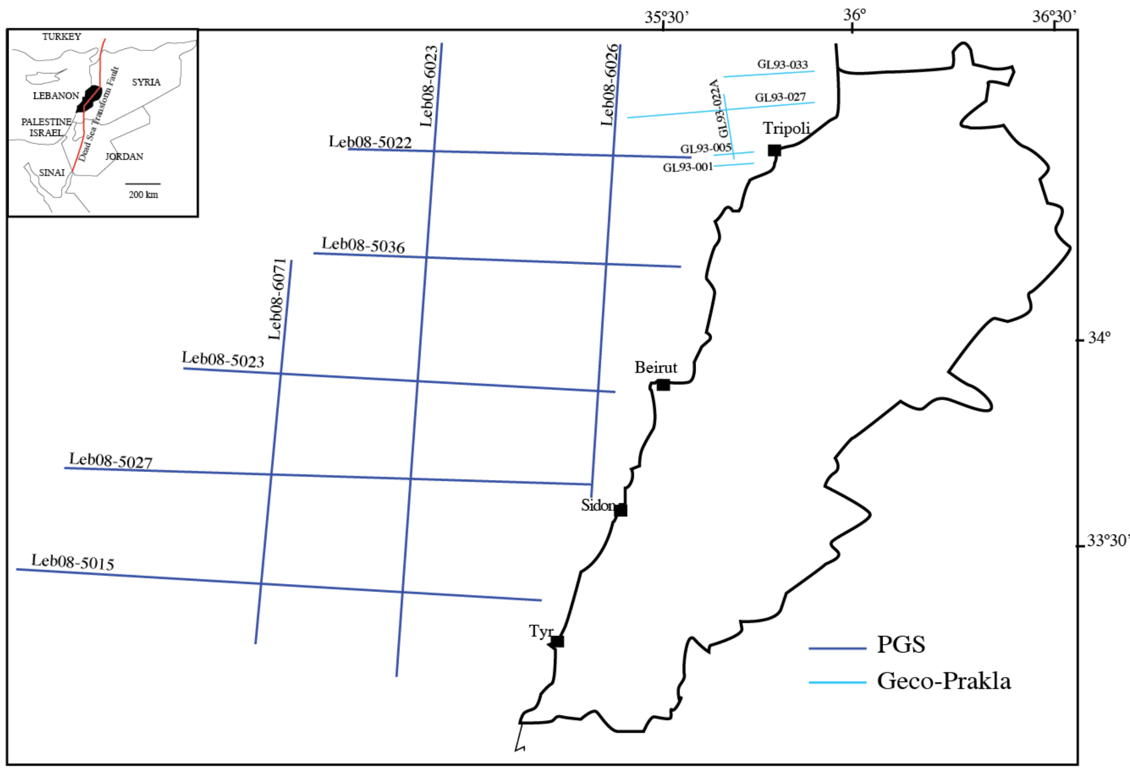


Fig2.3. Location map of the main seismic profiles studied *(courtesy of PGS and the MEW)*

Following seismic stratigraphic concepts (e.g., Mitchum et al., 1977; Catuneanu et al., 2009) a detailed study of the geometries of seismic packages and their bounding surfaces allowed to represent the architecture of the northern Levant Basin with relation to major geodynamic events affecting the eastern Mediterranean (Fig.2.4). The ages proposed for the seismic units are still speculative as they are extrapolated from wells drilled on the margin. The good seismic reflection continuity between the southern and northern Levant Basin reduces some the uncertainties linked with the ages allocation to seismic packages offshore Lebanon.

Wells drilled along the coastal area of Lebanon (Terbol-1 and Adloun-1) have been used in order to link the onshore geology to the offshore seismic data as no wells have yet been drilled in the northern Levant Basin.

Offshore isochron maps generated for the interpreted seismic packages were converted to depth using maps of stacked velocities (*courtesy of PGS*). The in-depth seismic facies analysis of the distal margin and basin permitted to propose a coherent depositional scheme for the northern Levant Basin offshore Lebanon (Mitchum et al., 1977, Sangree & Widmier, 1977, Roksandi'c, 1978, Sheriff, 1980; Van Wagoner et al., 1988 summarized in Catuneano et al., 2009).

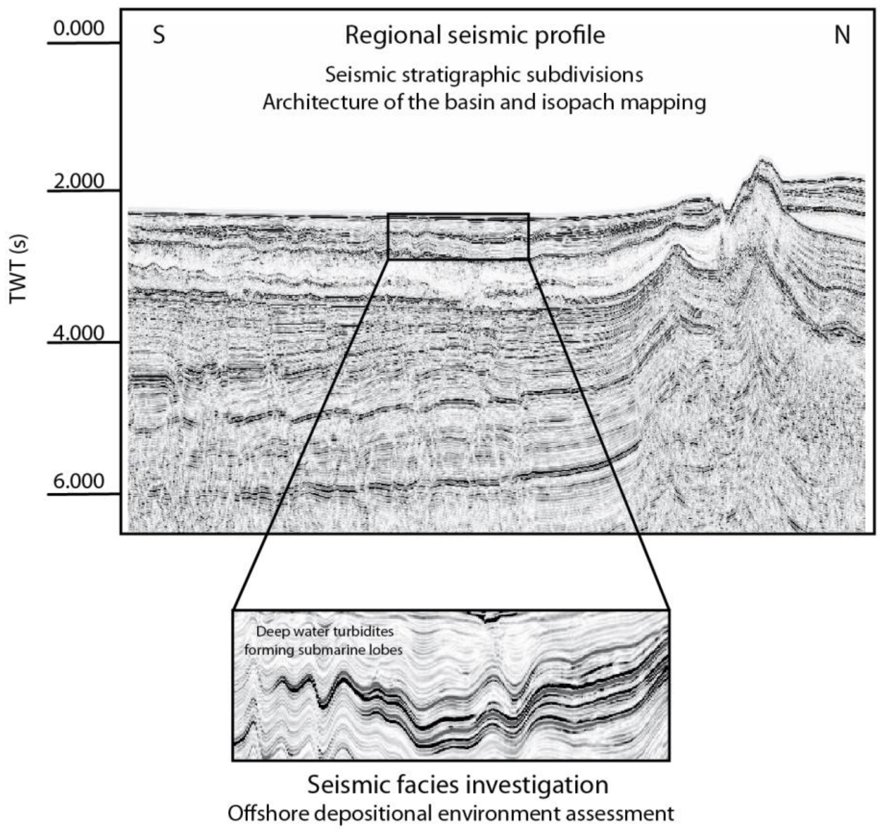


Fig2.4. Illustration showing the strategy followed in order to understand the architectural evolution and sedimentary infill of the northern Levant Basin offshore Lebanon *(Courtesy of PGS).*

II.2 Deep borehole data

The following six wells have been drilled between 1947-1967 onshore Lebanon (Ukla, 1970; Beydoun, 1977). They have been used in order to support our field investigations (Fig.2.1 and Appendix 2).

- Terbol-1: 2676 m - Middle/Upper Jurassic to Middle Miocene
- Adloun-1: 2080 m - Upper Jurassic to Upper Cretaceous
- El Qaa-1: 1908 m - Upper Jurassic to Neogene
- Sohmor-1: 353 m – Upper Cretaceous to Eocene
- Tell Znoub-1: 487 m – Upper Jurassic to Cenomanian
- Yohmor-1: 1717 m – Aptian to Eocene

The wells do not penetrate strata older than the outcropping Middle Jurassic, leaving behind an important part of the Early Mesozoic and Paleozoic history of Lebanon un-explored. The well data bring more constraints to the thicknesses of sedimentary units onshore Lebanon. The westernmost coastal wells (i.e., Terbol-1 and Adloun-1) permit reducing some of the uncertainties linked with ages allocations to the sedimentary packages interpreted on the seismic data; leading to a better understanding of the margin-basin platform evolution and potential facies extents.

III. Forward Stratigraphic Modeling

The Dionisos software used in this thesis is a deterministic "process-based" modeling tool that accounts for accommodation, supply and transport. Accommodation is controlled by sea level variations, plus basin and strata deformation induced by compaction, vertical uplift and subsidence, thrusts and growth faults, salt and shale diapirs" (Granjeon, 2009).

The use of this modeling approach in frontier areas reveals to be crucial in mimicking the stratigraphic evolution of margins and basins through time and predicting the potential depositional environments with regards to major geodynamic events and sea level fluctuations.

Many hypotheses of basin infill have been tested; constrained by the onshore assessment, seismic interpretation and coupled with a wide literature overview of the Levant region (Fig.2.5). The main data input parameters in the Dionisos model proposed in this thesis are further discussed in the forward stratigraphic modeling section under the chapter 6 of this thesis.

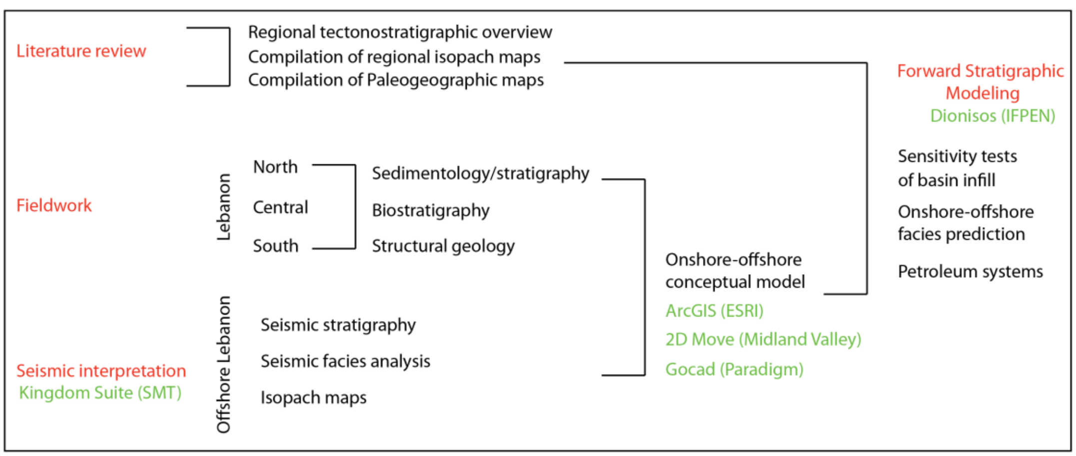


Fig2.5. Simplified methodology scheme underlining the importance of data integration (literature, onshore/offshore investigations) in the build-up of a coherent geological model for the northern Levant region. The Forward Stratigraphic Modeling approach is used in order to test several scenarios related to the basin.

CHAPTER III

Sedimentological & Stratigraphic Evolution of Northern Lebanon

The coupling between sedimentary macro-facies and micro-facies analysis as well as nannofossil and foraminifer biostratigraphy allowed for the first time to propose ages subdivisions to the still poorly constrained "Senonian" rock unit onshore Lebanon (Chekka Formation; Dubertret, 1975; Walley, 1997). In addition hiatuses have been identified around the Late Turonian to Late Santonian, Late Maastrichtian to Late Paleocene, Ypresian/Lower Lutatian to Late Burdigalian permitting to better understand the impact of local onshore deformation and/or more regional geodynamic events on the sediment deposition and preservation along the northern Levant margin onshore Lebanon. The sedimentary facies investigation point to a major drowning event that initiated towards the end of the Turonian and that lasted until the Early Eocene. Marly limestone and calci-turbidites have consequently been deposited on top of middle ramp rudist-prone Turonian platforms.

Throughout this article (Hawie et al., 2013a) a new conceptual model for the Miocene rock unit of northern Lebanon was proposed. It proved the impact of a pre-Burdigalian deformation on the rhodalgal sedimentary facies configurations and extent. The major phase of Mount Lebanon's uplift is expected to occur around the Tortono-Messinian with the development of large conglomeratic fan deltas in a continental setting.

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ORIGINAL PAPER

Sedimentological and stratigraphic evolution of northern Lebanon since the Late Cretaceous: implications for the Levant margin and basin

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Abstract

This paper presents an updated review of the Upper Mesozoic and Cenozoic sedimentological and stratigraphic evolution of the Levant margin with a focus on the northern Lebanon. Facies and micro-facies analysis of outcrop sections and onshore well cores (i.e. Kousba and Chekka) supported by nannofossil and planktonic foraminifers biostratigraphy, allowed to constrain the depositional environments prevailing in the Turonian to Late Miocene.

The “Senonian” (a historical term used to define the Coniacian to Maastrichtian) source rock interval was subdivided into four sub-units with related outer-shelfal facies: (1) Upper Santonian, (2) Lower, (3) Upper Campanian, and (4) Lower Maastrichtian. This Upper Cretaceous rock unit marks the major drowning of the former Turonian rudist platform. This paper confirms the Late Lutetian to Late Burdigalian hiatus, which appears to be a direct consequence of major geodynamic events affecting the Levant region (i.e., the continued collision of Afro-Arabia with Eurasia), potentially enhanced by regressional cycles (e.g., Rupelian lowstand).

The distribution of Late Burdigalian-Serravallian rhodalgal banks identified in northern Lebanon was controlled by pre-existing structures inherited from the pulsating onshore deformation. Reef barriers facies occur around the Qalhat anticline, separating an eastern, restricted back-reef setting from a western, coastal to open marine one.

The acme of Mount Lebanon’s uplift and exposure is dated back to the Middle-Late Miocene; it led to important erosion of carbonates that were subsequently deposited in paleo-topographic lows. The Late Cretaceous to Cenozoic facies variations and hiatuses show that the northern Lebanon was in a higher structural position compared to the south since at least the Late Cretaceous. This study further discusses the potential impact of regional drainage systems on the infill of the Levant Basin.

Keywords:

Northern Lebanon, Levant Basin geodynamics, Biostratigraphy, Campanian, Cenozoic, nannofossils.

1. Introduction

Located in the eastern Mediterranean region the Levant margin extends from northern Egypt to Turkey and presents a very complex geodynamic history. A rifting in the Early Triassic led to the breakup of Gondwana and to evolution of the Levant Basin (flooring the Lebanese offshore) that is infilled with about 10 km of Cenozoic sediments (Nader, 2011). New offshore gas discoveries in Israel and Cyprus (www.nobleenergyinc.com) illustrate well the important hydrocarbon potential of the Levant Basin. Thick siliciclastic reservoirs have been identified in the Cenozoic successions in Oligo-Miocene and Pliocene deepwater systems (Gardosh et al. 2006; 2008) marking an interesting duality between this siliciclastic-rich basin and a mostly carbonate-dominated margin. Numerous questions related to the type of source rocks expected for the Levant Basin (i.e., biogenic versus thermogenic) are yet to be answered. As no well has been drilled to date in the Lebanese offshore, a thorough understanding of the tectono-stratigraphic evolution and architecture of the Levant margin, helps in gaining insights into the sedimentary and stratigraphic aspects of the nearby basin.

Since the 1950's, a number of studies have focused on the stratigraphic evolution of Lebanon from the Mesozoic onwards (refer to Dubertret 1975; Beydoun 1977; Saint-Marc 1972; 1974; Beydoun and Habib 1995; Walley 1997; 2001; Nader 2000; Nader and Swennen 2004). The stratigraphic interpretation and the generation of geological maps were mainly based on macrofossils and lithology. Difficulties in subdividing the Upper Cretaceous and Cenozoic have precluded the correlation between sedimentary facies and sequence stratigraphy. Müller et al. (2010) provided new data on the stratigraphy of Lebanon through calcareous nannofossil datings of the Upper Cretaceous and Cenozoic rock units. This allowed to confirm and temporally constrain major hiatuses around the coastal areas (e.g., Tripoli, Nahr el Kelb, Sidon, Tyr) and in some parts of the central Bekaa (Fig.3.1). According to Müller et al. (2010), major sedimentary gaps occur in the Coniacian to Early Santonian, latest Maastrichtian to lowermost Paleocene, Lower Oligocene, and lower part of the Lower Miocene. Moreover, differences in hiatuses time span and sedimentary facies were noted between southern and northern Lebanon that are yet to be fully understood.

The Ras Chekka promontory and the Tripoli-Koura plateau (Fig.3.1) expose one of the most complete Cenozoic sections in Lebanon (Fig.3.1). Bordered to the south by the E-W-trending Batroun fault and to the north by the Tripoli-Homs depression, the study area is 45 km long and 7 to 13 km wide. To the East, it borders the northern section of the Mount Lebanon structure, particularly by a set of flexures affecting Upper Cretaceous and Jurassic rock units. Another set of flexures observed in younger Miocene units delimits the Zgharta plateau (Zp; e.g., the Jabal Terbol, 681 m high, and the Jabal Qalhat 403 m high) (Wetzel and Dubertret 1951; Elias 2006).

This study integrates sedimentological and biostratigraphic data for the complete rock sequence exposed in coastal northern Lebanon. Its main objective is to reconstruct the depositional environments from the Turonian to the Miocene through a detailed facies and microfacies analysis of outcrops (Kousba, Amioun, Afsdiq, and Chekka areas; Fig.3.1), and core material from various boreholes (Chekka Quarry-courtesy of the Cimenterie Nationale S.A.L., Lebanon). It also aims at presenting wider views on the regional stratigraphic evolution of the Levant area with relation to major geodynamic events leading to a better assessment of the sedimentary facies extent from the Levant margin into the basin.

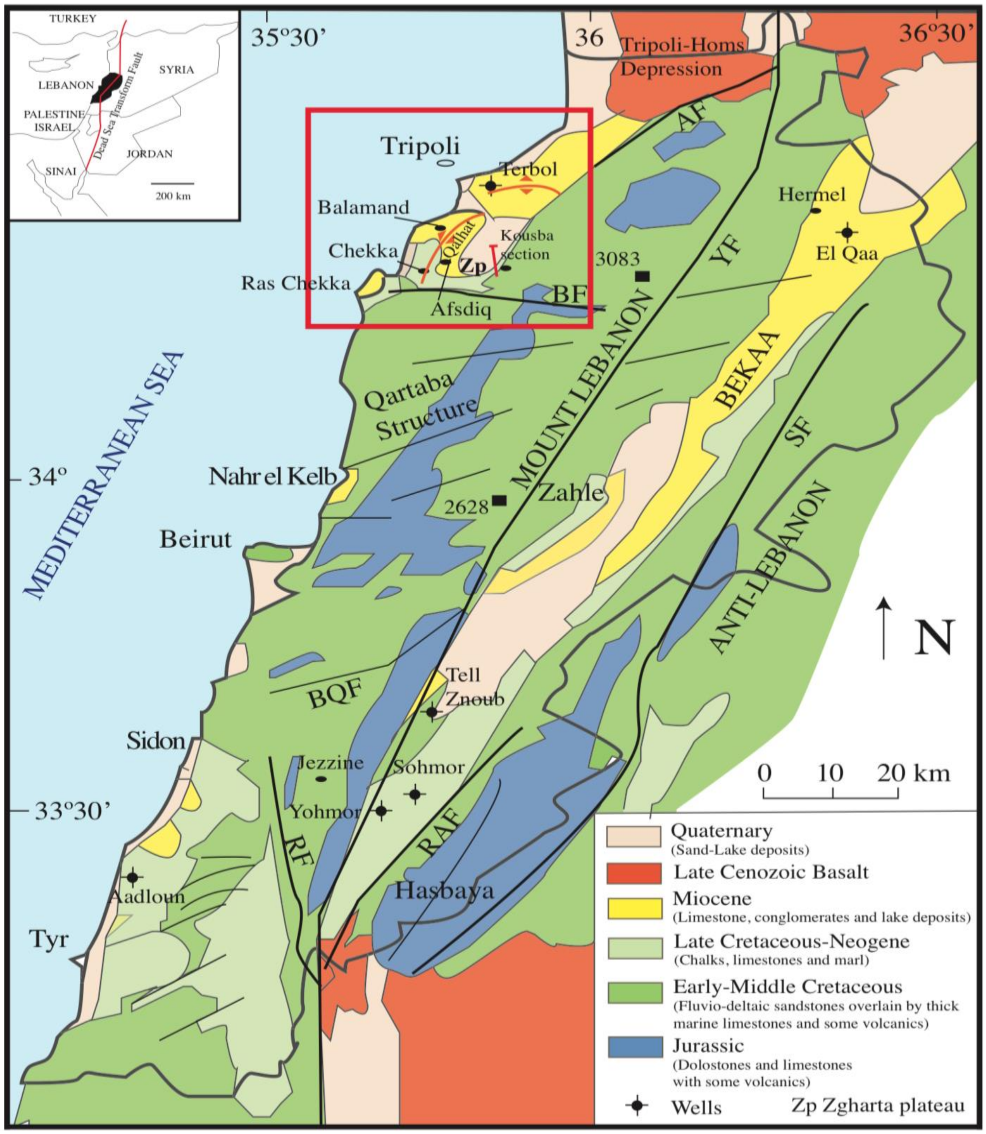


Fig3.1. Simplified geologic map of Lebanon showing the location of investigated area (square). The map is modified from Dubertret (1955). Major faults: AF: Akkar Fault, BF: Batroun Fault, YF: Yammouneh Fault, SF: Serghaya Fault, BQF: Beit ed Dine-Qab Elias Fault, RF: Roum Fault, RAF: Rachaya Fault

2. Geologic Setting

2.1 Tectonic framework of the Levant region

Studies of NE-SW-trending fault patterns and graben structures onshore (e.g., Syria: Palmyra trough; Israel: Judea Graben, Asher Basin) and offshore (e.g., Eratosthenes, Pleshet Basin offshore Israel) showed that the earliest phase of rifting that led to the breakup of Gondwana and the formation of the Neotethys Ocean dated back to the Late Permian to Early Triassic (Sawaf et al. 2001; Gardosh et al. 2006; 2008; 2010; Moustafa 2010; Yousef et al. 2010). After a period of quiescence, a second pulse of rifting in the Middle Triassic took place; it intensified towards the end of this time interval (Garfunkel

1998; Robertson 1998; 2007; Gardosh et al. 2010). A third major pulse during the Early Jurassic led to pronounced subsidence in the Levant basin **(**Fig.3. 2a**)** (Druckman 1977; Alsharhan and Salah 1996)

The collision of the Afro-Arabian Plate with the Eurasian Plate since the Late Cretaceous **(**Fig. 3.2b**)** led to the development of what is known as the Syrian Arc Fold Belt which is represented by two major convergence phases (Neev and Ben-Avraham 1977; Moustafa and Khalil 1989; Eyal 1996; Buchbinder and Zilberman 1997; Garfunkel 1998; Walley 2001). The first phase of the Syrian Arc folding (Late Cretaceous) induced an inversion of major normal faults formed during Early Mesozoic into sets of asymmetric folds present near the Levant margin and further inland (Walley 2001). During the Early Cenozoic, the second deformation phase (Eocene) was characterized by low-amplitude folds throughout the basin as well as marginal uplift and tilting of the easternmost part of the Levant Basin and further inland (Walley 2001). Regional uplift in the Levant area from the Late Eocene onwards might also be a consequence of the up-doming linked with the Afar plume in Ethiopia and Yemen (White and McKenzie 1989; Schilling et al. 1992; Baker et al. 1996; Hofmann et al. 1997; Zeyen et al. 1997; George et al. 1998; Segev and Rybakov, 2010). Left-lateral movements between Eurasia and Africa were enhanced due to the collision of the Indian Plate with the Eurasian Plate in Mid- to Late Eocene times and the initiation of block faulting in the Red Sea/Aden Gulf marking the onset of the separation of Arabia from Africa (Hempton 1987) **(**Fig.3. 2c**)**.

During the Early Miocene, the Levant margin and shelf area became emergent as a consequence of continuing Syrian Arc deformation (Buchbinder and Zilberman 1997). The Arabian Plate separated from the African Plate along the Levant Fracture, which consists of a plate-scale sinistral strike-slip fault system, including the Dead Sea Transform fault, the Yammouneh and the Ghab faults. The separation of the African and Arabian Plates was enhanced by escape tectonism of the Anatolian micro-Plate in Mid- to Late Miocene times (Hempton 1987) **(**Fig.3. 2c**)**.

2.2 Stratigraphic overview of northern Lebanon

The Jurassic rock series representing the core of the Mount Lebanon structure were deposited in a shallow marine carbonate platform environment (1000 m of monotonous limestone/dolomite) extending from the Coastal Ranges of Syria to the Coastal Chains and Galilee in northern Israel. Volcanic episodes led to the deposition of about 180 m of basalt and tuff overlain by shallow-marine carbonate deposits of Kimmeridgian-Tithonian? age in northern Lebanon (Laws and Wilson 1997; Abdel-Rahman 2002; Collin et al. 2010).

A major regression and exposure at the Jurassic-Cretaceous boundary led to the deposition of a 20-m-thick succession of fluvio-deltaic siliciclastic sediments (locally called the Chouf Formation) in northern Lebanon. In central and southern Lebanon, the same formation is about 400 m thick (Fig.3.2). Marine conditions prevailed during the Aptian; where massive cliff-forming limestone units have been described as being representative of a shallow marine shelf environment (Nader 2000). The end of this epoch was marked by a return to terrigenous clastic sedimentation in a restricted tidal to supratidal (lagoon) environment. The volcanic episodes were brought to an end before or at the beginning of the Albian (Wetzel and Dubertret 1951).

The Cenomanian-Turonian of northern Lebanon was deposited in a prograding carbonate-ramp setting. The deposition of a *Globigerina*-rich marly and chalky unit during the Late Cretaceous marks a global sea-level highstand (Haq et al. 1988; Hardenbol et al. 1998). Deep-marine settings prevailed until the early Middle Eocene (Walley 1998; Nader 2000)

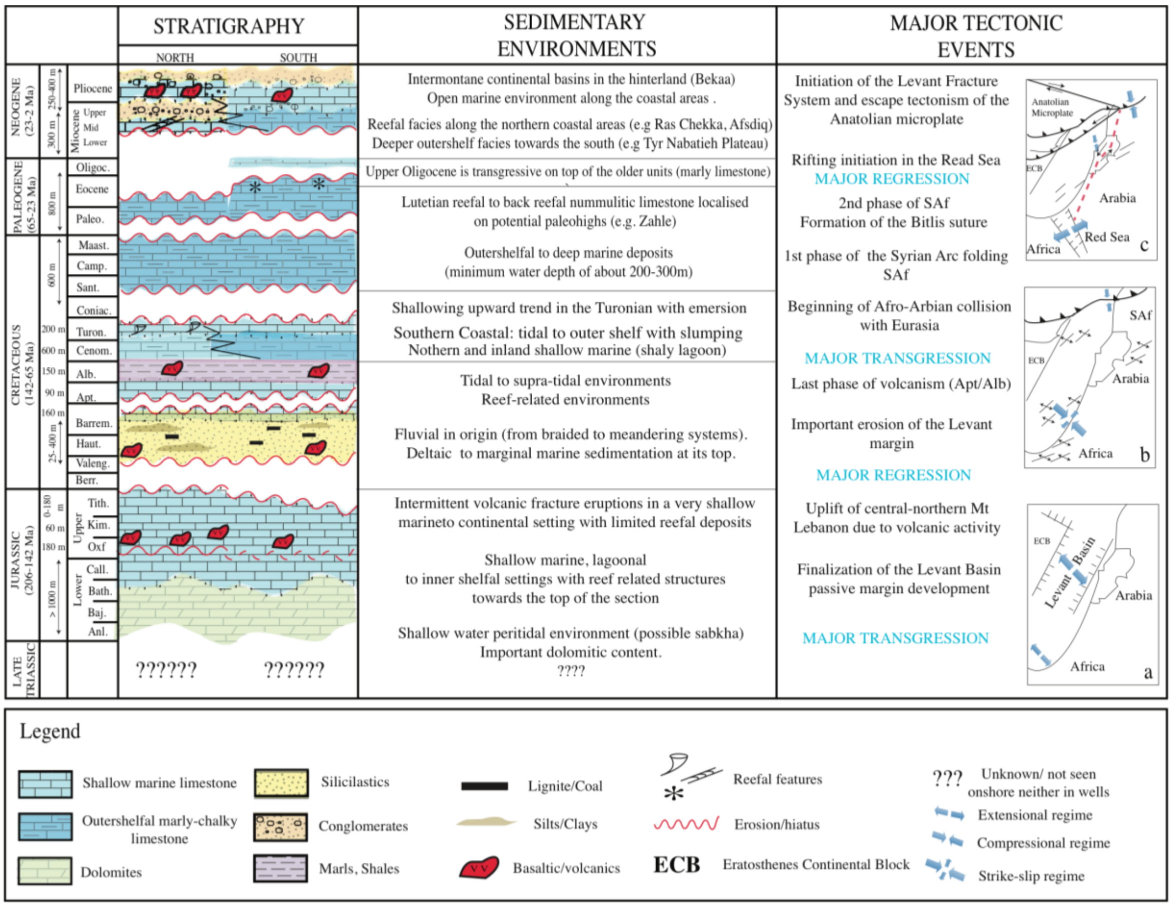


Fig3.2. General tectono-stratigraphic chart of Lebanon showing the major depositional environments and geodynamic events. Paleo-stress directions for the (a) Early-Mid Jurassic, (b) Maastrichtian and (c) Tortonian are represented by thick arrows (MEBE program; Hardy et al. 2010; Homberg et al. 2010)

The Levant coastal area and shelf became emergent in the Early Miocene. In northern Lebanon, the Miocene rock succession has been divided by Dubertret (1975) into (1) a marine unit described as being reefal ("Vindobonian"? – historical term used for the Langhian to Tortonian), and (2) a conglomeratic and lacustrine unit (Tortono-Messinian?). The Middle to Upper Miocene facies successions in the Bekaa valley (east of Tripoli) consist of about 200-800 m of lacustrine marl deposits overlain by 500-600 m of alluvial fan conglomerates (Wetzel and Dubertret 1951; Walley 1998; Müller et al. 2010). After the acme of Mount Lebanon's uplift at the end of the Miocene, the northern Lebanese coastal area (Zgharta plateau ZP in Fig.3.1) deepened below sea level, leading to the deposition of marine Pliocene sediments. The Quaternary rock unit is conglomeratic and unconformably overlies the Upper Cretaceous to Miocene successions (Dubertret 1975; Elias 2006).

3. Material and Methods

This study is based on field campaigns, whereby several sites have been investigated thoroughly. Fieldwork consisted of sedimentological, structural and stratigraphic observations and documentations. Some 300 samples were studied for microfacies and biostratigraphy.

Calcareous nannofossils were studied in smear slices under polarizing microscope at 1250 x magnification. The Cretaceous biozonation follows Thierstein (1976), Sissingh (1977) and Perch-Nielsen (1985); the Cenozoic biozonation used is based on Martini (1971) and Martini and Müller (1986).

Planktonic foraminifers were studied based on material from washed samples (calcareous shales) and in thin sections (carbonates). For calcareous shales, bulk samples were soaked in a weak peroxide solution and rinsed with tap water over sieves of 1 mm and 63 µm mesh width. Residues were oven-dried at 40 °C. The planktonic foraminifers zonation used follows those of Caron (1985), Toumarkine and Luterbacher (1985), Premoli Silva and Sliter (1995), and Robaszynski and Caron (1995).

At the Kousba locality (Fig.3.4), a 1860-m-thick Turonian to Upper Miocene section was sedimentologically logged in high resolution along the Nahr Abou Ali River (between 34°18'27.54"N; 35°51'48.00"E and 34°19'47.81"N; 35°51'37.97"E; Fig.3.7**)**. Surrounding locations (e.g., Amioun, Afsdiq, Ras Chekka) were visited in order to better constrain the facies changes and extent as well as to study stratigraphic contacts.

The Chekka Quarry exposes the entire stratigraphic thickness of the Chekka Formation (Coniacian-Paleocene), which is estimated locally to be in the order of 300 m; sediments comprise marls and chalky limestones. In this study, five wells (BH-3, BH-8, BH13, BH-26 and BH-27) as well as one, 45-m-thick outcrop section **(**Fig.3.4**)** were analyzed/described in order to provide a composite log covering the Chekka Formation. This has allowed to refine the information from previous studies, which have either focused on one dating technique or did not cover the entire sedimentary sequence (e.g., Wetzel and Dubertret 1945-1951; Tayyar 1975; Hawi 2000).

4. Results

4.1 Biostratigraphy and biozonation

The Late Cretaceous to Miocene biostratigraphic subdivisions were mainly carried out using the abundantly occurring nannofossils; they were supported (when needed/available) by planktonic foraminifers (see Fig.3. 3 for composite log and Fig.3. 5 for range charts).

4.1.1 Upper Cretaceous to Paleocene

Two Upper Cretaceous hiatuses have been noted in our study area around the Late Turonian to Late Santonian and between the Late Maastrichtian to Paleocene. A Turonian limestone unit was identified in Kousba (Fig.3.6, 3.7) and Chekka **(**Fig. 3.8, 3.9**)** based on the abundant occurrence of *Hippurites* and the co-occurrences of the nannofossil marker species *Eiffellithus eximius, Micula staurophora* and *Watznaueria barnesae.*

The latest Santonian (biozones CC16-CC17 of Sissingh (1977)) was only identified in the borehole BH-27 at Chekka from 55 to 47m below ground level (bgl; Fig.3.7) by the presence of the nannofossils *E. eximius, Marthasterites furcatus* and *Reinhardtites anthophorus.* The Santonian-Lower Campanian transition has been noted in the same borehole BH-27 (from 47 to 44 m bgl) through the occurrence of *Broinsonia parca* **(**Fig.3. 8). The Upper Santonian rock unit probably exists in the nearby Kousba area; however, due to the heavy vegetation cover it was impossible to date there.

The Lower Campanian at Chekka (BH-3, BH-8, BH-27) **(**Fig.3. 4) and Kousba were dated through the occurrences of the following nannofossils: *B. parca, E. eximius, M. staurophora, R. anthophorus, and W. barnesae*. Among keeled forams, the occurrence of *Globotruncana aegyptiaca* and the absence of latest Campanian/early Maastrichtian species such as *Gansserina gansseri* and *Globotruncanita conica* suggest that the strata correspond to the Aegyptiaca zone according to the biozonation of Robaszynski and Caron (1995).

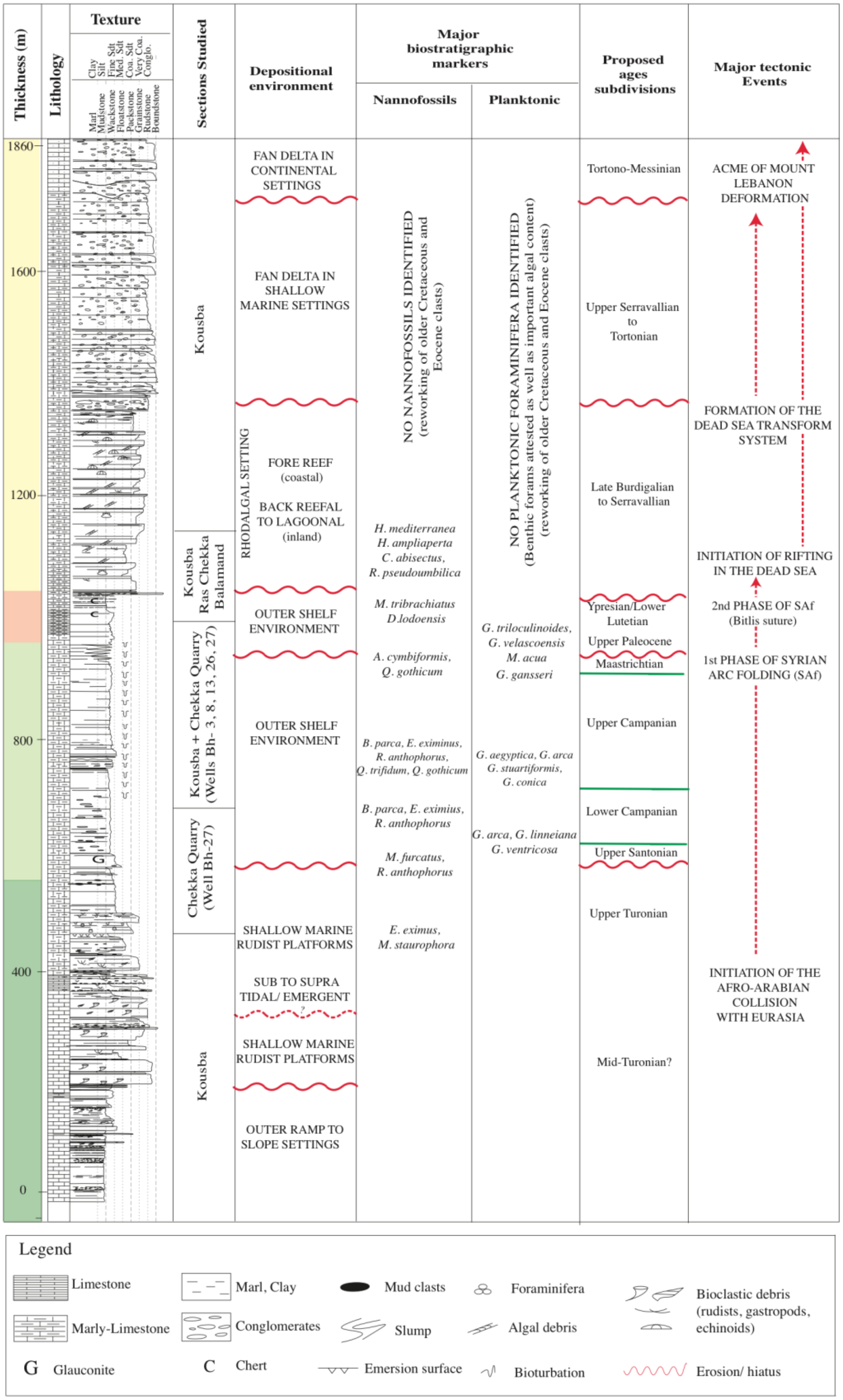
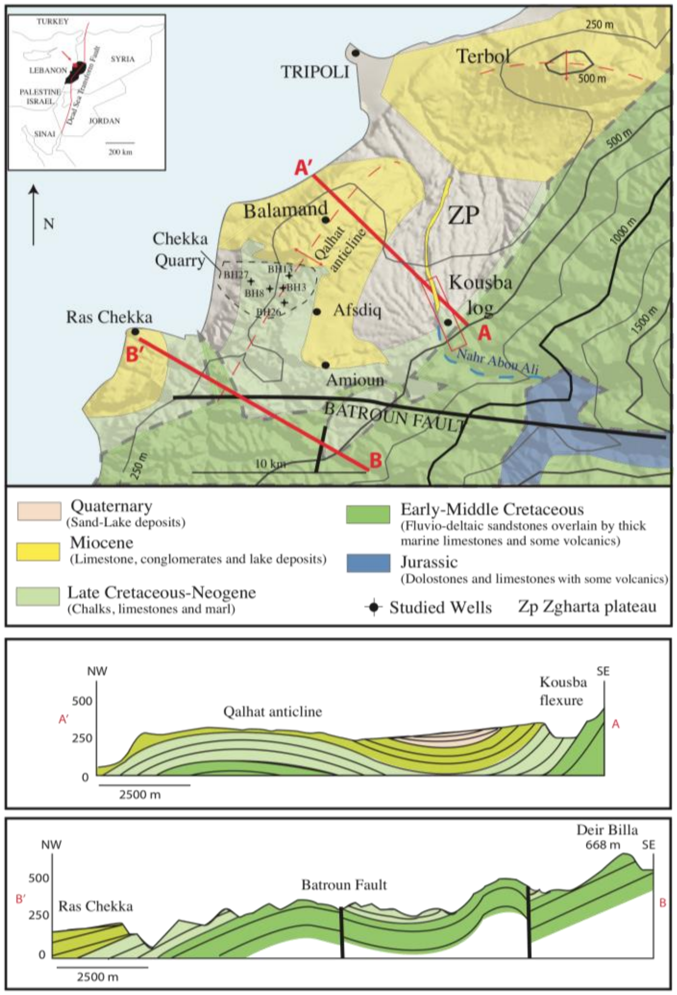


Fig.3.3. Composite log representing the complete Upper Cretaceous to Late Miocene succession compiled from several studied sites in northern Lebanon



a

Location	Dataset	Coordinates of the main studied locations	Elevation (asl)	Total thickness assessed	Purpose
Kousba	Field Section	B:34°18’27.54"N; 35°51.48.00"E E:34°19‘47.81"N; 35°51.37.97"E	305 m 220 m	1860 m	Facies analysis and dating of Upper Cretaceous and Cenozoic intervals with hiatuses indentification
Chekka Quarry	Field Section	B: N34°19.753’; E35°45.825’ E: N34°19.821’; E35°45.851’	208 m 221 m	45 m	
	Wells				
	BH-3	34°19' 47.658"N; 35°45'49.19"E	217 m	215 m	Dating and facies analysis of the Upper Cretaceous interval and hiatuses identification
	BH-8	34°19'46.91"N; 35°45'21.83"E	130 m	95 m	
	BH-13	34°20'4.869"N; 35°46'1.034"E	298 m	165 m	
	BH-26	34°19’26.04"N; 35°45’50.4"E	248 m	200 m	
	BH-27	34°19’55.96"N; 35°44’41.43"E	51 m	90 m	
Ras Chekka	Outcrop investigation	34°18’46.80"N; 35°41’24.90"E	40 m	40 m	Dating of Cenozoic hiatus +Miocene facies analysis
Balamand	Outcrop investigation	B:34°21’38.10"N; 35°46’56.75"E E:34°21’31.86"N; 35°47’7.74"E	344 m 368 m	25 m	
Afsdiq	Outcrop investigation	34°19’50.64"N; 35°47’24.24"E	321 m	15 m	

b

Fig.3.4. (a) Simplified geologic map of northern Lebanon (Dubertret 1975) showing the main logged field section of Kousba, the five studied wells in the Chekka Quarry and the nearby investigated sites of Ras Chekka, Balamand and Afsdiq. Two cross sections through the northern Lebanese coastal area reflect the major Qalhat anticlinal feature. (b) Overview of the dataset used for the geologic evaluation of northern Lebanon

The Late Campanian (biozone CC22) is also widely identified in the two main studied locations through the occurrence of the nannofossils *Quadrum gothicum* and *Quadrum trifidum*. Among keeled forams, the occurrence of *Globotruncana aegyptiaca* suggests that the strata correspond to the biostratigraphic Aegyptiaca zone according to the biozonation of Robaszynski and Caron (1995). The Campanian-Maastrichtian boundary biozone CC23 (Sissingh 1977) was identified only in the Chekka Quarry **(**Fig.3. 9**)** by the absence of the nannofossils *B. parca, E. eximius* and *R. anthophorus* as well as by the presence of the planktonic species *Gansserina gansseri* (Latest Campanian to Early Maastrichtian).

The occurrence of *Arkhangelskiella cymbiformis* (common), *Gartnerago obliquum, Micula staurophora, Prediscosphaera cretacea, Eiffellithus turriseiffelii, Q. gothicum,* and *W. barnesae* nannofossil species together with the absence of *B. parca*, *E. eximius* and *R. anthophorus* (last occurrence at the Campanian/Maastrichtian boundary) mark the Early Maastrichtian biozone (CC23-CC24).

The Uppermost Maastrichtian to Lower Paleocene is missing from the investigated locations in the northern Lebanon. The first occurrence of Paleocene rock units (biozones NP5 to NP8) has been recorded in the uppermost field section of the Chekka Quarry. This interval has also been identified through the concomitant presence of the planktonic foraminifers *Globigerina triloculinoides, Globigerina velascoensis and Morozovella acuta* (biozone P3-P4 according to Toumarkine and Luterbacher 1985). The Maastrichtian to Paleocene is covered by vegetation at Kousba.

4.1.2 Eocene to uppermost Lower Miocene

The Eocene-Miocene succession has been investigated in the Kousba area as well as in the surrounding villages of Balamand, Amioun and Ras Chekka **(**compare Fig.3. 1, Plate 3.2a-b and Plate 3.3a-f). A widespread angular unconformity separates the deepwater chalky Lower Eocene from the uppermost Lower Miocene rock unit in northern Lebanon.
At the Ras Chekka promontory, the unconformity separates the Early Lutetian/NP14 (through the nannofossil *D. sublodoensis* and the lack of the previous Ypresian markers) from the overlying Middle to Late Burdigalian *(*NN3-NN4 *Helicosphaera mediterranea, Helicosphaera ampliaperta, Cyclicargolithus abisectus, Reticufenestra pseudoumbilica)*.

At Balamand, the nannofossil assemblages point to an unconformity between the Early Eocene (Ypresian/NP13 *Marthasterites tribrachiatus, Discoaster. lodoensis)* and the Middle to Late Burdigalian *(*NN3-NN4*)*. At Kousba, the Ypresian NP 12 biozone has been identified with *Marthasterites tribrachiatus* and *Discoaster lodoensis* species underlying strata rich in pectens, thought to correspond to the Middle to Late Burdigalian.

4.1.3 Middle to Late Miocene

The Middle to Upper Miocene rock unit in Kousba (shallow marine carbonate rocks as well as conglomeratic unit in carbonate to argillaceous matrix) could not be dated by means of nannofossils and planktonic foraminifers due to their lithologies. Relevant datings of the Miocene rock units have been proposed by Dubertret (1975) based on macro fossil investigations and supported by studies of the structural evolution of Mount Lebanon. The rhodalgal rock interval was referred to as Middle Miocene (Late Burdigalian? to Serravallian) and the conglomeratic rock unit as Tortono-Messinian resulting from the interaction between Mount Lebanon Uplift and major sea level lowstands around the Middle to Late Miocene.

Older Upper Cretaceous to Eocene clasts have been noted in the Upper Miocene conglomeratic unit proving intense reworking of carbonate platforms.

The dip of Upper Miocene conglomerates in Kousba changes from 58-60° to about 30° and becomes subhorizontal towards the NW. This dip change marks the timing of the major development of Mount Lebanon. The Quaternary deposits observed in the study area unconformably overlie the previously deformed structure, filling the paleo-topographic lows (Fig.3. 6).

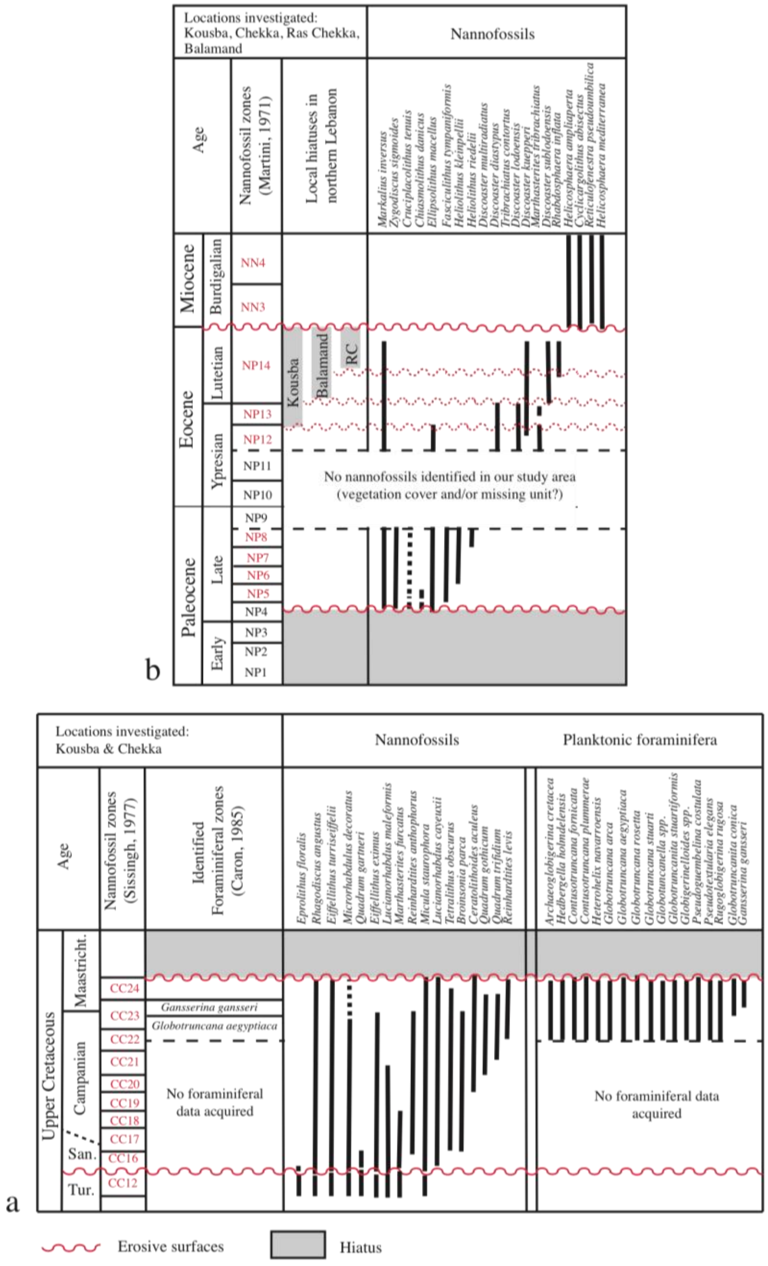


Fig.3.5 Summarized chart distribution of nannofossils and planktonic foraminifer in the several studied locations for the (a) Upper Cretaceous and (b) Paleocene to Miocene showing the main biozones and hiatuses identified in northern Lebanon

4.2 Sedimentological descriptions, facies analysis and paleo-environment assessment

4.2.1 Kousba geologic section

4.2.1.1 Turonian

Description

The lowermost part of the investigated section (from 0 to 24 m) consists of a creamy whitish, moderate to thinly laminated mudstone (refer to Fig.3. 7 for the complete sedimentary log). The beds thicknesses range between 0.5 and 2 m passing upward progressively into a more massive micritic unit. This mudstone-dominated interval is intercalated by four levels of breccias (1-2 m of micritic carbonate clast deposits) (Plate 3.1c).

Gastropod-rich wackestone to packstone lags of 1-2 m in thickness (from 24-44 m) are overlain by rudist rudstone interval (from 44-66 m) with thin micro-grainstone inter-layers (0.5 m) presenting from base to top, graded beddings, rippled bed tops, occasional contorted beds overlain by marly mudstones.

The base of the successive rudist rich boundstone unit is marked by an erosive surface (at 66 m) with heavily reworked and brecciated rudstone to grainstone interval (Plate 3.1d, e, f). The latter evolves into a bioclastic wackestone (rudists and gastropod debris) to packstone with chert bands of about 0.2 m thick (at 83- 86 m).

These facies develop upward into a fine crystalline dolostone with chicken wire structures, as well as silicified algal mats/ laminated domal microbialites (stromatolites) around 116 m (Plate 3.4a). They are overlain by rudist-rich boundstone units (about 5-10 meters thick) intercalated by packstone to grainstone textures with gastropod debris. A shift towards monotonous whitish heavily bioturbated marly mudstone facies occurs at 178 m.

Fig.3.6 Panoramic photograph showing the anticlinal structure in the Kousba area and overlying rock units with the proposed age subdivisions. Note that the bed dips are of about 58°-60° for the Upper Cretaceous to Serravallian rock units with no major angular unconformities. The dip values drastically change from 58°-60° to 30° starting from the Late Serravallian to Messinian becoming subhorizontal to the NW

Interpretation

The Turonian carbonate platforms have been extensively studied on the Arabian Plate (including Israel and Lebanon) presenting mainly ramp configurations with important rudist accumulations (e.g., Saint-Marc 1972; 1974; Frank et al. 2010). The facies association (FA1) (refer to Table.3.1) at the base of the Turonian rock unit in Kousba with dominantly mudstone textures intercalated by slumps as well as brecciated lags refers to gravity driven deposits in a slope to basinal settings leading to intense reworking of older Cretaceous carbonate platforms (Plate 3.1c). The micro-grainstone unit presenting graded beddings, rippled bed tops and occasional contorted beds, is interpreted as Ta-c Bouma turbidite cycles (Bouma, 1985).

A sharp transition into a bioclastic rudist-rich rudstone (with rippled bed tops and contorted beds) and localized rudist-rich boundstone textures marks a shallowing trend from outer ramp/slope to shallow marine settings. This facies association (FA2) is refers to a fore-reef depositional setting with reworking of localized *in situ* rudist reefal constructions (boundstone textures) developing in a favorable shallow marine conditions.

Fine crystalline dolostone textures with chicken wire structures, as well as algal mats and laminated domal microbialites reveal a shift into inter- to supra-tidal environments with temporary emersion periods attested through mudcracks (e.g., at 136 m). This facies association referred to as FA3 could be the result of a major sea level regression enhanced by the Levant marginal uplift around the Middle Turonian.

A progressive return to shallow marine platform settings is marked by rudstone boundstone successions (FA2) followed by deeper mudstone deposits at the Top of the Turonian series.

4.2.1.2 Santonian-Eocene

Due to major vegetation cover difficulties were encountered while assessing the Santonian to Eocene transition. The Chekka Quarry investigation (section 4.2.2) allows to cover in much more details the Upper Cretaceous rock interval.

Description

Monotonous chalky and marly limestone unit at the base of the Santonian-Eocene interval presents highly bioturbated levels with sets of dark chert beds of 0.2-0.5 m of thickness. The base of the Campanian rock unit studied in Kousba (as well as in Chekka) is identified by two dark chert layers representing a clear field marker.

The dominant micritic chalky limestone texture persists from the Late Santonian until the Early Eocene (Ypresian NP12). The unit loses its friability towards the Eocene-Miocene contact with abundant silica content seen through altered chert bands (from 1150-1160 m).

Interpretation

Starting from the Late Turonian a drastic change in sedimentary facies is attested in Kousba from rudist-rich boundstone and rudstone units (intercalated by packstone to grainstone textures) into a monotous whitish marly and chalky mudstone with chert bands. This facies association (FA4) observed along the whole Upper Cretaceous to Lower Eocene rock intervals is interpreted as representing a deep outer shelf environment. The Upper Cretaceous platform drowning is a widely described event observed along the whole Levant region (e.g. Israel: Flexer 1971; Lebanon: Dubertret 1975; Syria: Brew et al. 2001).

4.2.1.3 Miocene

Description

The Eocene-Miocene contact in Kousba is erosive with important reworking of carbonates and is marked by a thin conglomeratic lag of about one meter (with Lower Eocene clasts) (Plate 3.2.a, b). This contact has also been identified towards the northern Lebanese coast along Ras Chekka and Balamand sites presenting very similar characteristics (Fig.3. 1 and section 4.2.3).

In Kousba, a half-meter thick boundstone rich in pectens (at 1160 m) is overlain by a relatively thinly bedded (0.5 m to 1 m) bioclastic packstone to grainstone unit dominated by red algal (*Corralina and Lithothamnium*) debris with echinoids and bivalves (up to 1312 m) (Plate 3.4c).

A set of coarsening upward trends of bioclastic grainstone with abundant red algal fragments, echinoid debris and large lamellibranch shells (1312 to 1338 m) are topped by a 2 m algal boundstone. These units are overlain by a 110 m of monotonous bioclastic packstone to grainstone (algal, echinoid and shell fragments) presenting very little variations in sedimentary textures or structures. A decrease in the algal content is noted towards the top of the Middle Miocene succession (from 1420 onwards).

These facies are topped by sets of conglomeratic packages (about 400 m thick) consisting of carbonate matrix at their base evolving into clay-rich matrix towards their top. These cycles mark an alternation between clast- supported and mud-supported matrix with carbonate clasts representing Upper Cretaceous to Eocene reworked sediments. Stacked channelized conglomerate sheets (1-2 m) become more abundant towards the top of the Miocene conglomeratic unit with important erosion features (scours and flutes) noted at their base (Plate 3.2c, d, e) and marking the end of the Kousba log.

Interpretation

No evidences of karstification have been noted along the erosional contact possibly alluding to a submarine erosional event following the marginal deformation linked with the continued collision of Afro-Arabia and Eurasia.

The monotonous Middle Miocene facies association (FA5a) (Table.3.1) of packstone texture presenting important bioclastic content (i.e., mainly red algal fragments with echinoids and lamellibranch shells) observed in northern Lebanon point to a deposition in a relatively agitated protected setting, part of a rhodalgal platform system seen around the western and eastern Mediterranean at that time (Pomar 1991; 2001; Pomar et al. 1996; 2004; Brandano et al. 2005)

The deposition of conglomeratic units presenting stacked channelized sheets (1-2 m) around the Middle-Late Miocene (i.e., Late Serravallian-Tortonian to Messinian) is interpreted as a direct consequence of the rapid uplift of Mount Lebanon (Dubertret, 1975; Elias, 2006). Around that period intense erosion of Cretaceous and Eocene carbonate platforms led to the development of major fan deltas (FA6) deposited into the shallow marine settings of the northern Lebanese coastal area (i.e., conglomerates with carbonate dominated matrix). The conglomerate carbonate matrix is replaced by a reddish shaly and muddy matrix with an absence of fauna referring to a progressive shift from shallow marine into more continental settings (exposed to oxidation) as a consequence of the continued marginal uplift in the Late Miocene.

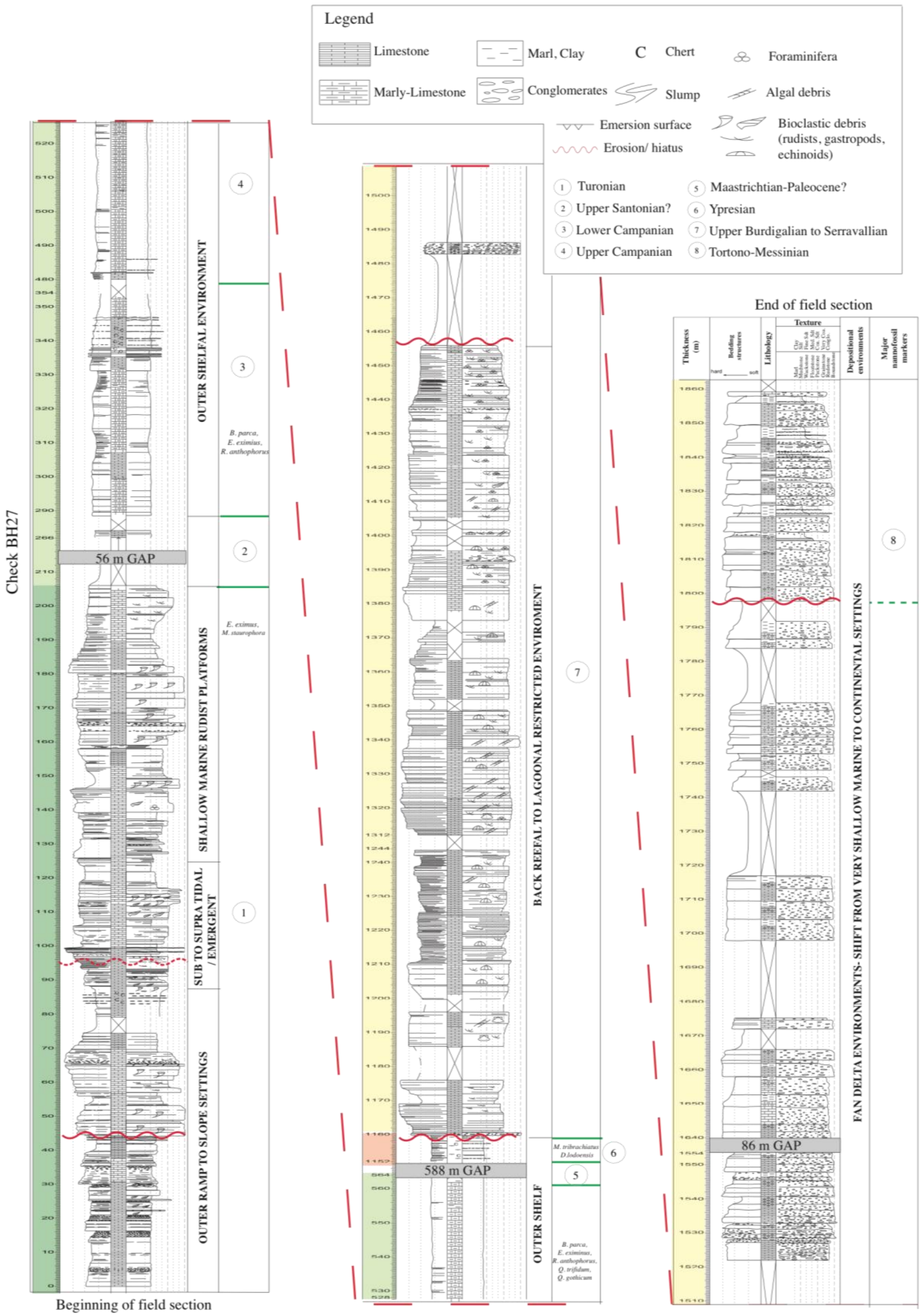


Fig.3.7 Detailed sedimentologic log of Kousba (northern Lebanon) showing the main sedimentary facies evolution from the Turonian till the Late Miocene as well as the age subdivisions deduced from biostratigraphic analysis

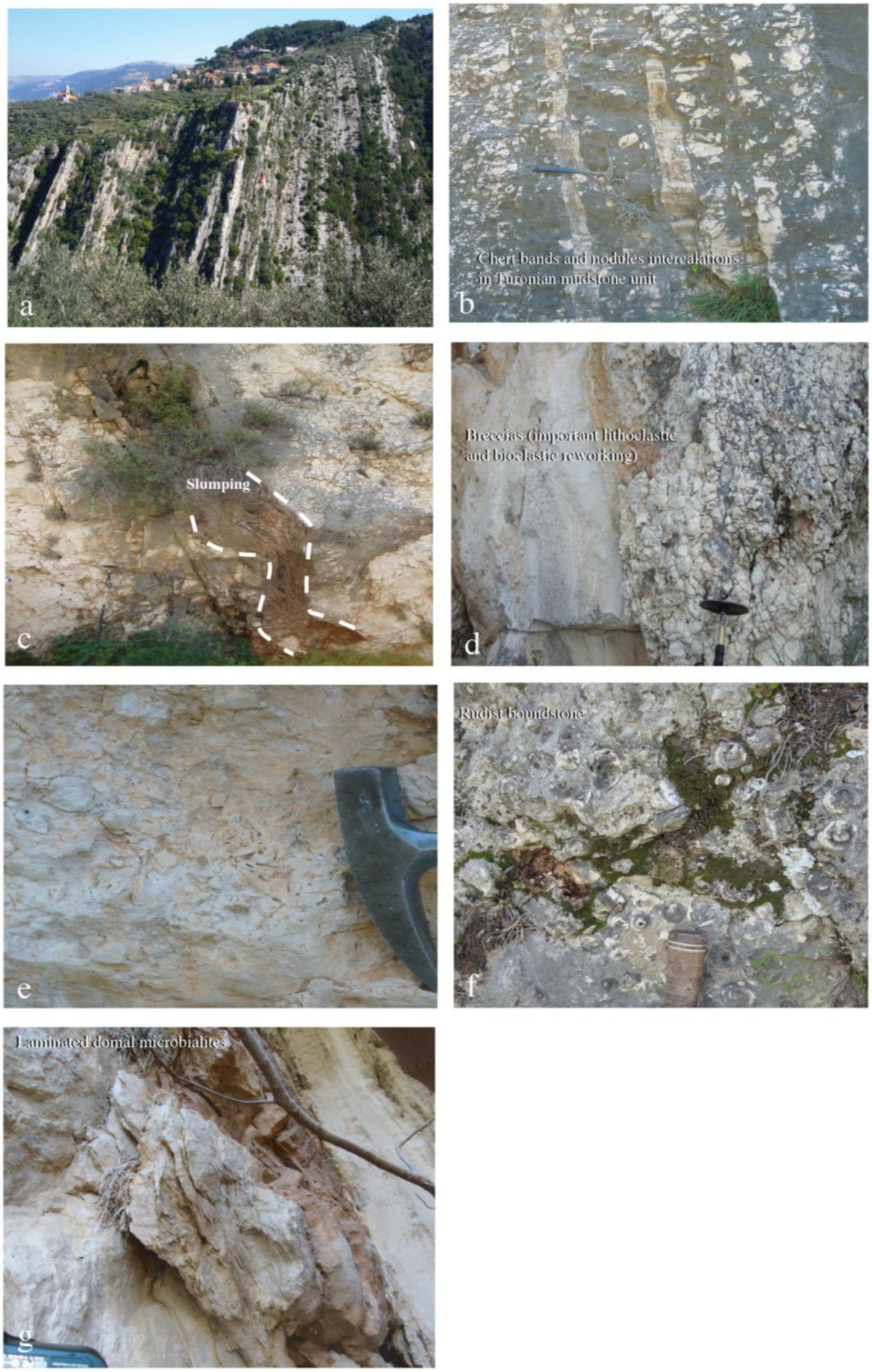


Plate 3.1. Turonian facies of Kousba: (a) General overview of the steeply dipping Turonian platforms, (b) Mudstone and chert beds intercalation, (c) Slumping, (d) Breccias attesting of important carbonate reworking (e, f) Rudist (Hippurites) boundstone, (g) Laminated domal microbialite

Facies associations			Unit thickness	Description	Sedimentary environments	Age	Location investigated
Mudstone/Wackestone with chert bands breccias and slumps	FA1		10-50 m	Dominantly mudstone to wackestone textures intercalated by gastropd rich lags (1-2 m), slumps and breccias (0.5-1 m of micritic carbonate clasts). Bed thicknesses of about 1-2 m.	Outer-ramp to slope settings presenting gravity driven deposits	Lower Turonian	Kousba and Chekka
Bioclastic rudist rudstone to boundstone with turbidites	FA2		1-70 m	Rudstone textures intercalated by rippled bed tops, contorted beds marking Tac Bouma turbidite sequences as well as by intercalations of boundstone units (1-3 m) Bed thicknesses ranging from 0.5 to 2 m.	Shallow marine/ rudist reefal settings (mainly fore-reef)	Middle Turonian	Kousba and Chekka
Dolostone with domal microbialites	FA3		1-5 m	Thin beddings of 0.2-0.3 m of crystalline dolostone textures with algal mats, laminated domal microbialites (0.2-0.5 m), chicken wire structures as well as mudcracks.	Very shallow marine to emergent settings. Sub to supra -tidal environments	Middle Turonian	Kousba
Chalky and marly mudstone with chert and turbidite intercalations	FA4		200-300 m	Micritic chalky and marly mudstone textures presenting bioturbations as well as pyrite and bitumen filled micro-vugs. Chert bands of 0.1- 0.3 m in thickness as well as nodule are identified The units are rich in planktonic formaminifer and nannofossils.	Outer shelf to deep marine depositional settings	Late Santonian to Lower Eocene	Kousba and Chekka
Limestone units rich in algal content presenting a variability in sedimentary texutres and structures	FA5	a	30-300 m	Boundstone rich in pectens (0.5-1 m) overlain by a monotonous bioclastic packstone to grainstone (red algal, echinoid and shell debris)	Lagoonal to protected inner rhodalgal plaftorm	Late Burdigalian to Serravallian	Kousba
		b		Coarse grained packstone to grainstone rich in lithoclastic and bioclastic content (red algae, echinoderm and bivalve debris). Channeling and breccias are noted.	Fore-reef to slope settings of a rhodalgal platform		Ras Chekka
		c		Massive rhodalgal packstone to wackestone unit (bedding of about 6 m) with no signs of erosion.	Middle rhodalgal ramp (oligotrophic setting)		Balamand
		d		Boundstone interval with corals, red algae and bivalves interfingered with a bioclastic packstone (red algae and bivalves debris)	Back-barrier/protected inner platform (euphotic)		Afsdiq
Stacked conglomerate sheets and channels. Cycles of clast and mud supported matrix	FA6		400 m	Sets of conglomeratic packages are composed of well rounded carbonate clasts and present carbonate dominated matrix at the bottom evolving into mud and clay dominated towards the top whith an increase in channelized features.	Fan deltas feeding into shallow marine and continental settings	Late Serravallian to Messinian	Kousba

Table.3.1 Summary of the facies associations' description and proposed depositional environments for the Upper Cretaceous to Upper Miocene rock interval of the northern Lebanese coastal area

Plate 3.2. Eocene-Miocene facies of Kousba: (a,b) The Eocene (outershelf) /Miocene (back reef to lagoon) erosive contact of Kousba, (c) Transition between the Serravallian (carbonate matrix) and the Tortono-Messinian? (shaly matrix) conglomerates, (d,e) Stacked channelized Tortono-Messinian? conglomeratic sheets

4.2.2 The Chekka Quarry:

4.2.2.1 Turonian-Late Santonian Transition

The 88 m deep borehole BH-27 (Fig.3.4, 3.8) was drilled recently by the Cimenterie Nationale S.A.L in the Chekka Quarry allowing to properly investigate the Turonian-Late Santonian transition (not observed in the Kousba area due to abundant vegetation cover)**.**

Description

The base of the well is marked by a 2 m whitish rudstone unit with important bioclastic (gastropods and rudist debris) and lithoclastic content. At 86-83 m below ground level (bgl), a set of thin-bedded limestones (beds of about 0.3-0.5 m thick) with fining upward rudstone/micro-grainstone textures evolve into wackestones/mudstones. Four units with dominantly fining upward trends of packstone to grainstone textures (from 82.5- 75 m bgl) are rich in gastropod and rudist debris, mudclasts and highly bioturbated levels (horizontal and vertical burrowing).

A change in the dominating sedimentary texture occurred from 75 to 67 m bgl where a thinly laminated packstone/floatstone develops into a highly bioturbated wackestone towards the top. Whitish argillaceous packstone to mudstone textures (from 67 to 55 m bgl) with abundant horizontal bioturbation show rare evidences of bioclasts and bivalves.

A stratigraphic marker (dated as Late Santonian) has been identified around 55 to 53 m bgl, consisting of a dark-greenish glauconitic sandstone on top of which a monotonous heavily bioturbated dark-brownish marly mudstone is deposited (53 to 32 m bgl). The section from 32 to 13 m bgl presents alternation of lighter grayish and dark grayish mudstone with horizontal and vertical bioturbations.

Interpretation

The facies studied in the well BH-27 represent the uppermost section of the Turonian rock interval also described in Kousba. The facies association (FA2) is observed at the base of BH-27 with rudstone/bioclastic grainstone carbonates (rudists and gastropods debris) going into wackestone/mudstone deposits (highly bioturbated), corresponding to a deepening upward trend.

The Upper Santonian rock interval was identified in the Chekka Quarry as a glauconitic rich unit at the base of a monotonous heavily bioturbated dark-brownish marly mudstone unit (FA4) marking the initiation of a major Late Cretaceous transgression (Haq et al.1988).

4.2.2.2 The Lower Campanian

Description

The lower part of the Chekka Quarry (Fig. 3.9a) is characterized by clayey matrix and is moderately rich in organic matter with bitumen/asphalt shows observed along major fractures and faults. The deepest parts of the cored wells BH-3 and BH-8 (Fig.3.4) include two thin black chert layers (about 5 cm) that mark the base of the Lower Campanian unit (also seen in Kousba- section 4.2.1.2).

The main sedimentary textures of the overlying Lower Campanian deposits can be described as massive fine micro-grainstones with intercalations of mudstone units, as well as moderate to low bioturbations. The facies progressively evolves into a low porosity compact mudstone affected by intense fracturing. This rock interval is rich in planktonic foraminifers (e.g., *Globigerina*).

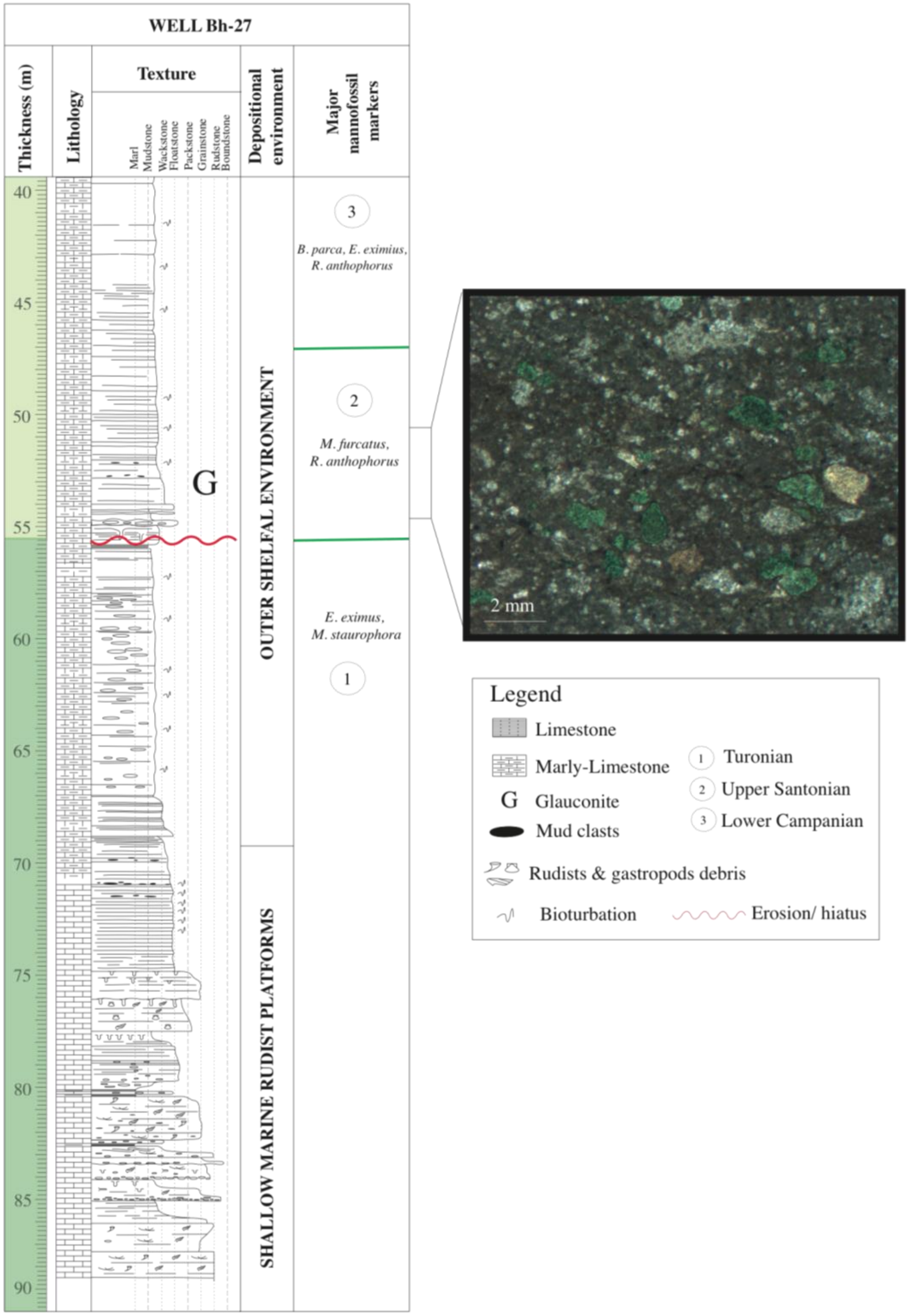


Fig.3.8. Sedimentary log of the well BH 27 showing the main sedimentary facies evolution from the Turonian to the Lower Campanian rock units as well as the ages subdivisions deduced from biostratigraphic analysis. The Turonian-Upper Santonian transition is marked by a glauconitic level referring to a major transgressional event in the Late Cretaceous

Interpretation

The overall facies associations presenting a dominantly massive mudstone unit rich in planktonic foraminifers is expected to be deposited in an outershelfal setting marking the drowning of the Turonian rudist platform.

4.2.2.3 Upper Campanian to lowermost Maastrichtian

The Upper Campanian rock unit in the Chekka Quarry reaches up to 200 m in thickness of whitish chalky limestone and has been identified in the wells BH-3, BH-8, BH-13, BH-26 (Fig.3. 4**)**.

Description

The investigated outcrop-section located in the uppermost part of the Chekka Quarry (Fig.3.4) represents some 45 m of light colored, chalky carbonate rock successions, with intercalated darker, marly beds (see Fig.3. 9a, b).

The first 17 m of the outcrop is represented by a major dominance of whitish, thick-bedded chalky limestone together with pyritic nodules and relatively intense bioturbation. The dominant, massive chalky musdstone passes upward into finely intercalated beddings (0.3-0.5 m) of marl and mudstone between 17 and 26.5 m (outcrop section).

This rock interval is overlain by a sequence that becomes less chalky and more clayey with darker grayish colors, dominantly marly (26.5 to about 35 m). The uppermost part (transition between Upper Campanian and lowermost Maastrichtian) of the section (35 to 43.5 m) is characterized by fine grainstone facies (with a sandy component) (Fig.3.9b) of whitish/light grayish colors (with pyritic content) and relatively thin intercalations of marly and clayey material (about 5 to 10 cm). Small cycles of fining upward trends from grainstones to packstones have been noted presenting undulating and moderately erosive bases. In this succession, planktonic foraminifers are well preserved and are more abundant than the benthic fauna. Agglutinated benthic foraminifers with hyaline tests were also observed.

Interpretation

The facies association of the dominantly marly and chalky mudstones of the Upper Campanian to Lower Maastrichtian point to a deep marine depositional environment. The high ratio of foraminifer-keeled forms to globular ones attested in Chekka, indicates an open marine outer-shelf environment with sufficient water depth (at least 200 to 300 m) allowing the complex foraminifers to achieve their full life cycle (Hart 1999).

Towards the Uppermost Campanian-Lower Maastrichtian an increase in the marl content reveals a possible deepening trend. It is followed by the deposition of thin fining upward micro-grainstone cycles with moderately erosive bases. The latter units reflect gravity driven processes in deep marine/outer shelf settings (FA4) that could have generated due to marginal instabilities caused by rapid uplifts and/or fast eustatic fluctuations around that period (i.e., turbiditic cycles and slumps) (Fig.3. 9).

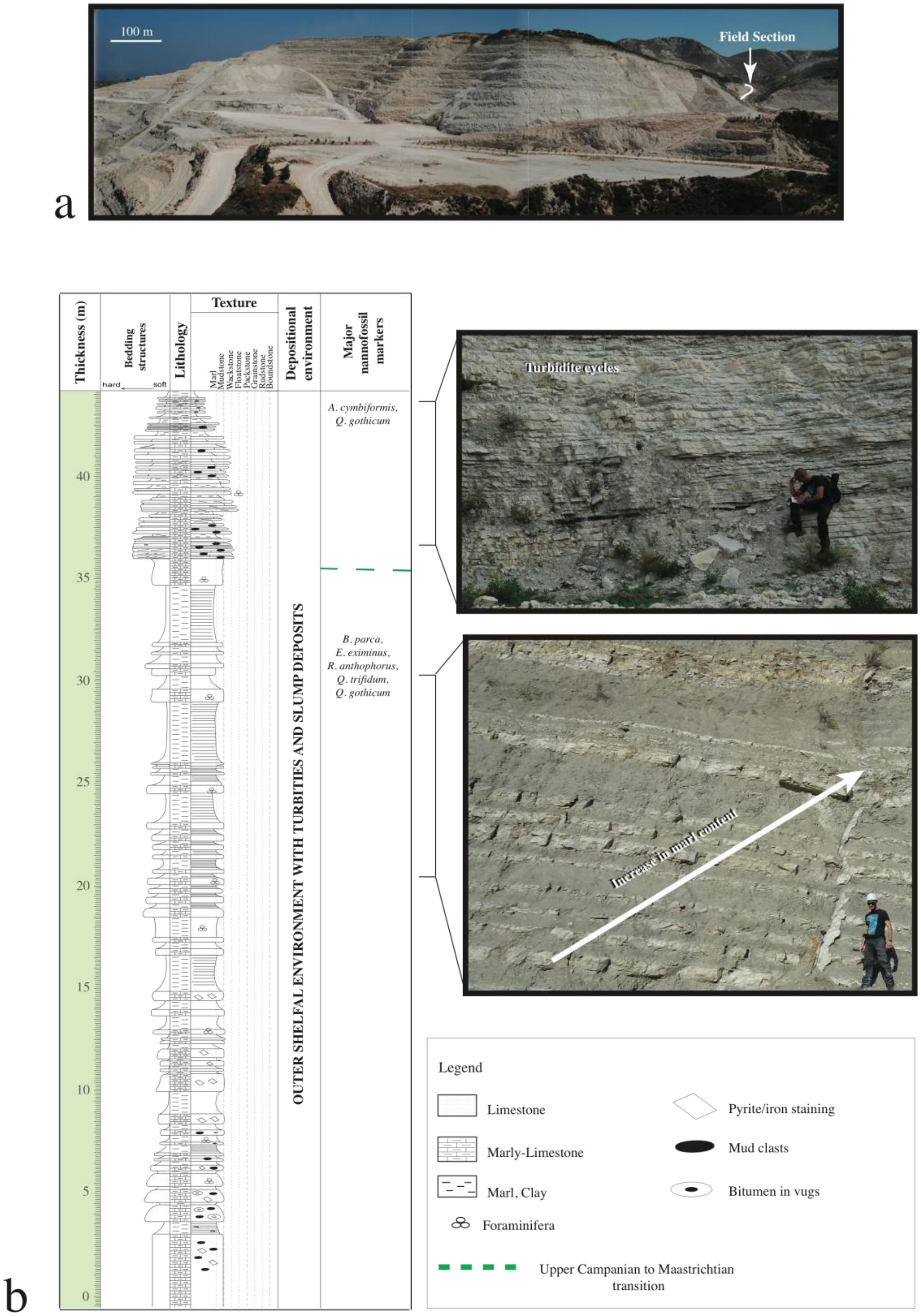


Fig.3.9. (a) Panoramic photograph showing the Lower Campanian marly limestone in the lower part of the Chekka Quarry. (b) The logged field section for the Upper Campanian- Maastrichtian transition in the Chekka Quarry

4.2.3 The Eocene-Miocene contact in neighboring sites

Description

The Eocene-Miocene unconformity described in Kousba was further studied in the Ras Chekka promontory, around the Balamand village and Qalhat sites (Fig.3.4 for location, Plate 3.3a-f). The Lower Eocene presents similar facies to the unit interpreted in Kousba, with intercalations of chert beds (of about 0.15-0.2 m) and mudstone layers. The overlying Middle Miocene rock unit represents massive bioclastic limestone unit presenting important red algal content. Note that the contact between the Lower Eocene and the Upper Burdigalian rock units is erosive with conglomeratic lags of about 0.5 to 2 m thick at the base.

The main Middle Miocene facies in Ras Chekka correspond to coarse-grained packstone to grainstones, rich in lithoclastic and bioclastic content (debris of red algae, echinoderms and bivalve). They are organized in irregular beds with internal erosive surfaces, often channelized, with intercalations of brecciated deposits (Plate 3.3b, c). A very low number of red algal knobs and bio-constructions have been identified (diameter of about 0.5 m) for this massive rock unit.

Packstone to wackestone textures very rich in red algal content have been observed in the Balamand region (i.e., Qalhat anticline) for the Middle Miocene rock unit. The bedding is very massive (3-5 m) presenting no evidences of channeling, reworking or brecciation.

A boundstone interval with corals red algae and bivalves has been identified on the eastern limb of the Qalhat anticline (i.e., Afsdiq village), (Plate 3.3g; Plate 3.4d), associated with bioclastic packstone (algal and bivalve debris) (Fig.3.1), allowing to better complete the understanding of this unit in northern Lebanon.

Interpretation

Three sub facies associations (FA5-b,c,d) have been described in the sites of Ras Chekka, Balamand and Afsdiq located west of the Kousba area. These sub facies refer to open marine depositional environments towards the northern Lebanese coastal area while more restricted settings prevailed along the eastern further inland locations in the Middle Miocene.

Packstone to grainstone units rich in red algal debris with channel incisions and breccias described in Ras Chekka are interpreted as being deposited in a quite agitated fore-reef setting favoring gravity driven processes along the slope (Plate 3.3b, c). This facies association is referred to as FA5b and has been described along the western Mediterranean region by Pomar et al. (2004) and Brandano et al. (2005) who also referred to an interfingering of these slope facies landwards with coral reefs. Our observations point to the same scenario of deposition while in the Balamand region a shift towards massive packtone to wackestone textures is observed suggesting a much calmer depositional environment (FA5c). Coral boundstone unit interfingering with bioclastic packstone (FA5d) identified in the Afsdiq village are expected to be deposited in a protected back reef setting.

Plate 3.3. Eocene-Miocene facies of Ras Chekka: (a, b) The investigated (A) Lower Lutetian and (B) Late Burdigalian-Serravallian contact around the Ras Chekka promontory, (c) Brecciated rhodalgal Miocene, (d, e) (A') Ypresian and (B) Late Burdigalian-Serravallian contact around Balamand, (f) Rhodalgal facies, (g) The corallian facies attested in the Afsdiq village on the eastern limb of the Qalhat anticline

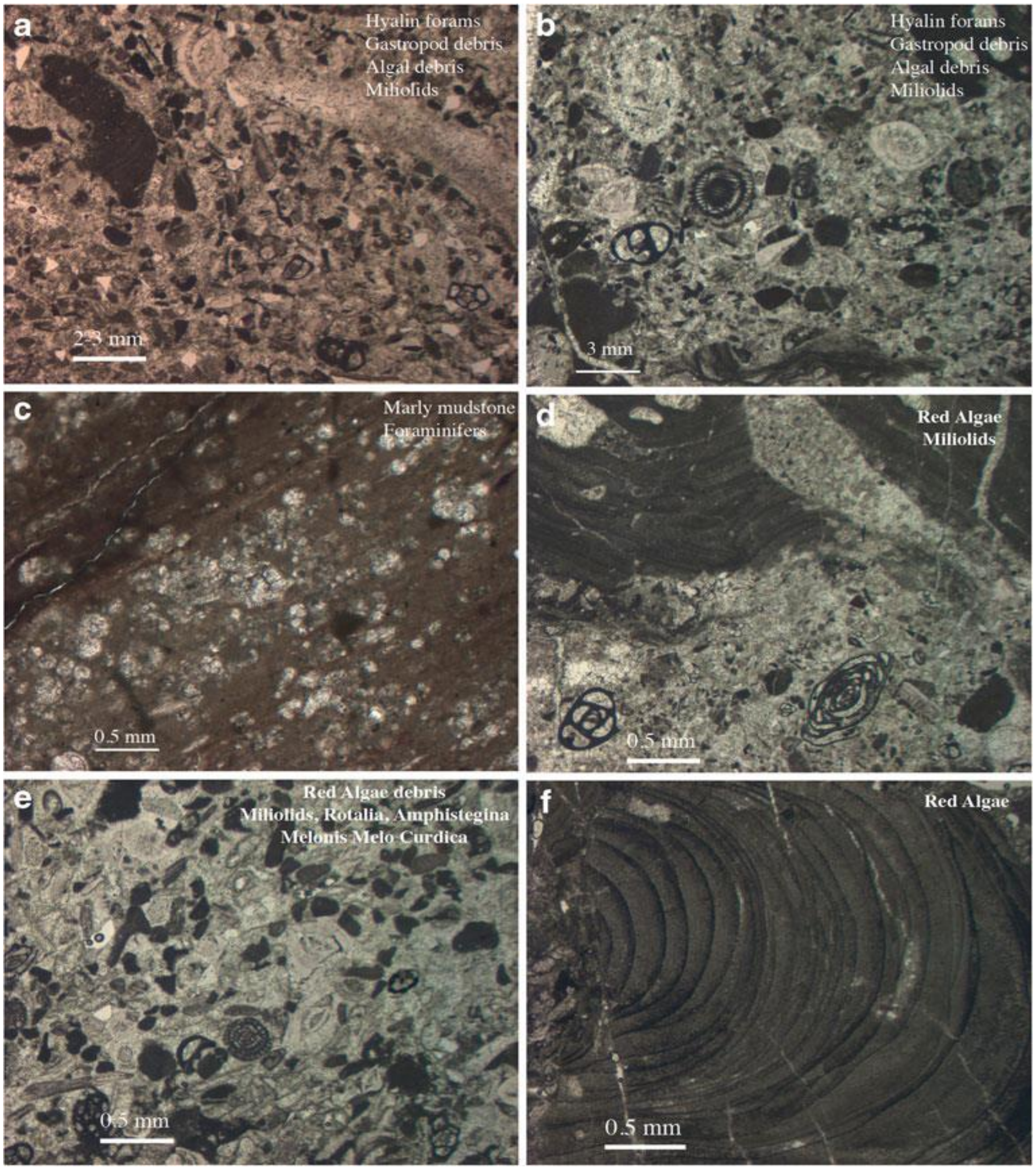


Plate 3.4. Plane polarized transmitted light photomicrographs showing the main microfacies investigated in northern Lebanon: (a,b) Bioclastic Turonian unit, (c) Upper Cretaceous marly mudstone, (d,e,f) Middle Miocene rhodalgal unit

5.Discussion

5.1 Regional stratigraphic evolution of the Levant

The Cenomanian-Turonian carbonate platform prevailed along the whole Levant margin, from northern Africa (e.g., Sinai,Egypt) passing by Israel, Lebanon and Syria, presenting important similarities in rudist species and in facies evolution (Nader 2000; Zakhera 2011). A maximum transgression has been reported by Sharland et al. (2001) from the Early Cenomanian to Early Turonian affecting the Arabian

Plate. A shallowing trend during the Mid-Turonian with a major regression identified by Haq et al., 1988 affected the Levant area (e.g., Israel) (Sandler 1996; Frank et al. 2010). The facies evolution attested in northern Lebanon fit well in this context of major eustatic fluctuations. A transition from mid-ramp settings - with slumping and turbidites - into shallow marine rudist platforms (and local reefs) is followed by the onset of an inter- to supra-tidal setting in Kousba.

The regional Cenomanian-Turonian carbonate platform facies belts show a deepening trend from the hinterland (e.g., Euphrates region) towards the coastal Mediterranean region extending further into the Levant basin (Mouty and Al-Maleh 1983; Brew et al. 2001).

A widespread deepening of sedimentary facies have been observed from the Late Turonian onwards on the Levant margin with outer shelf settings around northern Sinai, Galilee, Western Israel and Lebanon (e.g., 250-300 m of minimum depositional water depth in the Chekka region). At that period, central Syria, Jordan, Negev and southern Sinai should have been located in a more proximal middle to inner shelf position (Flexer 1971; Flexer and Honigstein 1984).

The Late Cretaceous hiatuses noted in northern Lebanon (Late Turonian to Late Santonian and Latest Maastrichtian to Paleocene) have been identified regionally and were described as interactions between major regressional cycles and the complex structural evolution of the Levant margin (e.g., initiation of the 1st phase of the Syrian Arc folding and the evolution of the Euphrates graben). A Late Turonian to Late Santonian hiatus is recorded in the Euphrates, Syria (Brew et al. 2001; Caron and Mouty 2007); Israel (Flexer 1971; Honigstein and Reiss 1989) and central Jordan (Powel and Moh'd 2011). The Latest Maastrichtian to Paleocene hiatus is mainly seen in Syria (Brew et al., 2001) and in Lebanon (Müller et al. 2010).

The data gathered in northern Lebanon (e.g., Ras Chekka, Balamand) reveals that the deepwater settings prevailed until the Early Middle Eocene with outershelfal facies composed of chalky limestone intercalated by chert bands.

The Middle Eocene to Lower Miocene unconformity is widely noticed on the Levant margin. Hence, the Oligocene to Middle Burdigalian pelagic marly mudstones are only commonly apparent in wells along the Mediterranean coastal plain (e.g., Latakia wells) as well as in offshore Israel (e.g., Ashdod well) and probably onshore southern Lebanon (Benjamini 1993; Gardosh et al. 2006; 2008; Müller et al. 2010; Bowman 2011). A recent study proposed by Hardenberg and Robertson (2007) point to the significance of structural control on the local deposition and preservation of this lowermost Miocene rock unit (i.e., Aquitanian to Burdigalian) onshore (e.g., Nahr el Kabir Basin around Latakia).

Major eustastic falls in the Eocene, Oligocene and Early Miocene (Miller et al. 2005; Haq et al. 1988) enhanced by the Levant margin uplift and deformation linked with the continued collision of Afro-Arabia with Eurasia and updoming in the Afar region have been proposed as arguments in order to explain the regional extent of the Middle Eocene to the uppermost Early Miocene hiatus (Walley 1998; Gardosh et al. 2006).

Rhodalgal platform settings dominated from the Burdigalian until the Serravallian times in the Mediterranean region, mainly in Lebanon and Israel. The end of the Miocene period is marked by the fast emergence of Mount Lebanon as well as by major eustatic falls (e.g., Tortonian and Messinian- Haq et al., 1988) leading to intense erosion of the Cretaceous and Eocene rock units along the margin as well as the deposition of large conglomeratic fans in paleo-topographic lows (i.e., Kousba).

5.2 Implications of Cenozoic geodynamics on the northern Lebanese architecture and facies variations

Our results support and refine previous published works (e.g., Dubertret 1975; BouDagher-Fadel and Clark 2006; Müller et al. 2010) in linking the Late Eocene to Early Miocene hiatus to erosion periods with relation to late phases of Alpine Orogeny and local Neogene structuration due to the Levant micro-Plate reorganization.

The Ras Chekka angular unconformity (cf. Plate 3.3a) presents important implications on the onshore architectural evolution in northern Lebanon with regards to major geodynamic events. BouDagher-Fadel and Clark (2006) dated through benthic and planktonic foraminifers the Ras Chekka angular unconformity as occurring in the Middle Miocene between the Langhian and Serravalian rock units. However our nannofossil dating in the same area (and for the same outcrop) points to an Early Eocene-Late Burdigalian angular unconformity reflecting a potential onshore pre-Burdigalian (and post Early Lutetian NP14) deformation possibly attributed to the regional flexural uplift in the Late Eocene to Oligocene of northern Arabia (Hardenberg and Robertson, 2007).

The Ras Chekka promontory would have represented at that time a limb of a paleo-structure (flexure) dipping to the west. This coastal area has been affected by less accentuated erosion compared to the eastern further inland (and structurally more elevated) locations (e.g., Balamand, Amioun, Kousba: Ypresian (NP12/NP13) is in contact with the Late Burdigalian) (Fig.3.10a). The presence of a pre-Late Burdigalian paleo-structure in northern Lebanon should have had major impacts on the onshore Middle Miocene sedimentary facies.

Previous works (e.g Pomar 1991; Pomar et al. 1996; Halfar and Mutti 2005) discussed the evolution of rhodalgal platforms in the western Mediterranean through the understanding of the impact of several factors as water temperature, lighting penetration, sediment-nutrient input, hydrodynamic conditions on the rhodalgal platform's rock textures, sedimentary facies configurations and biological activity. BouDagher-Fadel and Clark (2006) proposed idealized rhodalgal bank evolution schemes for the Lebanese coastal Middle Miocene based on the assessment of sedimentary textures and biologic (or bioclastic) content (channel facies, bank facies and protected inner platform facies).

Several controlling factors have been proposed for the volumetrically abundant algal deposits compared with corallian facies in the Mediterranean: (1) stronger thermal gradients associated with the emplacement of the East Antarctic Ice Sheet, leading to a wide spread upwelling; (2) climatic changes causing input of land derived nutrients in the oceans; and (3) cooler temperatures that prevented the expansion of coral reefs (Edgell and Basson 1975; Buchbinder and Le Roux 1993; Esteban 1996; Halfar and Mutti 2005; BouDagher-Fadel and Clark 2006; Powell and Moh'd 2011).

The examined E-W sedimentary facies evolution of the Late Burdigalian to Serravallian rock units of northern Lebanon around the present day Qalhat anticline points to the development of a rhodalgal rimmed platform configuration affected by a potential structural control on ecological settings (Fig.3. 10). The results linked with the sites investigated refer to a fore-reefal to slope setting towards Ras Chekka with intense lithoclastic and bioclastic reworking, as well as channel incisions. The sedimentary facies and textures drastically change towards the Balamand region (i.e., Qalhat anticline) with very thick algal accumulations deposited in calm settings (Plate 3.3). Localized coral polyps have been identified along the eastern limb of the actual Qalhat anticline (i.e., the Afsdiq village) while eastwards towards Kousba a bioclastic packstone to grainstone with algal and bivalve debris is described. Studies show that corallian biota mainly flourishes in euphotic zones with relatively high light conditions, and very shallow marine environments in a protected wave agitated to lagoonal settings (Pomar 2001). This points to a Middle Miocene inner platform setting prevailing eastwards of the Qalhat anticline.

The sedimentary facies and textures described around the present day Qalhat anticline suggest that the initiation of gentle pre-Late Burdigalian folding should have led to the formation of a restricted/protected platform setting (back reef to lagoon) eastward of the paleostructure (Fig.3.1). The euphotic settings (i.e., higher temperatures, less contact with cold water, considerable light penetration) must have developed along the crest of the broad paleo-structure, allowing corallian biota to optimally thrive; while fore-reef to slope settings should have developed towards the west (i.e., Ras Chekka) (Fig.3. 10a).
No indications of faults have been observed in the present day Qalhat scarp. The asymmetry of the anticline as described by Elias (2006), may imply that a SE dipping thrust fault ramp probably exists at depth and surfaces out westwards in the Lebanese offshore controlling the growth of the Qalhat structure. The scenario of a blind thrust fault may also be plausible (Fig.3.10).

Similar facies variations could also occur in rhodalgal carbonate ramp configurations that are characterized by their gentle slope passing gradually from shallow marine to basinal settings. The sedimentary facies configuration of such types of carbonate platforms is highly dependent on the relative position of the fair-weather wave base level. Ramps do not present smooth morphologies (Tucker et al. 1990). Gentle topographic highs and lows could impact on the depositional environments along the ramp (e.g., formation of beach barriers). Inner ramps are defined by their high organic productivity, presenting bioclastic grainstone and packstone facies (shoals of skeletal debris) formed through reworking by storm waves (Tucker et al. 1990). Patch reefs and mounds (grainstone to boundstone) as well as small reefal colonization occur seaward, in the back barrier or on topographic highs along deeper positions. Important red algal deposits is attested in mid ramp oligotrophic settings (i.e., decreased light penetration, cooler setting, around 50- 100 m depth) (Pomar 2001; Pomar et al. 2004). Ramp slope deposits are represented by rudstone and bioclastic grainstone to packstone facies with channeling and gravity driven sediments (Tucker et al. 1990; Pomar et al. 2004; Brandano et al. 2005).

However, the absence of proximal bioclastic beach deposits in our study area supported by the identification of a wide protected environment eastwards of the Qalhat anticline point to a rhodalgal platform setting presenting a rimmed configuration in northern Lebanon (Fig.3.10).

The drastic change of facies in the Serravallian-Tortonian? in Kousba, marks the onset of the Mount Lebanon relief with a development of a conglomeratic alluvial fan providing clasts from the erosion of the Upper Cretaceous/Paleogene carbonate platforms into the still prevailing shallow marine settings (conglomerates in carbonate matrix) (Fig.3.10, Plate 3.2). A certain degree of consensus has been noted on the major structural implications of the Levant Fracture system on the fast emergence of Mount Lebanon in the Late Miocene (e.g., Butler et al. 1998; Walley 1998; Beydoun 1999; Elias et al. 2007). The geometry of this transform plate boundary (i.e., presenting a right bend) as well as its sinistral kinematics led to the establishment of a major compression zone along northern Lebanon.

A gentle shift into a more terrigenous and argillaceous-rich matrix suggests of the evolution of the shallow marine environment into a more continental setting around the Tortono-Messinian with the acme of Mount Lebanon's formation (Plate 3.2d-e). Restricted lacustrine facies fed by braided fluvial channel systems in the northern Bekaa (i.e., Hermel) (Plate 3.5) and in Syria prove once again a structurally controlled deposition since Late Miocene times (Fig.3.10b) (Dubertret 1955; Walley 1998; Elias et al. 2007) (Fig.3. 10a).

5.3 North versus south Lebanon

Results of this contribution further support the hypothesis that northern Lebanon has been in a structurally elevated position from at least the Cenomanian-Turonian (Dubertret 1975; Beydoun 1995;

Walley 1997; 1998; Nader et al. 2007; Collin et al. 2010) and associated references), yet this does not imply that it has been subaerially exposed since that time.

Northern Lebanon presents shallower mid-ramp Cenomanian-Turonian carbonate platforms with occasional rudist reefs; compared with the outershelfal/slope deposits seen around Beirut (e.g., the so-called grotte au pigeon-Dubertret 1975; Walley 1997) and the Tyr Nabatieh plateau in the south of Lebanon. A drastic thickening of the Upper Cretaceous to Eocene unit is noted in the south referring to an increase in sea level. Our data show that the deep outershelfal chalky limestone (Late Santonian to Maastrichtian) is about 200-300 m near Chekka while the total thickness of this formation investigated by Renouard (1955) in the southern Bekaa is around 600 m.

In order to explain these north-south facies and thickness variations, Walley (1998) referred to the interruption of the coast parallel hinge line (represented in Lebanon by the NNE-SSW trending Western Lebanese Flexure) around southern Lebanon. The south might thus have corresponded to the SW extension of the Palmyride Basin with a lower topographic position and related deeper facies (Gvirtzman and Klang 1972; Bein and Gvirtzman 1977; Saint-Marc 1972; 1974; Frank et al. 2010). The Palmyride Basin has been inverted and folded around the Turonian times with the initiation of the Syrian Arc folding, creating localized highs and depocenters and leading to important thickness variations of the Upper Cretaceous to Eocene rock units (Dubertret 1955; Walley 1997).

This biostratigraphic study - supported by the works of Dubertret (1975), BouDagher-Fadel and Clark (2006) and Müller et al. (2010) - proves that the Eocene section in northern Lebanon is not completely preserved. In the south, the Eocene is thought to have been deposited in a subsiding setting while being preserved from the erosion observed in the successions exposed in northern Lebanon (e.g., Ras Chekka, Balamand, Kousba). The identification of the transgressive Upper Oligocene unit in the south and in the Nahr el Kelb valley (20 km north of Beirut) by Müller et al. (2010) can be explained by two scenarios: (1) the late Oligocene sea invasion has affected lowlands located in central to southern Lebanese coastal areas only; alternatively, (2) the Oligocene strata may have been deposited in our study area (north of Lebanon) and later on locally eroded due marginal uplift (Fig.3. 2). As no Oligocene clasts have been identified in the north, it is difficult to draw a single concluding scenario as for the widespread extent of the Oligocene deposition in Lebanon and the impact of the onshore structuration on its deposition and possible erosion.

The Late Burdigalian/Serravallian rhodalgal platform setting attested in northern Lebanon differs from the marly outer shelfal/ open marine environment affecting the Tyr-Nabatiyeh Plateau (south) described by Dubertret (1975). This supports once again the higher structural position (uplifted) of northern Lebanon compared to the south before the major initiation of the Lebanese sector of the Levant Fracture believed to occur in the Tortono-Messinian.

5.4 Implications for the Levant Basin deposition

Important subsidence has been noted in the Levant Basin (mainly facing Tripoli around the Latakia Ridge system- Bowman 2011) starting from the Late Cretaceous following the collision of Afro-Arabia with Eurasia and leading to increased sediment accommodation. Following the regional Cretaceous deepening trend towards the Levant coastal area and basin (Flexer 1971; Flexer and Honigstein 1984; Mouty and Al-Maleh 1983; Brew et al. 2001), the mid to outer ramp setting observed for the Turonian carbonate platforms of northern Lebanon (mainly in Kousba and Chekka) are expected to evolve into an outer ramp/slope and basinal settings towards the Levant Basin. The offshore distal equivalent of the outershelfal Coniacian to Lower Eocene chalky limestone (potential source rock) is thought to be made of hemipelagic to pelagic sediments (i.e., chalk and shales) as well as gravity driven deposits (e.g., distal calci-turbidites, slumps) interpreted on the Levant Basin seismic data (Gardosh et al. 2008; Lie et al. 2011; Bowman 2011).

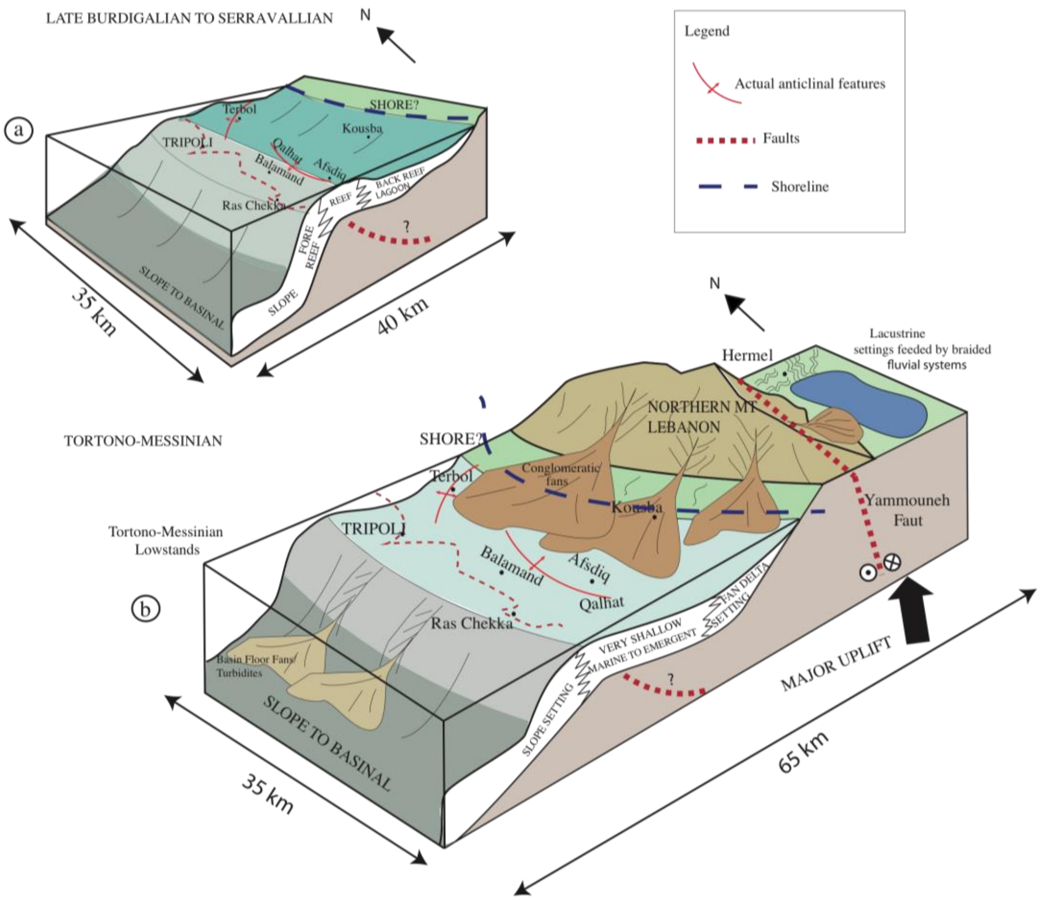


Fig.3.10. 3D schematic illustrations representing the Miocene facies evolution in northern Lebanon affected by the onshore deformation

The Cenozoic deposits (Eocene to Miocene) supplied from the Lebanese onshore reveal to be mainly of carbonate origin. The missing Mid-Upper Eocene to Late Burdigalian rock units in northern Lebanon should have been heavily eroded and deposited in the already subsiding basin following continuous tectonic uplift as well as major regressional cycles (e.g., Rupelian lowstand, Haq et al. 1988). However the scenario of non-deposition is not to be discredited, as no Middle-Upper Eocene to Lowermost Miocene clasts have yet been identified in northern Lebanon. In the very deep and distal part of the basin, finer sediments as silts, shales as well as turbiditic cycles are expected. The only Neogene siliciclastic units of Lebanon have been identified in the Hermel location in the northernmost Bekaa referring to a potential nearby source (Plate 3.5).

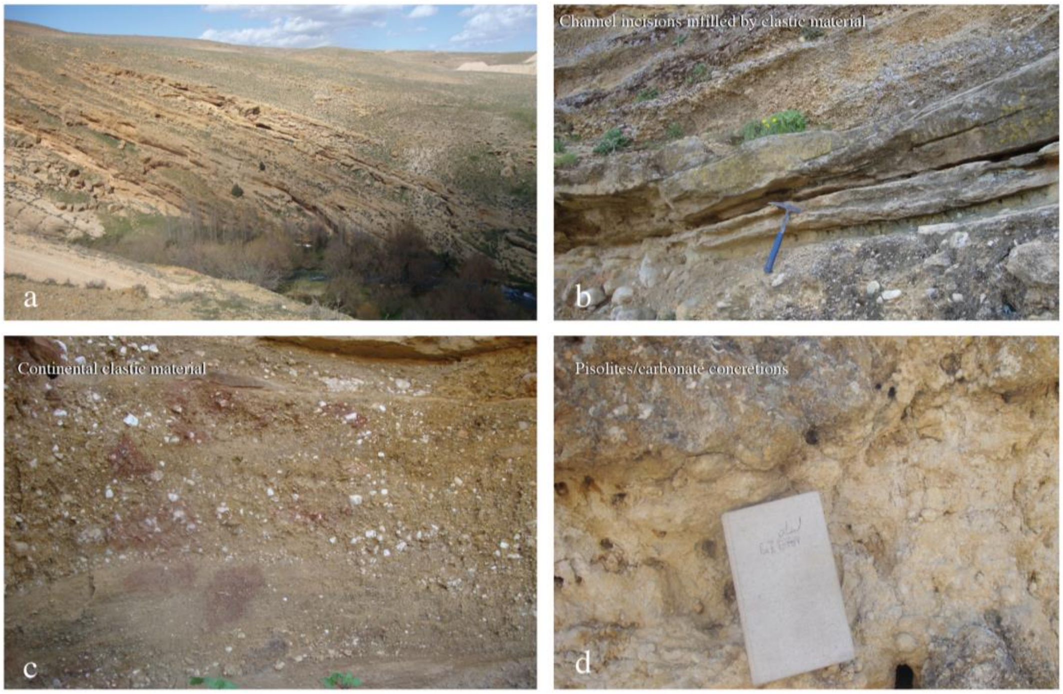


Plate 3.5. Neogene facies of Hermel: (a) General view of the lacustrine to fluviatile section of the Hermel area, (b, c) braided fluvial channel systems feeding into the intermontane lakes formed after the acme of Mount Lebanon's deformation at the end of the Miocene, (d) Marly lacustrine unit with pisolites

The Lebanese onshore could not have been the major and only provider of sediments into the Levant Basin (ca. 10 km of Cenozoic) due to its restricted scale (i.e., not more than a few thousands of square kilometers). Thus, the carbonate rich lithologies of the Levant margin (i.e., Lebanese onshore) could represent only a fraction of the deposits expected for the basin (carbonate and siliciclastics) supporting the basin-margin conceptual model proposed by Nader (2011). Thus, large plate-scale drainage systems should have impacted on the Levant Basin infill (i.e., Nile Delta, Nahr el Kebir around the Latakia region) bringing forward additional questions related to the reservoir characteristics expected (Hardenberg and Robertson 2007; Bowman, 2011; Nader 2011; Steinberg et al. 2011).

6. Conclusion

Fieldwork in the northern Lebanese coastal area coupled with facies and microfacies analysis led to the following conclusions:

A 1860 m thick stratigraphic log was achieved for the Turonian to Miocene rock succession in the Kousba area, supported by nannofossil and planktonic foraminifers biostratigraphy, allowing to complete the understanding of the northern Lebanese sedimentary and stratigraphic evolution.

The "Senonian" (onshore analogue for the potential source rock in the Levant Basin) has been divided in the Chekka area (through core and field investigation) into four sub-units with associated sedimentary facies: (1) Upper Santonian, (2) Lower Campanian, (3) Upper Campanian and (4) Lower Maastrichtian. A clear deepening trend has been noted at the end of the Turonian marking the major drowning of the rudist platforms in Lebanon and lasting till the Lower Eocene.

A widespread angular unconformity between the Lower Eocene and the uppermost Lower Miocene with carbonate reworking at the contact between the deep outer-shelf deposits of the Eocene and the rhodalgal Miocene. Northern Lebanon should thus have been deformed as a consequence of the major Cenozoic geodynamic events affecting the Levant region (i.e., continued Alpine Orogeny and margin updoming due to the Afar plume).

The Middle Miocene rhodalgal platform proximal-distal facies variations around the present day Qalhat anticline reflect a potential structural control on ecological settings prior to Late Burdigalian (and post Lower Eocene). A restricted/protected setting developed to the east of this structure with corallian facies identified around Afsdiq; while an open marine environment dominated the western coastal areas.

The onshore architecture of the Lebanese margin presents a structurally more elevated position in the north compared to the south since at least the Cenomanian-Turonian suggested by facies and thickness variations.

The facies variations from proximal margin (onshore) to toe of slope and then basinal, can be deduced in northern Lebanon. These variations are of substantial significance in understanding the effect of major geodynamic events on the Levant Basin architecture as well as on the expected duality of its infill by carbonates and siliciclastics supplied by other major pathways.

End of Article Hawie et al., 2013 a

CHAPTER IV

Sedimentological & Stratigraphic Overview of Lebanon

The fieldwork conducted in northern Lebanon (Chapter 3) aimed to establish a stratigraphic model for the marginal sector of the northern Levant Basin. Through this chapter we present the fieldwork conducted across Lebanon aiming to propose a more regional stratigraphic model for the onshore. The tectonostratigraphic framework of the Levant margin is then combined with the offshore studies presented later in this manuscript.

In the following paragraphs several sedimentary logs are presented: the Jezzine log in central Lebanon, Deir Billa-Ras Chekka log in northern Lebanon, the Zahle log on the eastern flank of Mount Lebanon, as well as a focus on the Miocene in the Beirut and the Tyr-Nabatieh plateau in southern Lebanon.

I. Late Jurassic-Cenomanian

Located to the south of Beirut, the Jezzine region is bound to the East by the Niha and Barouk flexures culminating at around 2000 m where the Jurassic strata make up the core of Mount Lebanon anticlinal structure (Figs.4.1, 4.2). These structures are consequently delimited by the Yammouneh fault overlooking at the Bekaa Valley. To the west a NNW-SSE trending fault named the Roum fault with a 35 km length splays from the sinistral Yammouneh fault reaching the Chouf area. The Jezzine log conducted along the Azibi valley (1520 m) allowed the investigation of the Upper Jurassic to Cenomanian rock units.

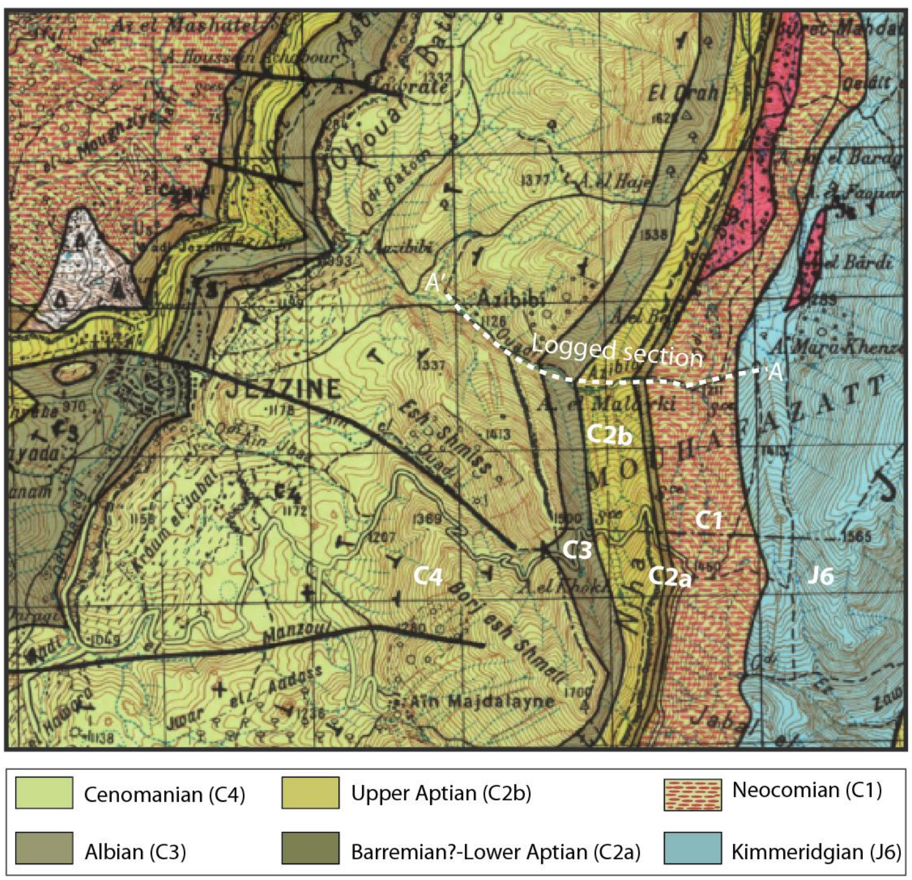


Fig4.1. Cropped area of the Jezzine Geologic map by Dubertert, 1975 (1:50000) showing the location of the logged sedimentary section (dashed line A-A')

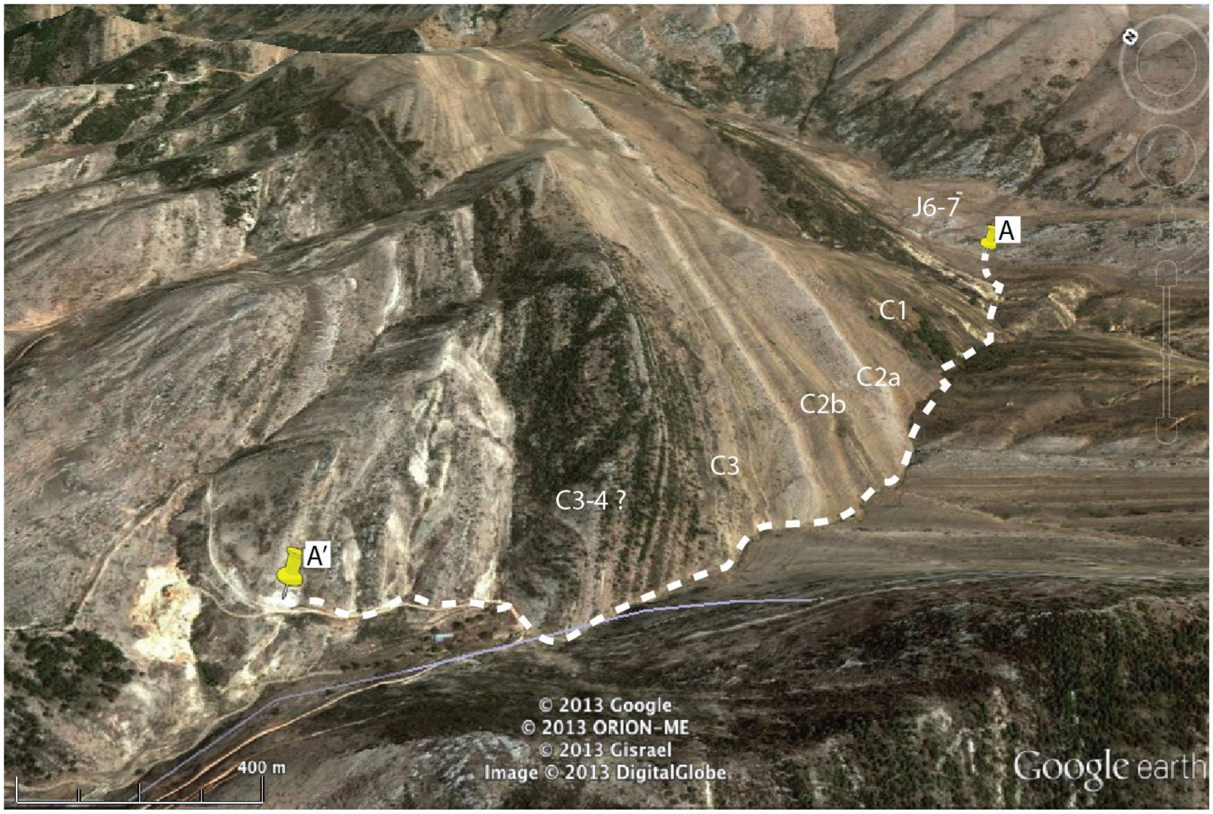


Fig4.2. Satellite image of the studied location along the Azibi Valley

The base of the log (from 0 to 25 m) presents a grayish wackestone to packstone unit presenting abundant quantities of fauna: gastropods, bivalves and foraminifers (Bikfaya Fm; Fig.4.3a, 4.5). The unit is highly bioturbated and slightly dolomitized at its top. A 20 m vegetation cover (from 25 to 45 m) is overlain by an oolitic and lithoclastic brownish grainstone unit (Salima Fm) with abundant bioclasts and bioturbation (from 45 to 55 m).

An erosive surface topped by a hardground marks the base of a thick Lower Cretaceous sandstone package that reaches 340 m in thickness (Fig.4.3b, 4.5). The bottom section (from 55 to 120 m) presents an alternation between poorly sorted medium to coarse-grained sandstone –with channelized features, trough cross bedding and wood debris (Chouf Fm; Fig.4.3d, 4.5) (interpreted as fluvial deposits with a NE-SW sediment transport direction)- and well sorted fine-grained cross bedded sandstone with dune sets intercalated by thin paleosols and some lignite debris (interpreted as aeolian environment with two major transport direction NE-SW and SE-NW) (Fig.4.3c, 4.5). A dominance of the aeolian deposits is noted from 120 to 395 m with some fluvial sandstone intercalations (e.g., 345- 360 m). The sandstones are overlain by a 20 m thick volcanic unit (from 395 to 415 m -basalt).

A brownish oolitic grainstone unit (Abeih Fm-Aptian) (Figs.4.4a, 4.5) is observed from 415- 540 m, with large foresets, sigmoid cross beds and a decreasing quartzitic content towards the top. The bedding varies between 1 and 2 m. The rock unit is rich in gastropod and bivalve fauna with moderate bioturbation. It evolves into a whitish highly bioturbated, gastropod rich mudstone to wackestone unit (Mdeirej Fm-Aptian- from 540-620 m) (Figs.4.4a, 4.5). An intercalation of marls and wackestone to packstone carbonate beds (of about 0.5-1.5 m) rich in gastropods, bivalves, orbitulina is observed (from 620 to 1030 m- Albian to Lower Cenomanian? (Figs.4.4b, 4.5). A drastic decrease in the marl content is noted starting from 1030 m with a monotonous dolomitized heavily bioturbated mudstone to wackestone rock unit. Chert bands (around 1125 m; 1235 m; 1250-1260 m; 1360 m; 1430 m) are intercalated by anhydrite pseudomorph, algal mat and chicken wire features (e.g. at 1210 m). Around 1450 m a major deepening of facies is noted with chalky mudstone and marls deposits.

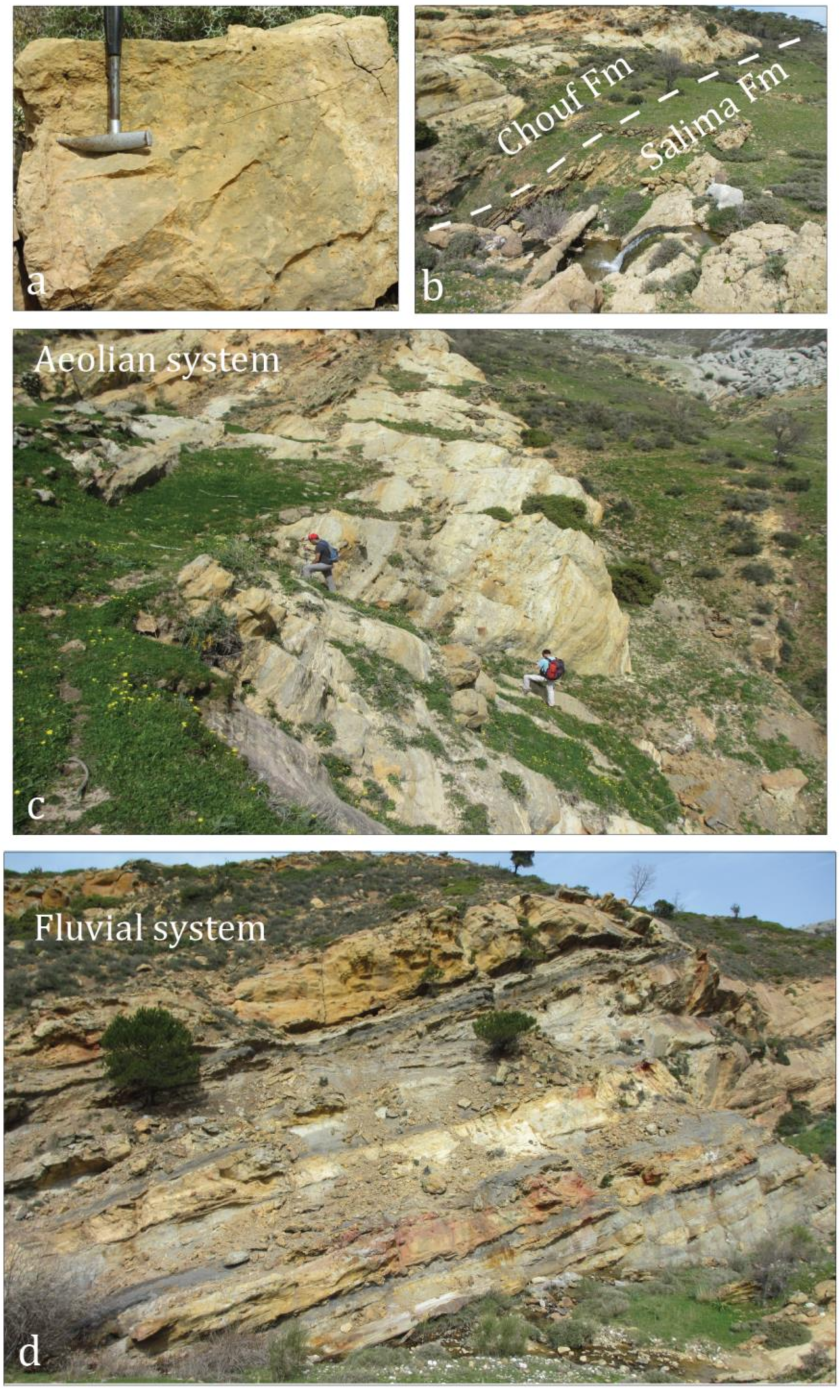


Fig 4.3. (a) Upper Jurassic wackestone to packstone rich in fossils, (b) Upper Jurassic (Salima Fm) Lower Cretaceous (Chouf Fm) contact (c) Lower Cretaceous aeolian system and (d) fluvial system.

Fig4.4. (a) Aptian shallow water rock units (facing the NW) and (b) Albian to Cenomanian intercalation of shallow marine carbonates and marls (facing facing SE)

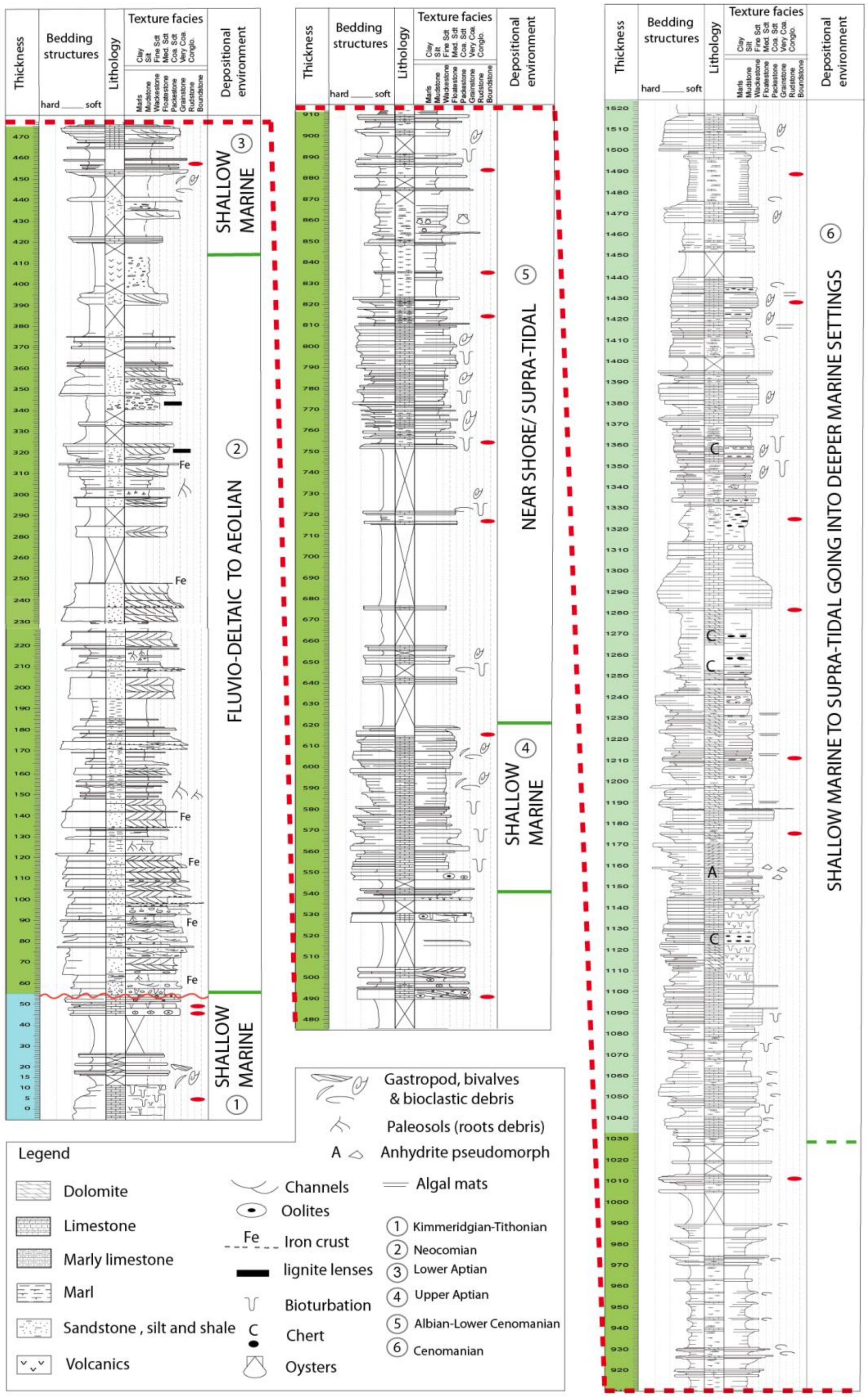


Fig4.5. Detailed sedimentary log of the Azibi location (Jezzine)

II. Cenomanian-Miocene

II.1 Deir Billa-Ras Chekka sedimentary logs

A geologic section running south of the Kousba section was thoroughly investigated. It is referred to as the "Deir Billa-Ras Chekka section" and is divided into 2 major sectors (Fig.4.6):

- The Deir Billa village (N 34°14'38.40"; E 35°48'39.06") (log of 410 m) allows the investigation of the Turonian to Senonian Transition (location A on Fig.4.6)

- The Ras Chekka (N 34°17'57.00"; E 35°42'24.12") section covers the Senonian to Middle Miocene rock units (log of 304 m).

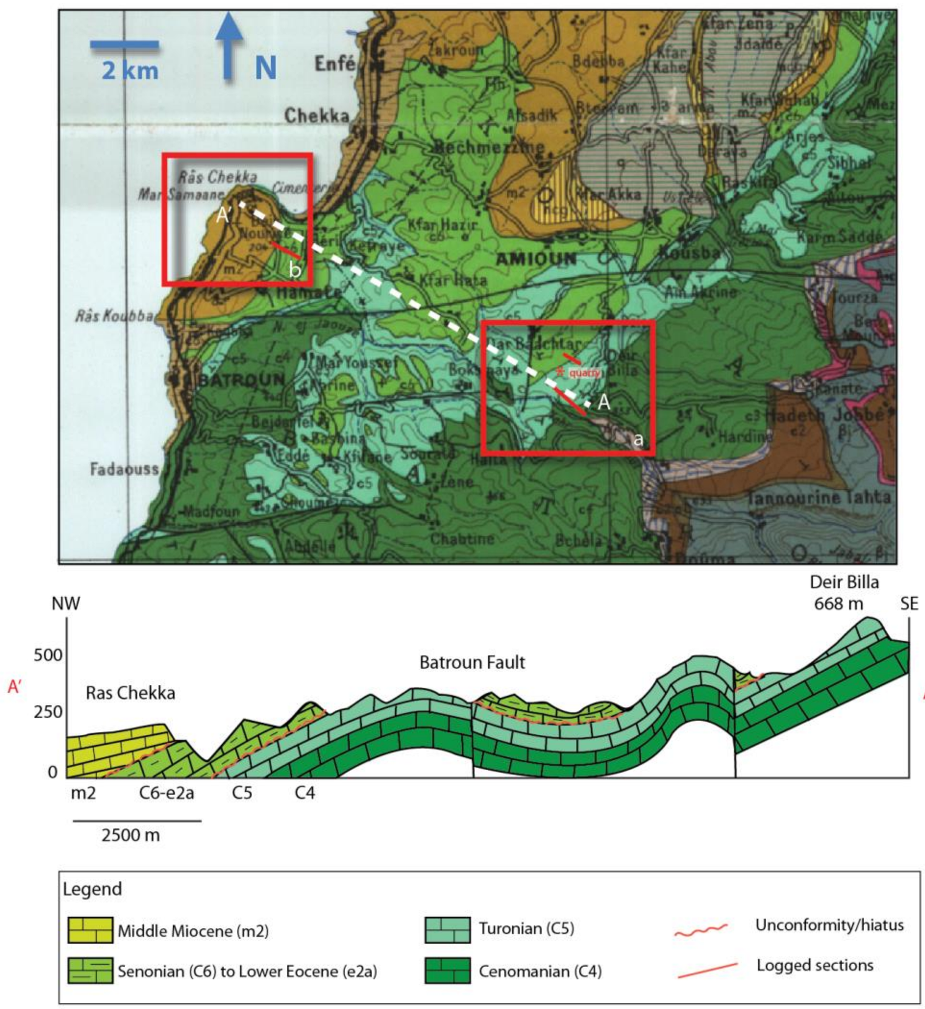


Fig.4.6. Simplified geologic map of northern Lebanon (Dubertret 1975) showing the main logged field section of Deir Billa-Ras Chekka

a. Deir Billa sedimentary log description (Fig.4.9):

The lower 20 m of the section represent massive packstone to grainstone whitish limestone beddings; intercalated by 5-10 cm thick chert bands, 6-10 cm diameter nodules (Plate 4.1a) as well as by quartz geodes (Plate 4.1b). A change in sedimentary textures occurs between 22 and 90 m with a dominating mudstone to wackstone unit. The bedding is clearer, with intercalation of argillaceous material. Internal erosive surfaces are noted with clastic reworking, slumping (Plate 4.1d) and some channeling (Plate 4.1c).

A bioclastic rich packstone to grainstone rock unit dominates the Deir Billa section from 90 to 166 m with abundant rudists, alge and gastropods (Plate 4.1e). Intercalations of bioclastic mudstone to wackstone are also attested with some shale lenses (104-106 m) (Plate 4.1f). An 8 m algal boundstone (152-160 m) has also been identified marking a clear facies shallowing trend (Plate 4.1g). Geopetal and calcite precipitation might represent early diagenesis phases (Plate 4.1h).

From 165 to 216 m a very massive, altered and moderately brecciated packstone to grainstone unit is overlain by a relatively thinly bedded bioclastic packstone unit of about 120 m in total thickness (beds between 0.5 and 2 m). This rock unit is expected to be deposited in a shallow marine to Inner ramp setting.

This first section of the Deir Billa log resembles closely what has been interpreted in Kousba for the Upper Cenomanian-Turonian rock units (Hawie et al., 2013a).

Fig.4.7. Panoramic view of the Deir Billa section showing the Cenomanian-Turonian and Senonian transition. The beds present an approximate dip of 26°

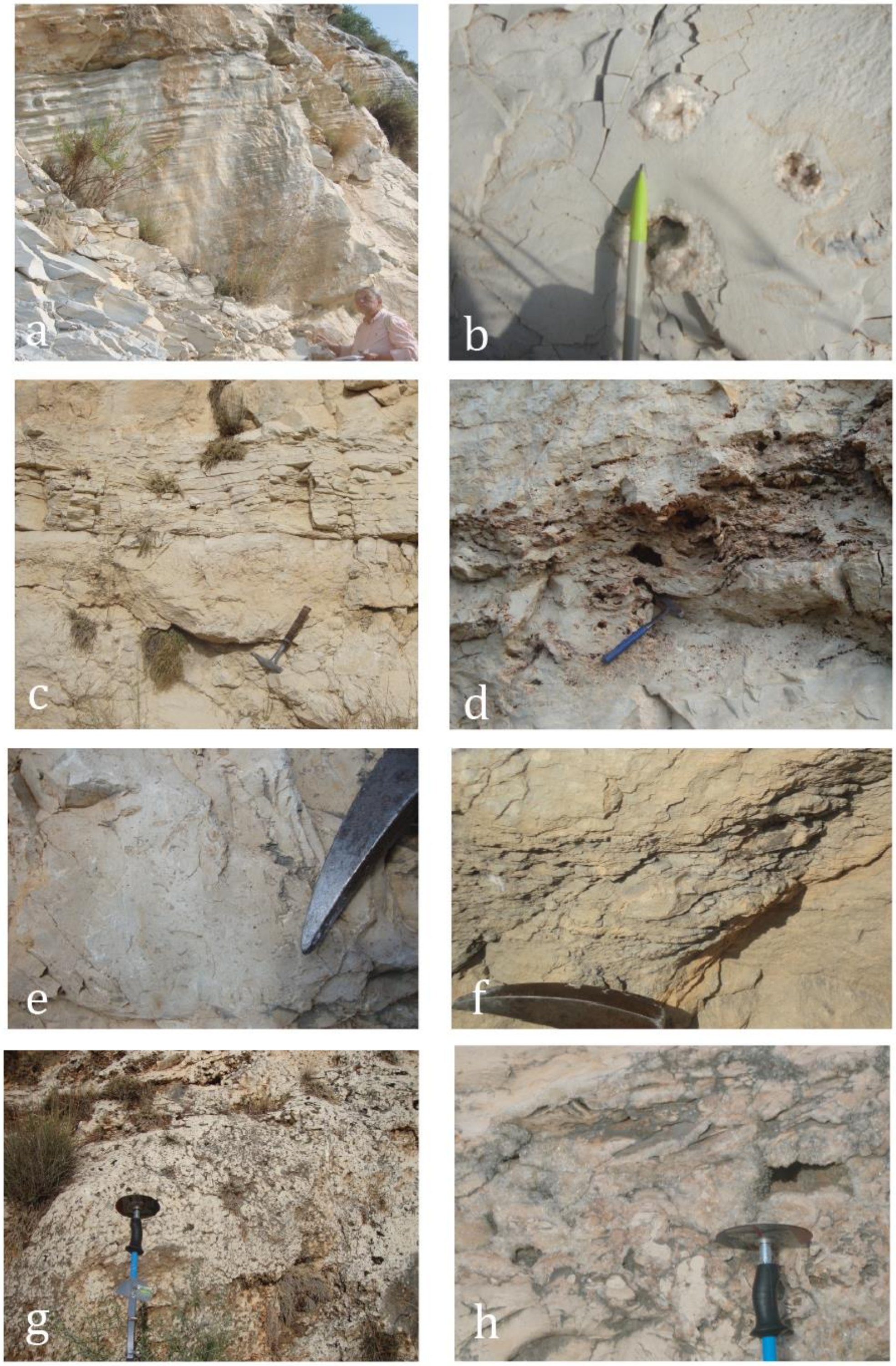


Plate 4.1. Cenomanian-Turonian sedimentary facies. (a) mudstone intercalated by chert beds, (b) calcite geodes, (c) internal incisions/channeling, (d) slump, (e) bioclastic grainstone, (f) reworked lignitic bands, (g) algal boundstone (h) calcite precipitation/geopetals

The Upper Turonian to Senonian transition has been investigated in two nearby locations north of the main section (Fig.4.6):

(1) Quarry (Figs.4.6, 4.8) (N 34°15'19.32"; E 35°48'5.88"): 8 m of mudstone rich in bioclastic content has been observed intercalated by a thin glauconitic level that represents the equivalent of the Late Santonian attested in the Kousba section.

(2) Hill- north of the quarry (N 34°15'36.60"; E 35°48'42.60"): a transition between a packstone to grainstone dominated unit (intercalated with finer chalky beds- Turonian) into a whitish chalky/marly limestone (Late Santonian- *M. furcatus, R. anthophorus, E. eximius*). The overall Upper Cretaceous bedding is concordant with the 25 degrees dipping observed for the Cenomanian-Turonian. The Lower Campanian has also been identified in the area (marly limestone with pyrite in micro-vugs) with *B. parca, E. eximius, R. anthophorus* nannofossils.

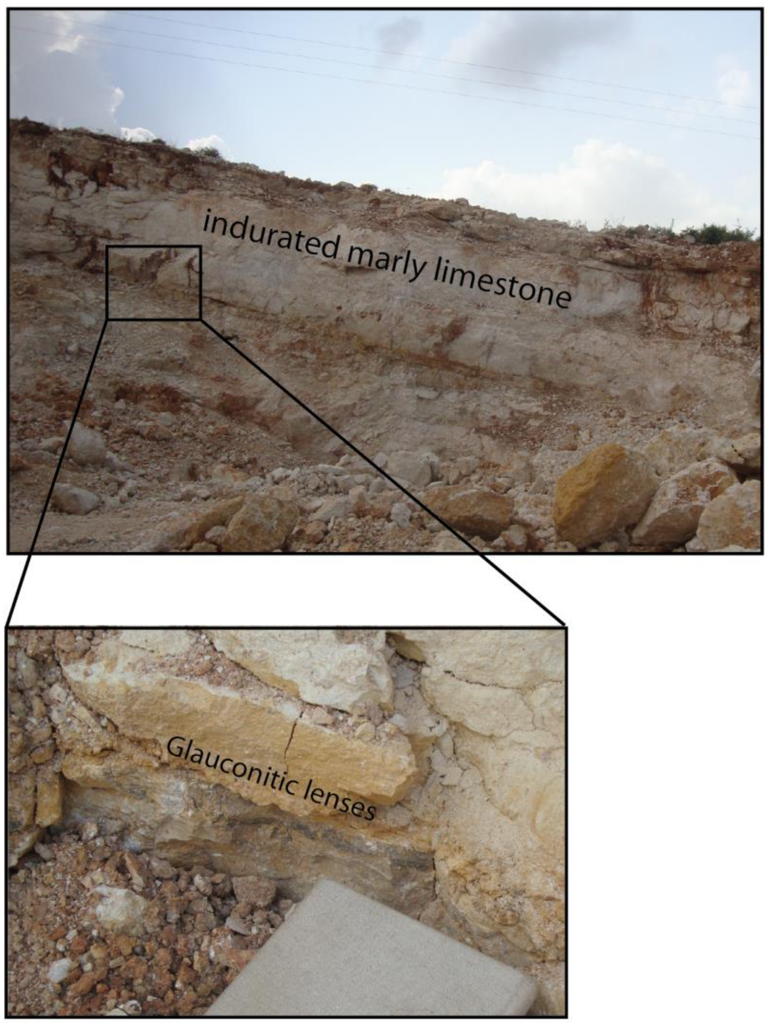


Fig.4.8. Marly limestone unit representing the Turonian-Senonian Transition

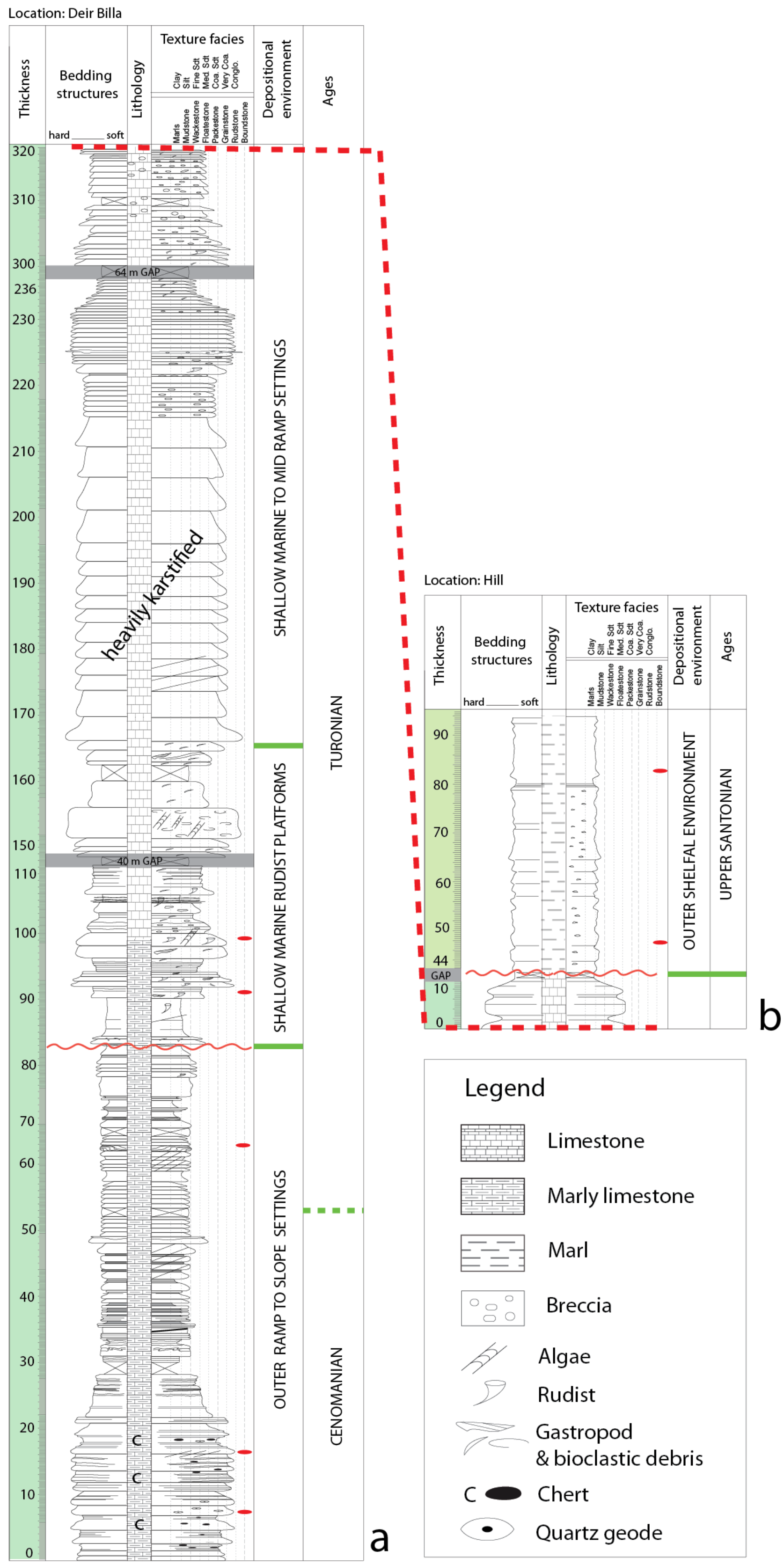


Fig.4.9. Sedimentary log of the Deir Billa section

b. Ras Chekka sedimentary log description:

The lowermost section (6 m) of the Ras Chekka outcrop (Fig.4.10, 4.11) represents the Upper Maastrichtian rock unit. The sedimentary facies refer to an intercalation of fine grainstone facies of whitish/light yellowish to grayish colors (with pyritic content) and relatively thin intercalations of marly and clayey material. Small fining upward cycles (from grainstones to packstones) present undulating and moderately erosive bases. They were interpreted as turbiditic cycles (Fig.4.11) (similar to the Chekka Quarry descriptions, see article Hawie et al., 2013a). This unit gradually becomes richer in marl content towards the top.

Fig.4.10. View of the Ras Chekka outcrop showing the studied sedimentary section

About 20 m of friable dark grayish marly limestone overlie the turbiditic cycles. It is topped by intercalations of marls and marly limestone beds containing moderate pyritic content (from 39 to 88 m) (Fig.4.11). The marly content appears to be drastically decreasing from 88 to 110 m as well as the pyritic content (Fig.4.11). Dating using calcareous nannofossil biostratigraphy (supported by unpublished Master thesis work of Hawi, 2000) pointed to an unconformity between the Upper Maastrichtian and the Upper Paleocene (NP5; *F. tynpaniformis, C. danicus*).

From 110 to 180 m an increase in the marl content is noted with minor intercalations of marly mudstone unit of about 0.5 m thick. About 100 m of vegetation cover is overlain by 15 meters of marly mudstone and chert intercalation (Fig.4.11). The rock unit has been dated as Lower Eocene. It is separated by an erosive contact from a Middle Miocene rock unit rich in lithoclastic and bioclastic content (debris of echinoderms, bivalves). Internal erosive surfaces and channeling were identified in the Miocene unit with brecciated deposits intercalated with argillaceous material.

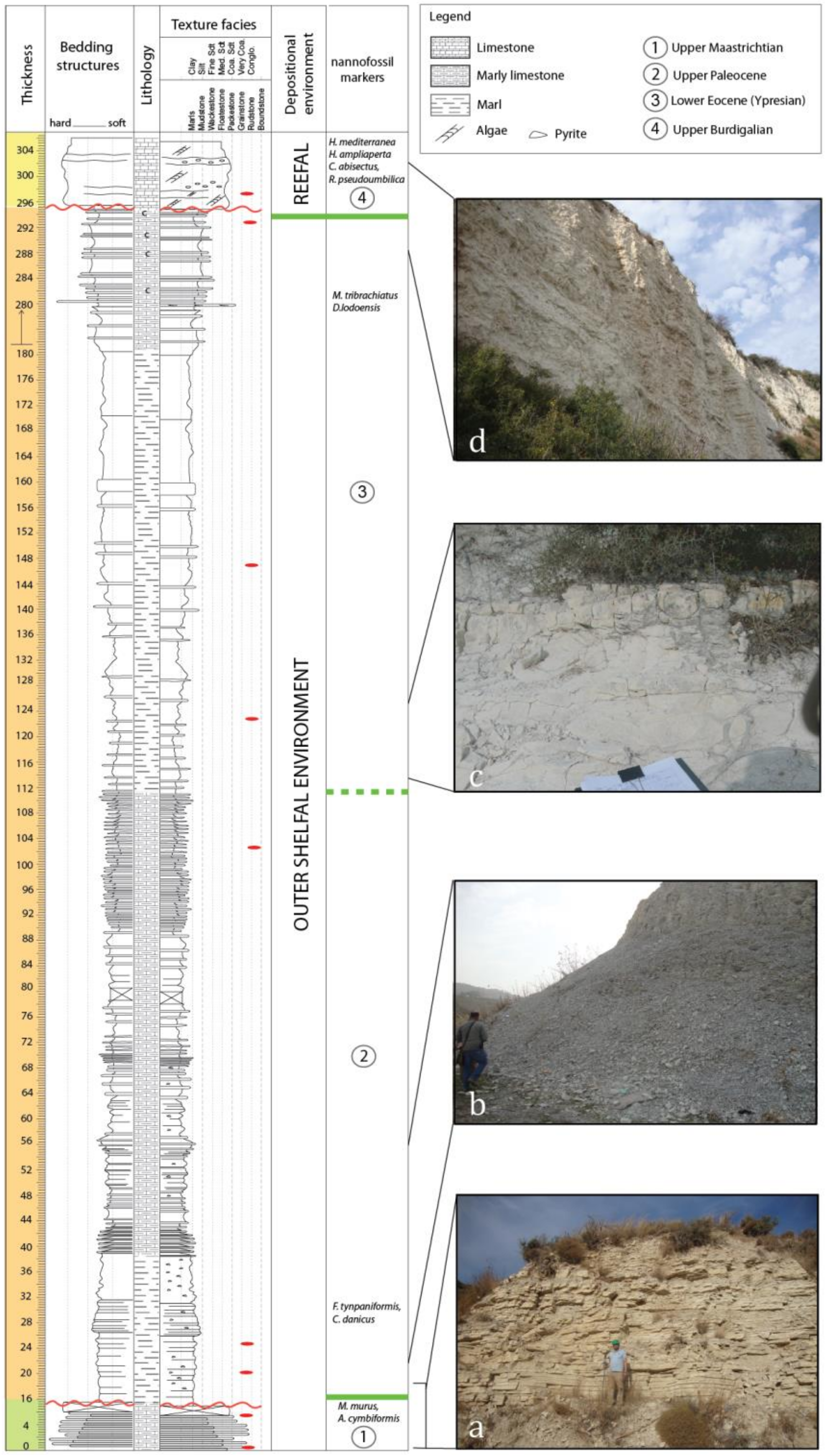


Fig.4.11. Sedimentary log of the Ras Chekka section

II.2 The Zahle sedimentary log

Located in the central part of Mount Lebanon, Zahle is bound to the west by the extensive Yammouneh fault, and to the east by the NNE-SSW trending Bekaa valley, a depression running in between Mount Lebanon and the Anti-Lebanon. A cross section passing by Ouadi el Aarayech ending near the Maalaqua village has been studied in order to investigate the succession of stratigraphic units and their contacts (A-A') (Figs.4.12, 4.13, 4.15). A composite sedimentary log **(1720 m)** has been completed for this section. A second geologic section (B-B') (Fig.4.12) was studied running NE of Ouadi el Aarayech. It covers the extension of the Zahle anticlinal feature and brings more constraints to sedimentary ages subdivisions as well as a better view of the anticlinal structure extent.

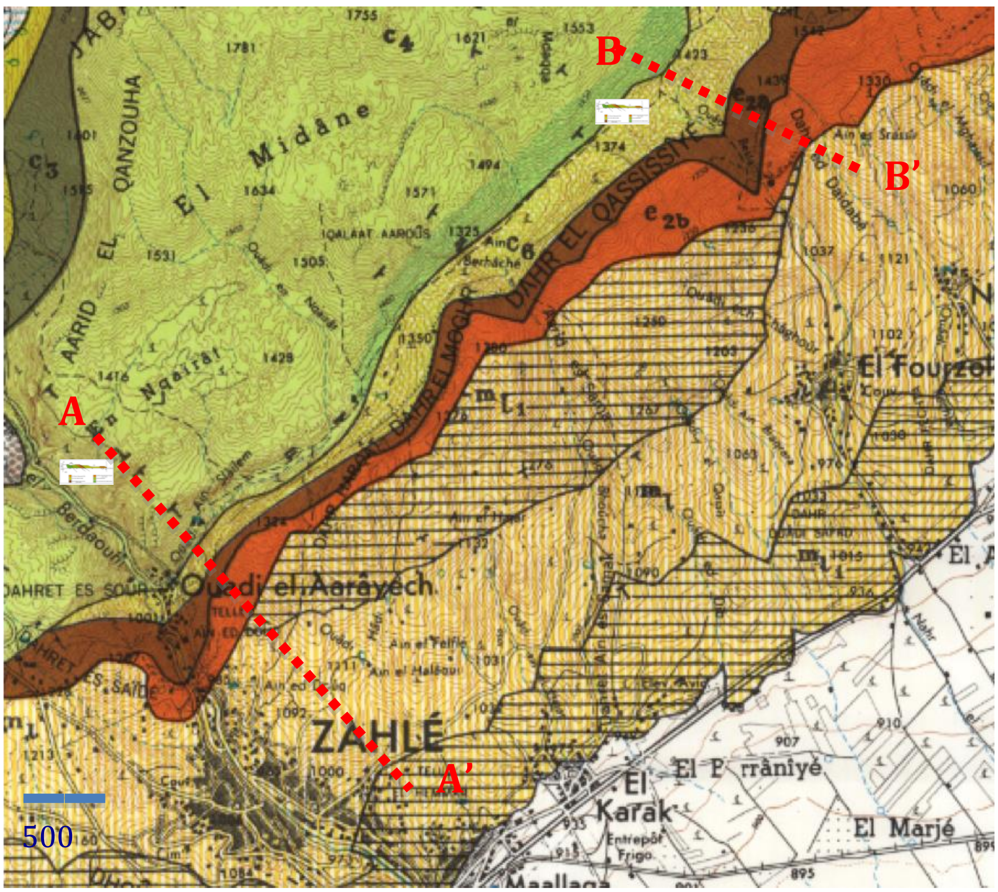


Fig4.12. Part of the geologic map of Zahle (1/50 000) showing location of the cross section A-A' and B-B'

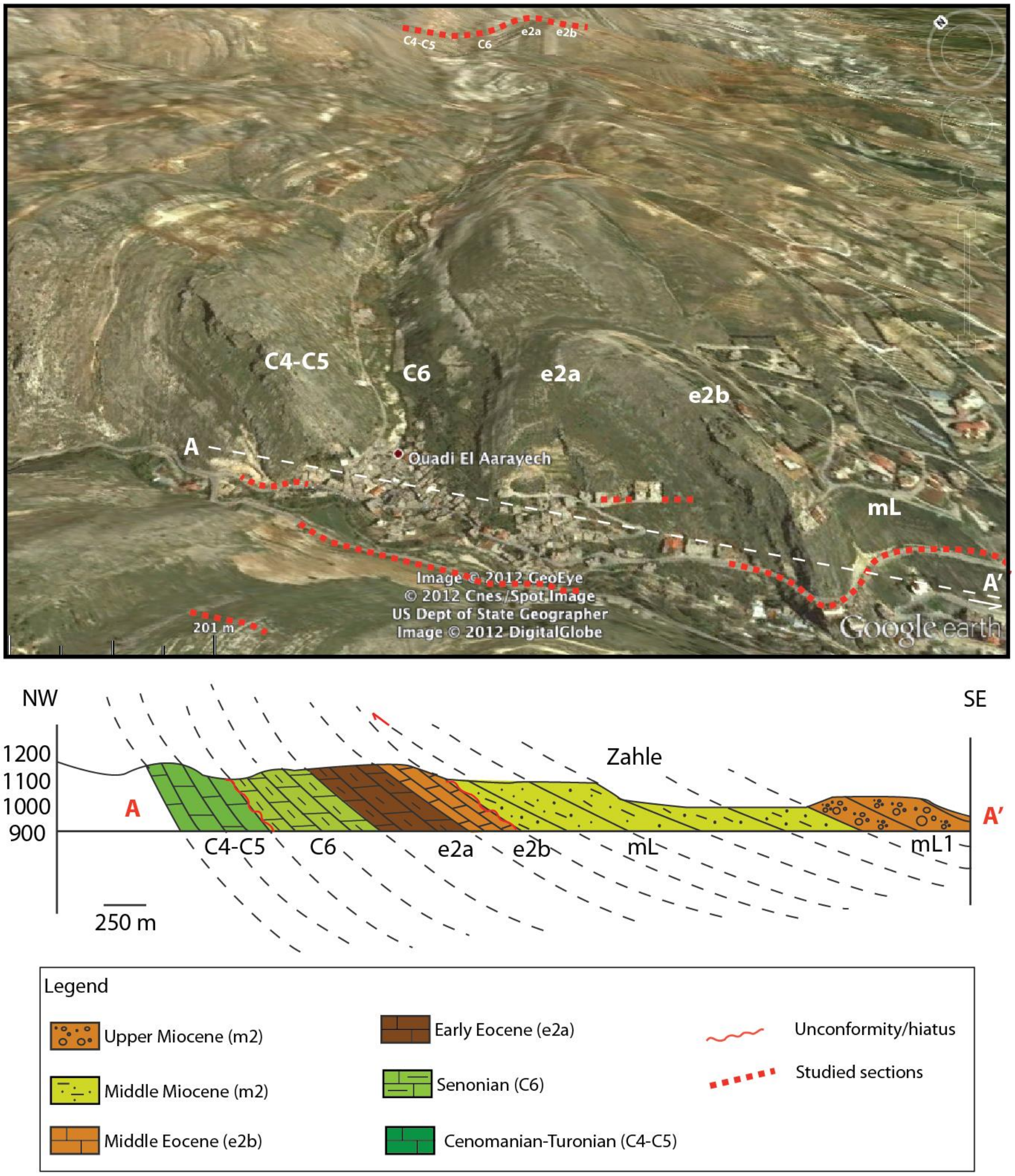


Fig4.13. Satellite image showing the Zahle anticline as well as the two sections studied

The bedding dip values for the Cenomanian-Turonian along the A-A' section change drastically in very limited distances (Fig.4.13). Dips around the Ouadi el Aarayech are of about 55-60° while around the B-B' the dip values are of about 40-45°. However the bed dips reach a maximum of 80° in between both sections. The bedding pattern and the overall dip values mainly measured along the section B-B' refer to concordant deposition from the Upper Cretaceous till the Middle Eocene. Thus dip measurements conducted along both geologic sections in Zahle cannot be used as confident and strong arguments to prove the presence/or absence of an angular unconformity in between the Turonian and Senonian rock units.

The contact between the Eocene and Middle Miocene is deformed and faulted (studied along the section A-A'). Bed dips measured for the Middle Eocene unit range between 35-45° while shallower dips are recorded for the Middle Miocene rock unit (i.e., 25-28°) alluding to the presence of an angular unconformity in between those two units (refer to the sedimentological investigation of the Miocene along coastal Lebanon and the inland for further insights into the structuration of Mount Lebanon).

The beginning of the A-A' section (0 to 108 m) (Fig.4..15) is thought to be Cenomanian (N35˚51'54.001''; E035˚53'18.0'') and is marked by a massive bioclastic packstone/grainstone with echinoid and gastropod debris, intercalated by 1-4m thick brecciated units (Plate 4.2a,b). Some argillaceous intercalations are noted on top of undulating internal erosive surfaces. Towards the top of this section an increase in silica content is noted with abundance of chert nodules (Plate 4.2c).

A major change of texture between 108 -160 m has been observed with a monotonous mudstone unit (0.50 m to 1 m bedding) moderately rich in Ammonites topped by 6-8 m of brecciated limestone. Another fine-grained unit (160 to 200 m) with wackestone to mudstone textures is overlain by a set of brecciated limestone (Plate 4.2d) (200 to 220 m).

Intercalations of mudstone and thin marly interbeds (375 to 430 m) with bioturbation (Upper Campanian to Lower Maastrichtian) overlie 150 m of vegetation cover. This interval becomes richer in marly and chalky content before being intercalated by 0.3-0.5 m thick chert bands (Lower Eocene to Lower Middle Eocene unit) (486 to 710 m)

A drastic change in sedimentary facies is noted around the Monte Alberto Hotel (N33°51'23.69''; E035°53'38.33''). The facies evolve from an intercalation of mudstone with chert into 130 m of very massive, heavily brecciated limestone unit. The base of this unit has been also dated using calcareous nannofossil biostratigraphy as Middle Eocene (Fig.4.14a). Internal erosive surfaces with argillaceous and muddy intercalations are noted showing important lithoclastic reworking. A clear abundance of bioclastic content (large *Nummulites*- Plate 4.2f) is noted in the upper 80 m of the brecciated and channelized unit (Plate 4.2e,f,g).

The nummulitic rock unit is overlain by a 120 m unit composed of marls and intercalated by conglomeratic sheets of about 0.5 m in thickness (with nummulitic clasts) as well as by fresh water carbonates. Important mono-specific fauna content is noted with very abundant micro-sized gastropods (i.e., *Hydrobia, Melanopsis* as well as *Planorbis*) (Fig.4.14b) dated as Middle Miocene by Dubertret (1975). Lignitic lenses and thin beds are also present (Plate 4.2h). The Middle Miocene is interpreted as being of lacustrine origin.

A gap of about 660 m in our sedimentological section is caused by the disappearance of Miocene fresh sections below the Zahle village. However localized outcrops have been continuously observed and refer to a very similar lacustrine depositional environment.

Conglomeratic facies in red argillaceous matrix (Fig.4.14c) overlie the creamy colored lacustrine marls. The transition is gradual with no major erosion noted or change in dips. Carbonate clasts in a reddish argillaceous matrix reveal important reworking of the previously deposited carbonate platforms (i.e., Cretaceous, Eocene). An increased sandy component is attested with thin lignitic lenses intercalations revealing a change from a lacustrine environment into an exposed fan delta/fluviatile continental one in the Late Miocene.

Plate 4.2. (a,b) Cenomanian bioclastic grainstone, (c) Chert nodules in Cenomanian mudstone, (d) Marly limestone, (e,f) Brecciated and channelized sub reefal Eocene, (g) Nummulites, (h) Lignitic bed

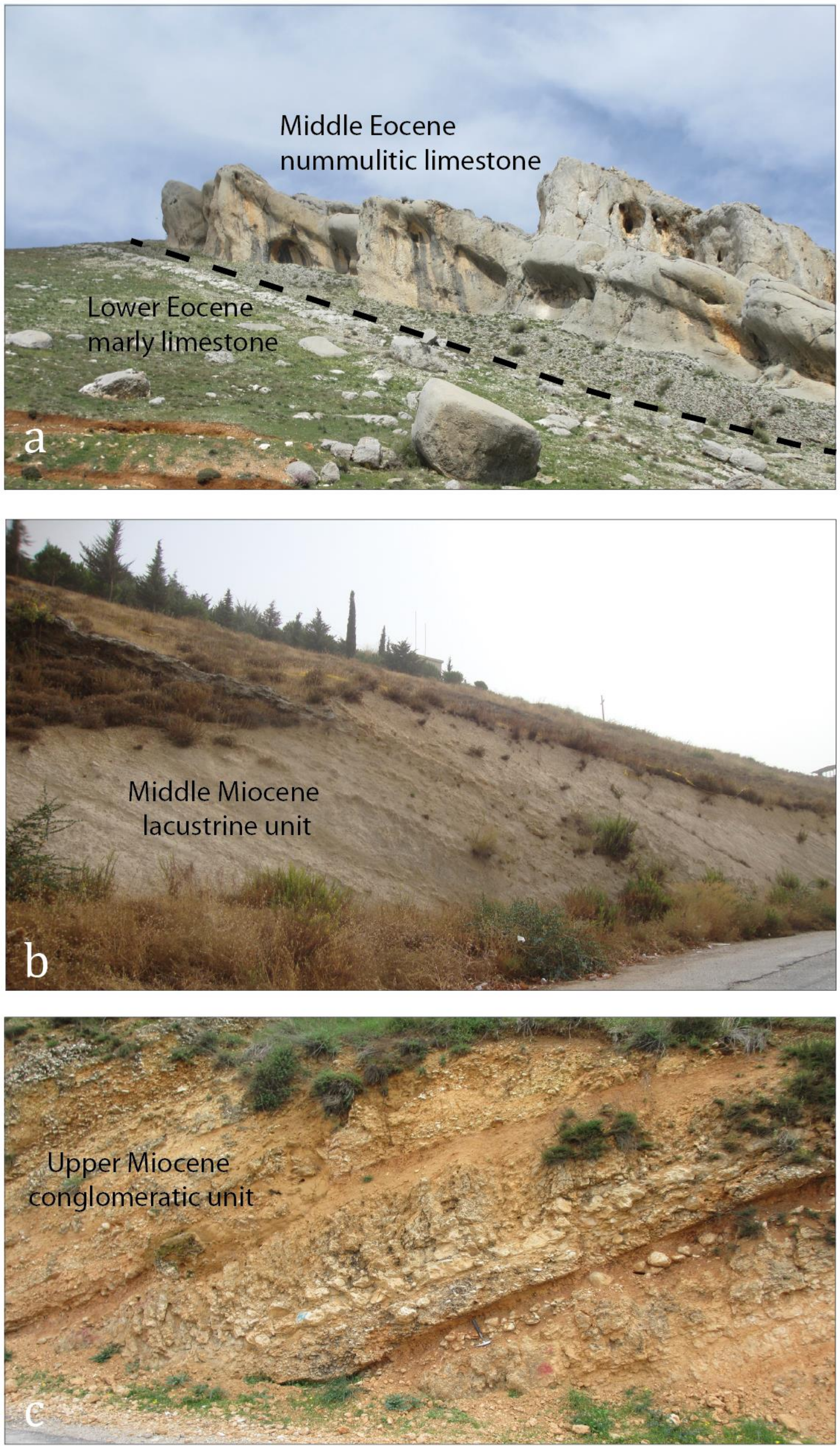


Fig4.14. (a) Middle Eocene nummulitic unit, (b) lacustrine Middle Miocene and (c) Late Miocene conglomerates

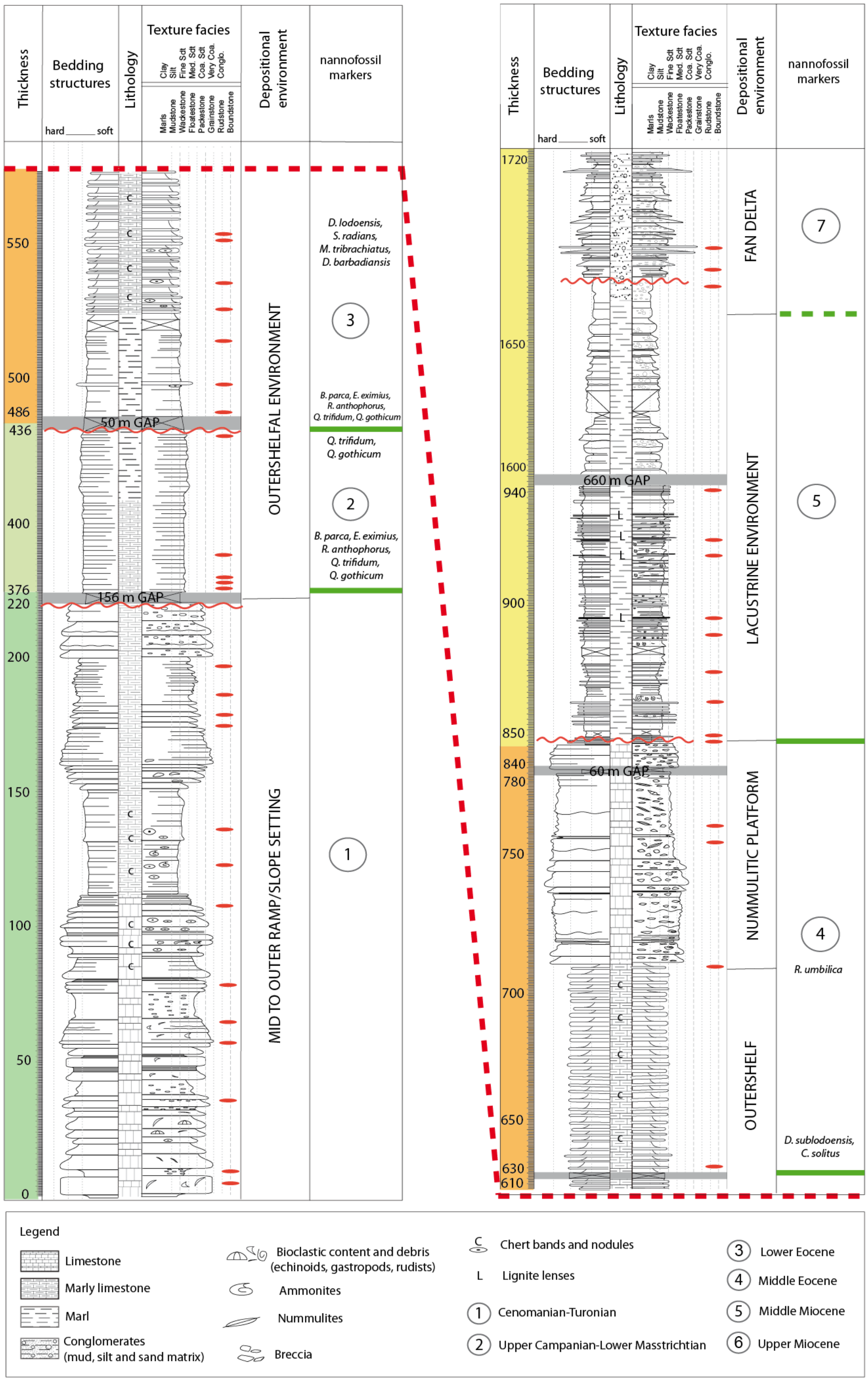


Fig4.15. Detailed sedimentary log of the Ouadi al Aarayech

The configuration of the second section studied north of Ouadi el Aarayech shows the Upper Cretaceous to Middle Eocene rock unit succession that present conformable dip values (Fig.4.16). Additional age constraints have been brought using calcareous nannofossils biostratigraphy. The Lower Campanian has not been dated in the area (missing or very thin?). A clear erosional surface has been identified around the base of the Middle Eocene with breccias overlying compact and silicified marly limestone unit alluding to possible tectonic pulses occurring at that time. It is overlain by a wackestone/packestone unit rich in *Nummulites* (Fig.4.17).

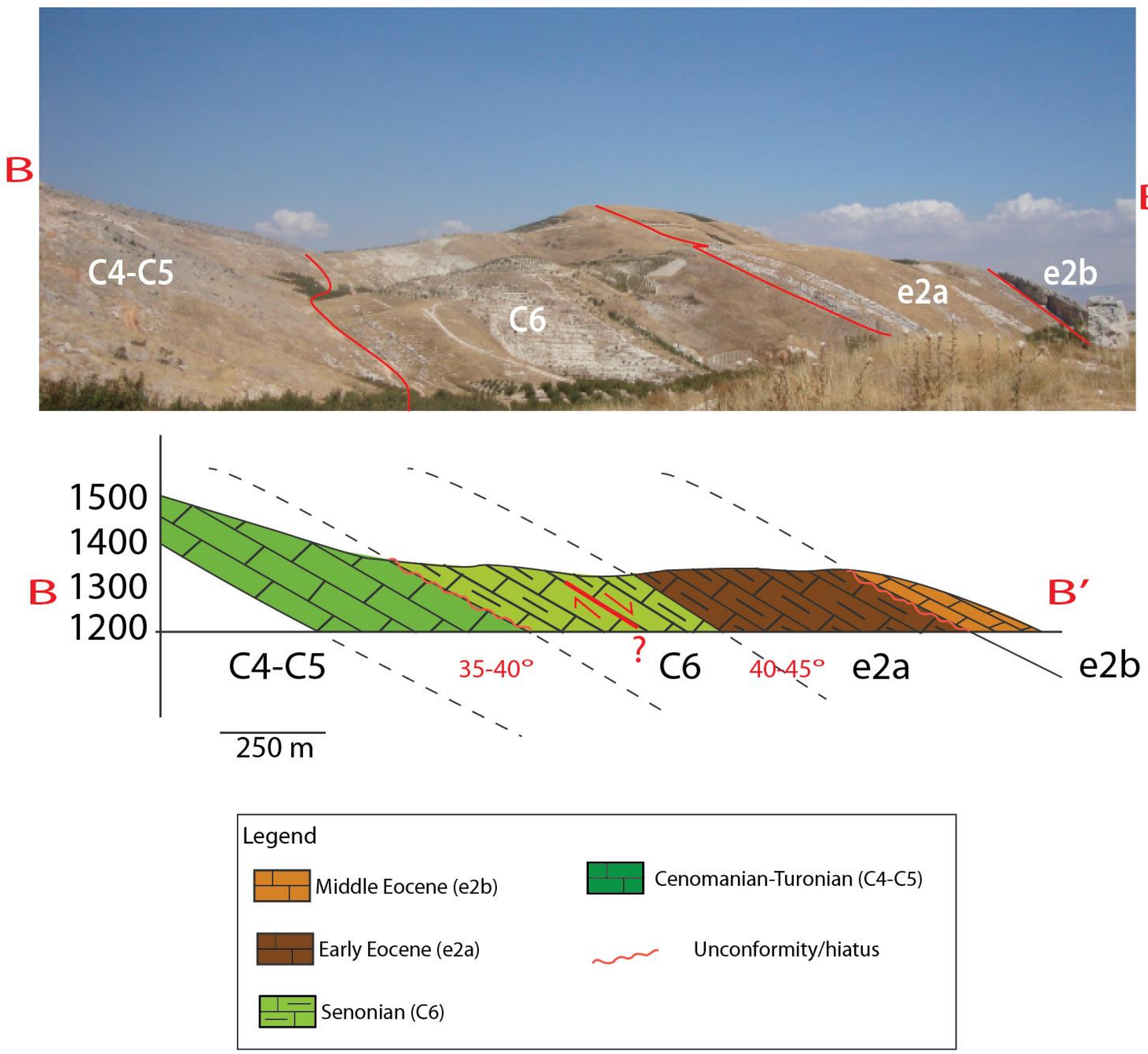


Fig4.16. Section B-B' located north of the main Ouadi el Aarayech section showing concordant bedding from the Cenomanian to Middle Eocene

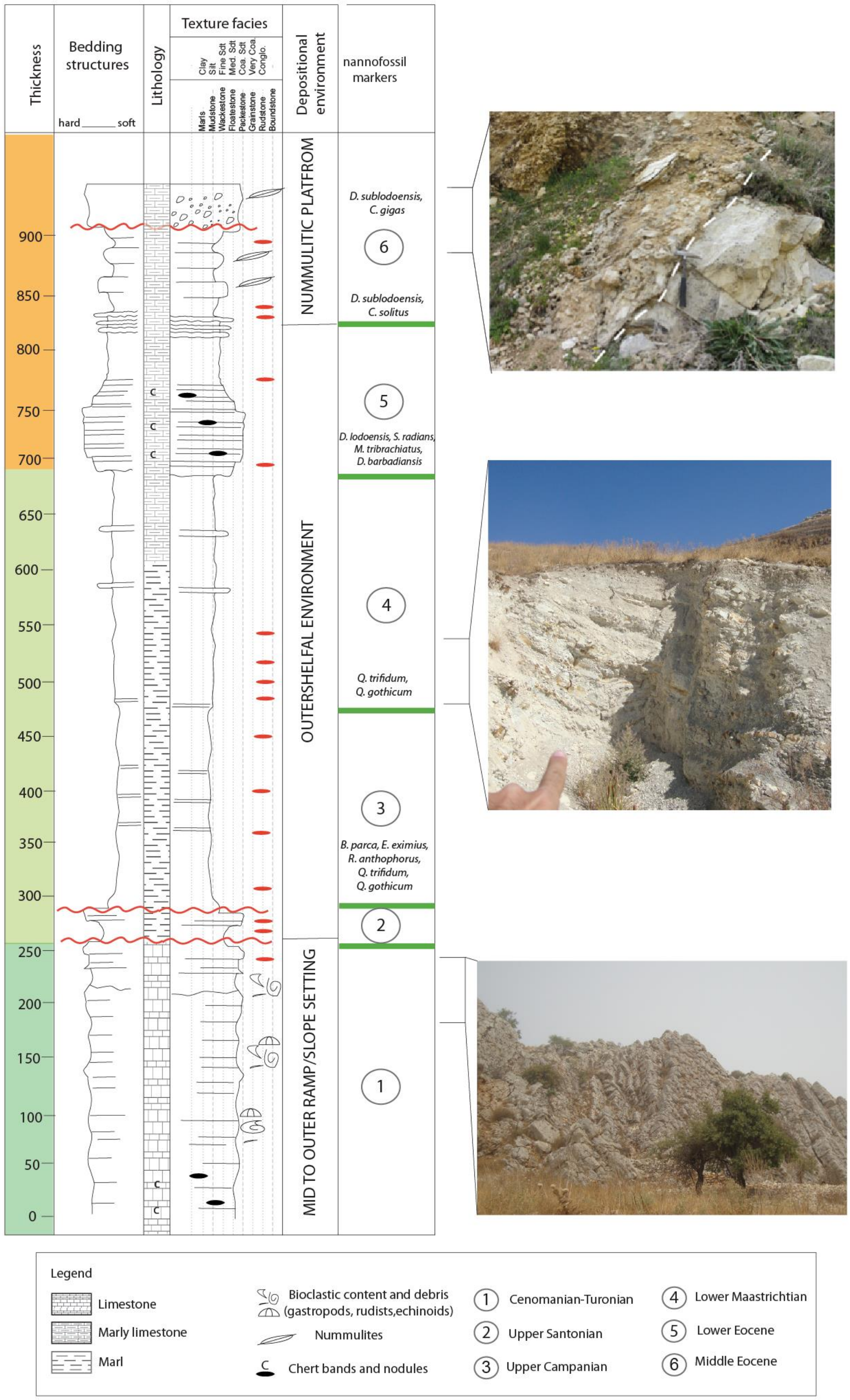


Fig4.17. Sedimentary log of the section B-B' from the Cenomanian-Turonian till the Middle Eocene

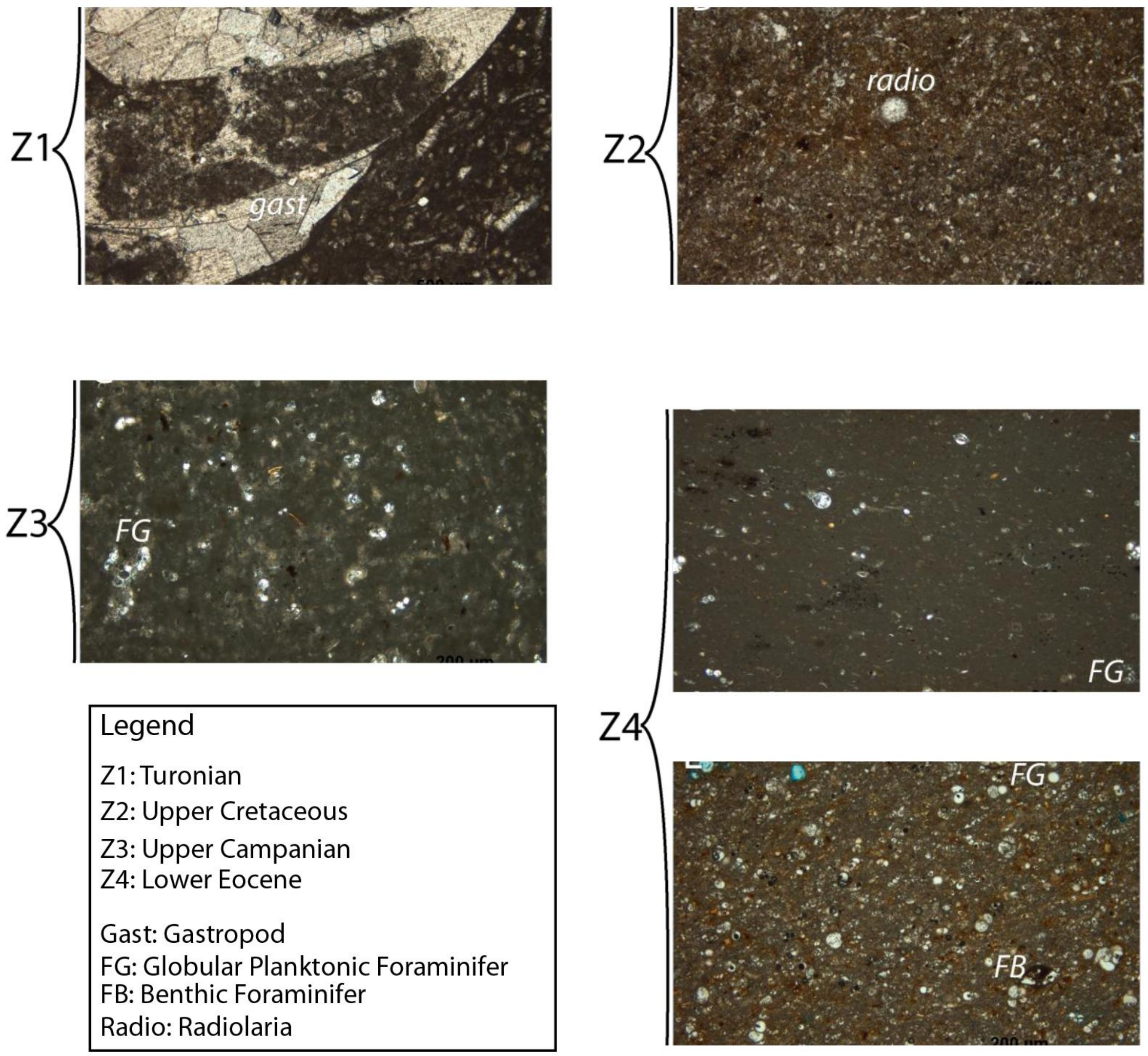


Fig4.18 Micro-facies of the Turonian to Lower Eocene rock units of the Zahle locality

II.3 Tyr-Nabatieh plateau

As the work conducted along the Jezzine location did not tackle the Upper Cretaceous to Cenozoic rock units a reconnaissance followed by further geologic investigations along the coastal southern Lebanon region was carried out. Due to some tight security measures a continuous Senonian to Late Miocene sedimentary log could not be completed. The main focus was thus set on the Maghdouche village where a 60 m section was logged comprising the Upper Cretaceous to Middle Eocene rock units (Fig.4.20). Outcrops of the Middle Miocene formation have been also studied in the Maghdouche area and compared to outcrops located further to the south in the Maamariyet el Kharab (on the way to Teffahta) bringing further insights into the sedimentary environments expected to prevail at that time in southern Lebanon (Fig.4.19).

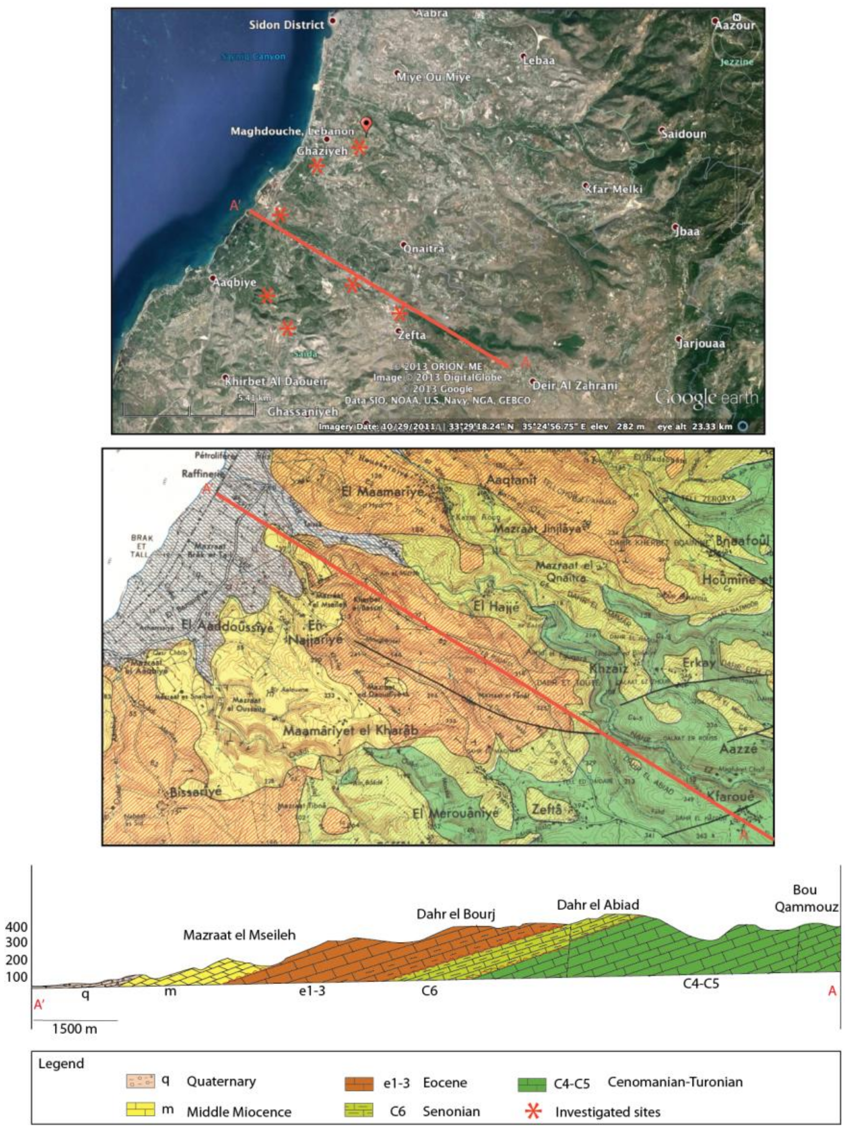


Fig4.19. Satellite image and geologic map (1:50 000- Dubertert, 1975) of the southern Lebanese coastal area showing the main studied locations

The lower 10 m of the sedimentary are mainly dominated by an intercalation of marls and chalky mudstones of Upper Cretaceous/Lower Eocene age. The marly content becomes less abundant and is overlain by musdstone/ wackestone textures intercalated by bioclastic grainstones presenting some moderate chert content (Lower Eocene) (from 10-45 m). A packstone unit with nummulitic rich banks is topped by a partly dolomitized grainstone unit represents the Middle Eocene unit (from 45-60 m).

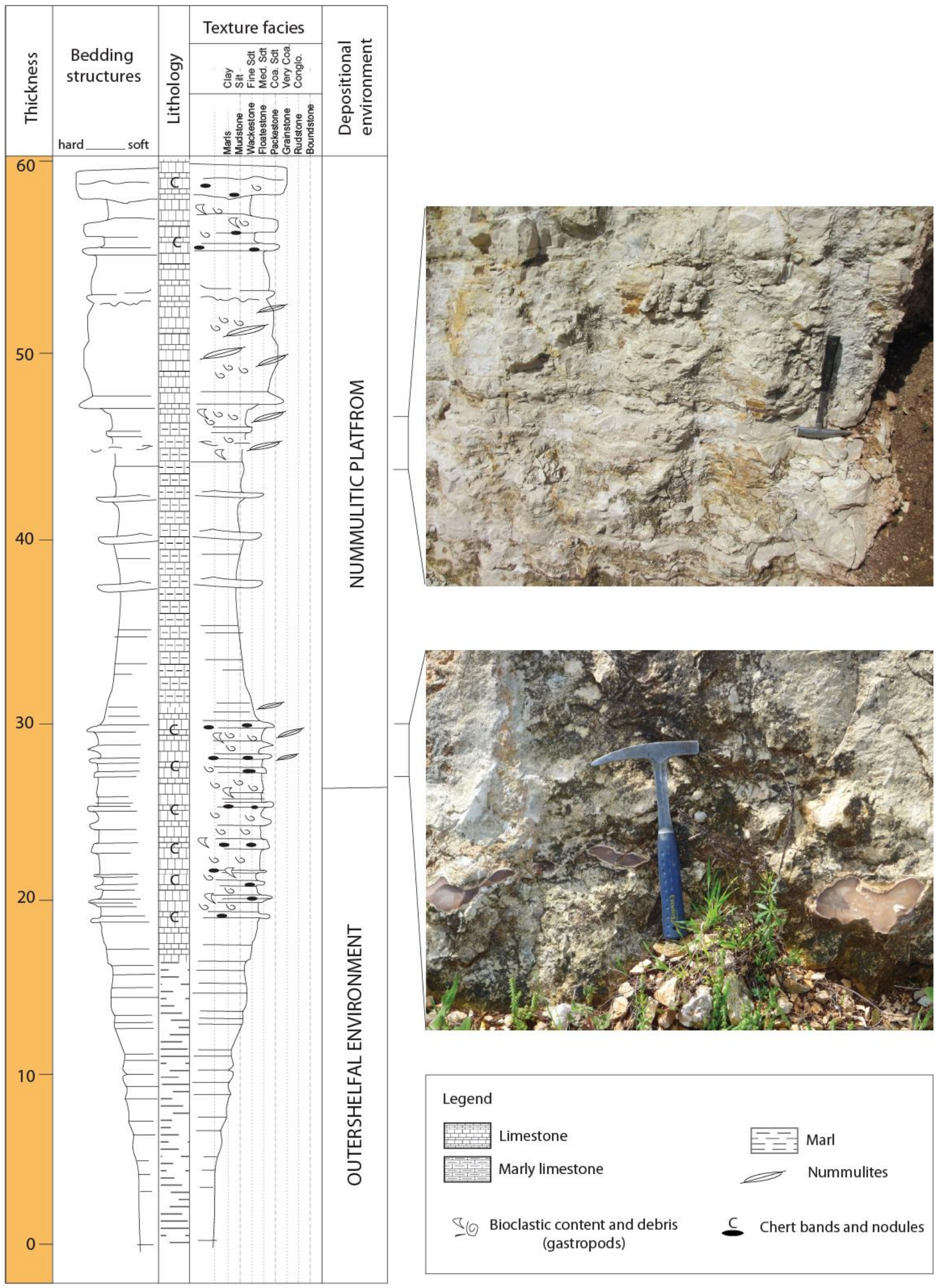


Fig4.20. Sedimentological log of the Eocene rock units in the Maghdouche area

The Miocene in the Maghdouche village presents intercalation of micro grainstone/packstone beds pinching out at their extremities rich in small shells of gastropods and pectens (highly bioturbated) and more argillaceous and marly intercalations (Fig.4.21).

Dating using calcareous nannofossils pointed out to a Langhian (NN5) age with the presence of *S. heteromorphus, C. abisectus*, *C. pelagicus, R. pseudoumbilica, H. carteri* amongst others, as well as reworking from Cretaceous and Eocene rock units have also been identified. Note that an increased quartzitic component has been identified towards the top of the Langhian unit. Beds don't seem to have a wide lateral variation with pinchouts, slumping as well as large incisions identified alluding to a deep water turbiditic depositional system.

Fig4.21. Langhian turbidite system in the Maghdouche village

Along the Teffahta road, at the Maamariyet el Kharab village a 25 m outcrop was studied (N33°27'12.87"; E035°20'38.39"). It was dated through calcareous nannofossils as Langhian (NN5). Intercalation of marly mudstone units and more competent micro-grainstone layers have been observed, they present undulating and erosive bases with fining upward trends layers. A major N-S incision truncates the previously deposited beds of the same age. Clear onlaps have been identified revealing the infill of these submarine incisions. The sedimentary facies are interpreted as proximal slope turbidites (Fig.4.22) with major slope channel incisions. Another 7 m outcrop (stratigraphically younger-located westwards; N33°27'45.29"; E035°20'2.36") was investigated presenting a clear increase in the sandy component, which raises questions as per the provenance of the quartzitic content.

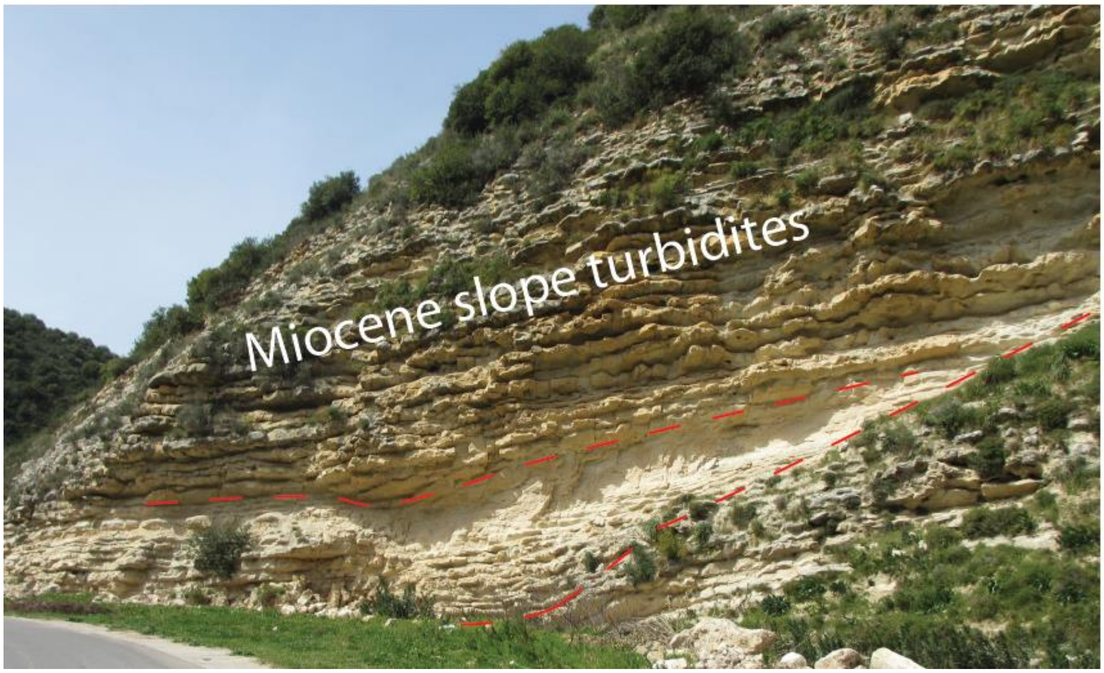


Fig4.22. Langhian proximal turbidite system in the Maamariyet el Kharab village

II.4 Beirut investigation

Another important sector that has been visited during our field campaign was the coastal most Beirut area with a focus on the Cenomanian and Miocene. The importance of understanding the sedimentary facies of these two units around central Lebanon. What is really striking is the drastic change of the sedimentary facies.

Very fine grainstone facies intercalated by chert beds (radiolarites) with large cross-bedded structures as well as slumping represent the Cenomanian facies (e.g Grotte au Pigeon) (Fig.4.23). Miocene outcrops are very limited in extent in central Lebanon and mainly around Beirut. However the identification of a 15 m rock exposure below the Charles Helou station (N33°53’46.45”; E035°30’57.76”) (Fig.4.24) at the entrance of the city permitted to have better view of the expected sedimentary facies and depositional environments prevailing at that period. The overall facies present a regular pattern of thicker very compact carbonate beds (0.3-0.7 m) intercalated by thinner marly mudstone interbeds (0.1-0.3 m). The beds present a moderate lateral continuity with some localized pinchouts. Undulating and gently erosive bases have been noted. No channels or major incisions were observed alluding to a deeper and calmer depositional environment than that observed in the south. The age of this outcrop has been allocated to the Langhian (NN5) as the following calcareous nannofossils have been identified (not very abundant): *S. heteromorphus, C. abisectus*, *C. pelagicus, R. pseudoumbilica, H. carteri, C. leptoporus.* All samples gathered present reworking of Cretaceous to Eocene carbonates.

Fig4.23. Photographs showing the sedimentary facies of the Cenomanian rock unit facing Beirut. Note the intercalation between fine grainstone beds and chert bands

Fig4.24. Photograph showing the Langhian sedimentary facies around the Charles Helou station in Beirut. It is expected that this turbiditic unit has been deposited in a basinal position

Discussion

The sedimentological and stratigraphic investigation of the several sites studied onshore Lebanon permitted to additionally constrain the major depositional environments affecting the Upper Mesozoic till the Cenozoic period. In each section, detailed identification of the various sedimentary facies permitted to trace the vertical and lateral evolution of the main rock units of Lebanon supporting the regional and local stratigraphic framework presented in Chapter 2 and 3 of the Levant margin.

After continuous phases of rifting along the Levant region (i.e., Levant Basin and Palmyrides), shallow marine settings prevailed in Lebanon in the Late Jurassic. Shelf carbonates rich in gastropods and bivalves were deposited in an already rifted domain. Around that period the eastern Mediterranean margin witnessed epicontinental settings with a wide spread homogenous carbonate deposition (Collin et al., 2010). Abundant fluvial and aeolian deposits of Lower Cretaceous age mark a return to emergent conditions with more than 340 m of sediments deposited in the Jezzine area. This unit is missing in northern Lebanon (Dubertret, 1975; Walley, 1998). The depositional patterns identified in the Jezzine locality point to a fluvial sediment transport oriented NE-SW. This shows the impact of central and southern Lebanese architecture on the fluvial sediment transport direction. The thinning northwards of this rock unit as well the preferential fluvial direction reveal that northern Lebanon was in an uplifted position compared to the center and south (possible fault control), which could have represented at that time a subsiding block of the Palmyride Basin.

A return to shallow marine conditions prevailed in the Early Cretaceous with cliff forming rock units (Aptian) overlain by a terrigenous rich unit (Albian) sourced from a nearby emergent land (i.e., Arabian Shield, refer to Saint-Marc, 1974). An extensive marine domain is attested in the Cenomanian Turonian in the several studied sites (including Hawie et al., 2013a). An important deposition of carbonates rich in Ammonites and Rudists (*Hyppurites)* marks the continuation of the Early Cretaceous transgression. The presence of important dolomitization starting from the Upper Albian to Turonian (as seen in Jezzine, Zahle and Deir Billa) has been linked to an increased magnesium production provided by algal material (i.e., Corralinaceae) evolving in this shallow marine environment (Saint-Marc, 1974).

Following the comparison between the Cenomanian and Turonian sedimentary facies of northern (logs in Hawie et al., 2013a; Deir Billa log) and central/southern Lebanon (Zahle log; refer to Crognier, 2013) we can deduce that the inherited architecture of the margin as a consequence of Early Mesozoic rifting still impacts on the depositional environments observed at that period. The limit of the uplifted domain is expected to present a NE-SW trend (Palmyridian trend) from coastal central Lebanon into the hinterland. The drastic deepening of facies attested in all the sites studied starting from the Late Turonian until the Early Eocene reflect the widespread drowning of the Levant margin.

The main hiatuses attested in the several sections are correlated to the major geodynamic events affecting the Levant region and has been widely attested along the Arabian Plate (Sharland et al., 2001). Late Turonian to Late Santonian, Late Maastrichtian to Early Paleocene, Early/Middle Eocene to Middle Miocene hiatuses have been allocated to the continued marginal uplifts linked with the Afro-Arabian convergence and collision with Eurasia. No angular unconformities have been observed between the Turonian and Santonian. The observed angular unconformity separates between the Lower/Middle Eocene rock units from the Middle Miocene alluding to a possible pre-Middle Miocene deformation phase. This could explain the E-W Middle Miocene facies variations around Mount Lebanon where restricted lacustrine settings are observed in the Bekaa Valley and open marine towards the coastal area.

The sedimentary facies observed for the Middle Miocene unit onshore central and southern coastal Lebanon point to deeper depositional environments compared to the north. This facies variation is linked to the continuous impact of inherited Palmyridian structures on the depositional environments prevailing in the Middle Miocene (refer to the next section III for a complete synthesis of the Miocene rock unit onshore Lebanon).

III. Synthesis of the Miocene depositional model

Through the following section a geological model is proposed for the Middle and Upper Miocene rock units based on combination of the several field investigations in northern, central and southern Lebanon. The coupling between the tectonic evolution of the Levant margin and the observed sedimentary facies onshore Lebanon point to an inherited structural control on the depositional environments prevailing along the Levant margin starting from the Mesozoic.

The content of this section will be submitted to publication in Terra Nova journal.

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Abstract

Newly acquired field data onshore Lebanon reveal that the Middle and Upper Miocene rock units define a complete depositional profile from restricted continental to open marine settings. Lacustrine, alluvial fan, fan-delta, rhodalgal, marine-slope and basinal facies have been described. The facies spacial configuration in northern, central and southern Lebanon suggests that progressive structural deformations from the Mesozoic onwards impacted on the depositional conditions prevailing in the Neogene along the Levant margin.

1. Introduction

Throughout the past decades a rising interest in source to sink studies permitted to better assess the phenomena leading to erosion, transport and deposition, of sediments (Allen, 2008). This multi-disciplinary approach integrates structural and sedimentary geology, geomorphology, atmospheric and oceanographic sciences. The combination of several geological and geophysical techniques (e.g., field work; biostratigraphy; thermo-chronology; seismic reflection) permits a better evaluation of the architecture and sedimentary infill of frontier basins and their margins.

The Levant region has been affected by successive deformation phases linked with major geodynamic events (i.e, Mesozoic rifting in the Levant Basin and Palmyride area; convergence of Afro-Arabia and Eurasia along the Cyprus Arc and the evolution of the Levant Fracture System). Through this communication we propose a conceptual model of the Middle to Upper Miocene revealing the effect of the latter inherited structural deformation and sea level fluctuations on the sedimentary facies evolution onshore Lebanon and on the consequent infill of the northern Levant Basin.

2.Geological framework

The Levant region was shaped by diverse tectonic phases linked to plate scale geodynamic events from the Early Mesozoic onwards. Several phases of convergence and collision between Afro-Arabia and Eurasia in the Late Cretaceous, Middle-Late Eocene and Lower Miocene led to major marginal uplifts. The northward tilting of Afro-Arabia was caused by mantle plume activity around Eastern Africa (i.e, Afar plume located around Ethiopia and Yemen) concomitantly with rifting occurring in the Red Sea around the Late Eocene. Rapid shedding of Oligo-Miocene siliciclastic sediments was observed along the Levant Basin following the development of the Nile drainage system as well as canyons incising the Levant shelf (Steinberg et al., 2011; Macgregor, 2012).

A regional Oligocene to Lower Miocene hiatus has been attested along the Levant margin as a consequence of the uplifts and updoming of the region (Sharland et al., 2001; Müller et al., 2010). Scattered outcrops are restricted to structurally controlled basins developed locally close to major silicilastic sources (e.g. Negev-Zilberman & Calvo, 2013) or in submerged areas with carbonate deposition noted (e.g. Latakia; Hardenberg & Robertson, 2007). The northward propagation of the Levant Fracture System around the Middle-Late Miocene induced a shift from a rhodalgal system prevailing on the Levant coast to a continental setting (Boudagher-Fadel & Clark, 2006; Hawie et al., 2013a).

3. Middle and Upper Miocene sedimentary facies associations

We differentiate three major facies associations based on macro and micro scale sedimentological investigations (4.19) as well as related faunal content allowing to propose tentative depositional environments for the Miocene rock unit onshore Lebanon (4.20, Table.1). These facies associations are presented in the order of the most proximal to the very distal.

FA1a

Description- A 190 m of very friable Middle Miocene marl has been described in the Zahle location (Fig.4.26, Table 4.1). This rock unit sits unconformably on nummulite rich strata of Middle Eocene age (add species). The Middle Miocene is intercalated by 0.25- 0.5 m thick conglomeratic sheets presenting moderately rounded wackestone clasts rich in nummulitic fauna. Intercalation of marls and carbonate concretions forming thin beddings or about 0.2 m have been described in the lowermost 30 m of the Zahle sedimentary log. A rapid increase in the mono-specific fossiliferous content of this unit (i.e, small size gastropods: i.e, Hydrobia, Melanopsis) is noted in the upper 160 m with pisolitic content (diameter ranging between 2-6 cm) and lignitic lenses interbeds (1-3 m in length and about 2- 5 cm in thickness).

3.1 Facies association 1

Such facies associations are interpreted as lacustrine deposits and have been seen along the whole Bekaa valley including the Hermel location with thicknesses ranging between 400 an 600 m.

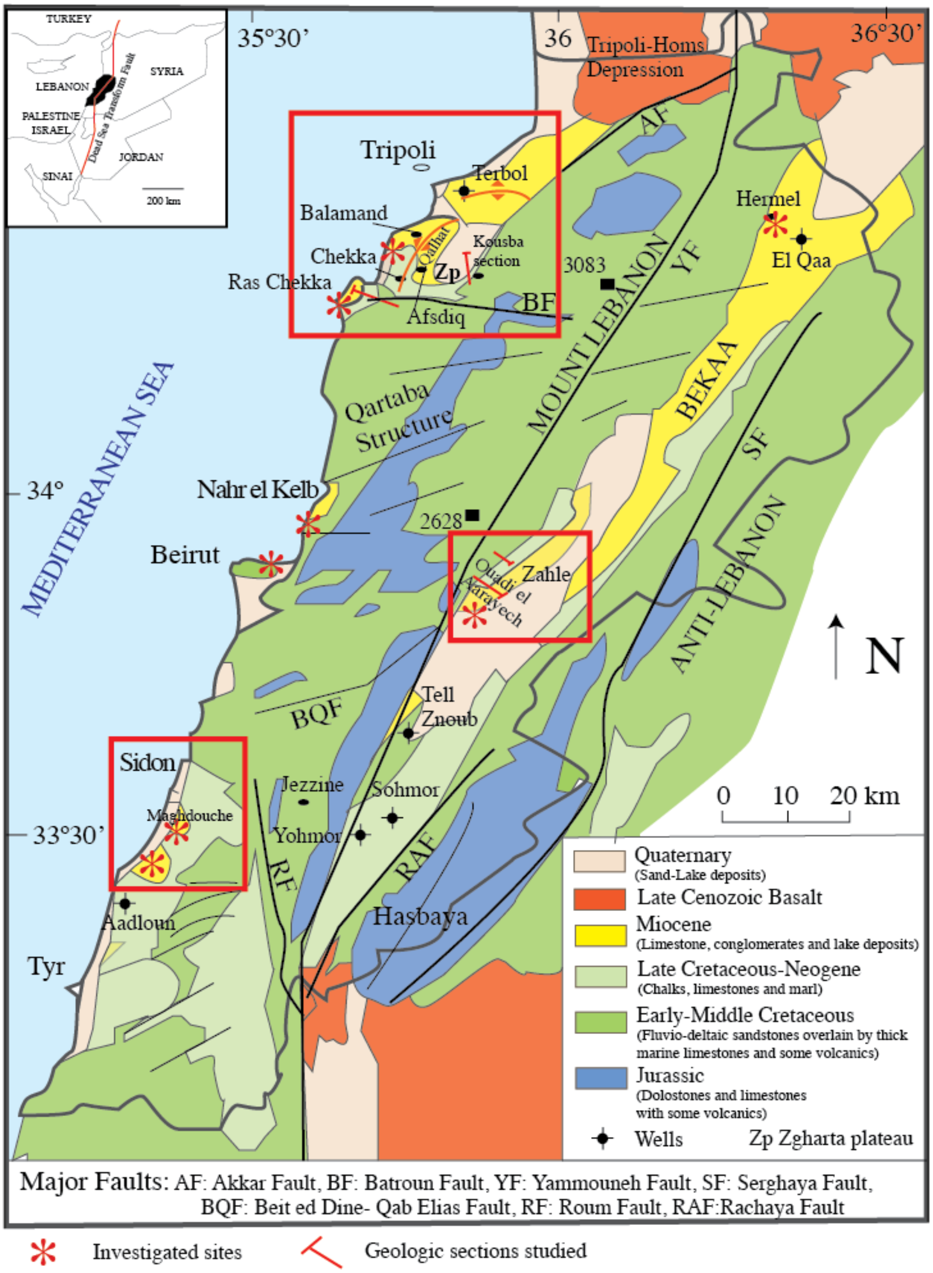

Fig4.25 Geologic map of Lebanon (modified from Dubertret, 1975) showing the major locations investigated (red squares)

FA1b

Description- This facies association is thought to be of Tortono-Messinian age as it overlies the Middle Miocene unit along Lebanon and is composed of reworked clasts of Cretaceous to Middle Miocene age (refer to Dubertret, 1975 and Hawie et al., 2013a).

(1) In northern Lebanon, more specifically in the Kousba area, the Upper Miocene unit presents sets of conglomeratic packages of about 400 m in total thickness (4.20, Table.4.1). An alternation between clast-supported and mud-supported matrix with internal carbonate clasts of Upper Cretaceous to Eocene age was observed. The base of the conglomeratic unit (about 250 m thick) is formed by a carbonate matrix while clayey content increases towards the top as more abundant stacked and channelized conglomerate sheets (1-2 m) presenting prominent erosional features (scours and flutes) have been described.

(2) Towards the Bekaa valley, in the Zahle locality, the conglomeratic facies (more than 600 m in the Bekaa) overlie the creamy colored lacustrine marls (FA1a). However no carbonate matrix has been identified. The red argillaceous and muddy content is very abundant here with a sandy component attested as well as thin lignitic intercalations (4.20, Table.4.1).

The facies association FA1b refers to a fan delta system in Kousba developing due to the rapid uplift of Mount Lebanon and the consequent change in depositional environment into a more continental setting. The lack of carbonate matrix for the conglomeratic sheets in Zahle shows that this environment was already continental and did not have a connection with the open marine realm (alluvial fan setting).

3.2 Facies association 2

FA2a

Desciption- Localized in northern Lebanon, a 300 m outcropping limestone unit has been described in the Kousba locality. The base of the unit is identified by a 0.5- 1.5 m of boundstone rich in pectens overlying unconformably a Lower Eocene marly limestone (Fig.4.26, Table.4.1).

Sets of coarsening upward trends of monotonous grainstone to packstone textures are rich in lithoclastic and bioclastic content (i.e., red algae, bivalve, echinoderm debris). Very little variations in sedimentary textures or structures have been noted towards the top of the Middle Miocene succession with a decrease in the overall algal content.

FA2b

At the Ras Chekka promontory, an unconformity separates between the Early Lutetian/NP14 (through the nannofossil D.sublodoensis) from an overlying 50m Middle to Late Burdigalian rock unit (NN3–NN4 Helicosphaera mediterranea, Helicosphaera ampliaperta, Cyclicargolithus abisectus, Reticufenestra pseudoumbilica). Here, a massive packstone to grainstone unit is intercalated by brecciated levels of about1.5 to 2 m thick. Internal channel incisions have also been observed.

This facies association refers to fore-reef settings (in a rhodalgal platform system) evolving along coastal northern Lebanon on the western flank of the Qalhat anticline (Hawie et al., 2013a).

FA2c

At the Balamand locality the angular unconformity separating the Lower Eocene marls from the Middle Miocene rock unit has been identified. The contact between the two units is erosive with conglomeratic lags of a bout 1.5 m in thickness. The Middle Miocene unit is composed of packstone to wackestone unit (bedding of about 6 m) with abundant red algal. No internal incisions or breccias have been identified.

This facies association has been interpreted as representing calm euphotic to oligotrophic settings evolving on top of the present day Qalhat anticline.

FA2d

On the eastern limb of the present day Qalhat anticline in the Afsdiq locality, a unique boundstone interval rich in corals was observed and is interfingered by a bioclastic packstone rock unit (i.e., red algae and bivalve debris).

The presence of the very localized coral polyps in this area clearly reveals that a very shallow and protected euphotic environment prevailed in the Middle Miocene along the eastern flanks of the present day Qalhta anticline.

The overall FA2 association is assimilated to a rhodalgal platform system affected by a pre-existing paleotopagraphic high localized around the present day Qalhat anticline. This interpretation explains the sedimentary facies variability around the anticline (refer to Hawie et al. 2013a).

3.3 Facies association 3

FA3a

Desciption- The Miocene in the Maghdouche village (southern Lebanon) presents intercalation of micro grainstone/packstone beds (pinching out at their extremities) and more argillaceous and marly strata. Beds do not present a wide lateral continuity while slumping as well as incisions have been identified. This rock unit is rich in small shells of gastropods and pectens and is highly bioturbated (Table.4.1).

Towards the top of the studied section an increase in quartzitic content has been observed.
Dating using calcareous nannofossils pointed out to a Langhian (NN5) age with the presence of S. heteromorphus, C. abisectus, C. pelagicus, R. pseudoumbilica, H. carteri amongst others, as well as reworking from Cretaceous and Eocene rock units.

Along the Teffahta road, at the Maamariyet el Kharab village a 25 m outcrop was studied (Figs.4.25, 4.27, Table.4.1). It was dated through calcareous nannofossils as Langhian (NN5) and presents intercalation of marly mudstone units and more competent micro-grainstone layers with undulating and erosive bases. They present planar to convolute laminations (Tb, Bouma, 1985) and are overlain by current ripples (Tc, Bouma, 1985)

A major N-S incision truncates the previously deposited beds of the same age. Clear onlaps have been identified revealing the infill of these incisions. Another 7 m outcrop (stratigraphically younger; located westwards) was investigated presenting a clear increase in the sandy component, which raises questions as per the provenance of the quartzitic content.

These sedimentary facies have been interpreted as proximal slope turbidites with slope channel incisions.

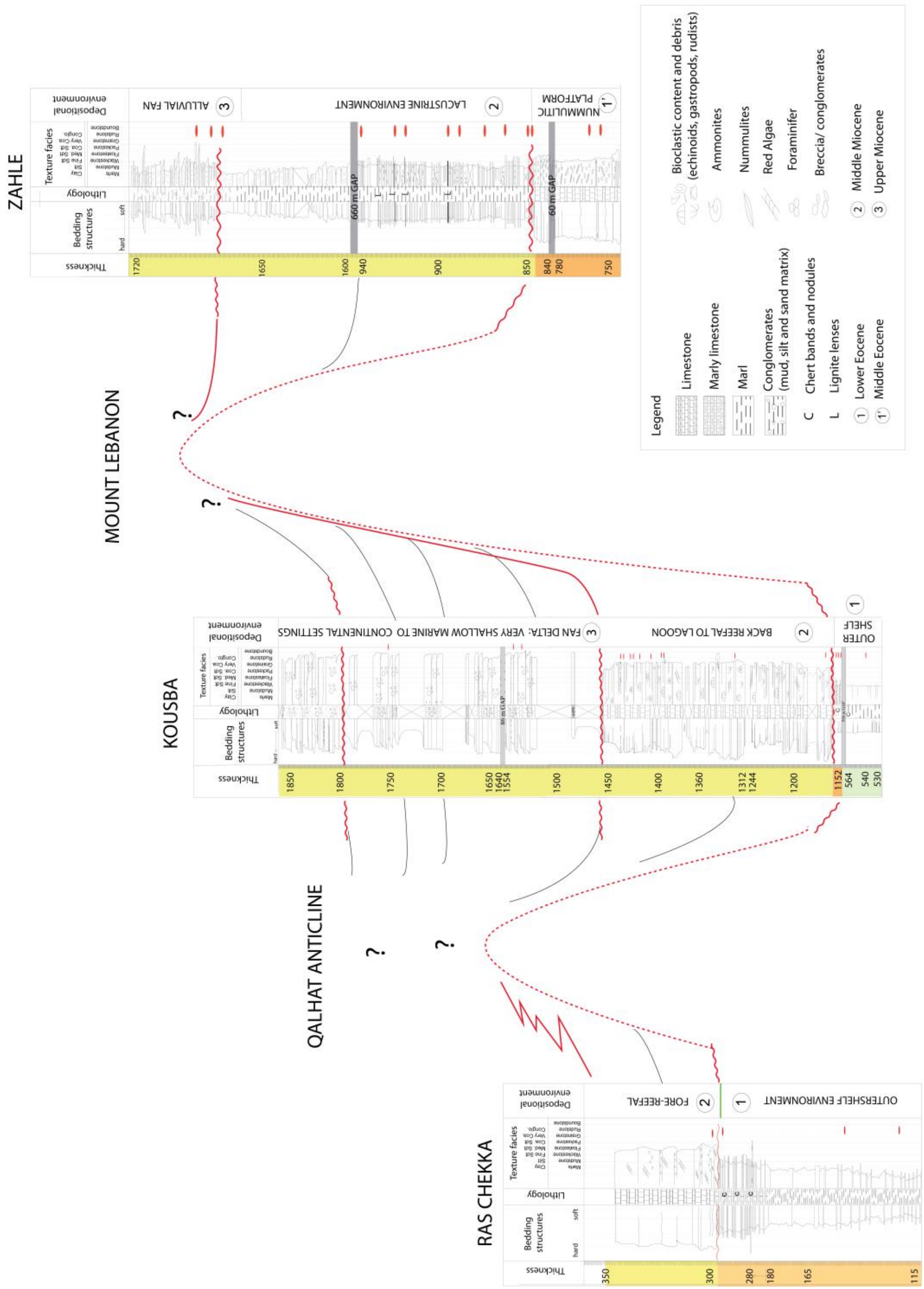

Fig4.26 Generalized measured log sections of key exposures of Middle to Upper Miocene rock units representing an E-W transect along the Bekaa and northern Lebanon

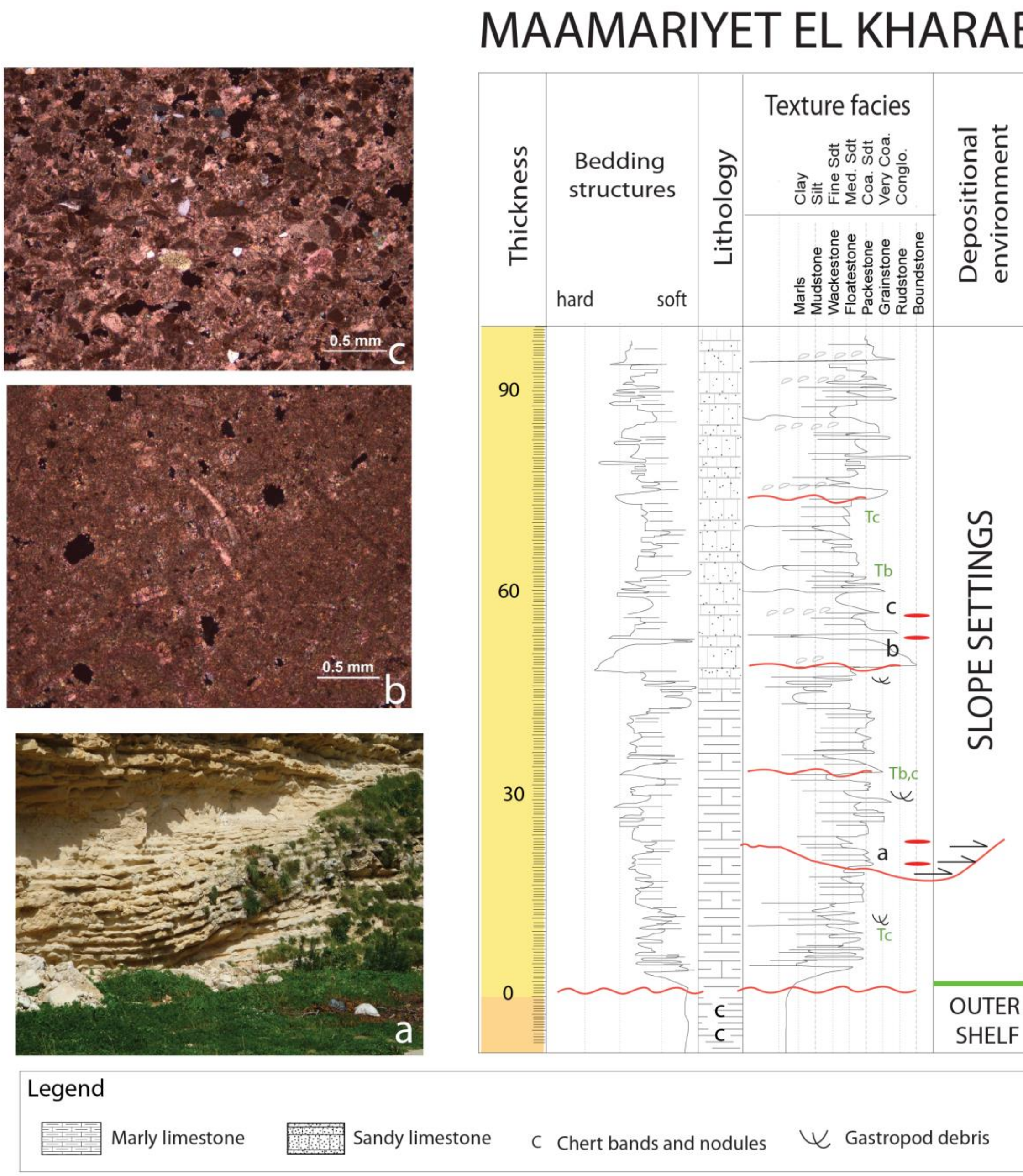

Fig.4.27 Logged section of southern Lebanon (Maamariyet el Khrab) showing the main sedimentary facies and depositional environment of the Langhian unit

FA3b (central Beirut)

Desciption- Miocene outcrops are very scarce in central Lebanon and mainly around Beirut. However the identification of a 15 m rock exposure below the Charles Helou station (N33°53'46.45"; E035°30'57.76") (Fig.4.25, 4.28) at the entrance of the city permitted to have better view of the expected sedimentary facies and depositional environments prevailing at that period. The overall facies present a regular pattern of thicker very compact carbonate beds (0.3-0.7 m) presenting moderate lateral continuity and intercalated by thinner marly mudstone interbeds (0.1-0.3 m). Undulating and gently erosive bases have been noted (Table.4.1). The age of this outcrop has been allocated to the Langhian (NN5) as the following calcareous nannofossils have been identified (not very abundant): S. heteromorphus, C. abisectus, C. pelagicus, R. pseudoumbilica, H. carteri, C. leptoporus. All samples gathered present reworking of Cretaceous to Eocene carbonates.

The lack of channel incisions in this portion of the Beirut locality outcrop allude to a deeper and calmer basinal environment compared to the one observed in southern Lebanon.

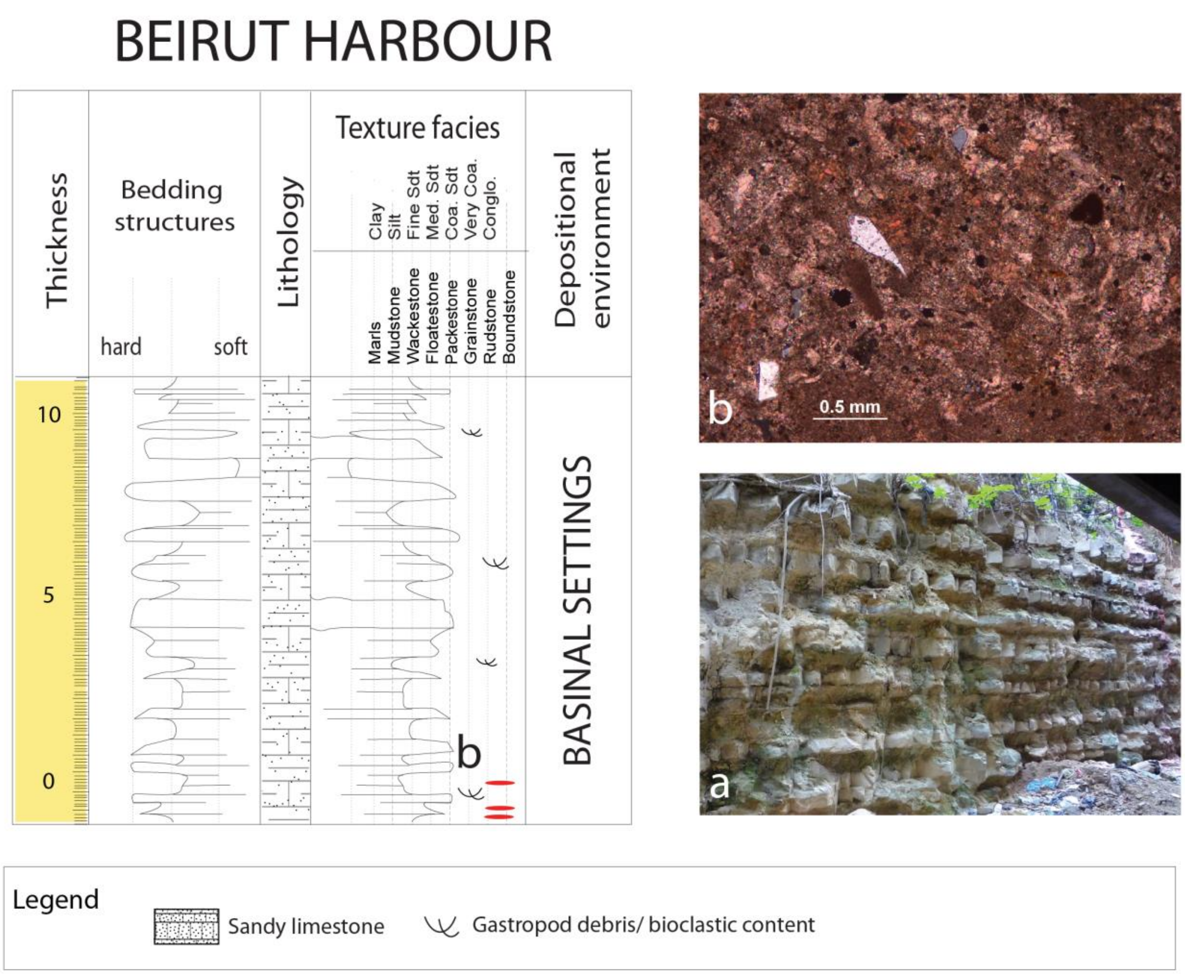

Fig.4.28 Logged section of Beirut showing the main sedimentary facies and depositional environment of the Langhian unit

Facies associations			Unit thickness	Description	Sedimentary environments	Age	Location investigated
Restricted continental setting with dominantly lacustrine deposits fed by braided fluvial systems and fan deltas	FA1	a	400-600 m	intercalation of marls and fresh water carbonate concretions (bedding: 0.2 m). Mono-specific fossils (i.e, small size gastropods) and pisolitic content (diameter ranging between 2-6 cm). Lignitic lenses (1-3 m in length ; 2- 5 cm thick).	Restricted lacustrine setting	Middle Miocene	Zahle, Hermel
		b b’	400 m	Sets of conglomeratic packages are composed of well rounded carbonate clasts and present carbonate dominated matrix at the bottom evolving into mud and clay dominated towards the top whith an increase in channelized features.	Fan deltas feeding into shallow marine and continental settings	Late Serravallian to Messinian	Kousba
Rhodalgal limestone units presenting a variability in sedimentary texutres and structures	FA2	a	30-300 m	Boundstone rich in pectens (0.5-1 m) overlain by a monotonous bioclastic packstone to grainstone (red algal, echinoid and shell debris)	Lagoonal to protected inner rhodalgal plaftorm	Late Burdigalian to Serravallian	Kousba
		b		Coarse grained packstone to grainstone rich in lithoclastic and bioclastic content (red algae, echinoderm and bivalve debris). Channeling and breccias are noted.	Fore-reef to slope settings of a rhodalgal platform		Ras Chekka
		c		Massive rhodalgal packstone to wackestone unit (bedding of about 6 m) with no signs of erosion.	Middle rhodalgal plaftorm setting (oligotrophic)		Balamand
		d		Boundstone interval with corals, red algae and bivalves interfingered with a bioclastic packstone (red algae and bivalves debris)	Back-barrier/protected inner rhodalgal platform setting (euphotic)		Afsdiq
Slope to deep marine settings impacted by gravitational instabilities	FA3	a	20-60 m	Intercalation of micro grainstone/packstone beds with small gastropods and pecten shells (highly bioturbated) and more argillaceous and marly intercalations. Increased quartzitic component towards the top of the unit. Beds don’t present a wide lateral extent with pichouts, slumping as well as large incisions identified	Agitated slope deposits with proximal slumps and turbidites	Langhian to Serravallian	Maghdouche, Maamariyet el Kharab
		b	15-25 m	Regular pattern of very compact carbonate beds (0.3-0.7 m) intercalated by thinner marly mudstone interbeds (0.1-0.3 m). The beds present a moderate lateral continuity with some localized pinchouts. Undulating and gently erosive bases noted. No major incisions noted.	Basinal settings	Langhian	Beirut

Table.4.1 Summary of the facies associations’ description and proposed depositional environments for the Middle and Upper Miocene onshore Lebanon

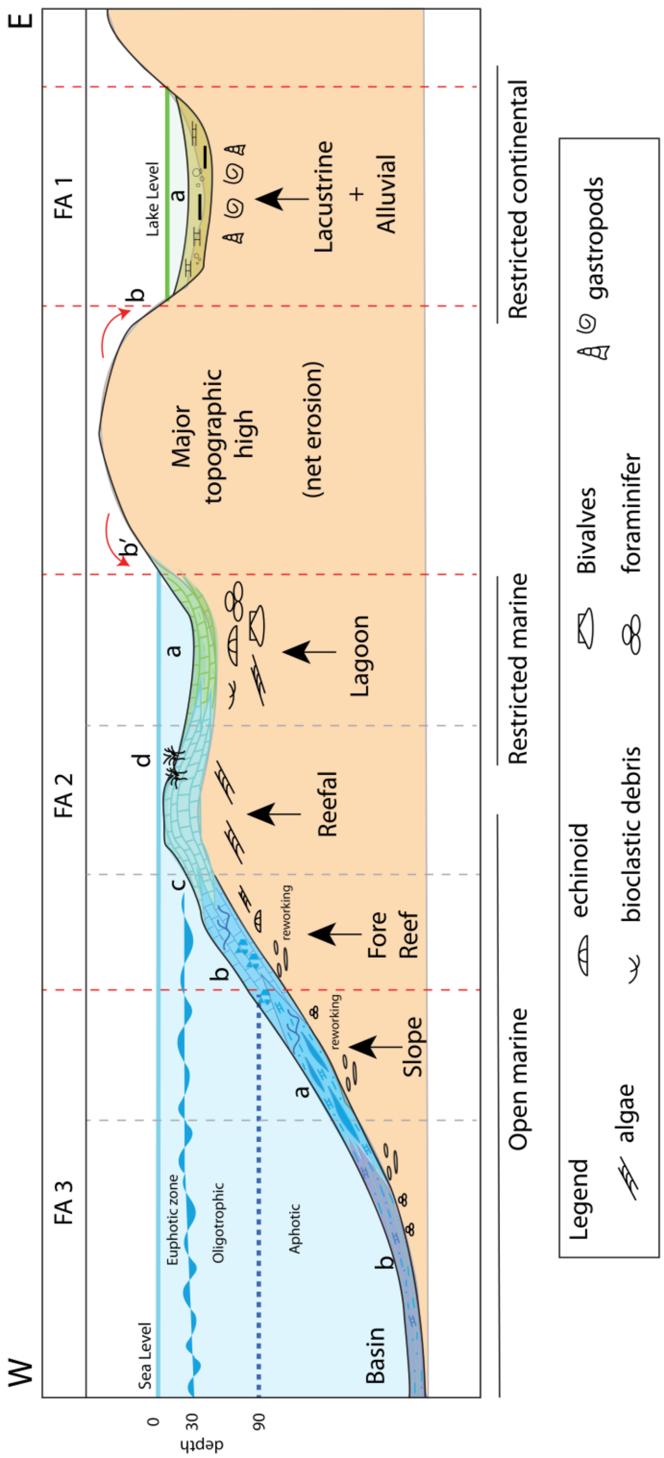

Fig.4.29 Onshore-offshore general facies scheme for Lebanon, showing the major depositional environments and associated fauna

4.Discussion and conclusions

Through the sedimentological and stratigraphic investigation we infer that the Miocene unit described onshore Lebanon has been deposited in an already structured domain (refer to Fig.6 for the discussion). Four major structural provinces have been deduced (i.e, northern, central and southern Lebanon as well as the Bekaa hinterland) and are expected to be linked to multi-scale deformations occurring at several timeframes from the evolution of the Palmyride Basin in the Early Mesozoic to the Afro-Arabian collision with Eurasia as well as the splitting between Arabia and Africa along the Levant Fracture System in the Middle-Late Miocene.

4.1 Impact of Palmyridian structure on the Miocene facies:

The facies associations described along coastal Lebanon clearly refers to a structural differentiation between the north and south along the Beirut area. Rhodalgal systems have been described to the north with very limited coralian reefal features while basinal and slope settings prevail around central and southern coastal Lebanon. The study also reveals that the Cenozoic stratigraphic column in southern Lebanon compared to the north is more preserved. The Middle and Upper Eocene, Upper Oligocene and Upper Lower Miocene have been mainly dated in southern Lebanon underlying the Middle Miocene while in the north only the Early Eocene has been attested (refer to Müller et al., 2010, Boudagher Fadel & Clark, 2006 and Hawie et al., 2013a).

Studies presented by Chaimov (1992), Sawaf et al. (2001) and Brew et al. (2001) have discussed the tectono-stratigraphic evolution of the NE-SW Palmyride basin in Syria from the Triassic onwards, separating between a more elevated northern domain and a downthrown southern structural domain. The impact of this onshore structuration is thought to extend into Lebanon. Dubertret (1975) as well as Walley (1997; 1998) have observed important thickness and facies variations for the Lower and Upper Cretaceous units e.g., about 400 m of Lower Cretaceous sandstone was described around Jezzine and is almost completely absent in northern Lebanon while turbiditic facies have been observed for the Cenomanian of Beirut compared to extensive shallower carbonate platforms in northern Lebanon). Recent studies along northern Israel (Frank et al., 2010) allowed delimiting the extent of the Palmyride depression towards southern Galilee area through sedimentological and stratigraphic investigations of the Upper Cretaceous.

Following our results we believe that this north-south structuration of the Palmyridian failed rift has not only impacted on Mesozoic sediments but also on the Cenozoic rock units and more specifically on the Miocene leading to a deposition of deeper marine sediments in central and southern Lebanon.

Recently the use of high-resolution 2D and 3D seismic data allowed to better constrain the architecture and depositional environments expected for the northern Levant Basin (Refer to Chapter 5- Furstenau et al., 2013; Hawie et al., 2013b). It has been deduced that around Beirut a major depression (old structural control?) has hindered the Mesozoic and Cenozoic platforms evolution in that location as compared to wider shelf extension along northern and southern Lebanon.

4.2 Impact of the Afro-Arabian collision on the Miocene facies:

Age equivalent strata of the central Lebanese hinterland (i.e. Bekaa valley: Zahle) reveal that in the Middle Miocene a restricted lacustrine environment persisted inland compared to an open marine settings towards the coastal area. The presence of nummultic clasts (of Middle Eocene age) intercalated in Middle Miocene marls point to intensive reworking and erosion along a possible paleotopographic highs that separate the Bekaa valley from the open marine settings prevailing along coastal Lebanon

The identification of an angular unconformity between the Eocene and Middle Miocene in northern Lebanon (Ras Chekka and Balamand Hawie et al., 2013a) and in southern Lebanon (very gentle- Dubertret, 1975) allude once again to the initiation of major deformations as a result of the continuing collision of Afro Arabia with Eurasia in the Cenozoic period between the Lower Eocene (Ypresian/Lutetian) and Middle Miocene (Late Burdigalian). However such topographic relief is not expected to be very prominent yet in the Middle Miocene. The increase in quartzitic content in the slope turbidites of southern Lebanon in the Langhian to Serravallian alludes to nearby erosion of siliciclastic material. However further studies are needed to shed light on the origin of this sandy component.

On a smaller scale the work conducted on the rhodalgal Miocene of northern Lebanon along the Tripoli-Koura plateau point to the impact of this pre Late Burdigalian and post Ypresian-Lutetian phase of deformation that led to a sedimentary facies control around the paleo-Qalhat structure separating between a restricted marine environment to the east from an open marine one west of the high.

4.3 Impact of the Levant Fracture System on the Miocene facies:

The drastic change in sedimentary facies observed in the Tortono-Messinian period onshore Lebanon from marine into continental settings along the coastal areas have been linked to the northward propagation of the Levant Fracture System (Beydoun, 1999) enhanced by sea level lowstands. Prominent fan deltas are expected to erode and drive sediments from the rising carbonate rich mountains into paleotopographic lows and most probably driven by canyon systems into the continental slope and basin.

The work conducted by Goedicke (1972) and Beydoun (1976) refers to canyon incisions extending into the offshore after an Oligocene or Early Neogene initiation as a result of Mount Lebanon's uplift and the establishment of the drainage systems to the east. New dataset proposed by Hawie et al. (2013b) and by Fürstenau et al. (2013) using 2D and 3D seismic data clearly point to major slope incisions and deposition of fan lobes and associated turbidites in the northern Levant Basin offshore Lebanon as well as the input of sediments provided by more regional drainage systems as the Nile Deep Sea Cone to the south as well as coastal Syria (i.e., Latakia area- Nahr el Kabir).

Refer to Chapter 5 for a complete description of the offshore Lebanon realm.

Our reconstruction of the Middle-Upper Miocene illustrates the impact of structural deformation on the depositional environments and thus on the associated sedimentary facies providing a paleogeographic perspective of this poorly constrained rock unit. The work also illuminates the impact of geological processes as rifting and orogeny on bathymetry, sediment accommodation, transport and deposition from a source to sink perspective.

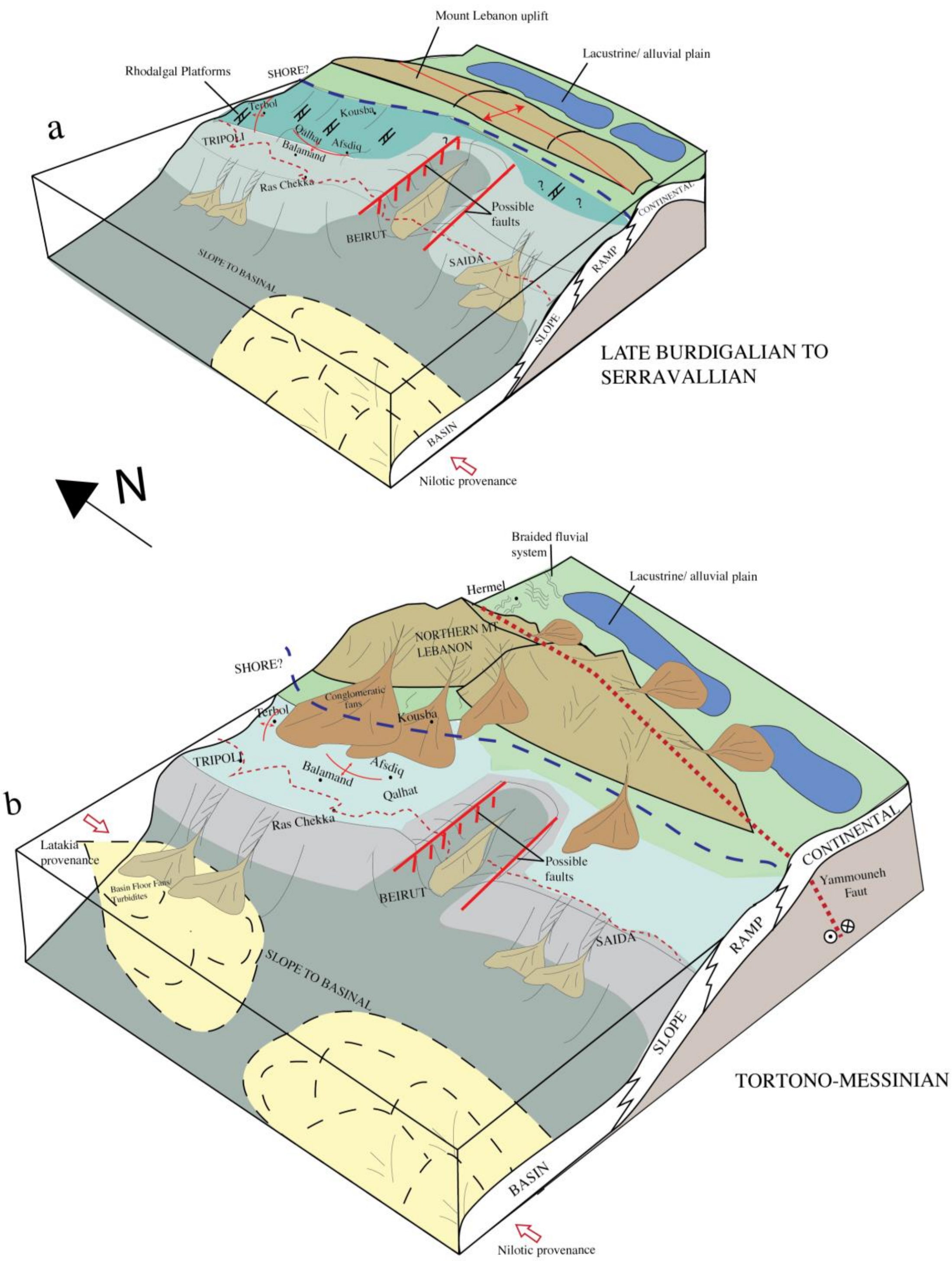

Fig.4.30 3D onshore-offshore schematic illustrations representing the evolution of the Miocene depositional environments affected by the onshore deformation. For the offshore section refer to Chapter 5.

Synopsis

Through this chapter an overview of the stratigraphic column of Lebanon from the Upper Jurassic till the Late Miocene is presented.

- A1520 m sedimentary log for the Jezzine area reveals the evolution from shallow marine carbonate platforms in the Late Jurassic into continental settings in the Early Cretaceous (major depocenter around central and southern Lebanon) and then back into very shallow marine settings until the Cenomanian-Turonian.

- A complete sedimentary log in the Deir Billa-Ras Chekka lead to the identification of major hiatuses in the Late Turonian to Late Santonian, Late Maastrichtian to Late Paleocene, Ypresian/Early Lutatian to Late Burdigalian.

- No angular unconformity has been identified between the Late Turonian and Late Santonian in northern Lebanon. The Coniacian to Early Santonian and Late Maastrichtian to Late Paleocene hiatuses seem to be linked to widespread marginal uplift pulses resulting from the initiation of convergence of Afro-Arabia with Eurasia in the Late Cretaceous.

- An angular unconformity has been observed along the northern Lebanon coastal area (i.e., Ras Chekka) between the Lower Eocene and Middle Miocene rock units. A drastic change of depositional environment from outer-shelf in the Early Eocene to rhodalgal settings in the Middle Miocene reveals a major westward sea retreat enhanced by the fast marginal uplift induced by the continued collision of Afro-Arabia with Eurasia in the Middle Eocene onwards and the initiation of the Levant Fracture System in the southern Levant region.

- Two sedimentary sections have been studied in Zahle and supported by calcareous nannofossil biostratigraphy providing age constraints for the Upper Cretaceous to Eocene rock units. Hiatuses and unconformities have been identified around the Late Turonian and Upper Santonian, Early Maastrichtian to Early Eocene and Middle Eocene to Middle Miocene. The Lower Campanian and Paleocene have not dated in both sections (missing? or very thin?).

- The Late Lutetian was investigated in details in the Zahle area. This sub-reefal Nummulitic unit (e2b) is composed of calcareous material with important brecciation of the same age. Note that the Middle Eocene unit is absent in northern Lebanon (completely eroded? or not deposited?)

- The Middle Miocene strata consist of lacustrine deposits intercalated by lignitic beds and levels of conglomeratic material of mainly Middle Eocene age (i.e., with nummulitic content). The lacustrine deposits are thought to represent the continental equivalent of the rhodalgal Middle Miocene attested around coastal Lebanon alluding to possible presence of a topographic high separating between coastal Lebanon and the hinterland.

- The work conducted by Nemo Crognier at IFPEN (Master thesis, 2013) has brought additional biostratigraphic and sedimentary environment assessment for the Turonian to Maastrichtian in the Zahle section. The reader is referred to this master thesis for additional details.

- Complete the understanding of the sedimentary facies of the Eocene to Miocene along coastal central and southern Lebanon. Here the Eocene rock unit is almost completely preserved as well as the Upper Oligocene (refer also to Boudagher-Fadel & Clark, 2006 and Müller et al., 2010) supporting the structural differentiation between the north that is expected to be in an uplifted position compared to central and southern Lebanon from at least the Late Jurassic.

- Reveal that a much deeper depositional environment persisted in central and southern Lebanon compared to shallower marine rhodalgal settings in the north. The area around Beirut seems to be the structurally deeper position of the Lebanese onshore with outershelfal to basinal facies identified for the Miocene.

What can be concluded is that onshore Lebanon has been affected by the major geodynamic events recorded in the many hiatuses identified onshore. A structural, stratigraphic and sedimentological differentiation has been noted between northern Lebanon that is expected to be in an uplifted position compared to the south where deeper depositional environments have been identified starting from the Cenomanian. The extent of the depositional environments into the offshore is further discussed in the Chapter 5 permitting to propose an onshore offshore understanding of the northern Levant margin and basin.

CHAPTER V

Geodynamic Evolution and Sedimentary Infill of the Northern Levant Basin

Offshore investigations

This section comprises the seismic interpretations conducted for the northern Levant Basin based on 8 regional 2D profiles from the MC2D LEB 2008 PGS multi-client survey. Additional discussions around 2D profiles from the Geco-Prakla 1993 survey (courtesy of the MEW) allowed to correlate between the northern Lebanese onshore and the deeper offshore. Two published articles are presented and they are supported by further unpublished material discussing the architecture and tectono-stratigraphic evolution of the northern Levant margin and basin.

Age allocations to seismic packages are still a speculative task as no wells have been drilled so far in the northern Levant Basin. The latter are based on interpretations and age allocations from the southern Levant Basin where well data along the distal margin and proximal basin is available (for further details refer to published articles from the southern Levant Basin cited in Hawie et al., 2013b). A published N-S seismic profile is presented below in order to show the good continuity of reflectors between the southern and northern Levant basins reducing the uncertainties linked with the proposed ages for the northern Levant Basin (Fig.5.1).

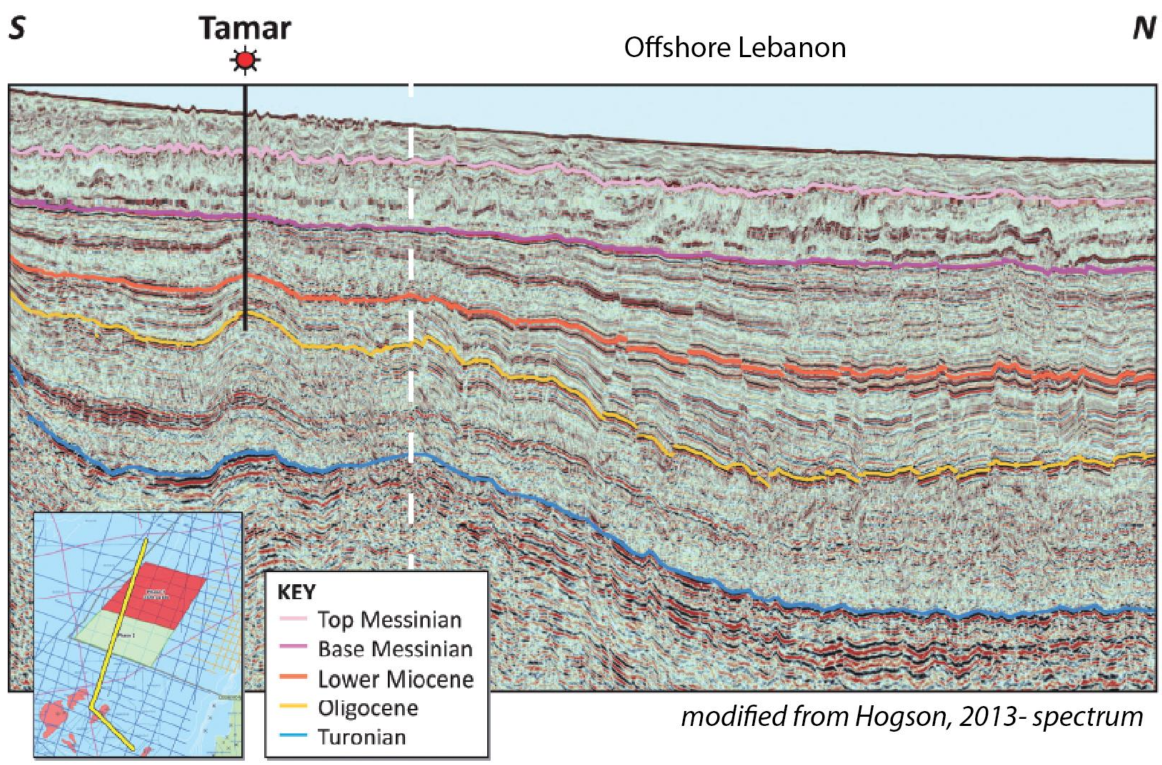

Fig5.1. N-S seismic profile showing the transitional domain between the southern and northern Levant Basin. Note the good continuity of seismic reflectors along the whole basin.

I.1 Tectono-stratigraphic evolution of the northern Levant Basin (offshore Lebanon)

The following article entitled "Tectono-stratigraphic evolution of the northern Levant Basin (offshore Lebanon)" has been published in the *Marine and Petroleum Geology* journal under Hawie et al. (2013b). Some of the article's content has been presented at the *AAPG Barcelona* (April 2013) and the *American Geophysical Union (AGU)* conferences (December 2013).

Synopsis

Through this publication the authors highlight for the first time through 2D seismic interpretation the impact of regional geodynamic events on the architecture of the northern Levant Basin. In addition, a new onshore-offshore tectono-stratigraphic framework supported by fieldwork and dating campaigns (refer to section I of this chapter) has been proposed. The author proved that:

- The northern Levant Basin has been affected by rifting that is expected to have ended in the Middle Jurassic.
- Starting from the Turonian the convergence between Afro-Arabia and Eurasia led to the initiation of a flexural basin facing the Latakia Ridge offshore northern Lebanon followed by important marginal uplifts. A continuation of the advance of this flexural basin is noted until the Earliest Middle Miocene with a shift of depocenter from northern to southern Lebanon.
- The initiation of the Levant Fracture System in the Middle Miocene and its propagation onshore Lebanon in the Late Miocene to Pliocene has induced major marginal uplifts with the fast emergence of the Lebanese mountains. In the offshore realm, a set of strike-slip faults has been identified cutting the whole pre-Messinian evaporite succession.
- A mixed carbonate-siliciclastic system is expected to prevail along the Levant Basin while the margin onshore Lebanon is carbonate dominated. The detailed seismic facies analysis investigation alluded to the possibility of the contribution of regional sources and pathways to the infill of the northern Levant Basin (i.e., from the north, east and south).

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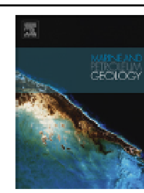

Tectono-stratigraphic evolution of the northern Levant Basin (offshore Lebanon)

CrossMark

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ABSTRACT

Seismic interpretation constrained by a detailed assessment of the Levant paleogeography allowed subdividing the sedimentary infill of the northern Levant Basin (offshore Lebanon) in eight major seismic packages. Fifteen seismic facies have been identified with distinctive characteristics. The Levant Basin architecture is pre-determined by a Late Paleozoic/Early Mesozoic rift that led to the formation of a passive margin. Dominant aggrading carbonate platforms are observed along the Levant margin and deepwater mixed-settings (i.e., carbonates and siliciclastics) are suggested to prevail in the basin. The collision of Afro-Arabia with Eurasia led to the development of a flexural basin in the northernmost offshore Lebanon since the Late Cretaceous. A southward migration of this flexural depocenter in the Miocene is hindered by the change in the stress field along the Latakia Ridge and by the westward escape of the Anatolian Plate in Late Miocene and Pliocene times. Interplay between major geodynamic events as well as sea level fluctuations in the Mesozoic and Cenozoic induced important marginal uplifts and emersion. Sediments sourced from the erosion of Nubian siliciclastic material and from the exposed granitic Red Sea rift shoulders and Arabian Shield, were driven into the Levant Basin. The sediment sources diversity, the mechanisms of sediment transport through varied pathways (i.e., the Levant margin canyons, the Latakia region and the Nile Delta deep-sea cone) are expected to strongly impact the reservoir characteristics and prospectivity of the northern Levant Basin.

Keywords: East Mediterranean, geodynamics, seismic stratigraphy, seismic facies analysis, sediment sources and pathways

1. INTRODUCTION

For the past decades a focus on the link between sedimentary basins' genesis and lithospheric activity led to the proposal of basin classification schemes. Two major types of basins have been described according to (1) their type of lithospheric sub-stratum, (2) position with regards to plate boundaries as well as (3) the mode of plate motion nearest to them (e.g., Buck, 1991; Allen and Allen, 2005). The first results from extension and stretching of the lithosphere (i.e., rift-drift suite) while the second is induced by lithospheric loading/unloading and flexural deformation (e.g. foreland basins). Following plate kinematics successive types of deformations could affect a basin's architecture and its consequent sedimentary infill (Allen and Allen, 2005), as is the case of the Levant Basin that has consecutively undergone rifting, collision, and strike-slip deformations.

The Levant Basin is located in the easternmost part of the Mediterranean region, and is delimited by (1) the Cyprus and Larnaca Thrust zone to the north, (2) the Eratosthenes Seamount to the west, (3) the Nile Delta deep-sea cone to the southwest as well as (4) the Eastern Mediterranean coast (Roberts and Peace, 2007; Homberg and Bachmann, 2010) (Fig.5.2). Several exploration and production projects dating back to the 1960's shed light on prolific hydrocarbon provinces found offshore Egypt (Nile Delta) (e.g Dolson et al., 2005). Significant hydrocarbon accumulations have recently been discovered in the southern Levant Basin in Oligo-Miocene and Pliocene canyon and deepwater turbiditic systems (e.g. Noa, Mari B, Nir, Gaza Marine, Tamar, Leviathan and Aphrodite) (Gardosh et al., 2008) (Fig.5.2). In contrast, the northern Levant Basin is still considered as a frontier area given that no wells have been drilled so far offshore Lebanon and Syria (Nader and Swennen, 2004; Nader, 2011).

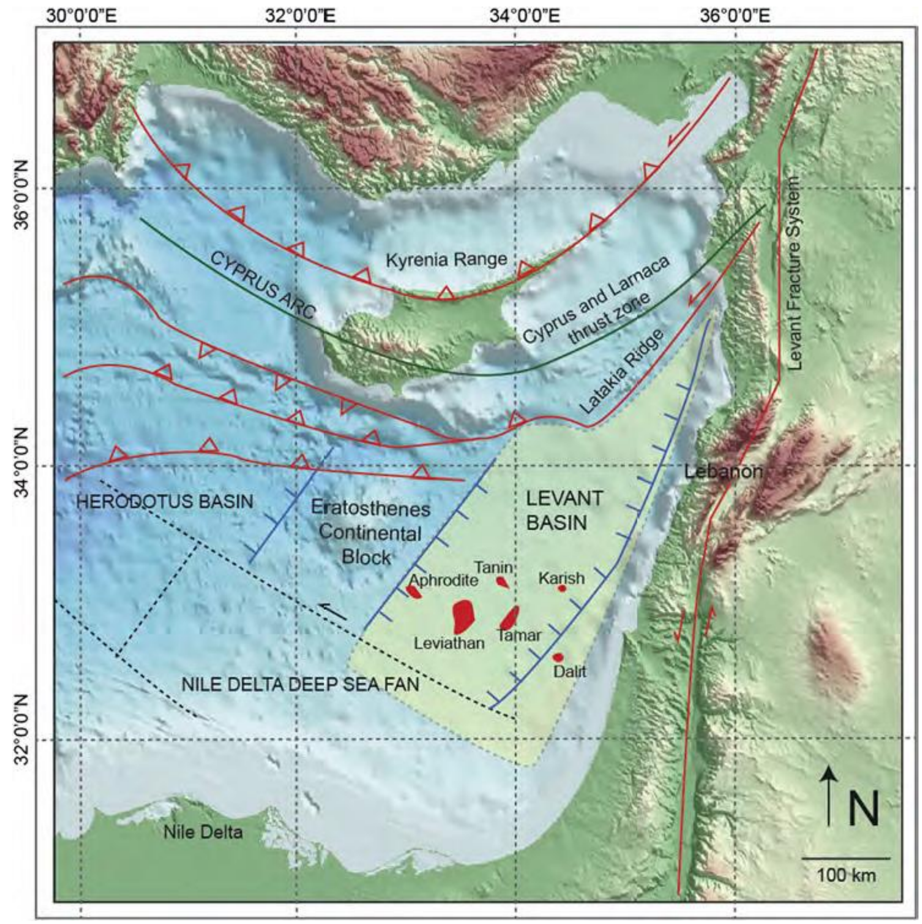


Fig5.2. Location map of the study area showing the topography, bathymetry as well as the major structural elements bounding the Levant Basin. The major gas fields are colored in red.

Recent studies provided onshore-offshore correlations for the southern Levant area (i.e., Israel) through the use of well and seismic data. A new age-constrained tectono-stratigraphic framework has been proposed revealing a thick Cenozoic unit below the Messinian evaporite cover in the Levant Basin (e.g. Beydoun and Habib 1995; Gardosh et al., 2008, 2011; Steinberg et al., 2011). The relatively few industrial studies published for the northern Levant Basin (Lebanon) focused on depicting expected petroleum systems and plays in this frontier sector (e.g. Roberts and Peace, 2007; Lie and Trayfoot, 2009; Lie et al., 2010). Scientific investigations (e.g. Carton et al., 2009; Elias, 2007) using shallow coverage seismic data tackled mainly the impact of the Late Miocene and Pliocene tectonic evolution offshore Lebanon. Still, uncertainties regarding the Upper Cretaceous and Cenozoic rock unit age's subdivisions and depositional environments persist, hindering the proposal of a proper tectono-stratigraphic framework for the northern Levant margin and basin.

The aim of this paper is to investigate the architectural evolution of the northern Levant Basin offshore Lebanon, through a comprehensive analysis of regional 2D seismic profiles (Fig.5.3) and partial correlations with adjacent exposed strata. The offshore depositional systems have been assessed through the application of seismic stratigraphic concepts and facies analysis (Catuneanu et al., 2009). In the light of the latest published work (Müller et al., 2010; Nader 2011, Hawie et al., 2013), a new onshore-offshore geologic model has been proposed. It was supported by the use of well data of the coastal northern Levant margin (Lebanon: Terbol and Adloun; Beydoun, 1977; Fig.5.4) as well as by publications tackling the

Levant tectono-stratigraphic evolution (e.g. Brew et al., 2001; Hardenberg and Robertson, 2007; Gardosh et al., 2008; Bowman, 2011). The consequences of tectonic interactions and sea level fluctuations on the basin infill are further discussed in a paleogeographic perspective, revealing a carbonate-dominated margin and an expected mixed carbonate and siliciclastic basin. This paper also intends to highlight the diversity of sedimentary sources, pathways and reservoirs expected for the northern Levant Basin offshore Lebanon.

2. GEOLOGIC SETTING

Three main phases of tectonic pulses over a period of 120 Ma affected the Levant Basin with a NW-SE and NNW-SSE general extensional direction (e.g. Brew et al., 2001; Gardosh et al., 2010). The early rift phases are believed to have occurred in the Late Paleozoic/Early Mesozoic, and followed by pulses in the Middle Triassic (Sawaf et al., 2001; Gardosh et al., 2010; Yousef et al., 2010). A Triassic evaporitic sequence was intercepted by onshore wells in Syria and Israel, and reveals that a restricted depositional environment prevailed during that period along the Levant margin (Druckman, 1974; Brew et al., 2001). A final pulse of rifting took place in the Early Jurassic concomitantly with the deposition of pyroclastics and volcanics along the Levant margin (e.g., Asher Basin in Israel) (Druckman, 1977; Hirsch et al., 1998). During the early stages of the Levant Basin's formation (i.e., Paleozoic to Middle Jurassic), a shallow marine/shelf environment is believed to have occurred in the deep basin, while fluvio-deltaic to shallow marine settings prevailed along the margin (Collin et al., 2010; Gardosh et al., 2010).

New seismic data demonstrate that the splitting of the Eratosthenes Continental Block ECB (continental crust) from Arabia was caused by the presence of a set of transfer-transform faults cross-cutting obliquely the northern African margin (Montadert et al., *in press*). Therefore, the existence of a transform zone along the eastern margin of the Levant Basin (previously proposed by Dewey et al., 1973; Bein and Gvirtzman, 1977; Robertson and Dixon; 1984, Stampfli and Borel, 2002; among others) is ruled out as it cannot explain the observed NW-SE extensional direction (Gardosh et al., 2010). Rifting activity ceased and a post rift-phase was marked by the gradual initiation of a passive margin in the Late Jurassic succeeded by the deposition of marine carbonates as well as deepwater siliciclastics on the westward-deepening slope (Cohen, 1976; Gardosh, 2002; Roberts and Peace, 2007). A major emersion period occurred in the Early Cretaceous. Siliciclastic sediments were deposited along Afro-Arabia due to the erosion of old uplifted basement highs and outcropping rift shoulders (i.e, Afro-Arabian Shield, Rutbah high, Syria; Brew et al., 2001; Ziegler, 2001) as well as exposed Paleozoic sandstones (Walley, 1997).

Gravity data presented by Beydoun (1977) and Khair et al. (1993; 1997) supported by regional gravity and seismic refraction surveys (e.g. Makris et al., 1983; Netzeband et al., 2006; Segev et al., 2006) prove that the crust flooring the Levant region is continental rather than oceanic. It thins from about 35 km inland to about 7 km under the Levant Basin.

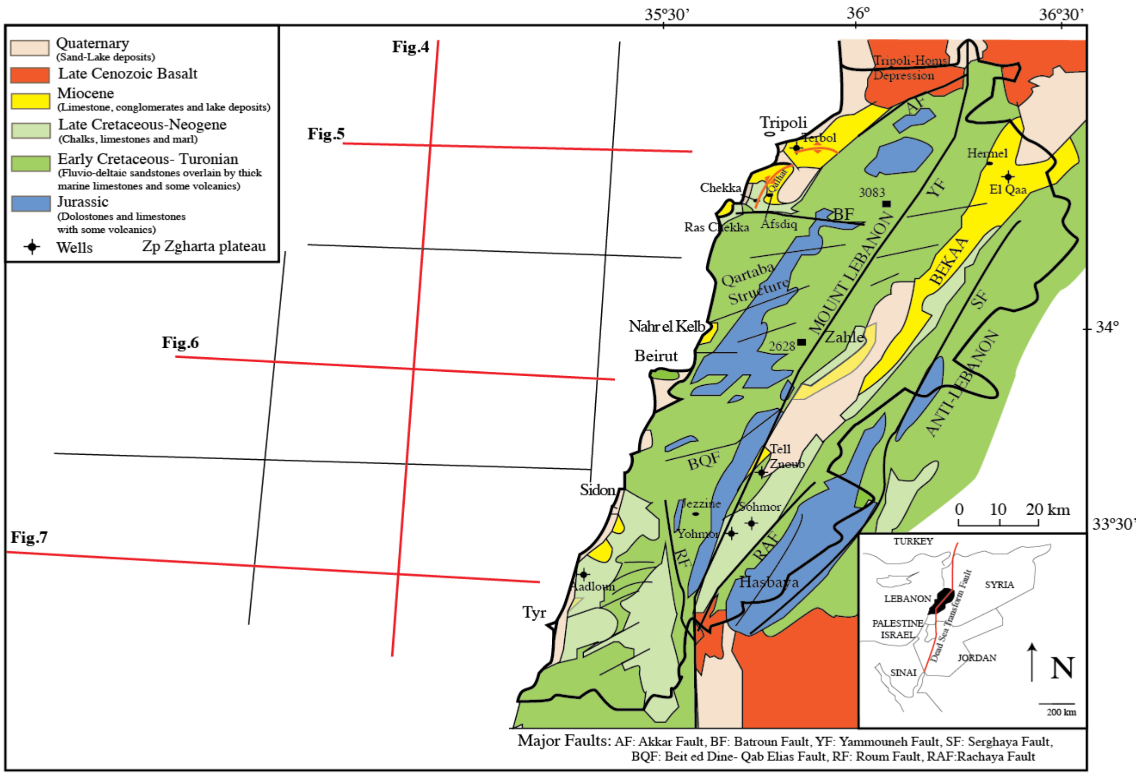


Fig5.3. Geologic map of Lebanon (modified from Dubertret, 1975) showing the seven onshore wells drilled between 1947-1967 (Beydoun, 1977) and the offshore reflection seismic lines gathered from the MC2D LEB 2008 survey (courtesy of PGS).

The collision of the Afro-Arabian Plate with the Eurasian Plate was initiated in the Late Cretaceous. It led to the inversion of Early Mesozoic normal faults into sets of asymmetric-shaped folds along the Levant margin and low amplitude folds throughout the basin (Dubertret, 1975; Garfunkel, 1998; Walley, 2001). The Levant margin regional uplift and northward tilting of the Afro-Arabian Plate have been linked to the settlement of the Afar mantle plume in Ethiopia and Yemen in the Late Eocene (White and McKenzie, 1989; Zeyen et al., 1997; George et al., 1998; Bosworth et al., 2005). Around that period an important westward sea retreat assumed to be of hundreds of kilometers exposed the Afro-Arabian Plates (Dercourt et al., 1993; Ziegler, 2001; Steinberg et al., 2011) and resulted in the accumulations of Tertiary siliciclastic sediments in the Levant Basin. The siliciclastics are sourced from Red Sea rift shoulders as well as Paleozoic Nubian sandstone exposed on the African margin (Gardosh et al., 2008; Macgregor, 2012).

Arabia separated from Africa along the Levant Fracture System, as a response to the opening of the Gulf of Aden and Red Sea (Beydoun, 1999) driven by the Anatolian Plate's westward motion in the Late Miocene (Hempton, 1987). During the Early Middle Miocene uplift was triggered along the mountainous backbone of Israel (Zilberman and Calvo, 2013). Towards the Late Miocene, Mount Lebanon was strongly uplifted as a consequence of the transpressive movements along the N-S sinistral Levant Fracture that presents a right bend onshore Lebanon (Beydoun, 1999; Gomez et al., 2006). Intense erosion and canyon incision on the basin margin was caused by the fast marginal uplift and major sea level lowstand event known as the 'Messinian Crisis' (Cita and Ryan, 1978). Consequently, a thick evaporitic sequence reached more than 2000 m in the Levant Basin. The Early Pliocene was marked by a basin inundation. At

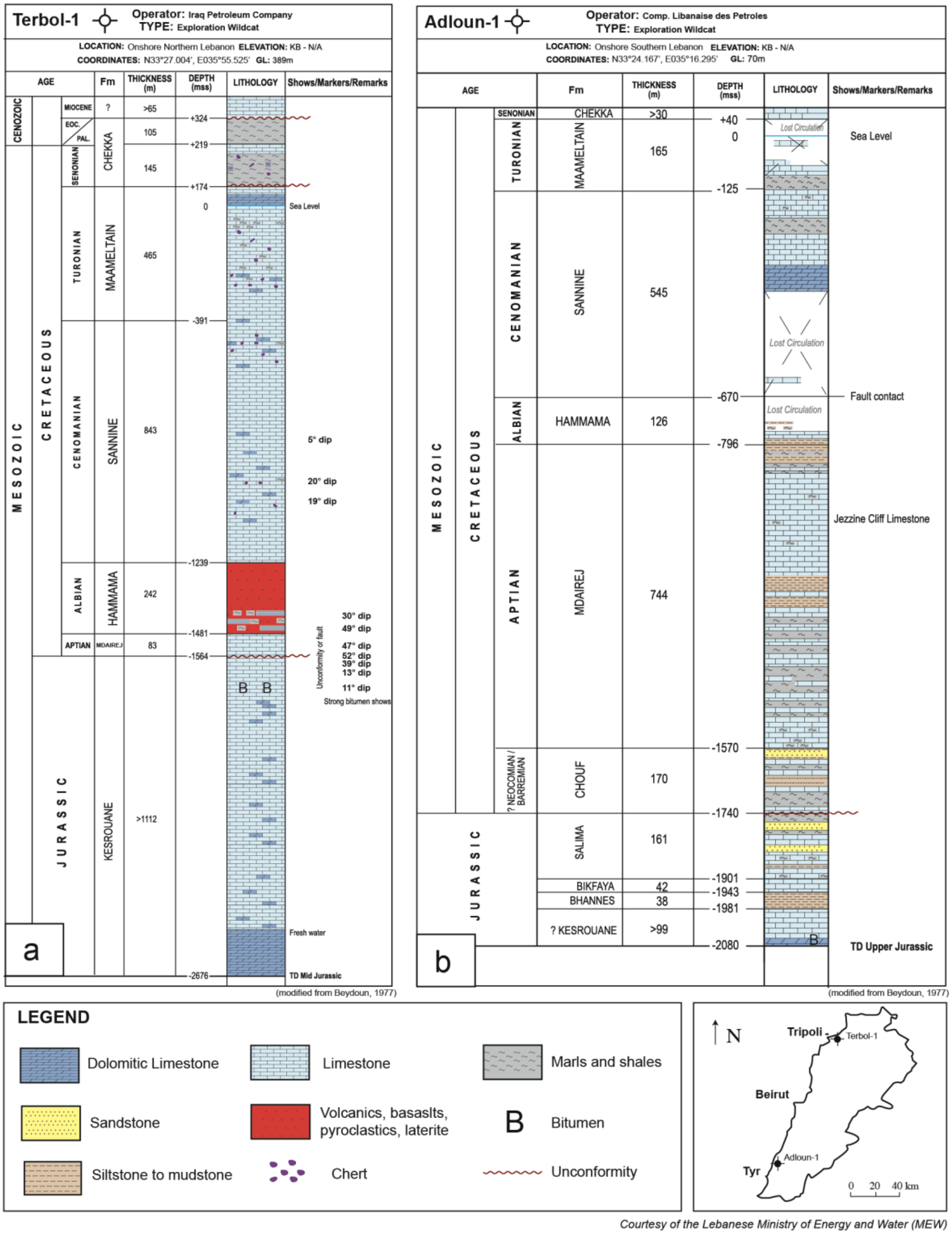


Fig5.4. Stratigraphic logs of Terbol-1 (north) and Adloun-1 (south) coastal wells modified from Ukla, 1970 and Beydoun, 1977. These wells are the most proximal to the northern Levant Basin offshore Lebanon.

that time Arabia resumed its independent movement from Africa supported by the continuing extension in the Red Sea (Hempton, 1987). An intra-Pliocene sea level drop followed by a resumption of a highstand led to further sea invasion of coastal areas while fluvial and lacustrine environments persisted inland (Dubertret, 1975; Druckman et al., 1995; Müller et al., 2010).

3. DATA SET AND METHODOLOGY

This study covers an area of about 35,000 km^2 comprising the northern Levant Basin offshore Lebanon as well as its eastern margin (Fig.5.3). The data set used in this paper was gathered from the MC2D LEB 2008 Petroleum Geo-Services (PGS) multi-client survey. It approximates 960 km of regional 2D seismic lines (9 seconds TWT), covering the northern Levant Basin. The ages proposed for the seismic units interpreted from the southern and northern Levant Basin (e.g., Gardosh et al., 2006, 2008, 2010; Roberts and Peace, 2007; Carton et al., 2009; Lie and Trayfoot, 2009; Lie et al., 2010; Bowman, 2011; Montadert et al., *in press*) remain speculative as they are mainly extrapolated from wells drilled on the Levant margin and proximal part of the basin.

The methodology proposed is based on the interpretation of seismic packages and their bounding surfaces (onlap, toplap, downlap and truncations) for the Lebanese offshore. Isochron maps have been generated for the seismic packages and have been depth converted using maps of stacked velocities (courtesy of PGS). The isopach maps illustrate the depocenters variations and architectural evolution of the northern Levant Basin with regards to major geodynamic events.

The seismic facies analysis of the northern Levant Basin -following seismic stratigraphic principles presented by Mitchum et al. (1977), Sangree and Widmier (1977), Roksandi'c (1978), Sheriff (1980) Van Wagoner et al. (1988) and summarized in Catuneanu et al. (2009)- was constrained by published 3D seismic interpretations (e.g. Fürstenau et al., 2013) and combined within a broader regional paleogeographic context (e.g. Ponikarov, 1966; Brew et al., 2001; Bowman, 2011; Gardosh et al, 2008) permitting to propose potential depositional environments for the several studied seismic intervals.

Recent stratigraphic and sedimentological results of the Lebanese margin (Boudagher-Fadel and Clark, 2006; Collin et al., 2010; Müller et al., 2010; Hawie et al., 2013) brought additional dating constraints and depositional environment interpretations for the Jurassic to Pliocene units. The knowledge gathered from the Levant margin was then extrapolated to the basin through the use of two onshore coastal wells (i.e., Terbol-1 and Adloun-1- Fig.5.4) leading to the development of an onshore-offshore stratigraphic framework for the northern Levant region.

4. RESULTS

4.1 Seismic stratigraphic interpretation

Nine horizons were identified on the regional 2D seismic profiles and have been referred to as "R1 (oldest)-R9 (youngest)". The seismic packages (SP) are defined by their large-scale reflection configurations, specific stratigraphic contacts with their lower and upper bounding surfaces, stratal terminations as well as the types of seismic facies observed in each package. The interpretations allocated for each of the identified fifteen seismic facies are based on old pioneer works (e.g., Mitchum et al., 1977; Roksandi'c, 1978) supported by regional studies discussing the stratigraphic and sedimentological evolution of the Eastern Mediterranean region (seismic and well data). Refer to Tables 5.1 and 5.2 for a summary of the seismic interpretation results (additional material not included in the article).

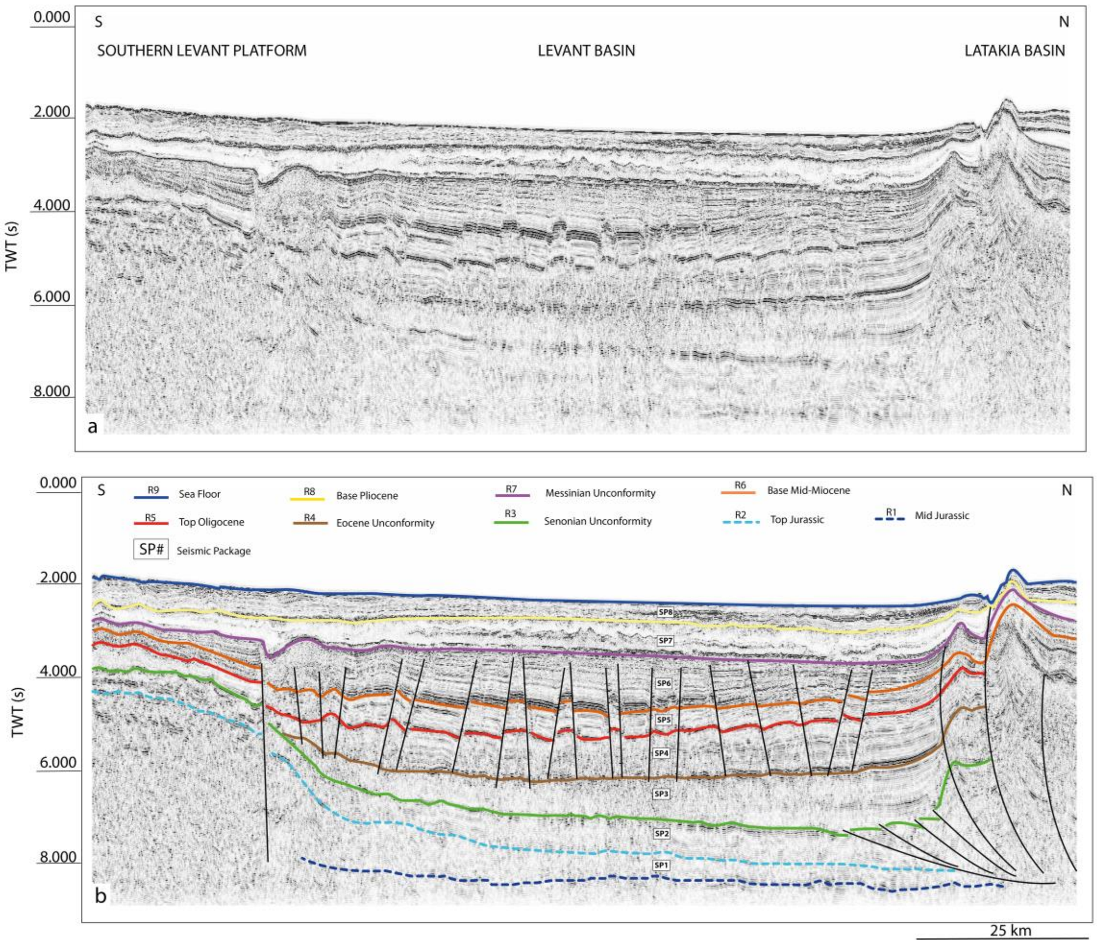


Fig5.5. Regional N-S seismic section showing the northern Levant Basin (offshore Lebanon) architecture delimited by the Latakia Ridge to the north and the extensive Levant platforms towards the south. Refer to Fig. 5.3 for seismic profile location

SP1

Description - The deepest horizon R1 (Fig.5.5b) separates a high amplitude, moderate frequency reflection package in the basin, from an overlying moderate to low amplitude seismic package (SP1) with sub-parallel reflections. About 25 km offshore Tripoli (northern Lebanon), the SP1 onlaps on the R1 horizon (Fig. 5.6b). This unconformable contact is absent from the central offshore section (Fig. 5.7b) and much less prominent offshore southern Lebanon (Fig. 5.8b). Two main seismic facies have been identified. Towards the distal margin, high amplitude, moderate continuity reflectors presenting aggrading configurations are referred to as (F1- Figs. 5.6, 5.8) while basinwards continuous sub-parallel reflections with intercalations of moderate and low amplitude reflectors are observed (F2- Figs. 5.6, 5.7, 5.8).

Interpretation – The onlapping unconformable contact in northern and southern Lebanon marks the limit between tilted fault blocks along the distal margin and the overlying deep marine sediments (SP1). Published data from the Levant Basin refer to an end of rifting around the Middle Jurassic period. Thus the interpreted R1 horizon offshore Lebanon (Figs. 5.5b, 5.6b, 5.7b, 5.8b) could represent the equivalent of the "Base Onlap" (Montadert et al., *in press*) and "Mid-Jurassic" (Gardosh et al., 2006; Lie et al., 2010)) horizons interpreted in the nearby Eratosthenes and southern Levant sectors. Aggrading carbonate platforms attested onshore Lebanon and Israel (Collin et al., 2010; Gardosh et al., 2010; Hawie et al., 2013) seem to extend towards the distal margin-side (F1) while in the basin deep marine environments prevail with deposition of hemipelagic material interbedded by silts, shales and carbonates (F2) (e.g., Mitchum et al., 1977; Roksandi'c, 1978; Gardosh et al., 2006).

SP2

Description - The R2 horizon (Fig. 5.5b) is overlain by the (SP2) characterized by aggradational and wedge-shaped configurations proximal to the Levant margin (F1) and high amplitude sub-parallel reflections towards the basin. Distal downlapping terminations have been observed on R2 along the northern Levant Basin. The wedge-shaped configuration is missing from central Lebanon's margin. Offshore northern Lebanon, a 550 ms thick wedge-shaped body of very low amplitude (F3) is localized at the Levant margin-basin transition (Figs. 5.6, 5.9a). About 32 km west of Tyr (south) (Fig.5.3), moderate amplitudes mound-shaped reflections (F4) have been recognized at the toe of the SP2 wedge-shaped configurations (Fig. 5.8).

Interpretation – A major sequence boundary at the Jurassic-Cretaceous transition (Haq et al., 1988; Sharland et al., 2001) is induced by a major sea-level lowstand and equivalent land emersion of the Afro-Arabian Plate. This led to the erosion of important amounts of carbonate and clastic material and their consequent deposition in the basin. Thus, the R2 horizon could refer to the Late Jurassic-Early Cretaceous sequence boundary. The aggrading wedge-shaped configurations (F1) around the distal Levant margin are interpreted as the offshore extension of Lower Cretaceous carbonate platforms observed onshore Lebanon (e.g., Dubertret, 1975; Saint-Marc, 1972, 1974; Hawie et al., 2013). Mass transported deposits or margin-basin fans have been identified offshore northern Lebanon (F3) (Roberts and Peace, 2007). Whereas in the south, mound-shaped bodies (F4) could stand for carbonate buildups seen along the Mediterranean on ramp to foreslope settings around the Aptian to Coniacian (e.g., Tunisia, Algeria, Spain) (Monty et al., 2009). These mounds/buildups usually strive in transgressive and highstand periods (Brunton and Dixon, 1994). The facies (F4) could also represent Late Jurassic to Early Cretaceous volcanoes with their cinder cones as evidences of volcanism have been observed around that period onshore Lebanon (Dubertret, 1974; Laws and Wilson, 1997; Walley, 1997).

SP3

Description - The R3 horizon corresponds to a major marine onlapping surface (Figs. 5.6b, 5.7b, 5.8b). This horizon is overlain by the SP3 with parallel continuous configurations and very low amplitude facies in the northern Levant Basin (F2- Figs. 5.6, 5.8). On the margin-side the SP3 presents low amplitude aggrading configurations intercalated by moderate amplitude reflectors. Prominent thrusts and positive flower structures are observed offshore northern Lebanon (Figs. 5.5, 5.6) marking the northern limit of the Levant Basin (known as the Latakia Ridge- e.g. Hall et al., 2005; Bowman, 2011).

Interpretation – The major subsidence event noted after the post-rift phase in the Levant Basin is synchronous with fast marginal uplift of the Afro-Arabian Plate due to its collision with Eurasia starting from the Turonian (Brew et al., 2001; Bowman, 2011). The R3 horizon is referred to in the Levant Basin as the "Senonian Unconformity" (Lie et al., 2010; Gardosh et al., 2006, 2008, 2011), or "BL4" (Montadert et al., *in press*). Starting from the Coniacian a major drowning event affected the whole Levant margin with a drastic deepening of sedimentary facies. On the margin, Turonian rudist platforms pass distally to outer shelf deposits (i.e., marly limestone and turbiditic rock units) (Hawie et al., 2013).

SP4

Description - The R4 horizon delimits the SP3 and the SP4 (Fig. 5.5b) along the northern Levant Basin.

The base of the SP4 presents moderate amplitude, progradational to sub-parallel reflections (F5) with channel facies (F6) best-observed offshore Beirut (central Lebanon) (Figs. 5.7, 5.9b). It is overlain by a continuous, moderate to low amplitude package with parallel to sub-parallel configurations (F2).

Interpretation – The R4 horizon is assimilated to a regional/basin scale unconformity on top of which a thick Cenozoic series is deposited. This unconformity is known as the "Eocene Unconformity" (Lie et al., 2010; Kosi et al., 2012) and "BL3" (Montadert et al., *in press*) in the Levant Basin. Around the Late Eocene, marginal uplifts associated with the continued collision of Afro-Arabia with Eurasia as well as the evolution of the Afar Plume in Ethiopia and Yemen (White and McKenzie 1989; George et al. 1998; Segev and Rybakov, 2010) followed by major sea level lowstands (i.e., Rupelian 33.7 Ma; Haq et al., 1988) led to canyon incisions on the Levant slope, bringing siliciclastic material into the basin (Gardosh et al., 2008). The vertical facies stacking evolution of the SP4 refers to a change in the depositional settings, from a potentially clastic rich (carbonates and siliciclastics) unit provided from the margin into hemipelagic/pelagic sedimentation in deepwater settings. The widespread fault system that affects the overlying Oligo-Miocene units, detaches along the base of SP4 (Figs. 5.5b, 5.6b, 5.7b, 5.8b) (Kosi et al., 2012).

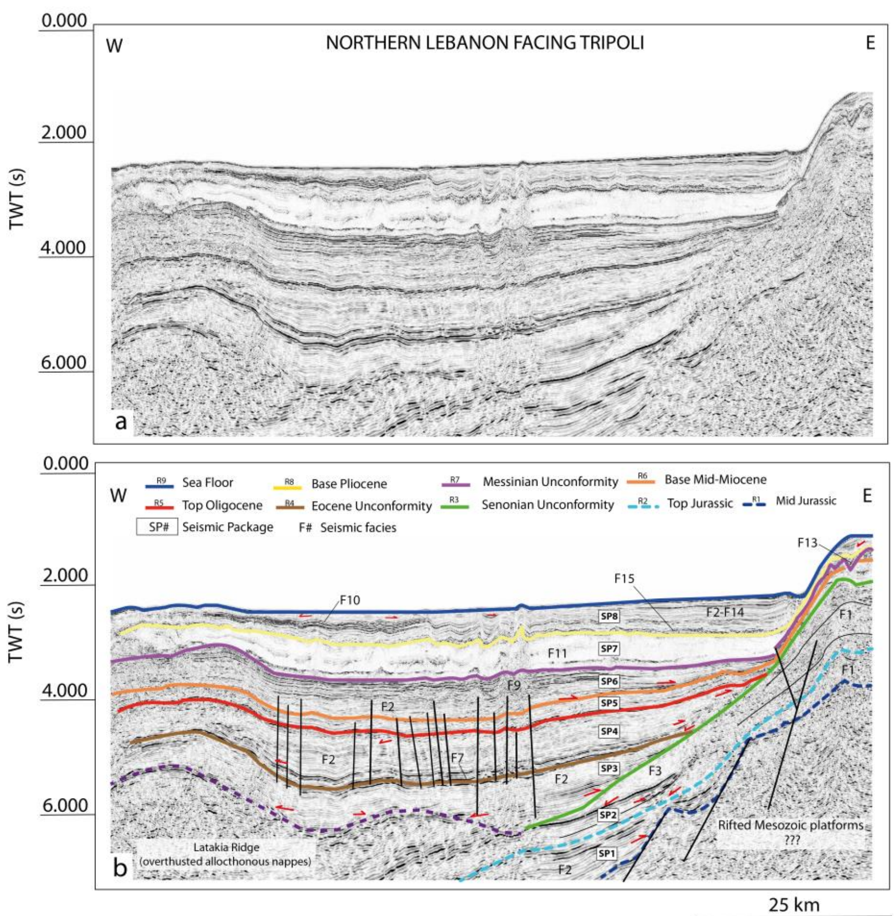


Fig5.6. E-W seismic profile showing the overall distribution of the interpreted seismic packages (SP) and the broad-scale stratigraphic architecture of the northernmost Levant Basin (facing Tripoli- refer to Fig. 5.3 for location). Note the advance of the Latakia allochthonous nappe onto the northern Lebanese offshore.

SP5

Description – Separated from the SP4 by a 100-150 ms thick continuous set of high amplitude reflectors (F7) (horizon R5; Figs. 5.5b, 5.6b, 5.7b, 5.8b) the SP5's configuration is sub-parallel presenting moderate amplitudes and continuity (F2). Distal downlapping has been attested on the R5 horizon. High amplitudes lobes localized towards the westernmost southern Lebanese offshore pinch out laterally (Figs. 5.8, 5.9e). along with associated chaotic bodies (F8) (Fig. 5.9e).

Interpretation – The horizon R5 is referred to in the Levant Basin as the "Base Miocene" (Lie et al., 2010; Bowman, 2011) and "BL2" (Montadert et al., *in press*)). The seismic facies F7 with high amplitude, moderate continuity has been allocated to stacked deep-water clastic deposits in early lowstands, which may present good reservoir characteristics (Gardosh et al., 2008; 2009; Montadert et al., *in press*). Hemipelagic deposits intercalated by deepwater channels, basin floor fans and mass transported (F8) deposits could refer to a slope/outer shelf or basinal depositional settings (Gardosh et al., 2009). It is noteworthy that the Lower Miocene rock unit is absent onshore Lebanon (Dubertret, 1975; Müller et al., 2010; Hawie et al., 2013).

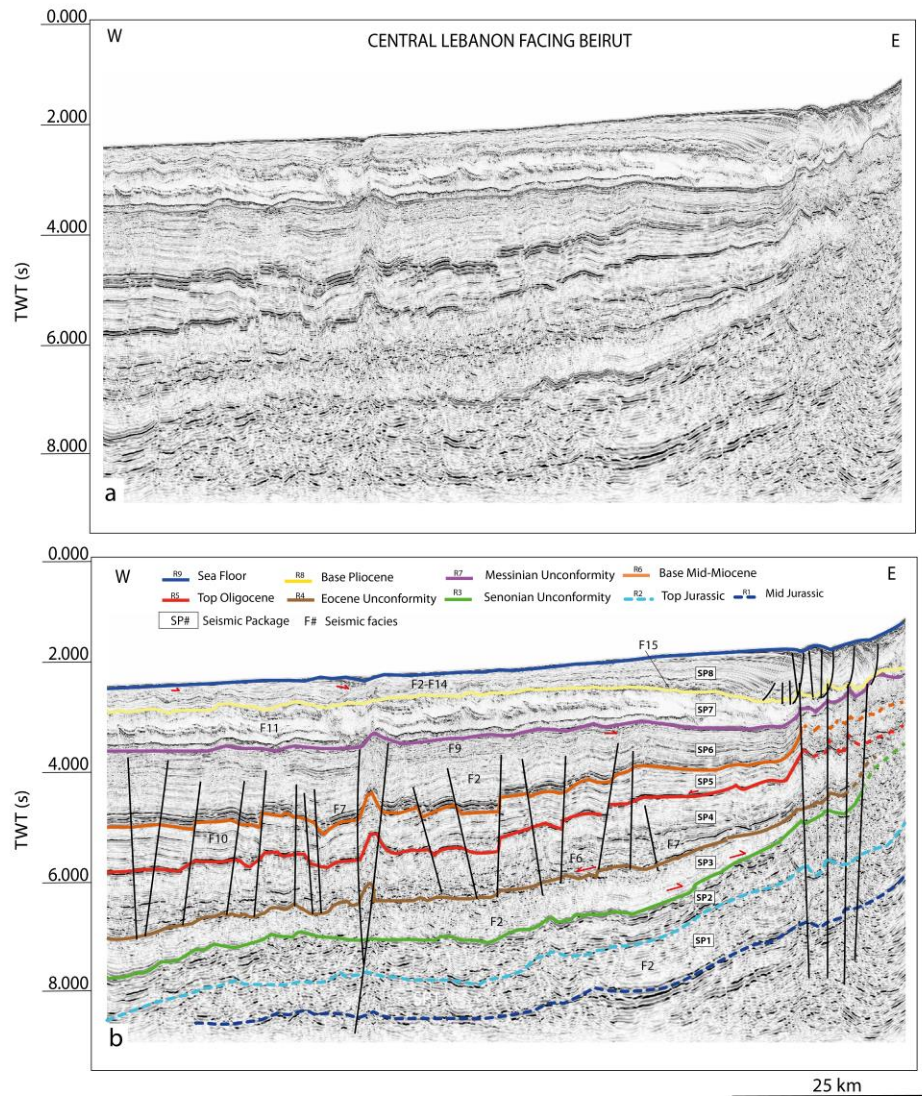


Fig5.7. E-W seismic profile showing the overall stratigraphic architecture of the central Lebanese offshore (facing Beirut- refer to Fig. 5.3 for location). Note the absence of shelf extension into the central Lebanese offshore

SP6

Description - The SP6 presents mainly parallel to sub-parallel reflections (F2) as well as some minor chaotic expressions. A series of high amplitude continuous reflectors (F7) at the base of SP6 pinch out towards the Levant margin (horizon R6; Figs. 5.5, 5.6, 5.7, 5.8). Some marine onlaps on the R6 horizon have been noted mainly in northern Lebanon (Fig. 5.6). Around the uppermost section of the SP6, a rapid change in the reflection configuration is marked by the presence of interpreted channelized facies (F6) that can reach more than 3 km in width offshore northern Lebanon (Figs. 5.6b; 5.9a), as well as high amplitude lobes (F9) on the distal margin and basin (F10) (Figs. 5.6, 5.9a).

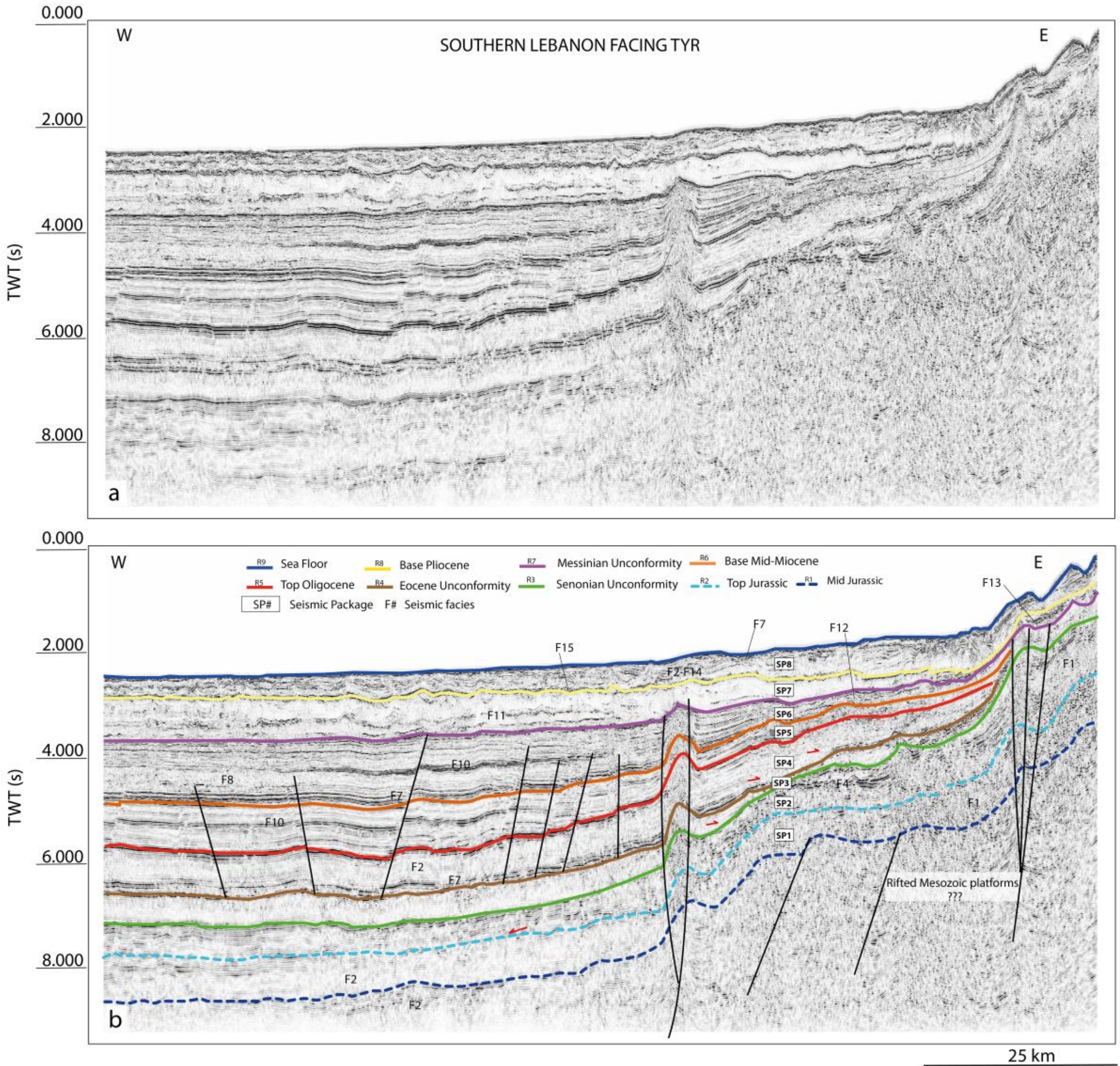


Fig5.8. E-W seismic profile showing the southern Lebanese offshore (facing Tyr- refer to Fig. 5.3 for location). Note the deeply rooted strike-slip faults cutting into most of the rock succession below the Messinian evaporite unit

Interpretation – The interpreted horizon R6 marks a basin wide unconformity and has been referred to as "Base Mid-Miocene" (Lie et al., 2010; Bowman, 2011) and "BL1" (Montadert et al., *in press*) in the Levant Basin. Here, stacked deep-water clastic deposits in early lowstands (F7) (Gardosh et al., 2008, 2009; Montadert et al., *in press*) as well as hemipelagic deposits are expected. Around the Middle Miocene period, the evolution of the Levant Fracture System induced a faster marginal uplift and intensified subsidence in the Levant Basin. Deeply rooted faults cutting through the pre-salt formation

(Figs. 5.7, 5.8) are expected to have initiated in the Late Miocene concomitantly with the northward propagation of the Levant Fracture.

The upper 700 ms of the SP6 present dense stacking of high amplitude reflectors underlining a major sedimentary input through canyons and distributary channels that develop into sand sheets (channel overfloods?) and turbiditic lobes in the basin (Figs. 5.6, 5.9a). RMS amplitude extractions have been conducted on 3D seismic data set by Fürstenau et al. (2013) permitting to map and delimit the major Middle-Upper Miocene sedimentary bodies. This increase in sedimentary flux in the northern Levant Basin coincides well with the fast marginal uplifts linked to the evolution of Mount Lebanon enhanced by major sea level lowstands around the Tortono-Messinian (Haq et al., 1988).

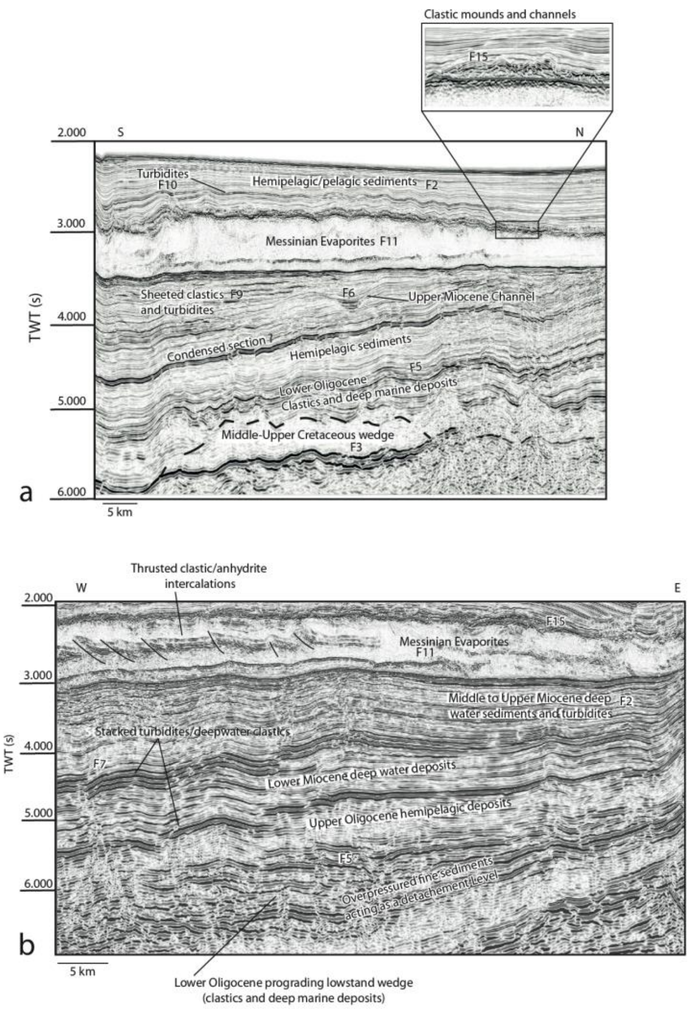


Fig5.9. Seismic facies images of the (a) Oligo-Miocene deepwater settings of northern Lebanon with channel incisions and turbidites. (b) Thick Oligo-Miocene succession in central Lebanon intercalated by deepwater turbidites and clastics. (c) Upper Miocene deepwater sediments overlain by the Messinian evaporite unit in southern offshore Lebanon. Note the presence of a localized Messinian lowstand delta (d) Canyon incising Cenozoic and Upper Mesozoic platforms offshore southern Lebanon. (e) Abundant stacked turbidites and basin fans intercalated by mass transport deposits in the Miocene succession SW offshore Lebanon

SP7

Description – The horizon R7 or "Base Messinian" is overlain by a reflection free package with some internal diffractions known as the Messinian evaporite sequence (SP7) (Lie et al., 2010; Bowman, 2011). The seismic data point to a superposition of three major high amplitude levels (F11) intercalating into this seismic package (Figs. 5.5, 5.6, 5.7, 5.8, 5.9a-c). This reflection free unit pinches out on the basin margin. A 30 km long and 300 ms thick localized body around southern Lebanon (F12) presents high amplitudes, internal progradational configurations and some chaotic reflections (Figs. 5.8, 5.9c). On the margin side, major erosional features (i.e. canyons, incised valleys) have been identified (F13) cutting deeply into previously deposited sedimentary units (Figs. 5.8, 5.9d).

Interpretation – The high amplitude intercalations observed in the Messinian evaporite unit are thought to be linked with anhydrite or overpressured clastic deposition induced by sea level changes in the Messinian (Garfunkel and Almagor, 1985; Garfunkel, 1984; Bertoni and Cartwright, 2007). Internal deformation (i.e., basinward thrusting) supports the hypothesis of an evaporitic withdrawal from the margin towards the basin. Around the Levant margin, incisions resulted from the fast emergence of Mount Lebanon and enhanced by major sea level lowstands (Dubertret, 1975; Walley 2001) leading to the continuous shedding of clastics into the Levant Basin. In southern Lebanon the localized prograding body (F13- Fig. 5.9c) identified towards the distal margin is interpreted as a lowstand deltaic system evolving in the Messinian period across the Mediterranean region (e.g. offshore Antalya (personal communication); Montadert et al., *in press*).

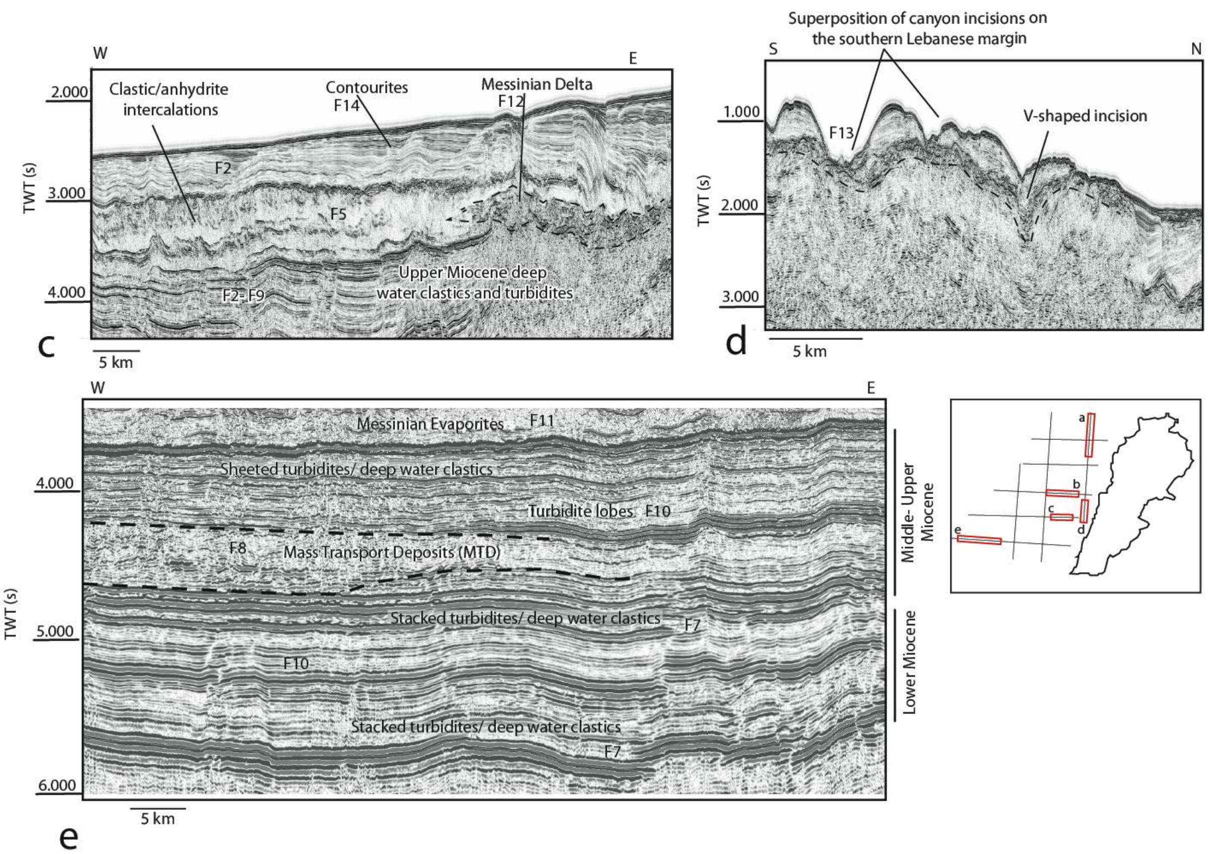


Fig5.9. *Continued*

SP8

Description – The horizon R8 (Figs. 5.5, 5.6, 5.7, 5.8) marks the top of the Messinian evaporite unit and the base of the SP8. Sub-parallel overall configurations (F2) with occasional high amplitude lobes (F10) as well as wavy configurations (F14) have been observed in the northern Levant Basin. Along the margin, this package presents progradational configurations. Mound-shaped reflections with high amplitudes and internal erosive surfaces lie on top of the Messinian evaporite unit (F15- Fig. 5.9a), which is localized in the eastern sector of the northern Levant Basin.

Interpretation – The Plio-Quaternary unit overlying the Messinian evaporites is deposited in a deep marine setting where hemipelagic to pelagic sediments are intercalated by turbiditic sheets. The mounded and channelized facies observed at the base of this unit have been drilled and are producing gas in the southern Levant Basin (3Tcf) offshore Israel. They were referred to as clastic mounds by Gardosh et al. (2009). The sub-parallel wavy configurations (F14) point to contourite systems induced by currents affecting the Mediterranean in the Plio-Quaternary (Heezen et al., 1966; Faugère and Stow, 1993).

4.2 Isopach mapping

Based on the conducted seismic interpretation, isochron maps were generated and later depth converted using maps of stacked velocities (courtesy of PGS) in order to account for the absence of offshore wells in the northern Levant Basin. The maps show the variation of thicknesses of the seismic packages (SP) with regards to major geodynamic events.

The Senonian to Eocene (SP3) depocenter is located facing the present day Latakia Ridge with estimated thickness exceeding 4000 m. Along the southern Lebanese offshore the sediment thicknesses are reduced from about 2000 m to 50 m. Rock units completely pinch out eastwards on what could represent a structural high (SH on Fig. 5.10a) on which Mesozoic and Cenozoic carbonate platforms are expected to have developed. Around the central offshore area facing Beirut, deeper settings accommodate an overall thicker sedimentary package (Fig. 5.10a).

The Oligocene (SP4) isopach map reveals quite similar trends to that of the Senonian to Eocene (SP3), with a maximum estimated thickness of about 2000 m facing the Latakia Ridge (Fig. 5.10b). The Oligocene depocenter presents a southward advance, covering the SH with deduced thicknesses of less than 500 m.

A southwestwards shift of the Lower Miocene (SP5) depocenter location is observed with more than 1400 m of sediments offshore Tyr. However around the Levant margin southern Lebanon and close to the Latakia Ridge to the north the thickness decreases to less than 600 m (Fig. 5.10c).

The Middle to Upper Miocene (SP6) unit reaches more than 2000 m offshore southern Lebanon (NW of Tyr) (Fig. 5.10d). Sedimentary units are thinner (less than 500 m) around the southern Lebanese margin extension as well as around the Latakia Ridge.

The Messinian evaporite sequence (SP7) exceeds 1800 m in the center of the basin (Fig. 5.10e) and pinches-out eastwards where a maximum of 1400 m of Plio-Quaternary (SP8) sediments reside (Fig. 5.10f).

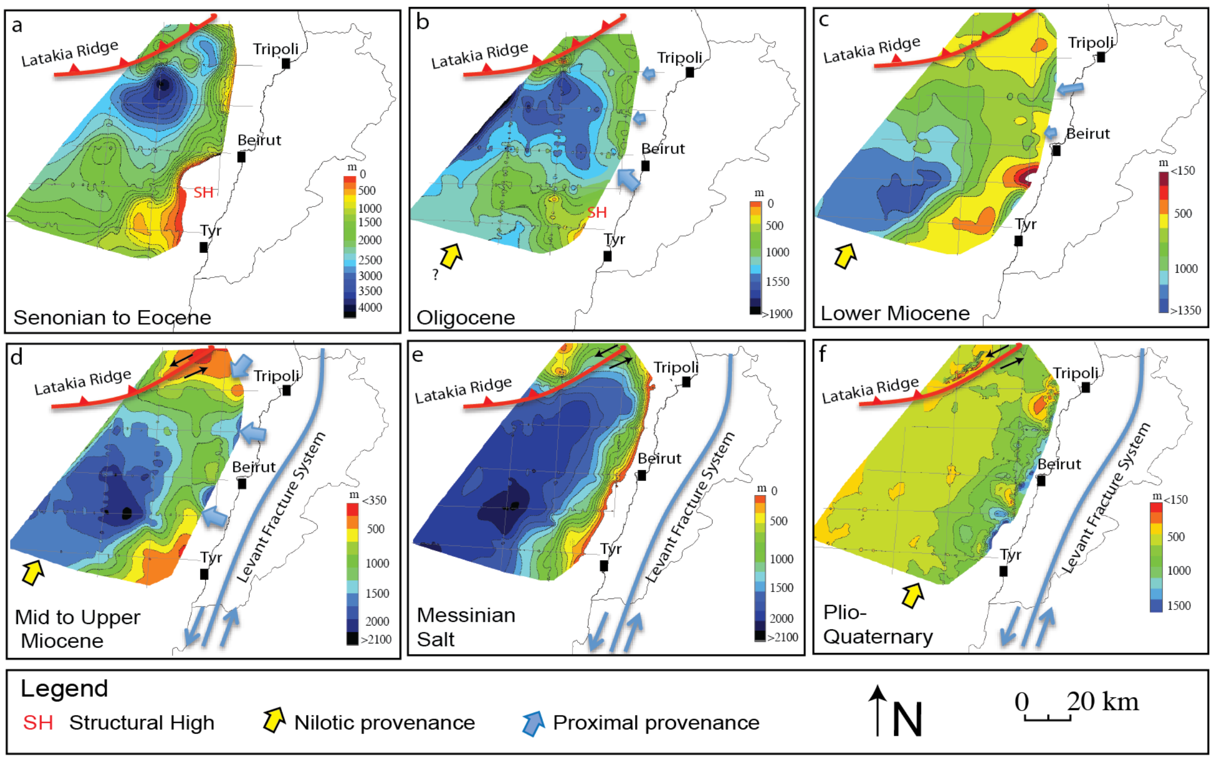


Fig5.10. Isopach maps representing the shift in depocenter location from northern Lebanon (Senonian to Oligocene) to its southern part (Early Miocene till Messinian) as a consequence of the collision of Afro-Arabia with Eurasia. The arrows mark the potential sediment pathways into the northern Levant Basin

5. DISCUSSION

5.1 New tectono-stratigraphic framework of Lebanon

Since the 1950s, a number of studies have focused on the stratigraphic evolution of Lebanon from the Mesozoic onwards (refer to Dubertret 1975; Beydoun 1977; Saint-Marc 1972, 1974; Beydoun and Habib 1995; Walley 2001). The available geological maps were based solely on macrofossils and lithological investigations, thus difficulties in dating the Upper Cretaceous and Cenozoic rock units were underlined by Walley (1997). New ages constrains (based on nannofossils and foraminifers) allowed to subdivide the Mesozoic and Cenozoic units onshore Lebanon as well as to depict major hiatuses (BouDagher-Fadel and Clark, 2006; Collin et al., 2010; Müller et al., 2010; Hawie et al., 2013). As the Cenozoic rock unit is heavily eroded around coastal areas, the link with the offshore remains quite uncertain. The use of published biostratigraphic data along the southern Levant distal margin and basin (e.g., Gardosh et al., 2006; 2008) reduces the ages uncertainties allocated to our seismic packages.

Thus, an updated onshore-offshore chronostratigraphic chart (Fig. 5.11) was built for the northern Levant region (Lebanon) as well as regional paleogeographic maps (Fig.5.12) that compile published information concerning Syria (i.e., Ponikarov, 1966; Dercourt et al., 1993; Brew et al., 2001; Ziegler, 2001). The Lebanese sector was constrained by old field investigations, well data (e.g., Saint-Marc, 1972; 1974; Dubertret, 1975; Beydoun, 1977; Walley, 1997) and by recent sedimentological and stratigraphic studies (i.e., Collin et al., 2010, Müller et al., 2010; Hawie et al., 2013). The 2D seismic results presented earlier supported by published seismic data for the northern Levant Basin (i.e., Lebanon- Lie and Trayfoot, 2009; Lie et al., 2010; Fürstenau et al., 2013; Syria (Latakia region)- Bowman, 2011) allowed to depict the potential depositional environments and the delimitation of the major facies expected in the basin.

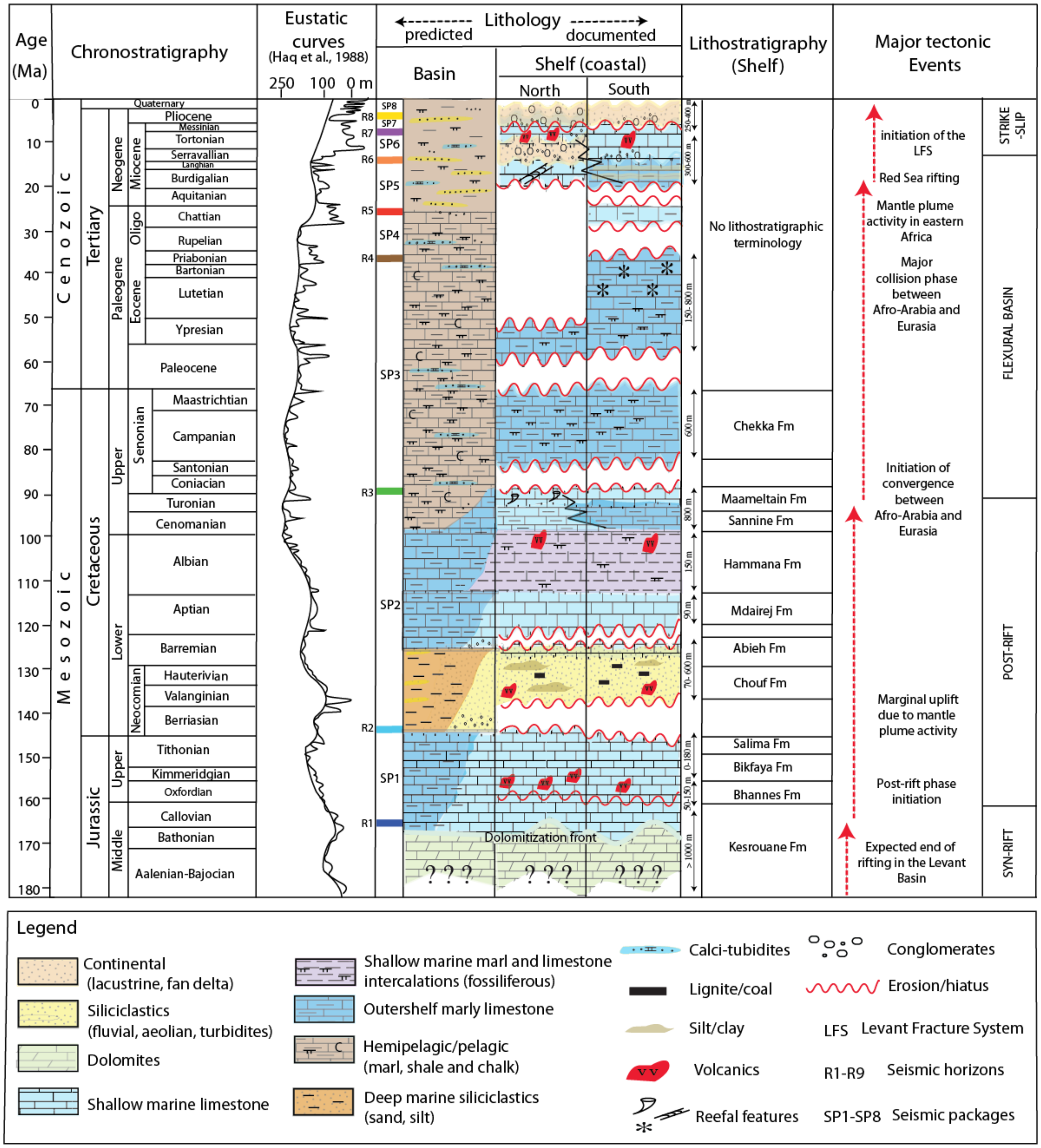


Fig5.11. Updated onshore-offshore chronostratigraphic chart depicting the major hiatuses' ages as well as the observed onshore sedimentary facies and their extrapolation into the northern Levant Basin offshore Lebanon

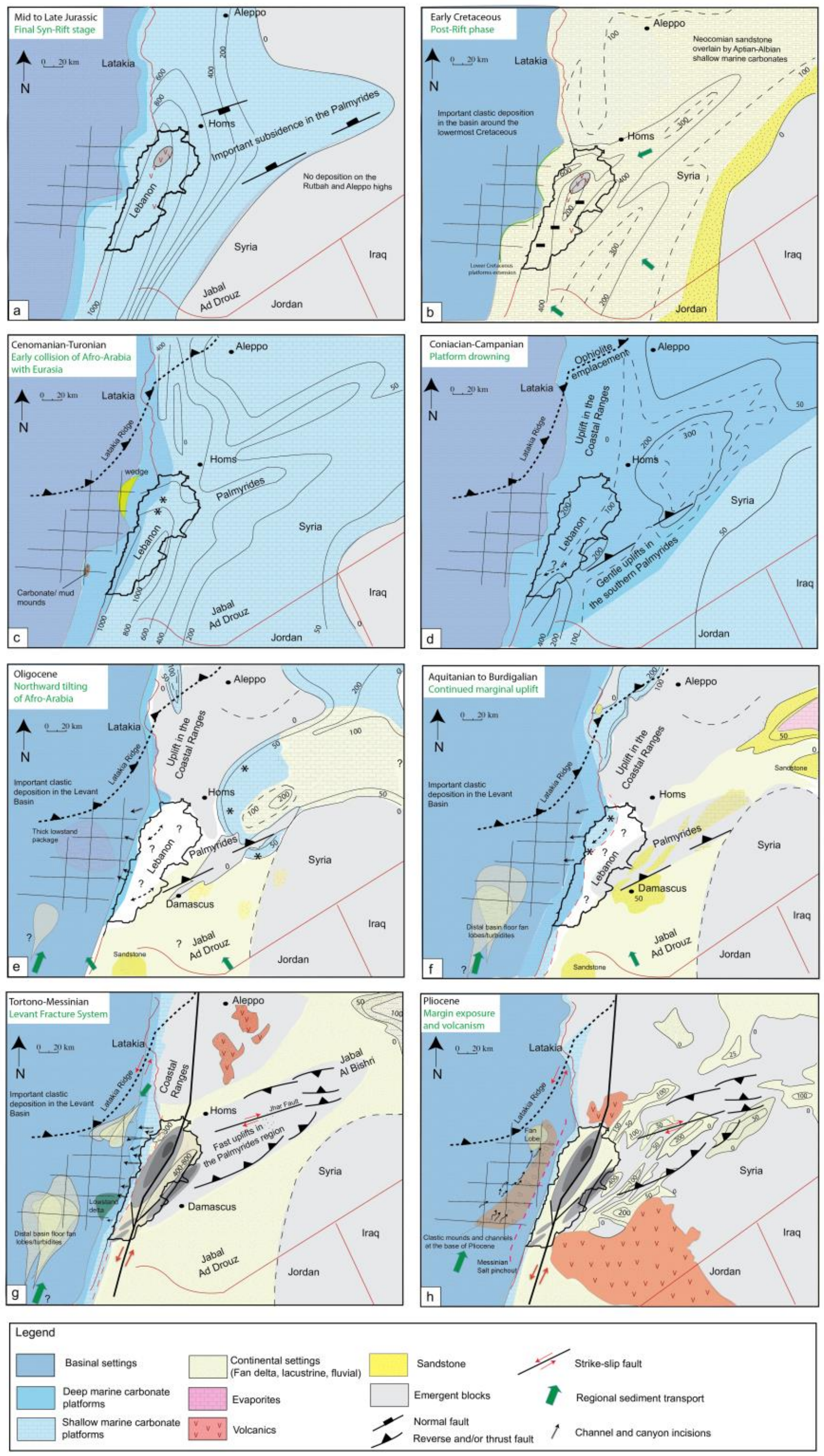


Fig5.12. Paleo-geographic maps summarizing the depositional environments prevailing in the Mesozoic and Cenozoic periods. The offshore facies have been deduced from the seismic interpretation (see results) and published data from the Levant Basin (eg. Gardosh et al., 2008; Bowman, 2011; Montadert et al., *in press*) while the onshore sedimentary facies are based on previous works cited in the text (e.g., Dubertret, 1975; Saint-Marc, 1972; 1974; Bou-Dagher Fadel and Clark 2006; Hawie et al., 2013)

5.1.1 Rift and syn-rift phase (Late Paleozoic-Middle Jurassic)

The several wells drilled onshore Lebanon (Fig.5.3) did not provide information on the Paleozoic to Triassic units. Regional sedimentary trends of the Late Triassic point to a quite similar depositional environment with that of the Early Jurassic, consisting of carbonates, clastics and evaporites (Buchbinder and Le Roux, 1993; Beydoun and Habib, 1995; Nader and Swennen, 2004). The recent work conducted by Collin et al., (2010) using benthic foraminifera and calcareous algae permitted to propose a depositional scheme for the Jurassic onshore Lebanon. Shallow marine carbonates have developed with water depths reaching not more than a few meters in sheltered low energy inner to middle shelf environment, at the junction of the Palmyride and Levant basins (Figs. 5.11, 5.12a) (Walley, 1997; Collin et al., 2010).

The interpreted tilted fault block morphologies observed offshore Tripoli and Tyr reveal that the architecture of the Early Mesozoic carbonate platforms has been affected by rifting pulses. Narrow carbonate platforms are observed offshore northern Lebanon (F1- Fig. 5.6) while wider and more extensive ones prevail in the south (F1- Fig. 5.8). The carbonate shelf extension is absent offshore central Lebanon (Fig. 5.7) suggesting a possible inherited structural control on carbonate platform evolution (Fig. 5.12a-d). Further structural investigations are needed in order to assess the link with the onshore domain. Hypotheses proposed allude to the extension of the Jhar Fault (i.e., line of Pan-African suturing of two different crustal blocks) into central Lebanon (Khair et al., 1993; Walley, 1998) and further offshore (i.e. "the Beirut-Damietta line") (Neev et al., 1985; Carton et al., 2009).

5.1.2 Late syn-rift/early post-rift phase (Late Jurassic-Earliest Cretaceous)

The post-rift phase should have initiated around the Late Middle Jurassic causing increased subsidence onshore and offshore Lebanon. An epicontinental shelf dominated the margin from the end of the Bathonian to the Kimmeridgian (Fig. 5.11- Kesrouane Fm; Collin et al., 2010) with more than 1100 m of carbonate rocks (limestone and dolostone) observed in the Terbol-1 coastal well (Fig. 5.4a). A global relative sea level fall followed by continental volcanism linked with late rifting stages led to the deposition of the variable Bhannes Fm with thicknesses ranging between 50-150 m of basaltic flows as well as rare intercalation of limestone beds (Laws and Wilson, 1997; Walley, 1998; Abdel-Rahman, 2002; Collin et al., 2010) (Figs. 5.4b, 5.11). A shallow carbonate platform unit (Bikfaya Fm-Salima Fm) dominated the uppermost Kimmeridgian-Tithonian. The Uppermost Jurassic unit has been preserved along coastal southern Lebanon and identified in the Adloun-1 well (Fig. 5.4b) with about 230 m of carbonate rocks, marl and sandy limestone intercalations. The shallow marine dolomitic limestone facies as well as the marly and sandy limestone are expected to evolve into deeper marine carbonate facies towards the northern Levant Basin offshore Lebanon.

A regional onshore unconformity is noted at the Jurassic-Cretaceous boundary, with the absence of Berriassian rock units from the Levant margin (Ponikarov et al., 1966; Dubertret, 1975; base of the AP8 mega-sequence of Sharland et al., 2001). Onshore Lebanon, the Chouf Fm (Neocomian) overlies this unconformity (Fig. 5.11) and is marked by the deposition of ferruginous sandstone provided from the erosion of uplifted basement as well as Paleozoic sandstones located on the Arabian Plate (i.e., Saudi Arabia, northeastern Jordan and south of Syria) (Fig. 5.12b) (Walley, 1998). Onshore isopach maps proposed for the Chouf Fm (supported by well data) reveal that this unit is absent in northern Lebanon (e.g. Terbol-1) and thickens towards central and southern Lebanon (Adloun-1: 170 m of carbonates, marls, silts and sandstones) reaching more than 300 m in the Jezzine area 20 km south of Beirut (Dubertret, 1975; Ukla, 1970) (Fig. 5.3). This thickness variation is a consequence of a NW-SE Late Jurassic-Early Cretaceous extensional phase in the southern Palmyride Basin that extended into central and southern Lebanon (Robertson and Dixon, 1984; Chaimov et al., 1992; Walley, 1998). It is also possibly induced by a mantle plume activity centered close to the Palmyrides (Laws and Wilson, 1997).

This remnant architecture of the Palmyride Basin (Figs. 5.4a-b, 5.12a-b, 5.13a-b) should have favored Lower Cretaceous sediment transport into the Levant Basin through central and southern onshore Lebanon (Dubertret 1975; Walley, 1998) (Fig. 5.12b). Discoveries of light oil accumulations offshore Sinai (Ziv-1 and Mango-1) and Israel (Helez oil field) (Gardosh et al. 2006, 2011) in the Lower Cretaceous sandstone unit reveal the prospectivity of this reservoir rock interval that is yet to be fully assessed.

5.1.3 Post rift phase (Early Cretaceous-Late Cretaceous)

During the Aptian massive cliff forming limestone units (Abieh and Mdairej Fm- Figs.5.4, 5.11) were deposited in a shallow marine inner shelf environment (Walley, 1988; Nader and Swennen, 2004). A return to terrigenous clastic sedimentation with clay material of restricted tidal to supratidal (lagoon) environment (Hammana Fm) marked the end of this epoch (Figs.5.11, 5.12b). A major E-W facies trend has been attested onshore Lebanon mainly affecting the Cenomanian (Sannine Fm)-Turonian (Figs.5.4, 5.11, 5.12c). Shallow marine reefal to lagoonal settings are observed inland and evolve into subtidal to deeper marine outershelf environments towards the coastal areas (Saint-Marc, 1972, 1974; Dubertret 1975; Hawie et al., 2013). The thicknesses of the Aptian to Turonian carbonate platforms can exceed 1500 m onshore Lebanon (Figs. 5.4, 5.11). These Cretaceous carbonate platforms are interpreted to extend tens of kilometers into the Levant Basin (Figs. 5.12b,c) presenting outer ramp to slope settings towards the distal margin, while in the basin, deepwater carbonates and shales intercalated by turbidites could be found.

5.1.4 Afro-Arabian collision with Eurasia (Late Cretaceous-Early Miocene)

A Late Turonian to Late Santonian hiatus has been identified onshore Lebanon (equivalent of the base AP9 according to Sharland et al., 2001) (Figs.5.11; Müller et al., 2010). This hiatus is representative of a wide marginal uplift linked with the collision of Afro-Arabia with Eurasia starting from the Turonian. The interpreted Senonian unconformity offshore Lebanon (major onlapping surface- Fig.5.6, 5.7, 5.8) can thus be correlated to onshore equivalent age-constrained strata (Hawie et al., 2013). The drowning of the Cretaceous carbonate platform occurred in the Late Turonian and persisted throughout the Paleocene and Early Middle Eocene times (Figs.5.11, 5.12d, 5.13d). Deepwater chalky and marly limestone units intercalated by chert beds (Chekka Fm; Dubertret, 1975; Walley, 1977; Hawie et al., 2013, Fig.5.4) have been observed in the Terbol-1 and Adloun-1 coastal wells. The transition from carbonate rich to marly prone unit is expressed by lower seismic amplitudes along the distal margin offshore Lebanon (Fig.5.6). The isopach maps (Fig.5.10) support the hypothesis of the initiation of a foreland basin along the northernmost part of the Levant Basin starting from the Late Cretaceous with clear thickening trends of the Senonian to Oligocene rock units (SP3-SP4) towards the front of the Latakia Ridge reaching more than 4000 m (Fig.5.10a, b).

An angular unconformity between the Lower Eocene and Late Burdigalian rock unit has been observed onshore northern Lebanon (Hawie et al., 2013) and in the Terbol-1 well core (Fig.5.4), delimiting between a deep marine Lower Eocene marly limestone from a rhodalgal Middle Miocene unit (Fig. 5.11). The southern coastal Lebanon seems to have been in a structurally deeper position where the Middle and Upper Eocene as well as the Upper Oligocene rock units were preserved from erosion (Müller et al., 2010). The "Eocene Unconformity" is the equivalent of the base of AP11 of Sharland et al. (2001). It marks an important deposition of carbonate clastic material in the Levant Basin. Siliciclastic sediment flux provided from the south through the Nile Delta drainage system around the Oligo-Miocene are thought to contribute to the Levant Basin infill (Fig. 5.12f) (Dolson et al., 2005; Macgregor, 2012). The shift of the northern Levant Basin depocenter from northern Lebanon (facing the Latakia Ridge) gradually to southern Lebanon in the Lower Miocene marks the continuation of the advance of the flexural basin that initiated in the Late Cretaceous (Fig. 5.10c).

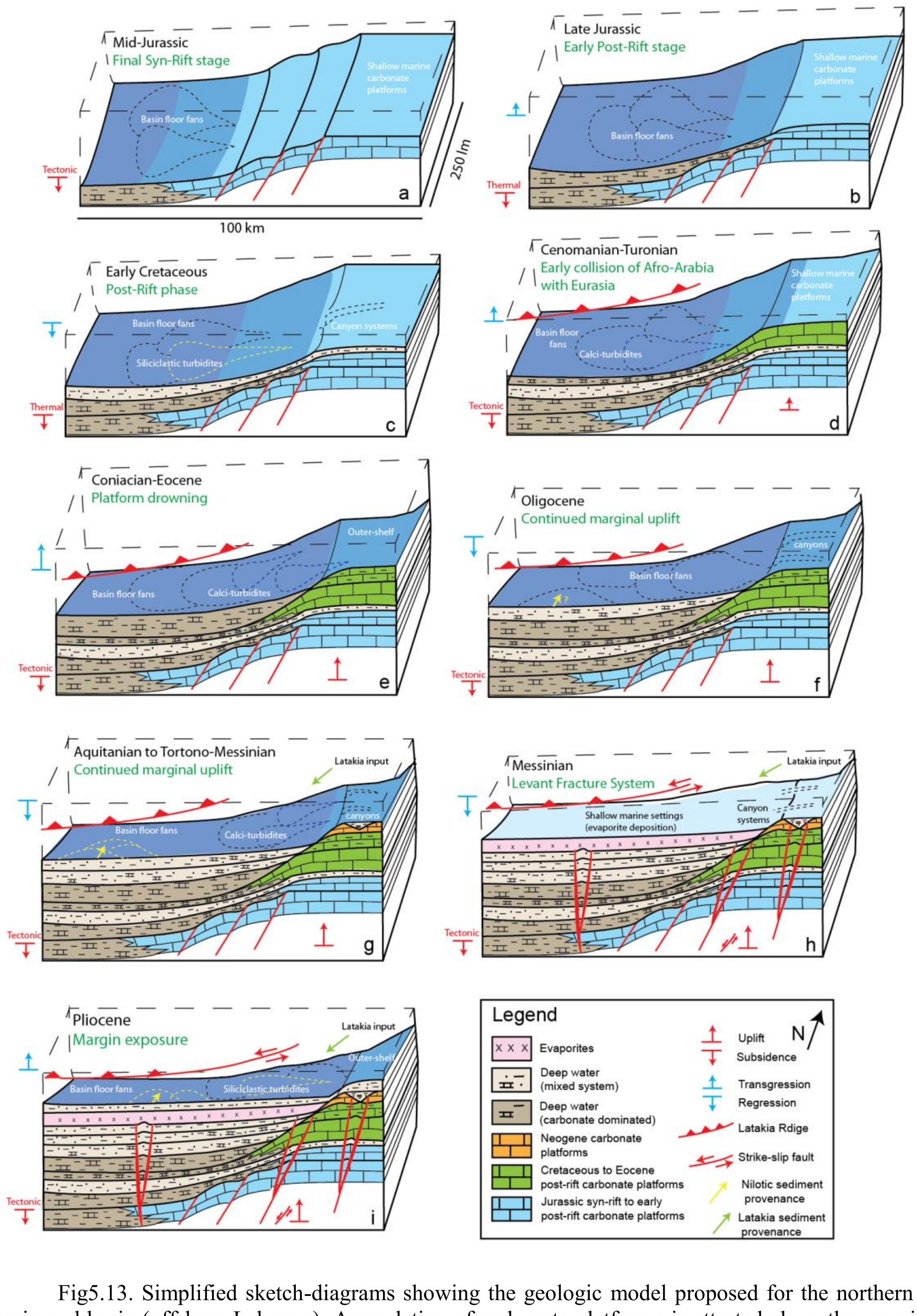


Fig5.13. Simplified sketch-diagrams showing the geologic model proposed for the northern Levant distal margin and basin (offshore Lebanon). Aggradation of carbonate platforms is attested along the margin while deep-water mixed settings prevail in the basin. Regional drainage systems are expected to have contributed to the filling of the northern Levant Basin offshore Lebanon.

5.1.5 Levant Fracture System evolution (Middle Miocene-Present)

Sedimentary facies variations allude to the presence of a topographic high around Mount Lebanon from the Late Burdigalian onwards. Rhodalgal platforms evolved along the coastal areas (Hawie et al., 2013), while lacustrine settings prevailed in the Bekaa valley (Dubertret, 1975). The fast emergence of Mount Lebanon in the Tortono-Messinian (Fig.5.12g) as a consequence of the northern propagation of the Levant Fracture System (LFS), favored continental sedimentation on the margin (Fig.5.11). Carbonate material was eroded from emerged lands and deposited as conglomeratic fans in paleotopographic lows (Dubertret, 1975; Walley, 1998; Müller et al., 2010; Hawie et al., 2013). The onshore transpressive phases have also been identified offshore Lebanon with deeply rooted strike-slip faults inducing flower structures morphologies (Figs.5.7, 5.8). By the Late Miocene time, the Latakia Ridge was already a prominent structure affecting the evaporite deposition (Fig.5.6). This compression is re-activated into a sinistral strike slip motion at the beginning of the Pliocene with total uplift of the Latakia Ridge of about 40-60% (Brew et al., 2001; Hall et al., 2005; Bowman, 2011). The Messinian evaporites cap all the previously discussed successions with thicknesses exceeding 1500 m in the basin. The rapid Mediterranean inundation in the Early Pliocene led to the deposition of clastics overlain by hemipelagic to pelagic deposits (Fig. 5.12h). The Plio-Quaternary interval is affected by thin-skinned tectonism as the evaporitic unit is driven downslope towards the center of the Levant Basin (Letouzey et al., 1995).

5.2 New conceptual model for the Levant Basin infill

The seismic interpretation results supported by the onshore knowledge indicate that a mixed carbonate-siliciclastic system developed along the northern Levant region. An aggradation of carbonate platforms prevail along the margin (Fig. 5.13a, b, d) while a mixed system is expected in the deep basin. More than 10 km of Cenozoic sediments are expected to be found offshore Lebanon (about 6 km of Oligo-Miocene) (Fig. 5.10b,c,d) (Nader, 2011) while a thinner onshore unit covers the coastal areas (about 700 m) and the Bekaa valley (about 1300 m) (Dubertret, 1975; Walley, 1997; Hawie et al., 2013).

Debates around the provenance and extent of gas rich Oligo-Miocene siliciclastic reservoirs found in the southern Levant Basin still persist. Two main scenarios should be taken into account while assessing the expected reservoir potential of the northern Levant Basin: (1) silicilastic material provided mainly through the Nile Delta (e.g. Steinberg et al., 2011) or (2) through other pathways (i.e. Latakia canyons, Levant margin canyon systems) as a consequence of the erosion of uplifted basements and exposed siliciclastics (e.g. Shaliv, 1991; Bowman, 2011).

5.2.1 The Miocene depositional model of northern Lebanon-Latakia

The 2D seismic facies interpretation conducted for the Middle-Upper Miocene in northern Lebanon -supported by 3D seismic data analysis (Fürstenau et al., 2013) – point to deltaic systems towards the inland, canyons incising the Levant margin, feeder channels/levee in the proximal basin and sheeted turbidite lobes towards the distal basin section (Figs. 5.9a, 5.12f, g, 5.13f, g). These seismic facies associations concur with mud/clastic rich submarine models proposed by Reading and Richards (1994). The isopach maps of the Lower and Middle-Upper Miocene (Fig. 5.10c, d) reveal major sediment entry-points from the northern Lebanese onshore sector as well as from the Latakia region in Syria (Lie et al., 2010; Bowman, 2011; Skiple et al., 2012; Fürstenau et al., 2013) (Figs. 5.12g, 5.13g).

The erosion of the Levant margin in the Miocene period is a direct consequence of the interplay between the evolution of the Levant Facture System, the continued collision of Arabia with Eurasia and major lowstand cycles (e.g. the Burdigalian and Tortono-Messinian; Haq et al., 1988). Conglomeratic material is thought to be provided from the northern Lebanese onshore due to the erosion of Cretaceous to Miocene carbonate platforms contemporaneously with Mount Lebanon's uplift (Hawie et al., 2013). Reduced siliciclastic accumulations are provided from northern Lebanon in the Middle-Late Miocene period, as the Lower Cretaceous sandstone unit is very thin/missing there (Fig.5.11)

Well data from the onshore Latakia region (i.e., Nahr el Kebir depression) have underlined the presence of sandstone, clay and conglomerates of Early to Middle Miocene age with a thickening trend towards the inland (Bowman, 2011). This alludes to the presence of Miocene siliciclastic and carbonate sources feeding into the northernmost Levant Basin (Ponikarov et al., 1966; Brew et al., 2001; Hardenberg and Robertson 2007).

5.2.2 The Miocene depositional model of southern Lebanon

The superposition of canyon systems on the southern Levant margin from the Oligocene and Miocene reveals that old pathways have been re-used with more recent lowstands (Gradosh et al., 2008). This could also be the case of the southern Lebanese plateau (Fig.5.9d) (Druckman et al., 1995). The reservoirs found along the southern Levant canyon systems are thought to be provided from the erosion of fluvial Miocene sandstones of the Hazeva Fm (Nubian sandstone) (Gardosh et al., 2008). Sand provided from the northern Israeli margin could also be diverted towards the deeper northern Levant Basin and thus such scenario should not be discredited. As no outcropping Oligo-Miocene siliciclastic unit has been found in the Lebanese onshore the reservoir potential of the canyons offshore south Lebanon is still uncertain.

The southern Nile Delta province is thought to represent the main source of sediments that could explain the abnormally thick Oligo-Miocene in the Levant Basin (Steinberg et al., 2011). The good sandstone reservoirs of the "Tamar" and the new "Karish" discovery (about 4 km from the Lebanese borders) in the southern Levant Basin (Fig.5.2) are expected to be driven through the Nile deep-sea drainage system. Distal turbidites and basin floor fans could extend as far as the northern Levant Basin offshore Lebanon (Said, 1981; Dolson et al. 2005; Macgregor 2012) (Figs.5.8, 5.12, 5.13g). Thus, high amplitude lobes localized in the SW part of the Lebanese offshore (Fig.5.9e) could reflect this potential sediment transport from the south (Fig.5.12f,g)

Boyd et al. (2008) proposed two mechanisms related to the transport of siliciclastics from areas in Egypt into the Levant Basin involving (1) coarse Oligocene clastics in northern Egypt transported northwards by canyons and that could have acted as a source for basin floor sheet sands; (2) longshore current interaction with tides leading to a diversion of the sand load down slope.

5.2.3 Pliocene reflooding

Following lowstand periods in the Pliocene, deepwater turbiditic sands, basin floor fans as well as large clastic sand mounds (50-300 m thick) have been deposited on top of the Messinian evaporite unit (Gardosh et al., 2009). Lower Pliocene reservoirs containing significant gas accumulations (a total of 3 Tcf) have been discovered since the year 1999 in Israel (i.e., Noa, Marie, Gaza Marine fields).

A very similar seismic configuration has been attested in Lebanon for the Pliocene unit where turbiditic and clastic mound have been described in the northern Levant Basin (Fig.5.9a). RMS amplitude maps of the Lower Pliocene unit underline the presence of south to north driven channel systems supporting once again a possible nilotic provenance (Figs.5.12h, 5.13i) (Fürstenau et al., 2013).

6. CONCLUSIONS

The conducted seismic interpretation underlines the importance of the use of seismic stratigraphic concepts coupled with fieldwork in unraveling the tectono-stratigraphic evolution of the northern Levant frontier basin.

The data presented offshore Lebanon support the passive margin model for the Levant Basin with tilted fault block morphologies affecting the Early Mesozoic carbonate platforms. Rifting is interpreted to have ended around the Middle-Jurassic followed by the onset of deepwater settings in the basin. The collision of the Afro-Arabian Plate with the Eurasian Plate since the Turonian led to the formation of a foreland basin with subsidence enhanced at the front of the Latakia Ridge. Continued southwards advance of this foreland basin is noted until the Early Miocene with a shift of depocenter location from the north to the south of Lebanon. Around the Middle to Late Miocene major uplifts along the Levant margin and increased subsidence in the basin are linked with the onset of the Levant Fracture System.

A new tectono-stratigraphic framework was proposed for Lebanon based on the recent onshore and offshore results revealing a carbonate dominated proximal margin and an expected mixed carbonate-siliciclastic prone basin. The presence of a very thick Oligo-Miocene rock unit in the northern Levant Basin could be explained by the contribution of regional drainage systems in its infill. The seismic interpretation points to a probable northern sediment entry-point through the Latakia region and a potential southern one linked with the Nile Delta deep-sea cone. However detailed 3D seismic investigations and stratigraphic modeling (Granjeon and Joseph, 1999) are needed in order to bring further insights into the sediment provenance and pathways.

End of Article Hawie et al., 2013 b

I.2 Supporting material

Additional material has been added to the previous seismic interpretation in order to bring more insights into how the seismic stratigraphic interpretation and facies analysis were conducted. The following Table.5.1 summarizes the major characteristics of each seismic package and its relation with its lower and upper bounding surfaces and stratal termination. Furthermore, the fifteen seismic facies discussed earlier in Hawie et al. (2013b) have been compiled in Table 5.2.

The three major seismic profiles for northern central and southern Lebanon have been filled with a color code that represents the expected type of deposits for the Levant distal margin and basin (Fig.5.14). The proposed depositional systems are to be validated/constrained in the future through well drills.

One of the major uncertainties that prevail while trying to link onshore Lebanon with its offshore resides not only in the ages allocations to sedimentary packages (due to the lack of wells drilled offshore) but also in the absence of shallow marine seismic data that covers the shallower margin as well as the poor well coverage onshore coastal Lebanon (mainly around Beirut). The combination of a varied data set offshore Tripoli (i.e., deep and shallow marine seismic data (also refer to Beydoun & Habib, 1995) as well as the fieldwork and well data (courtesy of PGS and MEW) allows reducing significantly the margin/basin correlation uncertainties (Figs.5.15, 5.17).

Along the N-S Geco-Prakla profile (Figs.5.15, 5.16) two major canyons incising the distal shelf were identified. They present wide U-shaped morphology and seem to erode deeply into older successions. Looking at the actual river locations it seems that the canyons identified on the seismic data could represent the offshore extent of the major rivers of northern Lebanon.

Onshore work conducted along southern Lebanon supported by well data and deep marine seismic data allows to propose a relatively constrained onshore offshore correlation showing the wide platform extension onshore and the deeper basinal settings in the Levant Basin (Fig.5.17).

Interpreted major seismic packages		Lower bounding surface	Upper bounding surface	Seismic facies attested	Large scale reflection configuration
Plio-Quaternary	SP 8	Downlaps/Truncation	Truncation	F2-F10-F12-F13-F14-F15	Parallel to sub-parallel configuration (basin) Progradational oblique tangential configuration (margin)
Messinian	SP 7	Conformable (basin) Truncation + downlaps (margin)	Truncation/conformable	F11-F12-F13	Reflection free configuration with some internal diffraction Intercalation of 3 sub-parallel clastic/anhydrite units
Mid to Upper Miocene	SP 6	Conformable Onlap on margin	Truncation/conformable	F2-F6-F7-F9-F10	Parallel to sub-parallel reflections as well as some oblique parallel configurations and minor chaotic reflections
Lower Miocene	SP 5	Downlaps Onlaps on margin	Truncation/conformable	F2-F7-F10	Progradational/ to sub-parallel configuration
Oligocene	SP 4	Downlaps Onlaps on margin	Truncation/conformable	F2-F5-F6-F7	Progradational complex sigmoid to oblique sub-parralel with some chaotic intercalations that acts as a decollement level
Senonian -Eocene	SP 3	Onlaps	Conformable	F2	Parallel configuration with some chaotic configuration
Lower to Mid Cretaceous	SP 2	Downlaps/conformable	Conformable	F1-F3-F4-F5	Parallel to sub-parallel with divergent configuration with condensed and mounded intervals (basin) Aggradational and wedge shaped configuration (margin)
Mid to Upper Jurassic	SP 1	Onlaps	Conformable	F1-F2	Parallel to sub-parallel reflections as well as some configurations with minor chaotic reflections

Facies analysis scheme

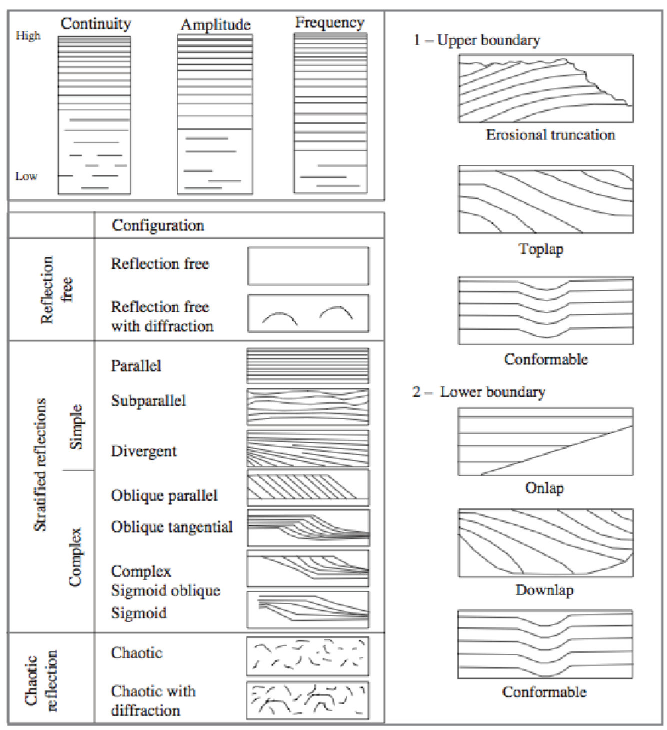


Table 5.1. Seismic packages interpretation of the northern Levant Basin offshore Lebanon

Seismic Facies Characteristics of the Levant Basin (Offshore Lebanon)

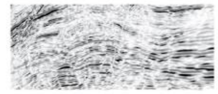
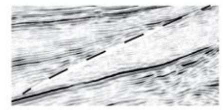
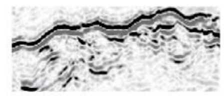
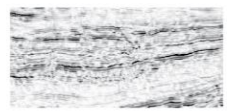
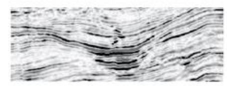
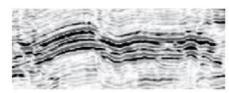
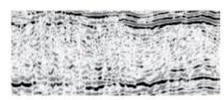
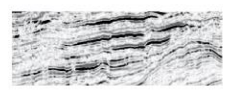
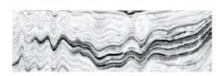
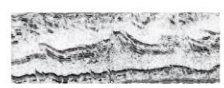
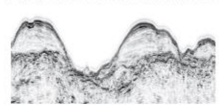
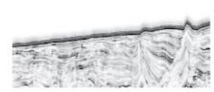
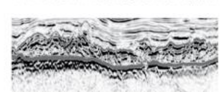
Facies	Continuity	Amplitude	Frequency	Configuration	Interpretation	Seismic image
F1	High	High	High	Parallel reflections with aggradational to progradational patterns	Aggrading to prograding carbonate platforms	
F2	Moderate to high	Moderate to Low	Moderate to high	Parallel to sub-parallel	Deep water hemipelagic/ pelagic sedimentation with fine turbiditic intercalations	
F3	Low	Low	Low	Reflection free with some sub-parallel intercalations	Deep water carbonate wedge (Tallus? Debris flow?)	
F4	Moderate	Moderate	Moderate	Mounded reflections	Carbonate mud-mounds	
F5	Moderate to high	Moderate with high amplitude levels	Moderate	Progradational oblique parallel to tangential	Prograding clastics and shales wedge	
F6	Low	High	Moderate	Parallel to sub-parallel localized packages	Channel infill	
F7	High	High	Moderate	Parallel to sub-parallel (body pinchout)	Stacked turbiditic units	
F8	Low to moderate	Very Low	low	Chaotic with diffractions	Mass transport deposits in deep water settings	
F9	Moderate to low	High	Low to moderate	Parallel-pinchout	Sheeted turbidites/clastics (Channel overfloods?)	
F10	Moderate to high	Moderate with high amplitude levels	Moderate	Parallel to sub-parallel lobes pinching out at extremities	Deep water turbidites forming submarine lobes	
F11	Moderate to high	High	Moderate	Sub-parallel	Clastic/ or anhydrite intercalation in the evaporitic section (reflection free unit)	
F12	Low	High	Moderate	Progradational reflections with some chaotic intercalations	Lowstand delta/clastics	
F13	Low to moderate	High	Moderate to low	Sub-parallel to chaotic locally progradational	Incised valley and/or canyon infill	
F14	Moderate to high	Moderate	Moderate	Sub-parallel/wavy	Contourite mud waves	
F15	Low	High	Low	Chaotic	Clastic mound deposition with potential evaporitic intercalations	

Table 5.2. Seismic facies characterization of the northern Levant Basin offshore Lebanon

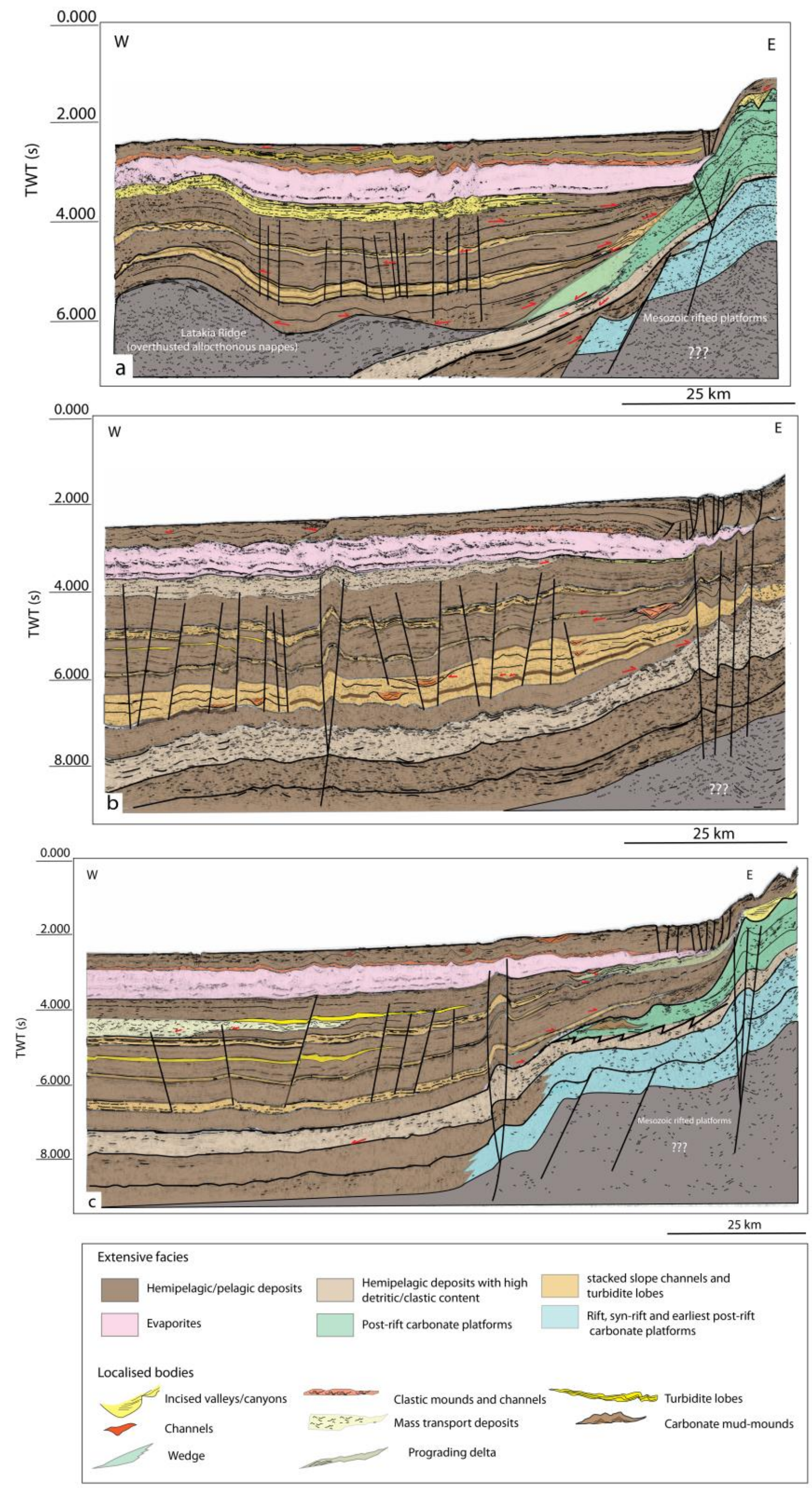


Fig5.14. Color-coded profiles showing the interpretation allocated to the seismic facies of (a) northern (b) central and (c) southern Lebanon previously summarized in table 5.2.

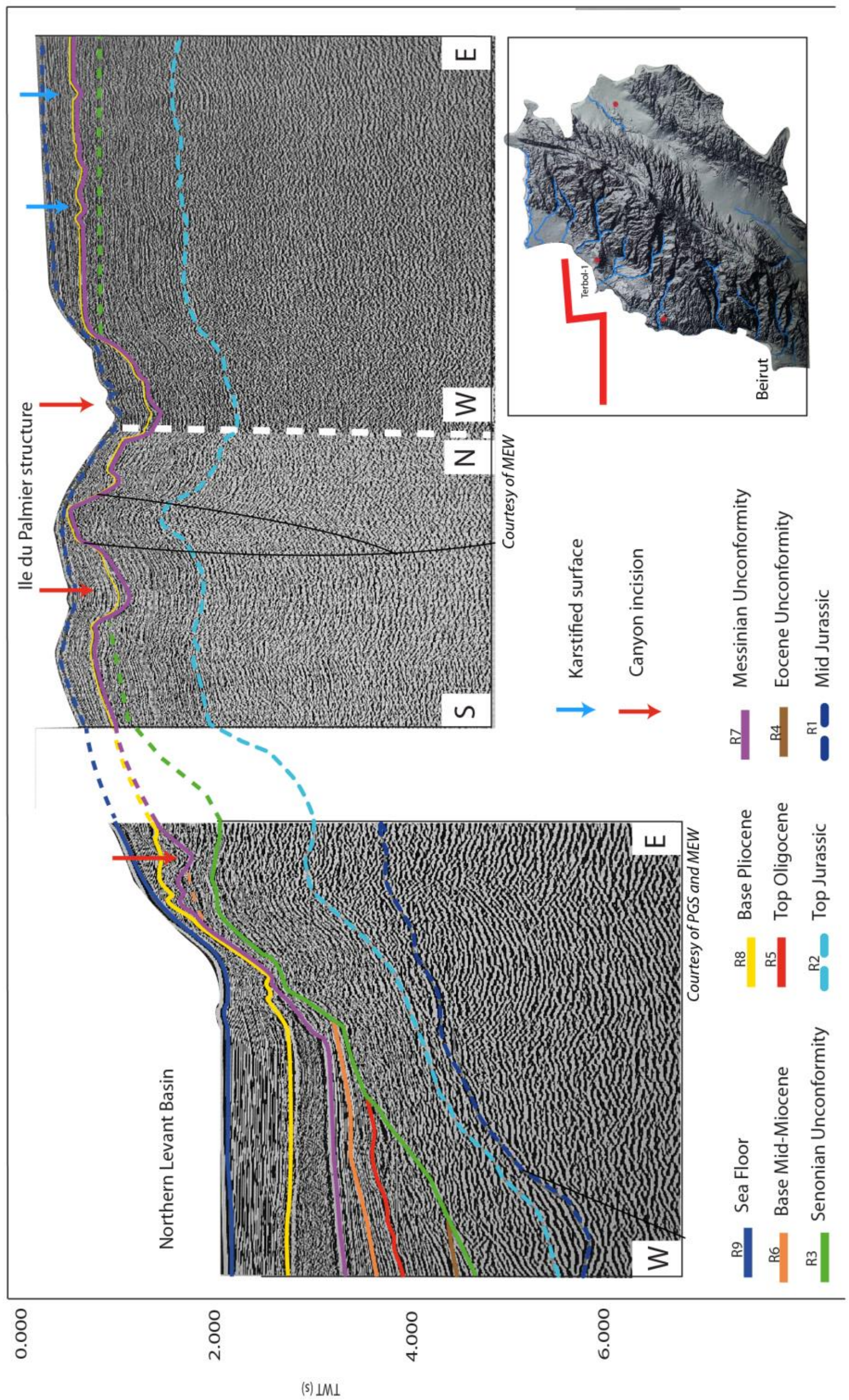


Fig5.15. Correlation between shallow marine and deep marine seismic profiles revealing the shelf extension along northern Lebanon and the transition from the Levant margin into the basin. Note the presence of deeply incised canyons along the Levant shelf.

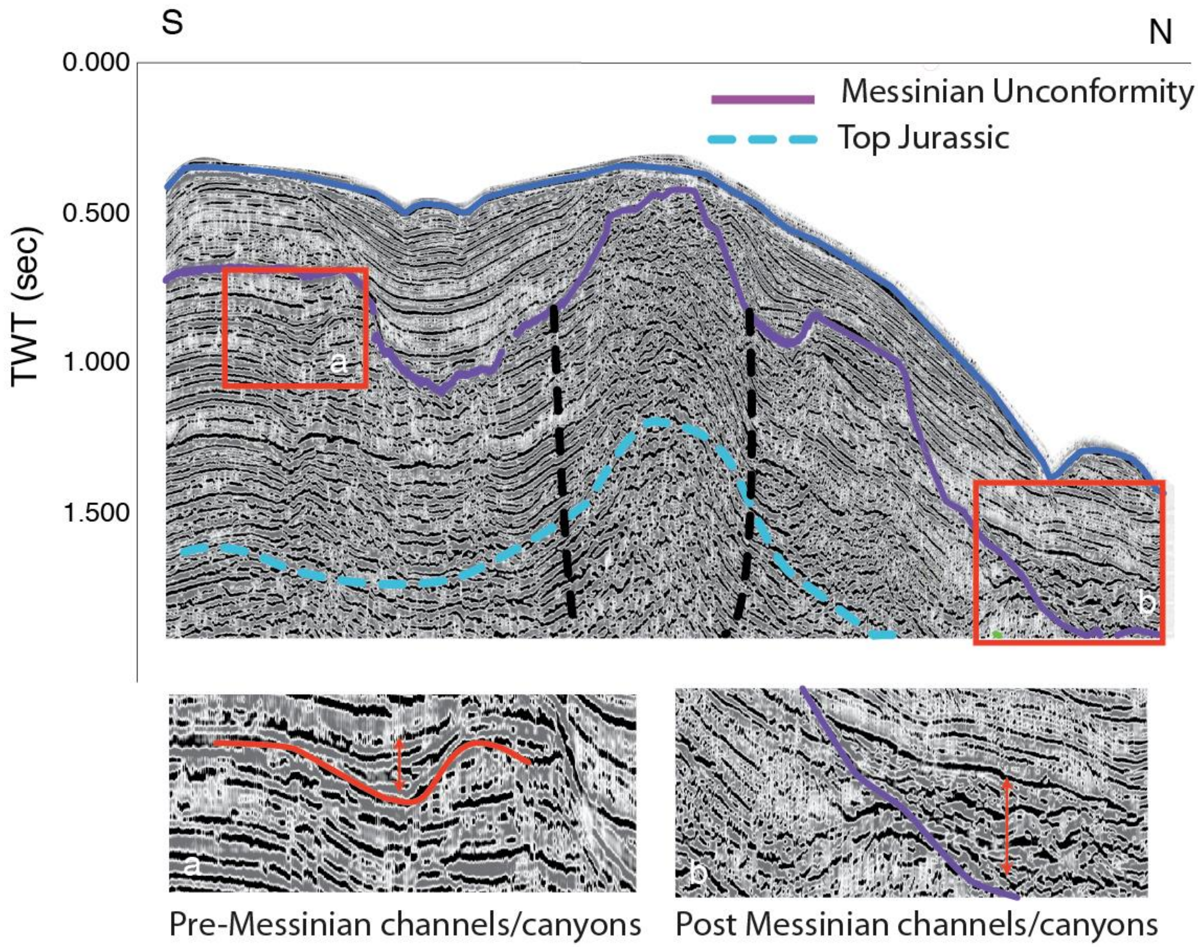
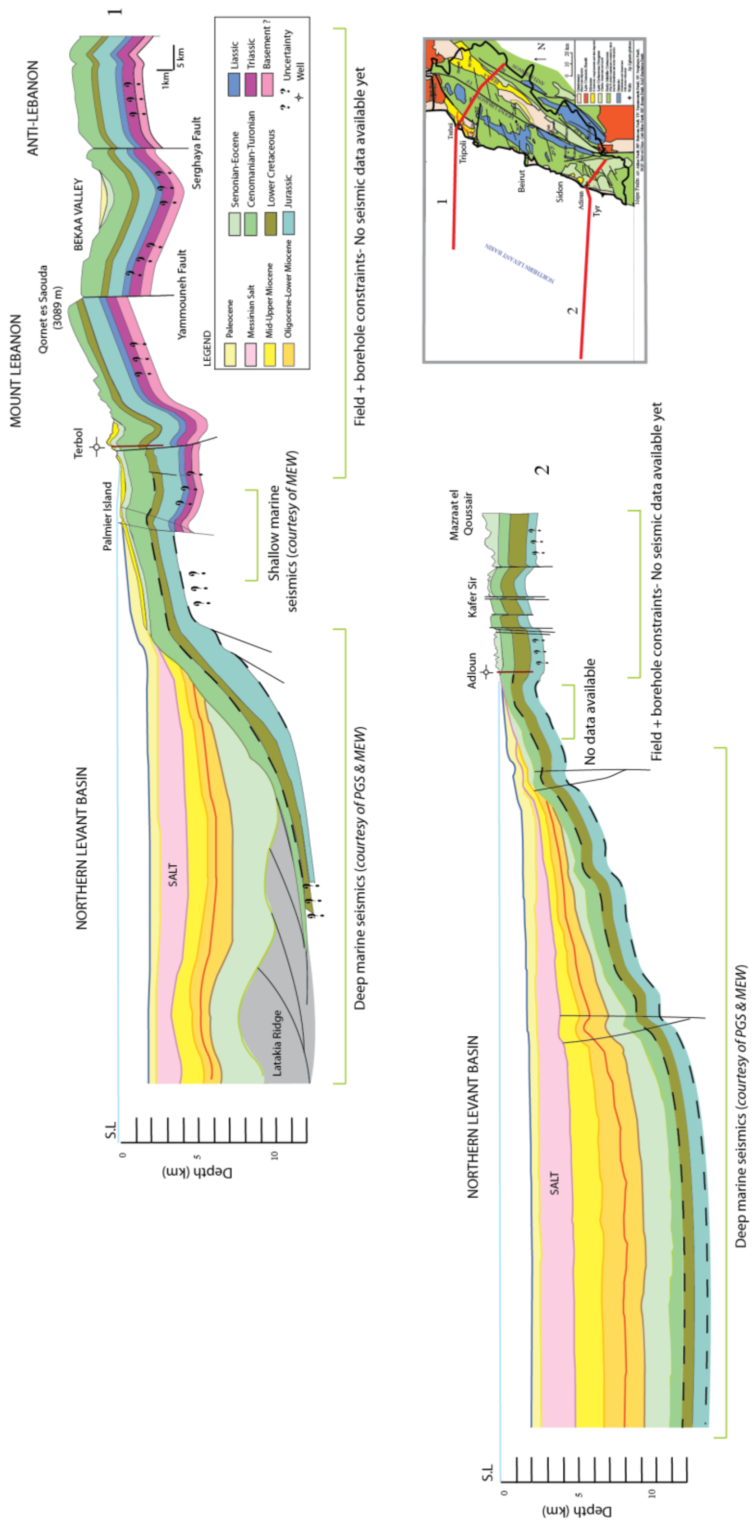


Fig5.16. Seismic profile (GL93-022A) showing the Ile du Palmier structure affected by major Messinian canyon incisions (refer to Fig.2.3 for location). The identification of pre-Messinian channels/canyons in the proximity of major Messinian canyons could support the hypothesis of successive localized canyon incisions linked with the marginal uplifts and sea level lowstands in the Upper Mesozoic and Negene.

Fig5.17. Onshore-offshore tentative correlations of northern and southern Lebanon based on the available seismic, borehole and field data sets.



II Sedimentary infill of the northern Levant Basin

This paper was presented at the 11th Offshore Mediterranean Conference (OMC) and Exhibition in Ravenna, Italy, March 2013. It was selected for presentation by OMC 2013 Program Committee following review of information contained in the abstract submitted by the authors.

The tight collaboration with PGS has resulted in the publication of the following extended abstract entitled “Aspects of the depositional history of the Levant Basin, offshore Cyprus and Lebanon” at the OMC conference under Fürstenau et al. (2013).

Synopsis

The importance of this article lies in unraveling geomorphologic features offshore Lebanon on a new 3D data set (courtesy of PGS) bringing further constraints to the offshore conceptual model proposed by Hawie et al. (2013b).

A focus on the Miocene and Pliocene rock units (proven reservoirs in the southern Levant Basin) reveals a diversity of sedimentary pathways expected to contribute to the infill of the northern Levant Basin offshore Lebanon. The 3D published data allude to the need for further source to sink investigations along the Levant region (refer to chapter 6)

- Several canyons and conduits leading into the northern Levant Basin have been identified and mapped based on RMS amplitude extractions over specific Miocene and Pliocene intervals.
- These conduits include channelized systems developing into lobes distally, which could have delivered clastic material from the Levant margin into the basin.
- Three main sedimentary pathways have been identified on the seismic data for the Miocene (i.e., Latakia region, Levant margin, and the Nile Delta deep-sea cone).
- N-S trending channels observed along the Lower Pliocene unit allude to the continued influx of sediments from the south into offshore Lebanon.

Aspects of the depositional history of the Levant Basin, offshore Cyprus and Lebanon

J. Fürstenau, *Petroleum Geo-Services,*
N. Hawie, *Université Pierre et Marie Curie-CNRS and IFP Energies nouvelles,*
J.Comstock, C.J. Lowrey, *Petroleum Geo-Services.*

ABSTRACT

The giant gas discoveries of Tamar, Leviathan and most recently Aphrodite, found within the Oligo-Miocene strata of the Levant Basin, have proven the significant hydrocarbon potential of the Eastern Mediterranean. Nevertheless, the region can still be considered underexplored and it is likely that deeper plays will be tested in the very near future.

The geological development of the Levant Basin is complex, and the nature and origin of the basin fill are currently poorly understood. The well data for the Levant Basin is sparse and the Lebanese offshore area remains undrilled. However, valuable information can be obtained from the seismic data acquired across the basin. A dense 2D grid and multiple overlapping new 3D surveys, which provide a regionally consistent 3D seismic coverage, have been acquired. This data provides clearer imaging of the present structural pattern, within the regional context, and allows investigation of the depositional history of the northern Levant Basin.

Several key horizons have been interpreted; providing a stratigraphic framework ranging from Upper Jurassic to present. Several canyons and conduits leading into the northern Levant Basin have been identified on the seismic data and amplitude extraction surfaces over specific Miocene intervals illustrate the distributary pattern of these sediment conduits. These conduits include channelized systems that may have delivered clastic material; from the east and northeast, probably coming off the Levant Margin, and from the south probably from the Nile Delta. The development of these channels coincides with a change in the depositional geometry of the basin that may be attributed to the onset of the final uplift of the Palmyrides.

1.INTRODUCTION

The Tamar, Leviathan and Aphrodite discoveries focused significant industry attention onto the Levant Basin and proved the presence of a working petroleum system in the offshore area. However, no well data is published or released yet and little is known about the nature of the depositional units. In addition there has been little discussion regarding the nature or method of the sedimentary fill of the Levant Basin and limited evidence has only been locally presented.

With such sparse data it is necessary to call upon all possible information and use an integrated approach to address source-to-sink aspects of the Levant Basin. Combining our knowledge of the onshore geology, the sedimentary patterns identified in seismic data, and seismic characteristics defined from offshore areas allows the identification of sediment pathways. These pathways can be placed within specific tectono-stratigraphic contexts and integration of all data allows informed discussion of the likely nature and distribution of the sedimentary sequences.

2.TECTONO-STRATIGRAPHIC FRAMEWORK

Located within the Eastern Mediterranean region, the Levant Basin is a Late Paleozoic/Early Mesozoic rift basin flanked by several tectonic features; the Eratosthenes Continental Block (ECB) and Herodotus Basin to the west, the Nile Delta and associated cone to the south, the Levant Margin to the east and the Cyprus Arc to the north (Fig.5.18).

Three major tectonic phases, each comprising several episodes, have shaped the Levant Margin and Basin (e.g. Walley, 1998; Gardosh et al., 2006; Nader, 2011). From late Palaeozoic to early Mesozoic times the Eastern Mediterranean region was subject to an extensional tectonic regime associated with the opening of the Neotethys. Several episodes of rifting and partial spreading occurred within the area leading to the evolution of the Palmyrides and the Levant Basin. The post rift phase in the Levant Basin was initiated at the end of the Jurassic (Walley, 1998; Brew et al., 2001; Gardosh et al., 2006, Nader, 2011). In Late Cretaceous to Palaeogene time the Levant Basin and margins were subject to a compressive regime resulting in the Syrian Arc folding and linked to the collision of the Afro-Arabian plate with the Eurasian plate. During this period many of the extensional faults associated with the preceding rift phases were inverted, with the orientation of individual segments of the Syrian Arc reflecting the former rifting axes (Walley, 1998).

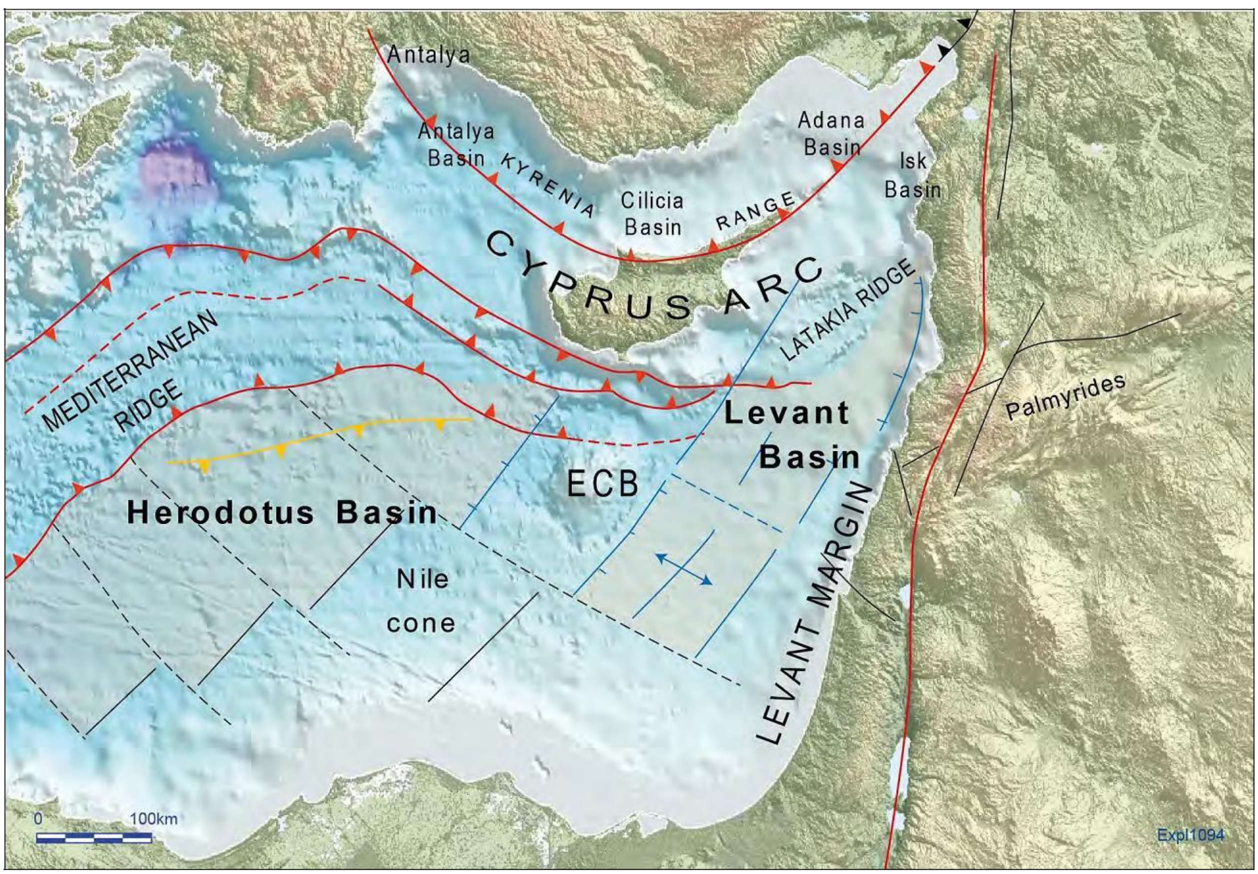


Fig5.18. Structural overview of the Eastern Mediterranean region.

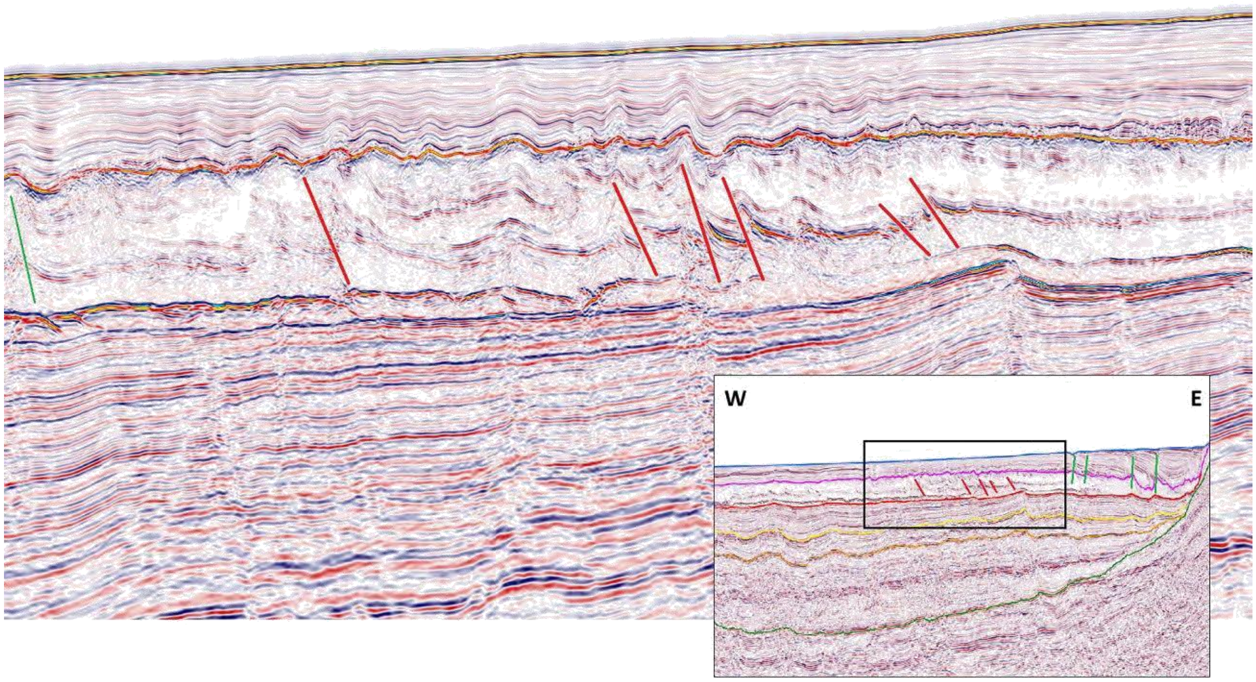


Fig5.19. Close up of W-E trending seismic cross section through the Levant Basin offshore SE Lebanon illustrating incipient salt mobilisation.

The initial closure of Neotethys led to the deformation and subduction and/or accretion of its margins against Eurasia in the areas of present day Cyprus and southern Turkey. Evidence of Neotethian crust obduction can be found in the NW Syrian Baer Bassit and in the Mamonia Complex of western Cyprus (Gardosh et al., 2011). During the Late Eocene to Late Oligocene the Levant Basin was affected by a second episode of continent-continent collision that shaped the Levant Margin.

The third major tectonic phase affecting the Levant Basin came with the development of the left lateral, strike slip Levant fracture system in early to middle Miocene times. Displacement along the system is associated with the opening of the Red Sea (Walley, 1998; Brew et al., 2001) and the increased northwest plate velocity of the Arabian plate relative to the African plate.

In addition to the deeply rooted movements, the youngest succession in the Levant Basin is subject to thin-skin tectonism due to salt mobilisation (Fig.5.19). Normal faulting is seen along the margin side while downslope, in the subsiding basin, reverse faulting affects salt layers and leads to shortening and buckling of the intercalated and overlying sediments. Salt diapirism is also noted in some localised areas in the Levant Basin.

The Levant Basin hosts a sedimentary column of approximately 12 km with sediments ranging from Jurassic/Cretaceous to Recent in age (Fig.5.20). The Mesozoic succession is primarily deepwater carbonates in the basin and platform carbonates closer to the shelf. Sand and shale are seen closer to the margin in channelized deposits, talus debris fans and in more distal fan complexes (Gardosh et al., 2011). Above the regional Eocene unconformity are primarily marl and shale with sand in channelized systems terminating in deep sea fan deposits. The Messinian is represented by a regionally extensive thick package of evaporites.

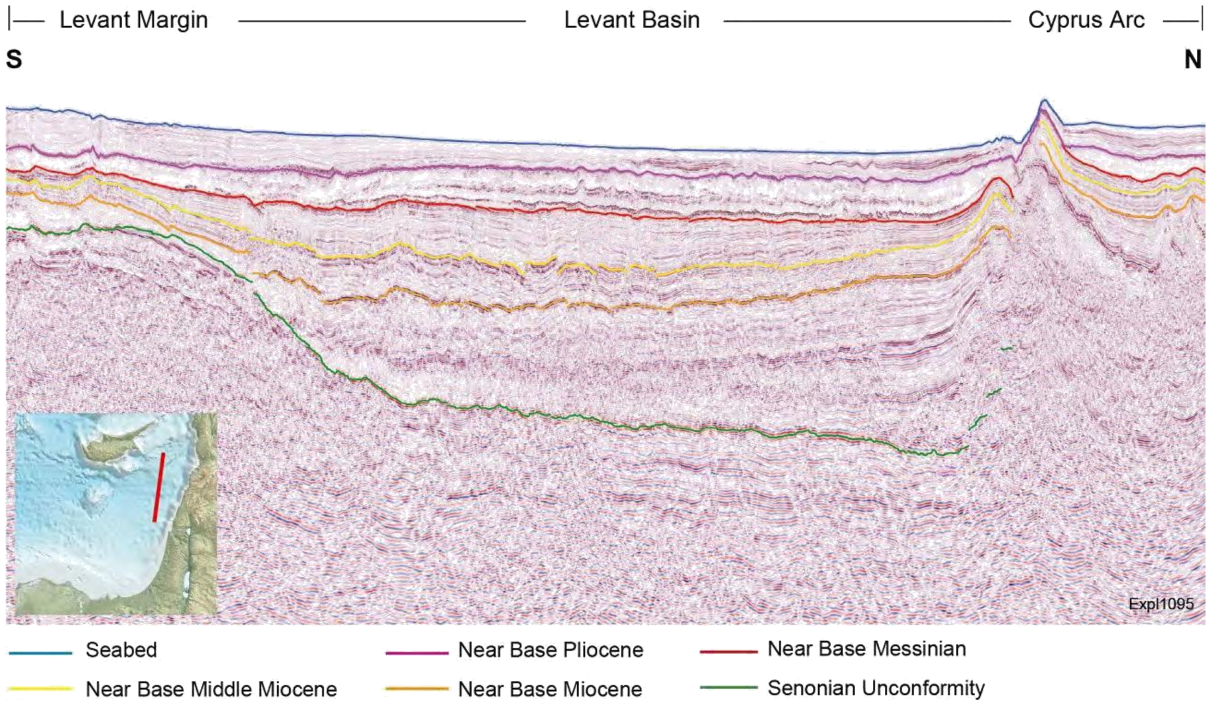


Fig5.20. S-N trending seismic cross section through the Levant Basin.

The use of seismic stratigraphy allowed to subdivide the basinal succession into several units. Six horizons are identified and mapped regionally. The lowermost horizon is the Senonian Unconformity (SenUnc, green) marking the Late Cretaceous carbonate platform drowning and subsequent onset of clastic deposition in the deeper parts of the basin. The Near Base Miocene (BMioc, orange) and Near Base Middle Miocene (BMMioc, yellow) subdivide the pre-salt column. The base of the Messinian evaporite layer is represented by the Near Base Messinian horizon (BMes, red) and the Near Base Pliocene horizon (BPlio, pink) marks the renewed onset of deepwater clastic deposition. The current seabed is represented by the Seabed (SBed, blue) horizon.

3. SEDIMENT SOURCING

Hydrocarbon exploration, dating back to the 1960s, focused attention on the massive hydrocarbon accumulations of the Egyptian Nile Delta province located in Cretaceous, Miocene and Pliocene siliciclastic sediments (Dolson et al., 2005). More recently major gas discoveries in the Levant Basin, mainly in the Israeli and Cypriot sector (Tamar, Dalit, Leviathan, Tanin, Aphrodite, approximately 40 Tcf of reserves; www.nobleenergyinc.com) have shed light on the prospective reservoirs of Oligo-Miocene canyon infill, deep water turbidite and Pliocene clastic mounds and channel systems that floor the Eastern Mediterranean.

The assessment, and reassessment, of deeper Mesozoic source rocks and reservoirs in the Levant Basin continues. Older discoveries of light oil accumulations offshore Sinai (Ziv -1 and Mango-1) and Israel (Helez oil field) (Gardosh et al., 2006, Gardosh et al., 2011) in Lower Cretaceous sandstones reveal the potential reservoir quality of this interval in the Levant Basin. Major regression cycles are noted at the Jurassic-Cretaceous boundary with canyon incisions affecting the Levant slope leading to the development of deep marine turbidite systems and basin floor fans (Dubertret, 1975; Haq et al., 1988; Gardosh et al., 2011).

Thick Lower Cretaceous siliciclastic accumulations, thought to be derived from erosion of the Nubian sandstones of Egypt and northeast Africa, crop out onshore of the Levant margin mainly in Lebanon (Chouf Fm., maximum thickness of 400 m; Dubertret 1975), Syria and Israel (Chouf Fm. equivalents). Recent reviews, using seismic and well data, of thick reservoir strata from the Oligo-Miocene (Gardosh et al. 2008, Nader 2011) has increased interest in the possible distribution and provenance of these units in the Levant Basin. No wells have yet been drilled in the Syrian and Lebanese offshore so the extent of these siliciclastic systems is yet to be proven. However, several source areas have been proposed for provenance of siliciclastic rich sediments though to be deposited in the Levant Basin after the onset of Late Eocene major geodynamic events affecting the Afro-Arabian Plate.

3.1 Cenozoic sedimentary pathways and sediment sources from the south and east

Volcanism and regional up-doming under Eastern Africa, which eventually resulted in the opening of the Red Sea and Gulf of Suez (i.e. Afar plume in Ethiopia and Yemen), also produced a northward tilting of the African Plate. This tilt favored sediment transport directed from central-eastern Africa towards the Levant Basin through the Nile Delta drainage system. The abundant palaeo-climatic data gathered for the Nile catchment area indicate that wet climatic conditions from the Oligocene to Pliocene, combined with sea level fluctuations, resulted in extensive erosion of granite from the Red Sea rift shoulders and exposed Nubian siliciclastics in Egypt and Sudan (Said, 1981; Macgregor, 2012). This erosion provided an ample sediment source, not only for the Nile Delta but, through channelized systems, also to the northern part of the Levant Basin (Dolson et al., 2005; Gardosh et al., 2008; Macgregor, 2012). The Nile Delta province has been referred to as the main sediment source that could explain the abnormally thick Oligo-Miocene unit in the Levant Basin (Steinberg et al., 2011).

Small volumes of sediment derived from the remnants of fluvial Miocene sandstones (thought to have been produced from the erosion of neighboring Nubian sandstone in Egypt and Jordan) were trapped in the Israeli hinterland (i.e. Hazeva Formation) due to subsidence movements along the Dead Sea Rift. These, in turn, form the source for sediment delivered to the easterly-derived Miocene canyon systems incising the Israeli shelf and extending into the offshore (Gardosh et al., 2008). A major provenance area in Arabia has been discredited because no major canyons or submarine fans have yet been identified. However, more investigations focused upon Arabian palaeo-drainage systems are needed.

3.2 Cenozoic sedimentary pathways and sources from the north

The presence of sandstone, clay and conglomeratic intercalations of Lower to Middle Miocene age around the Nahr el Kebir depression, Latakia region, Syria has been taken to indicate the presence of a potential northern siliciclastic source on the Levant margin that could feed into the Levant Basin (Ponikarov et al., 1966; Brew et al., 2001; Hardenberg & Robertson, 2007; Bowman, 2011). Continental siliciclastic sediments of Middle Miocene age have also been identified in the Hermel area in the northern Bekaa valley in Lebanon (Dubertret, 1975).

Seismic data from offshore Syria (Bowman, 2011) point to the presence of laterally extensive, mounded, variable amplitude reflectors in the north-eastern Levant Basin. These are interpreted as Lower Miocene deep-water turbidites and basin-floor fans intercalated with pelagic marls and shales that could act as potential reservoirs (about 600 m in thickness). Lower Miocene deposits thicken landwards suggesting a provenance along the Levant Margin (Bowman, 2011). The onshore Miocene continental units are also present around Damascus (i.e. fan deposits of about

550 m of total thickness) and in the Palmyride area. The provenance area for this unit is thought to be the erosion of the distant Arabian platform crystalline basement (Ponikarov et al., 1966).

During Mid to Late Miocene time, major, and multiple, onshore deformation events linked to the evolution of the Levant Fault System and the continued collision of Arabia with Eurasia led to the development of major mountain chains (e.g. Mount Lebanon). The regional uplift and the Tortono-Messinian regressional cycles resulted in exposure and erosion of the Levant margin with significant quantities of clastic material being deposited in palaeotopographic lows (e.g. Levant Basin).

The interpreted Middle and Upper Miocene seismic package of the Latakia and northern Lebanese offshore includes the presence of distal turbidite lobes and channels, as interpreted from chaotic seismic facies with high amplitudes (Lie et al., 2011; Bowman, 2011). These sediments represent the basinal extension of the Miocene continental facies observed onshore.

The above indicates the existence of a wide variety of potential sediment sources and pathways providing the sediment for the infill of the Levant Basin (Fig.5.21). Future investigations should also take into consideration the likely variation in reservoir quality associated with the different provenance areas and depositional environments.

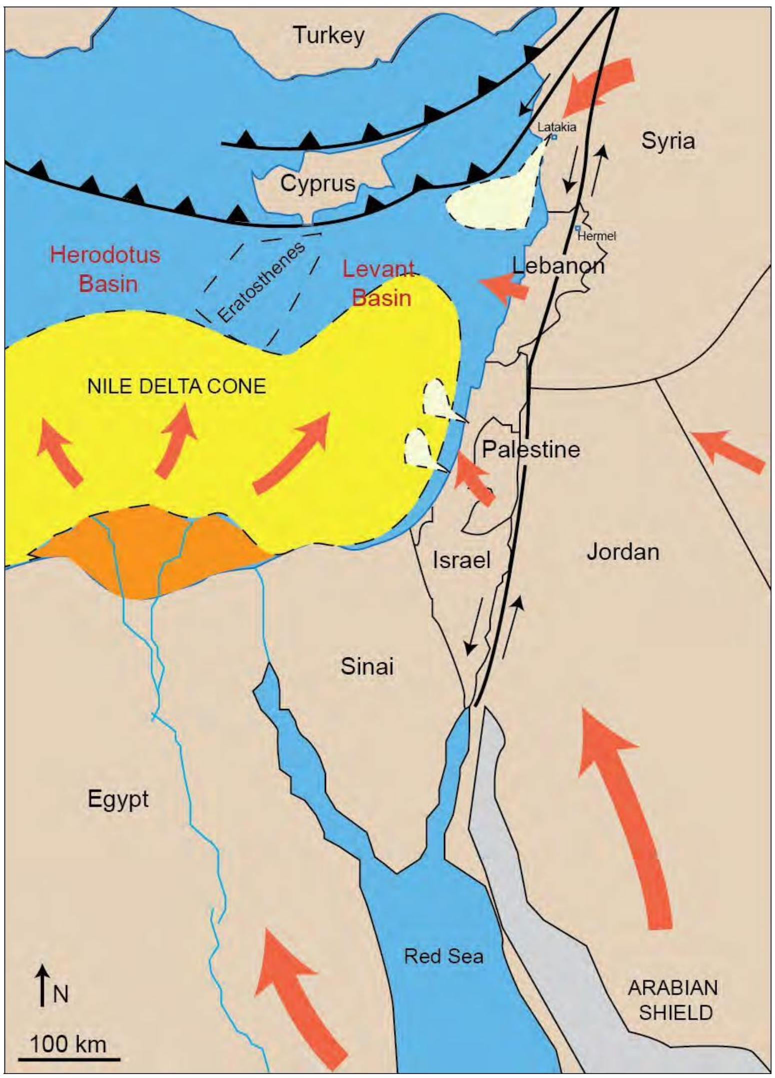


Fig5.21. Miocene sedimentary sources and pathways. Red arrows indicate the transport direction.

3.3 Levant Basin distributary patterns

It is expected that the sediment source areas discussed above can be linked to distributary patterns in the Levant Basin and analysis of seismic data can reveal the sediment dispersal and depositional loci for specific time intervals.

The Lower Miocene package, proven to be prospective in the southern Levant Basin, has a maximum thickness around southern Lebanon (Fig.5.22). The package then gradually thins towards the eastern Levant Margin and towards the southern Levant Basin facing Israel and north facing central and northern Lebanon. Little is known about the geodynamic/structural history of this offshore area but the outline of this thick body suggests fan-like deposition with a south-western source (Fig.5.22).

Seismic cross sections (2D coverage) from that area suggest the presence of individual depositional fans; most likely fed by channelized systems originating from the south-southwest (Fig.5.23). These can be identified as high-amplitude packages within the succession in both the Upper and Lower Miocene sections. A windowed rms amplitude extraction map view, from the Upper Miocene section, is shown in Fig.5.23 and shows the highest amplitude reflections correspond with the thickest areas in Fig.5.22 above.

An amplitude map of the uppermost Miocene seismic interval located directly below the Messinian evaporites has been generated showing several significant palaeo-topographic features in northern Lebanon (Fig.5.24). The general direction of sediment transport is directed from the northeast to the southwest with channelized systems developing into fan and lobe-shaped distributary patterns. These channels imply the presence of sediment sources in northern Lebanon and Syria within this time period. After cutting through the margin slope the main channel trends more southerly and develops more of a fan or lobe-shaped morphology, which itself shows minor channelized features. These features are interpreted as distributary channels. The image also visualises the NW-SE trending expression of the recently described Piano Key Faults (Kosi et al., 2012).

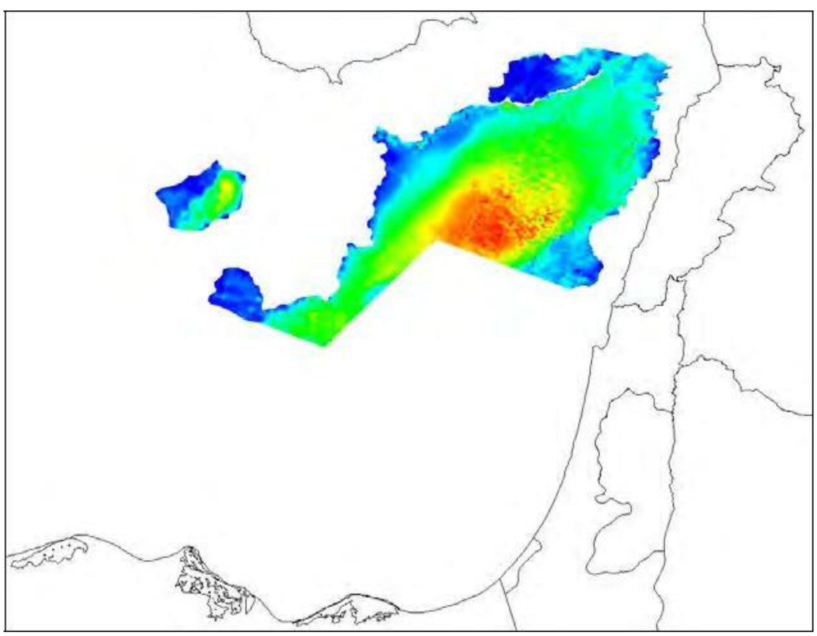


Fig5.22. Isochron map of the Lower Miocene. Warm colors represent greater, cool colors smaller, time differences.

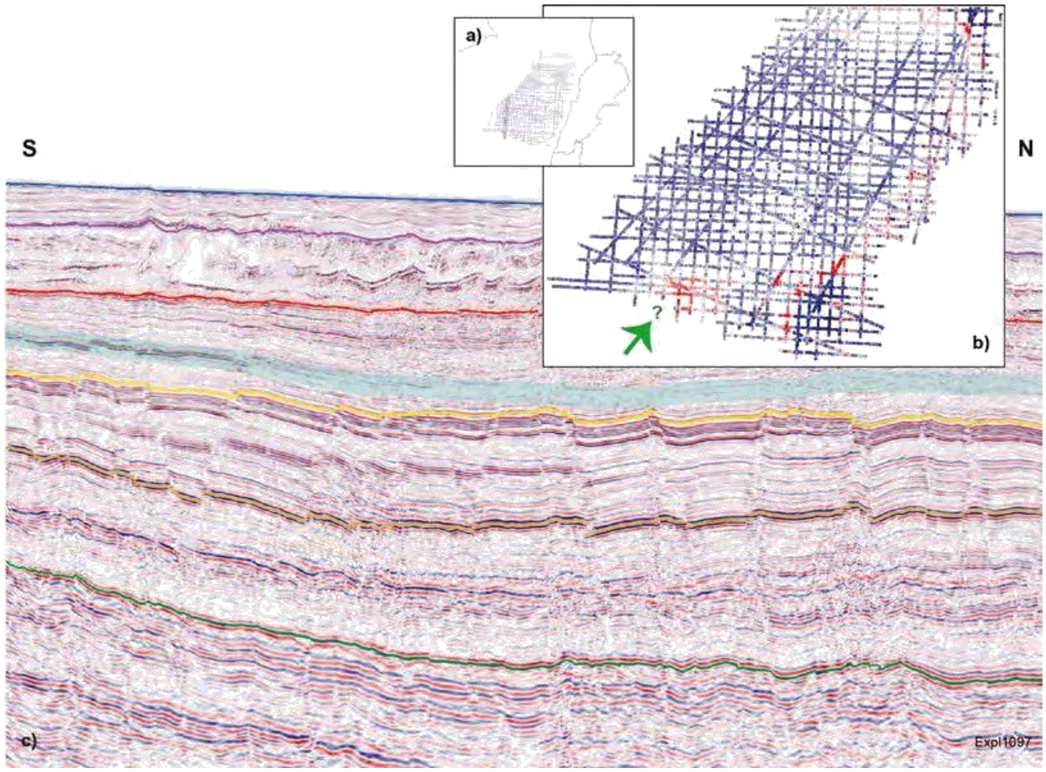


Fig5.23. Upper Miocene fan systems. (a) Seismic line overview and (b) windowed rms amplitude map covering a high-amplitude interval (blue window in the (c) seismic cross section) in the central Levant Basin. On the amplitude map high amplitudes are shown in red, low amplitudes are in blue colors. The green arrow indicates potential sediment transport direction. Note a second high-amplitude interval in the Lower Miocene section.

Above the Messinian evaporite sequence, in the Early Pliocene seismic unit, the sediment routing appears to initiate from the southwest again. The amplitude map in Fig.5.25 shows a variety of interesting features:

(1) Numerous extensive SW-NE trending channels (i.e. oriented parallel to the Levant Margin) are interpreted to originate from the south-southwest carrying sediment to the north-northeast and developing into a fan distributary system around the north-eastern part of the Levant Basin. These sedimentary systems are thought to represent the distal extension of the Nile Delta Cone with sediments being sourced from the African Margin and transported initially by the Nile River.

(2) A series of normal faults, trending parallel to the Mesozoic Levant Margin, cut through the Pliocene sediments and are a result of the extension above the Messinian salt as the salt and overlying sediments mobilise basinward. (3) The third, and related, feature is southwest-northeast trending ridges that are located in a farther basinward position compared to the more marginally located normal faults. These ridges result from the shortening of the Pliocene sediments as they move basinward above the mobilised salt. Reverse faulting in the Messinian evaporites is expressed by the anticlinal structures of the Pliocene sediments.

As the incipient salt mobilization affects the total post-Messinian column, the seabed also shows NE -SW trending anticlinal forms alluding to continued recent compressional deformation (Fig.5.26). The amplitude map of the seabed offshore Lebanon visualizes the recent situation of sediment dispersal in the northern part of the Levant Basin. Numerous channelized canyons can be identified which direct sediments from the Levant Margin far out into the basin with minimal nearshore deposition. Across the Jounieh Plateau NW of Beirut these channels appear partially redirected and/or abandoned. Channels originating in northern Lebanon are visible. Sediment delivery off the Levant Margin however seems restricted in comparison to the extent of the older systems.

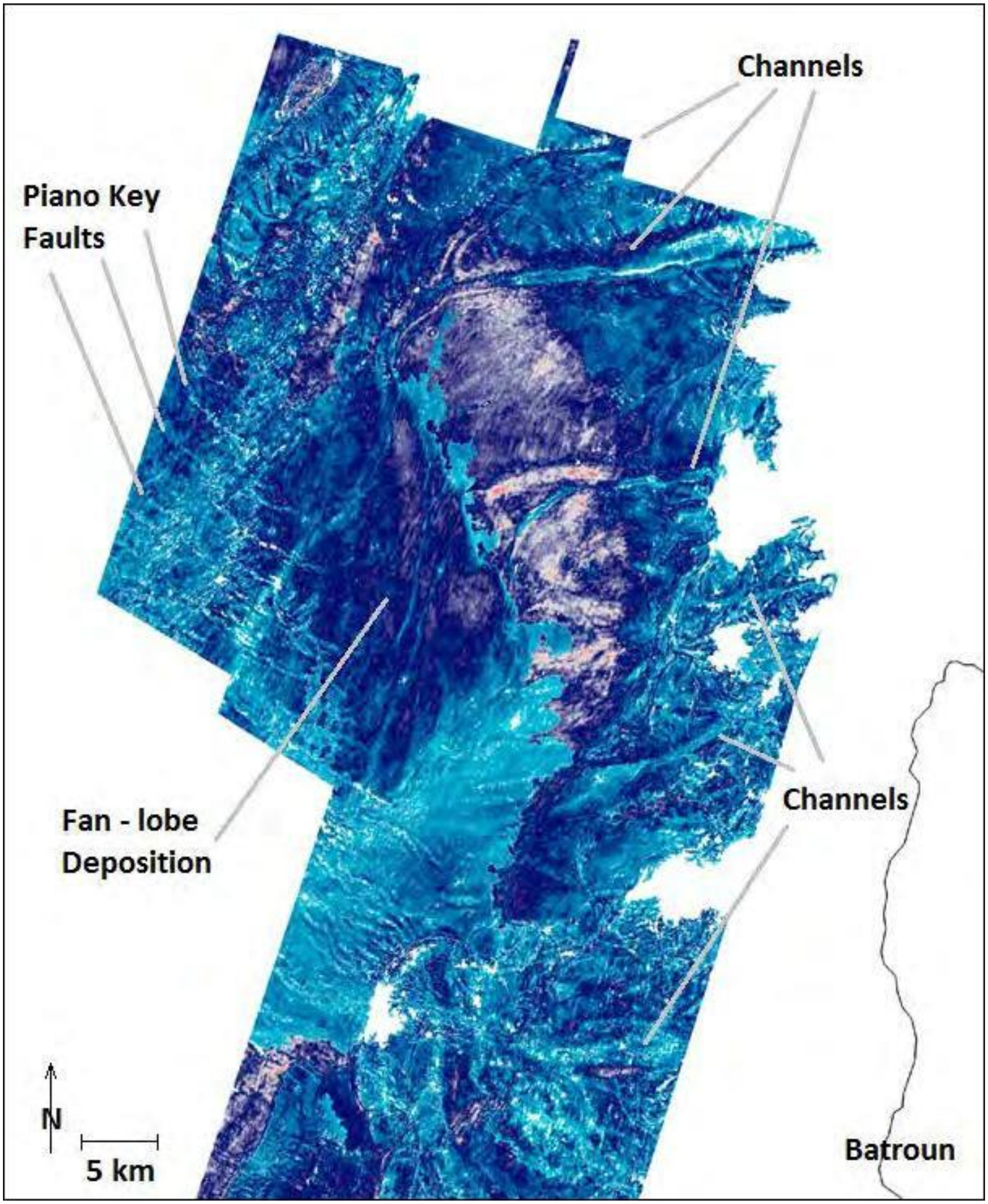


Fig5.24. Late Miocene fan system with feeder and distributaries. On the amplitude map low amplitudes are shown in blue, higher amplitudes in light blue and highest amplitudes in red colors. NE-SW trending channels are clearly visible as well as fan topography and Piano Key Faults.

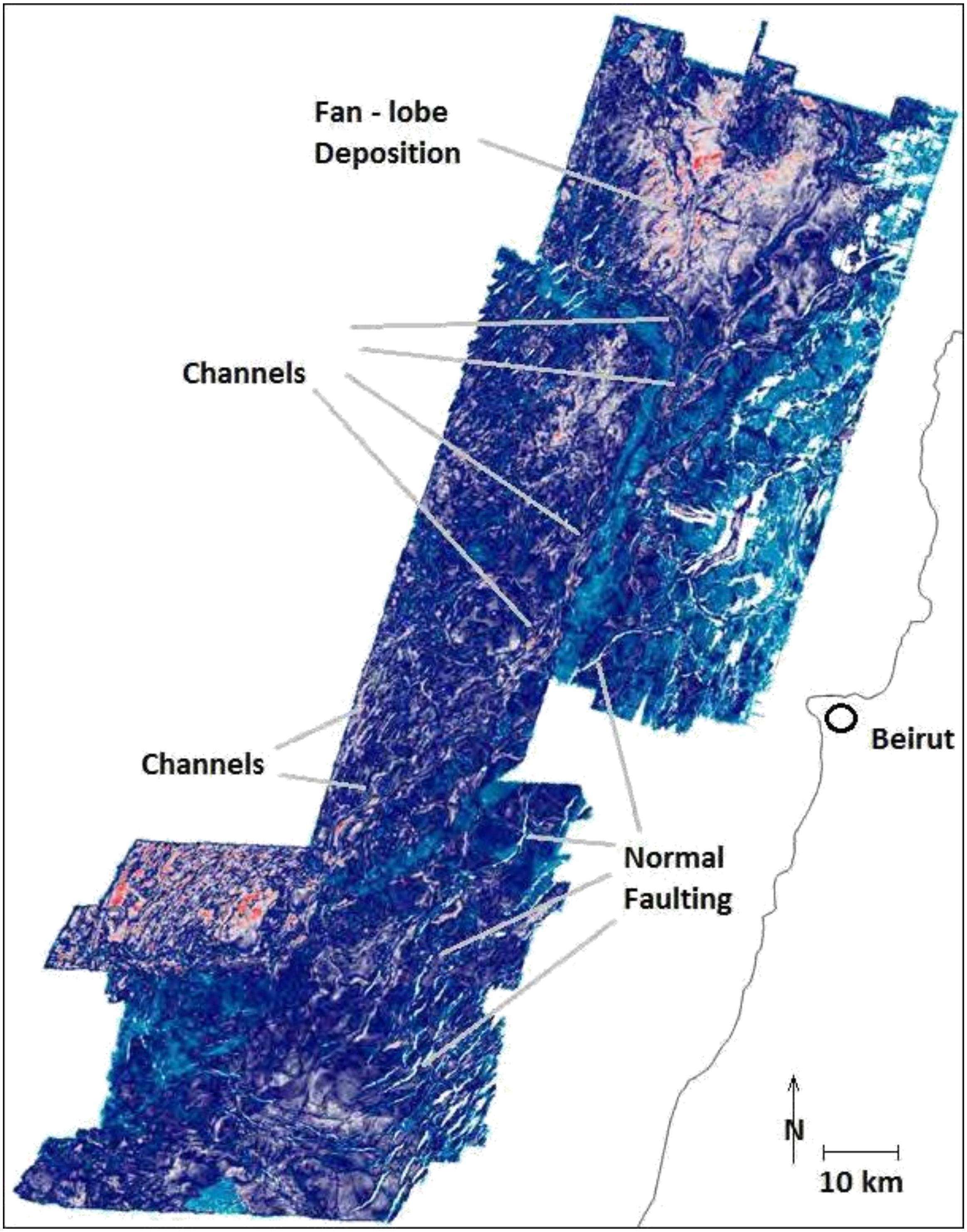


Fig5.25. Amplitude map showing the Early Pliocene distributary system. Low amplitudes are shown in blue, higher amplitudes in light blue and highest amplitudes are in red colors. Notice channel and deposition systems inferred to originate from the Nile Delta. (Note: The image shows data from an intermediate processed cube with rim zone areas of low fold coverage. Full fold coverage will be available in the fully processed volume.)

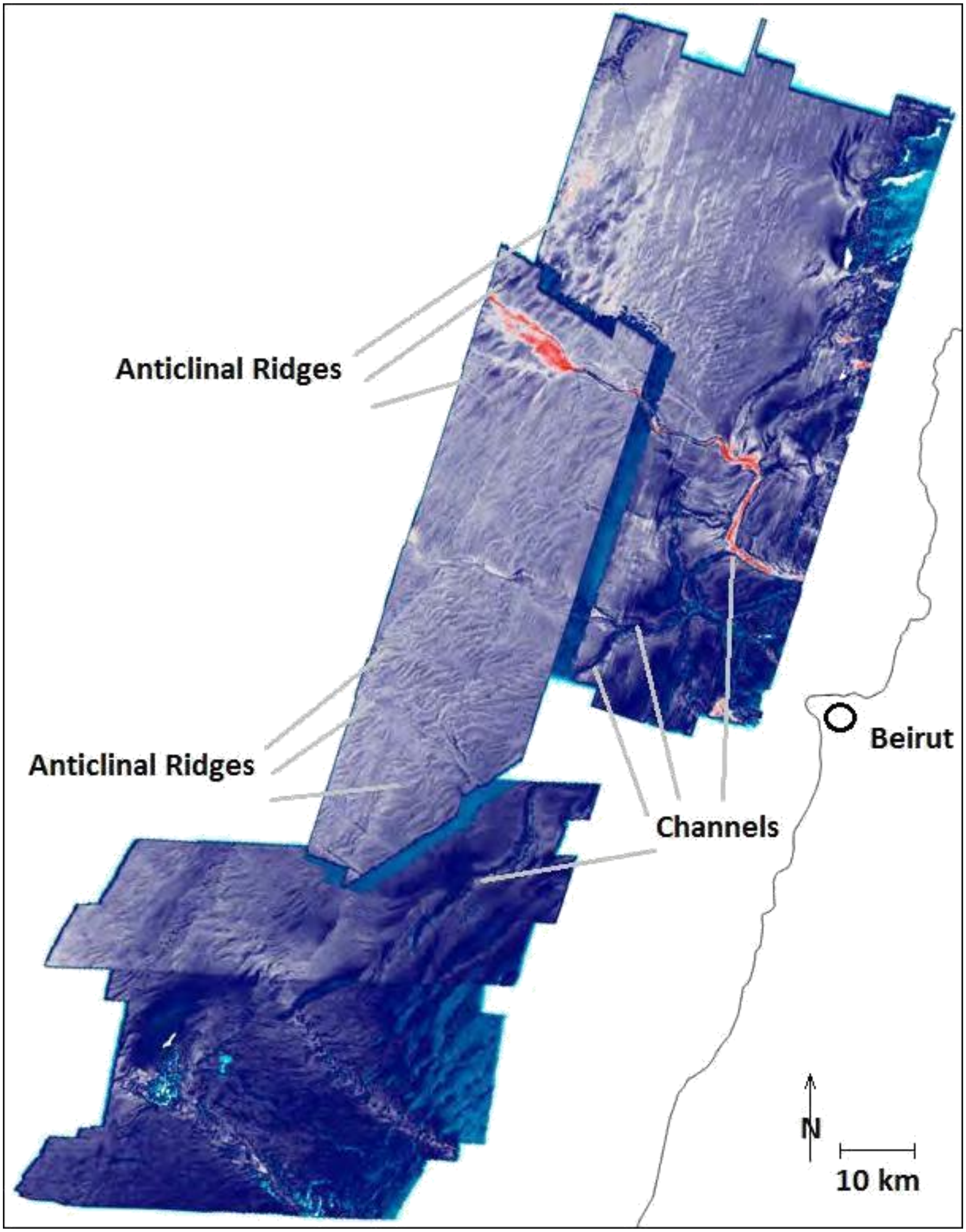


Fig5.26. Recent channelling and related deposits at seabed. Low amplitudes are shown in blue, higher amplitudes in light blue and highest amplitudes are in red colors. Channelized canyons originating from the east are offset by faulting. Anticlinal ridges form basinward as the Messinian salt and overlying Pliocene sediments are mobilized. (Note: The image shows data from an intermediate processed cube with rim zone areas of low fold coverage. Full fold coverage will be available in the fully processed volume).

4. CONCLUSIONS

The Levant Basin is now a proven prospective region but the Eastern Mediterranean can still be considered a frontier area with respect to hydrocarbon exploration. Very limited well information is available and accordingly very little is known about the nature and distribution of sediments. Seismic data serve as a valuable tool to approach analysis of the basin development.

The major sourcing of Levant Basin sediments is proposed to be to the south and is most likely linked to the development of the Nile cone and associated fan systems. The uplift and tilt of the African plate is seen as the main driver for sediment transport, and seismic data from the Levant Basin suggests a northward transport of sediments for younger time intervals (Late Miocene).

For the Late Miocene, seismic data also show southward-directed sediment dispersal in the northern part of the Levant Basin. Sediment sourcing from the Levant Margin is thought to contribute to the Levant Basin infill at all times but although important with respect to the prospectivity of the basin, it is not regarded as the main contributor to its infill.

End of Article Fürstenau et al., 2013

CHAPTER VI

Source to Sink Assessment of the Northern Levant Basin

I. Principles of forward stratigraphic modeling by Dionisos

Conceptual geological models are still being tested through analogue and numerical modeling techniques that allow geoscientists to predict the impact of several factors (e.g. tectonic deformation, subsidence versus uplift, eustatic sea level fluctuations, sediment flux) on the sedimentation of a basin (Shafie & Madon, 2008)

Numerical models fall under two main categories:

- Deterministic models are based on the hypothesis that any specific input condition is associated to a set output. However the main challenges reside in the chaotic and unpredictable behavior of sedimentary systems as channel meanders (Granjeon, 1997)

- Stochastic models use probability in order to explain non-deterministic systems

Dionisos is a deterministic 3D multi-lithology forward stratigraphic model that simulates basin infill on regional spatial and time scales (Granjeon, 1996). It reproduces the net product of sediment supply, transport and accommodation with regards to uplift, subsidence and sea level fluctuations.

Dionisos model combines empirical water and gravity-driven diffusion equations in order to simulate the sediment transport and deposition: (1) Linear slope-driven diffusion (transport proportional to slope) also referred to as hill-slope creeping and (2) a non-linear water and slope-driven diffusion equation known as water discharge driven transport (refer to Willgoose et al., 1991 and Tucker & Slingerland, 1994) leading to the following sediment transport equation:

$$Q_S = -(K_s + K_w Q_w^n S^{m-1})\, \vec{\nabla}\, h$$

Qs: sediment flux [km2/y]; h [m]: elevation; Ks and Kw : diffusion coefficient respectively for the slow creeping transport and the faster water-driven process [km2/y]; Qw: dimensionless local water discharge at the cell (normalized by 100 m3/(s.km)); S is the local gradient of the basin slope; n and m are constant, usually between 1 and 2.

Since the successive studies of Culling (1960) and Carson & Kirkby (1972), diffusion equations have been utilized in geological and geomorphological investigations to represent moderate and large-scale spatially averaged sediment transport. Hydraulic equations presented by Begin et al. (1981) and Paola et al. (1992) have also been used in order to mimic sediment transport along continental settings (e.g. fluvial systems, alluvial fan; Murray & Paola, 1994; Jordan & Flemings, 1991).

With the development of high-resolution sea bottom imagery/bathymetry the concept of sediment transport through diffusion has been extended seawards to represent deltas (Kenyon & Turcotte, 1985), continental shelves (e.g. Jordan & Flemings, 1991; Granjeon, 1996) and deeper marine basins (e.g. Einsele et al., 1996; Tinker et al., 2008).

Through the past decade a focus on a wide set of drainage systems allowed to depict global generic relationships to define some of the parameters of the diffusion equation that permits to assist geoscientists in assessing ancient source to sink systems where lack of sufficient data is noted (e.g. Milliman & Syvitski, 1992; Sømme et al. 2009a,b).

A look at more than 280 modern river systems have been proposed by Milliman & Syvitski (1992) and Dai & Trenbertch (2002) who revealed that:

- Water discharge (Qw) increases with the drainage area (Fig.6.1a).
- Sediment load increased with the increase in the drainage area (Fig.6.1b).
- Runoff (r=Qw/A) decreases slightly with the increase in drainage area (Fig.6.2).

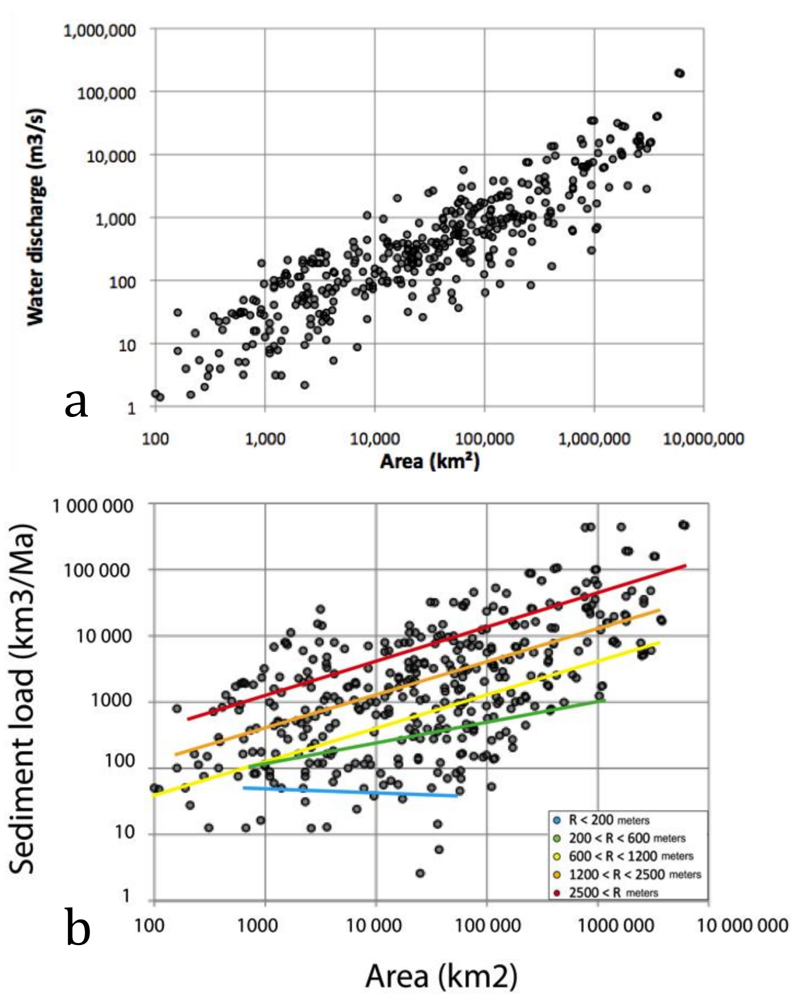


Fig.6.1 Global relationships showing (a) increase in water discharge (Qw) with drainage area (Dai &Trenberth, 2002) and (b) increase in sediment load with regards to drainage area and relief (R) (Milliman & Sivitsky, 1992)

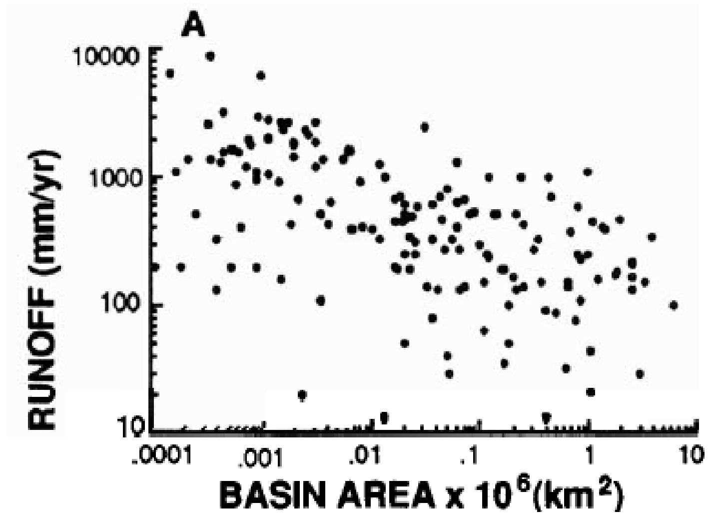


Fig.6.2 Global relationships showing the decrease in runoff with basin area.

The runoff is affected by relief as small values are observed for lowlands and coastal plains while high values for high mountains (2000 to 5000 mm/y; Fig.6.3). As larger drainage area includes a multitude of smaller drainage systems, a progressive decrease of average runoff is noted for a specific relief depending on its drainage area.

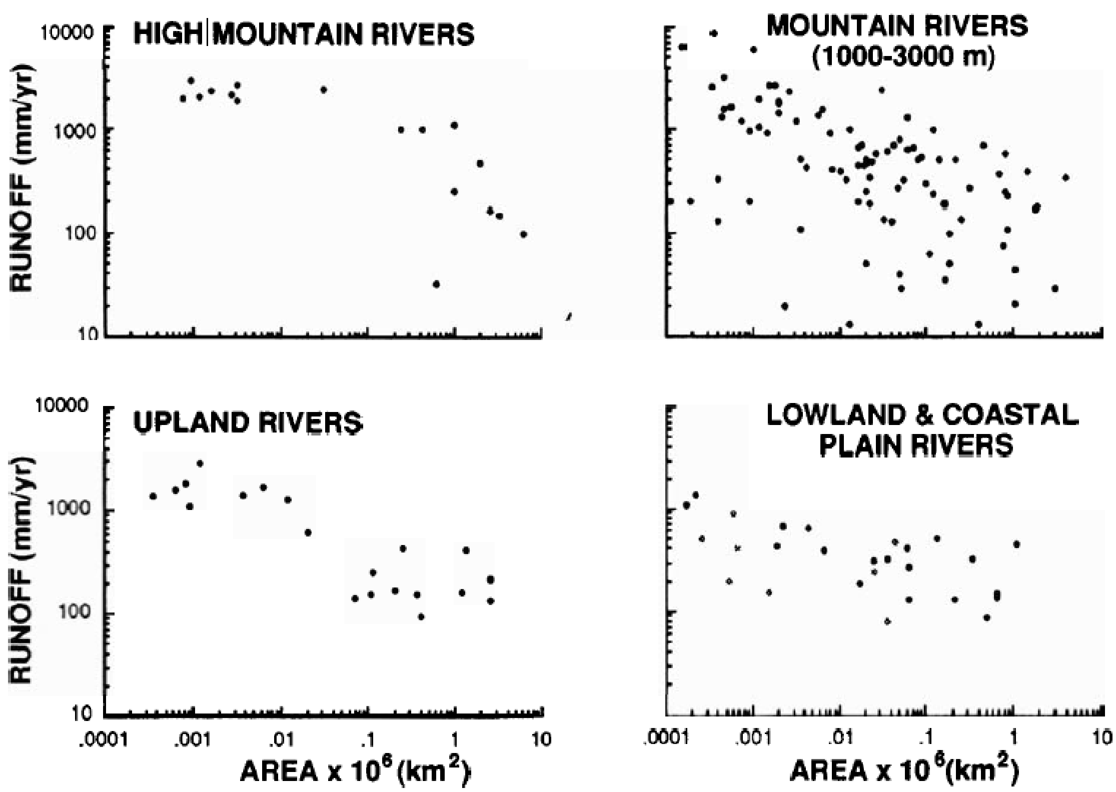


Fig.6.3 Global relationships linking the runoff to the basin area and to the topography (lowland versus highland).

The average diffusivity coefficient represents the ratio between sediment discharge, basin slope: (Average sediment thickness (km) x basin length (km))/ (time span (Ma) x basin slope (m/km)). Diffusive coefficients obey to fuzzy rules related to the behavior of sediments e.g., silt and clay are more diffusive than sand, which is also more diffusive than gravel and cobble. The ration between water-driven and gravity driven coefficient increases with grain size as coarse sediments are more sensitive to flow regimes than fines sediment as the latter are transported easily even with low water discharges Qw (Euzen et al., 2004).

A wide range of diffusivity coefficient values has been identified in the literature for linear diffusion models depending on different case studies (e.g. fom less than 0.01km2/ka (Gawthorpe et al., 2003) to more than $1.6x10^7$ km2/ka (Burgess et al., 2006). In the case of a non-linear equation the sediment flux is proportional to the water discharge and the diffusion coefficients reveal to present lower values than for linear models (Gvirtzman et al., 2013).

The use of numerical modeling to represent geomorphological and geological processes provides the possibility for a wide range of scientists working on different disciplines (including oil and gas) to test many scenarios of basin infill histories. In addition sensitivity studies can be performed in order to better analyze and assess the several impacting parameters on the basin infill.

II. Study area

The Dionisos model comprises the northern Levant margin and basin including onshore/offshore Lebanon, the Palmyrides as well as the northern section of the southern Levant Basin.

A sector of about: 320 km x 320 km2 has been delimited with a grid size of 5x5 km2 (Fig.6.4). The Upper Jurassic to Present stratigraphy has been included in the model in order to be used in future investigations.

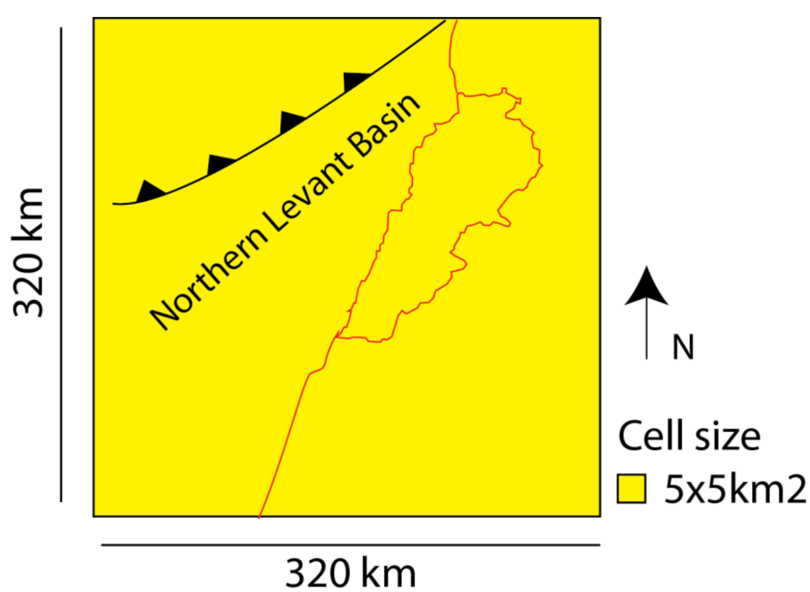


Fig.6.4 Sketch representing the main parameters of the study area modeled.

III. Methodology

III.1 Input data

Two essential input parameters are required to quantify the sediment accommodation (Jervy, 1988) (Fig.6.5a) have been included in the model:

- Isopach maps are used in order to constrain subsidence along the Levant margin and basin (Fig.6.5b).
- Bathymetric investigation permits to account for the depositional environments to be modeled (Fig.6.5.c).

In the next paragraphs the input parameters are presented and described with their related uncertainties.

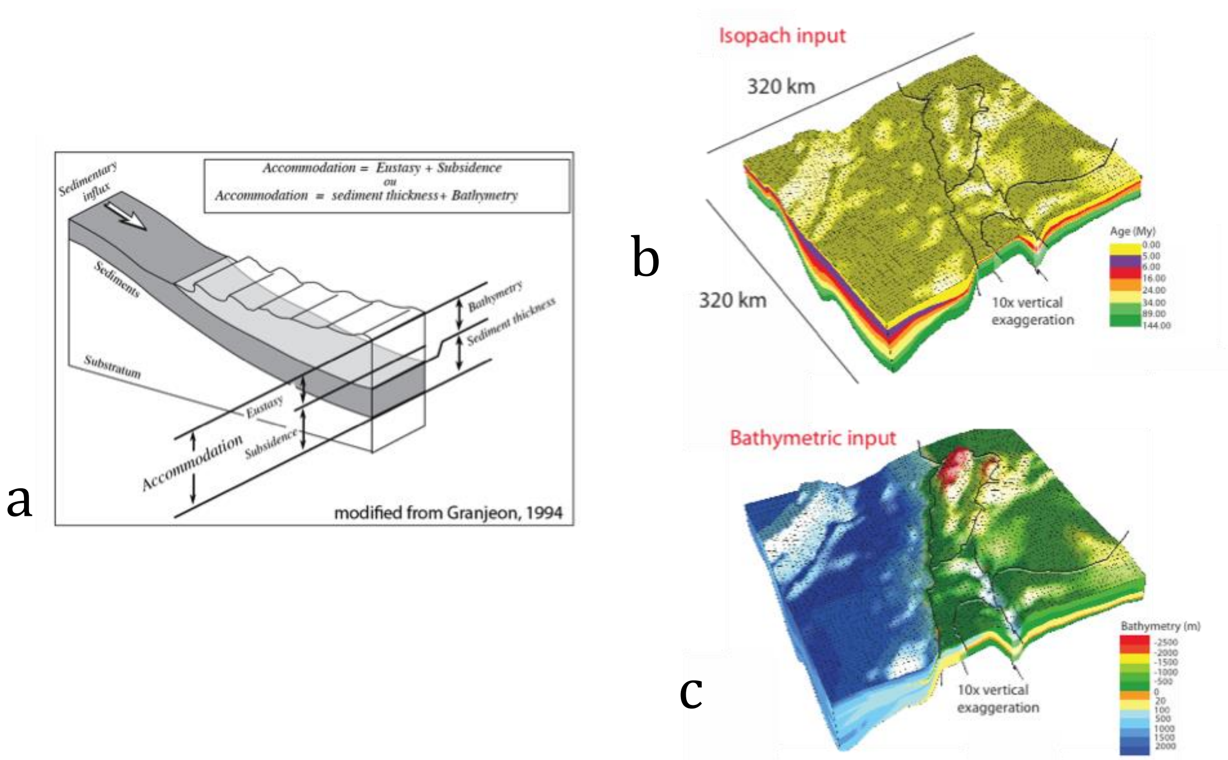


Fig.6.5 (a) Accomodation calculation equations (b) overall static model build through the isopach maps input from the Upper Jurassic till the Present (c) overall bathymetric model input.

III.1.1 Isopach maps

Several regional isopach maps have been achieved for the Levant margin and basin from the Jurassic till the Plio-Quaternary (Ukla, 1970; Ponikarov, 1966; Brew et al., 2001; Gardosh et al., 2008; Powell & Moh'd, 2011) (Table 6.1) supported by additional constraints to the Neogene unit's thicknesses (e.g. Dubertret, 1975; Hardenberg & Robertson, 2007; Zilberman & Calvo, 2013; Hawie et al., 2013a).

A compilation and digitalization of these maps was done using ArcGIS software. Raster calculations have been applied in order to propose age equivalent onshore-offshore maps followed by spatial interpolation using the natural neighbor method (Fig.6.7). This method finds the closest subset of input samples to a query point and applies weights to them based on proportionate areas to interpolate a value (Sibson 1981).

Six onshore-offshore isopachs were built based on this methodology for the Lower Cretaceous, Upper Cretaceous to Eocene, Oligocene-Lower Miocene, Middle Upper Miocene, Messinian Salt and Plio-Quaternary.

Description

What is clearly noticeable on these isopach maps is the impact of the Palmyride Basin on the Jurassic and Cretaceous accommodation. Thickness values of about 700m are observed along the Palmyride region while more than 1500m are attested along the Levant coast (refer to Fig.6.8 for the whole paragraph). Low sediment thickness values (300-0m) are observed on the Rutbah and Aleppo highs. In the Upper Cretaceous to Eocene thickening trends have been identified towards the central and northern Palmyride area (about 1400m) as well as offshore Lebanon facing the Latakia Ridge (more than 3500m). Thinning on top of the Rutbah and Aleppo highs is still apparent.

The Oligocene to Lower Miocene rock units are almost completely absent from the Levant margin. Some restricted outcrops have been preserved and studied mainly in the Latakia and Negev localities (e.g. Hardenberg & Robertson, 2007; Zilberman & Calvo, 2013). A major depocenter was noted in the Levant Basin at the front of the Nile Deep Sea cone as well as facing the central Lebanese offshore. The Middle and Upper Miocene rock unit thickens offshore Lebanon reaching 1500-2000m. It attains 600m onshore northern Lebanon coastal area while in the south about 100m is preserved onshore (refer to Hawie et al., 2013a and Chapter 4). In the Bekaa valley as well as in the Dead Sea the unit could reach up to 500-1000m in thickness.

Around the Pliocene period enhanced subsidence in the Dead Sea allowed the settlement of thick rock units while in the Levant Basin the maximum thicknesses of this unit reside towards the margin side and facing the Nile Deep Sea cone.

Uncertainties

The several uncertainties linked with isopach mapping compilation are mainly related to

- Biostratigraphy and ages subdivisions: some ambiguity can be present while comparing ages gathered through the use of macro-fossils (old studies) and the ones with a much higher confidence dating using foraminifera and nannofossils (recent studies). In the case of the Levant region the biostratigraphic work was mainly conducted in the 1960's (e.g. Dubertret, 1975; Ponikarov, 1966) and was additionally constrained by new studies (e.g. Hardenberg & Robertson, 2007; Collin et al., 2010; Müller et al., 2010; Hawie et al., 2013a)

- Availability of borehole and geologic sections studied and their resolution (onshore and offshore). A wide onshore availability of borehole data was noted for the Levant region except Lebanon (only 7 wells drilled) while in the Levant Basin ages allocations to isopach maps is still bound to many uncertainties as only marginal wells have been drilled in the southern Levant region and some deeper ones (gas discoveries) reaching the upper sedimentary column (Oligocene).

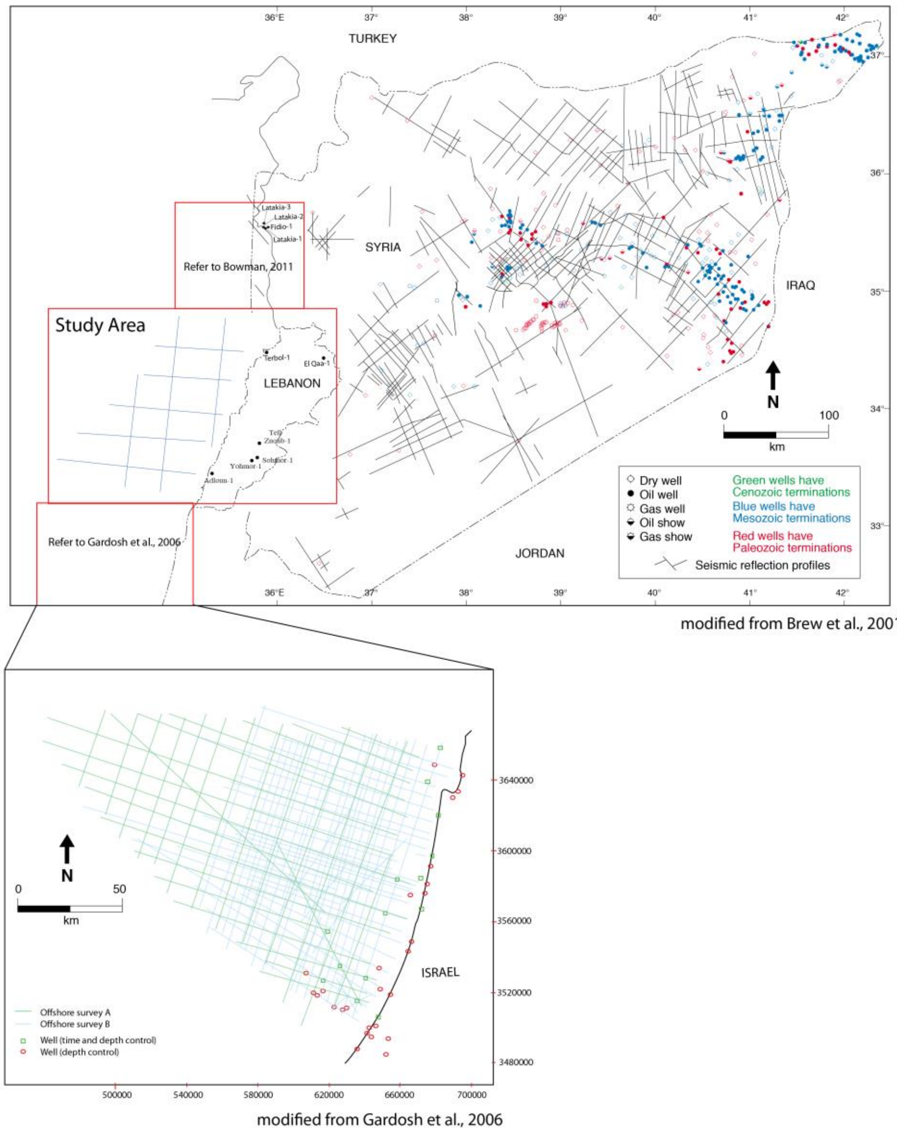


Fig.6.6 Overall well and seismic data sets used in the Levant region for the generation of isopach maps

- Seismic data quality and resolution in the basin and around the margin allowing to correlate between well data (if present) and the deeper units. In the case of the northern Levant Basin the correlation is based mainly on seismic reflectors continuity in between the southern and northern Levant Basin as well as seismic stratigraphic interpretations with no well control.

Data	Location	Maps Compiled	References
Isopach maps	Offshore Lebanon	Upper Jurassic to Turonian Senonian- Eocene Oligocene Lower Miocene Middle-Upper Miocene Messinian Salt Plio-Quaternary	Hawie et al., 2013b
	Onshore Lebanon and Syria	Middle Jurassic Upper Jurassic Lower Cretaceous Cenomanian-Turonian Coniacian-Campanian Maastrichtian-Danian Paleocene-Lower Eocene Middle Eocene Upper Eocene Oligocene Lower Miocene Middle Miocene Upper Miocene Pliocene	Ponikarov, 1966; Ukla 1977; Brew et al., 2001
Depth maps	Offshore Israel	Middle Jurassic Middle Cretaceous (Senonian Unc) Base Oligocene (Eocene Unc) Top Lower Miocene Base Messinian Top Messinian Sea floor	Gardosh et al., 2008

Table 6.1 Overview of the ispoach and depth maps used in the generation of the regional isopach maps used in the static model.

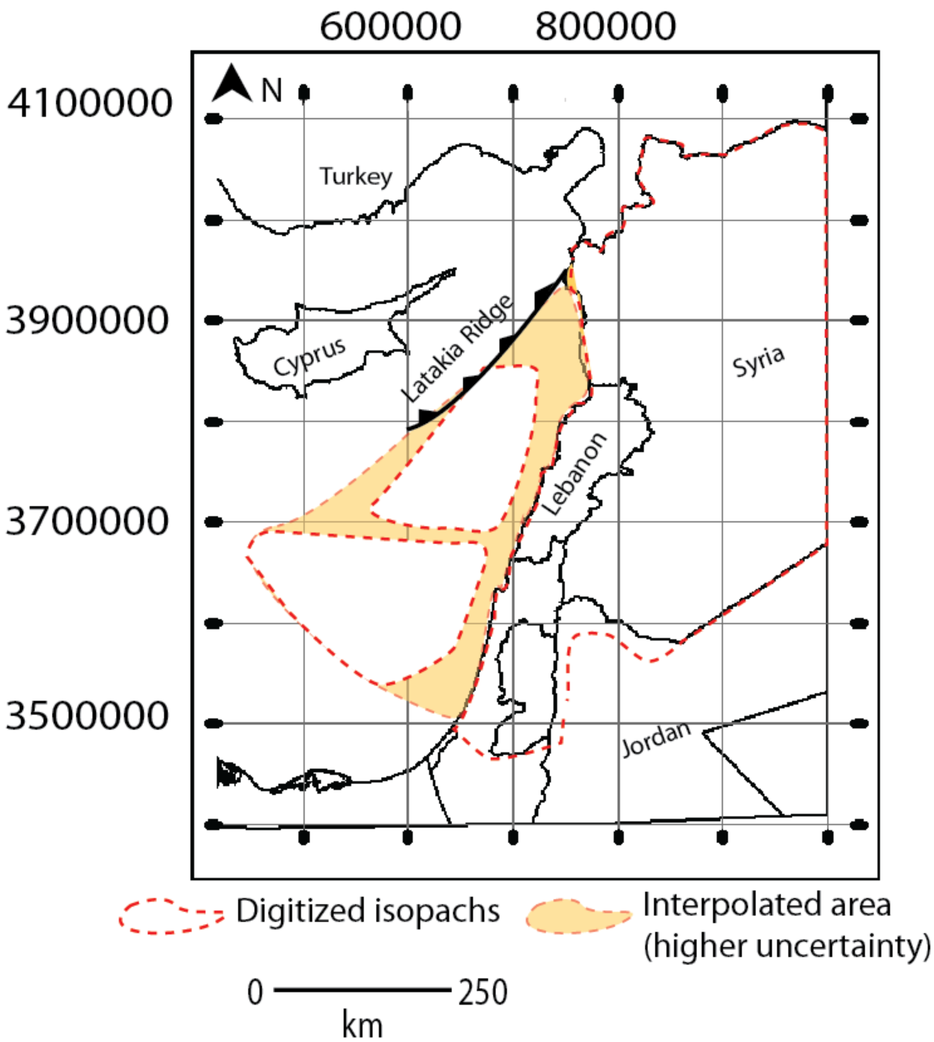


Fig.6.7 Map showing the extent of the digitized isopach maps (moderate to good confidence) as well as the interpolated area (low confidence).

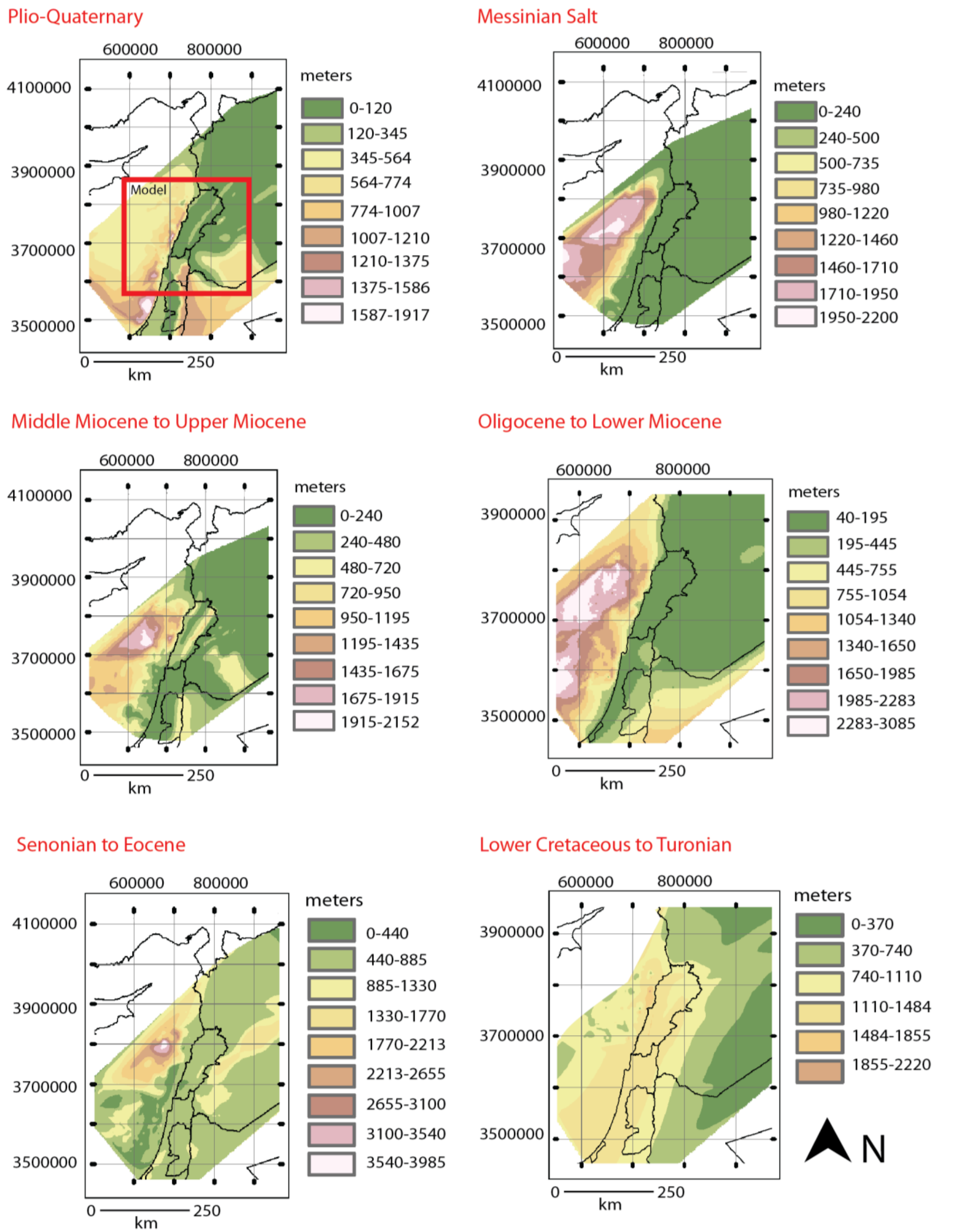


Fig.6.8 Generated regional isopach maps of the Levant region form the Lower Cretaceous to the Plio-Quaternary. The modeled area is highlighted with a red square.

III.1.2 Bathymetric investigation

Bathymertry is usually assessed through the use of sedimentological and stratigraphic concepts (lithology) mainly supported by biostratigraphy that allow a better evaluation the realm in which the sediments were deposited and to provide more refined bathymetric values (e.g., refer to Hawie et al., 2013a; Crognier, 2013). In addition structural investigations supported by stratigraphic and thermo-historical techniques could reveal varied aspects related to the architectural evolution of basins and their margins. Simple surface restorations have been conducted on 2D onshore offshore sections (northern and southern Lebanon) in order to have additional constraints on the expected bathymetries offshore to support the depositional environment model proposed in Hawie et al. (2013b).

In the following Table 6.2 an overview of the general bathymetric trends expected for the Levant margin and basin and the techniques used for their assessment is presented. As the static model comprises the whole stratigraphic column from the Upper Jurassic to the present it was important to propose first hand paleo-bathymetric approximations that can characterize the regional structural evolution of the region:

(1) Honoring the location of the Rutbah and Aleppo highs and the Palmyride Basin extension in the Upper Jurassic and Lower Cretaceous.

(2) Representing the initiation of the low amplitude folding along the southern Levant margin (i.e., Israel) and the southern Palmyride region starting from the Upper Cretaceous.

(3) Showing the major marginal uplift in the Late Eocene to Oligocene -due to the continued collision of Afro-Arabia with Eurasia and the evolution of the Afar Mantle Plume- with a shift into positive bathymetries of the Levant margin.

(4) The impact of the Levant Fracture system on the subsidence in the Dead Sea as well as the associated major uplifts along Mount Lebanon and the Palmyride area.

The extensive onshore work presented earlier in the manuscript using sedimentological and biostratigraphic investigations (e.g. Hawie et al., 2013a; Crognier, 2013) permitted to obtain higher resolution constraints to the bathymetries along the margin from the Late Cretaceous period to the Late Miocene.

Age	Data & main References		Techinques used
	Bathymetry	Paleo-topography	
Late Jurassic	Large epicontinental shelf with very shallow marine settings. Rock unit missing on the paleotopographic highs (Aleppo and Rutbah) and mainly present along the Palmyride basin and the Levant margin. Values used between 0-10 m. Deepening trend towards the Levant Basin (Ponikarov, 1966; Dubertret, 1975; Ziegler, 2001; Collin et al, 2010; Hawie et al., 2013b)	Rifted topography on the margin with Aleppo and Rutbah as uplifted rift shoulders (Chaimov et al, 1992; Brew et al., 2001). We use the models proposed by Buck et al., 1991 in order to estimate approximate values of uplift for rift systems (between 700 & 1500 m). Post rift in the Levant Basin, initiation of fast subsidence (Gardosh et al., 2008; 2011; Hawie et al., 2013b)	Lithospheric extension models Structural studies Sedimentological investigations Macro-fossil analysis Foraminifer biostratigraphy Seismic, well, outcrop data
Early Cretaceous	The Levant margin is emergent with continental settings attested i.e., development of fluvial and aelian systems leading to the deposition of important sand quantities along the margin (Dubertret, 1975; Ponikarov, 1966; Brew et al., 2001; Gardosh et al., 2011; Hawie et al, 2013b). Deep marine settings expected in the Levant Basin	Topography is expected to be similar to the Jurrassic with the preservation of the Palmyride structure. Chaimov et al., 1992 discusses the possibilty of having some uplifts in the southern palmyride region due to mantle plumes. Central and southern Lebanon represent a paleo-topographic low with thicknesses of sandstone reaching up to 350 m compared to a 0-25 m in the north. Thermal subsidence in the Levant Basin.	Stratigraphic studies Sedimentological investigations Structural analysis Heavy minerals Seismic, well, outcrop data
Aptian to Turonian	Open shallow marine settings dominate the Levant margin. A wide deposition of carbonate material along the Palmyride area and the Levant has been noted while continental settings dominate the hinterland (Dubertret, 1975; Ponikarov, 1966; Ziegler, 2001). The Turonian rudist facies have been closely studied in Lebanon and refer to inner ramp settings around western Lebanon developing into middle ramp settings (refer to Saint-Marc 1972; 1974; Hawie et al., 2013a; Crognier, 2013)	Topography is expected to be similar to the Jurrassic with the preservation of the Palmyride structure. Chaimov et al., 1992 Initiation of low amplitude high wavelenght folding in the southern Palmyride region linked with the convergence of Afro-Arabia with Eurasia in the Turonian. The Rutbah high is still emergent until the Late Cretaceous (Brew et al., 2001).	Stratigraphic studies Sedimentological investigations Structural analysis Foraminifer biostratigraphy Macro-fossil studies (rudists, ammonites) Seismic, well, outcrop data
Senonian to Eocene	Carbonate platform drowning with outershelf to deep basinal settings. In lebanon depth ranges between 300 and 600 m (Hawie et al., 2013a; Crognier, 2013), Middle shelf settings are expected (100-300 m) inland Syria and Israel while along the highs surrounding the Palmyride Basin inner shelf settings are observed (less 100 m) (Ponikarov, 1966; Flexer et al., 1986; Brew et al., 2001)	Initiation of marginal uplifts due to the convergence of Afro-Arabia with Eurasia and fast deepening along the Levant Basin with depocenter formation facing the Latakia Ridge (Hawie et al., 2013b). However the whole area is still submerged . Inititation of low amplitude large wavelength folding in the southern Palmyrides (Chaimov et al., 1992).	Stratigraphic studies Sedimentological investigations Structural analysis Ostracod, nummulite and nannofossil biostratigraphy Seismic, well, outcrop data
Oligocene	This rock unit is mostly attested in wells along the coastal margin onshore Israel (Buchbinder et al., 2005) and Syria (Hardenberg & Robertson, 2007; Bowman et al., 201) and almost completly absent onshore Lebanon (Muller et al., 2010; Hawie et al., 2013a). Lower Oligocene expected to present shallow marine settings along the coastal areas while towards the end of this period mass transported deposits have been noted with marginal emergence.	Major peneplanation surface linked to updoming seen along the Afro-Arabian plate and more specifically in the Judean hills as well as in the Negev area as a possible effect of the continuous plate convergence and the initiation of the Afar Mantle plume leading to uplifts of around 1-2 km around the Red sea area Depocenter offshore located facing Latakia Ridge with deep-water settings (Sengor, 2001; Gani et al., 2007; Zilberman & Calvo 2013).	Stratigraphic studies Sedimentological investigations Structural analysis nannofossil biostratigraphy Apatite Fission Track analysis Seismic, well, scarce outcrop data
Early Miocene	The Lower Miocene rock unit is also restricted from the onshore Levant margin. The unit is deposited in a continental setting with deposition of fluvial and lacustrine material along the southern Levant margin (i.e. Israel, Zilberman & Calvo, 2013) while towards the northern coastal area shallow marine settings prevailed (0-90 m) (Ziegler, 2001; Hawie et al., 2013a)	Fast uplift in the Palmyride region as well as folding onshore Lebanon due to the continuous collision of Afro Arabia with Eurasia (Chaimov et al., 1992; Walley, 1998; Brew et al., 2001; Hawie et al., 2013). Note that the structural differenciation between northern (uplifted) and southern Lebanon is still attested in the Burdigalian.	Stratigraphic studies Sedimentological investigations Structural analysis nannofossil biostratigraphy Seismic, well, scarce outcrop data
Middle-Late Miocene	Rhodalgal systems in the Middle Miocene (0-100 m depth) in coastal northern Lebanon while towards the central and southern deeper slope to basinal settings are observed (> 150 m?) while inland continental settings dominate (Brew et al., 2001; Hawie et al., 2013a; Zilberman & Calvo, 2013) The Upper Miocene rock unit is mostly continental along the Levant region.	Fast marginal uplift related to the propagation of the Levant Fracture system. Evolution of Mount Lebanon reaching a maximum elevation at present day of 3089 m in northern Lebanon while in the south heights of about1800 m are reached. Around the Middle to Late Miocene uplift in the Judean Mountain as well as in the northern Palmyrides and Syrian Coastal Ranges are also noted.	Stratigraphic studies Sedimentological investigations Structural analysis Foraminifer and nannofossil biostratigraphy Seismic, well, outcrop data

Table 6.2 List of the major referenced bathymetric and paleo-topographic trends expected for the Levant region and the associated techniques used in their assessment.

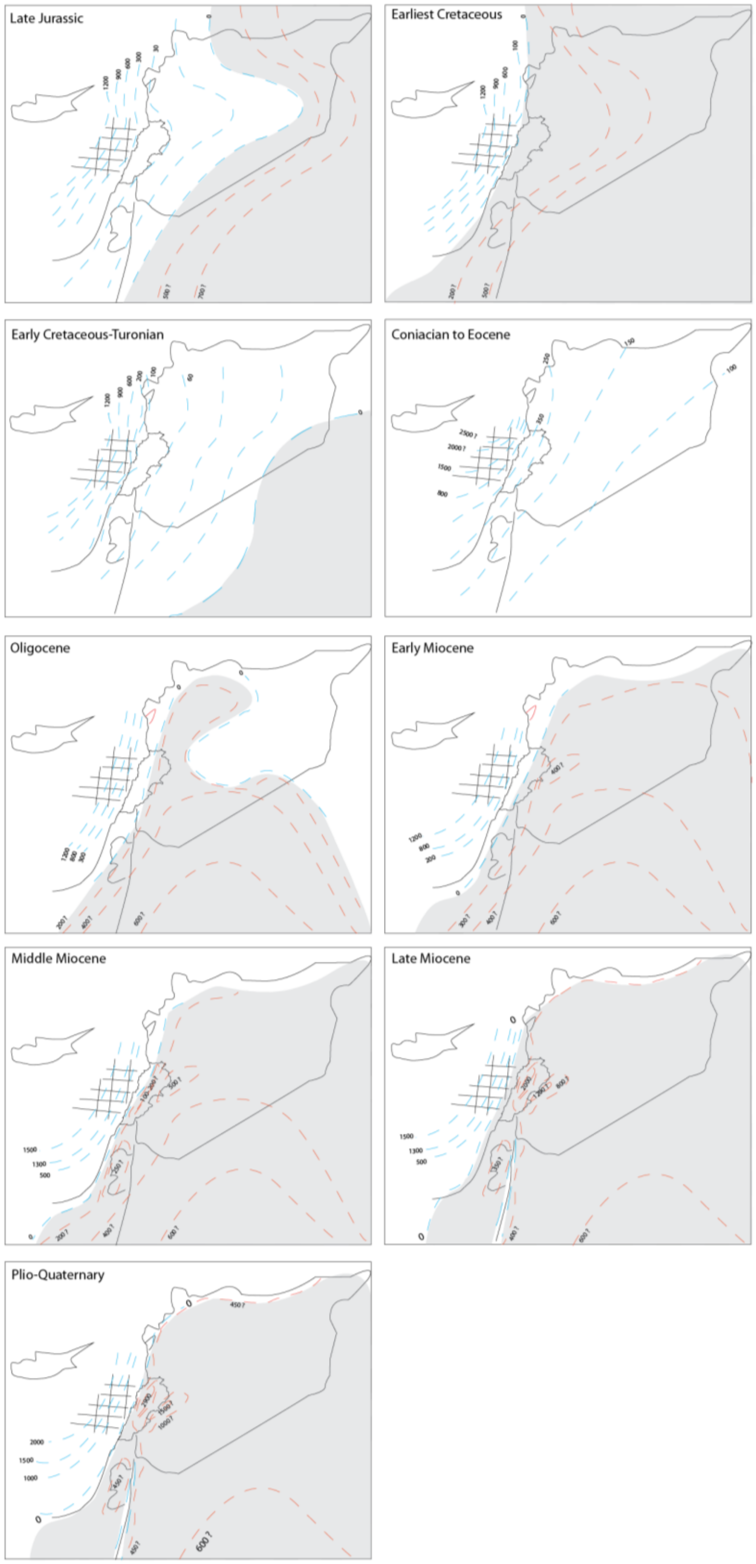


Fig.6.9 Simplified bathymetric trends for the broad Levant region based on the literature review presented in Table 6.2 and on surface restorations for the Lebanese offshore.

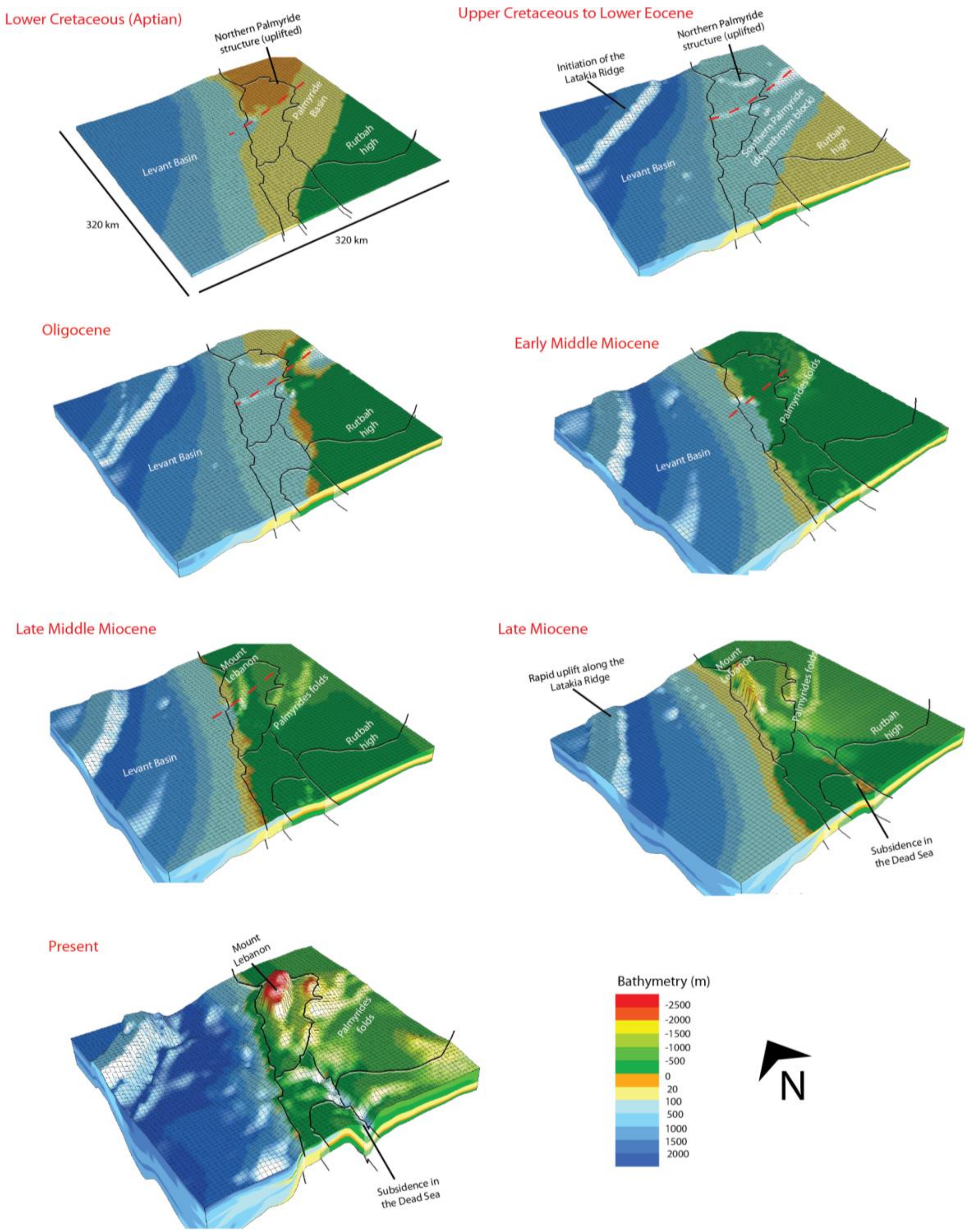


Fig 6.10 Bathymetric maps viewed in the Dionisos software

III.2 Simulation strategy

The static Dionisos model was built for the whole Upper Jurassic to Present column using the isopach and bathymetry maps. However, forward stratigraphic simulations are only focused on the Middle-Upper Miocene rock unit (from 16 to 6 Ma-excluding the Messinian salt deposition- Modeling time steps of 1Ma) of the northern Levant Basin and this for several reasons:

(1) The availability of a high-resolution seismic data for the upper sedimentary column (refer to Hawie et al., 2013b and Fürstenau et al., 2013 in Chapter 5).

(2) The wide field investigations focused on the Middle and Upper Miocene in northern central and southern Lebanon (refer to Hawie et al., 2013a and Chapter 4).

(3) The need to answer questions related to the thick Miocene infill attested for the northern Levant Basin with regards to the margin and thus the contribution of the several sources presented earlier in the manuscript.

(4) The impact of the multi-source system on the expected reservoir risk analysis.

In the following paragraphs an overview of the workflow followed for the northern Levant frontier Basin assessment. Sink and source volumes have been presented taking into account the important uncertainties that still prevail. A description of each source of sediments has been included in order to provide an updated review of the published work that could have an impact on some of the decisions and assumptions made during the source to sink assessment and modeling phase.

Different forward stratigraphic simulation results are then presented starting by (1) the best-fit scenarios of the "rhodalgal carbonate factory and multi-source system" supporting our geological model presented in Hawie et al. (2013b); followed by (2) a "single source and carbonate factory" assessment and sensitivity study. The aim of the second section of the simulations is to assess the plausibility of a single source system in the complete infill of the northern Levant Basin.

III.3 Source to sink volumes

Following the seismic interpretation presented earlier in the manuscript a multi-source system is thought to contribute to the filling of the northern Levant Basin starting from the Oligo-Miocene.

In order to better assess the potential impact of each sediment source on the infill of the sink and the possible weight allocated to each of them a source to sink methodology has been put forward allowing to have for the first time and with the scarcity of data in this frontier region an order of magnitude of expected volumes deposited in the northern Levant Basin sink. However major challenges still prevail due to the lack of wells drilled in the offshore (e.g., complexity in accurately assessing the Nile deep sea cone contribution to the infill).

Several techniques of volume calculations are currently being used in source to sink assessments depending on the availability of data (e.g. Allen 2008; Martinsen et al., 2010; Macgregor, 2012). The investigation of the rocks' thermal history (i.e., Apatite-Fission Track Analysis-AFTA and Helium diffusion during U-Th decay) unravels crucial information on the rise of a rock unit during uplifts and erosion. Allen (2008) refers to other dating techniques that can be used in order to capture the fine scale climatic changes (e.g., cosmogenic studies). The combination of thermo-historical techniques with hydrological and field investigations (i.e., identification of planation surfaces, field cross sections) provides realistic rates of eroded thicknesses and volumes (e.g. Macgregor, 2012).

III.3.1 Sink volume assessment:

In order to proceed with a source to sink evaluation a delimitation of the northern Levant Basin offshore Lebanon and Syria has been conducted. The 2D area calculated is approximately 31000 km^2 (excluding offshore Cyrpus). The compilation of isopach maps proposed for the northern Levant margin and basin have been used in order to calculate to compacted volume of the Middle-Upper Miocene (excluding Messinian Salt and the thickness outside our study area, i.e., Cyprus) that is of about 33 000 km^3 (Fig.6.11).

As no hard data and information is available yet for the type of sediments in the northern Levant Basin uncompacted volume have not been calculated in order to simplify the source to sink model that is to be fine-tuned in the future when additional data becomes available.

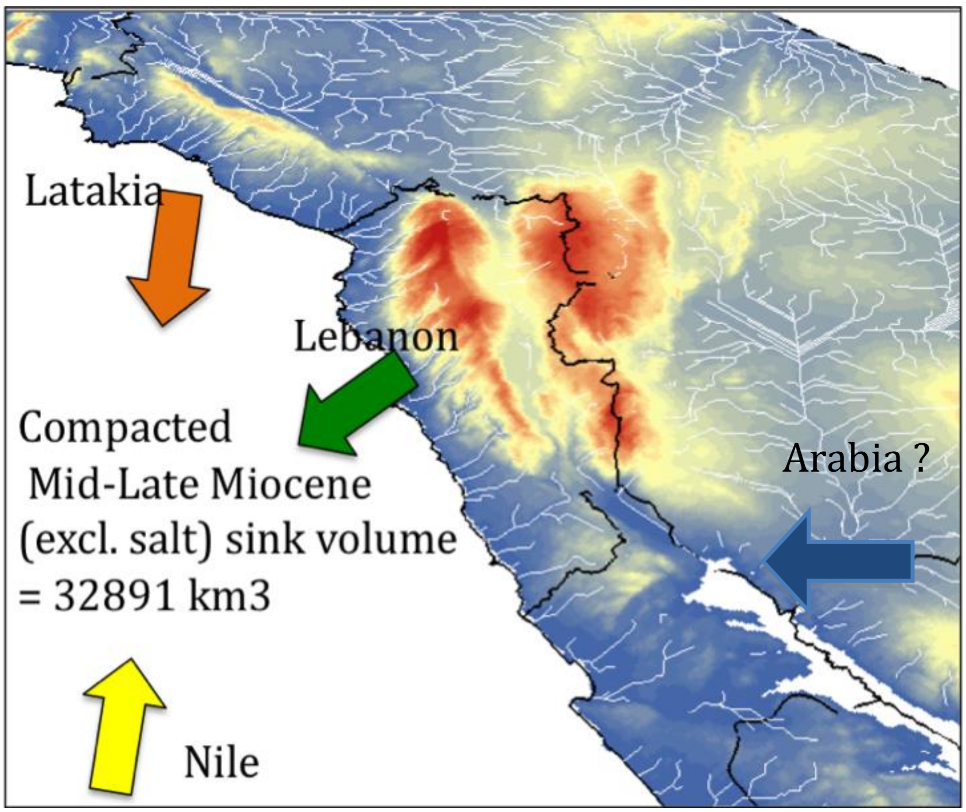


Fig 6.11 Overview of the approximate sink volume and possible contributing sources (arrows)

III.3.2 Source volume assessment:

III.3.2.1 Nile Delta:

Overview:

The main regional drainage system that is thought to provide important quantities of sediments into the Levant Basin is the Nile drainage system. Several studies tackling the evolution of the River Nile allow a thorough review of the development of this drainage system. Geologists working on the African region have proposed opposing views (Macgregor, 2012).

The first school of thought supports a late connection of the River Nile with the Mediterranean (through Ethipia, Eritrea and Sudan), expected to occur starting from the Late Messinian times (e.g., Wendorf & Schild, 1976; Said, 1981; Issawi & McCauley, 1992) and even Holocene (e.g. Salama, 1987; 1997). The work conducted focused mainly on:

- Radar imagery analysis that support a Miocene SW flowing river direction in southern Egypt thought to feed the Niger region
- Observation of the current Nile course (mainly its immaturity in central Sudan)
- Mineralogical studies supporting a reduction in of contribution from Ethiopian volcanic sources.

The second school (McDougall et al., 1975; Burke & Wells, 1989; Craig et al., 2011; amongst others) supports the idea of an Oligocene initiation of drainage systems along the Red Sea shoulders (i.e., the Blue Nile and other Ethiopian tributaries) reaching its actual course through Sudan and Egypt as huge sediment quantities evidenced in the Nile cannot be explained solely by the Egyptian hinterland. In addition the presence of the Uweinat-Darfur high would hinder a river westward course to Chad. A recent study proposed by Abdelkareem et al. (2012) highlights the potential of an Oligo-Miocene easterly river course along the Qena valley leading to sediment transport into the Levant Basin.

The Lake Albert, the Sudd basin and the White Nile are thought to have developed around 0.5 Ma to present (Pickford & Senut, 1994; Salama, 1987).

Said (1981) and Woodward et al (2007) show that 70% of the water reaching Aswan (prior to the dam construction) originates from the Blue Nile and from the Atbara -a major Ethiopian sourced tributary- while 30% is provided from the White Nile.

Mineralogical and paleo-climatic data indicate that wet conditions have prevailed over most of the Oligocene to Pliocene period leading to increased sediment flux from regions north of the Ethiopian volcanic outcrops (Said, 1981; Macgregor et al. 2002). The Red Sea Hills represent the major source of Nile sediments as it has been strongly affected by uplift and erosion starting from the Oligocene (e.g., Burke & Wells, 1989; Said, 1981; Bosworth, 2005). Uplifts of about 1 km should have affected the Ethiopian highlands (at 31 Ma, Sengor, 2001) followed by important marginal uplift of the rift shoulders around 11Ma (Wolfenden et al., 2004) and a final sediment surge in the Lower Pliocene that could have been linked with additional uplifts of about 1 km (Gani et al., 2007).

Erosion and source-sink volumes have been compiled by Mcgregor (2012) who subdivided the present-day Nile catchment area into several segments: Egyptian Limestone Plateau, Egyptian Nubian subcrop, Red Sea Hills, Sudan, and Ethipian Highlands. The compiled average eroded material and volumes have been calculated using several techniques as Apatite Fission Track analysis, planation surface analysis and back-calculation from offshore sink volumes (the reader is referred to the wide literature review presented in Macgregor, 2012).

As pointed out by Macgregor (2012) important uncertainties lie in source to sink studies and in the case of the Nile region volumes of sediments deposited in the Herodotus and Levant Basin can be only calculated for very broad time intervals (as Oligo-Miocene). Relatively limited and poor stratigraphic constraints as well as errors in time-depth conversions and the uncertainties linked with drainage systems evolution, carbonate dissolution, aeolian sediment dispersion impact on the uncertainty assessment of the source to sink volumes.

Several source to sink scenarios have been proposed based on the volume calculation leading to the proposition of a best fit model that compensate the compacted volumes attested in the source with that observed in the sink (Herodotus and Levant Basin) (188000 km^3 for Plio-Pleistocene and 393000 km^3 for the Oligo-Miocene).

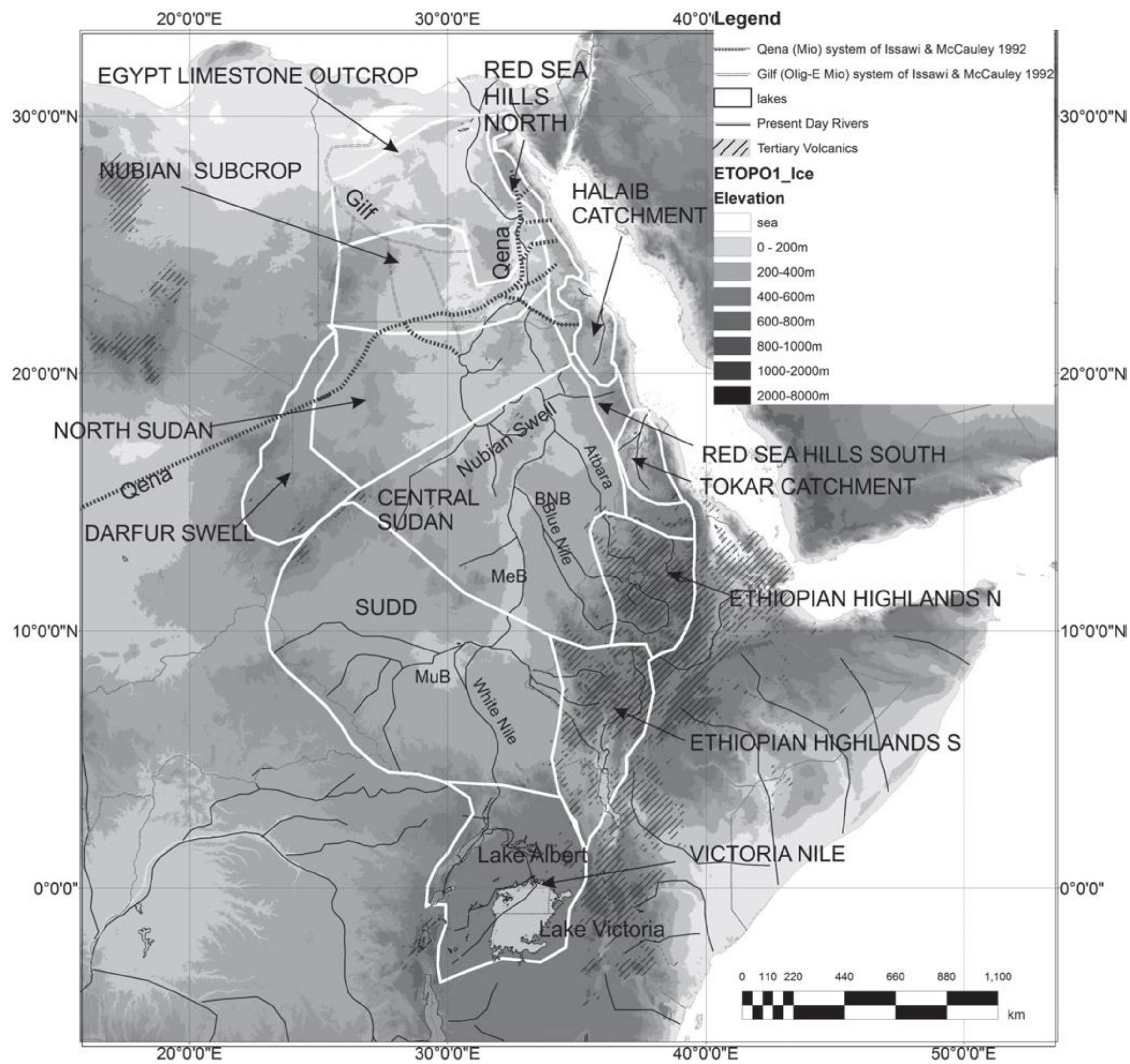


Fig.6.12 Present-day extent of the Nile catchment area

Workflow and assumptions used in the model:

In order to represent the approximate volume reaching the northern Levant Basin in the Middle to Upper Miocene period and due to the low time resolution for compacted sink volume calculation expressed by Macgregor (2012) an assumption related to the sediment fluxes from the Nile delta into the Levant Basin was followed in our calculation: " the sediment input rate from the Oligocene to Miocene is constant through time". Following our seismic interpretation we were able to propose some first hand delimitation of potential lobes localized in SW offshore Lebanon for the Lower Miocene to Upper Miocene alluding to a potential influx of sediments from the south (Hawie et al., 2013b). The proposed isopach map for the nilotic Oligo-Miocene sedimentary unit reaching the Levant Basin based on a compilation of several data sources (references in Macgregor, 2012) has been used in order to calculate the approximate sediment volume reaching the northern Levant Basin and has been compared to the data published under Hawie et al. (2013). A maximum value of 2 km of deposits has been multiplied by the areal extent of the expected nilotic sediments in the northern Levant Basin (about 23500 km^2 following the isopach extent in Macgregor, 2012). The total Oligo-Miocene compacted volume generated for the northern Levant Basin is 46 800 Km^3. However it is crucial to state that due to the lack of wells drilled in the northern Levant Basin the volumes proposed present a relatively high uncertainty rate. Thus the Middle-Upper Miocene compacted nilotic sediment volume in the northern Levant Basin equals 18400 km^3 (i.e., (Total Oligo-Mio volume)/ 28 Ma (i.e., Oligo-Miocene period) x 11Ma (Middle-Upper Miocene period)).

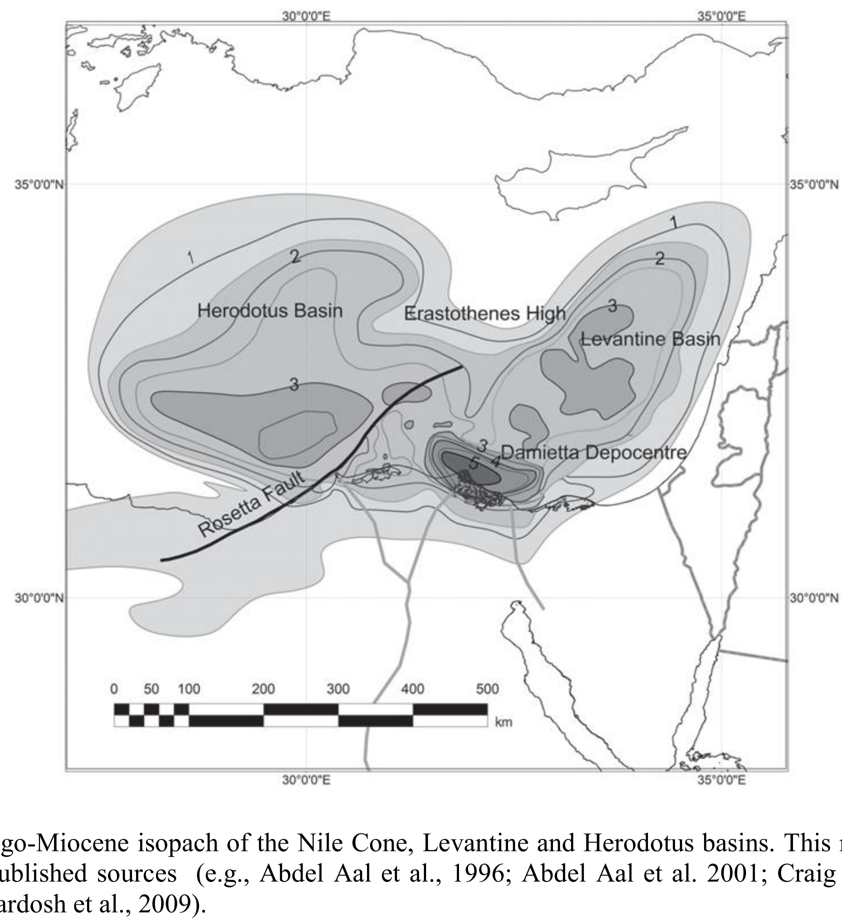


Fig.6.13 Oligo-Miocene isopach of the Nile Cone, Levantine and Herodotus basins. This map is a compilation of a variety of published sources (e.g., Abdel Aal et al., 1996; Abdel Aal et al. 2001; Craig et al., 2011; Steinberg et al.,2011 ; Gardosh et al., 2009).

III.3.2.2 Lebanon and western coastal Syria (Latakia)

Overview- Lebanon:

Following the work of Beydoun (1976) who presented an overview of the major geomorphologic and predominant drainage systems of western Lebanon it has been concluded that more than 2525x 10^6 m^3 of surface water runoff annually discharges (about 80 m3/s) through 15 major streams and rivers of western Lebanon into the Mediterranean Sea (Fig.6.14). Overall the sediment transport is oriented northwards due to longshore currents and WSW-ENE oriented waves. Previous studies focused on the acquisition and interpretation of bathymetric maps on Lebanon (Carlisle, 1965) and the consequent identification of about 18 submarine canyons along the southern half of the continental slope. The investigation of Goedicke (1972) over the central and part of the northern segment of the shelf and upper continental slope between Beirut and Ras Chekka permitted the identification of 10 additional canyons.

The work conducted by Goedicke & Sagabiel (1976) refers to sediment movement downslope along canyons (samples and cores recovered from 450 m depth). Graded bedding as well as slumped material has been identified as well as turbiditic units (Beydoun, 1972). Goedicke (1972) proposed that most of the submarine canyons represent the offshore extent of important land valleys that could have initiated during the Oligocene or Early Neogene after the Mount Lebanon's uplift and the establishment of the drainage systems (Beydoun, 1976). New dataset proposed by Hawie et al. (2013b) and by Fürstenau et al. (2013) also shed light on some of these canyon features using 2D and 3D seismic data.

Overview- western coastal Syria (Latakia)

The Latakia ridge separates between the Syrian sectors of the Levant Basin from the Cyprus and Latakia Basin to the north (Hall et al., 2005; Bowman, 2011). Recent studies focusing on mass wasting offshore Syria (Tahchi et al., 2010) have shed light on a post Miocene canyon system cutting the western Syrian margin and shelf destabilizing sediments on the margin and leading to their consequent deposition in the northern most sector of the Levant Basin. A major canyon termed the "Latakia canyon" runs north-south and parallel to the Latakia Ridge is considered as the offshore prolongation of the Nahr el Kabir valley. Through the use of high quality seismic data, Bowman (2011) noted the presence of deep-water turbidites and basin-floor fans inter-bedded with pelagic marls and shales in the Lower Miocene. The landward thickening trend of this unit has been assimilated to a sediment provenance from the Levant Margin and more specifically from the Nahr el Kabir depression (Brew et al., 2001). The Middle and Upper Miocene present chaotic and high amplitude reflections with clear evidence of channels and erosional incision, especially within the deeper part of the basin alluding to a sediment transport from the coastal Syrian area to the northern Levant Basin. The change in the structural style affecting the Latakia ridge from a compressive into a strike slip system as well as the fast marginal uplift in the Late Miocene should have involved important mass wasting and sediment transport into the Levant Basin.

Workflow and assumptions used in the model:

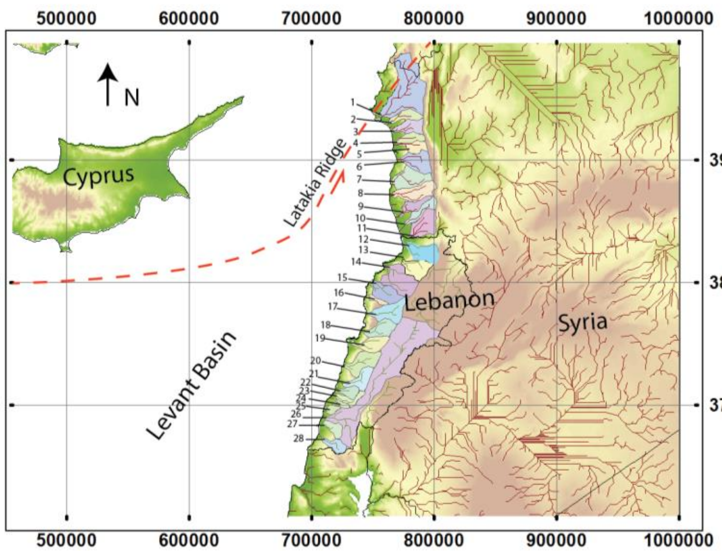
In order for us to calculate maximum eroded volumes from the Lebanese onshore (as well as from the western Syrian coastal area) a workflow has been followed using ArcGIS. It entitles the use of topographic map/digital elevation model of Lebanon (SRTM30) in order to delineate major catchment areas. Thus, major rivers feeding into the Mediterranean have been identified (Fig.6.14) allowing to better understand what portion of the Lebanese/Syrian onshore contributes to the infill of the Levant Basin. The main assumption followed in the calculation is based on the interpretation of the evolution of Mount Lebanon: the expected fast uplift and erosion starts in the Middle Miocene and intensified in the Upper Miocene to Pliocene.

Our willingness to test maximum values of eroded material from sources lies in understanding if the Lebanese onshore can solely be the main contributor to the basin infill in the Miocene. In order for us to propose coherent values we have decided to subdivide the geological map of Lebanon based on outcropping ages and assimilate to each area (2D workflow perspective) an approximate erosion rate in order to account for areas that might have been eroded more than others (e.g., Jurassic crest of Mount Lebanon) (Table 6.3).

Future works focalized on assessing onshore erosion rates should include a 3D workflow that takes into account the topography and geology in order to propose more refined measurements. It is also important to note that in order to simplify the model proposed, dissolution rates and re-precipitation of carbonates have not been considered. decompaction factors are also not applied.

LEBAN(

	ne eroded:
COASTAL	25.5 km3 00 km3 81km3 3.8 km3
BEKAA	2.1 km3 65 km3 0.5 km3
	467.4 km3



oded:

LOCATION	#	CATCHMENT AREA (km2)		MAJOR RIVERS
COASTAL SYRIA	1	1106	2D total drained area = 3540	Nahr el Kabir el Shimali
	2	170		
	3	217		
	4	146		
	5	151		No names assigned
	6	319		
	7	384		
	8	339		
	9	161		
	10	194		
	11	353		Nahr el Kabir el Jounoubi
LEBANON	12	343	2D total drained area = 5593	Nahr Ostouane (+sur.)
	13	274		Nahr el Bared
	14	494		Nahr Abou Ali
	15	291		Nahr el Jaouzi (+sur.)
	16	53		
	17	346		Nahr Ibrahim
	18	244		Nahr el Kalb
	19	240		Nahr Beirut
	20	329		Nahr el Damour
	21	226		Nahr Bisri
	22	118		Nahr Saitanik
	23	120		Nahr el Zahrani
	24	51		Rivers passing by Merwaniyeh (+sur.)
	25	65		Nahr Abou Aswad
	26	2117		Nahr el Litani
	27	134		Nahr abou Zeble (+sur.)
	28	148		River passing between the Azziye and Henniye villages

Table 6.3 Maximum eroded volumes from Lebanon and coastal Syria (Latakia) based on simplified 2D polygon-subdivision workflow in the Middle and Upper Miocene (major uplift and erosion periods).

Fig. 6.14 Catchment area calculations for Lebanon and coastal Syria based on ArcGIS workflow

IV Test results

Several simulations have been conducted in order to test a variability of hypotheses of basin infill. First, a rhodalgal carbonate factory representing the Middle Miocene unit is presented. The realistic model proposed is then used in the following sources tests to account for carbonate production along the Levant margin and hemipelagic deposition in the basin. Then the multi-source model described in Hawie et al. (2013b) is tested and the "best fit" scenarios (honoring volume and sedimentological and seismic facies extent) is discussed. Finally sensitivity studies of transport parameters of a single source model are then proposed for (1) the Nile Deep Sea cone, (2) the Latakia region and (3) an Arabian source.

Different values of the diffusion equation parameters have been tested (i.e., K values between 0.01 to >10 km2/ka and Qw values between 60 and >200 000 m3/s). The feasibility of the supplies is evaluated based on global relationships between sediment loads, water discharge (Qw) and drainage area seen in modern geomorphological systems (refer to section I of this chapter; Milliman & Syvitski, 1992; Syvitski & Milliman, 2007).

IV.1 Carbonate and pelagic production

A rhodalgal carbonate production factory was described for the Middle Miocene rock unit onshore Lebanon (Hawie et al., 2013a). The Plate 6.1 presents the values used for the production rates versus depth in the model. The values are based on the already presented literature that describes rhodalgal systems reaching up to 100 m in depth in oligotrophic settings (Testa and Bosence, 1999; Pomar, 2001; Pomar et al., 2004). From 0 to 50 m the carbonate production overcomes the pelagic one while in deeper settings (>100) the system becomes dominated by the pelagic realm. Along the whole Mediterranean rhodalgal systems have prevailed from the Late Burdigalian until the Early Turonian due to appropriate cold water-temperature conditions and high nutrient input (Hafar & Mutti, 2005).

Two scenarios are proposed:

(1) A real case scenario with realistic production rates values for rhodalgal production between 60-80 m/Ma and pelagic rates of about 30m/Ma (Cita et al., 1978) (Plates 6.1, 6.2).

   a. Only 15 to 20% of the northern Levant Basin is infilled with pelagic sediments (starved basin).

   b. Rhodalgal production is attested along the Levant margin while in southern Lebanon it is missing or very restricted towards the flanks of the evolving Mount Lebanon. Good rhodalgal facies spacial configuration.

(2) Very high values of pelagic production reaching more than 150 m/Ma (Plates 6.3).

   a. The basin is completely infilled and thus fits the volume data.

   b. Rhodalgal production is high along the margin including southern Lebanon, which contradicts the results presented in this thesis.

Only Carbonate Production: Rhodalgal system

Production vs. water depth

Bathy (m)	Algal	PelagicMud
0	1	0.2
10	1	0.2
20	0.8	0.2
50	0.7	0.3
100	0.1	1
200	0	1

Test 1: Moderate values

Carbonate production rate vs time

Age (My)	Production rate (m/My)	
	Algal	PelagicMud
7	0	30
10	5	30
16	60 to 80	30

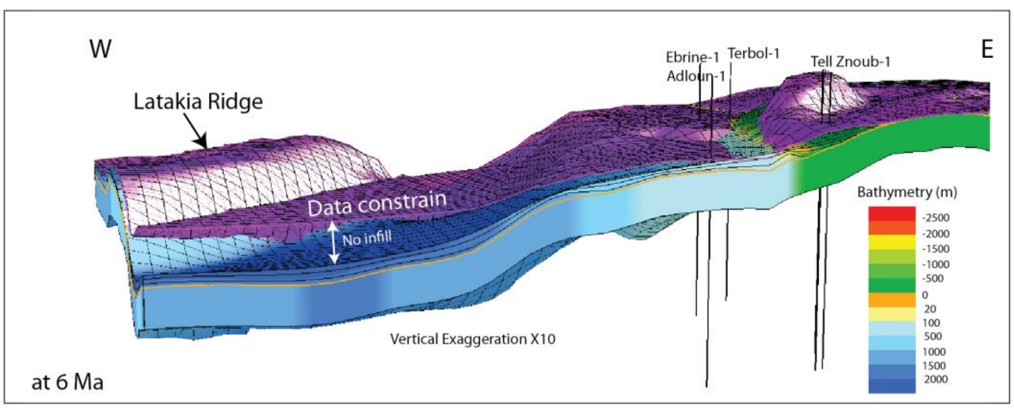


Plate 6.1 Overview of the parameters used in the realistic simulation of rhodalgal carbonate platforms developing along the Levant margin and hemipelagic deposits in the basin.

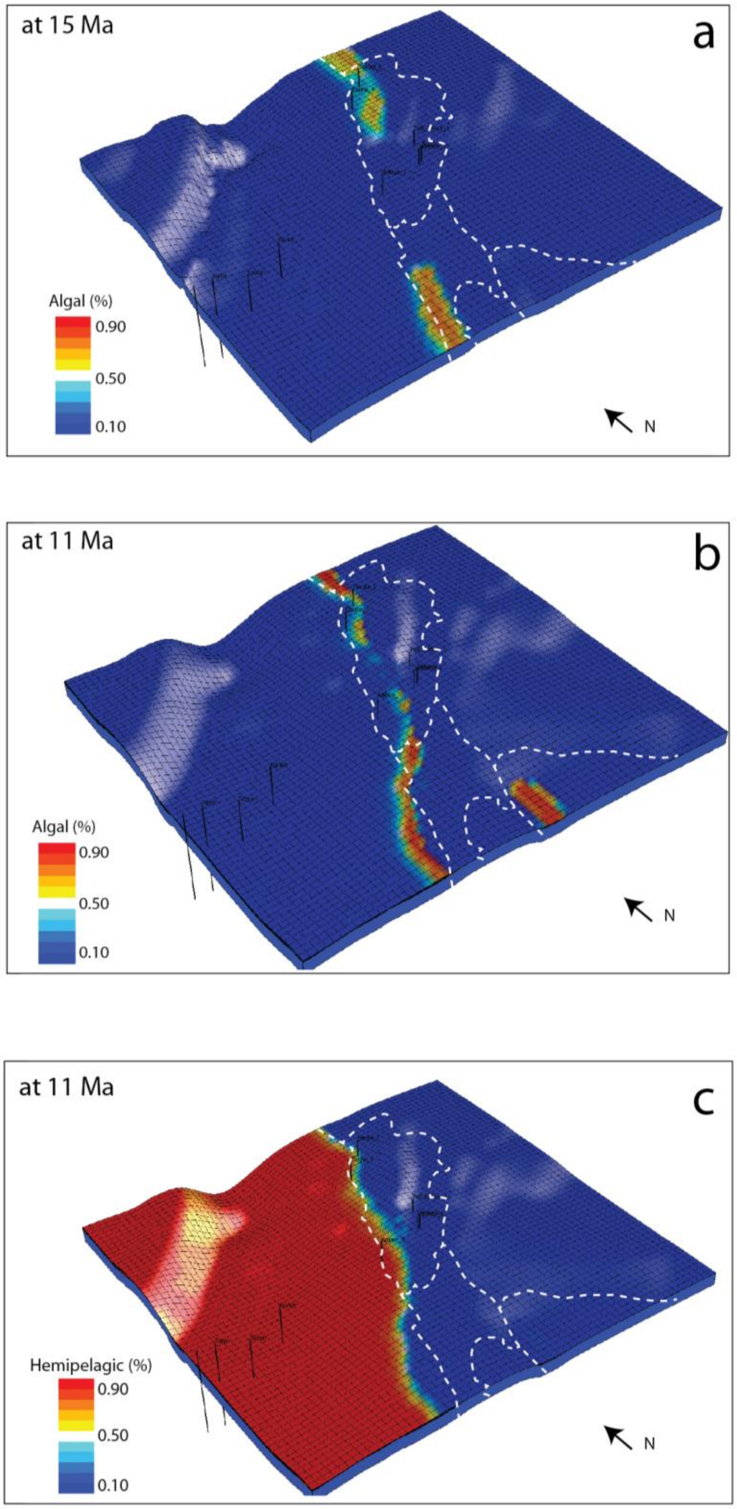
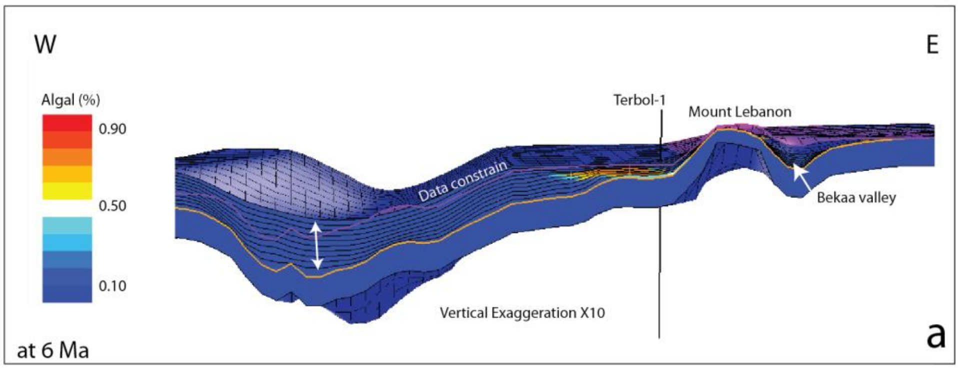


Plate 6.2 Map view of the moderate values carbonate simulations showing (a,b) the spatial extent of the expected rhodalgal systems along the Levant margin. Rhodalgal platforms around central and southern Lebanon are missing or expected to be very restricted. (c) Hemipelagic deposition along the Levant slope and basin.

Test 2: High values

Carbonate production rate vs time

Age (My)	Production rate (m/My)	
	Algal	PelagicMud
7	0	150
10	5	150
16	100	150



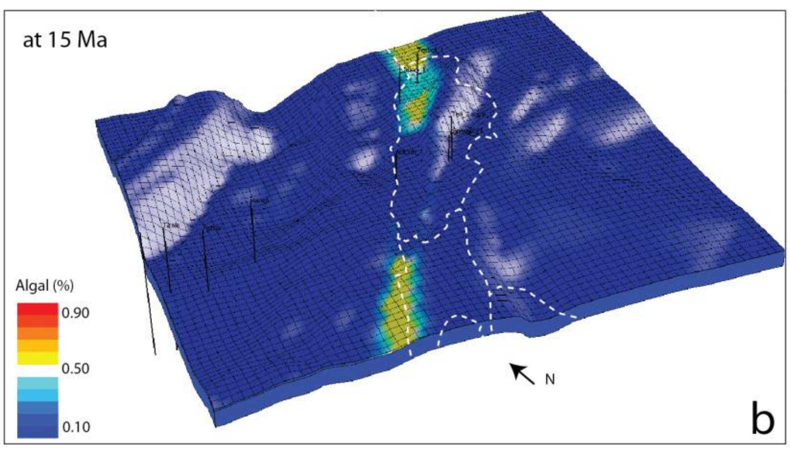
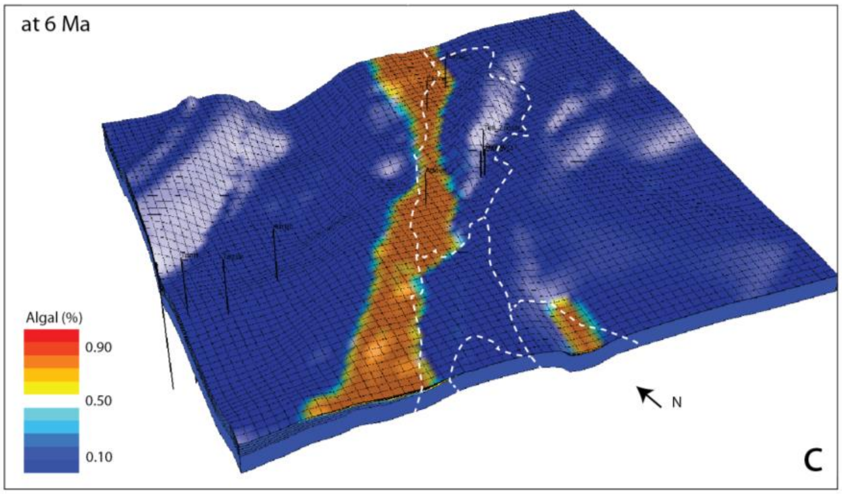


Plate 6.3 Overview of the parameters used in order to completely infill the northern Levant Basin (a). Map view (b) of the rhodalgal platform evolution showing the localization of carbonate production in northern Lebanon (at 15 Ma) as attested in the field investigation presented earlier in the manuscript.



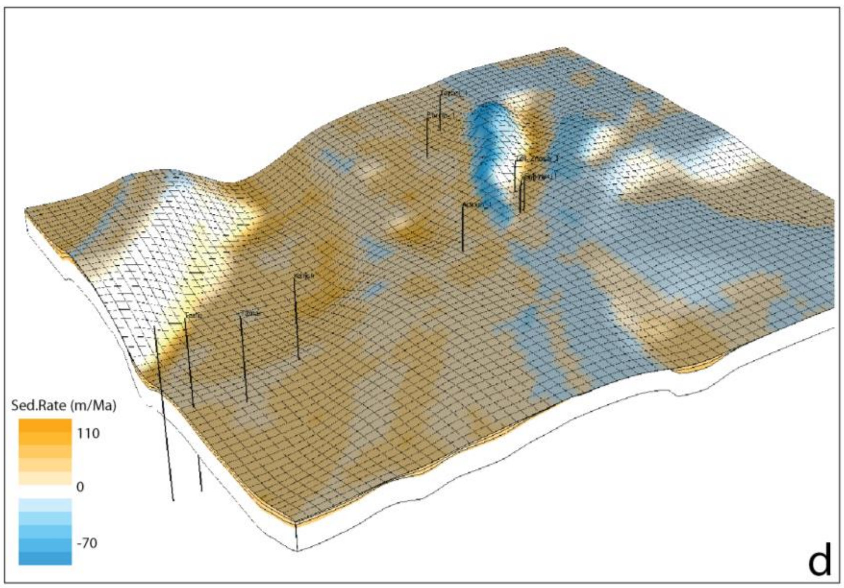


Plate 6.3 (c) Rhodalgal platform evolution along the whole Levant margin (at 6 Ma) contradicting the field investigations presented earlier in the manuscript. (d) Overall sedimentation rates showing erosion of the Levant margin, specially Mount Lebanon and the Palmyride area as well as sediment deposition in the Levant Basin.

IV.2 Multi-source infill

The following scenarios put in play all the possible sources that can contribute to the infill of the Levant Basin (i.e, Nile, Lebanon, Latakia, Arabia). The values used for the sedimentary volumes are based on previous calculations proposed for each system as well as acquired from the literature (e.g. Mcgregor, 2012; Gvirtzman et al., 2013): Nile load reaching the northern Levant Basin between 1200-144 km3/Ma (from 16 to 6 Ma), Latakia input of about 250 to 350 km3/Ma (from 11 to 6 Ma) and the Arabian source of about 650 km3/Ma (between 16 to 11 Ma as sediments will be accumulated later in the Dead Sea rift)

Three scenarios are proposed: one using realistic Qw values and an other one using high Qw values in order to assess the sediment transport potential for low Ksand values.

(1) Water discharge for southern source Qw =2830 m3/s (current Nile) and 60-80 m3/s for the northern source (equivalent to Nahr el Kabir) and for the Arabian source 800-1000 m3/s (Plate 6.4, 6.5)

  a. The low to moderate Ksand values 0.01 to 1 Km2/Ka are insufficient in transporting sediments into the basin. Large progradations are attested towards the sediment entry zones (mainly from the south). The basin is starved. This test does not honor the mapped facies extent in the basin.

  b. For Ksand between 1 and 3 km2/Ka the basin becomes moderately infilled. The facies' extention does not honor the data as more basinal extent is required.

  c. The Ksand values reaching more than 3 km2/Ka lead to a good basin infill and honors the facies spacial extent offshore Lebanon (Plate 6.6).

(2) In order to infill the basin with low Ksand values (=0.1 km2/Ka) the following parameters should be used: a water discharge for the southern source of Qw= 50 000 m3/s; for an Arabian source Qw=20 000 m3/s and for the northern source Qw= 2000 m3/s. The generated model honors moderately the basinal bathymetries and facies extent (Plate 6.7, 6.8).

(3) For moderate Ksand values of 1 km2/Ka the use of Qw values for nilotic input and Arabia input of 8000 m3/s and values of more than 500 m3/s for Latakia lead to a moderate basin infill, however the northern sector still presents lower bathymetries than expected (Plate 6.9).

Carbonate Production + Multi-source

Production vs. water depth

Bathy (m)	Algal	PelagicMud
0	1	0.2
10	1	0.2
20	0.8	0.2
50	0.7	0.3
100	0.1	1
200	0	1

Carbonate production rate vs time

Age (My)	Production rate (m/My)	
	Algal	PelagicMud
7	0	30
10	5	30
16	60 to 80	30

Boundary supply

Total Supply Nile (south): 1200-1400 km3/Ma
Source width:160 km
Sand 10%, Clay 90%
Age: from 16 to 6

Total Supply Latakia (north): 250-300 km3/Ma
Source width:100 km
Sand 10%, Clay 90%
Age: from 11 to 6

Total Supply Arabia (east): 650 km3/Ma
Source width:150 km
Sand 30%, Clay 70%
Age: from 16 to 11

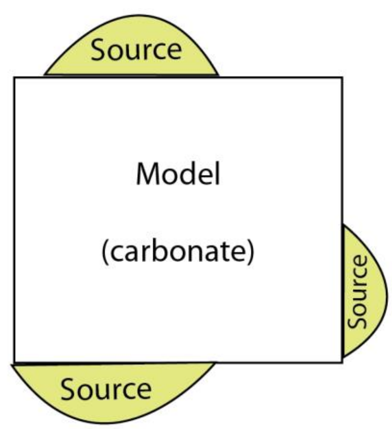


Plate 6.4 Overview of the source parameters used in the simulations of the multi-source system.

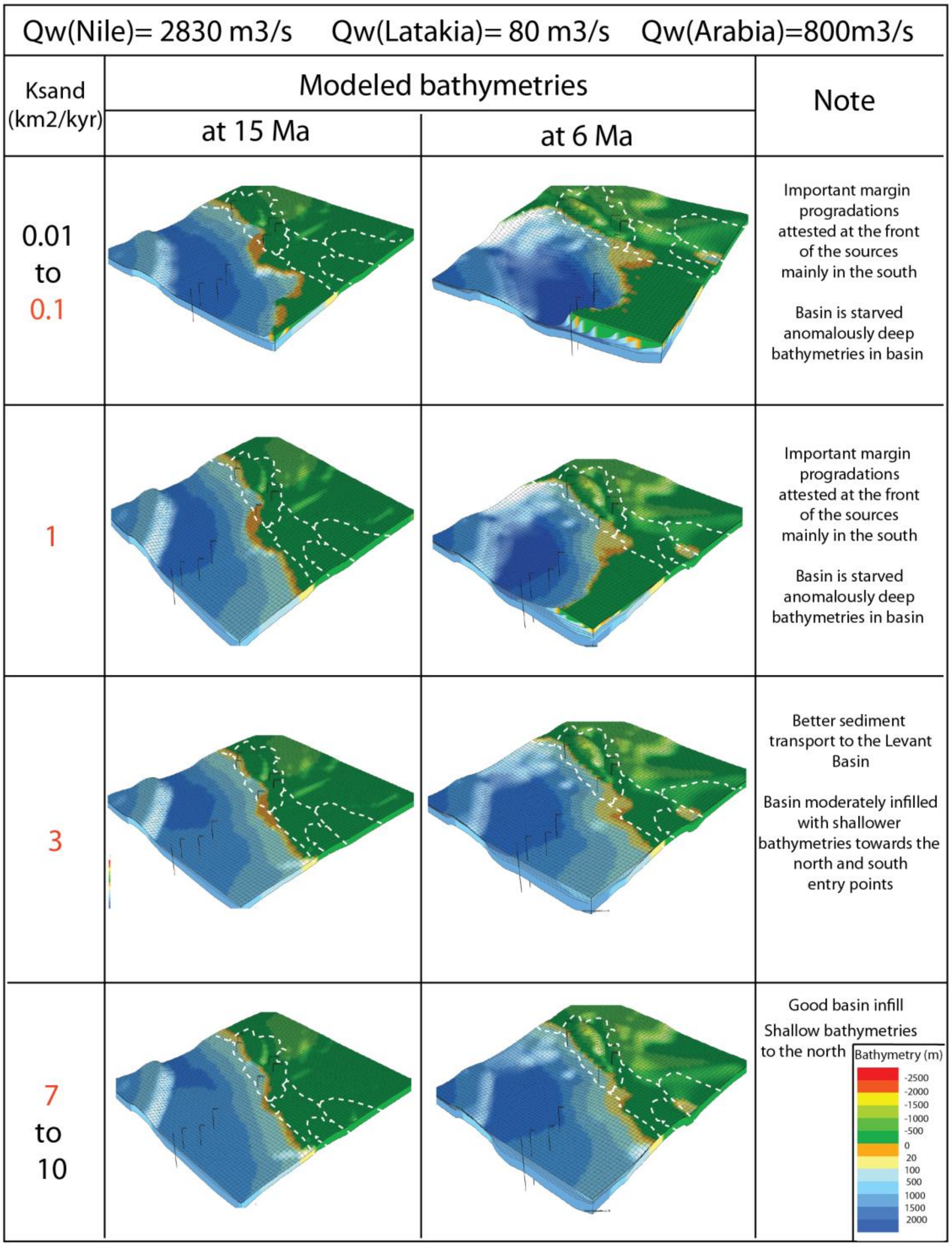


Plate 6.5 Modeled bathymetries (Qw versus Ksand) for the multi-source scenario.

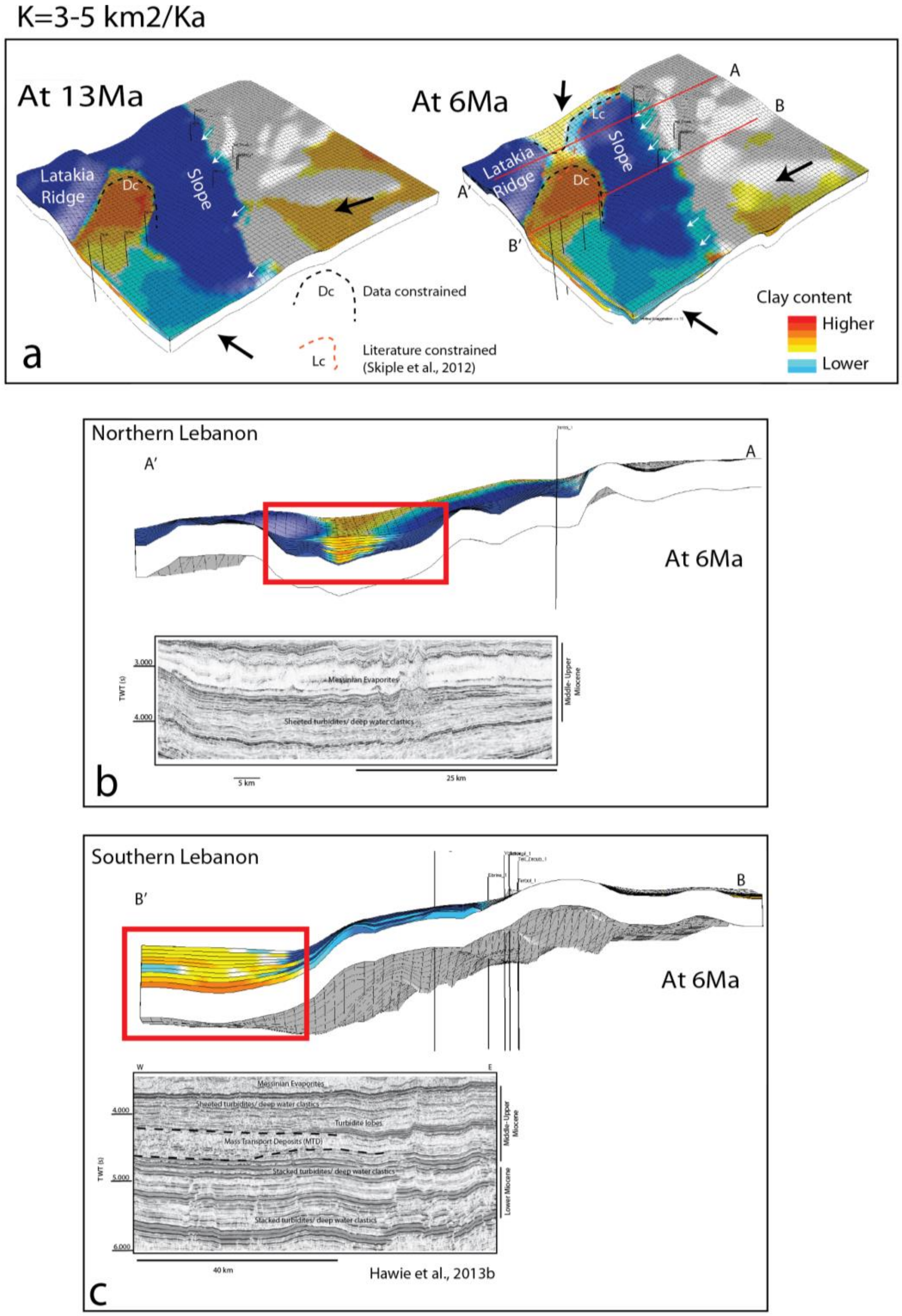


Plate 6.6 (a) Map view of the best-fit modeled facies showing the lobe shaped infill reaching the Beirut area in the Levant Basin at 13 Ma followed by the influx of sediments from the north starting from 11 Ma. (b,c) Onshore-offshore section view of northern and southern Lebanon compared to the equivalent seismic data. Note the presence of lobe shaped architectures pinching out to the sides, interpreted on the seismic data as fan lobes or turbidites (Hawie et al., 2013b).

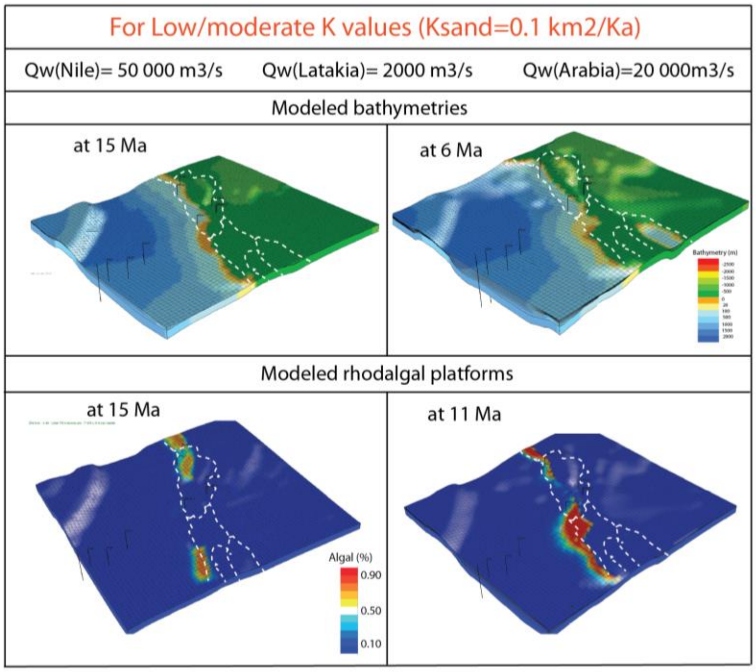


Plate 6.7 Best fit modeled bathymetries and rhodalgal platform extension for low Kvalues.

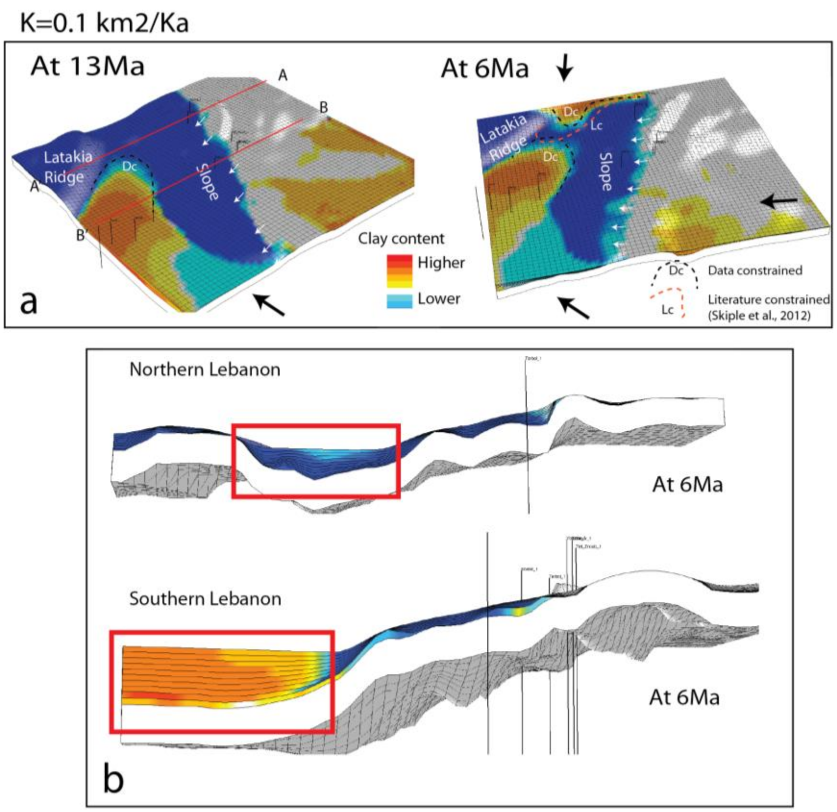


Plate 6.8 (a) Map view of the modeled facies extent for the multi-source system for low Ksand values. (b) Onshore-offshore sections of northern and southern Lebanon showing the lobe configurations identified on seismic data

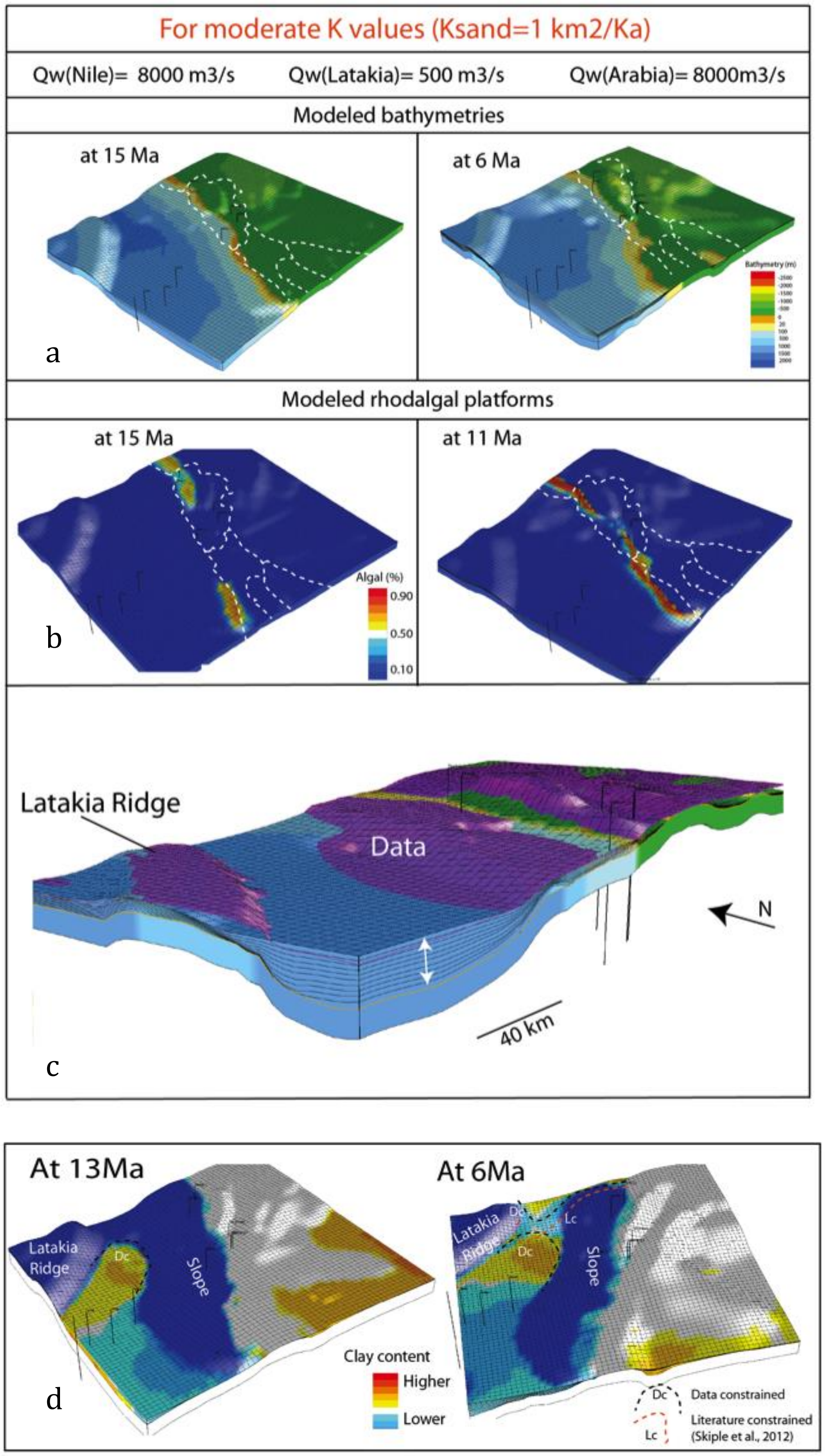


Plate 6.9 Map view of the multi-source simulations for moderate Ksand values showing (a) the modeled bathymetries (b) rhodalgal facies extent (c) the best volume fit and the (d) lobe shaped sediment input from the southern and northern Levant Basin.

IV.3 Sensitivity studies: single source infill

In the following paragraphs several simulations have been conducted in order to assess the plausibility of the occurrence of a single source infill that could fit the volume data presented in this manuscript. The modeled single source system is unable to fit the interpreted basinal facies presented in Hawie et al., (2013b). The realistic carbonate production rates presented in section IV.1 have been included in all the scenarios.

IV.3.1 Nilotic sediment source

In order to represent the sediment entry from the south a source of 160 km wide has been added. It is important to note that the used parameters for the southern source are not completely representative as the continent realm providing sediments is located about 120 km to the south. However the tests provide an order of magnitude of the major parameters and hydraulic conditions needed in order to infill the northern Levant Basin. Future studies using basinal well data (still confidential) should propose a wider extension for the model in order to have constraints in the deep part of the Levant Basin.

Three scenarios of water discharge values have been proposed:

(1) For actual Nile water discharge Qw= 2830 m3/s (Plate 6.11)

a. Ksand values between 0.01 and 1 km2/Ka result in important progradation along the southern sediment entry point while the basin is starved. Note that the higher the Ksand the more sediment transport to the basin is noted for a same Qw.

b. Ksand value of 3 km2/Ka is not sufficient to infill the basin resulting in higher bathymetries in the deep basin while towards the entry point lower bathymetries are attested.

c. Ksand between 7-10 km2/Ka results in a very good basin infill.

(2) For much lower water discharge Qw= 900 m3/s (Plate 6.12)

a. Ksand=0.01 to 7 km2/Ka results in a starved basin with high progradation rates along the southern sediment entry point.

b. Ksand= 10 km2/Ka leads to a good basin infill, however the bathymetries in the south are still much shallower than they are expected to be.

(3) For higher water discharge of Qw= 55 000 m3/s (Plate 6.13)

a. Ksand values ranging between 0.01 to 0.1 km2/Ka result in the formation of bathymetric profile that is shallow towards the south getting deeper northward. Thus do not fit the data. In order to provide a coherent basin infill more than 65 000 m3/s of water discharge is required.

b. Ksand values of >1 km2/Ka lead to a good basin infill with the expected bathymetric profile.

Note that if nilotic sediment volumes are drastically increased in the model the basinal area is the only sector of the Levant offshore that is affected while sediment accumulation is absent from the margin side and proximal basin.

Carbonate Production + Nilotic input

Production vs. water depth

Bathy (m)	Algal	PelagicMud
0	1	0.2
10	1	0.2
20	0.8	0.2
50	0.7	0.3
100	0.1	1
200	0	1

Carbonate production rate vs time

Age (My)	Production rate (m/My)	
	Algal	PelagicMud
7	0	30
10	5	30
16	60 to 80	30

Boundary supply

Total Supply (1800 to 2200 km3/My)
Source width 160 km
Sand 10%, Clay 90%
Age: from 16 to 6

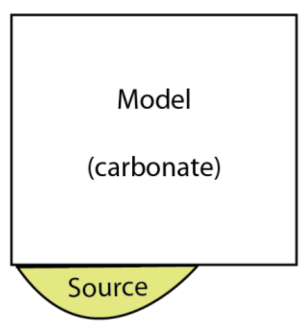


Plate 6.10 Overview of the parameters used in the simulations for the nilotic single source system.

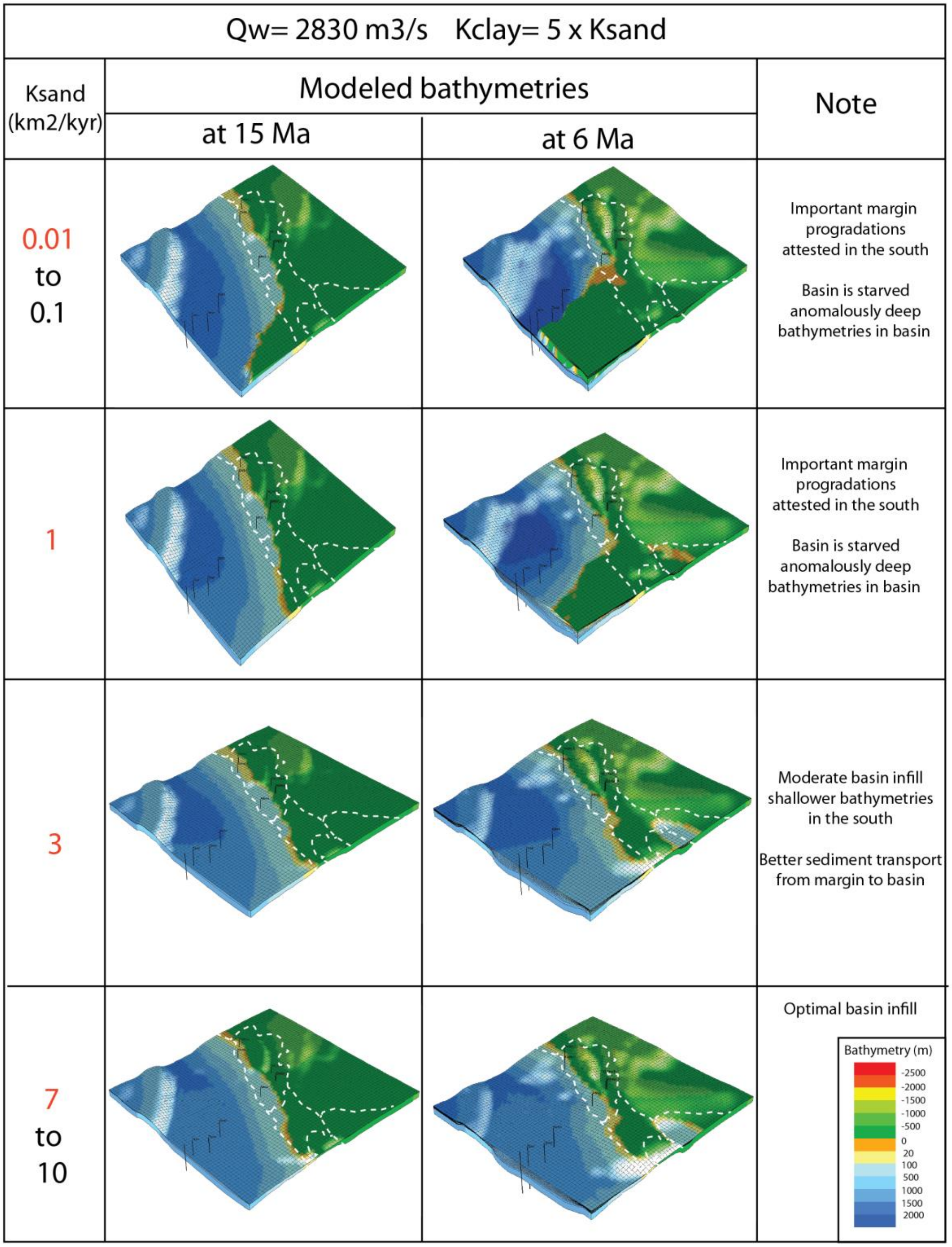


Plate 6.11 Modeled bathymetries for the nilotic single source scenario with the Qw parameter of 2830 m3/s.

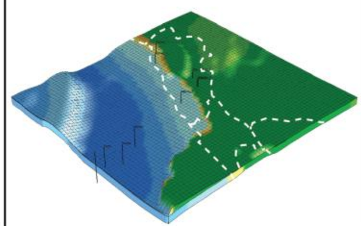
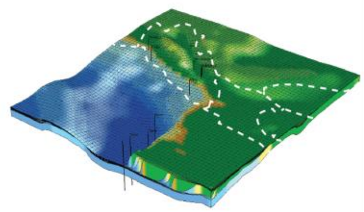
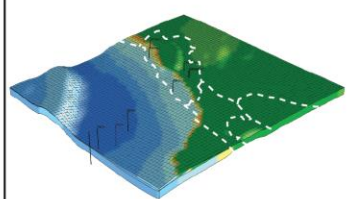
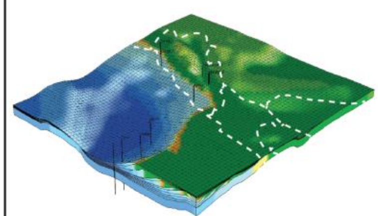
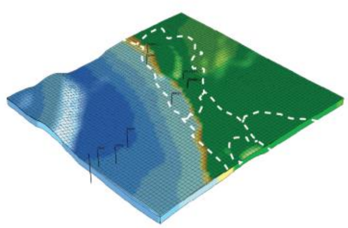
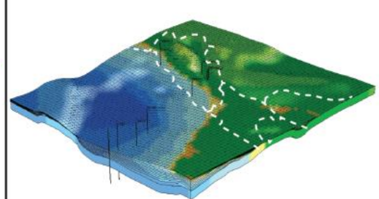
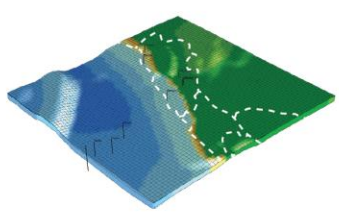
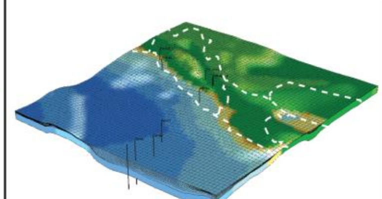
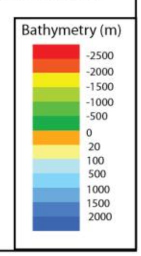
Qw= 900 m3/s Kclay= 5 x Ksand			
Ksand (km2/kyr)	Modeled bathymetries at 15 Ma	Modeled bathymetries at 6 Ma	Note
0.01 to 0.1			Important margin progradations attested in the south Basin is starved anomalously deep bathymetries in basin
1			Important margin progradations attested in the south Basin is starved anomalously deep bathymetries in basin
3 to 7			Important margin progradations attested in the south Better basin infill however bathymetries are still deeper in central Lebanon
10			Optimal basin infill 

Plate 6.12 Modeled bathymetries for the nilotic single source scenario with the Qw parameter of 900 m3/s.

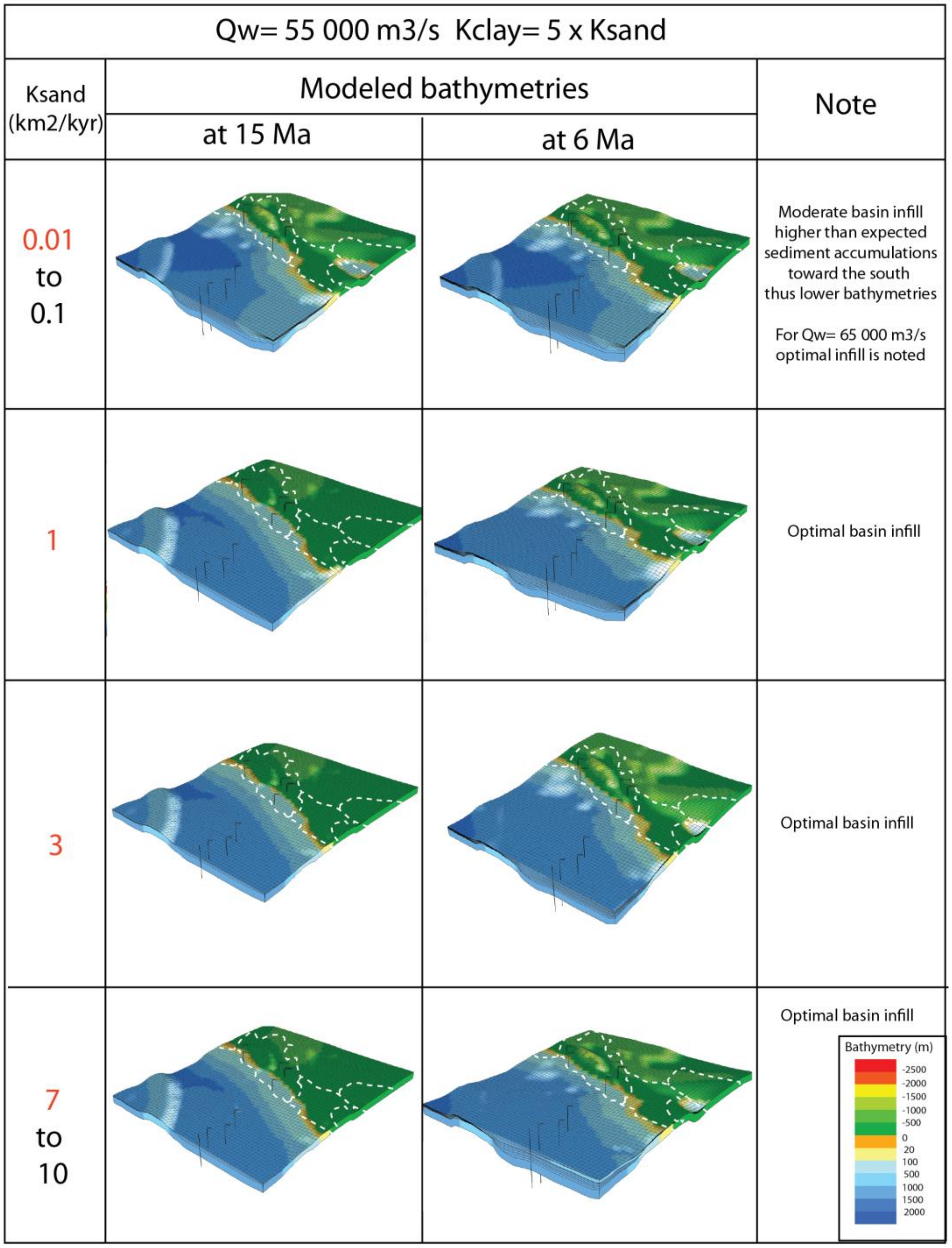


Plate 6.13 Modeled bathymetries for the nilotic single source scenario with the Qw parameter of 55 000 m3/s.

IV.3.2 Coastal Syria (Latakia) sediment source

This source is located in the northern sector of the modeled area. The timing of the expected sediment provenance from the Syrian coastal region is concomitant with the Late Miocene strike slip initiation along the Latakia Ridge (Hall et al., 2005; Bowman, 2011). Thus in order for this source to infill completely the northern Levant Basin sink sediment volumes modeled should be doubled (i.e., between 4000-4400 m/Ma).

Three water discharge scenarios have been proposed in order to assess the parameters needed to infill the northern Levant Basin solely from this source:

(1) Water discharge Qw =2830 m3/s (current Nile) (Plate 6.15)

a. For Ksand values ranging between 0.01 and 1km2/Ka major sediment progradations and accumulations are observed offshore northern Lebanon. The basin is starved and bathymetries are anomalously deep.

b. If higher Ksand values (between 1 and 10km2/Ka) are used a better basin infill is observed however sediment accumulations are still noted towards the northern Lebanese offshore leading to lower bathymetries than expected.

(2) Water discharge Qw= 60 m3/s (current Nahr el Kabir) (Plate 6.16)

In this case the use of anomalously high Ksand values does not lead to a complete basin infill and to a good fit. Sediment progradation and accumulation is observed along the northern entry point while the basin is completely starved and thus bathymetries reach unexpected high values. The high sediment supply is not transferred into the basin due to low Qw values even if Ksand values are drastically increased.

(3) Water discharge Qw= 150 000 to >200 000 m3/s (close to Amazone River) (Plate 6.17)

The very high water discharge rates do not seem to be sufficient to transport sediments from the northern sector of the Levant Basin towards the south even with high Ksand values. Thus, bathymetries are shallower than expected in the northernmost Levant Basin. The southern most modeled area is not completely infilled with sediments.

Carbonate Production + Coastal Syria input (Latakia)

Production vs. water depth

Bathy (m)	Algal	PelagicMud
0	1	0.2
10	1	0.2
20	0.8	0.2
50	0.7	0.3
100	0.1	1
200	0	1

Carbonate production rate vs time

Age (My)	Production rate (m/My)	
	Algal	PelagicMud
7	0	30
10	5	30
16	60 to 80	30

Boundary supply

Total Supply (1800 to 2200 km3/My)
Source width:100 km
Sand 10%, Clay 90%
Age: from 11 to 6

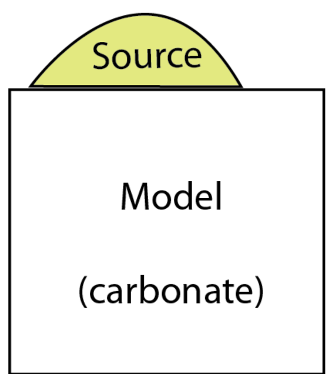


Plate 6.14 Overview of the input parameters used in the simulation of a single source system providing sediments from the northern Levant sector (coastal Syria, Latakia)

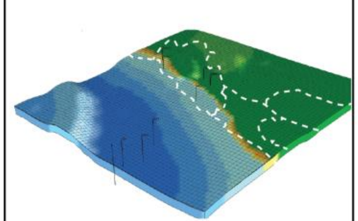
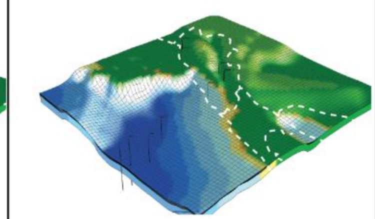
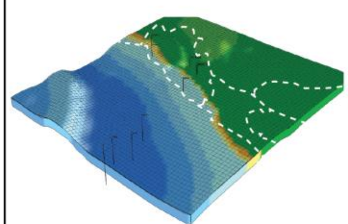
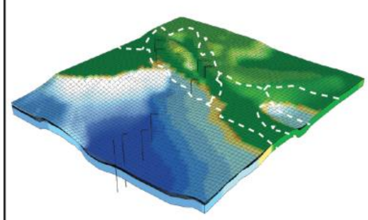
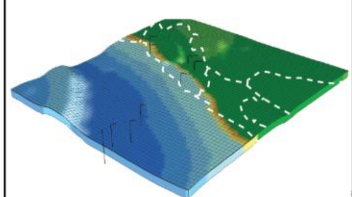
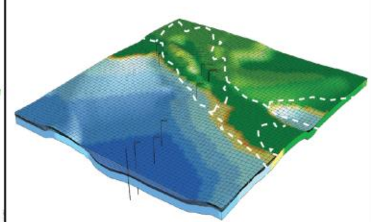
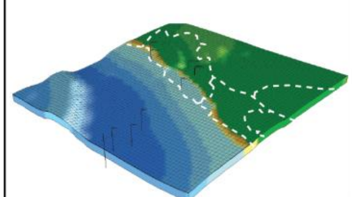
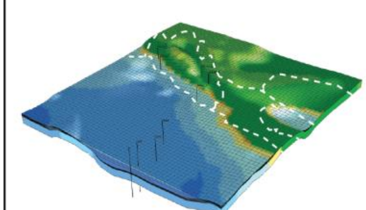
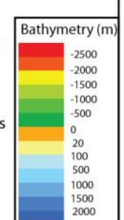
Qw= 2830 m3/s Kclay= 5 x Ksand			
Ksand (km2/kyr)	Modeled bathymetries		Note
	at 15 Ma	at 6 Ma	
0.01 to 0.1			Important margin progradations attested in the north Basin is starved anomalously deep bathymetries in basin
1			Important margin progradations attested in the north Basin is starved anomalously deep bathymetries in basin
3			Reduced margin progradations attested in the north Basin is still underfilled deep bathymetries in basin
7 to 10			No marginal progradation in northern Lebanon good basin infill Shallow bathymetries offshore northern Lebanon 

Plate 6.15 Modeled bathymetries for the Latakia single source scenario with the Qw parameter of 2830 m3/s.

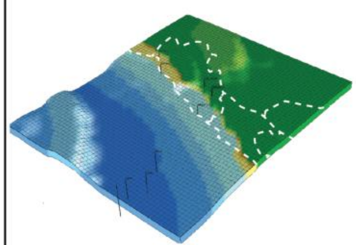
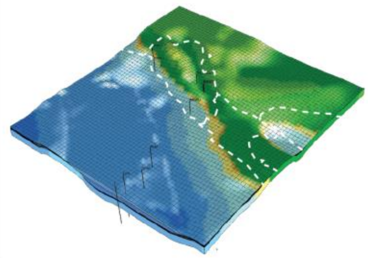
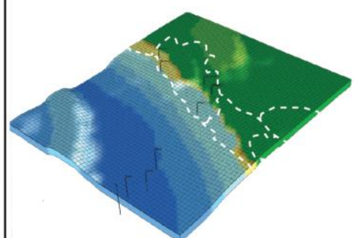
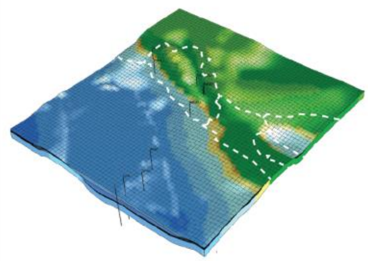
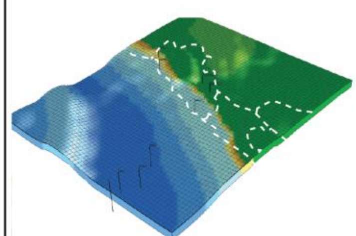
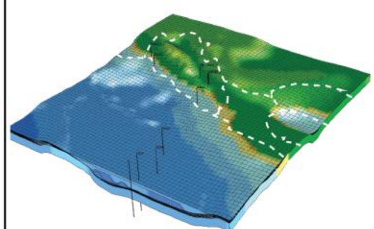
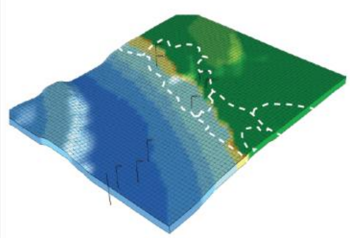
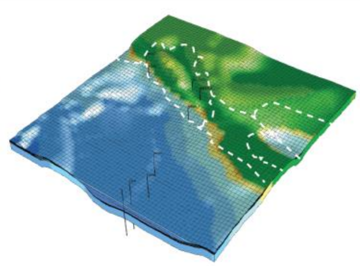
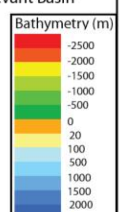
Qw= 150 000 m3/s Kclay= 5 x Ksand			
Ksand (km2/kyr)	Modeled bathymetries		Note
	at 15 Ma	at 6 Ma	
0.01 to 0.1			Good sediment transport from the north into the Levant Basin Sediments do not reach sufficiently the south
1			Good sediment transport from the north into the Levant Basin Sediments do not reach sufficiently the south
3			Good sediment transport from the north into the Levant Basin Sediments do not reach sufficiently the south
7 to 10			Good sediment transport from the north into the Levant Basin Sediments do not reach sufficiently the south 

Plate 6.16 Modeled bathymetries for the Latakia single source scenario with Qw of 60 m3/s

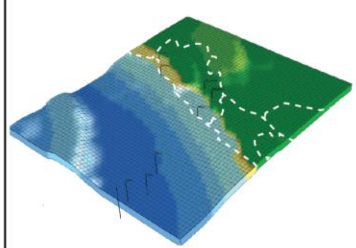
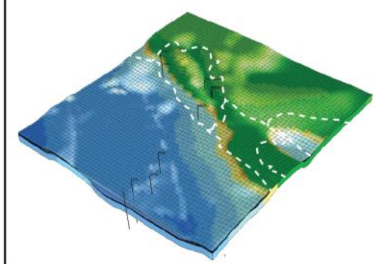
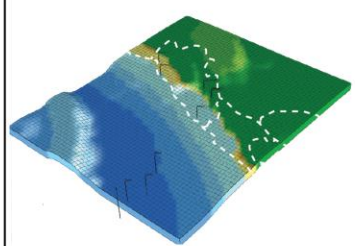
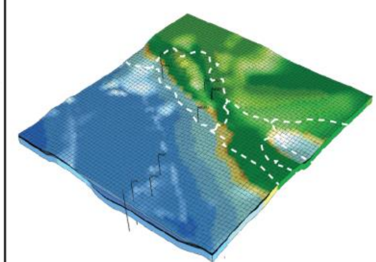
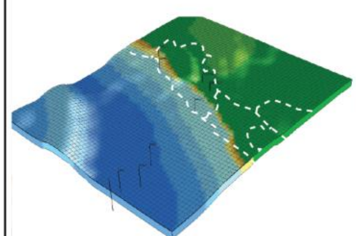
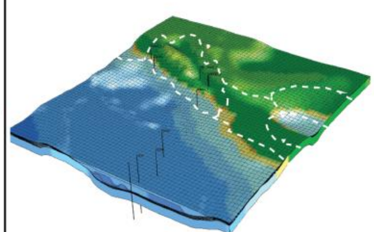
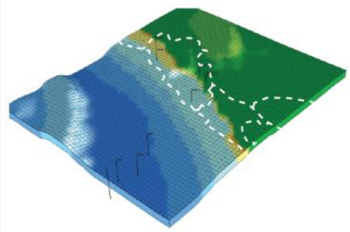
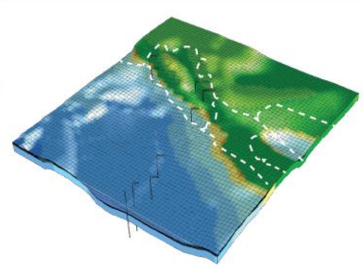
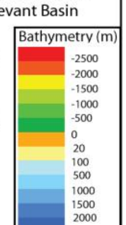
Qw= 150 000 m3/s Kclay= 5 x Ksand			
Ksand (km2/kyr)	Modeled bathymetries at 15 Ma	Modeled bathymetries at 6 Ma	Note
0.01 to 0.1			Good sediment transport from the north into the Levant Basin Sediments do not reach sufficiently the south
1			Good sediment transport from the north into the Levant Basin Sediments do not reach sufficiently the south
3			Good sediment transport from the north into the Levant Basin Sediments do not reach sufficiently the south
7 to 10			Good sediment transport from the north into the Levant Basin Sediments do not reach sufficiently the south 

Plate 6.17 Modeled bathymetries for the Latakia single source scenario with the Qw parameter of 150 000 m3/s.

IV.3.3 Arabian sediment source

Finally an Arabian sediment source has been tested. The total sediment volume supplied by the tested source would range between 1800-2000 km3/Ma in order to fill the basin.

The following Plates 6.18, 6.19, 6.20 show the different tests conducted using values of diffusion coefficient (K) between 0.01 (very low) to >10 km2/ka (very high) (with Kshale= 5x Ksand) and water discharge values between 2830 m3/s (equivalent of the current Nile discharge values) and >190 000 m3/s (equivalent of the current Amazon River).

<u>For Qw=2830 m3/s:</u>

(1) Ksand values between 0.01 and 1 km2/ka reveal to be unsuccessful in matching the data. Important progradation and overfilling of the margin side is attested while the basin is still starved. Note that when Ksand values increase progradation along the margin decreases and basinal infill increases.

(2) For Ksand values of 3 km2/ka a moderate data-match has been noted with good basin however the margin is overfilled. In offshore northern Lebanon the basin is over-filled due to sediment supply from the margin. Offshore central and northern Lebanon deeper bathymetries are attested due to the diversion of sediment transport around paleotopographic highs (i.e., Palmyrides and Mount Lebanon).

(3) For Ksand values between 7-10 km2/ka the basin is overfilled and sediment spill over the Latakia Ridge. The margin is not homogenously infilled.

Additional scenarios have been tested in order to assess the amount of water discharge needed to infill the northern Levant Basin for low Ksand values (0.01 to 0.1 km2/ka). Successive tests show that more than 190 000 m3/s (current Amazon River) of water discharge are needed to begin infilling moderately the northern Levant Basin (Plate 6.20).

Arabian source + carbonate production

Production vs. water depth

Bathy (m)	Algal	PelagicMud
0	1	0.2
10	1	0.2
20	0.8	0.2
50	0.7	0.3
100	0.1	1
200	0	1

Carbonate production rate vs time

Age (My)	Production rate (m/My)	
	Algal	PelagicMud
7	0	30
10	5	30
16	60 to 80	30

Boundary supply

Rain Fall (200 mm/yr)
Source width (300 km)
Sand 20%, Clay 80%
Age: from 16 to 6

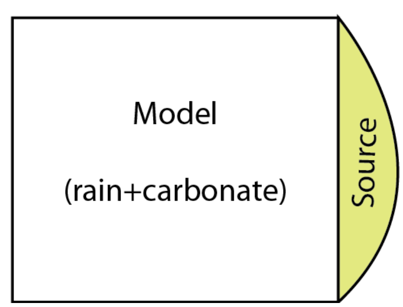


Plate 6.18 Overview of the input parameters used for a possible major Arabian source providing sediments into the Levant Basin

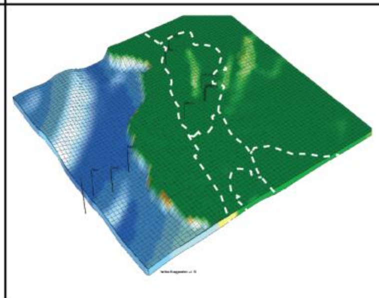
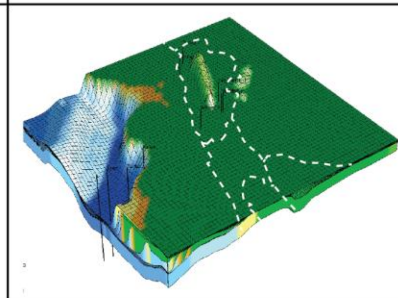
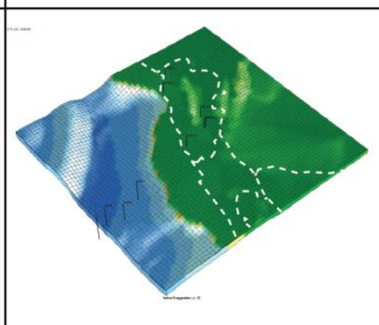
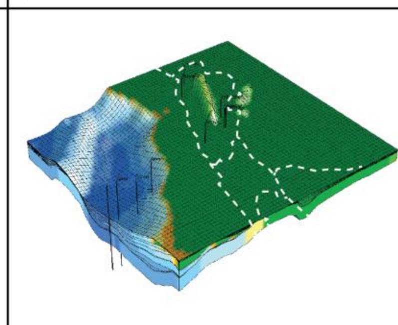
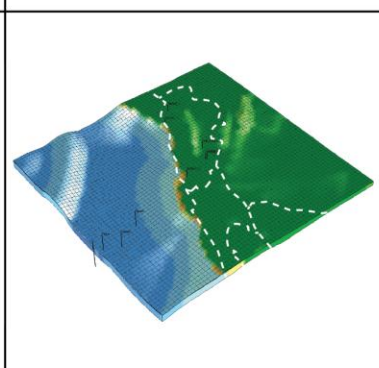
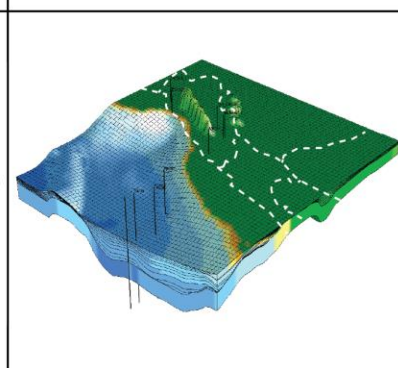
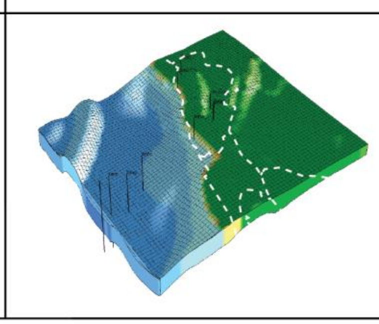
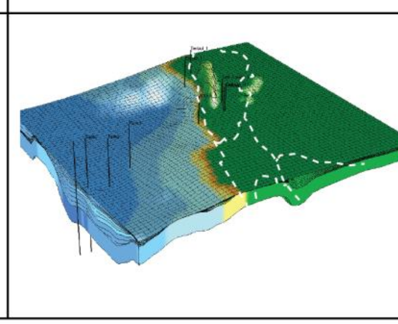
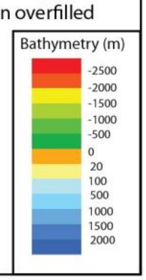
Qw= 2830 m3/s Kclay= 5 x Ksand			
Ksand (km2/kyr)	Modeled bathymetries at 15 Ma	Modeled bathymetries at 6 Ma	Note
0.01 to 0.1			Anomalous margin progradations Basin is starved
1			Anomalous margin progradations Basin is still underfilled Better sediment transfer from the margin into the basin
3			Moderate margin progradations attested in the south and north good basin infill
7 to 10			Good margin infill Basin overfilled 

Plate 6.19 Modeled bathymetries for the Arabian single source scenario with the Qw parameter of 2830 m3/s

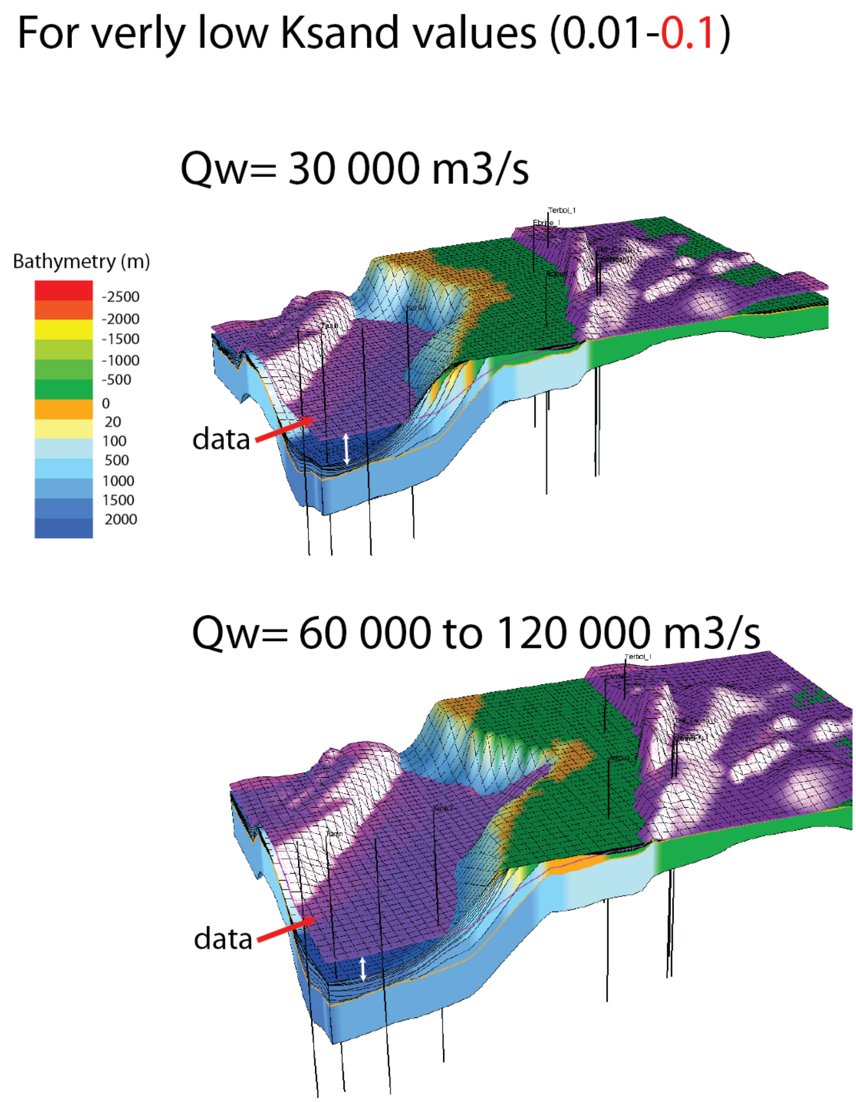


Plate 6.20 Modeled bathymetries for the Arabian single source scenario with high Qw parameters proving that for low Ksand values sediments are trapped along the margin while the basin is starved.

Discussion

To assess the feasibility and the expected order of magnitude of the variety of sources contributing to the infill of the northern Levant Basin, we use global relationships that define the present day drainage systems (refer to Figs.6.1, 6.2, 6.3; Milliman & Syvitski, 1992; Syvitski & Milliman, 2007). The present-day parameters of water discharge, sediment load, drainage area and diffusion coefficient are compared with the ones applied in order to achieve a best-fit model of the several scenarios proposed. By the term "best fit model" we allude to a good volume infill of the distal margin and basin and to a moderate to high facies spacial configuration correlation.

In the case of a carbonate and hemipelagic-dominated infill, the viability of the parameters used for carbonate production versus time and shape of the rhodalgal carbonate factory are evaluated through comparisons with published data from around the Mediterranean and more specifically in its eastern sector (e.g. Cita et al., 1978; Pomar, 2001; Halfar & Mutti, 2005; Hawie et al., 2013a).

It is important to note that the calibration of the most plausible model is constrained by the offshore 2D seismic data studied as well as the field investigations of the Middle to Upper Miocene along Lebanon.

Carbonate and hemipelagic/pelagic infill

The use of realistic values attested in the Mediterranean in terms of carbonate production does not lead to a complete basin infill. Rhodalgal systems develop in euphotic to oligotrophic settings reaching a maximum depth of about 100 m. The thicknesses attested onshore Lebanon (mainly in the north: Kousba area) for the Middle Miocene rhodalgal carbonates attains about 300 m (about 60 m/Ma). Neogene hemipelagic/pelagic material production described in the eastern Mediterranean varies between some meters per Ma (Low: 2-10 m) to a maximum of 100 m/ Ma (Cita et al., 1978). In their forward stratigraphic model Gvirtzman et al. (2013) use a value of 10m/Ma for the pelagic sediment contribution (low value) of the Levant Basin. The realistic case proposed in this manuscript applies 60-80 m/Ma for carbonate production versus 30-40 m/Ma for hemiplegic/pelagic production.

Following the realistic scenario proposed a good fit with the rhodalgal facies spacial configuration is observed. Major rhodalgal platforms develop in northern Lebanon and are very restricted/ missing around Beirut and the south where deeper slope to basinal settings are attested

In order to illustrate the influence of the several potential sources on the infill of the northern Levant basin a multi-source model was built using moderate and realistic values for the several sources using the previously described assumptions in section III.3. The final proposed model honors the volumes expected to infill the northern Levant Basin in the Middle to Upper Miocene but also respects the facies descriptions of the Miocene rock unit onshore Lebanon as well as the seismic interpretation. However what is still uncertain is the proportion of the expected lithologies in the basin (e.g. sand versus clay) provided by each source.

Multi-source system

The best-fit model honoring sedimentary volumes and facies has been achieved for realistic present-day Qw values (Nile: 2830 m3/s; Arabia: 800 m3/s; Latakia: 80 m3/s) and Ksand values ranging between 3 and 7 km2/Ka. The moderate values used for the rhodalgal production fit well with the onshore study of the Middle Miocene rock unit. Rhodalgal platforms are attested to the north while around Beirut and southern Lebanon deeper settings are attested due to the impact of the Palmyridian basin on the depositional environments.

The interpreted lobe-shaped geometries observed on the seismic profiles in the southwestern part offshore Lebanon reaching Beirut have been successfully modeled showing the influence of a potential nilotic sediment provenance.

The modeled Latakia input is coherent with the proposed seismic interpretation as well as with the mapped amplitudes published under Skiple et al. (2012). There, sediment accumulations are expected to prevail along offshore northern Lebanon following the Latakia Ridge trend.

The water pathways for the Arabian source seem to feed into the southern Levant margin and southern Lebanon as they are diverted by the evolving Palmyridian structures as well as by the Lebanese mountains.

For the low Ksand values (=0.1 km2/Ka) scenario water discharges in the order of magnitude of the present day Zaire river (Qw=50 000 m3/s) should be expected for the paleo-Nilotic system. An Arabian system presenting water discharge close to actual Mekong river discharge (Qw=20 000 m3/s) should contribute also to the infill (values are very 20x higher than expected). For a sediment load of 250 km3/Ma provided by the Syrian coast the water discharge used in this scenario is over valued (2000 m3/s) and still does not lead to an optimum basinal transport. A higher Ksand value (=1 km2/Ka) leads to a better sediment transport to the Levant Basin with Qw values for the southern and eastern source of 8000 m3/s.

The good volume and facies calibration of the multi-source system presents an important impact on the prediction of lithologies associated to each source infilling the northern Levant Basin and thus on the reservoir risk-assessment of petroleum systems. However this task cannot be fully achieved at the moment due to the lack of wells drilled in the northern sector of the Levant Basin. This remains a main limitation that should be accounted for in future studies dealing with petroleum system risk analysis.

Single sources

To summarize, the infill of the northern Levant Basin with one single source is not viable as the parameters of carbonate production and sedimentary transport are over estimated to achieve this purpose. A single source model does not generate a correct spatial configuration of interpreted sedimentary bodies along the distal margin and basin. The following paragraphs discuss the several scenarios of a single source model.

Nilotic source

The simulations conducted for the southern sediment provenance in the basin reveal that several best volume-fits can be achieved using a variability of values for the water discharge (Qw) and the diffusion coefficient (Ksand). The sediment load values required to infill the Levant Basin (1800-2200 km3/Ma) are realistic compared to the Nile drainage basin area (3000 000 km2). Note that the values used reflect only the parameters needed at the entry of our model (thus about 120 km north of the current northern African-continent).

In order to infill the basin using moderate Qw values (between 900 and 2830 m3/s) high Ksand values should be added. However in order to achieve a best fit scenario using low to moderate Ksand values (0.01 to 0.1 km2/Ka) more than 65 000 m3/s of water discharge is required at the southern entry of our model (equivalent of the sum of Qw of the Zaire and Yangtze).

In the case of a drastic increase in sediment influx it seems that the only location that is to be infilled by this source is solely the deeper Levant Basin rather than the proximal margin.

High amplitude lobes - interpreted as basin fans or turbidites at the front of the Nile deep sea cone - have been observed on the 2D seismic data in the central and south western sector offshore Lebanon, the scenarios proposed for a single source from southern Lebanon fail to adhere to this constraint as sediments seem to be transferred along the whole basin reaching its northernmost part.

Important questions can be raised at that point: can longshore currents active in the Miocene transfer nilotic sediments further along the distal margin/ proximal basin? What is the impact of already existing canyons on sediment transported by these currents?

Latakia/coastal Syrian source

For the Latakia source scenario the several iterations proposed did not lead to a good volume fit even if very high values of water discharge and Ksand are used. Sediment accumulations are noted to the northern source entry zone, which is translated in lower than expected bathymetries in the Levant Basin.

Several additional arguments stand against the probability of occurrence of this scenario:

- The main impacting factor on the difficulty in transporting sediments is the big volume required (about 4400 m/Ma) to fill up the northern Levant Basin in the Late Miocene (in about 6 Ma). Even for hydraulic conditions that prevail in the biggest present-day rivers as the Amazon (Qw> 160 000 m3/s), sediments are still not fully transported basinwards.
- For a volume of 4400 km3/Ma the required drainage basin area ranges from 10 000 km2 (for elevations of more than 2500 m) to 3000 000 km2 (for elevations between 600 and 1200 m) (Fig.6.1b). The minimum drainage basin area (10 000 km2) represents the equivalent of the whole actual drainage area of Lebanon and the Coastal Ranges and Latakia in Syria (Fig.6.14) that feed the Levant Basin through a multitude of rivers. However drainage basin elevations along the Syrian coastal area range between 1000 and 1400 m which thus requires drainage basin areas of about 200 000 km2 in order to provide 4400 km3/Ma of sediment load (not realistic in this case).

Following the presented comparisons with actual drainage systems it does not seem plausible to infill Levant Basin from the Syrian coastal area. However an input from this region should not be discredited as seismic evidence clearly point to channelized systems providing sediments from the northernmost Levant Region (i.e. Latakia and coastal Syria).

An important question arises at that point and is difficult to be answered with the dataset provided in this thesis. Can there be any sediment influx from a regional Turkish drainage system at that period? What would be the role of the Latakia Ridge in acting as a basin divide between the northern Lebanese offshore and the Syrian and southern Turkish offshore?

Arabian sediment source

The tested Arabian sediment source contributing to the infill of the Levant Basin reveals that two good volume fit scenarios can be proposed:

(1) A need for about 1800-2000 km3/Ma of sediment load with Ksand values ranging between 3 and 6 km2/Ka (high values) with Qw=2830 m3/s (similar to actual Nile)

(2) For lower Ksand values (0.01 to 1 km2/Ka) a Qw of more than 190 000 m3/s is required (equivalent of Amazon River)

Several arguments stand against the high probability of a major Arabian contribution to the Levant Basin:

- The sediment load values correspond to a wide range of possible drainage basin areas depending on their relief. In order to have about 2000 km3/Ma of sediment load, the drainage areas can range from about 2000 km2 (for high relief more than 2500 m) to about 800 000- 1000 000 km2 (between 660 and 1200 m of elevation- fair values of uplifted Red Sea rift shoulders). Thus, following the fair elevation values, a drainage area similar to that of the Orinoco and Indus should have been feeding the northern Levant Basin from Arabia. Note that the maximum drained area in the Oligo-Miocene can reach up to 200 000 km2 (Gvritzamn et al., 2013).

- Looking at the hydraulic conditions it seems that in order to have values of Qw= 2830 m3/s (actual Nile) we would be needing relatively high Ksand values between 3 and 6 km2/Ka. While if we use low to normal Ksand values a huge water discharge equivalent to the Amazon River Qw>190 000 m3/s is needed. These hydraulic conditions of more than 80-100 times the actual precipitation on the Arabian Plate are not probable.

Eventhough a single source from Arabia is not plausible at this point, it is important to note that sediment provenance from the Levant hinterland should not be discredited (Gvirtzman et al., 2013). Major E-W canyon systems feeding into the Levant Basin have been identified onshore Israel and are expected to have transferred sediments from the Oligocene to the Middle Miocene offshore (Gardosh et al., 2006; Zilberman & Calvo, 2013).

No major E-W canyon has yet been identified in Lebanon that could extend from the Arabian hinterland towards the Levant Basin. However, the incisions observed along the southern Lebanese Tyr-Nabatieh plateau could represent reveal to be inherited from older drainage systems feeding from Arabia into the Levant Basin (refer to Beydoun, 1976; Garfunkel, 1981; Walley, 1998; Hawie et al., 2013b). Note that the deformation onshore Lebanon (mainly in the center and the northern onshore sector) should have obstructed Arabian sediment transport pathways in the Miocene.

Synopsis

Through this chapter a stratigraphic model was built using a compilation of onshore-offshore isopach maps supported by overall bathymetric maps. A source to sink approach has been followed leading to the evaluation and assessment of the parameters needed for Miocene sediment transport and accumulation in the Levant Basin.

Some concluding remarks concerning the Middle to Late Miocene infill of the northern Levant Basin are presented:

- Aggradation of rhodalgal platforms is expected to occur along the Levant margin while hemipelagic sediments have deposited in deeper basinal settings.

- Hypothesis related to the contribution of a single source to the infill of the basin has been discredited based on several reasons i.e., over-estimation of the sediment load volumes of each source, the hydraulic parameters (water discharge and diffusion coefficients) that drive sediments in the continental and marine domains as well as the inability to explain the seismic facies attested offshore Lebanon published in Hawie et al. (2013b).

- The comparison of the modeling results with present-day drainage system reveals to be a very effective workflow needed in order to assess the viability of contributing sources to the infill of the Levant Basin sink.

- A multi-source system providing sediments from the south (Nile), east (Arabia) and north (coastal Syria) could present a good-fit scenario where volumes and facies spacial configuration are honored.

This raises important questions related to the expected types of sediments driven by each source and their impact on the reservoirs expected in the northern Levant Basin.

CHAPTER VII

General Discussion

I. Challenges and constraints related to source to sink studies

Onshore-offshore data integration in frontier basins appears to be of significance in unraveling the history of deformation and the consequent impact on sediment erosion, transport and deposition. Many challenges and difficulties have been noted in the assessment of sedimentary basins evolution, which directly impact on source to sink studies and thus on stratigraphic modeling.

In their studies, Csato et al. (2009), Macgregor (2012), Gvirtzman et al. (2013) amongst others discussed uncertainties in (1) age's allocation to sedimentary packages, (2) bathymetric assessment of basinal units, (3) sources location, timing and sedimentary load (local versus regional sources) as well as (4) the type of source to sink systems (single versus multi-source). In order to answer to these uncertainties a wide combination of data sets and methodologies has been used (e.g seismic interpretation, field work, well data, biostratigraphy, heavy minerals, thermo-chronology) (e.g. Allen, 2008; Martinsen et al, 2010).

The work conducted in the northern Levant Basin proves that data integration of different scales and sources could reduce significantly some of these uncertainties. However, as in all frontier basins, the lack of well data sets hinders the complete assessment of basin evolution and infill. In our approach the use of onshore and offshore data allowed to constrain the stratigraphic model proposed for the Miocene unit.

(1) *Onshore:*

The combination of sedimentological logging (6500 m of logs) of surface exposed rock units and well core data with biostratigraphic studies (i.e., nannofossil and foraminifer) onshore Lebanon permitted to reduce the uncertainties linked with ages subdivision, vertical and lateral facies and bathymetric assessment for the onshore Miocene rock unit (refer to chapter, 3 and 4; Hawie et al., 2013a; Crognier, 2013).

Hiatuses and angular unconformities identified onshore (e.g., Early/Late Eocene to Middle Miocene) refer to the impact of continuous margin deformation and consequent sediment erosion, transport and deposition following geodynamic events.

The Miocene case study onshore Lebanon represents a good example of the impact of continuous marginal deformation on sediment facies spatial configuration (i.e., N-S and E-W facies variations; refer to chapter 3 and 4 of this manuscript). Open marine settings have been identified in the Middle Miocene towards the coastal area contrasting with restricted lacustrine settings in the Bekaa Valley.

Through onshore assessment sediment transport pathways can be identified (e.g. major Oligo-Miocene rivers and canyons, fan deltas, alluvial fans; refer to Beydoun, 1977; Gardosh et al., 2008; Hardenberg & Robertson, 2007; Hawie et al., 2013a). In the case of the Levant region gas discoveries occurred in Oligo-Miocene canyon systems rich in siliciclastic reservoir material (Gardosh et al., 2006; Gvirtzman et al., 2013; Zilberman & Calvo, 2013).

The onshore investigation coupled with literature review brought important constraints for onshore sedimentary facies delimitation, carbonate factories but also for the quantification of the minimum rates of carbonate production, an important parameter used in the source to sink assessment and forward stratigraphic modeling (discussed later).

(2) *Offshore*:

Three main constraints have provided added values and uncertainties reduction to the northern Levant Basin tectono-stratigraphic assessment.

The use of seismic stratigraphic concepts and facies analysis for the northern Levant Basin allowed the identification of eight major seismic packages in the offshore from the Late Jurassic till the Present. Shallow marine seismic data offshore northern Lebanon (Geo-Prakla; Beydoun, 1977) help in achieving the onshore-offshore correlation.

The use of scarce basinal well constraints as well as margin-basin correlations from the southern sector of the Levant Basin (e.g., Gardosh et al., 2008, 2010; Hogson, 2013) contributed to the reduction in ages uncertainties allocated to seismic packages offshore Lebanon (mainly for the Cenozoic rock unit- refer to chapter 5 and to Hogson, 2013).

The geometries of seismic facies and their extent provide a clearer understanding of the sediment provenance from local and regional sources and pathways (Levant margin, Nile, Latakia and Arabia) into the Levant Basin sink (Hawie et al., 2013b; Fürstenau et al., 2013).

Some of these offshore constraints have been used in previous assessments of a variety of source to sink systems as the Pannonian Basin in eastern Hungary (Csato et al., 2009), Gulf of Lion in southern France (Rabineau et al., 2005), Norwegian margin (Sømme et al., 2009b, Martinsen et al., 2010) Gulf of Mexico (Alzaga-Ruiz et al., 2009). They are supported by wider data sets (e.g., offshore well data and logs, abundant 2D and/or 3D seismic data).

The lack of well data offshore Lebanon reveals to be a major limiting factor in uncertainty reduction of age, lithology and provenance volumes of the northern Levant Basin.

II. The importance of global relationships in the assessment of multi- source systems

The Multi-disciplinary "source to sink" approaches in this study revealed the importance of using actual global relationships in order to assess ancient drainage systems. Few examples of application of source-to-sink analysis to ancient systems have been published as there are still many challenges prevailing. One of the most important is the preservation of the complete source to sink systems through time (Martinsen et al., 2010).

The extensive drainage system database proposed by Milliman & Syvitski, (1992), Syvitski & Milliman, (2007) as well as Sømme et al. (2009b) reveals to be of importance when assessing the governing source to sink parameters (i.e., water discharge, sediment load, drainage area and diffusion coefficient).

However in the case of the northern Levant Basin a combination of this regional sediment transport assessment with local carbonate production increases the complexity of the source to sink assessment as carbonate factories should be well studied and hemipelagic rates approximated.

In the Oligo-Miocene stratigraphic model proposed by Gvirtzman et al. (2013), carbonate production rates of 50m/Ma were used and pelagic deposition of 10m/Ma estimated based on thickness and duration of older known pelagic rock units (Santonian to Middle Eocene). These calculations accounted for about 8-10 % of the total Oligo-Miocene infill of the southern Levant Basin.

In order to reduce the uncertainties linked with the missing volumes of Oligocene to Lower Miocene unit onshore Lebanon (completely eroded) only the Middle and upper Miocene rock interval has been modeled. The realistic rates used in our model for rhodalgal carbonate production range between 60-80 m/Ma. They are approximated through geological sections and sedimentary logs in northern Lebanon (i.e., Kousba; Hawie et al., 2013). Studies of well data in the Levant offshore by Cita et al. (1978) reveal that rates of Neogene hempelagic to pelagic material averages 30-40 m/Ma (pre-Messinian salt) thus about 20-25% of the Levant basin infill.

The use of global relationships permitted to discredit the possibility of having a single major source providing sediments from Arabia and Latakia into the Levant Basin as the transport parameters and sediment load should be overestimated in order to achieve the complete filling of the Levant Basin (refer to chapter 6). These results support the hypothesis presented by Steinberg (2011) that refers to the Nile system as being the main sediment provider into the basin.

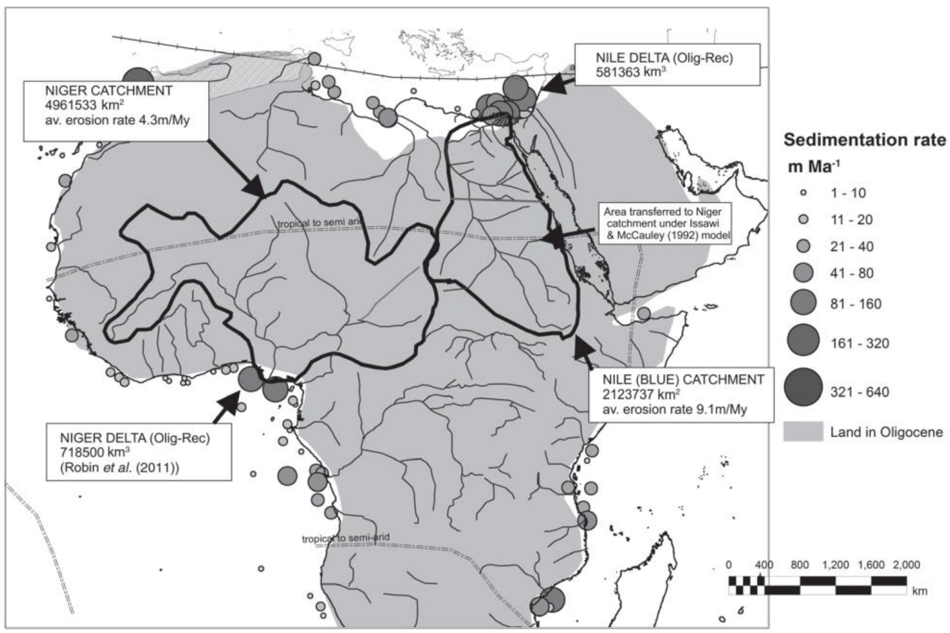


Fig7.1 Oligocene to recent sedimentation rates along Africa showing the extensive Nile catchment area (from Macgregor, 2012)

The best fit model that honors sedimentary and seismic facies analysis as well as volumes accommodates 50 % of sediments from the Nile, 20 % of local carbonate and hemipelagic deposits while the last 30 % are sourced from Arabia, Lebanon and Coastal Syria. However these percentages may vary when well data becomes available. In their model Gvirtzman et al. (2013) revealed a contribution of 65-70% of nilotic sediments to the Basin infill while 15-20 % from Arabia through major Canyon systems. The reduction in percentages northwards from 70 to 50% for the nilotic sediment provenance is linked to the increased distance to sediment source.

What this investigation fails to predict is the exact lithologies expected for the Miocene rock unit of the Levant Basin. However looking at the general granulometry of the possible sediments deposited we can see that the further away we move from the source, finer sediments are deposited.

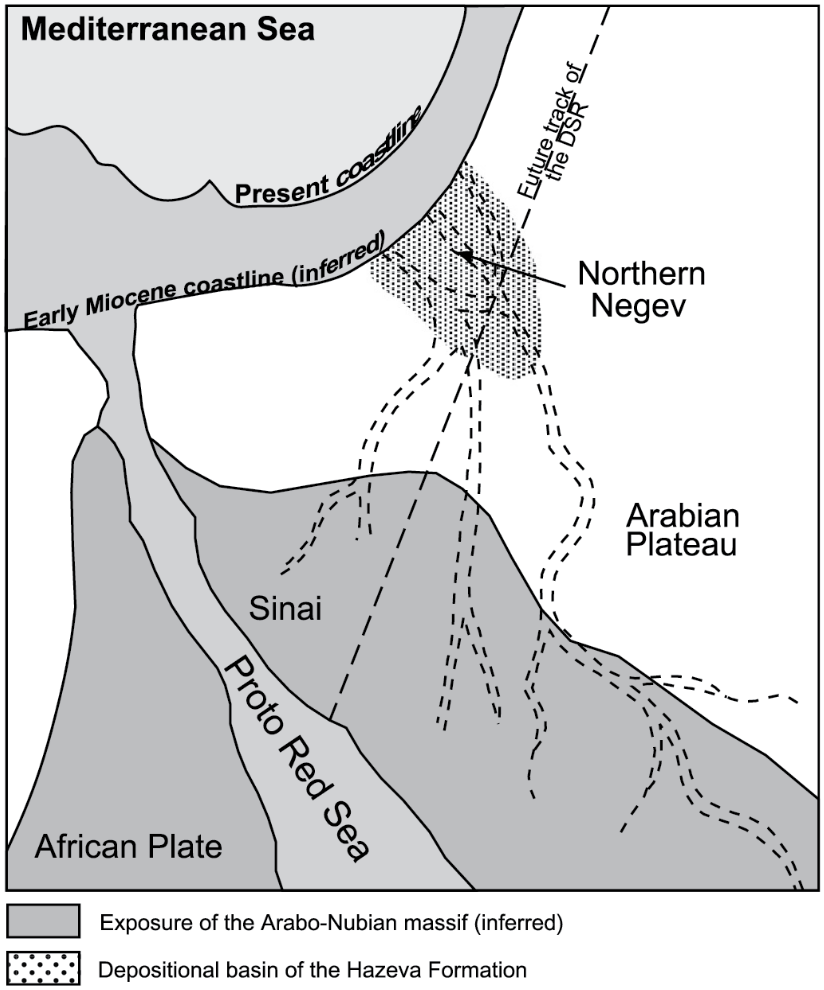


Fig7.2 Paleogeographic map of the Early Miocene fluvial system (from Zilberman & Calvo, 2013).

III. Added values of forward stratigraphic modeling in frontier basins exploration

Even though numerical stratigraphic modeling in frontier regions is bound to many challenges linked with the scarcity of data (and its variable scales) this tool appears to be of importance in representing in a 3D domain the expected morphologies of margins and basins (Granjeon & Joseph, 1999).

The use of source to sink studies and modeling in exploration of frontier basins can reveal to be very beneficial in reducing the uncertainties linked with geological model proposed as well as with the petroleum system assessment (e.g., Rabineau et al., 2005, Csato et al., 2009, Sømme et al., 2009b, Martinsen et al., 2010; Gvirtzman, 2013).

The diffusive numerical modeling tests allow at that point to represent the impact of each sediment transport parameter on the bathymetries expected and sediment spatial distribution. The combination of the onshore knowledge with the seismic interpretation and facies delimitations permits a fair calibration of the model that should be further constrained with offshore well data in the years to come. By doing so, a lithology-bound model can be conducted confidently in the Levant Basin.

The validation by modeling of the multi-source system in the Middle and Upper Miocene has repercussions not only on this rock unit but on the whole Oligo-Miocene system of the Levant Basin as the Nilotic and Arabian sources are active since the Middle-Late Eocene (Steinberg, 2011; Macgregor, 2012; Gvirtzman, 2013; Zilberman & Calvo, 2013). The major gas discoveries in the southern Levant Basin in Upper Oligocene and Lower Miocene rock units (i.e., Tamar, Leviathan, Aphrodites, Karish) are stored in nilotic sandstone turbidite sheets referred to as the Tamar Sands. Reservoir rocks have been also identified in Miocene canyon and Pliocene turbidite systems along the southern Levant margin sourced from Arabia (Gardosh et al., 2006; 2008).

Additional questions related to the extent and volume of siliciclastic sediments from the Nile, Arabia and the Latakia region into the northern Levant Basin are yet to be answered.

The use of integrated data sets (e.g. well, outcrop, seismic) can help reduce uncertainties in the exploration of frontier basins. The combined applications of source to sink methodologies and numerical techniques as forward stratigraphic modeling (Dionisos-IFPEN) provide a platform for exploration geologists to test the viability of their different basin infill scenarios as well as to predict and map potential sedimentary facies extension along margins and basins.

CONCLUSIONS & RECOMMENDATIONS

The combination of field investigations, 2D seismic interpretations (supported by 3D) as well as forward stratigraphic modeling resulted in the proposition of an updated tectono-stratigraphic framework for the northern Levant margin and basin from the Late Mesozoic onwards. The impact of regional geodynamic events on the architectural evolution and sedimentary infill of the northern Levant Basin have been assessed thoroughly leading to the following conclusions:

- The Levant region witnessed multiple episodes of deformations linked with major geodynamic events affecting the African, Arabian and Eurasian Plates.
    - Rifting phases initiated in the Early Mesozoic lead to the concomitant evolution of the Levant and Palmyride Basins.
    - The convergence between Afro-Arabia and Eurasia started in the Turonian. It induced the formation of a flexural basin facing the Latakia Ridge offshore northern Lebanon. A shift of depocenter location from northern to southern offshore Lebanon marks the continuous advance of this flexural basin until the end of the Early Miocene.
    - An angular unconformity along Lebanon between the Lower Eocene and Middle Miocene rock units proves the occurrence of a pre-Burdigalian and post Ypresian deformation phase onshore Lebanon. It resulted from the continuous convergence between Afro-Arabia and Eurasia.
    - The initiation of the Levant Fracture System in the Middle Miocene and its propagation onshore Lebanon in the Late Miocene is accommodated in the offshore realm by a set of strike-slip faults.
- Onshore hiatuses in the Late Turonian to Late Santonian, Late Maastrichtian to Late Paleocene, Ypresian/Early Lutatian to Late Burdigalian have been dated in Lebanon. They correlate well with the major successive geodynamic events.
- The northern Levant margin is dominated by a thick Mesozoic carbonate rock column while in the basin a carbonate-siliciclastic mixed-system is expected with Cenozoic sediments reaching more than 10 km in thickness.
- The Middle Miocene unit onshore Lebanon presents a diversity of sedimentary facies as a consequence of the successive deformations. Rhodalgal platforms have been described north of Beirut while towards the southern coastal area deepwater settings prevail. In the Bekaa Valley lacustrine facies have been observed attesting of a restricted continental setting.
- A diversity of sedimentary pathways contribute to the infill of the Levant Basin (i.e., Levant canyon systems, Nile Deep Sea cone and Latakia region).
- Hypothesis related to the contribution of a single source to the infill of the basin have been discredited by stratigraphic modeling based on several reasons i.e., over-estimation of the sediment load volumes of each source, the hydraulic parameters (water discharge and diffusion coefficients) that drive sediments in the continental and marine domains as well as the inability to explain the seismic facies attested offshore Lebanon.

- A multi-source system providing sediments from the south (Nile), east (Arabia) and north (coastal Syria) represents the best-fit scenario raising questions about the expected reservoir type sediments driven by each source and their spacial extent into the basin.

Perspectives

Additional investigations are needed in order to consolidate the study proposed in this PhD thesis but also to drive new ideas.

- Additional fieldwork and petrological analysis is required for the Neogene section of the Hermel area (north) and the Tyr-Nabatieh (south) plateau area in order to present a detailed description of the continental and deep marine settings prevailing at this period (use of polens and nannofossil dating).
- Apatite Fission Track Analysis should be conducted in order to answer to uncertainties linked with major uplift periods. This could bring further information on the timing of emergence and erosion of the Chouf Fm (sandstone).
- Focus on 3D interpretation of geomorphologic features on the Miocene and Pliocene to propose an enhanced seismic facies analysis and thus a better delimitation of sedimentary bodies.
- More refined modeling is required once 3D data is interpreted to better understand sedimentary system evolution with regards to onshore and offshore deformation of the Oligo-Miocene.
- Simulation of Cretaceous to Eocene carbonate platforms can be of interest while trying to assess their source rock potential.

REFERENCES:

Abdel Aal, A., Shrallow, J.A., Nada, H. & Shaarawy, O. 1996. Geological Evolution of the Nile Delta, Egypt, using Regional Seismic Interpretation.Egyptian General Petroleum Corporation 14th Exploration and Production Conference, **1**, 240–353.

Abdel Aal, A., El Barkooky, A., Gerrits, M., Meyer, H. J., Schwander, M. and Zaki, H., 2001. Tectonic evolution of the eastern Mediterranean basin and its significance for the hydrocarbon prospectivity of the Nile Delta deepwater area. GeoArabia, 6, 363–384.

Abdel-Rahman, A. M., 2002. Mesozoic volcanism in the Middle East: geochemical, isotopic and petro- genetic evolution of extension-related alkali basalts from central Lebanon. Geological Magazine, 139, 621 – 640.

Abdelkareem, M., Ghoneim, E., El-Baz, F. & Askalany, M. 2012. New insight on palaeoriver development in the Nile Basin of the eastern Sahara. Journal of African Earth Sciences, 62, 35–40.

Abu El-Ella, R., 1990. The Neogene-Quaternary section in the Nile delta, Egypt: geology and hydrocarbon potential. Journal of Petroleum Geology 13, 329–340.

Al Abdalla, A., Barrier, E., Matar, A. & Müller, C., 2010. Late Cretaceous to Cenozoic tectonic evolution of the NW Arabian platform in NW Syria. In: Homberg, C. & Bachmann, M. (eds) Evolution of the Levant Margin and Western Arabia Platform since the Mesozoic. Geological Society, London, Special Publications, 341, 305–327.

Al Maleh A. K. & Mouty M., 1988. — The sedimentologic and paleogeographic evolution of the Palmyrian region during the Cretaceous, in Saffarini G. A. et al. (eds), Geology of Jordan and adjacent area. Proceedings of the Third Jordanian Geological Conference Special Publication 3: 213- 244.

Al Tarazi, E., Abu Rajab, J., Gomez, F., Cochran, W., Jaafar, R. & Ferry, M. 2011. GPS measurements of near-field deformation along the southern Dead Sea Fault System. Geochemistry, Geophysics, Geosystems, 12, Q12021, doi:10.1029/2011GC003736.

Al-Saad, D., Sawaf, T., Gebran, A., Barazangi, M., Best, J. & Chiamov, T., 1992. Crustal structure of central Syria: The intracontinental Palmyride moun- tain belt. Tectonophysics, 207, 345–358.

Allen, P. A. 2008. From landscapes into geological history. Nature, 451, 274–276.

Allen, P. A. and Allen J.R. 2008. *Basin analysis : principles and applications* (2. ed.). Malden, MA. Blackwell, London

Allen, P. A. and Allen, J. R., 2005. Basin analysis: principles & applications: Blackwell Science, Oxford, UK, 549 pp

Allen, P.A. (1997) Earth Surface Processes. Blackwell, London.

Allen, P.A., Burgess, P.M., Galewsky, J. and Sinclair, H.D. 2001. Flexural-eustatic numerical model for drowning of the Eocene periapline carbonate ramp and implications for Alpine geo-dynamics. Bulletin Geological Society of America, 113, 1052-1066.

Alsdorf, D., Barazangi, M., Litak, R., Seber, D., Sawaf, T. &Al-Saad, D., 1995. The intraplate Euphrates depression–Palmyrides mountain belt junc- tion and relationship to Arabian plate boundary tectonics. Annali di Geofisica, 38, 385–397.

Alsharhan, A. S. & Nairn, A. E. M.,1997. Sedimentary Basins and Petroleum Geology of the Middle East. Elsevier, Amsterdam, 843.

Alsharhan, A.S. and Salah M.G., 1996. Geologic setting and hydrocarbon potential of north Sinai, Egypt. Bulletin of Canadian Petroleum Geology, 44, 615–631.

Argus, D.F., Gordon, R.G., 1991. No-net-rotation model of current plate velocities incorporating plate motion model NUVEL-1, Geophys. Res. Lett. 18, 2039-2042.

Baker, J., Snee, L., Menzies, M., 1996. A brief Oligocene period of flood volcanism in Yemen: implication for the duration and rate of continental flood volcanism at the Afro-Arabian triple junction. Earth Planet. Sci. Lett., 138, 39–55.

Barrier, E. & Vrielynck, B., 2008. The Middle East Basins Evolution (MEBE) Atlas of Palaeotectonic Maps.

Begin, Z.B., Meyer, D.F., Schumm, S.A., 1981. Development of longitudinal profiles of alluvial channels in response to base-level lowering. Earth Surface Processes and Landforms 6, 49-68**.**

Bein, A. and Gvirtzman, G., 1977. A Mesozoic fossil edge of the Arabian plate along the Levant coastline and its bearing on the evolution of the eastern Mediterranean. In: Biju-Duval, B. and Montadert, L. (Eds.) Structural History of the Mediterranean Basins. Editions Technip, Paris, pp. 95–110.

Bellahsen, N., Faccenna, C., Funiciello, F., Daniel, J.M. & Jolivet, L. 2003. Why did Arabia separate from Africa?

Insights from 3-D laboratory experiments. Earth and Planetary Science Letters, 216, 365–381, doi:10.1029/2009TC002482.

Benjamini. C., 1993. Paleobathymetry of the Eocene of Israel. Isr. Geol. Soc., Annu. Meet., Arad, Abstr. 17p.

Bentham, P., Hanbal, I., Cotton, J., Longacre, M. B. and Edwards, R., 2007. Crustal structure and early opening of the eastern Mediterranean Basin– key observations from offshore northern Egypt. 3rd North African/Mediterranean Petroleum and Geosciences Conference and Exhibition, Abstract, 4.

Bertoni, C. and Cartwright, J.A., 2007. Clastic bodies at the base of the late Messinian evaporites of the Levant region, Eastern Mediterranean. In: Evaporite Deposits, ed. C. Schreiber, Geological Society of London Special publication, 285, 37-52.

Best, J.A., Barazangi, M., Al-Saad, D., Sawaf, T. and Gebran, A., 1993. Continental margin evolution of the Northern Arabian Platform in Syria. Am. Assoc. Petrol.Geol. Bull., 77, 173-193.

Beydoun, Z.R., 1972. A new evaluation of the petroleum prospects of Lebanon with special reference to the pre Jurassic. In: Arab Petroleum Congr., 8th, Algiers, Proc., 80(B-3): 15 pp.

Beydoun, Z.R., 1976. The geology of Syria and Lebanon (maritime regions). In: W. Kanes, A.E.M. Nairn and F.G. Stehli (Editors), The Ocean Basins and Margins, 4. The Mediterranean. Plenum Press, New York, N.Y.

Beydoun, Z. R., 1977. Petroleum prospects of Lebanon: Re-evaluation. AAPG Bulletin, 61, 43-64.

Beydoun, Z.R. and Habib, J.G., 1995. Lebanon revisited: new insights into Triassic hydrocarbon prospects. Journal of petroleum geology, 18, 75-90.

Beydoun, Z.R., 1995. Productive Middle East clastic oil and gas reservoirs: their depositional settings and origin of their hydrocarbons. Special Publication of the International Association of Sedimentologists, 22, 331–354

Beydoun, Z.R., 1999. Evolution and development of the Levant (Dead Sea Rift) Transform System: a historical-chronological review of a structural controversy. In: Mac Niocaill, C. & Ryan, P.D. (Eds.) 1999. Continental Tectonics. Geological Society, London, Special Publications, 164, 239-255.

Bohannon, R. G., 1986. How much divergence has occurred between Africa and Arabia as a result of the opening of the Red Sea? Geology, 14: 510-513.

Bosworth, W., 1992. Mesozoic and early Tertiary rift tectonics in East Africa. Tectonophysics 209, 115–137.

Bosworth, W., Huchon, P. and McClay, K., 2005. The Red Sea and Gulf of Aden Basins. Journal of African Earth Sciences, 43, 334–378.

BouDagher-Fadel, M. and Clark, G-N., 2006. Stratigraphy, paleoenvironment and paleogeography of Maritime Lebanon: A key to Eastern Mediterranean Cenozoic history. **Stratigraphy**, 3, 81-118.

Bouma, A.H., 1985. Normark WR, Barnes NE Submarine Fans and Related Turbidite Systems. New York, NY: Springer-Verlag.

Bowman, S.A. 2011. Regional seismic interpretation of the hydrocarbon prospectivity of offshore Syria. GeoArabia, 16, 95-124.

Boyd, R., Ruming, K., Goodwin, I., Sandstrom, M., and Schroeder-Adams, C., 2008, Highstand transport of coastal sand to the deep ocean: A case study from Fraser Island, southeast Australia. Geology, 36,15-18.

Brandano, M., Vannucci, G., Pomar, L., Obrador, A., 2005. Rhodolith assemblages from the lower Tortonian carbonate ramp of Menorca (Spain): Environmental and paleoclimatic implications. Palaeogeo., Palaeoclimat., Paleoeco., 226, 307–323

Brew, G., Barazangi, M., Al-Maleh, A. K. and Sawaf, T., 2001.Tectonic and geologic evolution of Syria. GeoArabia, 6, 573-615.

Brew, G., Best, J., Barazangi, M. and Sawaf, T. 2003. The tectonic evolution of the NE Palmyride mountain belt, Syria: the bishri crustal block. Journal of the Geological society, 160, 677-685

Brunton, F.R. and Dixon, O.A., 1994. Siliceous sponge–microbe biotic associations and their recurrence through the Phanerozoic as reef mound constructors. Palaios, 9, 370–387.

Buchbinder, B., and Le Roux, J. P., 1993. Inner platform cycles in the Ardon Formation: Lower Jurassic, southern Israel. Israel Journal of Earth Sciences, 42, 1-16.

Buchbinder, B., and Zilberman, E., 1997. Sequence stratigraphy of Miocene–Pliocene carbonate– siliciclastic shelf deposits in the eastern Mediterranean margin (Israel): effects of eustasy and tectonics. Sediment. Geol. 112, 7-32.

Buchbinder, B., Calvo, R., and Siman-Tov, R., 2005. The Oligocene in Israel: A marine realm with intermittent denudation accompanied by mass-flow deposition. Isr. J. Earth Sci., 54, 63-85.

Buck, W.R., 1991. Modes of continental lithospheric extension. Journal of Geophysical Research , 96, 20,161-20,178

Burke, K. & Wells, G.L. 1989. Trans-African drainage system of the Sahara, was it the Nile? Geology, 17, 743–747.

Burrus, J, 1984. Contnbtmon to a geodynam•c synthes•s of the Provenqal basin (north-western Mediterranean), Mar Geol. 55, 247-269.

Butler, R.W.H., Spencer, S. and Griffiths, H.M., 1997. Transcurrent fault activity on the Dead Sea Transform and its implication for plate tectonics and seismic hazards. Journal of the Geological Society, London, 154, 757-760.

Butler, R.W.H., Spencer, S. and Griffiths, H.M., 1998. The structural response to evolving plate kinematics during transpression: evolution of the Lebanese restraning bend of the Dead Sea Transform. In: Holdsworth RE, Strachan RA, Dewey JF (eds) Continental Transpressional and Transtensional Tectonics. Geological Society, London, Special Publications, 135, 81–106.

Carlisle, D. H., 1965. A continuous *seismic* survey off the coast of *Lebanon*. Massachusetts Institute of Technology.

Caron, M., 1985. Cretaceous planktonic foraminifera. In: Plankton stratigraphy Eds: Bolli HM, Saunders JB, Perch-Nielsen K. p. 17–86

Carton, H., et al. 2009, Seismic evidence for Neogene and active shortening offshore of Lebanon (Shalimar cruise), J. Geophys. Res., 114, B07407, doi:10.1029/2007JB005391.

Catuneanu, O., Abreu, V., Bhattacharya, J.P., Blum, M.D., Dalrymple, R.W., Eriksson, P.G., Fielding, C.R., Fisher, W.L., Galloway, W.E., Gibling, M.R., Giles, K.A., Holbrook, J.M., Jordan, R., Kendall, C.G.St.C., Macurda, B., Martinsen, O.J., Miall, A.D., Neal, J.E., Nummedal, D., Pomar, L., Posamentier, H.W., Pratt, B.R., Sarg, J.F., Shanley, K.W., Steel, R.J., Strasser, A., Tucker, M.E., and Winker, C., 2009, Toward the standardization of sequence stratigraphy: Earth-Science Reviews, 92, 1–33.

Chaimov, T., Barazangi, M., Al-Saad, D., Sawaf, T. and Gebran, A. 1990. Crustal shortening in the Palmyride fold belt, Syria, and implications for movement along the Dead Sea fault system. Tectonics, 9, 1369-1386.

Chaimov, T., Barazangi, M., Al-Saad, D., Sawaf, T. and Gebran, A. 1992. Mesozoic and Cenozoic deformation inferred from seismic stratigraphy in the southwestern intracontinental Palmyride fold-thrust belt, Syria. Bulletin Geological Society of America, 104, 704-715.

Chu, D., Gordon, D.G., 1998.Current plate motions across the Red Sea, Geophys. J. Int. 135, 313-328.

Cita, M. B. and Ryan, W. B. F., 1978. Messinian erosional surfaces in the Mediterranean. Marine Geology, 27, 193–366.

Cohen, Z., 1976. Early Cretaceous buried canyon: influence on accumulation of hydrocarbons in the Helez oil field, Israel. AAPG Bulletin, 60, 108–114.

Collin, P.Y., Mancinelli, A., Chiocchini, M., Mroueh, M., Hamdam, W. and Higazi, F., 2010. Middle and Upper Jurassic stratigraphy and sedimentary evolution of Lebanon (Levantine margin): Palaeoenvironmental and geodynamic implications. In: Homberg, C. and Bachmann, M. (Eds.) Evolution of the Levant Margin and Western Arabia Platform since the Mesozoic. Geological Society, London, Special Publications, 341, 227–244.

Craig, J., Grigg, D., Rebora, A., Serafini, G. & Tebaldi, E. 2011. From Neoproterozoic to Early Cenozoic, exploring the potential of older and deeper hydrocarbon plays across North Africa and the Middle East. In: Vining, B.A. & Pickering, S.C. (eds) Petroleum Geology, from Mature Basins to New Frontiers – Proceedings of the 7th Petroleum Geology Conference. Geological Society, London, 673–705.

Csato, I., Granjeon, D., Catuneanu, O. and Baum, G. R. (2013), A three-dimensional stratigraphic model for the Messinian crisis in the Pannonian Basin, eastern Hungary. Basin Research, 25: 121–148.

Csontos, L. 1995. Tertiary tectonic evolution of the Intra-Carpathian area: a review. Acta Vulcanologica, 7, 1–13.

Culling, W., 1960. Analytical theory of erosion. Journal of Geology 68, 336-344.

Daeron, M., Klinger, Y., Tapponnier, P., Elias, A., Jacques, E., and Sursock, A. 2005. Sources of the large A.D. 1202 and 1759 Near East earthquakes, Geology, 33(7), 529– 532, doi:10.1130/G21352.1.

Daeron, M., L. Benedetti, P. Tapponnier, A. Sursock, and R. C. Finkel, 2004), Constraints on the post-25-ka slip rate of the Yammouneh fault (Lebanon), using in situ cosmogenic ^{36} Cl dating of offset limestone clast fans, Earth Planet. Sci. Lett., 227, 105 – 119, doi:10.1016/j.epsl.2004.07.014.

Dai, A., Trenberth, K.E., 2002. Estimates of freshwater discharge from continents: Latitudinal and seasonal variations. Journal of Hydrometeorology 3, 660-687

Dercourt, J., Bassoulet, J. P., Baud, A., Butterlin, J., Camoin, G., Cavalier, C., Cacca, F., Enay, R., Fourcade, E., Guiraud, R., Lorenz, C., Marcoux, J., Masse, J. P., Orzag, F., Philip, J. 1992. Paleoenvironmental Atlas of the Tethys from Permian to Recent. 28th International Geological Congress, Kyoto, Japan, Proceedings, I-3-24, 1116

Dercourt, J., Gaetani, M., Vrielynck, B., Barrier, E., Biju Duval, B., Brunet, M.F., Cadet, J.P., Crasquin, S. & Sandulescu (eds), 2000. Atlas Peri-Tethys, Palaeogeographical maps, 24 maps and explanatory notes: I-XX. CCGM/CGMW, Paris, 269 pp

Dercourt, J., Ricou, L.E., and Vrielynck, B., 1993. Atlas Tethys paleoenvironmental maps: Paris, (Eds.) Gauthier-Villars, Paris 307 p.

Dercourt, J., Zonenshain, L.P., Ricou, L.-E., Kazmin, V.G., LePichon, X., Knipper, A.L., Grandjacquet, C., Sbortshikov, I.M., Geyssant, J., Lepvrier, C., Pechersky, D.H., Boulin, J., Sibuet, J.-C., Savostin, L.A., Sorokhtin, O., Westphal, M., Bazhenov, M.L., Lauer, J.P. and Biju-Duval, B., 1986. Geological Evolution of the Tethys Belt from the Atlantic to the Pamirs Since the Lias. Tectonophysics, v. 123, no. 1-4, p. 241-315.

Derin, B. & Gerry, E., 1986a. Halal-1, Reexamination of the Triassic/EarlyJurassic (2950–4311m). The Israel Institute of Petroleum and Energy Micropaleontology Laboratory, Tel Aviv, 2/86, 12.

Dewey, J. F., Helman, M. L., Turco, E., Hutton, D. H. W. & Knott, S. D. 1989. Kinematics of the western Mediterranean. In: Coward, M. P., Dietrich, D. & Parker, R. G. (eds) Alpine Tectonics. Geological Society, London, Special Publication, 45, 265–283.

Dewey, J.F. and Sengor, A.M.C, 1979. Aegean and surrounding regions: complex multiplate and continuum tectonics in a convergent zone. Geol. Sot. Am. Bull., 90:84-92.

Dewey, J.F., Episodicity, sequence, and style at convergent plate boundaries. In the continental crust and its mineral deposits, edited by D W Stangway, pp 553-573, 1980.

Dewey, J.F., Hempton, M.R., Kidd, W.S.F., Saroglu, F., and Sengor, A.M.C., 1986. Shortening of continental lithosphere: the neotectonics of Eastern Anatolia – a young collision zone, in Coward, M.P., and Ries, A.C., eds., Collision Zone Tectonics: Geological Society of London Special Publication 19, p. 3–36.

Dewey, J.F., Pitman, W.C. III, Ryan, W.B.F. and Bonnin, J., 1973. Plate tectonics and the evolution of the Alpine system: Geol. Soc. Am. Bull. 84, 3137-3180.

Dickinson, W. 1997. Panel throws down gauntlet. GSA Today, **7**, 25.

Dolson, J.C. & Shann, M.V. 2000. Egypt in the Twenty-First Century, Petroleum Potential in offshore trends. Geoarabia, **6**(2), 211–230.

Dolson, J. C., Boucher, P. J., Siok, J. and Heppard, P. D., 2005. Key challenges to realizing full potential in an emerging giant gas province: Nile Delta/ Mediterranean offshore, deepwater, Egypt. In: Dore, A. G. and Vining, B. A. (Eds.) Petroleum Geology: North – West Europeand Global Perspectives- Proceedings of the 6th Petroleum Geology Conference. Petroleum Geology Conferences Ltd. Published by the Geological Society, London, 607–624.

Dolson, J. C., Shann, M. V., Matbouly, S. I., Hammouda, H. & Rashed, M. R., 2000. Egypt in the twenty-first century: petroleum potential in offshore trends. GeoArabia, 6, 211–230.

Dolson, J. C., Shann, M. V., Matbouly, S., Harwood, C., Rashed, R. & Hammouda, H., 2001. The petroleum potential of Egypt. In: Downey, M. W., Threet, J. C. & Morgan, W. A. (eds) Petroleum Provinces of the Twenty-first Century. American Association of Petorleum Geol- ogists Memoirs, 74, 453–482.

Druckman, Y., 1974. The stratigraphy of the Triassic sequence in southern Israel. Israel Geologic Survey Bulletin, 64, 1-92.

Druckman, Y., 1977. Differential subsidence during the deposition of the Lower Jurassic Ardon Formation in western Jordan, southern Israel and northern Sinai. Israel Journal of Earth Sciences, 26, 45–54.

Druckman, Y., 2001. The hydrocarbon potential of Israel. Isr. Geol. Soc. Meet. Elat, Abstr., p. 28.

Druckman, Y., Gill, D., Fleischer, L., Gelbermann, E. and Wolff, O., 1995. Subsurface geology and structural evolution of the northwestern Negev, southern Israel. Israel Journal of Earth Science, 44, 115 – 136.

Dubertret, L., 1955. Carte géologique du Liban au 1/200000

Dubertret, L., 1975. Introduction à la carte géologique au 1/ 50000 du Liban. Notes et Mémoires sur le Moyen-Orient, 23, 345-403.

Ebinger, C. J. & Sleeep, N. H. 1998. Cenozoic magmatism throughout east African resulting from impact of a single plume. Nature 395, 788-791.

Edgell, H.S., Basson, P.W., 1975. Calcareous algae from the Miocene of Lebanon. - Micropaleontology, 21, 2, 165-184.

Edwards, M. and Grasemann, B. 2009. Mediterranean snapshots of accelerated slab retreat; subduction instability in stalled continental collision.- in van Hinsbergen, D., Edwards, M., Govers, R. (eds.): Collision and collapse at the Africa-Arabia-Eurasia subduction zone. Geological Society, London, Special Publications, 311, 155-192.

Einsele, G., Ratschbacher, L. & Wetzel, A. 1996. The Himalaya–Bengal Fan denudation–accumulation system during the last 20 Ma. Journal of Geology, 104, 163–184.

Elias, A., 2006. Le chevauchement de Tripoli-Saida: Croissance du Mont-Liban et risque sismique. Thesis IPG Paris, 231.

Elias, A., Tapponnier, P., Singh, S.C., King, G.C.P., Briais, A., Daeron, M., Carton, H., Sursock, A., Jacques, E., Jomaa, R., Klinger, Y., 2007. Thrusting offshore Mt Lebanon: Source of the tsunamigenic, 551 AD Beyrut-Tripoli earthquake. Geology, 35(8), 755– 758, doi:10.1130/G23631A.1.

Engdahl, E. R., Van Der Hilst, R. & Buland, R. 1998. Global teleseismic earthquake relocation with improved travel times and procedures for depth determination. Bulletin of the Seismological Society of America, 88, 722–743.

Eyal, Y., 1996. Stress field fluctuations along the Dead Sea rift region since the Late Cretaceous based on mesostructures. Tectonics, 2, 167–185.

Faccenna C, Jolivet L, Piromallo C, Morelli A. 2003. Subduction and the depth of convection in the Mediterranean mantle. J. Geophys. Res. 108, 2099.

Faccenna, C., Davy, P., Brun, J. P., Funiciello, R., Giardini, D., Mattei, M. & Nalpas, T. 1996.The dynamics of back-arc extension: an experimental approach to the opening of the Tyrrhenian Sea. Geophysical Journal International 126, 781-795.

Feinstein, S., Aizenshtat, Z., Miloslavski, I., Gerling, P., Slager, J. and McQuilken, J., 2002. Genetic characterization of gas shows in the east Mediterranean offshore of SW Israel. Organic Geochemistry, 33 (12), 1401- 1413.

Ferry, S., Y. Merran, D. Grosheny, and M. Mroueh, 2007, The Cretaceous of Lebanon in the Middle East (Levant) Context: in L.G. Bulot, S. Ferry, and D. Grosheny, (eds.), Relations between the northern and southern margins of the Tethys Ocean during the Cretaceous Period: Notebooks on Geology, Brest, Memoir 2007/02, Abstract 08 (CG2007_M02/08).

Flexer, A. and Honigstein, A., 1984. The Senonian succession in Israel—lithostratigraphy, biostratigraphy and sea level changes. Cretaceous Res., 5 (1984), pp. 302–312.

Flexer, A., 1971. Late Cretaceous palaeogeography of Northern Israel and its significance for the Levant geology. Palaeogeography, Palaeoclimatology, Palaeoecology, 10, 293–316.

Flexer, A., Rosenfeld, A., Lipson-Benitah, S. and Honigstein, A., 1986. Relative sea level changes during the Cretaceous in Israel. Am. Assoc. Petrol. Geol. Bull. 70, 1685-1699.

Frank, R., Buchbinder, B., and Benjamini, C., 2010. The mid-Cretaceous carbonate system of northern Israel: facies evolution, tectono-sedimentary configuration and global control on the central Levant margin of the Arabian Plate. Geological Society, London, Special Publication, 341, 133-169.

Freund, R., Garfunkel, Z., Zak, I., Goldberg, M., Weissbrod, T. & Derin, B. 1970. The shear along the Dead Sea Rift. Philosophical Transactions of the Royal Society of London, Series A, 267, 107–130

Freund, R., Goldberg, M., Weissbrod, T. Druckman, Y. & Derin, B., 1975. The Triassic-Jurassic structure of Israel and its relation to the origin of the Eastern Mediterranean. Israel Geological Survey, Bulletin, 65, 1-26.

Fürstenau, J., Hawie, N., Comstock, J., Lowrey, C.J., 2013. Aspects of the depositional history of the Levant Basin offshore Cyprus and Lebanon. Offshore Mediterranean Conference, Ravenna, Italy.

Gani, N.D.S., Gani, M.R. & Abdelsalem, M.G. 2007. Blue Nile incision on the Ethiopian Plateau; pulsed plateau growth, Pliocene uplift and hominid evolution. GSA Today, 17, 4–11.

Gardosh, M., 2002. The sequence stratigraphy and petroleum systems of the Mesozoic, southeastern Mediterranean continental margin. PhD thesis, Tel Aviv University.

Gardosh, M., Druckman, Y. and Buchbinder, B. 2009. The Late Tertiary Deep-Water Siliciclastic System of the Levant Margin – An Emerging Play Offshore Israel. American Association of Petroleum Geologists Search and Discovery Article #10211.

Gardosh, M., Druckman, Y., Buchbinder, B. and Calvo, R., 2008. The Oligo-Miocene Deepwater System of the Levant Basin. Geological Survey of Israel, 33, 1-73.

Gardosh, M., Druckman, Y., Buchbinder, B. and Rybakov, M., 2006. The Levant Basin offshore Israel: stratigraphy, structure, tectonic evolution and implications for hydrocarbon exploration. Geophysical Institute of Israel, 1–119.

Gardosh, M., Garfunkel, Z., Druckman, Y. and Buchbinder, B., 2010. Tethyan rifting in the Levant Region and its role in Early Mesozoic crustal evolution. In: Homberg, C. and Bachmann, M. (Eds.) Evolution of the Levant Margin and Western Arabia Platform since the Mesozoic. Geological Society, London, Special Publications, 341, 9–36.

Gardosh, M., Weimer, P and Flexer, A., 2011. The sequence stratigraphy of Mesozoic successions in the Levant margin southwestern Israel: A model for the evolution of southern Tethys margins. AAPG Bulletin, 95, 1763-1793

Garfunkel, Z. 1981. Internal structure of the Dead Sea leaky transform (rift) in relation to plate kinematics. Tectonophysics, 80, 81–108, doi:10.1016/0040- 1951(81)90143-8.

Garfunkel, Z. and Almagor, G., 1985. Geology and structure of the continental margin off northern Israel and the adjacent part of the Levantine Basin. Mar. Geol., 62, 105-131.

Garfunkel, Z. and Ben-Avraham, Z. 2001. Basins along the Dead Sea Transform. In: Cavazza, W., Ziegler, P.A., Robertson, A.H.F. & Crasquin-Soleau, S. (eds) Peri-Tethyan Rift/Wrench Basins and Passive Margins. Peri-Tethys Memoir, 6. Mémoires du Musée National de l'Histoire Naturelle, 186, 607–627.

Garfunkel, Z. and Derin, B., 1984. Permian – Early Mesozoic tectonism and continental margin formation in Israel and its implications to the history of the eastern Mediterranean. In: Dixon, J. E. and Robertson, A. H. F. (Eds.) The Geological Evolution of the Eastern Mediterranean. Geological Society, London, Special Publications, 17, 18–201.

Garfunkel, Z., 1984. *Large-scale submarine rotational slumps and growth faults in the eastern Mediterranean.* Marine Geology*,* 55*,* 305-*324*

Garfunkel, Z., 1998. Constrains on the origin and history of the Eastern Mediterranean basin; collision-related processes in the Mediterranean region. Tectonophysics, 298, 5–35

Garfunkel, Z., 2004. Origin of the Eastern Mediterranean basin: a reevaluation. Tectonophysics, 391, 11–34.

Gedeon, M.A., 1999. Structural analysis of latitudinal faults in the Mount Lebanon north of Beirut: their kinematics and their role in the tectonic evolution of Lebanon. M.Sc. thesis, American University of Beirut.

Geological Society, London, 158, 1-4.Gomez, F., Khawlie, M., Tabet, C., Darkal, A.N., Khair, K. & Barazangi, M. 2006. Late Cenozoic uplift along the northern Dead Sea transform in Lebanon and Syria. Earth and Planetary Science Letters, 241, 913–931.

George, R., Rogers, N., Kelley, S., 1998. Earliest magmatism in Ethiopia: evidence for two mantle plumes in one flood basalts province. Geology 26, 923–926.

Girdler, R.W., 1990. The Dead Sea transform fault system. Tectonophysics, 180, 1-13.

Goedicke, T.R., 1972. Submarine canyons on the continental shelf of Lebanon. In: D.J. Stanley (Editor), The Mediterranean Sea, a Natural Sedimentation Laboratory. Dowden, Hutchinson and Ross, Stroudsburg, Pa., pp.655--670.

Goedicke, T.R. and Sagabiel, S., 1976. Sediment movement in Lebanese submarine canyons. In: N. Hulings (Editor), Symposium on the Eastern Mediterranean.

Gomez, F., Meghraoui, M., Darkal, A.N., Sbeinati, R., Darawcheh, R., Tabet, C., Khawlie, M., Charabe, M., Khair, K. & Barazangi, M., 2001. Coseismic displacements along the Serghaya Fault: An active branch of the Dead Sea Fault System in Syria and Lebanon. Journal of the

Gradmann, S., Hübscher, C., Ben-Avraham, Z., Gajewski, D., Netzeband, G.L., 2005. Salt tectonics off northern Israel. Mar. Pet. Geol., 22, 597–611.

Granjeon, D., 1996. Modélisation stratigraphique déterministe—conception et applications d'un modèle diffusif 3D multilithologique, Géosciences Rennes. Université de Rennes 1, Rennes.

Granjeon, D., Joseph, P., 1999. Concepts and applications of a 3-D multiple lithology, diffusive model in stratigraphic modeling. Numerical experiments in stratigraphy: recent advances in stratigraphic and sedimentologic computer simulations. SEPM Spec. Publ. 62, 197– 210.

Griffiths, H.M., Clark, R.A., Thorp, K.M. & Spencer, S., 2000. Strain accommodation at the lateral margin of an active transpressive zone; geological and seismological evidence from the Lebanese restraining bend. Journal of the Geological Society, London, 157, 45-68.

Guiraud, R., Binks, R.M., Fairhead, J.D., Wilson, M., 1992. Chronology and geodynamic setting of Cretaceous–Cenozoic rifting in West and Central Africa. Tectonophysics 213, 227–234.

Guiraud, R., Bosworth, W., 1999. Phanerozoic geodynamic evolution of northeastern Africa and the northwestern Arabian platform. Tectono- physics 315, 73–108

Gvirtzman, G. and Buchbinder, B., 1978. The Tertiary history of the coastal plain and continental shelf of Israel and its bearing on the history of the Eastern Mediterranean. Initial Report Deep Sea Drilling Project, 42B, 1195-1222.

Gvirtzman, G., Klang, A., 1972. A Structural and Depositional Hinge-Line Along the Coastal Plain of Israel, Evidenced by Magnetotellurics. Geological Survey of Israel Bulletin, 55, 18 p.

Halfar, J., Mutti, M., 2005. Global dominance of coralline red algal facies: a response to Miocene oceanographic events. Geology 33:481–484.

Hall, J.K., Calon, T.J., Aksu A.E., Meade, S.R., 2005. Structural evolution of the Latakia Ridge and Cyprus Basin at the front of the Cyprus Arc, Eastern Mediterranean Sea. Mar Geol 221, 261-297.

Hancock, P. C. & Atiya, M. S. 1979. Tectonic significance of mesofracture systems associated with the Lebanese segment of the Dead Sea transform fault. Journal of Structural Geology, 1, 143-153.

Haq, B. U., Hardenbohl, J. and Vail, P. R., 1988. Mesozoic and Cenozoic chronostratigraphy and eustatic cycles. In: C. K. Wilgus, B. J. Hastings, G. G. Kendall, H. Posamentier, C.A. Ross and J. C.Van Wagoner (Eds.), Sea-level changes: an integrated approach. SEPM Special Publications, 42, 71- 108.

Hardenberg, M.F. and Robertson, A.H.F, 2007. Sedimentology of the NW margin of the Araban plate and the SW-NE trending Nahr el Kabir half graben in northern Syria during the latest Cretaceous and Cenozoic. Sedimentary Geology, 201, 231-266.

Hardenbol, J., Thierry, J., Farley, M.B., Jacquin, T., de Graciansky, P.C., Vail, P.R., 1998. Jurassic chronostratigraphy. In: de Graciansky PC, Hardenbol J, Jacquin T, Vail PR (Eds.), Mesozoic and Cenozoic Sequence Stratigraphy of European Basins. Society of Economic Paleontologists and Mineralogists Special Publication 60 (chart).

Hardy, C., Homberg, C., Eyal, Y., Barrier, E., and Muller, C., 2010. Tectonic evolution of the southern Levant margin since Mesozoic. Tectonophysics 494, 211–225.

Hart, M.B., 1999. The evolution and biodiversity of Cretaceous Planktonic Foraminiferida. Geobios 32, 247-255.

Hawi, J.A., 2000. Calcareous Nannofossil biostratigraphy of the Ech-Chaqaa section, Chekka (N. Lebanon). M.S. Thesis, American University of Beirut, Lebanon.

Hawie, N, Deschamps, R., Nader, F.H., Gorini, C., Müller, C., Desmares, D., Hoteit, A., Granjeon, D., Montadert, L., Baudin, F., 2013. Sedimentological and stratigraphic evolution of northern Lebanon since the Late Cretaceous: implications for the Levant margin and basin. Arabian Journal of Geosciences doi: 10.1007/s12517-013-0914-5

Hay, W.W. 1998. Detrital sediment fluxes from continents to oceans. Chemical Geology, 145, 287–323.

Hay, W.W., Soeding, E., Deconto, R.M. & Wold, C. 2002. The Late Cenozoic uplift–climate change paradox. International Journal of Earth Science (Geologische Rundschau), 91, 747–774.

Heimann, A. & Ron, H., 1987. Young faults in the Hula pull-apart basin, central Dead Sea Transform. Tectonophysics, 141, 117-124.

Hempton, M. R., and A.M. C. Sengor, 1980. The East Anatolian transform fault: Its age, offset, and significance in the neotectonics of the eastern Mediterranean, EOS Trans. AGU, 62, 1033.

Hempton, M., 1987. Constraints on Arabian plate motion and extensional history of the Red Sea. Tectonics, 6, 687-705.

Hirsch, F. & Picard, L., 1988. The Jurassic facies in the Levant. Journal of Petroleum Geology, 11, 277-308.

Hirsch, F., Bassoullet, J. P., Cariou, E., et al. 1998. The Jurassic of the southern Levant: biostratigraphy, palaeogeography and cyclic event. In: Crasquin-Soleau, S. and Barrier, E. (Eds.) Peri-Tethys Memoir 4: Epicratonic Basins of Peri-Tethyan Platforms. Memoires du Museum National d'Histoire Naturelle, Paris, 179, 213 – 235.

Hofmann, C., Courtillot, V., Feraud, G., Rochette, P., Yirgu, G., Ketefo, E. and Pik, R., 1997. Timing of the Ethiopian flood basalt event and implications for plume birth and global change, Nature **389**, 838–841.

Hogson, N., 2013. The Miocene hydrocarbon play in Southern Lebanon. First break v30, 93-98

Homberg, C. and Bachmann, M., 2010. Evolution of the Levant Margin and Western Arabia Platform since the Mesozoic. Geological Society, London, Special Publications 2010, 341, 9–36.

Homberg, C., Barrier, E., Mroueh, et al., 2010. Tectonic evolution of the central Levant domain (Lebanon) since Mesozoic time. Geological Society, London, Special Publications, 341, 245-268

Honigstein, A. and Reiss, Z., 1989. Upper Cretaceous highresolution multiple stratigraphy, northern margin of the Arabian platform, central Israel. Cretaceous Res., 10, 107-135.

Hsu, K.J., Cita, M.B. and Ryan, W.B.F., 1973. The origin of the Mediterranean evaporites. In: Initial Reports of the Deep Sea Drilling Project (W.B.F. Ryan, K.J. Hsu , et al., eds), Vol. 13 pp. 1203–1231. US Government Printing Office, Washington, DC.

Ismail, S., Schulz, H.-M., Wilkes, H., et al. Sedimentology, geochemistry and hydrocarbon potential of the Late Cretaceous Shiranish Formation in the Euphrates Graben (Syria). Petroleum Geology Conference series 2010; v. 7; p. 811-819 doi: 10.1144/0070811

Issawi, B. & McCauley, J.F. 1992. The Cenozoic rivers of Egypt, the Nile problem. In: Adams, B. & Friedman, R. (eds) The Followers of Horus, studies dedicated to Michael Allen Hoffman 1944–1990. Egyptian Studies Association Publication, **2**. Oxbow Press, Oxford, 121–138.

Jervey, M.T., 1988. Quantitative geological modeling of siliciclastic rock sequences and their seismic expression. In: Wilgus, C.K., Hastings, B.S., Kendall, C.G.St.C., Posamentier, H.W., Ross, C.A., Van Wagoner, J.C. (Eds.), Sea Level Changes — An Integrated Approach. . Special Publication, vol. 42. Society of Economic Paleontologists and Mineralogists (SEPM), pp. 47–69.

Jestin, F., Huchon, P., Gaulier, J.M., 1994. The Somalia plate and the East African Rift System: present day kinematics, Geophys. J. Int. 116 637-654.

Jolivet, L. & Faccenna, C., 2000. Mediterranean extension and the Africa-Eurasia collision, Tectonics, 19, 1095–1107.

Jolivet, L., and Brun, J.P., 2008. Cenozoic geodynamic evolution of the Aegean: International Journal of Earth Sciences: doi: 10.1007/s00531-008-0366-4.

Jordan T. E. and Flemings P. B. 1991. Largescale stratigraphic architecture, eustatic variation, and unsteady tectonism : a theoritical evauation - Journal of Geophysical Research, 96 : p. 6681- 6699.

Kellner, A., El Khawaga, H., Brink, G. et al. 2009. Depositional History of the West Nile Delta – Upper Oligocene to Upper Pliocene. American Association of Petroleum Geologists Search and Discovery Article #30092.

Kenea, N.H., Ebinger, C.J., Rex, D.C. 2001. Late Oligocene volcanism and extension in the southern Red Sea Hills, Sudan, J. Geol. Soc. London 158, 285-294.

Kenyon, P.M., Turcotte, D.L., 1985. Morphology of a delta prograding by bulk sediment transport. Geol. Soc. Am. Bull. 96, 1457-1465.

Khair, K., Khawlie, M., Haddad, F., Barazangi, M., Chaimov, T. and Seber, D., 1993. Gravity modeling and geologic setting and tectonics of the central segment of the Dead Sea fault zone, Geology, 21, 739-742.

Khair, K., Tsokas, G. N. and Sawaf, T., 1997. Crustal structure of the northern Levant region: multiple source Werner deconvolution estimates for Bouger gravity anomalies. Geophysics Journal International, 128, 605-616.

Carson, M.A., Kirkby, M.J., 1972. Hillslope form and process. Cambridge University Press, Cambridge.

Kosarev, G., Kind, R., Sobolev, S. V., Yuan, X., Hanka, W. & Oreshin, S. 1999. Seismic Evidence for a Detached Indian Lithospheric Mantle Beneath Tibet. Science, 283, 1306–1309.

Kosi, W., Tari, G., Nader, F., Skiple, C., Trudgil, B., Lazar, D., 2012. Structural analogy between the "piano key faults" of deep-water Lebanon and the extensional faults of the Canyonlands grabens, Utah, United States. The Leading Edge, 824-830.

Laws, E. D. and Wilson, M., 1997. Tectonics and magmatism associated with Mesozoic passive continental margin development in the Middle East. Journal of the Geological Society, London, 154, 459–464.

Le Pichon, X. & Kreemer, C. 2010. The Miocene-to-Present kinematic evolution of the Eastern Mediterranean and Middle East and its implications for dynamics. Annual Review of Earth and Planetary Sciences, 38, 323–352, doi:10.1146/annurev-earth-040809-152419.

Le Pichon, X. 1982. Land-locked oceanic basins and continental collision: the eastern Mediterranean as a case example. In Mountain Building Processes, ed. K Hsu, pp. 129–46. London: Academic.

Le Pichon, X. and Angelier, J. 1981. The Aegean Sea, Phil. Trans. R. Soc. Lond., 300, 357–372.

Le Pichon, X., Gaulier, J.M. 1988. The rotation of Arabia and the Levant fault system. Tectonophysics 153:271–94.

Letouzey, J., Colletta, B., Vially, R. and Chermette, J.C., 1995. Evolution of salt-related structures in compressional settings. In: Jackson, M.P.A., Roberts, D.G. and Snelson, S. (Eds.) Salt Tectonics. A Global Perspective. AAPG Memoirs, 65, 41–60.

Lie, Ø. and Trayfoot, M., 2009. Seismic Characterization of the First 3D Surveys Offshore Cyprus and Lebanon. Abstract #10194, AAPG Convention, Denver, Colorado.

Lie, Ø., Skiple, C., and Lowrey, C., 2011. New insights into the Levantine Basin. v 8, issue 1

Linzer, H. G. 1996. Kinematics of retreating subduction along the Carpathian arc, Romania. Geology, 24, 167–170.

Litak, R.K., Barazangi, M., Brew, G., Sawaf, T., Al-Imam, A. & Al-Youssef, W., 1998. Structure and evolution of the petroliferous Euphrates graben system, southeast Syria. AAPG Bulletin, 82 (6), 1173-1190.

Lonergan, L. and White, N. 1997. Origin of the Betic-Rif mountain belt. Tectonics, 16, 504–522.

Macgregor, D.S., 2012. The development of the Nile drainage system: integration of onshore and offshore evidence. Petroleum Geoscience, 18, 417-431. doi: 10.1144/petgeo2011-074

Makris, J., Ben-Avraham, Z., Behle, A., Ginzburg, P., Gieze, P., Steinmetz, L., Whitmarsh, R.B. and Eleftheriou, S., 1983. Seismic refraction profiles between Cyprus and Israel and their interpretation. Geophysical Journal, Royal Astronomical Society, 75, 575-591.

Malinverno, A. and Ryan, W. B. F. 1986. Extension in the Tyrrhenian Sea and shortening in the Apennines as result of arc migration driven by sinking of the lithosphere Tectonics, 5, 227–245.

Mart, Y., 2013. Geodynamics of the Middle East domain since the Oligocene: research summary. Journal of the Geological Society 2013, v.170; p483-496.

Martini, E., Müller, C., 1986. Current Tertiary and Quaternary Calcareous nannoplankton stratigraphy and correlation. Newsl.Stratigr, 16 (2), 99-112

Martini, E., 1971. Standard Tertiary and Quaternary calcareous nannoplankton zonation. Proc. 2nd Planktonik conference, Roma. 1970. Tecnoscienza, 2, 739-785

Martinsen, O. J. , Sømme, T. O., Thurmond, J. B., et al. 2010. Source-to-sink systems on passive margins: theory and practice with an example from the Norwegian continental margin. Petroleum Geology Conference v. 7; p. 913-920.

May, P. R., 1991.The Eastern Mediterranean Mesozoic Basin: evolution and oil habitat. AAPG Bull., 75, 1215-1232.

McDougall, I., Morton, W.H. & Williams, M.A.J. 1975. Age and rates of erosion of trap series basalts at Blue Nile Gorge, Ethiopia. Nature, 254, 207–209.

McKenzie DP. 1970. Plate tectonics of the Mediterranean region. Nature 226:239–43

McKenzie, D.P., 1972; Active tectonics of the Mediterranean region. Geophysical Journal of the Royal

Astronomical Society, 30, 109-185.

Meade, R. H. 1972. Sources and sinks of suspended matter on continental shelves. In: Swift, D. J. P., Duane, D. B. & Pilkey, O. H. (eds) Shelf Sediment Transport. Dowden, Hutchinson & Ross, Stroudsburg, 249–262.

Meade, R. H. 1982. Sources, sinks, and storage of river sediment in the Atlantic drainage of the United States. Journal of Geology, 90, 235–252.

Miller, K.J., Kominz, M.A., Browning, J.V., Wright, J.D., Mountain, G.S., Katz, M.E., Sugarman, P.J., Cramer, B.S., Christie-Blick, N., and Pekar, S.F., 2005. The Phanerozoic record of global sea-level change. Science, 310, 1293-1298.

Milliman, J.D., Syvitski, J.P.M., 1992. Geomorphic/tectonic control of sediment discharge to the ocean: The importance of small mountainous rivers. Journal of Geology 100, 525-544**.**

Minster, J. B., and Jordan, T. H., 1978. Present-day plate motions. J. Geophys. Res.,83, p. 5331-5354.

Mitchum, J.R., Vail, P.R., Sangree, J.B., 1977. Stratigraphic Interpretation of seismic reflection pattern in depositional sequences. In: Payton, C.E. (Eds.), Seismic Stratigraphy—Applications to Hydrocarbon Exploration, Memoir Amer. Assoc. Petrol. Geol., 26, 117– 134.

Montadert, L., Nicolaides, S., Semb, P.H, Lie, ø., Petroleum Systems Offshore Cyprus. In: Marlow, L., Kendall, C. and Yose (Eds.) Petroleum Systems of the Tethyan Region. AAPG Special Publication., *in press.*

Monty, C. L. V., Bosence, D. W. J., Bridges, P. H., and Pratt, B. R. (Eds.) 2009. Carbonate Mud-Mounds: Their Origin and Evolution. Wiley-Blackwell.

Moores, E.M., Robertson, P.T., Malpas, J., Xenophontos, C., 1984. Model of the origin of the Troodos massif, Cyprus and other Mideast ophiolites. Geology, 12, 223- 226

Moustafa, A.R., 2010. Structural setting and tectonic evolution of North Sinai folds, Egypt. In: Homberg, C. & Bachmann, M. (eds) Evolution of the Levant Margin and Western Arabia Platform since the Mesozoic. Geological Society, London, Special Publications, 341, 37–63

Moustafa, A.R., Khalil, M.H., 1989. North Sinai structures and tectonic evolution. Middle East Research Center, Ain Shams University, Earth Science Series, 3, 215–231

Mouty, M., Al-Maleh, A.K., 1983. Étude géologique de la chaîne des Palmyrides. Établissement général de Géologie et de Ressources minières, Damas, Syrie IV, 257 p.

Müller, C., Higazi, F., Hamdan, W. and Mroueh, M., 2010. Revised stratigraphy of the Upper Cretaceous and Cenozic series of Lebanon based on nannofossils. In: Homberg, C. and Bachmann, M. (Eds.) Evolution of the Levant Margin and Western Arabia Platform since the Mesozoic. Geological Society, London, Special Publication, 341, 287-303.

Muller, R. D. and Roest, W. R. 1992. Fracture zone in the North Atlantic from combined Geosat and Seasat data, Journ of Geophy Res, 97, 3337-3350.

Murray, A.B., Paola, C., 1994. A cellular model of braided rivers. Nature 371, 54-57**.**

Nader, F. H, 2011. The petroleum prospectivity of Lebanon: an overview. Journal of Petroleum Geology, 34, 135-156

Nader, F. H. and Swennen, R., 2004. Petroleum prospects of Lebanon: Some remarks from sedimentological and diagenetic studies of Jurassic carbonates. Marine and Petroleum Geology, 21, 427-441.

Nader, F.H., 2000. Petrographic and Geochemical Characterization of the Jurassic-Cretaceous Carbonate Sequence of the Nahr Ibrahim Region, Lebanon. MSc thesis, American University of Beirut.

Nader, F.H., Swennen, R., and Ellam, R., 2007. Field geometry, petrography and geochemistry of a dolomitization front (Late Jurassic, central Lebanon). Sedimentology, 54, 1093–1119.

Neev, D., Ben-Avraham, Z., 1977. The Levantine countries: the Israeli coastal region. In: Nairn EM, Kanes WH (eds) The Ocean Basins and Margins. The Eastern Mediterranean, 4A. Plenum Press, New York, United States, 355–377.

Neev, D., Greenfield, L. L. and Hall, J. K., 1985. Slice tectonics in the Eastern Mediterranean Basin, in: Syanley, D. J. and Wezel, F. D. (Eds.) Geological Evolution of the Mediterranean Basin. Springer, New York pp. 249 – 269

Nemer, T., 1999. The Roum fault: extent and associated structures. M.Sc. thesis, American University of Beirut, Beirut.

Netzeband, G. L., Gohl, K., Hubscher, C. P., Ben-Avraham, Z., Dehghani, G. A., Gajewski, D. and Liersch, P., 2006. The Levantine Basin crustal structure and origin. Tectonophysics, 418, 167-188.

Noujaim Clark, G. & Boudagher-Fadel, M.K., 2001. The larger benthic foraminifera and stratigraphy of the Upper Jurassic/Lower Cretaceous of central Lebanon. Revue de Micropaléontologie, 44 (3), 215-232.

Oats, M., 2001. Origin and genesis of Lower Oliocene sand nounds, Afiq Canyon, Israel. Isr. Geol. Soc.Annu. Meet., Elat, Abstr. 89.

Paola, C., Heller, P.L., Angevine, C.L., 1992. The large-scale dynamics of grain-size variation in alluvial basins, 1:

Theory. Basin Research 4, 73-90.
Perch-Nielsen, K., 1985. Mesozoic calcareous nanno- fossils. In: Bolli HM, Saunders JB and Perch- Nielsen K (eds) Plankton Stratigraphy. Cambridge, 329 – 426.
Picard, L., 1959. Geology and oil exploration of Israel. Bull.Res. Council Isr., G8, 1-30.
Pickford, M., Senut, B. & Hadoto, D.1994. Palaeobiology of the Albertine Rift Valley, Uganda-Zaire, Introduction. In: Geology and Palaeobiology of the Albertine Rift Valley, Uganda-Zaire, Vol. II. CIFEG Occasional Publication 1994/29. Orleans, CIFEG, 9–27.
Pomar, L., 1991. Reef geometries, erosion surfaces and highfrequency sea-level changes, upper Miocene Reef Complex, Mallorca, Spain. Sedimentology, 38, 243–269.
Pomar, L., 2001. Types of carbonate platforms: a genetic approach. Basin Res., 13, 313–334.
Pomar, L., Brandano, M., and Westphal, H., 2004. Environmental factors influencing skeletal-grain sediment associations: a critical review of Miocene examples from the Western-Mediterranean. Sedimentology, v. 51, p. 627–651.
Pomar, L., Ward, W.C. and Green, D.G., 1996. Upper Miocene Reef Complex of the Llucmajor area, Mallorca, Spain. In: Models for Carbonate Stratigraphy from Miocene Reef Complexes of the Mediterranean Regions (Ed. by E. Franseen, M. Esteban, W.C. Ward & J.M. Rouchy), Soc. Econ. Paleont. Miner., Concepts in Sedimentology and Paleontology Series, 5, 191-225.
Ponikarov, V.P. 1966. The geology of Syria. Explanatory Notes on the Geological Map of Syria, scale 1:200 000. Ministry of Industry, Syrian Arab Republic.
Ponikarov, V.P., Kazmin, V.G., Kozlov, V.V., Krasheninnikov, V.A., Kikhailov, I.A., Razvalyaev, A.V., Sulidi-Kondratoev, E.D., Uflyand, A.K., Faradzhev, V.A., 1969. Syria. 215 pp.
Powell, J.H., Moh'd, B.K., 2011. Evolution of Late Cretaceous to Eocene alluvial and carbonate platform sequences in Jordan. GeoArabia, v.17, no.3, 29-82.
Premoli Silva, I., Sliter, W.V., 1995. Cretaceous planktonic foraminiferal biostratigraphy and evolutionary trends from the Bottaccione section, Gubbio, Italy. Paleontographia Italica, v82, 1-89.
Quennel AM. 1958. The structural and geomorphic evolution of the Dead Sea Rift. J. Geol. Soc. London 114:1–14
Reading, H.G., and M. Richards, 1994, Turbidite systems in deep-water basin margins classified by grain size and feeder system: AAPG Bulletin, 78, 792-822
Reilinger, R.E., McClusky, S.C., Oral, M.B., King, R.W., Toksoz, M.N., et al. 1997. Global positioning system measurements of present-day crustal movements in the Arabia-Africa-Eurasia plate collision zone. J. Geophys. Res. 102:9983–99
Renouard, G., 1955. Oil Prospects of Lebanon. AAPG Bulletin, 39, 2125-2169.
Ricou, L. E. 1994. Tethys reconstructed Plates, , continental fragments and their boundaries since 260 Ma from Central America to southeastern Asia. Geodin Acta, v7, 169-218.
Robaszynski, F., Caron, M., 1995. Foraminifères planctoniques du Crétacé : commentaire de la zonation Europe-Méditerranée. Bulletin de la Société géologique de France, Paris, t. 166, n° 6, p. 681-692.
Roberts, G. and Peace, D., 2007. Hydrocarbon plays and prospectivity of the Levantine Basin, offshore Lebanon and Syria from modern seismic data. GeoArabia, 12, 99-124.
Robertson, A. H. F. and Dixon, J. E., 1984. Introduction: aspects of the geological evolution of the eastern Mediterranean. In: Dixon, J. E. and Robertson, A. H. F. (Eds.) The Geological Evolution of the Eastern Mediterranean. Geological Society, London, Special Publications, 17, 1–74.
Robertson, A. H. F. and Woodcock, N. H., 1979. The Mamonia Complex, SW Cyprus: the evolution and emplacement of a Mesozoic continental margin. Geological Society of America Bulletin, 90, 651-665.
Robertson, A. H. F., 1998a. Mesozoic-Tertiary tectonic evolution of the easternmost Mediterranean area: integration of marine and land evidence. In: Robertson, A. H. F., Emeis, K. C., Richter, C. and Camerlenghi, A. (Eds.) Proceedings of the Ocean Drilling Program, Scientific Results, 160, 723–782.
Robertson, A. H. F., Ustaomer, T., Pickett, E. A., Collins, A., Andrew, T. and Dixon, J. E., 2004. Testing models of Late Palaeozoic-early Mesozoic orogeny: support for an evolving one-Tethysmodel. Journal of the Geological Society, London,161, 501-511.
Robertson, A.H.F, 1998b. Tectonic significance of the Eratosthenes Seamount: a continental fragment in the process of collision with a subduction zone in the eastern Mediterranean Ocean Drilling Program Leg 160). Tectonophysics, 298, 63-82.
Robertson, A.H.F. & Mountrakis, D. 2006. Tectonic development of the Eastern Mediterranean region: an introduction. In: Robertson A.H.F. & Mountrakis, D. (eds) Tectonic Development of the Eastern Mediterranean Region. Geological Society, London, Special Publications, 260, 1–9.
Robertson, A.H.F., 2007. Overview of tectonic settings related to the rifting and opening of Mesozoic ocean basins in the Eastern Tethys: Oman, Himalayas and Eastern Mediterranean regions. In: Karner GD, Manatschal

G and Pinheiro LM (eds) Imaging, Mapping and Modelling Continental Lithosphere Extension and Breakup. Geological Society, London, Special Publications, 282, 325–338.

Roksandi'c, M.M., 1978. Seismic facies analysis concepts. Geophys.Prospect. 26, 383– 398.

Royden LH. 1993.The tectonic expression of slab pull at continental convergent boundaries. Tectonics 12:303–25.

Sage L, Letouzey J 1990: Convergence of the African and Eurasian Plate in the Eastern Mediterranean, Petroleum and Tectonics in Mobile Belts, Paris, 49-68.

Said, R., 1981. The Geological Evolution of the River Nile. Springer, New York N.Y., 151 pp.

Saint-Marc P., 1974. — Étude stratigraphique et micropaléontologique de l'Albien, du Cénomanien et du Turonien du Liban. Notes et Mémoires sur le Moyen-Orient 13, 342 p.

Saint-Marc, P., 1972. Le Crétacé inférieur et moyen du bord occidental du Jabal-Sannine (Liban). Notes et Mémoires sur le Moyen-Orient, 13, 217-226.

Saint-Marc, P., 1980. Le passage Jurassique-Cretace et le Crétacé inférieur de la region de Ghazir (Liban central). Geologie Méditerranéenne, v.7, 237-245.

Salama, R.B. 1987. The evolution of the River Nile. The buried saline rift lakes in Sudan I. Bahr El Arab Rift, the Sudd buried saline lake. Journal of African Earth Sciences, **6**(6), 899–913.

Sandler, A., 1996. A Turonian subaerial event in Israel: karst, sandstone and pedogenesis. Isr. Geol. Surv.Bull. 85-52.

Sangree, J.B., Widmier, J.M., 1977. Seismic Interpretation of clastic depositional facies. In: Payton, C.E. (Eds.) Seismic Stratigraphy— Applications to Hydrocarbon Exploration, AAPG Memoirs, 26, 165– 184.

Sawaf, T., Brew, G. E., Litak, R. K. and Barazangi, M., 2001. Geologic evolution of the intraplate Palmyride Basin and Euphrates fault system, Syria. In: P. A. Ziegler, W. Cavazza,A. H. F. Robertson and S. Crasquin-Soleau (Eds.) Peri-Tethys Memoir 6: Peri-Tethyan Rift / Wrench Basins and Passive Margins. Mémoire du Muséum national d'Histoire naturelle, 86, 441-467.

Schandelmeier, H., Huth, A., Harms, U., Franz, G., Bernau, R., 1987. The East Saharan craton in southern Egypt and northern Sudan: lithology, metamorphism, magmatism, geochronology and structural development. Berlin. Geo wiss. Abh. A 75, 25–48.

Schiano, P., Clocchiatti, R., Ottolini, L. & Busa, T. 2001. Transition of Mount Etna lavas from a mantle plume to an island-arc magmatic source. Nature, 412, 900–904.

Schilling, J.-G., Kingsley, R.H., Hanan, B.B., Mccully, B.L., 1992. Nd–Sr–Pb isotopic variations along the Gulf of Aden: evidence for Afar mantle plume–continental lithosphere interaction. J. Geophys. Res. 97, 10,927–10,966.

Schlische, R.W., 1991, Half-graben basin filling models: New constraints on continental extensional basin evolution: Basin Research, v. 3, 123–141.

Segev, A. and Rybakov, M. 2010. Effects of Cretaceous plume and convergence, and Early Tertiary tectonomagmatic quiescence on the central and southern Levant continental margin. Journal of the Geological Society 167, 731-749, doi:10.1144/0016-76492009-118

Segev, A., Rybakov, M., Lyakhovsky, V., Hofstetter, A., Tibor, G., Goldshmidt, V. and Ben Avraham, Z. 2006. The structure, isostasy and gravity field of the Levant continental margin and the southeast Medi- terranean area. Tectonophysics, 425, 137–157.

Sengör, A. M. C., Yilmaz, Y. & Ketin, I. 1980. Remnants of a pre-Late Jurassic ocean in northern Turkey: fragments of Permian-Triassic Paleo-Tethys. Geological Society of America Bulletin, 91, 599-609.

Sengör, A.M.C. 2001. Elevation as indicator of mantle-plume activity. Geological Society of America Special Paper, 352, 183–225.

Sengör, A.M.C., Tuyusz, O., Imren, C., Sakinc,¸ M., Eyidogan, H., et al. 2005. The North Anatolian Fault: a new look. Annu. Rev. Earth Planet. Sci. 33:37–112

Shaliv, G., 1991. Stages in the tectonic and volcanic history of the Neogene basin in the Lower Galilee and the valleys. Isr. Geol. Surv. Rept. GSI/11/91, 94 p.

Sharaf, L.M., 2003, Source rock evaluation geochemistry of condensates and natural gases, offshore Nile Delta, Egypt: Journal of Petroleum Geology, v.26, no.2, p. 189-209

Sharland, P.R., Archer, R., Casey, D.M., Davies, R.B., Hall, S.H., Heward, A.P., Horbury, A.D. and Simmons, M.D., 2001. Arabian Plate Sequence Stratigraphy. GeoArabia, Special Publication 2, Bahrain. 371 pp. and 3 enclosures.

Sheriff, R. E. 1977. Limits on resolution of seismic reflections and geological detail derivable from them. In: Payton, C. E. (ed.) Seismic Stratigraphy-Applications to Hydrocarbon Exploration. American Association of Petroleum Geologists Memoir, 26, 15-46.

Sheriff, R.B., 1980. Seismic Stratigraphy. IHRDC, Boston, United States.

Sibson, R., 1981. A brief description of natural neighbor interpolation, in V. Barnett, ed., Interpreting Multivariate Data: John Wiley & Sons, 21–36.

Sissingh, W., 1977. Biostratigraphy of Cretaceous calcareous nanno- plankton. Geol. Mijnbouw, 56, 37-65.

Smith, A. G., Hynes, A. J., Menzies, M., Nisbet, E.G., Price, I., Welland, M. J. and Ferriere, J. 1975. The stratigraphy of the Othris Mountains, Eastern Central Greece: a deformed Mesozoic continental margin sequence. Eclogae Geologicae Helvetiae, 68, 463-481.

Sømme, T., Helland-Hansen, W., Martinsen, O. J. & Thurmond, J. B. 2009a. Relationships between morphological and sedimentological parameters in source-to-sink systems: a basis for predicting semiquantitative characteristics in subsurface systems. Basin Research, 21, 361–387.

Sømme, T., Martinsen, O. J.& Thurmond, J. B. 2009b. Reconstructing morphological and depositional characteristics in subsurface sedimentary systems: an example from the Maastrichtian-Danian Ormen Lange system, Møre Basin, Norwegian Sea. American Association of Petroleum Geologists Bulletin, 93, 1347–1377.

Spakman, W., Wortel, M.J.R. & Vlaar, N.J. 1988. The Hellenic Subduction Zone: a tomographic image and its geodynamic implications. Geophysical Research Letters, 15, 60–63.

SpakmanW, van der Lee S, van der Hilst R. 1993. Travel-time tomography of the European Mediterranean mantle down to 1400 km. Phys. Earth Planet. Inter. 79:3–74

Stampfli, G. M. and Borel, G. D. 2002. A plate tectonic model for the Paleozoic and Mesozoic constrained by dynamic plate boundaries and restored synthetic oceanic isochrones. Earth and Planetary Science Letters, 196, 17–33.

Stampfli, G.M., Marcoux, J. & Baud, A., 1991. Tethyan margins in space and time. In Channel, J.E.T., Winterer, E.L. & Jansa, L.F., eds., Paleogeography and Paleoceanography of Tethys. Palaeogeography, Palaeoclimatology, Palaeoecology, 87, 373-410.

Steinberg, J., Gvirtzman, Z., Folkman, Y. and Garfunkel, Z, 2011. Origin and nature of the rapid late Tertiary filling of the Levant Basin. Geology, 39, 355-358; doi: 10.1130/G31615.1

Syvitski, J. P. M. & Milliman, J. D. 2007. Geology, geography and humans battle for dominance over the delivery of fluvial sediment to the coastal ocean. Journal of Geology, 115, 1–19.

Syvitski, J. P. M., Peckham, S. D., Hilberman, R. & Mulder, T. 2003. Predicting the terrestrial flux of sediment to the global ocean: a planetary perspective. Sedimentary Geology, 162, 5–24.

Tahchi, E., Urgeles, R., Hübscher, C., Benkhelil, J., 2010. Mass Wasting at the Easternmost Cyprus Arc, Off Syria, Eastern Mediterranean.

Tayyar, H., 1975. Lower tertiary planktonic foraminifera from the Kfar Hazir area, Chekka region Northern Lebanon. M.S. Thesis, American University of Beirut, Lebanon.

Temple, P.G., Perry, L.I., 1962. Geology and oil occurrences in southeast Turkey. American Association of Petroleum Geologists Bulletin 46, 1526–1612.

Thierstein, H.R., 1976. Mesozoic calcareous nannoplankton biostratigraphy of marine sediments. Marine Micropaleontology 1, 325-362.

Tinker, J., deWit, M. & Brown, R., 2008. Linking source and sink: evaluating the balance between onshore erosion and offshore sediment accumulation since Gondwana break-up, South Africa. Tectonophysics, 455, 94-103.

Toumarkine, M., Luterbacher, H., 1985. Paleocene and Eocene planktic foraminifera, in: Bolli HM, Saunders JB, Perch-Nielsen K (Eds.), Plankton stratigraphy. Cambridge University Press, p. 87-154.

Tucker, G.E., Slingerland, R., 1994. Erosional dynamics, flexural isostasy, and long-lived escarpments: a numerical modeling study. Journal of Geophysical Research 10, 12229-12243**.**

Tucker, M.E., Wright, V.P., Dickson, J.A.D., 1990. Carbonate sedimentology. Blackwell scientific publications, Oxford.

Turner, S., Arnaud, N., Liu, J., Rogers, N., Hawkesworth, C., Harris, N., Kelley, S., Van Calsteren, P. & Deng, W. 1996. Post-collision, shoshonitic volcanism on the Tibetan Plateau: implications for convective thinning of the lithosphere and the source of ocean island basalts. Journal of Petrology, 37, 45–71.

Ukla, S., 1970. Subsurface geology and well correlation in north and central Lebanon. Master's thesis, American University of Beirut, Lebanon, 125 pp.

Vail, P.R., Mitchum R.M. and Thompson S., 1977. Seismic stratigraphy and global changes in sea level. Part 4: Global cycles of relative changes of sea level. American Association of Petroleum Geologists Memoirs, v. 26, p. 83-97.

Van Wagoner, J.C., Posamentier, H.W., Mitchum, R.M., Vail, P.R., Sarg, J.F., Loutit, T.S., Hardenbol, J., 1988. An overview of the fundamentals of sequence stratigraphy and key definitions. In: Wilgus, C.K., Hastings, B.S., Kendall, Ch.St.C.G., Posamentier, H.W., Ross, C.A., Van Wagoner, J.C. (Eds.) Sea-Level Changes—An Integrated Approach, Spec. Publ. Soc. Econ. Paleont. Miner., vol. 42, pp. 39–45

Walley, C. D., 2001. The Lebanon passive margin and the evolution of the Levantine Neotethys. In: P. A. Ziegler, W. Cavazza,A. H. F. Robertson and S. Crasquin-Soleau (Eds.) Peri-Tethys Memoir 6: Peri-Tethyan Rift/Wrench Basins and Passive Margins. Mémoire du Muséum national d'Histoire naturelle, Paris, 86, 407-439.

Walley, C.D., 1988. A braided strike-slip model for the northern continuation of the Dead Sea Fault and its implications for the Levantine tectonics. Tectonophysics, 145, 63-72.

Walley, C.D., 1997. The lithostratigraphy of Lebanon: a Review. Lebanese Scientific Bulletin, 10, 81-108.

Walley, C.D., 1998. Some outstanding issues in the geology of Lebanon and their importance in the tectonic evolution of the Levantine region. Tectonophysics, 298, 37-62.

Wendorf, F. & Schild, R. 1976. Prehistory of the Nile Valley. Academic Press, New York.

Westaway, R., 2004. Kinematic consistency between the Dead Sea fault zone and the Neogene and Quaternary left-lateral faulting in SE Turkey.Tectonophysics 391 (1–4), 203–237.

Wetzel, R.M.F., Dubertret, L., 1945-1951. «Cartes Géologiques du Liban 1/ 50 000e. Feuille de Tripoli» avec notice explicative. République Libanaise, Ministère des Travaux Publics, Beyrouth.

White, R.S and McKenzie, D. 1989. Magmatism at rift zones: The generation of volcanic continental margins and flood basalts. Journal of Geophysical Research, 94, 7685-7729

Willgoose, G.R., Bras, R.L., Rodriguez-Iturbe, I., 1991. A physically based coupled network growth and hillslope evolution model, 1, theory. Water Resources Research 27, 1671-1684**.**

Wilson, J.T., 1966. Did the Atlantic close and then re-open? Nature 211, 676-681.

Wolfenden, E., Yirgu, G., Ebinger, C., Deino, A. & Ayalew, D. 2004. Evolution of the northern Main Ethiopian Rift, birth of a triple junction. Earth and Planetary Science Letters, 24, 213–228.

Wood, B.G.M., 2001. Intraplate primary and subsidiary basin formation and deformation: -an example from central Syria. Unpublished Ph.D. Thesis, University of Oxford, United Kingdom.

Woodward, J.C., Macklin, M.G., Krom, M.D. & Williams, M.A.J. 2007. The Nile, Evolution, Quaternary River Environments and Material Fluxes. In: Gupta, A. (ed.) Large Rivers, Geomorphology and Management. John Wiley & Sons, Chichester, 261–289.

Wortel R and Spakman W (2000) Subduction and slab detachment in the Mediterranean–Carpathian region. Science 290: 1910–1917.

Yousef, M., Moustafa, A. R. and Shann, M., 2010. Structural Setting and Tectonic Evolution of Offshore North Sinai, Egypt. In: Homberg, C. and Bachmann, M. (Eds.) Evolution of the Levant Margin and Western Arabia Platform since the Mesozoic. Geological Society, London, Special Publications, 341, 65–84.

Zakhera, M.S., 2011. Cenomanian-Turonian rudists from Western Sinai, Egypt: Systematic paleontology and paleoecologt. Geobios, Vol 44, Issue 4, p 409-433

Zeyen, H., Volker, F., Wehrle, V., Fuchs, K., Sobolev, S.V. and Altherr, R., 1997. Styles of continental rifting: crust-mantle detachement and mantle plumes. Tectonophysics, 278, 329-352.

Ziegler, M. A., 2001. Late Permian to Holocene paleofacies evolution of the Arabian plate and its Hydrocarbon occurrences. GeoArabia, 6, 445–504.

Zilberman, E and Calvo, R., 2013. Remnants of Miocene fluvial sediments in the Negev Desert, Israel, and the Jordanian Plateau: Evidence for an extensive subsiding basin in the northwestern margins of the Arabian plate. Journal of African Earth Sciences, 82, 33-53.

APPENDIX

APPENDIX 1: Onshore source rock overview

A wide source rock distribution has been observed along the Levant margin (i.e., Euphrates, Palmyride, Nile Delta and Levant coastal areas) with deposits ranging from Paleozoic/Lower Mesozoic shallow marine shales (e.g., Silurian, Lower Ordovician, Middle Carboniferous, Triassic, Middle Jurassic) to deeper marine shales in the Upper Cretaceous and Cenozoic (i.e., Eocene, Oligo-Miocene) (Abu El-Ella, 1990; Al-Maleh & Mouty, 1988; Alsharhan & Nairn, 1997; Ismail *et al*., 2010; Nader, 2011). A good understanding of the shelve and margin source rock deposition is crucial in assessing the Levant basin's prospectivity (May, 1991; Dolson et al., 2000; 2001; 2005; Wever, 2000; Feinstein et al., 2002; Sharaf, 2003; Montadert, *in press*).

A sampling campaign of the outcropping source rocks in Lebanon has been conducted (Fig.a.1). Several locations have been sampled based on the best outcropping rock units permitting to a have a first hand overview of the potential source rock characteristics. This section reveals to be important in setting ground to detailed studies that are/should be conducted in the nearby future. The gathered samples have been characterized using RockEval6 at the IFPEN.

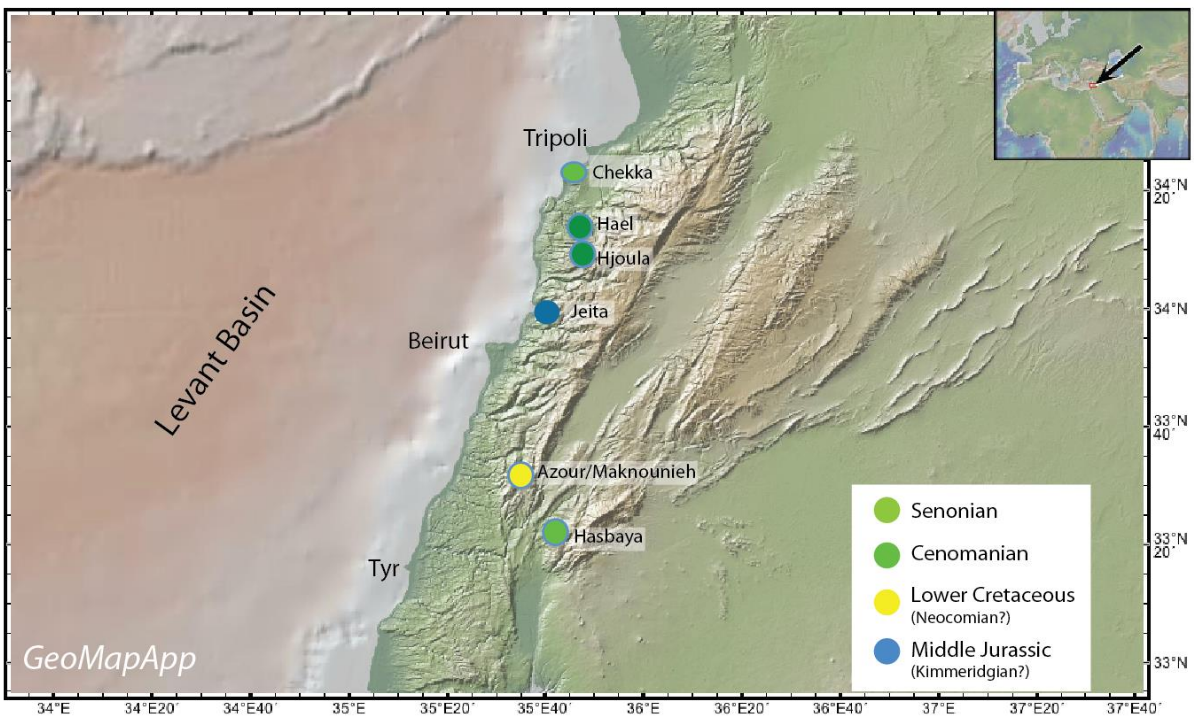


Fig a.1 Topographic map showing the major locations sampled for source rock characterization

(1) **Jurassic:**

a. Kimmeridgian? of the Jeita (N33°56'38.16"; E035°38'26.89") area was deposited in a very shallow marine to continental setting (calcified sandstone with coaly intervals). The richest levels are about 20 cm thick intercalated by marls (Figs.a.1, a.2a).

i. <u>RockEval6 results:</u>

- TOC: 1.25-2.6% (note we have important oxidation so levels should be higher)

- Tmax: 431 °C
- HI: between 16-33 mg HC/g TOC
- Type III

b. Liassic? of the Nahr Ibrahim (near Jeita; N34° 4'41.58"; E035°48'6.96") area does not represent source rock characteristics after RockEval6 tests.

(2) **Cretaceous:**

a. Neocomian? of Jezzine (Azour (N33°33'1.20"; E035°32'58.80") & Maknounieh (N33°31'25.14"; E035°32'49.62")) was deposited in a fluvio-deltaic settings (intercalation of sandstone and lignitic to coaly levels) with the richest levels of about 0.5m to 1m (Figs.a.1, a.2b)

i. RockEval6 results:

- TOC: very variable 2-5% with abnormal values going into the 25-57% in Maknounieh (cretaceous forest fires??)
- Tmax: around 403 going into 450-575 °C (in the Maknounieh region)
- HI: between 16-33
- Type III

b. Cenomanian from the Hael and Hjoula (samples courtesy of Mr Pierre Abi-Saad) region representing tidal to deep marine outer shelf to shelf margin conditions (Lithographic Limestone) (Figs.a.1, a.2c)

i. RockEval6 results:

•TOC: very variable 0.25-1.3%
•Tmax: 410-435 °C
•HI: between 330 (light rock section) and 650 (for the darker section)
•Type II

c. Senonian? of Hasbaya deposited in an outer shelf deep marine conditions. Most potential source rock (Figs.a.1, a.2d)

i. RockEval6 results:

•In situ SR as well as fracture related asphalt seeps (deeper SR??)
•Rock Eval: mainly Type II

	TOC %	Tmax °C	HI (mg HC/g TOC
In Situ Source Rock	**10-12**	**402-409**	**670**
Asphalt seeps	**45**	**423**	**770**

Fig.a.2 Photographs showing the potential source rock sampled. (a) Kimmeridgian (b) Lower Cretaceous (Neocomian?) (c) Cenomanian and (d) Senonian

To summarize, the study of the onshore source rock characteristics as well as hydrocarbon seeps, proved that the outcropping units in Lebanon are immature. However future investigations should focus on estimating the maturity of the prospective source rocks in the Bekaa Valley (no seismic data is yet available for the Lebanese onshore which complicates this fact) and on the deeply buried limbs of Mount Lebanon. The most prospective onshore source rock is the Senonian (seen in Hasbaya and Chekka).

Geochemical finger-printing should be conducted on samples from the several seeps seen (mainly asphalt on faults in the Senonian in the Hasbaya (south) and Metrit (north) regions, Eocene in the Yohmour and Sohmour (south) regions) in order to better understand the hydrocarbon provenance (in situ maturation and migration or not) and thus assess the different petroleum systems in the area. The reader is referred to the ongoing PhD thesis of Samer BouDaher at Aachen University entitled “Source rock maturation and petroleum generation and migration modeling of the Levantine Basin, offshore Lebanon an integrated approach”.

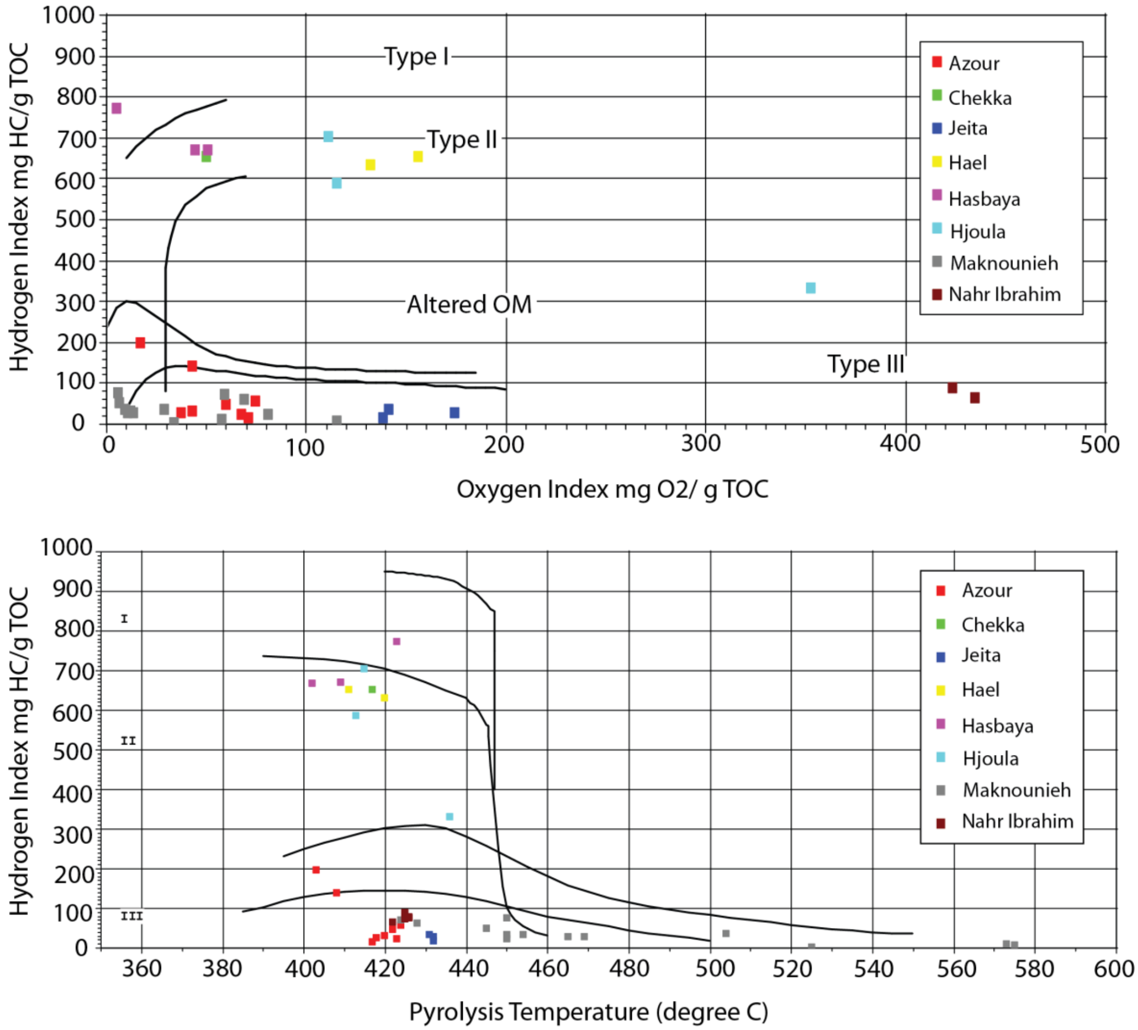


Fig.a.3. Source rock characterization: HI versus OI and HI versus Tmax (RockEval6-IFPEN)

ANALYSIS	SITE	STAGE	S1	S2	S3	Tmax	HI	OI	OI CO	TPI	TOC	RC	MINC	CaCO3
			Rock_Eval6 Parameters											
			mg HC/g de roche	mg HC/g de roche	mg CO2/g de roche	°C	mg HC/g de TOC	mg CO2/g de TOC	mg CO/g de TOC		%	%	%	%
AZ1	AZOUR	NEOCOMIAN	0.25	111.54	9.92	403	195	17	10	0.00	57.06	47.26	0.60	5
AZ2	AZOUR	NEOCOMIAN	0.02	0.64	0.94	420	30	43	24	0.04	2.17	2.07	0.18	2
AZ2A	AZOUR	NEOCOMIAN	0.01	0.54	0.81	418	25	38	21	0.03	2.15	2.07	0.19	2
AZ4	AZOUR	NEOCOMIAN	0.02	0.69	2.16	423	22	68	24	0.02	3.19	3.04	0.16	1
AZ5	AZOUR	NEOCOMIAN	0.11	13.53	17.88	422	46	60	20	0.01	29.62	27.75	0.80	7
AZ6	AZOUR	NEOCOMIAN	0.01	0.26	1.33	417	14	71	27	0.03	1.87	1.79	0.20	2
AZ7	AZOUR	NEOCOMIAN	0.27	32.00	9.99	408	139	43	18	0.01	23.07	19.94	0.50	4
AZ8	AZOUR	NEOCOMIAN	0.04	4.54	6.10	424	56	75	21	0.01	8.15	7.53	0.26	2
BITUME	CHEKKA	SENONIAN	0.24	29.08	2.25	417	651	50	9	0.01	4.47	1.96	7.97	66
FOSBEIGE	HJOULA	CENOMANIAN	0.01	0.78	0.83	436	332	353	23	0.01	0.23	0.14	10.70	89
FOSGRIS	HJOULA	CENOMANIAN	0.09	4.16	0.82	413	587	115	14	0.02	0.71	0.33	11.36	95
GE1	JEITA	KIMMERIDGIAN	0.01	0.41	3.57	432	16	139	11	0.03	2.58	2.43	7.28	61
GE2	JEITA	KIMMERIDGIAN	0.01	0.32	2.01	432	28	174	15	0.04	1.15	1.06	5.50	46
GE3	JEITA	KIMMERIDGIAN	0.01	0.42	1.78	431	33	142	16	0.02	1.26	1.17	7.79	65
HA1	HASBAYA	SENONIAN	0.93	69.15	4.64	402	668	45	9	0.01	10.35	4.37	7.24	60
HA2	HASBAYA	SENONIAN	3.87	82.16	6.25	409	670	51	9	0.04	12.27	4.91	7.59	63
HA3	HASBAYA	SENONIAN	6.80	342.15	2.34	423	771	5	2	0.02	44.36	15.29	4.14	35
HAEL	HAEL	CENOMANIAN	0.07	3.41	0.72	420	631	133	16	0.02	0.54	0.23	11.64	97
HAEL1S	HAEL	CENOMANIAN	0.27	8.50	2.03	411	652	156	18	0.03	1.30	0.51	10.78	90
HJOULA	HJOULA	CENOMANIAN	0.08	3.86	0.61	415	703	111	8	0.02	0.55	0.20	10.89	91
MA1	MAKNOUNIEH	CENOMANIAN	0.04	0.37	11.32	525	1	34	3	0.10	33.00	32.61	0.65	5
MA2	MAKNOUNIEH	CENOMANIAN	0.03	8.19	2.25	504	35	10	6	0.00	23.63	22.83	0.32	3
MA3	MAKNOUNIEH	CENOMANIAN	0.01	0.81	0.40	465	28	14	8	0.01	2.88	2.80	0.13	1
MA4	MAKNOUNIEH	CENOMANIAN	0.06	6.56	2.51	450	32	12	8	0.01	20.34	19.65	0.30	3
MA5	MAKNOUNIEH	CENOMANIAN	0.03	0.55	1.94	450	23	81	18	0.06	2.40	2.28	0.11	1
MA6	MAKNOUNIEH	CENOMANIAN	0.12	19.02	1.55	450	76	6	5	0.01	25.08	23.39	0.19	2
MA8	MAKNOUNIEH	CENOMANIAN	0.02	2.31	0.90	469	27	11	7	0.01	8.52	8.28	0.15	1
MA9	MAKNOUNIEH	CENOMANIAN	0.01	1.86	1.63	454	34	29	14	0.01	5.55	5.32	0.11	1
MA10	MAKNOUNIEH	CENOMANIAN	0.10	23.56	3.10	445	49	6	5	0.00	47.83	45.68	0.51	4
MA11	MAKNOUNIEH	CENOMANIAN	0.07	5.19	34.66	573	9	58	22	0.01	59.86	57.91	1.90	16
MA12	MAKNOUNIEH	CENOMANIAN	0.03	1.46	27.37	575	6	115	7	0.02	23.75	22.81	1.83	15
MA13	MAKNOUNIEH	CENOMANIAN	0.11	22.82	19.36	424	70	59	15	0.00	32.74	30.09	0.97	8
MA14	MAKNOUNIEH	CENOMANIAN	0.02	3.40	3.85	428	61	69	22	0.01	5.59	5.15	0.21	2
NI2	NARHIBRAHIM	LIASSIC?	0.01	0.12	0.82	426	78	551	36	0.06	0.15	0.11	11.40	95
NI3	NARHIBRAHIM	LIASSIC?	0.01	0.11	0.81	426	74	534	23	0.05	0.15	0.12	10.60	88
NI4	NARHIBRAHIM	LIASSIC?	0.01	0.08	0.69	425	72	628	32	0.11	0.11	0.08	10.33	86
NI5	NARHIBRAHIM	LIASSIC?	0.01	0.22	1.06	425	88	424	31	0.05	0.25	0.20	10.19	85
NI6	NARHIBRAHIM	LIASSIC?	0.01	0.09	0.65	425	78	543	42	0.08	0.12	0.09	10.57	88
NI7	NARHIBRAHIM	LIASSIC?	0.01	0.10	0.69	422	63	435	36	0.07	0.16	0.13	10.64	89
NI8	NARHIBRAHIM	LIASSIC?	0.01	0.12	0.71	425	87	515	36	0.05	0.14	0.11	10.44	87

Table a.1. Detailed RockEval6 results for the different locations and source rock ages studied

APPENDIX 2: Onshore Lebanon wells (*Courtesy of MEW*)

Refer to Fig.2.1 for well location

Sohmor-1

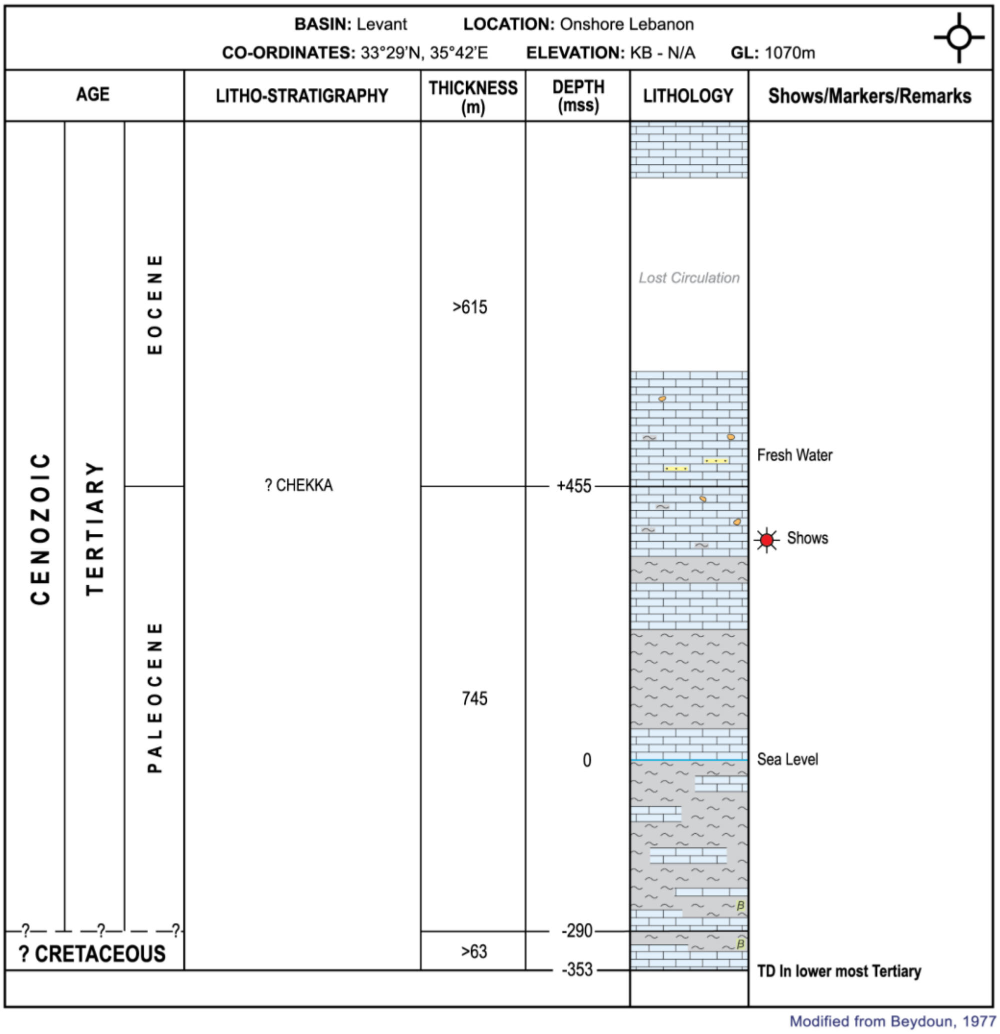


Fig. a.4 Sohmor-1 well

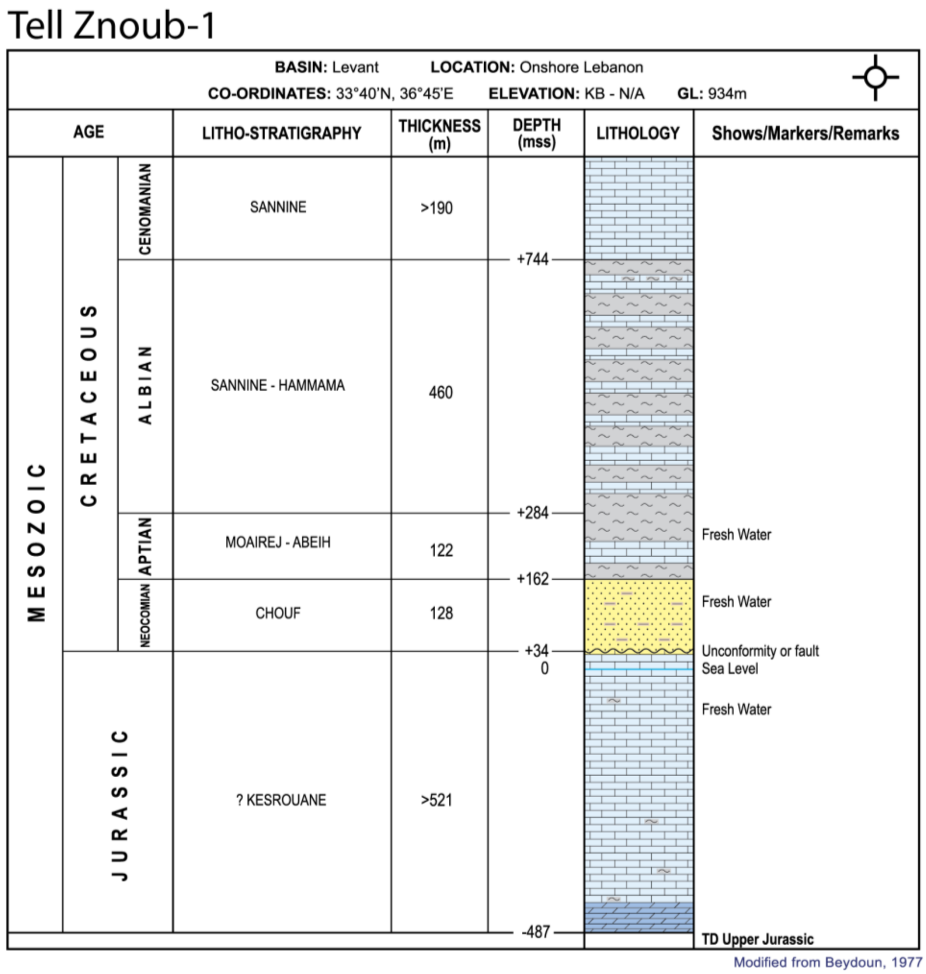


Fig. a.5 Tell Znoub-1 well

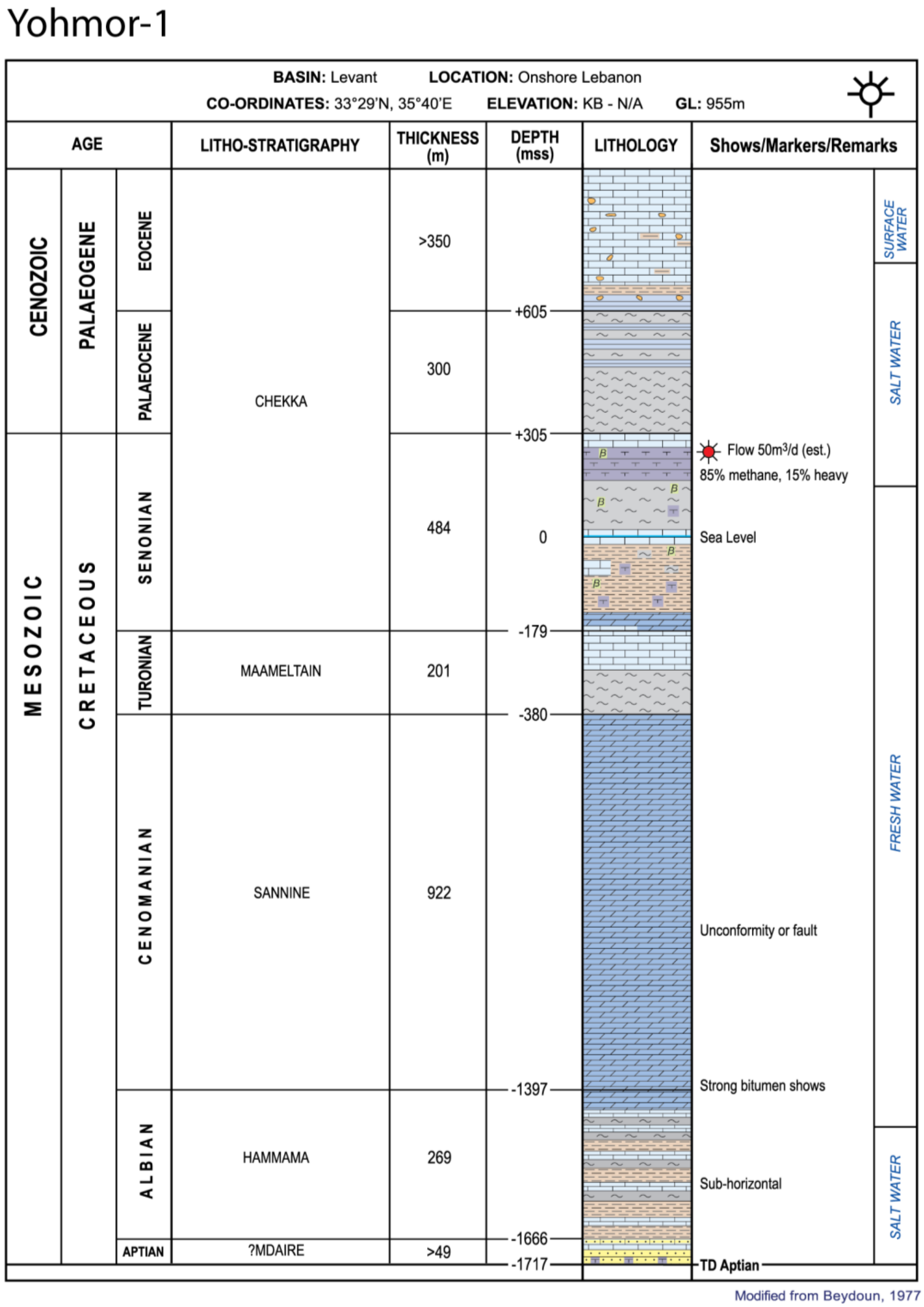


Fig. a.6 Yohmor-1 well

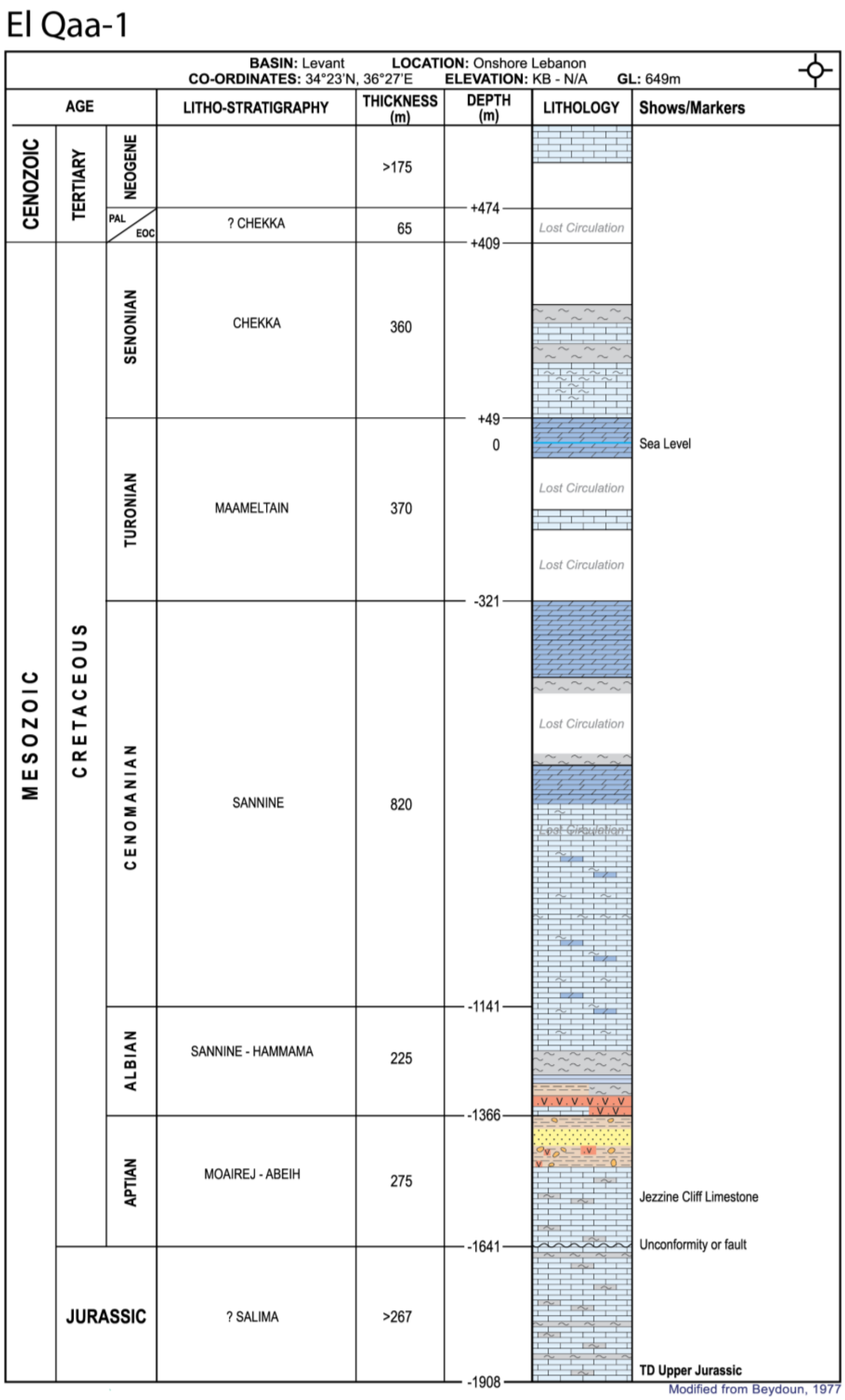


Fig. a.7 El Qaa-1 well