




A Review of the Offshore East Mediterranean Mesozoic-Cenozoic Petroleum Systems

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Abstract

A geological overview on the East Mediterranean realm, featuring the tectono-stratigraphic evolution and associated depositional environments as well as the known petroleum systems, is provided in this contribution. The Levant Basin, the (northern) Western Desert, and the Nile Delta are the main focus of this review because they include significant oil and gas discoveries (a total of 63,000 MMBOE has been forecasted for these regions), providing a considerable amount of data. The onshore-offshore extension of the Northern Western Desert (to Herodotus Basin) is compared to that of the Eastern Levant Margin—both share similar tectono-stratigraphic evolutions until the establishment of the Levant Fracture System. The Upper Cretaceous source rocks distribution across the Western Desert margin is, nevertheless believed to be controlled by increased bio-productivity and

nutrients with sediment transport from nearby hinterland, contrasting an upwelling scenario for the same source rocks in the Levant Basin. The possibility of mixing hydrocarbon from these deeper kitchens with the known overlying microbial gas accumulated in the Oligo-Miocene interval has been proven by the Karish discovery in the Levant Basin and through modeling the probability for fracturing the Eocene sealing unit. This may well occur in offshore Western Desert. The Nile has been the principal sediment feeder of the East Mediterranean basins since the Late Miocene. The Nile Delta is characterized by Oligo-Miocene petroleum systems, while the deeper Mesozoic systems still need further studies. The presence of carbonate plays has already been demonstrated by the discovery of the giant Zohr field. Succeeding in finding similar prizes requires understanding the complexity of such heterogeneous, yet attractive carbonate reservoirs. The East Mediterranean realm remains a frontier hydrocarbon province with a considerable wealth of knowledge that will help in understanding sedimentary basins at the intersections of major plate boundaries and the association of deep lithospheric processes and major shallow and surface processes.

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1 Introduction

The Mediterranean coastline stretches over 46,000 km on the African, European and Asian continents, hosting around 480 million people whose growing energy demands need to be met with optimal development of georesources. The East Mediterranean region, where northern Egypt occupies a significant part, is located—from a geological perspective—at the triple junction point between the Eurasian Plate in the North, the African Plate in the Southwest, and the Arabian Plate in the East (Fig. 1). This region is characterized by an

older, thicker, cooler, and stronger lithosphere compared to the western part of the Mediterranean Sea (Fig. 1; Roure et al., 2012). It is also commonly believed that this region belongs to the southern, passive margin of the Tethys, including evidence of its associated rifting, post-rift subsidence, and inversion phases. Hence, deep mantle dynamics and the evolution of plate boundaries resulted in the specific subsidence and thermal histories of the East Mediterranean sedimentary basins that influenced local petroleum systems.

During the last decades, the East Mediterranean region has witnessed exceptional oil and gas exploration developments, demonstrated by significant discoveries (Figs. 1 and 2) and the opening of new frontiers and acreages. The industrial advances happened together with an impressive set of scientific achievements in various fields (geophysics, seismic data acquisition and interpretations, geodynamics and structural geology, tectono-stratigraphy and sedimentology, as well as petroleum systems analyses and geochemistry, e.g., Hawie et al., 2013; Ghalayini et al., 2014; Bou Daher et al., 2014; Tassy et al., 2015; Ghassal et al., 2016; Grohman et al., 2018; Papadimitriou et al., 2018a, 2018b; Symeou et al., 2018; Inati et al., 2018; El Hajj et al., 2019). Hence, a huge amount of data, viable concepts, and expertise have been made available for this region.

Egypt is situated in the southern part of the Eastern Mediterranean region, where the first hydrocarbon exploration and production operations occurred at the beginning of the previous century. In 2015, the discovery of the giant Gas Field Zohr, located south of the Eratosthenes Seamount between the Herodotus and Levant Basin (Fig. 1), sparked new interest in the overall region. Egypt's total oil and gas discoveries amount to 29,000 MMBOE in 2009, principally from three petroleum provinces (Dolson et al., 2014): Gulf of Suez (11,500 MMBOE), Nile Delta (11,200 MBOE) and the Western Desert (5,700 MBOE). Dolson et al. (2014) predicted an ultimate yet-to-find of 37,600 MBOE for Egypt resources (revised to 38,600 MBOE, Dolson, 2018) in agreement somehow with the USGS forecasts for the Nile Delta (223 TCF, or 38,000 MMBOE) and the Levant Basin (117 TCF, or 20,000 MMBOE) (Kirschbaum et al., 2010; Schenk et al., 2010 and 2012).

More than 70 TCF (around 12,500 MBOE; Fig. 2) of natural gas were recently discovered in the Levant Basin (East Mediterranean region), which lies offshore Cyprus, Egypt, Israel, and Lebanon (Fig. 1). New plays have been proposed, and new un-explored areas may yield additional significant discoveries (e.g., Ghassal et al., 2016; Montadert et al., 2014; Nader, 2011, 2014). Nevertheless, the East Mediterranean region is characterized by a general lack of published geological data, a complex geodynamic and tectono-stratigraphic evolution, and high exploration costs. It is one of the typical frontier exploration areas, where numerical solutions, such as stratigraphic forward modeling (SFM), complex burial/

thermal modeling (including petroleum systems modeling; PSM) (Barabasch et al., 2019; Grohmann et al., 2021), and uncertainty modeling with machine learning (Ducros & Nader, 2020), proved to be an excellent help for enhancing reservoir play fairways predictions.

In the last two decades, a significant amount of 2D and 3D seismic reflection data have been acquired throughout the East Mediterranean region. These activities generated a considerable amount of new data on the stratigraphic intervals below the Messinian salt, sparking the interest for academic and industry-led investigations. Recent seismic reflection acquisition offshore Egypt (Western Desert) also yielded invaluable information for a promising future exploration era. According to PGS (Petroleum Geo-Services; <https://www.pgs.com>), the exhaustive new 2D and 3D seismic data covering more than 80,000 km² confirm the viability of this new exploration frontier area. Hence, seismic data interpretations already showed the possible extension of the Pliocene sandstone play from the Nile Delta, potential for Zohr-type pre-salt carbonate and pre-salt sandstone plays. The offshore area is believed to be an extension of the prolific onshore Western Desert.

Recent research work, which focused on the Levant Basin and was based on such substantial new data, provided new concepts for better understanding the crustal, structural, and stratigraphic characteristics of this region, as well as its key petroleum systems (e.g., Bou Daher et al., 2016; Ghalayini et al., 2015; Grohmann et al., 2018, 2021; Hawie et al., 2017; Inati et al., 2018; Papadimitriou et al., 2018a, 2018b; Symeou et al., 2018). These contributions together with the previous work of Abdel Aal et al. (2001), Shaaban et al. (2006), Dolson et al. (2014), Tassy et al. (2015), and Ghassal et al. (2016) on the Nile Delta and the Western Desert, Gardosh and Druckman (2006) and Gardosh et al. (2008) on offshore Israel and Bowman (2011) on offshore Syria, to name a few, encompass the collective geological knowledge of the southern East Mediterranean region. Gvirtzman et al. (2014), Hawie et al. (2017), Nader et al. (2018), and Grohmann et al. (2021) have proposed 3D stratigraphic forward models for the Levant Basin and offshore Egypt (Nile Delta). Still, to date, no comprehensive regional stratigraphic model exists for the southern East Mediterranean region. The area stretching from the Sinai Hinge Zone and the Nile Delta in the South to the Cyprus Arc in the North, and from the inverted Palmyra Trough and the Levant Fracture System to the East to the Eratosthenes Seamount and Herodotus Basin to the West (Fig. 1) requires detailed local studies but also has to be investigated as a whole (e.g., Wood, 2015) in order to achieve an overall geological understanding.

This chapter aims to provide a general overview of the geologic settings, the tectonic history, the depositional evolution, and petroleum systems of the East Mediterranean region, focusing on the Levant Basin, the Western Desert,

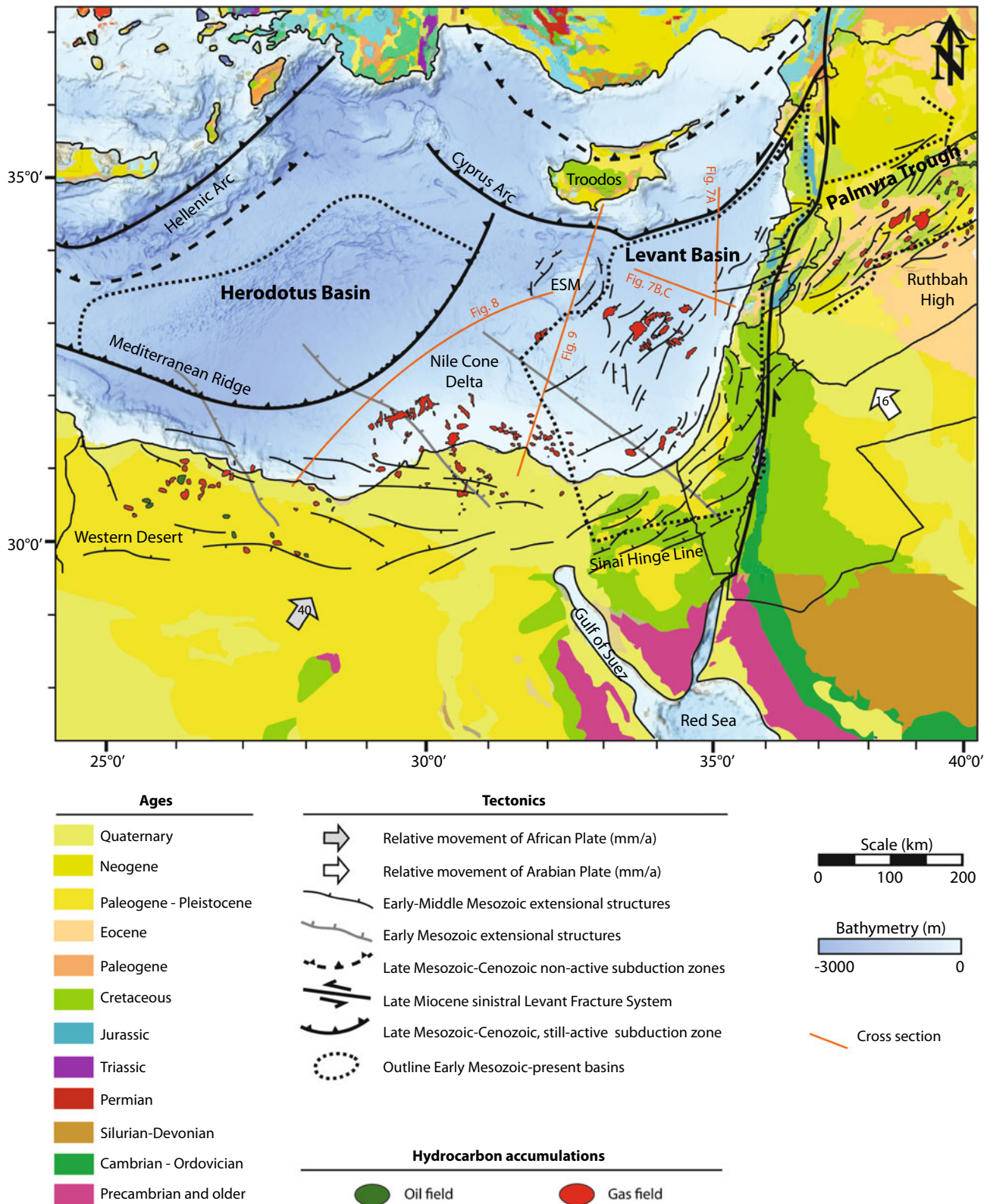


Fig. 1 Simplified geological map of the East Mediterranean region together with the main tectonic features as well as present-day oil and gas fields. In this work, the main focus lies on the regions representing the former northern margin of Gondwana, characterized by Early Mesozoic extensional structures that can be traced from the Western Desert in northeastern Egypt over Israel and Lebanon up to Syria as well as on their main adjacent sedimentary basins, the Herodotus Basin in the West, and the Levant Basin in the East. The orange lines indicate the location of regional cross-sections shown in Figs. 7, 8, and 9, respectively (Geological map based on data from Asch (2003) and Thiéblemont (2016); bathymetry taken from NOAA, 2022; tectonic features based on Dilek & Altunkaynak, 2009; Tassy et al., 2015; Ghalayini et al., 2018)

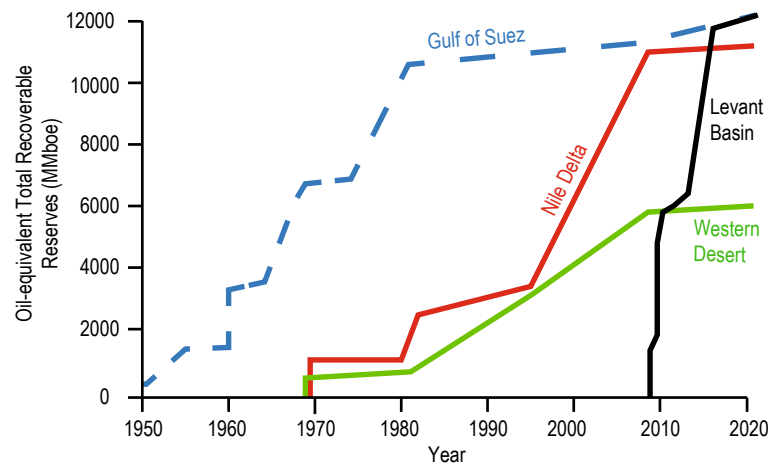


Fig. 2 Schematic creaming curves for the East Mediterranean region including the Gulf of Suez, Nile Delta, Western Desert, and Levant Basin (see text for references)

and the Nile Delta. This approach is made possible by integrating and synthesizing a great wealth of information from published data.

2 Geological Setting

2.1 Geodynamic Evolution

The East Mediterranean geodynamics are principally associated with the Pangea breakup in the Late Paleozoic, the interactions of the resulting separate plates, and the evolution of the Tethys Ocean (Fig. 3). The disintegration of Gondwana and the opening of the Tethys (Fig. 3a) led to the creation of major sedimentary basins in this region (e.g., Palmyra, Levant, Herodotus; Figs. 1 and 3) and their filling. By the Late Cretaceous (Fig. 3b), the overall extensional tectonics became compressional and initiated the closure of the Tethys ocean. The older Mesozoic basins started to be inverted in the East Mediterranean region. The Afro-Arabian plate moved northward, and a north-verging subduction zone evolved at the southern margin of Eurasia (Hawie et al., 2014, and references therein; Fig. 3b). There, slab pull-related forces resulted in new oceanic crust and the obduction of ophiolitic complexes (e.g., Lord et al., 2009; Swarbrick & Robertson, 1980). The Troodos ophiolites that are exposed in Cyprus mark the southern limit of the Tethyan Ocean and rest on Mesozoic platform carbonates, most probably belonging to the Afro-Arabian passive margin (Roure et al., 2012). Traces of basin inversions have been investigated primarily onshore, along the eastern and southern margins of the Levant Basin (cf. Syrian Arc structures in Palmyra Basin and along the Levant margin) and to a lesser extent offshore, e.g., the Cyprus Arc System (Symeou et al., 2018).

In the aftermath of the Tethys Ocean closure and the prominent Afro-Arabia collision with the Eurasian blocks, the Afar mantle plume contributed to the uplift and tilting of Afro-Arabia northern margins. Faccenna et al. (2013) applied mantle circulation computations to confirm the association of the Afar mantle upwellings with the Aegean slab pull (Fig. 4). The igneous province of Ethiopia demonstrates localized mantle upwelling about 30 Ma while rifting took place in the Red Sea and the Gulf of Suez (as of Late Eocene–Early Oligocene). The first phase of uplift of the Red Sea shoulders and the Levant margins are also ascribed to the Late Eocene–Early Oligocene (Faccenna et al., 2013). At almost the same time, the northern edge of the Arabian Plate collided with the Anatolian blocks. Zagros-Bitlis subduction took place as of Early Oligocene. During the Miocene (Fig. 3c), Africa's motion slowed down as the rifting of the Gulf of Suez transferred to the Gulf of Aqaba, while Arabia kept its northward motion. This resulted in the initiation of the Levant Fracture System (Fig. 3d) from the Gulf of Aqaba, through the Dead Sea Fault northward through Lebanon and Syria (Nader, 2014). These events (Fig. 4) were contemporaneous with slab steepening and break off events (15–10 Ma, respectively), with the emplacement of mantle convection dynamics and northward flow from Afar to Anatolia (Faccenna et al., 2013). Thus, such mantle dynamics may be considered as the driving force for the observed increased subsidence and sedimentary filling of Herodotus and Levant basins together with the uplift of the surrounding margins. The significant inversion effects of the Levant Fracture System on the eastern margin of the Levant Basin (including the Lebanese mountains) continued in the Late Miocene and were followed by the tectonic westward escape motion of Anatolia, which has been well illustrated along the Cyprus Arc System (Montadert et al., 2014; Symeou et al., 2018).

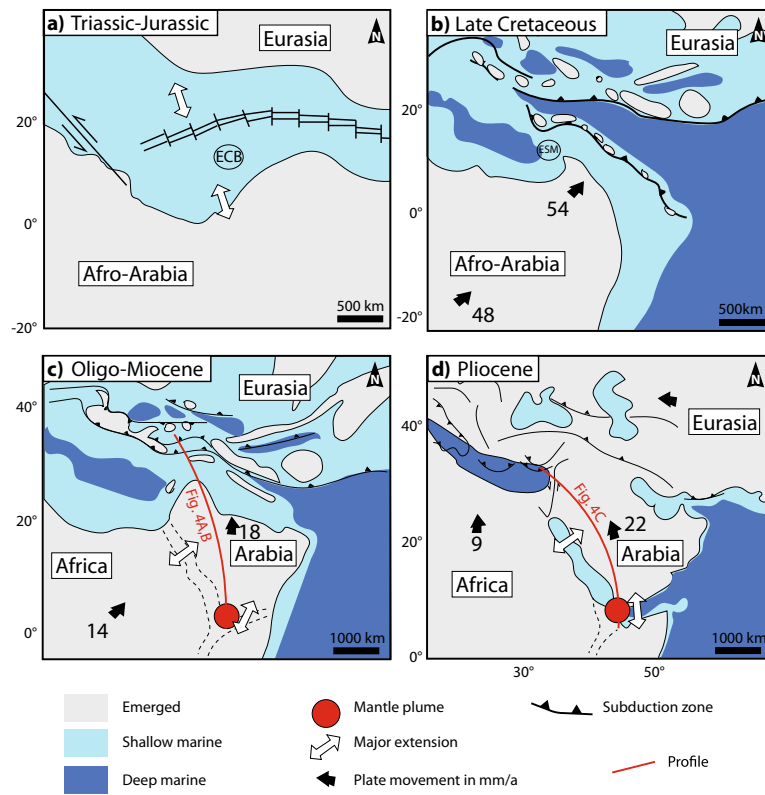


Fig. 3 Tectonic evolution of Afro-Arabian and Eurasian realm illustrating, **a** the Early Mesozoic rifting and disintegration of northern Gondwana, **b** the change from an extensional toward compressional tectonic setting with the subduction of the Afro-Arabian Plate below Eurasia, **c** the beginning of the separation of Arabia and Africa in the Oligocene caused by the Afar mantle plume and the opening of the Red Sea, causing further, **d** isolation of the Mediterranean Sea in the Late Miocene-Pliocene. Figure modified from Hawie et al. (2017) and Symeou et al. (2018)

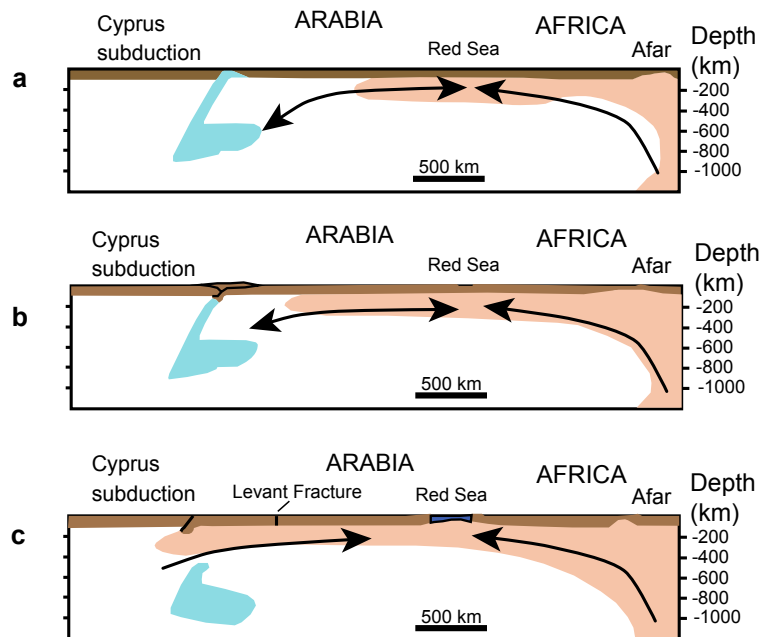


Fig. 4 Geodynamic evolution of the East Mediterranean illustrated by regional cross-sections for **a** 30 Ma, **b** 20 Ma, and **c** 10 Ma, showing the mantle flow (arrows) below the African, Arabian, and Eurasian plates. Note the mantle upwelling in Afar, the Red Sea opening, the collision, subduction, and slab break off in Cyprus (from Faccenna et al., 2013)

Moreover, the breakup of Afro-Arabia (through the rifting and opening of the Red Sea) with an accelerated northward drift of the Arabian Plate in the Oligocene (Fig. 3c) resulted in the ultimate isolation of the Eastern Mediterranean basins (remnants of Tethys oceanic domain). Hence, the uplifted hinterland provided a massive amount of eroded sediments, which were washed into the East Mediterranean basins. Due to the thin continental crust and oceanic crust, the Levant and Herodotus basins, respectively, subsided further, becoming major depocenters. At the same time, their margins were uplifted and affected by further tectonics associated with the opening of the Red Sea, the Levant Fracture System, escape tectonics of the Anatolian block, and the evolution of the Nile system (Inati et al., 2018). The Levant Fracture System led to the re-organization of the sediment input pathways (i.e., major rivers) into the Levant Basin (Hawie et al., 2017; Nader et al., 2018). The general settings were also shaped by the Miocene-Pliocene evolution of the Nile River and the Messinian Salinity Crisis. The latter resulted in drying up the Mediterranean Sea and the deposition of up to 2 km of evaporites between 5.96 and 5.33 Ma (Krijgsman et al., 1999), while the former brought an immense amount of sediments and disturbed the overall stratigraphic configuration of the East Mediterranean.

2.2 Tectono-stratigraphic Evolution

Rifting of the Tethys Ocean is believed to have occurred in two phases (late Early Carboniferous—related to the Variscan orogeny and Early Permian), with seafloor spreading following the second phase (Stampfli et al., 2001). Several major tectonic features concerning the East Mediterranean existed since that early time, such as the Palmyra and Dakhla basins, the Eratosthenes platform, and the Heletz high (Fig. 5a). The latter is defined as an uplifted rift shoulder of the Eastern Mediterranean Basin, with similar examples found in Egypt, Libya, and Tunisia (Roure et al., 2012; Stampfli et al., 2001).

By the end of the Middle Jurassic (Figs. 3a and 5a), active rifting ceased, allowing (post-rift) passive thermal subsidence in the Eastern Mediterranean basins (Fig. 5b). “Mesogean” oceanic spreading started, which refers to a new oceanic domain formed principally in the Cretaceous, extending from the Maghreb Ocean to the West to the Neo-Tethys to the East, and covering mostly the East Mediterranean region (Barrier et al., 2018; Dercourt et al., 1986). The end of the rifting and active extensional tectonic subsidence in the Eastern Mediterranean region is represented by the “breakup” horizon on seismic data (Montadert et al., 2014), regarded as a key surface that overlies the tilted blocks morphologies across the continental, marginal, and

basin domains. The Eratosthenes and Troodos carbonate platforms as well as the marginal domains prevailed, surrounded by slope–basinal deeper marine carbonates. By the end of the Jurassic, the Eastern Mediterranean basins were surrounded by flooded lowland, marginal marine, shallow mixed shelf to the South, the Rutbah and Mardin paleohighs to the southeast and the East, and the Mesogea Ocean to the North. Localized volcanic activities occurred as well.

In the Campanian, the collision and closure of Mesogea continued with the thrust belt advancing southward (Figs. 3b and 5b). The Troodos platform (in Cyprus) was consumed by thrusting. Uplift led to subaerial exposure and mountain ranges just north of Baer Bassit (northern Syria), which became sources for sediment influx. A regional foredeep basin prevailed to the South of the thrust faults (and accretionary tectonic melange) (Papadimitriou et al., 2018a, 2018b). Further south, Egypt hinterlands continued to supply Nubian sand sediments toward Dakhla Basin and the Mediterranean. By the Late Cretaceous (Fig. 3b), the Mesogea Ocean was almost closed due to the Alpine orogeny, encroaching the northern periphery of Afro-Arabia. The initiation of the “Syrian Arc,” a belt of intra-plate structural inversion affected the Egyptian through Syrian margins, coinciding with the start of ophiolite obduction on the passive margin of Arabia. In the Maastrichtian, most of the East Mediterranean basins became sites of deeper marine deposition (Fig. 5b). The southern margin was characterized by slope–basinal marine carbonates and the eastern margin by carbonate and terrigenous platforms (Nader, 2014).

In the Early Eocene, as the almost S–N extension switched from the Suez to the Aqaba and all along the eastern margin of the Levant Basin, major carbonate platforms covered the northern Mardin, southern Rutbah, and the Western Desert areas (Fig. 6). Localized carbonate platforms prevailed in Sinai as well. The eastern margin of the Levant Basin was the site of deeper marine carbonates (slope/basinal) passing to deeper marine clastics toward the West. In the Middle Eocene, further extension occurred along the eastern margin of the Levant Basin. The East Mediterranean basins were limited by deeper marine carbonates (slopes/basin) with carbonate platforms to the South and terrigenous platforms with clastics near the shoreline. Channel incisions and widespread slumping suggest syn-depositional differential relief and possibly tectonic instability (Ghalayini et al., 2014; Hawie et al., 2013). The advance of orogeny continued through the Eocene, with significant narrowing of the seaway between North Arabia and Eurasia (Anatolian block). The Taurides were affected by uplift and mountain building and associated erosion. In the Late Eocene, the marine domain retreated to the North. In Egypt, several delta fans prevailed with fluvio-lacustrine domains extending to the south and lowland erosional plains in the southeast and along the southeastern margin of the

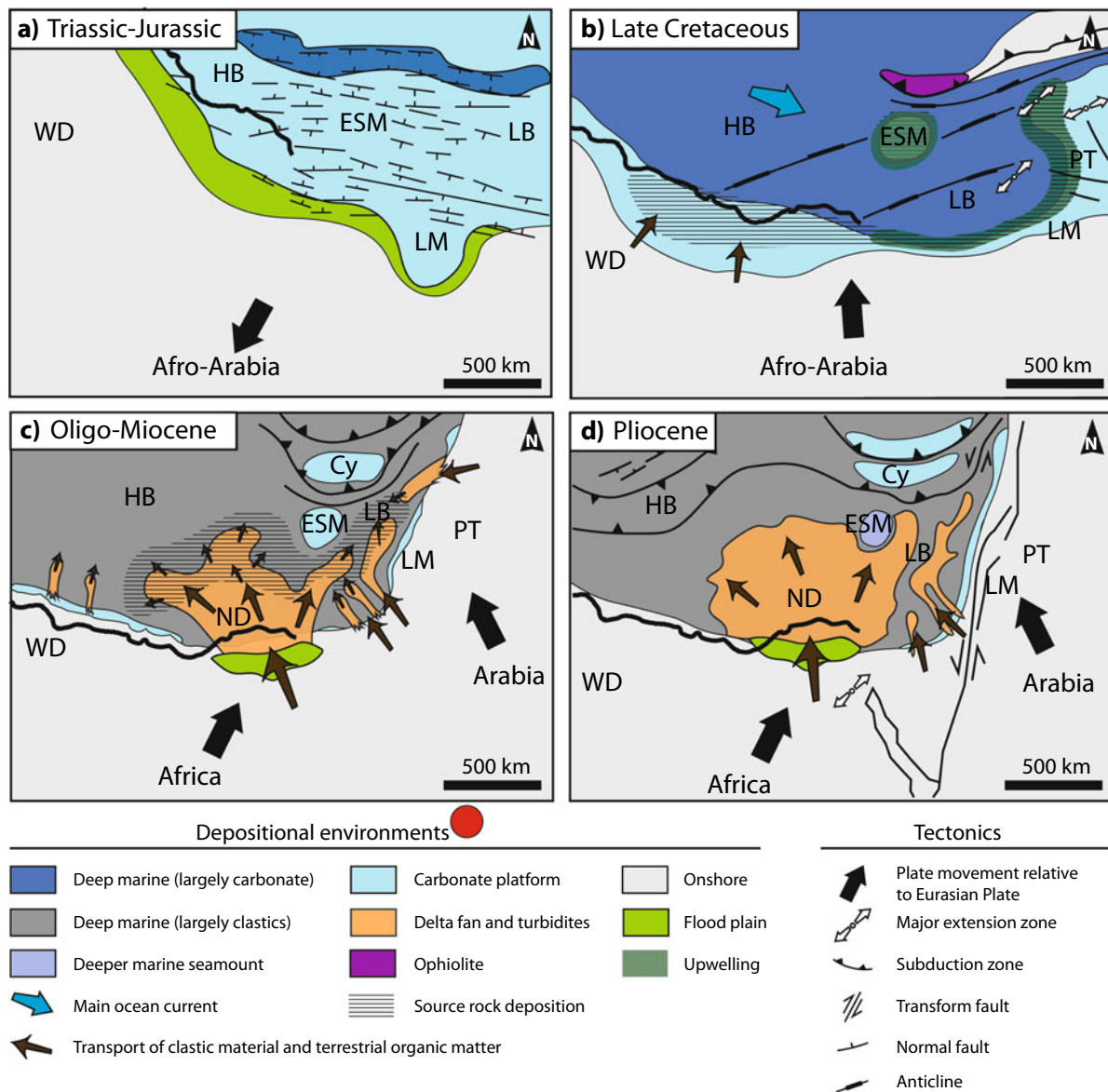


Fig. 5 Regional paleogeographic reconstruction of the East Mediterranean region together with the major tectonic and sedimentary depositional evolutions (maps based on Barrier et al., 2018 and modified after interpretations given in Bou Daher et al., 2015; Hawie et al., 2017 and Grohmann et al., 2018, 2021): **a** Triassic-Jurassic, **b** Late Cretaceous, **c** Oligo-Miocene, and **d** Pliocene. Used abbreviations: WD: Western Desert, HB: Herodotus Basin, ESM: Eratosthenes Seamount, LB: Levant Basin, PT: Palmyra Trough, Cy: Cyprus

Levant Basin, which became separated from the Palmyra Basin. The former contained deep-marine clastics, while the latter remained dominantly filled by carbonates. While Afro-Arabia moved northward, subduction along the northern margin of the Mesogea Ocean advanced closing the remnant seaway and starting a continent-to-continent collision at the northeastern part of the East Mediterranean region.

The main phase of continent-continent collision occurred in the Oligocene, coinciding with the Afar mantle plume activity (Fig. 3c). Afro-Arabia was tilted to the North, conveying considerable amounts of sediment to the Levant

Basin (Fig. 3c), resulting in the deposition of thick clastic Oligo-Miocene intervals in the Levant Basin (Fig. 6 and 7A). The Gilf-, El Bahr-, and Fayum deltas became the main Nubian sediment input sources from Egypt hinterland toward the North. As the thrust belt advanced southward, the Troodos platform was consumed (Papadimitriou et al., 2018a, 2018b). Uplift led to subaerial exposure and mountain ranges, which became sources for sediment influx. In the Early Miocene, continent-to-continent collision along northern Arabia was underway, resulting in major uplifts. The Cyprus Arc System is related to that collision, forming the southernmost thrust belt (Fig. 5c). To its North, a

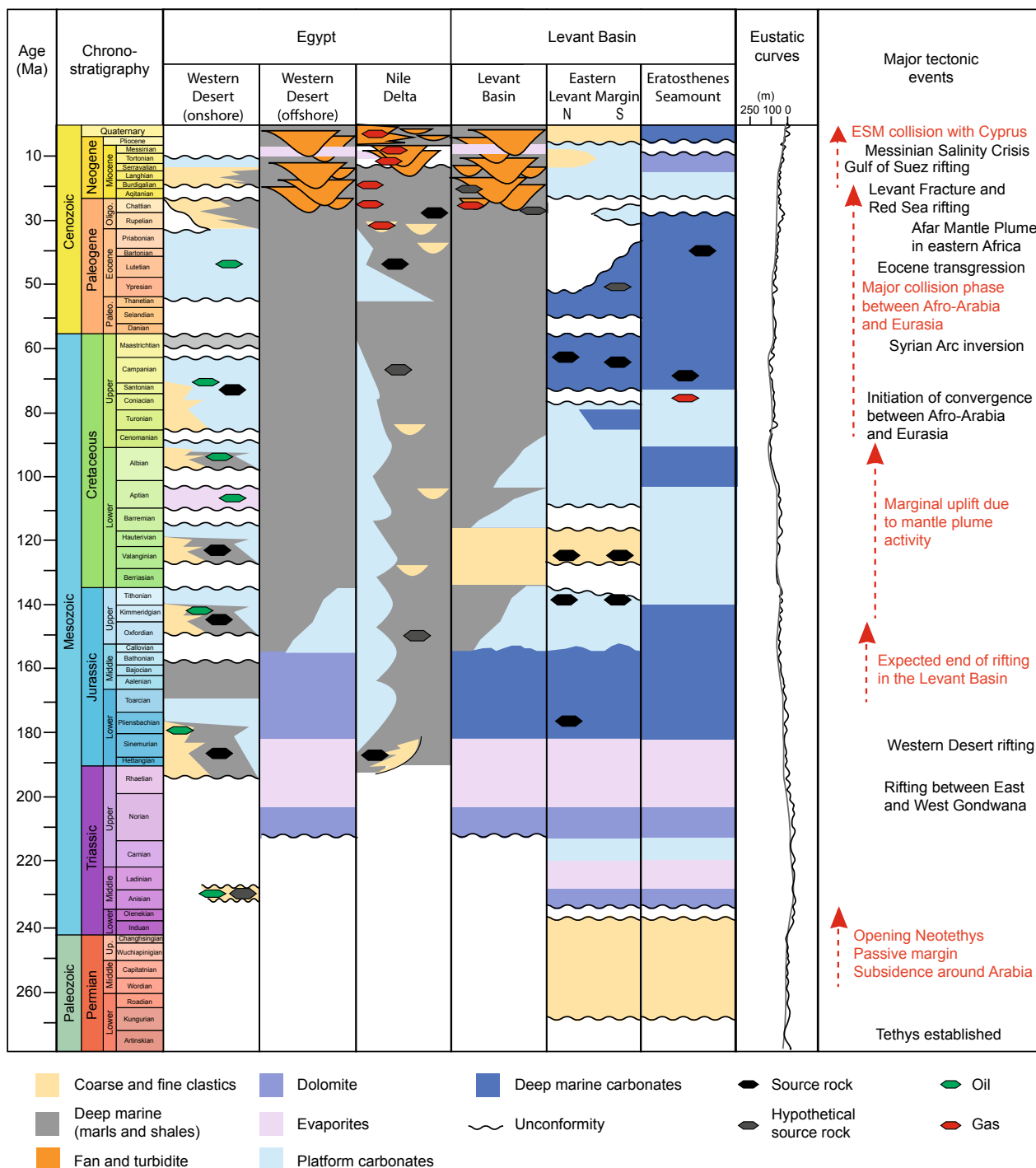


Fig. 6 Simplified lithostratigraphic chart of the East Mediterranean region together with petroleum source rock intervals as well as oil as gas reservoir formations (Figure based on the work by Dolson et al. (2014) and several authors, see text for references)

flexural uplift (forebulge) prevailed (Symeou et al., 2018). To the East, major flexural subsidence (foredeep) marked the northern margin of the Levant Basin. Lattakiya Basin (northern coastal Syria; Fig. 1) was formed and channeled sediments from northern mountain ranges. Sediments also

originated from Anatolia through Homs Gap (northern Syria). The development of a foreland basin south of the Cyprus Arc System is believed to occur on attenuated continental crust, which resulted in significant subsidence (Inati et al., 2018). Sediments from Arabia and Egypt principally

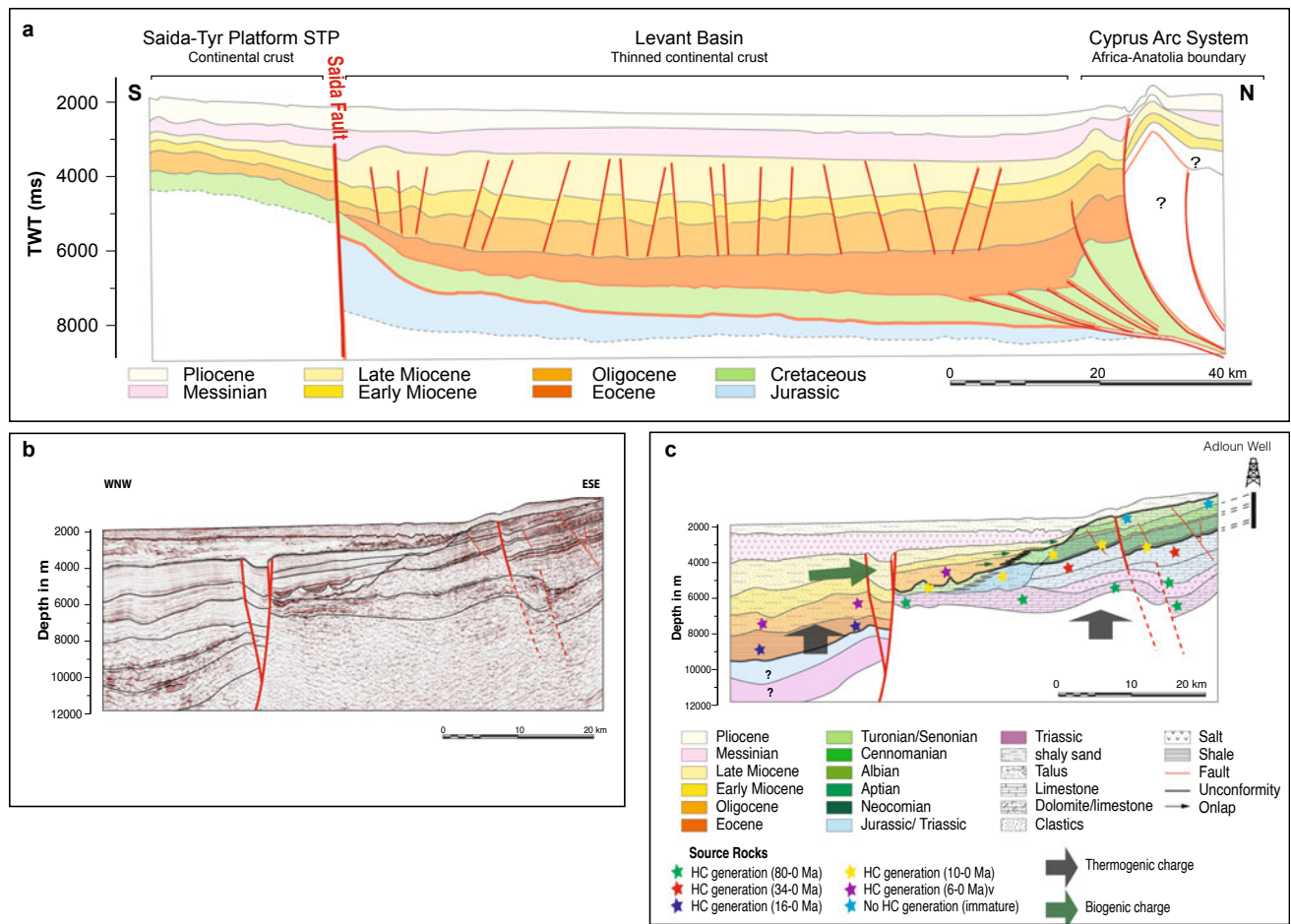


Fig. 7 Key Levant Basin cross-sections, based on seismic data (courtesy of Petroleum Geo-Services, PGS and the Lebanese Petroleum Administration): **a** S-N trending cross-section featuring the Saida-Tyr Platform (STP) part of the Levant Eastern Margin (LEM), the basin stratigraphic and structural characteristics and its northern limit with the Cyprus Arc System; **b** and **c** PSTM 2D Seismic profile and its structural, stratigraphic and petroleum systems interpretations. Locations of the cross-sections are indicated in Fig. 1. This figure is slightly modified from Nader et al. 2018

filled this foreland basin, while its depocenter migrated southward during the Cenozoic (Hawie et al., 2013). The Messinian drawdown may have accentuated the discharge of sediments locally from the hinterland (Fig. 5c and d).

Further collision occurred with major uplift along the eastern and southern margins. The Nile became the major basin feeder in terms of clastic sediments (Fig. 5c), while El Arish and Sinai deltas supplied important amounts of sediments too (Barrier et al., 2018; Dolson et al., 2014). From the North, sediments originated from the uplifted mountainous ranges and the Paleo-Euphrates river system and reached the Mediterranean through the Lattakiya Basin and Nahr el-Kabir (Hawie et al., 2017). In the Pliocene, the Levant Fracture was already in place, completely separating Arabia from Africa and cutting off most of the sediment supply from the Arabian plate toward the Levant Basin (Figs. 3d and 5d). Anatolia went through westward lateral tectonic escape (with

the Cyprus Arc system changing from S-N compressional to strike-slip dextral motion). A lateral slab tear has been documented below Anatolia (around the Antalya Basin). Compression associated with uplift dominated the northern part of the Levant Basin. No more input of sediments from the North was possible—except the Troodos ridge and the Lebanese mountains. The latter had accelerated uplift through transpressional tectonics (Nader, 2014).

An overview of the different stratigraphic units from the ESM, the Levant Margin and Basin over the Nile Delta toward the Western Desert is provided in Fig. 6. Further, Figs. 7, 8, and 9 show representative regional cross-sections—based on seismic interpretation—of the three main regions Levant, Western Desert, and Nile, respectively. The evolution of their depositional environments and their related petroleum systems will be discussed in detail in the following sections.

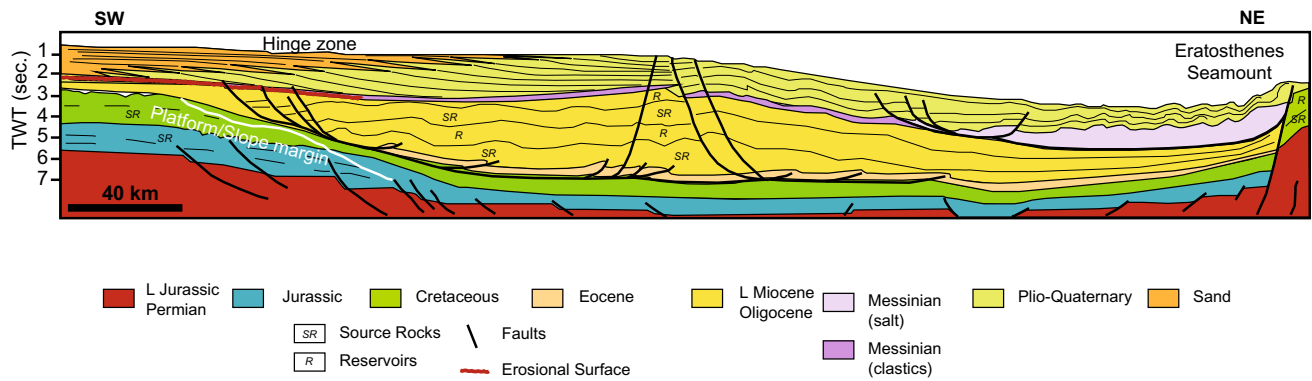


Fig. 8 Cross-section from offshore Western Desert passing by the Nile Delta toward the Eratosthenes Seamount. The Mesozoic platform/slope margin is delineated (white line) and can be also observed on the Eastern Levant Margin (see Fig. 7b) invoking similar configuration for the East Mediterranean margins from the Western Desert to the eastern Levant, prior to the Cenozoic tectonics and basin filling, particularly through the Nile (from Tassy et al., 2015)

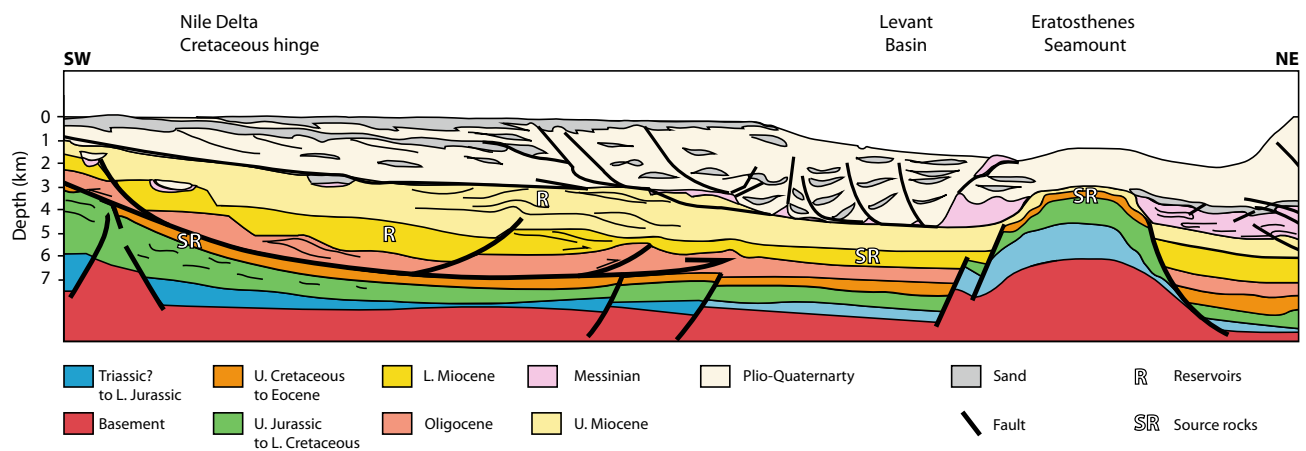


Fig. 9 Cross-section from the Nile Delta to Eratosthenes Seamount and Cyprus showing similar Mesozoic configuration underlying the complex Cenozoic basinal filling architecture governed by major supply of sediments from the Nile, margin instability and gliding tectonics toward the North (modified from Dolson et al., 2001 and Wood, 2015)

3 The Levant Basin

3.1 Depositional Environments

During Early Triassic times, the “Eastern Mediterranean Rift,” extending from Tunisia to Palmyra (central and North Syria), was filled by thick marine deposits, mainly present as dolomite (Nader, 2014; Fig. 6). In the shallow regions along the Eastern Levant Margin (ELM), as well as on top of the Eratosthenes Seamount, which always represented a bathymetric high since its disintegration from the Afro-Arabian margin in the Triassic (e.g., Ghalayini et al., 2014; Montadert et al., 2014; Robertson, 1998; Segev & Rybakov, 2010), sequences of evaporites, dolomites, as well as platform carbonates, developed during the Carnian between 237 and 227 Ma (e.g., Garfunkel & Derin, 1984, Fig. 6). The continuous rifting around the Triassic-Jurassic boundary led

to extensional subsidence of the whole area that prevailed together with the deposition of slope and deeper marine carbonates, promoting the accumulation of organic-rich facies (Fig. 6).

In the Late Jurassic and toward the Early Cretaceous, the open sea retreated with the evolution of rather shallow carbonate platforms along the ELM and in the southern part of the Levant Basin. In contrast, its northern part together with the ESM remained in a rather deep environment (Grohmann et al., 2021, and references therein). In the Early Cretaceous, post-rift thermal subsidence continued in the Levant Basin, which became filled by deeper marine clastics derived from Afro-Arabia (Nader, 2014). Along the ELM, these clastics are bounded by an unconformity to their top and base, the latter one comprising a slightly larger time span toward the South from the end of Kimmeridgian (152 Ma) to Valangian (140 Ma). The ESM and the Troodos platform, at that time, shrank but remained in a rather shallow environment

with the deposition of platform carbonates. In the late Aptian, the global settings remained the same with the development of a belt of carbonate platforms on the margins of the Levant Basin which was filled with slope–basinal and deeper marine clastics. Terrigenous clastic platforms also prevailed toward the onshore areas (Fig. 6). Active extension and thus tectonic subsidence occurred again in the Palmyra and Abu El Gharadig basins (Fig. 5c; Barrier et al., 2018), while the remaining area underwent passive thermal subsidence. The Mardin (Turkey) and Rutbah (Iraq) paleohighs became the major providers of continental sediments found mainly in the northern part of the Levant Basin (Nader, 2014).

The Cenomanian is associated with a major sea-level rise and transgression, which affected the eastern Mediterranean basins with the development of large carbonate platforms covering the entire Mardin and parts of the Rutbah paleohighs (Nader, 2014). The Levant Basin and the Palmyra Basin in the northern part of the ELM hosted deeper marine carbonates, whereas the southern ELM as well as the ESM developed shallower carbonate buildups (Fig. 5b). The transition toward these general shallower conditions is marked by the regional top Turonian (also referred to as Base Senonian) Unconformity along the ELM (Bou Daher et al., 2016).

The closure of the Mesogea Ocean in the Late Cretaceous, just before the collision of the Afro-Arabian and Eurasian Plates, was accompanied by a general sea-level rise together with post-rift subsidence. This resulted in the drowning of the whole Levant region leading to more deep-marine, pelagic carbonate sedimentation (e.g., Gardosh et al., 2008; Nader, 2014). Major inversion began especially on the margins of the Levant Basin (e.g., Syrian Arc structures, Cyprus Arc). At the same time, a large-scale upwelling system affected the whole Levant region forcing the deposition of Upper Cretaceous source rocks along the ELM (Almogi-Labin et al., 1993; Bou Daher et al., 2014, 2015), the ESM (Grohmann et al., 2018, Fig. 5b), and the Western Desert Basin (Ghassal et al., 2018). Similar upwelling processes might have occurred in the Nile Delta, southern Levant Basin, and Eratosthenes in the Eocene, resulting in the deposition of important source rocks.

In the Paleocene, the overall settings did not change considerably. The Sinai region became the domain of a terrigenous platform with deposition of clastics, while the anticlinal structures became uplifted and subaerially exposed—some surrounded by carbonates (Figs. 7b, c). The Azraq and Euphrate grabens witnessed passive thermal subsidence. Together with the Palmyra and Levant basins, these grabens became sites of sedimentation of deep-marine clastics, probably derived from the highlands (Baer Bassit, Mardin, Rutbah, and Sinai).

The uplift and tilting of the African and Arabian northern margins due to plate collision (with Eurasia) in the

Oligocene led to considerable denudation of the subaerially exposed hinterland and the rapid filling of the basins with siliciclastics (Gardosh et al., 2008; Nader, 2014; Figs. 5c and 6). The pathways for this sediment transfer were numerous ancient rivers and submarine canyons along the eastern and southern margins of the Levant Basin (Hawie et al., 2017). Today, the Nile River is the only major sediment source for the Levant Basin (Fig. 5d).

3.2 Petroleum Systems

During several periods, depositional conditions were suitable for the formation of petroleum source rocks of different qualities, which occur either throughout the whole East Mediterranean realm or rather localized in certain smaller regions. Based on Rock-Eval® data, Fig. 10 shows a comprehensive overview of the major source rocks of the East Mediterranean region.

Terrigenous clastic intervals of Early Jurassic age are among the oldest proven source rocks that can be found in the East Mediterranean. Such intervals are found in the southern Levant Margin (Figs. 5a and 6; Gardosh et al., 2008). Triassic to Mid-Jurassic organic-rich limestones are believed to provide potential source rocks with mixed marine-terrestrial Type II–III kerogen in Lebanon, based on regional correlation with the nearby Palmyra Basin (Ghalayini et al., 2018). El Hajj et al. (2019) investigated dysodiles and organic-rich facies from the Upper Jurassic and the Lower Cretaceous intervals surface exposed in Lebanon (ELM), revealing a very good to excellent source rock potential (Total Organic Carbon (TOC) contents 13–19 wt.%; hydrogen index (HI): up to 649 mg HC/g TOC; T_{\max} : 424–428 °C; vitrinite reflectance (VR) < 0.5%). During the Late Cretaceous sea-level rise, deposition of deeper marine source rocks took place throughout the East Mediterranean region (Bou Daher et al., 2014). The source rocks along the Levant Margin are related to a large-scale upwelling system (Almogi-Labin et al., 1993; Bou Daher et al., 2014 and 2015; Grohmann et al., 2018 and 2021; Fig. 5b). Along the Levant Margin, such source rocks can be found as fine-grained limestone intervals of Turonian to lower Maastrichtian age, showing good source rock qualities with TOC contents up to 11 wt.% in Lebanon (Bou Daher et al., 2014 and 2015) or as phosphatic shales and limestones of Maastrichtian to Paleocene age with even higher TOC contents up to 22 wt.% in Israel or Jordan (e.g., Almogi-Labin, 1993; Abed et al., 2005; Abu-Mahfouz et al., 2020). The thickness of these intervals can reach up to 200 m in Lebanon (Bou Daher et al., 2014) and Israel (Almogi-Labin et al., 1993), and up to 400 m in N-NE Jordan (Abed et al., 2005). As typical for upwelling systems, these source rocks are rather restricted

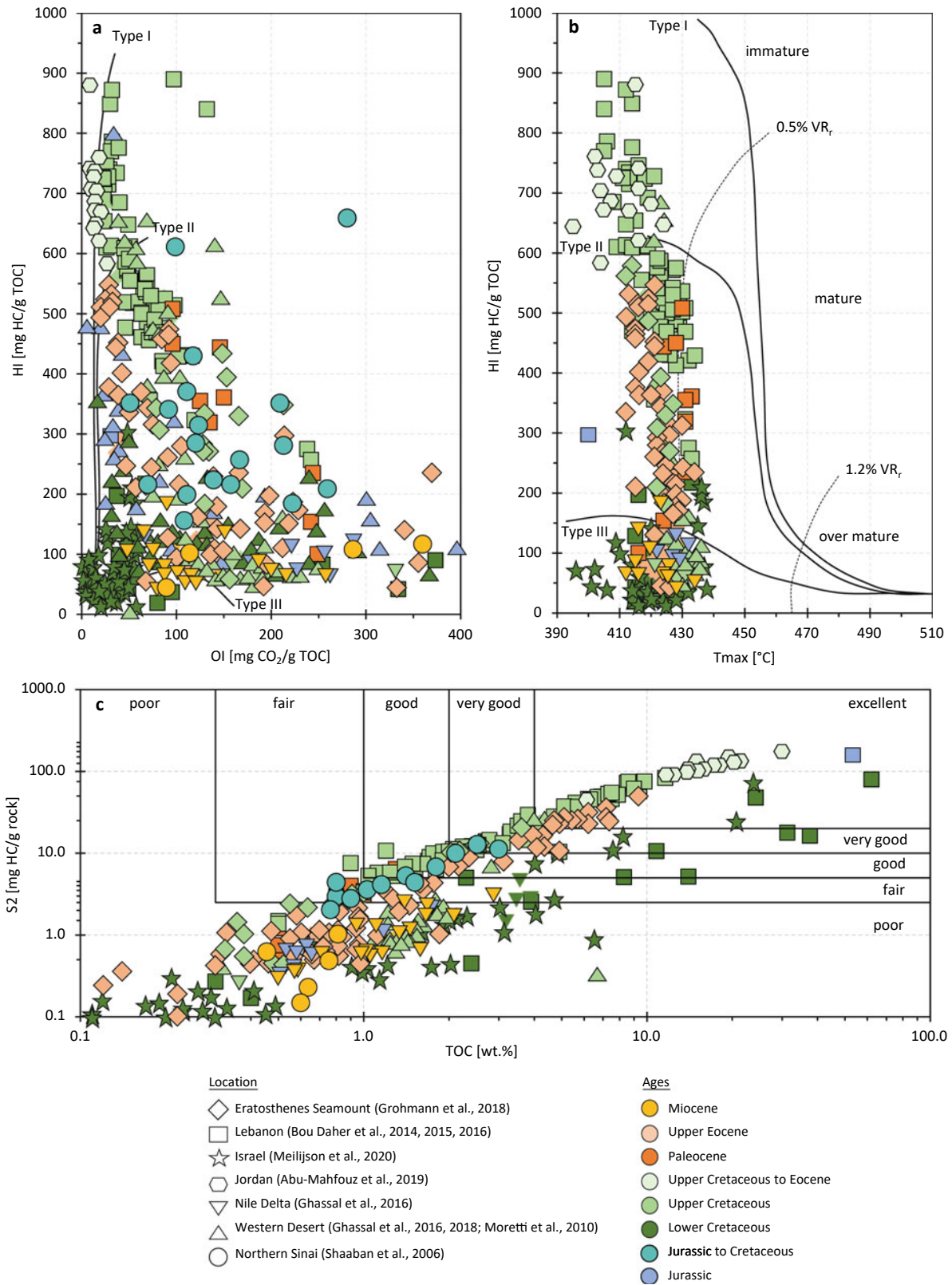


Fig. 10 A selection of various source rocks in the Eastern Mediterranean realm, based on Rock-Eval Pyrolysis data: **a** shows the kerogen classification based on hydrogen index (HI) and oxygen index (OI); **b** correlation of HI and the thermal maturity parameter Tmax; and **c** source rock quality classification based on the total organic carbon (TOC) content as well as the hydrocarbon generation potential (S₂)

to the paleo-shelf and upper margin regions, and it is unlikely that they extend into the deepest part of the basin. Further, all these intervals contain partly organic sulfur-rich Type II-S kerogen with high HI values generally ranging between 400 and 800 mg HC/g TOC classifying them good to excellent source rocks (Abed et al., 2005; Bou Daher et al., 2014 and 2015); Fig. 10a). Such Type II-S kerogen is expected to start generating petroleum at lower temperatures than a sulfur-lean kerogen type would do. Similar source rock intervals of Late Cretaceous and of Eocene age are found on the ESM, which are believed to be related to either the same or to similar upwelling processes in the area (Grohmann et al., 2018). Information on these source rocks was based on the interpretation of geochemical data from a few, mainly onshore locations. In a recent study by Grohmann et al. (2021), the depositional processes of these source rocks were numerically modeled. The results of this study support the geochemical interpretations and provide a numerical model of the spatiotemporal source rock distribution for petroleum system modeling, changing important source rock parameters from a user-defined choice to a model-based input. At the basin-marginal locations, where all studied samples originate from, these source rock sections are commonly thermally immature with VR values < 0.4% onshore Lebanon (Bou Daher et al., 2014, 2015) and < 0.3% in Jordan (Abed et al., 2005) and along the ESM (Grohmann et al., 2018). The integration of the numerical source rock models and petroleum system modeling increases the probability for finding thermogenic Late Cretaceous petroleum systems in certain offshore areas, such as offshore northern Lebanon or South and East of the ESM (Grohmann et al., 2021, Fig. 11).

Considerable amounts of terrestrial organic matter were most likely transported along with the clastic material that was shed into the Levant Basin upon the separation of the Afro-Arabian plate in the Oligo-Miocene and the strong uplift of the Levant margins (Hawie et al., 2013, 2017; Inati et al., 2018). In contrast to the upwelling-related Cretaceous source rocks, which are probably rather restricted to the shelf regions, the Oligo-Miocene source rocks might be much more widely distributed and can even occur in much greater thickness. The numerical simulations by Grohmann et al. (2021), for example, have shown that terrestrial organic matter might be accumulated to different extents in all the clastic fan and turbidite deposits in the Levant Basin. While TOC contents are generally low (<1 wt.%), cumulative thicknesses of moderately organic-rich rocks might reach more than 1000 m. All the Oligo-Miocene source rocks are mainly immature (VR < 0.5%), based on gas

shows in some wells rather close to the basin's margin (e.g., Feinstein et al., 2002). Within the deeper basin, however, thermal maturities might reach the early onset of the thermogenic oil window (Grohmann et al., 2021). Despite this, the high sedimentation rates during these periods, together with rather low geothermal gradients, provided perfect conditions for microbial gas generation (Schneider et al., 2016). Thus, these source rocks might be the primary source of microbial gas, which is present in almost all accumulations within the area, discovered during the last decades. Although gas makes up by far the most significant contribution in all these discoveries, some indications of a mixed oil-gas system are also available (e.g., Karish field; Ducros & Nader, 2020).

The highest generation of microbial gas can be expected below temperatures of about 45 °C (e.g., Katayama et al., 2022). Even at low geothermal gradients, such temperatures occur at depths, where compaction of the organic matter containing shale and marl deposits is still rather low; these rocks cannot act as proper seals yet. Thus, it can be expected that only minor amounts of the total generated gas were trapped (e.g., Barabasch et al., 2019). Next to the many, rather moderately filled clastic reservoirs, recently, shallow-marine carbonate reservoirs with rudist biofacies of Cretaceous age (e.g., Zohr field) were discovered hosting gas accumulations. Assuming that most generated gas was lost due to the lack of proper seals above the clastic reservoirs in the basin during the main generation phase, the entrapment within adjacent carbonate reservoirs seems reasonable. This assumption is also supported by statistics, where several rather small to moderate (clastic) reservoirs (1–16 Tcf) compete with one large (30 Tcf, Zohr) (and few minor) carbonate ones. Thus, the focus on carbonate-dominated regions adjacent to the main delta and turbidite deposits both along the Levant Margin as well as in the Western Desert might increase the chance for more and significant discoveries. The ultimate cap-rock in the East Mediterranean region, offshore (Levant and Herodotus basins), is the up to 2 km thick Messinian salt (or evaporite) interval. However, most clastic reservoirs appear to be sealed by the surrounding and overlying fine-grained siliciclastic facies (marls and clays). The Upper Cretaceous, rudist-carbonate reservoirs are either sealed by the overlying marl (a result of platform drowning in the latest Cretaceous) or ultimately by the Messinian evaporites. In addition, several Mesozoic and Cenozoic intervals of evaporites, marls, and shales may act as excellent sealing units for potential reservoirs (Fig. 6).

The turbidite systems may create their own sealing and trapping mechanisms, which, however, as described above, might not have been properly working in the early microbial as

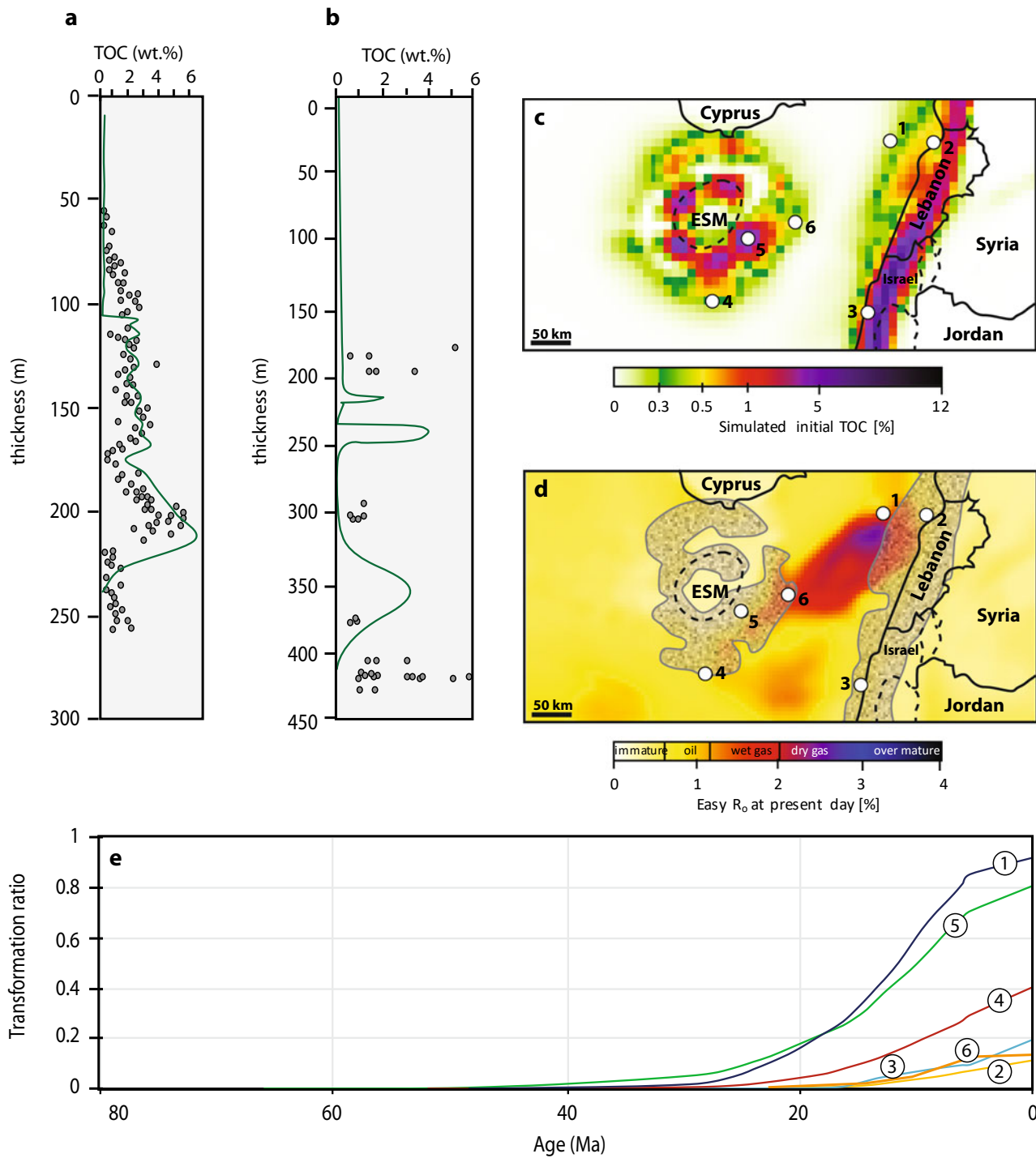


Fig. 11 Combined results of a simulated source rock distribution model (obtained from stratigraphic forward modeling) incorporated in a numerical petroleum system model: **a** and **b** comparison of measured and simulated total organic carbon (TOC) contents in the Upper Cretaceous source rocks onshore Lebanon and offshore Cyprus, respectively; **c** map showing the distribution of TOC contents obtained from the stratigraphic forward model incorporated as input parameter to the petroleum system model; **d** map showing the overlap of source rocks and thermal maturity windows; and **e** the evolution of Upper Cretaceous source rock transformation ratio for 5 selected locations with the highest likelihood for thermogenic hydrocarbon generation. Figure modified from Grohmann et al. (2021)

generation stages due to low compaction. Nevertheless, trapping is partly a result of paleoclimatic conditions and the evolution of source-to-sink sediment transfer. The tectonic evolution resulted as well in four-way closure features, trapping considerable hydrocarbon accumulations (Ghalayini et al., 2018; Symeou et al., 2018). The most significant tectonic event capable of such trapping is the inversion that resulted from convergence and ultimate collision of the Afro-Arabian and Eurasian plates, also termed as Syrian Arc deformations. This phase was followed by the breakup of Arabia and Africa and the evolution of the Levant Fracture systems, which led to transpression and major strike-slip faults and associated structures. The latter also shows excellent four-way closures on seismic data (Ghalayini et al., 2014).

4 The Northwestern Desert

4.1 Depositional Environments

The Western Desert of Egypt covers an area of approximately 700,000 km², which represents about two thirds of the total area of the country. The northern part of this area borders the Mediterranean Sea–West of the Nile Delta, including a continental shelf passing northward into the deep offshore Herodotus Basin (Fig. 1), where the sedimentary fill is likely to exceed 13,000 m (Schlumberger, 1984). Structurally, the Northwestern Desert formed a part of the southern margin of the Mesogea Ocean (Figs. 3 and 5) and was a tectonically active from the Paleozoic to the Early Cenozoic, when basin reconfigurations occurred (Fig. 8; Hantar, 1990; Said, 1962).

The sedimentary column of the Northwestern Desert comprises strata straddling from Cambrian-Ordovician to Quaternary, reaching a thickness of more than 10,600 m in the Abu El Gharadig Basin (Schlumberger, 1995). Within this section, four major sedimentary cycles occurred, with maximum, southward transgression in Carboniferous, Upper Jurassic, Middle and Late Cretaceous, middle Miocene and Pliocene times. However, maximum northward transgression phases occurred during the Permo-Triassic and Early Jurassic and continued in the Early Cretaceous, and again in the Late Eocene to Oligocene, with a final phase in the Late Miocene (Schlumberger, 1984; Fig. 6).

Onshore Western Desert, most of the known stratigraphic units alternate between carbonates and clastics with a basinward succession (shallow carbonate to deeper clastic turbidites; Fig. 6). This is probably due to both tectonics and sea-level fluctuations, as the onshore part of the Western Desert is located on the unstable shelf (Said, 1962) at the margin with the Herodotus Basin. The offshore Western Desert is characterized by Triassic–Lower/Middle Jurassic dolomite and evaporite sequences, overlain by thick

deep-marine clastics of Late Jurassic to Miocene age. Wood (2015) and Tassy et al. (2015) used offshore–onshore seismic and well data to illustrate the Jurassic and Cretaceous stratigraphic architecture and structural configuration across the Egyptian margin. Their results demonstrate a striking similarity between the Levant and Egyptian margins, with Jurassic carbonate platforms prograding toward the East Mediterranean basins and the overlying aggrading and retrograding Cretaceous carbonate platforms (Figs. 7 and 8). Tassy et al. (2015) further proposed that the varying Cretaceous shelf edge slope morphologies (abrupt to distally steepen) control the deposition of shallow-marine sediments and their export to the deeper basin. Similar slope morphologies have been observed on the Eastern Levant Margin (ELM) and the Eratosthenes Seamount (ESM), highlighting basin fill onlaps (Hawie et al., 2013; Papadimitriou et al., 2018a, 2018b). The basin sediment extension offshore the Western Desert is characterized by thick mass transport deposits (Tassy et al., 2015). Wood (2015) consider the basal Abu Roash shales (Late Cenomanian age) a detachment surface that was active during the margin uplift and steepening of the slope coinciding with the “Syrian Arc” inversions (Fig. 8). Turbidite systems are believed to occur in the Oligo-Miocene intervals similarly to those observed in the Levant Basin (Dolson et al., 2014; Nader et al., 2018; Figs. 5c and 6) and could be very attractive for future exploration.

4.2 Petroleum Systems

The Khatatba and Ras Qattara formations that are exposed in the Shushan Basin in the Western Desert include Early Jurassic source rocks of a mixed Type II-III, rather gas prone kerogen type with low HI values of 100–260 mg HC/g TOC; however, very high TOC contents of up to about 50 wt.% can be reached (Shalaby et al., 2011). With thermal maturities between 0.5 up to 3.5% VR, they cover the whole range from early oil to late gas window maturities, which were reached between the Late Cretaceous and Tertiary (Shalaby et al., 2011). Therefore, most of the hydrocarbon generation potential has already been transformed, and these source rocks are believed to be responsible for thermogenic oil and gas generation in the Western Desert and the Nile Delta (e.g., Shaaban et al., 2006; Wigger & Bailey, 1997). Similar source rocks containing mainly terrestrial organic matter can be also found in the Upper Jurassic as well as in the Lower Cretaceous sections of the Northwestern Desert. TOC contents of these intervals are rather low with maximum values of about 2.4–3.1 wt.%, while HI values are generally lower than 240 mg HC/g TOC (Fig. 10), emphasizing a strong contribution of terrestrial organic matter (El Atfy et al., 2019).

The Late Cretaceous source rocks found in the Western Desert are thought to be the result of increased bio-productivity caused by increased nutrient input via deposition of detrital material (Ghassal et al., 2018; Fig. 5b), in contrast to the source rocks along the ELM, which have been related to a large-scale upwelling system that affected the whole Levant Margin (see above).

The Triassic clastics in the onshore Western Desert host mainly oil accumulations (Fig. 6). The Lower and Upper Jurassic shallow-marine coarse clastics, in the same region, also host oil. The onshore Western Desert basins also include evaporite (and dolomite) oil reservoirs (Albian) and shallow platform carbonate oil reservoirs (Upper Cretaceous and Eocene). The common Cretaceous reservoirs in the Western Desert are within the Bahariya and Abu Roash formations (Ghassal et al., 2018). Previous interpretation of seismic data (onshore and offshore; e.g., Tassy et al., 2015) and newly acquired data suggest a continuity of the known onshore reservoirs (and generally the related petroleum systems) to the proximal shelf area. Further into the basin, the platform slopes may also host carbonate buildups with potential reservoirs as also observed on the eastern margins of the Levant Basin (Ghalayini et al., 2018). In the distal offshore, the Oligo-Miocene turbidite systems may as well provide potential reservoirs, especially for microbial gas accumulation. The turbidite systems may also provide trapping layers with finer sediments, which are ultimately sealed with the Pliocene shales and Messinian evaporites.

5 The Nile Delta

5.1 Depositional Environments

The Nile Delta is located between the Western Desert and the Levant Basin along the northern margin of the African Plate (Morgan, 1990; Fig. 1). The Nile Delta Basin was influenced by several tectonic events since the beginning of the Mesozoic (Tassy et al., 2015; Zaghoul et al., 1999a). The oldest known stratigraphic record in the Nile Delta Basin is assigned to the Middle Triassic; however, due to the lack of outcrop or well penetration in the Nile Delta Basin, the stratigraphy can only be inferred by regional paleogeographic interpretations. In the southern Nile Delta Basin, the Triassic sedimentary sequence was interpreted as a tidal flat deposit by Kerdany and Cherif (1990), whereas Guiraud and Bosworth (1999) suggest a carbonate platform depositional environment in the South and deep-marine environment in the North. Further opening of the Neo-Tethys in the Early Jurassic caused the expansion of a wide Jurassic-Cretaceous carbonate platform from the Western Desert to Sinai (Parisot et al., 1996; Tassy et al., 2015; Figs. 5a, b). The oldest sedimentary rocks penetrated are indeed these shallow-marine Early Jurassic

carbonates (Ghassal et al., 2016; Fig. 6). Various depositional environments were inferred for the better known Lower Cretaceous that could range from lagoonal to open shelf (Harms & Wray, 1990; Zaghoul et al., 1999b). The depositional environment changed from open marine in the Aptian to alternating marine and alluvial deposits in the Albian (Figs. 5b and 6) and again to open marine during the Cenomanian, lasting until the end of the Cretaceous (Guiraud & Bosworth, 1999).

During the Late Cretaceous–Early Eocene period, regional sedimentation was influenced by the Syrian Arc inversions, resulting in E-NE-trending structures occurring contemporaneously with the closure of the Tethys (Harms & Wray, 1990; Zaghoul et al., 1999a). The Syrian Arc event was responsible for regional erosion; thus, these rocks are not widely preserved (Ghassal et al., 2016). This is a plausible reason for limited penetration of the Upper Cretaceous to Eocene succession in most Nile Delta wells (Harms & Wray, 1990).

The opening of the Gulf of Suez and the Red Sea during the Chattian-Aquitainian produced dominant extensional NW-trending faults resulting as the African and the Arabian plates diverged (e.g., Bosworth, 1994; Patton et al., 1994). The rift reactivated Syrian Arc structures and developed coastal faults that enhanced the gravitational sliding of the Oligocene shales over the pre-Oligocene carbonate rocks in the hinge zone along with the extrusion of basaltic flows (Hussein & Abd-Allah, 2001). It triggered the formation of highs in southern parts and lows to the North of the delta area. Few wells penetrated the Oligocene, showing various lithologies from upper to middle slope deposits, open marine deposits, fluvial clastics, and basalt (Harms & Wray, 1990). The Oligocene deposits were derived from the South through a canyon (up to 300 m depth) with about 12 entry points, whereas the southern Nile Delta was subaerially exposed (Dolson et al., 2001) following an eustatic sea-level fall (Guiraud & Bosworth, 1999). Fluvio-deltaic sedimentation prevailed toward the Nile Delta, while shallow-marine and deepwater shales were deposited beyond the hinge zone (Dolson et al., 2001). The hinge zone created a paleo-topography in which the delta sediments were accumulated (Tassy et al., 2015). It is typified by a significant increase in dip rates north of seismically mappable Cretaceous-Eocene horizons and associated WNW–ESE-trending basement fault (Sarhan & Hemdan, 1994). The early Oligocene shoreline shifted rapidly northward, where fluvial and shallow-marine sandstone facies were deposited during the maximum highstand (Dolson et al., 2001). The tectonically induced lowstand continued during the upper Oligocene and is characterized by upper- to mid-fan deposits overlain by outer-fan clastics (El-Heiny & Enani, 1996). In addition, reactivation of the older listric normal faults (of Cretaceous-Eocene age) led to throws

sometimes exceeding 400 m and gravitational instability affecting the Oligo-Miocene strata, which probably generated fluid leakage to the seafloor (Tassy et al., 2015). Listric normal faults during the latest Cretaceous-Eocene period affected the whole Tertiary basinal argillaceous strata along the hinge zone causing spatial extensions (Fig. 9). An uplift, associated with the Gulf of Suez rift, took place during the Miocene and detrital clastic sedimentation prevailed. The Miocene sediments were mainly controlled by structures related to the opening of the Red Sea and Gulf of Suez (Zaghloul et al., 1999b). The sea level rose more prominently during the Middle Miocene. Thus, the thicknesses of the Middle Miocene sediments are greater than the Lower Miocene ones (Fig. 9; Harms & Wray, 1990; Zaghloul et al., 1999b). Throughout the middle-late Miocene, a prevalent uplift interrupted marine sedimentation conditions that prevailed during the Early Miocene (Farouk et al., 2014). A rapid sea-level fall occurred in the East Mediterranean region, affecting particularly the Nile Delta Basin (bounded by reactivated listric faults) and resulted in the development of a major unconformity (Hanafy et al., 2016). Regression occurred in the Late Miocene, especially during the Messinian salinity crisis (Guiraud & Bosworth, 1999). This is expressed by an abrupt sea-level fall resulting in fluvial incision on the delta plain and the transport of a large volume of deltaic sediments outboard (Dolson et al., 2001). Deposits of this time are nearly absent in the southern Nile Delta Basin, while sandy shale lithologies covered the eastern part of the basin (Zaghloul et al., 1999b). This also left a wide erosional surface and Grand Canyon scale incised valleys (Barber, 1981). During the Pliocene, marine transgression occurred and resulted in deposition of marine sediments that filled the Messinian incised valleys (Dolson et al., 2001; Ross & Uchupi, 1977). Then, fluvial and fluviomarine deposits prevailed (Zaghloul et al., 1999a). The Pleistocene is mainly composed of fluvial sandy facies (Zaghloul et al., 1999b).

5.2 Petroleum Systems

The oldest proven East Mediterranean source rocks of Early Jurassic age (found on the northern margins of the African and Arabian plates) are believed to be buried deeply below the Nile Delta (e.g., Shaaban et al., 2006). These source rocks, as mentioned above, comprise mainly a mixed Type II-III, rather gas prone kerogen (e.g., Shaaban et al., 2006; Wigger & Bailey, 1997).

With the separation of the Afro-Arabian plate in the Oligo-Miocene and the strong uplift of the Levant area, the pelagic, carbonate-dominated depositional environment changed and huge amounts of clastic materials were shed into the Levant Basin coming from both the Nile Delta as

well as from the Eastern Levant Margin (e.g., Hawie et al., 2013 and 2014; Inati et al., 2018; Fig. 5c). It is also likely that relatively high amounts of terrestrial organic matter were transported along with the clastic material. This fact is reflected in the type of source rocks, which were deposited during this time. Whereas Cretaceous and Eocene source rocks are mainly composed of Type II and Type II-S marine-derived kerogen (Fig. 10), the Oligo-Miocene sections are rather characterized by a mixed Type II-III kerogen. Consequently, source rock qualities are generally lower, with HI values often clearly below 200 mg HC/g TOC, as for example, in the Nile Delta (e.g., Ghassal et al., 2016; Fig. 10). Further, the idea of low TOC and low quality, but thick clastic source rocks, is supported by observations by Rasoul and Khaled (2019), who report thick (>1000 m) intervals of Oligocene sand and siltstones with low but rather homogenous concentrations of terrestrial organic matter in the Nile Delta.

Due to the limited penetrations, the pre-Paleogene reservoirs are poorly understood in the Nile Delta Basin. Most of the known reservoirs in the Nile Delta are Cenozoic in age (Oligocene, Miocene, and Pliocene/Quaternary) and primarily host thermogenic and microbial gas (e.g., Monir & Shenkar, 2016). The Nile Oligo-Miocene reservoirs are made up of deepwater slope channels as well as fluvial channels, while the Messinian and younger reservoirs are related to Nile turbidite and fan delta facies (Cross et al., 2009; Keong et al., 2014; Pigott and Abdel Fattah, 2014). The traps are mainly rotated-fault blocks, 4-way dip closures, and anticlines (Monir & Shenkar, 2016). The Nile Delta lithologies are very heterogeneous, including siliciclastics of variable grain sizes as well as argillaceous carbonates (Cross et al., 2009; Nabaway et al., 2018).

6 Discussion

The current geodynamic understanding of the East Mediterranean region comprises the Tethyan oceanic evolution, the associated lithospheric mantle upwelling within the Afro-Arabian plate and subduction slab pull and rupture at its boundary with Anatolia, the opening of the Red Sea and the establishment of the Levant Fracture System, and finally the westward escape tectonism of Anatolia. The Mediterranean margin of Egypt has been affected by the above geodynamic events whose imprints are recorded in the Herodotus and Levant basins (as well as their continental margins) and the Nile Delta Basin. In this chapter, the geodynamic driving forces, tectono-stratigraphic features, depositional environments and petroleum systems of the Levant Basin (and its ELM and ESM), the Western Desert (passing northward to the Herodotus Basin), and the Nile Delta are presented. The similarities along the East

Mediterranean southern and eastern margins are demonstrated since these areas were part of the Mesogea Ocean southern passive margin and underwent the same geodynamic history since the Paleozoic (break up of Pangea) until the Cenozoic (separation of Africa and Arabia). Therefore, the onshore–offshore extension that is relatively well known across the Levant Basin can provide clues for the new exploration frontier across the Northwestern Desert margin and the Herodotus Basin. Figure 6 illustrates in a simplified form these similarities in terms of lithostratigraphic successions, potential source rocks, and reservoir rocks. For example, the Lower Jurassic, Upper Jurassic/basal Cretaceous, Upper Cretaceous source rocks are equally found in the onshore ELM and the Western Desert.

Upon the convergence of the African and Arabian Plates with the Eurasian blocks, the first phases of inversion took place along the East Mediterranean margin, resulting in the “Syrian Arc” structures. Changes in the orientations of these structures and further deformation associated to the Levant Fracture System (Nader, 2014) result in different structural patterns along the ELM compared to the Egyptian margins as well as in distinct structural trapping mechanisms. The evolution of the Levant Fracture, leading to the complete separation of Arabia from Africa and cutting off all major eastern sediment pathways to the Mediterranean basins (including a northern Paleo-Euphrates source), left the Nile as the main sediment feeder to the East Mediterranean basins. The huge amount of sediments channeled through the Nile included complete petroleum systems with source rocks prone for microbial gas generation, turbidite sand reservoirs, and shale seals. The entire Nile Delta Basin system exists today, and sediments can be traced from source to sink. This contrasts with the older, Oligo-Miocene sediment pathways from the hinterland to the Levant and Herodotus basins, which are more difficult to define.

Based on the proposed correlation between the Eastern Levant Margin and the northern Western Desert, the potential of the Upper Cretaceous source rocks needs to be revisited. First, the onshore–offshore extension of these source rocks, where thermal maturities are expected to be high enough for thermogenic hydrocarbon generation, has been investigated (Ghassal et al., 2018; Grohmann et al., 2021). Two conceptual depositional environment models are proposed for the Late Cretaceous source rocks found in the Western Desert and the Levant Basin. While in the former area, the organic-rich intervals are thought to result from increased bio-productivity and nutrient input through deposition of detrital material sourced from the immediate hinterland (Ghassal et al., 2018); in the latter area, an upwelling model has been proposed limiting the organic-rich interval to a specific zone along the slope (Bou Daher et al., 2016). Without available well data in the offshore, a major uncertainty remains for any analysis of petroleum systems

confirming or rejecting any proposed concept. Recently, numerical simulations of depositional pattern over time, including source rock deposition, combined with basin and petroleum system modeling (Bou Daher et al., 2016; Grohmann et al., 2021), confirmed the upwelling model pertaining to the Levant Basin and suggested the two regions, where the source rocks and favorable thermal maturities co-exist. They are located about 50 km offshore northern Lebanon as well as about 50–100 km southeast of the ESM, where respective intervals might be present and lie within the oil-window thermal maturity since the Eocene. The latter region, southeast of the ESM, is close to the Zohr discovery which is reported to be charged by microbial gas. Hence, if more reservoir structures could be identified along the southern flank of the ESM, both thermogenic and microbially charged reservoirs should be taken into consideration.

Additionally, the occurrence of such an upwelling system during the Late Cretaceous along the eastern margin of the Levant Basin was prompted by a number of paleogeographic and paleoclimatic factors that have been more or less unchanged throughout the Late Cenomanian to Late Eocene period (Dercourt et al., 2000). Thus, during the Late Cenomanian to Late Eocene upwelling period in the East Mediterranean, petroleum source rocks were deposited on the shelf at times of high sea level, e.g., Campanian–Maastrichtian. At times of low sea level, some organic matter rich deposits were probably deposited along the slope with varying quantity and quality due to a shift of locations of high primary bio-productivity and changes of their lateral extent.

Numerical modeling, if coupled with suitable analog studies (Grohmann et al., 2021), may overcome the issues pertaining to the lack of control and calibration wells. In addition, the relatively recent development of seismic data processing and interpretation techniques appears to be attractive for revealing possible source rocks (Liu et al., 2007). Finally, regional correlation and robust structural geological interpretations based on state-of-the-art concepts remain essential. This type of petroleum geology requires complex regional efforts that cross over disciplines and state borders—something that remains difficult in this part of the world.

Bou Daher et al. (2016) and Barabasch et al. (2019) showed that hydrocarbons generated from the potential Upper Cretaceous source rocks in the eastern Levant Basin would migrate up dip through the margins toward the east. The authors suggested that unless the sealing Eocene marl and clay units are breached, the Oligo-Miocene microbial and the deeper Cretaceous thermogenic systems would not mix and not charge the same structures. Furthermore, Ducros and Nader (2020) proposed areas in the Levant Basin prone to fracturing of the Eocene equivalent sealing unit leading to mixing of thermogenic and microbial systems (Fig. 12) based on machine learning and uncertainty analysis. This is indeed demonstrated by the Karish discovery, offshore

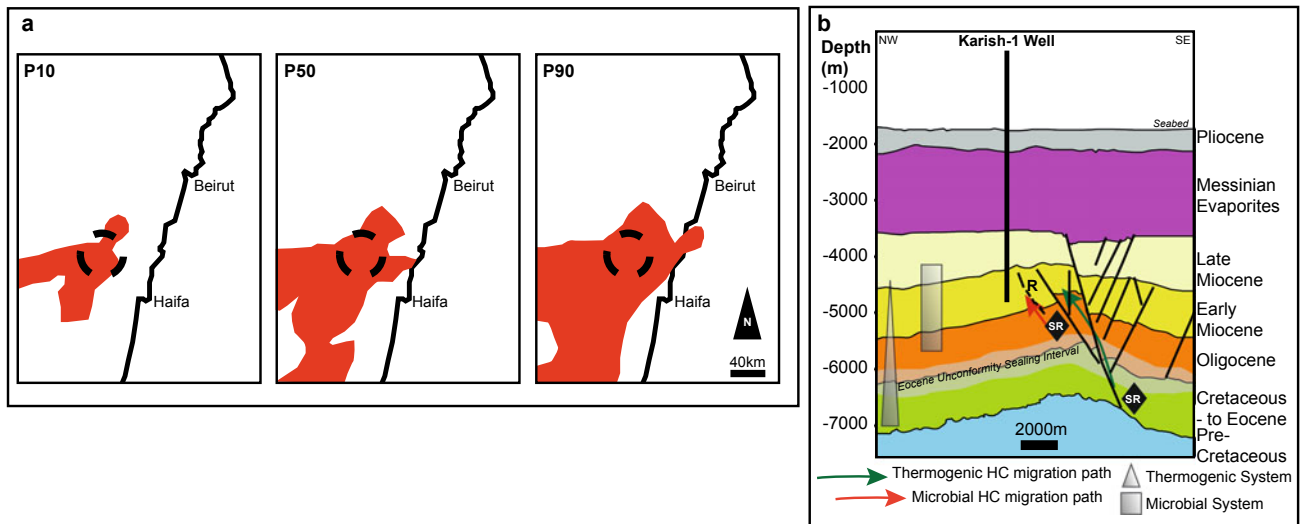


Fig. 12 Schematic illustrations of the probability of fracturing the Eocene marl unit in the Levant Basin (considered as a regional seal between the Mesozoic and Cenozoic petroleum systems): **a** maps showing the extension of the areas with a calculated index of fracturing $> 80\%$ (red areas on maps)—this index is defined as fluid pressure/geostatic stress, and calculated through uncertainty and sensitivity analysis over 50 simulations of the reference basin model (for more details, check Ducros & Nader, 2020); and **b** interpreted seismic profile crossing the Karish field, offshore Israel (location indicated with detached circles in **a**), based on Energean internet published reports, showing major fracturing and faulting across the Cretaceous–Cenozoic intervals. SR is source rocks, and R is reservoir

Israel, which contains a mixed oil-gas accumulation and is located along a major deep-rooted fault system. Based on the discussion above, particularly, in relation to the correlation between the margins of the Levant Basin and the northern Western Desert, similar mixing of petroleum systems can occur as well in offshore Western Desert.

The discovery of Zohr field is regarded as a game-changer in the exploration activities across the East Mediterranean realm. Such rudist-carbonate buildups of Cretaceous age are believed to be present in many locations, based on seismic data interpretation. They are surrounded by Oligo-Miocene shale and clastics and ultimately capped by the Messinian evaporites. Such isolated buildup or structure have been reported along the margins of the Levant (Eratosthenes flanks and eastern margin/Lebanon, Israel; Ghalayini et al., 2018; Papadimitriou et al., 2018a, 2018b) and Herodotus (offshore Western Desert) basins. These are ideal traps for any type of petroleum accumulation. Cemented carbonate reservoirs might also provide more optimal reservoirs with respect to the less compacted sandstones at the early stages of the microbial gas generation and entrapment. This might explain the huge amount of gas hosted in Zhor field (30 Tcf).

7 Conclusions

This chapter presents a general geological overview on the East Mediterranean realm integrating geodynamic evolution, tectono-stratigraphic features, and depositional environments as well as the known petroleum systems. The focus is

set on the Levant Basin, the Western Desert, and the Nile Delta, where major discoveries have been reported and a considerable amount of data exists. These regions within the East Mediterranean are believed to include more than 63,000 MMBOE (based on various previous studies, cited above). Their common geodynamic history until the separation of the African and Arabian plates entices correlated petroleum systems. The general onshore–offshore extension of the Northwestern Desert (to Herodotus Basin) is comparable to a certain degree with the Eastern Levant Margin—until the establishment of the Levant Fracture System. The Upper Cretaceous source rock distribution across the Western Desert margin is, nevertheless believed to be controlled by increased bio-productivity and nutrients with sediment transport from nearby hinterland, contrasting an upwelling scenario for the same source rocks in the Levant Basin. In addition, the possibility of mixing hydrocarbons from such deeper kitchens with the overlying microbial gas accumulated in the Oligo-Miocene interval has been proven through modeling the probability for fracturing the Eocene sealing unit and the discovery of Karish. The Nile Delta includes such Oligo-Miocene systems and is regarded as the principal sediment feeder of the East Mediterranean basins since the Late Miocene.

The presence of carbonate plays has been demonstrated by the discovery of the giant Zohr field. Though complex and challenging to predict, similar reservoirs are expected to be present and will need further geological concept development, numerical modeling, and integration of regional knowledge to be discovered.

Finally, the East Mediterranean realm remains a frontier hydrocarbon province with the potential to bring surprising discoveries that will support the region's societal development, but also a considerable wealth of knowledge that will help in understanding sedimentary basins at the intersections of major plate boundaries and the association of deep lithospheric processes and major shallow and surface processes.

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