



Sedimentological and stratigraphic constraints on Oligo–Miocene deposition in the Mogod Mountains, northern Tunisia: new insights for paleogeographic evolution of North Africa passive margin

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Abstract

Understanding the sediment distribution and basin context of the different Oligo–Miocene successions in the eastern Maghrebides thrust belt of northern Tunisia is challenging and several contrasting models have been proposed. We present the results of detailed field mapping together with facies, microfacies and microfaunal analyses of the NE Mogod Mountains that allowed refining the Bizerte geologic map and reconstructing the Oligocene–early Miocene depositional environment of northern Tunisia. Facies characterization of the Jebel Sebaâ, Cap-Blanc and Bizerte Town sections demonstrate their deposition by submarine gravity flows typical of the Numidian Flysch Formation, rather than the Fortuna Formation as previously proposed. This is supported by the occurrence of deep marine microfossils. The association of deepwater massive sandstone facies and a high proportion of shale-clast conglomerates in the Jebel Zoukar, Ras El Korane and Jebel Sebaâ sections are interpreted as bypass channel facies, representing proximal deposition. The section at La Baie des Carrières is distinguished by its high glauconite content, a rich microfauna of larger benthic foraminifera, *Ditrupea* and echinoids is typical of a shallow marine depositional environment and interpreted as part of the Grès de Bejaoua Formation. The Oligocene sections at Beni Aouf and Nefza also show Grès de Bejaoua affinities, but with some deepening of the marine environment represented by pelagic foraminifera-rich mudstones, and calcareous glauconitic sandstones. The facies distribution, depositional environments and the sediment routing of these time equivalent deposits appears to be dictated by topographic highs and inherited faults (e.g. salt dome paleohigh, El Hairech-Ichkeul ridge, Zaghouan Thrust fault and faults affecting the basin-floor). Within this framework, the northern part of the salt dome area acted as topographic high that guided the fluvial drainage pattern of the Fortuna Formation along a SW-NE trend. The absence of early Miocene deposits in the Tellian domain indicates that this area has been part of a forebulge setting since the late Oligocene. Corresponding foredeep subsidence led to submergence of the Bizerte-Nefza area and deposition of the deep marine Numidian Flysch Formation. The advance of the fold-and-thrust belt since the late Burdigalian–Langhian induced the vertical stacking of foredeep deposits over the forebulge succession.

Keywords Facies analysis · Oligocene–miocene · Numidian flysch formation · Grès de bejaoua formation · Fortuna formation · Foreland basin

Introduction

Since the Middle–Late Eocene (45–35 Ma), the North African margin has been involved in the Alpine orogenic events of the western Mediterranean area (De Lamotte et al. 2009; Roure et al. 2012; Soussi et al. 2014; Khomsi et al. 2016; Leprêtre et al. 2018). In northern Tunisia, the accommodation space created from different flexural phases was rapidly filled with large amounts of terrigenous sediments. This occurred throughout the Numidian basin, from deep-water offshore to the correlative shallow marine and continental deposits onshore in North Africa (Fig. 1a).

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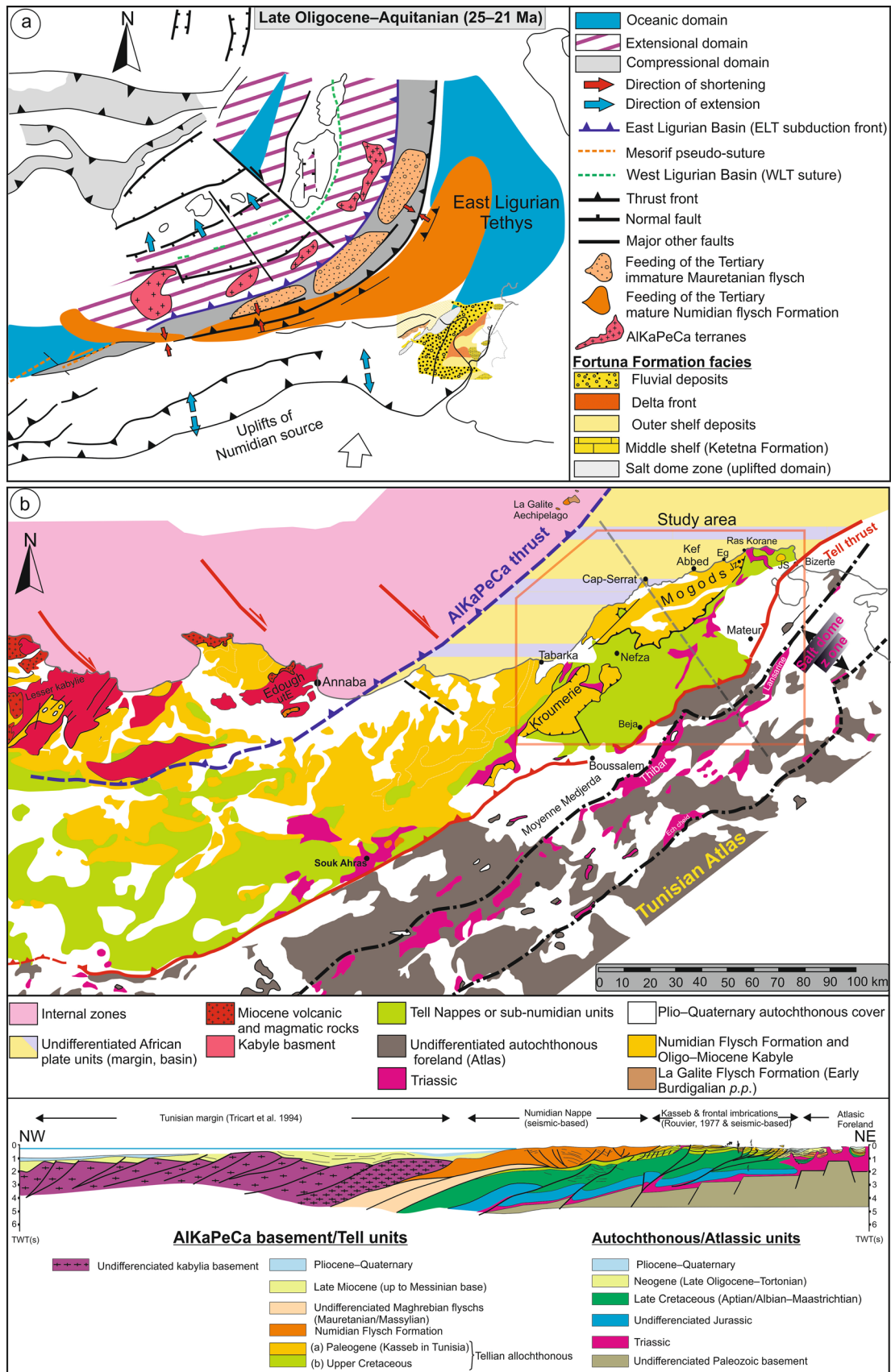


Fig. 1 a Paleogeographic reconstruction showing the distribution of the Oligocene–early Miocene (25–21 Ma) siliciclastic deposits in Tunisia and in the western Mediterranean domain (modified from Leprêtre et al. 2018). **b** Structural map and cross-section of the onshore and offshore domains of the eastern Maghrebides thrust belt. The boxed area corresponds to the studied area (slightly Modified from Wildi 1983; Leprêtre et al. 2018). *JZ* Jebel Zoukar, *JS* Jebel Sebaâ, *Eg* El Garn

The principal Oligocene–early Miocene deposits in Tunisia are mainly siliciclastic (Figs. 1, 2), including: (1) fluvial-to-deltaic deposits of the Fortuna Formation, which outcrops widely in central and north-eastern Tunisia (Burolet 1956; Wezel 1968; Hoyez 1989; Yaïch 1997; Boukhalfa et al. 2020); (2) siliciclastic and bioclastic deposits of the Grès de Bejaoua (also known as the Moyenne de la Medjerda) Formation that discontinuously outcrop north of the salt-dome zone in Beja, Boussalem, and Hedil areas (Biely and Salaj 1971; Rouvier 1977; Hoyez 1989; Yaïch 1997; Boukhalfa 2011); and (3) the turbidite succession of the Numidian Flysch Formation, which outcrops in the extreme north of Tunisia (Fig. 1b) and forms the highest structural unit along the Maghrebides thrust belt system (Wezel 1968; Rouvier 1977; Carr and Miller 1979; Hoyez 1989; El Maherssi 1992; Yaïch 1997; Guerrero et al. 2005; Thomas et al. 2010; Riahi 2004; Riahi et al. 2009, 2010, 2014, 2015; Soussi et al. 2014; Pinter et al. 2016; Stow et al. 2019). On La Galite Island (Fig. 1b), the succession consists of micaceous, feldspathic, and calcareous deposits (Yaïch 1997; Rekhiss 2002; Belayouni et al. 2010).

Despite the extensive study of these formations, the sedimentology and depositional environments of the Oligocene–early Miocene deposits of the easternmost Mogod Mountains, northern Tunisia (Figs. 1b, 3), remain undifferentiated. Furthermore, a controversy remains concerning their interpretation as fluvial, shallow marine shelfal or turbiditic in origin. The confusion and controversial interpretations of these deposits arises in part from the geological maps of Bizerte area published, respectively, by Crampon (1971), Biely et al. (1971) and Melki et al. (2001). In the later work, only two time equivalent siliciclastic units were presented (Fig. 3). These include: the Oligo–Miocene Numidian Flysch Formation outcropping to the NW of Bizerte (Ras El Korane, Jebel Zoukar and El Garn localities); and the Fortuna Formation represented by outcrops at Jebel Sebaâ, Henchir Beni Aouf, Henchir Beni Naïm, Bizerte Town, Cap-Blanc, and La Baie des Carrières (Fig. 3). This twofold distinction is completely different to that of Biely et al. (1971), where the Jebel Sebaâ and outcrops under the buildings of Bizerte Town are considered as tectonic klippen. Also, the sedimentary successions of Henchir Beni Aouf, Henchir Beni Naïm and La Baie des Carrières are considered as analogues of the Grés de Bejaoua Formation.

Consequently, the different interpretations and hence significance of these Oligo–Miocene sedimentary units has hampered the understanding of the geology and paleogeography of the Oligo–Miocene deposits of the easternmost Mogod Mountains and the Bizerte area. This region occupies a key geological position by linking the Maghrebides and the Sicilide segment (Fig. 1). Additionally, the significance of the Tellian Oligocene, *sensu* Rouvier (1977) in the Nefza, Barbara, and Beni Aouf areas remains a matter of discussion (see Ould Bagga et al. 2006; Rouvier 2007). What is still poorly constrained is how a deep marine domain during the Oligocene did not register sedimentation during the early Miocene, whereas its time equivalent shallower parts recorded deposits with planktonic foraminifera (e. g. in Jebel Ben Amara and Kasseb Dam).

In the present work, we re-examine the different Oligo–Miocene outcrops in the easternmost part of the Mogod Mountains in the Bizerte area to analyze their depositional environments, and to compare them with the established criteria for distinction of the Fortuna Formation in the central Tunisia, the Grès de Bejaoua and Numidian Flysch Formation in the north (Fig. 4). Facies, sedimentary structures, faunal content, depositional process and architectural elements are used to interpret depositional environments for each succession. This then allows refinement of the proposed geological map and helps to establish the paleogeography that existed during the Oligocene–early Miocene time. Finally, we will discuss the basin configuration during this period and propose the causative phenomena of the uplift of the Tellian domain. The main outcomes of the present work will highlight the links between the Flysch succession infilling the Maghrebian Flysch basin (Mauretanic/Massylian) *sensu* Guerrero et al. (2005) and the coeval more external deposits (Tellian Oligocene, Bejaoua and Fortuna formation) which still not straightforward.

State of the art

The available published sedimentological and stratigraphic data on the Oligo–Miocene deposits in Tunisia provide a substantial data-base to distinguish between the Numidian Flysch, Fortuna and Grés de Bejaoua Formations (Burolet 1956; Gottis and Sainfeld 1956; Glaçon and Rouvier 1967; Wezel 1968; Rouvier 1977; Biely et al. 1971; Bajanik and Salaj 1972; Hoyez 1975; Lorenz 1978; Carr and Miller 1979; Ben Ismail-Lattrache 1981; Beaudoin et al. 1986; Parize et al. 1986; Hoyez 1989; El Maherssi 1992; Hooyberghs 1992; Yaïch 1997; Yaïch et al. 2000; Guerrero et al. 2005; Stow et al. 2009; Thomas et al. 2010; Boukhalfa 2011; Riahi et al. 2010, 2014, 2015; Pinter et al. 2016; Boukhalfa et al. 2020). In this section we present the accepted criteria that will be used later in the assessment of the depositional

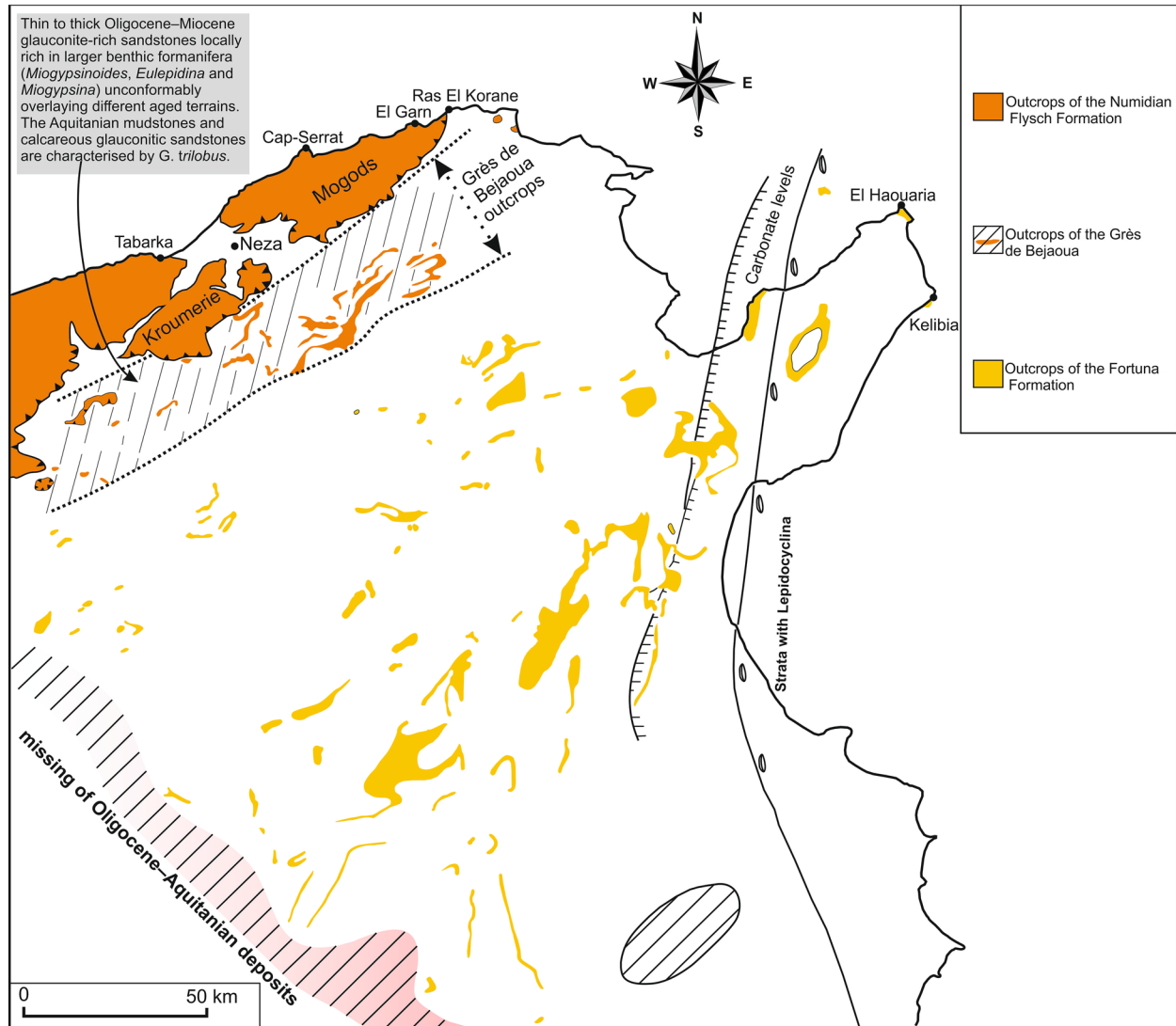


Fig. 2 Distribution of the Oligocene–early Miocene siliciclastic deposits in Tunisia (Hoyez 1989). These deposits include: (1); the fluvial to deltaic deposits of the Fortuna Formation that widespread outcrops in central and oriental parts of Tunisia (Burolet 1956; Yaïch 1997), (2); the siliciclastic and bioclastic deposits of the “Grès de

environments of the studied Oligocene–early Miocene deposits of the easternmost Mogod Mountains, northern Tunisia (Fig. 4).

Numidian Flysch Formation

In Tunisia, the Numidian Flysch Formation is composed of an alternation of green, gray and brown mudstones and yellowish quartz arenites (Qt92–99 F1–4 L0–3). The lower portion of the sequence is mainly clayey with subsidiary fine-grained sandstones and ascribed to the Oligocene (Upper Rupelian–Lower Chattian), whereas the arenaceous strata become thicker and more common in

Bejaoua” that outcrop north of the “salt domes zone”; and (3); the deep marine sandstones and mudstones of the Numidian Flysch Formation which form the highest structural unit in the Maghrebides thrust belt system

the early Miocene (Aquitanian: N4–N5 zones). These are capped in their uppermost part by siliceous rocks and marls of the Babouch Member which was reported as well dated as mostly Burdigalian (Early Miocene: N6–N7 zones) by means of planktonic foraminifers (Fig. 4). The total thickness of this formation is estimated at up to 2200 m. The sedimentary succession is typical of a deep-water turbidite system where sedimentation resulted principally from subaqueous density flow processes. The common observed sedimentary structures include scours, sole markings (flute casts and groove marks) and dewatering structures. The sediment facies are represented by conglomerates, thick massive sandstones with common water-escape structures,

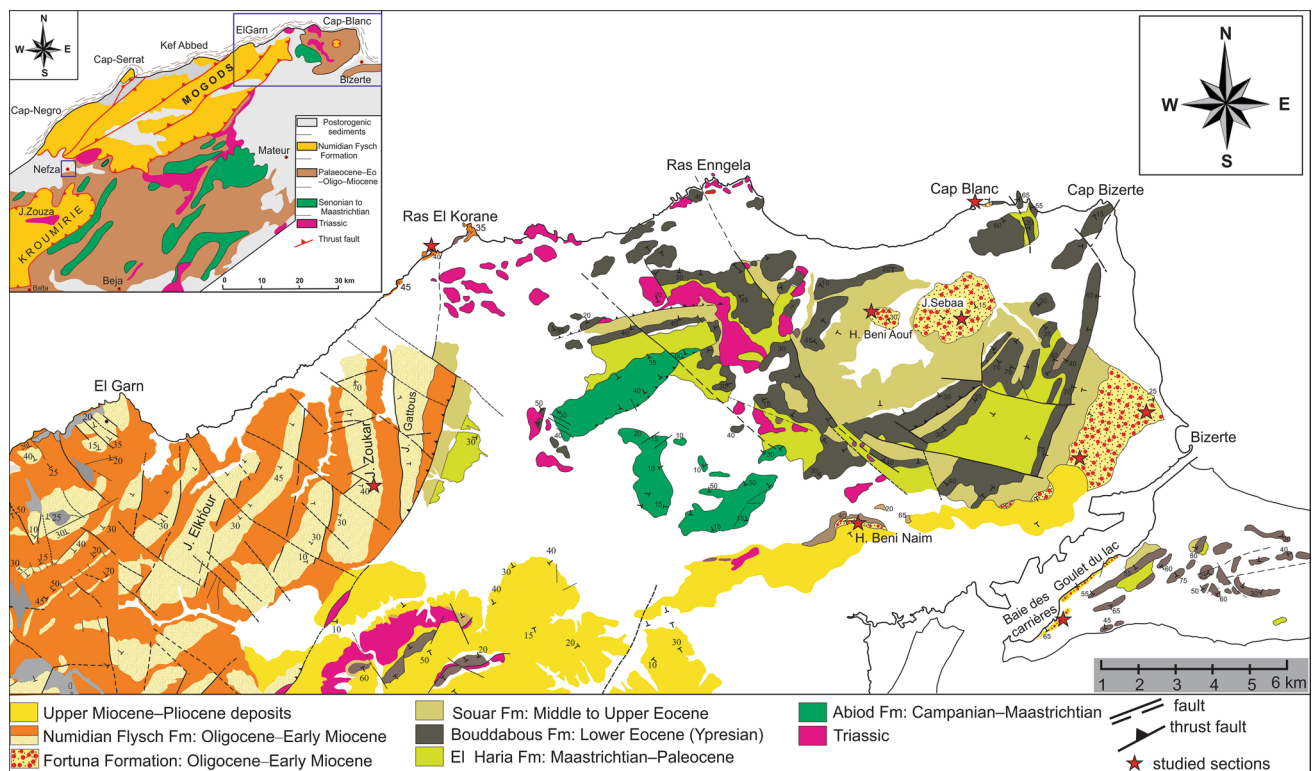


Fig. 3 Geological map assemblages of Kef Abbed (Lamos 1983) and Bizerte areas (Melki et al. 2001). The studied Oligocene–early Miocene sedimentary successions are indicated with red stars. On this

map, the outcrops of Jebel Sebaâ, Henchir Beni Aouf, Henchir Ben Naïm, Cap-Blanc and La Baie des carrières were considered as Fortuna Formation

thick-to-thin-bedded graded sandstones, parallel-laminated mudstones and siltstones, mudstones, and chaotic deposits. These latter include large-to-small-scale slide-slump units, slurry sands, muddy debrites, shale-clast conglomerates and injectionite sands. The mudstones commonly yield a moderate richness in planktonic foraminifera, small benthonic foraminifera and nannofossils in both the Oligocene and the early Miocene deposits. The integration of planktonic/benthonic ratio with ichnofacies indicates a deep-water marine bathyal depositional environment (see Riahi et al. 2014).

Fortuna Formation

The Fortuna Formation (Oligocene–Lower Miocene) in central and eastern Tunisia (Fig. 2) is composed of detrital sediments arranged into three units (Yaïch 1997; Gómez-Gras et al. 2003; Boukhalifa 2011). The lower and middle units are typical of deltaic and lagoonal environments; while the upper unit is characteristic of a braided fluvial environment (Yaïch 1997; Gómez-Gras et al. 2003). The lower part (Oligocene: Upper Rupelian–Lower Chattian) of the Fortuna Formation is characterized by fine-grained sandstones and mudstones with local *Nummulites* rich-carbonates (Fig. 4). The upper unit (upper Aquitanian–Burdigalian: N4–N5

zones) comprises conglomerates and quartz-pebble sandstones, with common woody debris, including larger tree stems. The succession is arranged into 0.5–4 m thick beds with abundant cross-lamination and cross-bedding, indicating E and NE directed paleocurrents parallel to main structural trend of the Tunisian Atlas (Hoyez 1989; Yaïch 1997; Gómez-Gras et al. 2004). Petrologically, the Fortuna Formation sandstones are texturally mature quartz arenites (Qt95–98 F0–4 L1–4) with scarce feldspars and low amounts of rock fragments. Recycling of ancient sedimentary formations is an important process to account for the high quartz-grain content. It is generally accepted that the source area was located to the SW, in the Sahara Platform region.

Grès de Bejaoua Formation

The Grès de Bejaoua Formation, also known as the Grès de la Moyenne de Medjerda, is Oligocene–Middle Miocene in age and crops out widely in the northern Tunisia, mainly in Beja, Zahret Madien, Boussalem, Hedhil and Bizerte areas (Fig. 2). The Oligocene succession is fully marine and characterized by highly glauconitic sandstones, sandy limestone and claystone rocks (Fig. 4). This formation is generally

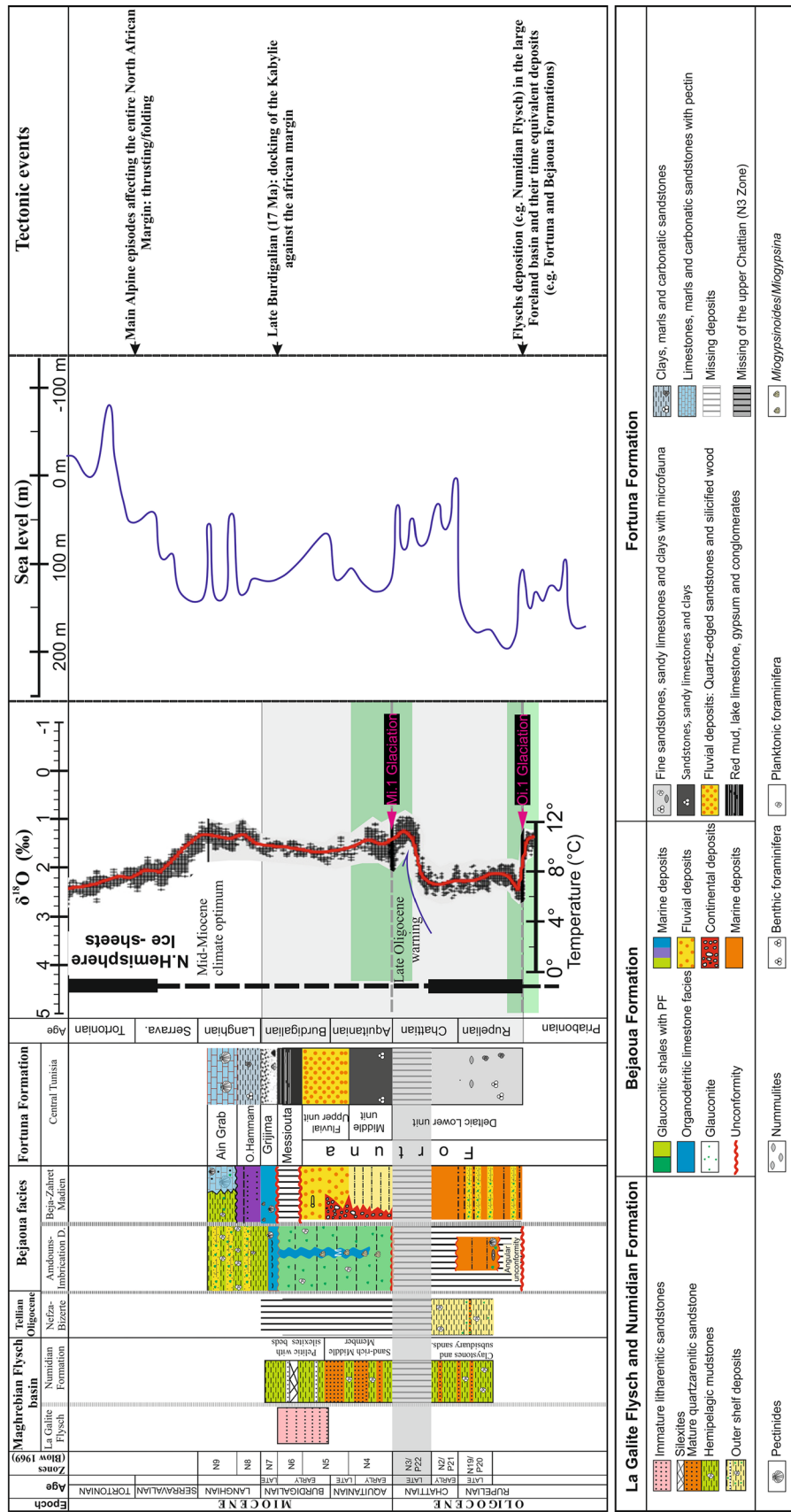


Fig. 4 Age and lithologic characteristics of the Fortuna Formation, “Grès de Bejaoua” and Numidian Flysch Formation correlated with the global sea level and regional tectonic events. Age of the Numidian Formation is based on Glaçon and Rouvier (1967), El Mahersi (1992) and Riahi et al. (2010, 2015), while the age of the la Galite Flysch Formation is based on Belayoumi et al. (2010). The stratigraphic attribution of the Fortuna and Bejaoua Formations are based on synthesis of various published data (Biey and Salaj 1971; Bajajnik and Salaj 1972; Boukhalfa et al. 2020; Hooyberghs 1973, 1977, 1987; Ben Isamil-Latrathe 1984; Yaïch 1997). Averaged global oxygen isotope data of benthic taxa from more than 40 ODP sites, with major climate events highlighted (redrawn from Zachos et al. (2001)). Sea level variation is based on the global eustatic chart of Haq et al. (1987) and Van Sickle et al. (2004)

thin in outcrops (Wezel 1968; Biely et al. 1971; Hoyez 1989; Yaïch 1997; Boukhalfa 2011; Boukhalfa et al. 2020), although its true thickness is difficult to estimate. The early Miocene deposits of the Grès de Bejaoua lie north of the salt dome domain and unconformably overlie deformed different terrains (e.g. upper Cretaceous–Paleocene deposits of Jebel Ben Amara, and *Globigerina-Nummulites* rich limestones of Ypresian age in the imbrication zone). They are mainly represented by interbedded glauconitic sandy limestones and mudstones (Fig. 4) containing common *Miogypsinoides* and *Miogypsina*. The upper Aquitanian is characterized by *Globigerinoides trilobus* (Wezel 1968; Biely et al. 1971; Hoyez 1989; Yaïch 1997; Boukhalfa 2011).

Data and methods

This study is based on detailed logging and facies analysis at six localities. The studied localities include: Ras El Korane, Jebel Zoukar, Jebel Sebaâ, Henchir Beni Aouf, Cap-Blanc section and La Baie des Carrières. Five of these were logged in detail (Fig. 5), whereas the outcrops at Henchir Beni Naïm, as well as those in the Bizerte Town and the Nefza Window, have been only examined in terms of facies, due to poor preservation and limited extent of outcrops. The total measured thickness logged is approximately 2500 m. Careful attention was paid to lithology, bed thickness, grain properties, paleocurrent directions, lateral continuity of beds, and sedimentary structures. The lithostratigraphic sections were logged initially at a scale of 1:100, and followed by more detailed logging at scales 1:10 and 1:20, so that even the smallest sedimentological structures observed were included. A facies hierarchical classification was conducted and, therefore, facies groups were the first order classification defined based on: (1) texture of the pebbly, sandy or silty divisions of the beds; (2) relative thickness of mud interbeds; and (3) glauconite occurrence and bioclastic content in sediments. In the second order, facies groups were subdivided into 18 constituent facies on the basis of sedimentary structures, grading and bed thickness. This is similar to the facies scheme of Pickering and Hiscott (2015), although we have not adopted their distinction between disorganized and organized facies. Petrographic analysis (more than 20 thin sections) was conducted on glauconite-rich sandstones from La Baie des Carrières, Henchir Beni Aouf, and the Nefza Window. Specific attention was given to elements that seem to be reworked within the different Oligo–Miocene outcrops and served in seeking the analogy between different successions.

For age determination, we collected more than 30 samples, tied to logged sections from the various sites within the study area. The age determination and depositional environment

characterization were based on planktonic and benthic foraminifera for the Jebel Sebaâ, Cap-Blanc and Ras el Korane sections. Assessment of the age of the Numidian Flysch Formation at Jebel Zoukar was based on Palynological results acquired during our implementation of an oil industry project (Soussi et al. 2012). In an attempt to narrow the age range for the glauconitic sandstones of the La Baie des Carrières section, the age determination was primarily based on larger benthic foraminifera. The term deep-water is here applied in reference to palaeoenvironments of the slope, rise and basin plain, whereas shallow-marine is used for shelfal depths (see e.g., Shanmugam 2006; Mulder 2011). The facies distribution of the Fortuna Formation during the Oligocene and the early Miocene times were adopted from paleogeographic maps of Yaïch (1997).

Results

Biostratigraphy of the studied sections

Jebel Sebaâ

The sedimentary succession outcropping at Jebel Sebaâ comprises two sandstone units [unit A (SUA) and unit B (SUB)] encased within partially covered mudstones (Fig. 5). We collected two samples from a recently dug water well at the section base (Fig. 5). In these samples, a common mixed benthic and planktonic foraminiferal assemblage is observed. The assemblage of deep water agglutinated foraminifera includes: *Reofax* sp., *Bathysiphon* cf. *latissimus*, *Uvigerina* sp., *Cibicidoides* sp., *Karrevulina coniformis*, *Recurvoides* gr. *walteri*, *Rhabdammina* spp., *Ammodiscus* cf. *angustus* (Berry), and *Nothia* sp. The faunal content attests to a mid-bathyal water depth.

La Baie des Carrières

Close to Bizerte town, an Oligocene 100 m-thick sedimentary succession is well exposed at Menzel Abdurrahman. This is known as the La Baie des Carrières section (Figs. 3, 5). It consists of glauconitic, greenish to bluish mudstones interlayered with thin-to-thick-bedded calcareous sandstones (Fig. 5). The succession is topped with thin-to-medium-bedded sandy glauconitic and glauconite-rich mudstones. At the top, the succession is unconformably overlain by the Tyrrhenian deposits.

The lowermost part of the section is bioclastic, in beds ranging from 30 to 50 cm in thickness, and shows wackestone–packstone textures, with large benthic foraminifera (*Eulepidina* and *Nephrolepidina*) and some planktonic foraminifera (samples 1–4 in Figs. 5, 10d). Preservation of the larger benthic foraminifera varies from moderately well

to well; and a moderate number is fragmented. The large foraminifera are characterized by a relatively diverse assemblage of lepidocyclinids (*Eulepidina* and *Nephrolepidina*) and nummulitids (*Operculina* and *Heterostegina*). Other bioclasts include rare planktonic formaminifera, *Ditrupa* and echinoids. The assemblage of *Lepidocyclina-Operculina-Ditrupa* indicates Late Rupelian–Early Chattian age, which concurs with Biely et al. (1971) and Boukhalfa et al. (2020) results.

Cap Blanc

The Cap Blanc section occurs on the coast immediately to the west of Bizerte Town (Fig. 3). The section is composed of predominantly brown/grey-brown mudstones with thicker sandstone beds in the uppermost part (Fig. 5). Sandstone dykes, channels with rip-up clasts, and debrites are also recorded toward the top of the section. Seven samples were analysed for planktonic microfauna at Cap Blanc. Two of these samples yielded the following assemblage: *Cassigerinella chipolensis*, *Globigerina praebuloides*, *Globigerinelloides* spp., *Laterostomella* spp., *Globigerina ciproensis angustumbilicata*, which indicates an Oligocene age, whilst the others contained a diverse assemblage of agglutinates (*Haplophragmoides* spp., *Recurvoides* spp., *Karriella* cf. *bradyi*, *Trochammina* spp. and *Ammodiscus* spp.), rare nodosarids, buliminids and small rotaliids. The faunal content attests to a mid-bathyal water depth.

Beni Aouf

The age assessment of Beni Aouf section is based on thin section analysis, which shows the dominance of planktonic foraminifera. Microfacies analysis reveals richness in planktonic foraminifera and echinoderm fragments. Within this framework, Bajanik and Salaj (1971) indicated the presence of *Globigerina oligoceanica*, *Cyclamina cancellata* Brady and *C. vendunensis* Berry of Early Oligocene age. Planktonic foraminifera and echinoids suggest an offshore domain below the storm wave base.

Ras El Korane

The Ras El Korane area is situated in the easternmost part of the Mogod Mountains (Fig. 3), and outcrops on the coastline, a few kilometers north of Bechateur village. The section is characterized by typical turbidites and associated re-sedimented facies. The lower half of the section comprises mainly brown–grey mudstones with an increase of sandstone and quartz-pebble-rich beds toward the top of the section. The total section is over 650 m thick. The biostratigraphy of Ras el Korane has been the subject of several previous investigations (El Maherssi 1992; Yaïch 1992; Torricelli and Biffi 2001).

Through the different studies, there is a general consensus to consider this section as Oligocene at its base and lower Miocene in its uppermost part. More recently, Torricelli and Biffi (2001) proposed that the uppermost part corresponds to the Upper Oligocene and consequently represents a tectonic duplication of part of the lower section.

Jebel Zoukar

The stratigraphy of the Numidian Flysch Formation at Jebel Zoukar has never previously been assessed. On the behalf of northern Tunisia offshore oil exploration project (Soussi et al. 2012); five samples (Z1, Z2, Z3, Z4 and Z5) (Fig. 5) were investigated for palynology (Show 2012: internal palynological report). The analysis revealed a relatively abundant dinocysts assemblage. In samples Z1 and Z2, the dinocyst assemblage includes very common *Lentinia serrata* spp., *Spiniferites* spp., *Achomosphaera* spp., and rare *Lingulodinium machaerophorum*, *Deflandrea phosphoritica*, *Glaphyrocysta retiintexta*, *Diphyes colligerum* and *Homotryblum aculeatum/floripes*. This assemblage suggests an age close to the Eocene–Oligocene boundary (Show et al. 2012).

Three samples (Z3, Z4 and Z5) were analyzed in the Oued Ibrahim mudstones interval and revealed a dinocyst assemblage of relatively high abundance. It includes common *Homotryblum plectiluman*, *Spiniferites* spp., *Operculodinium* spp., *Cyclopsiella* spp., and *Selenopemphix nephroides* with rare *Chiropteridium* sp., *Cribrorperidium tenuitabulatum*, *Palaeocystodinium golzowense* and *Tuberculodinium vancampoeae*. This assemblage indicates a Late Oligocene–Early Miocene age.

Sedimentary features of the studied sections

Sediment facies

In the present study, facies analysis represents the main tool applied to the different Oligo–Miocene measured stratigraphic sections. We describe here the principal methodology and terms used. The term 'facies' implies a body of sedimentary rock, or sediments, with specific physical, chemical and biological characteristics. Sedimentary structures, bedding thickness, texture and composition are the chief attributes used to define the different facies. For bed thickness, the terminology is: laminae < 1 cm; very thin beds, 0.01–0.03 m; thin-bedded (0.03–0.1 m), medium-bedded (0.1–0.3 m), thick-bedded (0.3–1 m), and very thick-bedded (> 1.0 m). For the sediment gravity flows deposits, the scale of individual facies matches the scale of single flow deposits. The classification is based closely on Pickering and Hiscott (2015), Pickering et al. (1986) and Stow (1985, 1986), but without

applying their second-order classification into disorganized and organized facies.

Six facies groups are identified based on: (1) texture of the pebbly, sandy or silty divisions of the beds; (2) relative mud interbeds thickness; and (3) glauconite occurrence and bioclastic content. These facies groups are subdivided into 18 constituent facies. The identified facies and facies groups (Fig. 6) are fully described below and illustrated with photographs (Figs, 7, 8, 9, 10, 11, 12, 13, 14, 15).

Facies group A: Conglomerates and pebbly sandstones (> 5% pebble grade)

FA-1: Matrix-supported conglomerates

Matrix-supported conglomerates are quartz pebble dominant in composition with a supporting coarse-grained sand matrix (Fig. 6). They are most common at the base of the thickest sandstone packages, and bed thicknesses

vary from thin to thick, typically ranging from 0.2 to 3 m thick. In some cases, the bed bases exhibit excellent sole marking with flute casts. Clasts lack a well-ordered fabric and beds are typically poorly sorted with subrounded to rounded dominant forms. The size of pebbles ranges from fine pebble (exceeding 7 cm in diameter) to boulder grade. Larger clasts are often concentrated at the base of a bed and then sharply pass up into clast-poor pebbly sand. Preferential orientation, grading and stratification of the clasts are mostly absent. In the studied sections, this facies includes silicified carbonate clasts ranging from small to large cobbles (> 4–254 mm). This facies corresponds to lithofacies B of Pinter et al. (2016) and FA-1 of Thomas and Bodin (2013). It commonly occurs with graded-stratified pebbly sandstones and/or structureless massive sandstones.

Facies groups	Facies code	Facies	Distinctive sedimentary features	Thickness	Jebel sebaa		Ras Korane		Cap Blanc	Baie des Carrières	Bizerte Town	Beni Aouf/Beni Naim
					% total section	% Massive sands facies association	% total section	% Massive sands facies association	% total section			
FG A: Conglomerates	FA-1	Matrix supported conglomerates	Thicknesses are 0.5–5 m. In some cases, beds or layers may be thin to very thin stringers of gravel as little as one pebble thick. Beds may be flat-based to deeply scoured.	0.2–3 m	9	26	~ 2	5				
	FA-2	Shale clast conglomerates	Highly lenticular/erosive beds	0.3–1.5 m				10	1.50			
	FA-3	Normally graded pebbly sand	- Well-defined normal grading - Common scour structures tend to give most beds an irregular appearance.	1 m	1			5-10				
	FA-4	Graded-stratified graded pebbly sand	-Beds show an overall grading from base to top, although layers of coarser clasts are repeated upward throughout beds. Stratification may be parallel, oblique, multiple sets. Strata may pinch and swell and split into irregular stringers and lenses.	0.5–6 m	11	~30	20					
FG B: Sandstones	FB-1	Thick/medium bedded	Beds may be lenticular to parallel-bedded, +/- shale clasts, amalgamation horizons, basal loading and scouring, rare cross stratification, common water-escape structures.	0.5–5 m	10	29	~ 8	16	5		*****	
	FB-2	Graded sandstones	Beds may be lenticular to parallel-bedded, +/- basal loading and scouring, normal turbidite structural sequence, water-escape structures.	1–3 m								
	FB-3	Stratified sandstones	Fine- to coarse-grained, planar to low-angle cross-bedded sandstone. Bed thickness is generally 1m. Beds are mostly tabular, but some lenticular beds are also present.	0.4–3 m	5	14	~ 3.5				*****	
FG C: Sand-Mud couplets	FC-1	Interbedded sandstones and mudstones	Parallel-laminated, structured (fine grained Turbidites)	0.6–7 m	11		~7		16		*****	
FG D: Mud and clays	FD-1	Thick irregular silt and mud	Thin to medium beds with horizontal silt laminae in mud, with some slightly lenticular, indistinct silt laminae. Silt:mud ratios range from about 2:1 to about 1:2	0.8–2 m							*****	
	FD-2	Hemipelagic mudstones	Mudstones dominant (hemipelagites and fine-grained turbidites), with thin, medium, and thick bedded sandstone turbidites	5–100 m	55		49		73			
FG E: Chertica	FE-1	Contorted sandstones and mudstones	Folded to an indistinctly bedded strata in irregularly shaped layers or horizons.	0.8–10 m			~7		~ 3			
	FE-2	Slurry sands	Highly disorganized beds with distinctive clasts population up to 5 cm in Ø. Unusual sedimentary structures (primary flow-related and post-depositional water-escape-sediment deformation structures).	1–1.5 m			~2		2			
	FE-3	Clast-rich mudstones	Completely disorganized units with no apparent sedimentary structures. They comprise clasts of all sizes supported in a muddy matrix, and include contorted soft-sediment clasts in some cases	2–15 m								
FG F: Glauconitic sandstones, mudstones and limestone	FF-1	Very thick/thick-bedded highly glauconitic sandstones	High glauconite content (up to 60%), fine to medium-grained calcareous sandstones.	0.3–1 m							*****	
	FF-2	Medium-bedded glauconitic sand-mud couplets	-Thin to medium bedded glauconitic sand-mud beds with tabular and lenticoid shape. The limy sandstone beds are structureless except of local flaser-bedding and parallel lamina. Occurrence of common benthic foraminifera (<i>Rotalia</i> , <i>Miliolida</i> and <i>Amphistegina</i>) • highly rich in glauconites • Most of the mudstone contains no clear internal sedimentary structures.	0.10–0.3 m							*****	*****
	FF-3	Glauconitic, greenish to bluish mudstones		5–15 m							*****	*****
	FF-4	Bioclastic lepidocyclinid nummulitid wackestone-packstone	- Parallel laminated, bioclastic with a sandy lime glauconitic sandstone lithology. - Common larger benthic foraminifera (<i>Eulepidina</i> and <i>Nephrolepidina</i>) and planktonic foraminifera.	0.3–0.5 m							*****	*****
	FF-5	Thin to medium sandy lime glauconitic sandstones	- Medium to thick lime glauconitic sandstones displaying fish teeth. Individual beds are up to 50cm thick, generally interbedded with glauconitic, greenish to bluish claystone intervals.	0.3–0.5 m							*****	*****

Fig. 6 Summary of facies groups, individual facies and their occurrence in the different studied sections. This classification is based on Pickering and Hiscott (2015); Pickering et al. (1986) and Stow (1985, 1986)

FA-2: Shale-clast conglomerates

Shale-clast conglomerates are distinguished by highly lenticular/erosive beds, characteristically from 0.3 to 1.5 m in thickness. The beds are either quite structureless or with crude coarse-tail grading, but shale-clast imbrications and long-axis alignment is apparent. The clast populations are characterized by abundant very poorly sorted rounded to elongate shale clasts that contribute up to 70% of the bed volume with a matrix made up by mud, finer quartzose pebbles and coarse sand. Typically, the shale clast conglomerates tend to form the lower part of graded beds and equally occur as shale clast 'nests' at the base of sandstone beds or between sandstone beds. The mud clasts are generally pebble sized (40 mm) and form laterally impersistent zones (lensoid shaped), oriented subparallel to the bedding. This facies is interpreted as the product of substrate erosion of passing flows (Pinter et al. 2018).

FA-3: Normally graded pebbly sandstones

Facies FA-3 occurs as thick-to-very thick beds and characteristically exhibits obvious normal grading. Individual beds are up to 1 m thick, averaging 0.8 m thick and typically show erosive to slightly erosional basal contacts. The clasts are poorly sorted, ovoid to subrounded, and vary in size from small to large pebbles (> 4–64 mm). The pebbles commonly fill the irregular scoured depressions at the basal surface of a bed with random to subparallel orientation to the paleocurrent direction as inferred from sole marks and cross-stratification. The zone thickness depends on the erosional scour depth and degree of lag deposit within the host facies.

FA-4: Graded-stratified pebbly sandstones

FA-4 facies occurs as thick-to-very thick beds in the different studied successions. Beds are medium to very thick, with archetypal bed thicknesses from 0.4 to 6 m and show an alternating occurrence of pebble layers and sand-rich layers with extremely variable shape. Generally, individual strata have gradational contacts with both normal and inverse grading. Large-scale cross-stratification and parallel-stratification are common and represented by an alternation of granule sand and pebbles with coarse- to medium-grained sand. Also, imbricated clasts are common. The individual flow deposit is difficult to define because of the composite nature of many pebbly sandstone units. For example, they may form part of a much thicker megaturbidite bed. The facies is typically poorly sorted, from sand to coarse pebble size, and with cobbles as scour fills and irregular stringers. FA-4 facies co-occur commonly with other conglomerates

and sandy facies as part of fining-and coarsening-upward successions.

Facies group B: sandstones ($\geq 80\%$ sand grade, $< 5\%$ pebble grade)**FB-1: thick/medium-bedded structureless massive sandstones**

These tend to occur as thick-to-very thick, fine-to-medium, and some coarse-grained sandstones. Beds are typically sharply bounded by planar surfaces and are dominantly ungraded and contain no sedimentary structures. Commonly, bed thicknesses are 0.5–5 m. The basal surface is slightly erosive and the upper surface is indistinct due to successive amalgamation by the overlying beds. Granules up to 1 cm pebble-sizes are generally scattered within the sandstone beds. Composite bedsets can reach thicknesses of 8 m due to the amalgamation of successive massive sandstone beds. Extensive water-escape structures are prominent in the upper half of the beds.

FB-2: graded sandstones

Facies FB-2 occurs as thick-to-very thick beds (1–3 m thick) showing normal grading from base to top and involves medium-to-coarse-grained and locally pebbly sandstone. Most beds have an irregular geometry due to the common scour structures. Composite graded beds with a shale clast zone and the quartz-pebble upper zone have been noted in the studied sections. Upwards this facies may include well developed parallel lamination and fit with lithofacies B3 of Pinter et al. (2016).

FB-3: stratified sandstones

This facies is composed of fine-to-coarse-grained, planar to low-angle cross-bedded sandstone. Granule horizons are common and tend to occur along horizontal bedding. Beds are up to 1 m thick. They are mostly tabular, less commonly lenticular. These beds may be amalgamated with structureless massive sandstones and/or conglomeratic facies.

Facies group C: sandstone–mudstone couplets**FC-1: interbedded sandstones and mudstones**

This facies occurs as thin-to-medium beds (0.1–0.3 m thick) of sandstone overlain by mudstone, mostly with sheet-like geometry. Normally, graded beds are common, with sharp and erosive bases, grading from sandstone to mudstone.

Climbing ripples, cross-lamination and parallel lamination are common. Grain size varies from fine sand to silt to clay and shows moderate-to-poor sorting. The sandstone composition shows a quartz-dominated mineral assemblage, with minor feldspar, and rock fragments.

Facies group D: mudstones

Facies FD-1: thick irregular siltstone and mudstone laminae

FD-1 is represented by thin-to-medium beds (0.1–0.3 m thick), containing horizontal siltstone laminae in mudstone, with some faintly lenticular, indistinct and wispy siltstone laminae typical of Stow turbidite divisions. Silt: mud ratios range from about 2:1 to about 1:2. The siltstone laminae have sharp to gradational tops and bases.

Facies FD-2: mudstones

This facies commonly occurs in thick sections (5–100 m thick) and bedding is generally ill-defined or absent. It is represented by laterally extensive packages of mudstones of various colors (brown, green, grey, etc.); mostly lacking any clear sedimentary structures. In some sections, there is fine-scale parallel lamination typical of Stow turbidites (upper divisions only), whereas other parts show clear bioturbation and trace fossils (*Chondrites*, *Trichichnus*).

Facies group E: chaotic deposits

Chaotica deposits occur typically adjacent to the sandstone bodies and include an indistinctly bedded to unstratified, well-bedded and non-bedded type. They are typically more common within the finer-grained facies (facies groups C and D). They are represented by contorted sandstones and mudstones, debris-flow deposits (slurry sand and muddy debris) and injectionite sands. Chaotica deposits are mostly related to local deformation and remobilization of sandstones and siltstones related to intra-basin slope instability (Pinter et al. 2016).

FE-1: contorted sandstones and mudstones

Facies FE-1 comprises folded to indistinctly bedded strata. The thickness of the deformed packets is typically on the order of meters, although the range is from centimeters to 10 m. The bounding surfaces are planar to highly irregular with discrete shear surfaces that define the bounding surfaces of the deposit. Also, there is a remarkable change in layer thickness along strike. In the studied area, this facies is also represented by chaotic slumped thin-bedded mudstone units.

FE-2: slurry sandstones

Slurry sandstones are typified by highly disorganized sandstone beds, typically up to 1 m thick. These are medium-to-fine-grained sandstones, with an overall mean grain size of about 0.35 mm. They also have a distinctive, well-dispersed clast population up to 5 cm in diameter, which include common 'sandstone balls', and less common shale clasts and quartz pebbles. The distinctive feature of these beds is their generally indistinct swirly or streaky fabric, with less common primary flow-related and post-depositional water-escape and soft-sediment deformation structures.

FE-3: clast-rich mudstones

This facies occurs as thick and very thick-bedded completely disorganized units with no apparent sedimentary structures. They comprise clasts of all sizes supported in a muddy (sandy, muddy) matrix, in most cases randomly dispersed, but more rarely with a bed-parallel preferred alignment. Clasts sizes range up to giant boulders and include contorted soft-sediment clasts in some cases.

Facies Group F: glauconitic sandstones, mudstones and limestones

FF-1: very thick/thick-bedded highly glauconitic sandstones

This facies occurs as very thick or thick-bedded highly glauconitic sandstones (0.5–6.5 m thick). It is distinguished by high glauconite content (up to 60%) and low clay-grade content in moderately sorted beds. It involves fine-to-medium-grained calcareous sandstones. Bounding surfaces are well defined with an absence of internal sedimentary structures, except diffuse subparallel lamination. Due to the high glauconite content, there is color oxidation of strata. This lithofacies co-occurs with all facies of group F.

FF-2: medium-bedded glauconitic sandstone–mudstone couplets

Facies FF-2 is represented by tabular and lensoid-shaped thin-to-medium bedded glauconitic sandstone–mudstone beds. Grain sizes are in the range of medium- to fine-grained sand, the sandstones are glauconitic and calcareous, while the mudstones are glauconitic and iron-rich. The calcareous sandstone beds are mostly structureless except for some flaser-bedding and parallel lamination. Thin section analysis shows common benthic foraminifera, such as *Rotalia*, miliolid, *Amphistegina* and rare planktonic foraminifera. Isolated corals and bivalve fragments are also observed.

FF-3: glauconitic, greenish to bluish mudstones

This lithofacies is represented by mudstones highly rich in glauconite and forming units ranging from 5 to 15 m thick. Most of the mudstones lack internal sedimentary structures, neither have they yielded any significant microfossils.

FF-4: bioclastic lepidocyclinid nummulitid wackestone–packstone

This facies is parallel laminated and commonly bioclastic with a sandy calcareous glauconitic sandstone lithology. It involves larger benthic foraminifera (*Eulepidina* and *Nephrolepidina*) and some planktonic foraminifera. Preservation of the larger foraminifera varies from moderately well to well preserved; and a moderate number is fragmented. The larger benthic foraminifera are marked by a relatively diverse assemblage of lepidocyclinids (*Eulepidina* and *Nephrolepidina*) and nummulitids (*Operculina* and *Hetorestegina*). Other bioclasts include rare planktonic foraminifera, *Ditrupea* and echinoids.

FF-5: medium-to-thick sandy calcareous glauconitic sandstone

This lithofacies is composed of medium-to-thick calcareous glauconitic sandstones displaying fish teeth. Individual beds are up to 50 cm thick (mean 35 cm). It is generally interbedded with glauconitic, greenish to bluish mudstone intervals.

Facies distribution

Jebel Sebaâ section

Detailed facies analysis of the sedimentary succession outcropping at Jebel Sebaâ has led to the recognition of three conglomerate/pebbly sandstone and three sandstone facies that stack from base to top forming two main sand packages, named SUA and SUB (Fig. 8a). These are associated with minor fine-grained sediments and thick mud-dominated successions. The lower unit, 26 m thick, is made up of amalgamated sandstone beds of facies FA-1 (< 1.5 m thick), and thick beds of facies FA-3, FA-4 and FB-1. These lithofacies are occasionally separated by mudstone partings. The upper unit, almost 8 m thick, comprises a composite unit made up of structureless massive sandstones (FB-1), graded sandstones (FB-2) and stratified sandstones (FB-3).

The matrix-supported conglomerates account for 26% of the massive sandstone facies association (i.e. facies groups A, B, and E). It is mostly recognized in SUA and associated with graded-stratified pebbly sandstones (FA-4) (Fig. 7a, b). Facies FA-1 is characterized by dispersed quartz pebbles (3–8 cm), fragmented shells and small-to-large cobbles

(> 4–254 mm) of limestone and silicified carbonate clasts in a sandstone matrix (Fig. 7c). Clasts lack a well-ordered fabric, and beds are characteristically poorly sorted with both sub-angular and well-rounded clasts. Excellent sole markings with flute casts were recorded at bed bases (Fig. 8h).

The graded-stratified pebbly sandstones (FA-4) typically occur in SUA (Fig. 7b, e) and account for 32% of the massive sandstone facies association. Beds display an alternation of pebble- and sand-rich layers. Planar or trough cross-stratification occurs as an alternation of granule-grade sand with pebbles and pebble to coarse-grained sand (Fig. 7f). Top truncation of this facies is common (Fig. 7b, d) and bed thickness is laterally variable from 0.3 to 6 m. The cross-sets indicate a current direction to the W (Fig. 7b, e). Towards the top of the SUA, recognizing individual flow deposits is difficult because of the composite nature of this unit.

The normally graded pebbly sandstones occur as a minor facies (3%) in the logged section and tend to occur as thick sandstone beds where grading is typically subtle, normal and affects the coarse-tail fraction (Fig. 7g, h). Individual beds are up to 1 m thick (average 80 cm) and typically show erosive to slightly erosional basal contacts (Fig. 7h). The clasts are poorly sorted, ovoid to subrounded, and vary in size from small to large pebbles (> 4–64 mm). The pebbles are concentrated in irregular scoured depressions at the basal part of a bed with random to subparallel orientation to the paleocurrent direction as inferred from sole marks (Fig. 7h). The structureless massive sandstones (FB-1) and graded sandstones (FB-2) form a composite unit divided by shale clasts in SUB (Fig. 8a). Overall, the beds grade from very coarse-pebbly sand-to-medium-grained sandstones. The FB-1 facies accounts for 29% of the massive sandstone facies association. The basal surfaces of beds are typically erosive, whereas the upper surfaces are indistinct due to successive amalgamation with the overlying beds. Granules up to 1 cm pebble-sizes are generally scattered within the sandstone beds. Bed-set packages comprise individual beds of 0.5–2 m in thickness. Composite bed-sets of amalgamated sandstones can reach thicknesses of 8 m (Fig. 8b). Extensive water-escape structures are mostly characteristics of the upper half of the beds (Fig. 8b, c) and can be divided into three basic types (Fig. 7c) including: (1) consolidation laminae, (2) convolute laminae displaying folds and “diapiric” structures, and (3) dish structures separated by vertical pipes. The FB-2 facies is characterized by well-defined normal grading, from pebbly sandstone to medium sandstone. They occur as thick-to-very thick beds (1–3 m thick) (Fig. 8d, e). The stratified sandstones (Fig. 7i) form 14% of the logged section and are composed of fine-to coarse-grained, planar to low-angle cross-bedded sandstone. Granule horizons along horizontal bedding as well as fluid escape features are common. Bed thickness varies from thin to thick, with a mostly tabular geometry.

Fig. 7 Lithofacies of the sedimentary succession at Jebel Sebaâ. **a** Matrix-supported conglomerates facies interbedded with cross-stratified pebbly sand facies. **b** Top truncation of the cross-stratified pebbly sand facies. **c** Close view of the gravelly conglomerates facies with reworked elements (see back arrows). **d** Vertical amalgamation of cross-stratified pebbly sand facies and matrix-supported gravelly conglomerates with obvious top truncation of FA-4 facies. **e** Trough cross-bedded sandstones and cross-stratified sandstones. **f** Stratified pebbly sand. The large-scale cross-stratification occurs and represented by an alternation of granule sand and pebbles with coarse- to medium-grained sand. Clast imbrications are well observed. The cross sets indicate a current direction to the W. **g** Thick to very thick normally graded pebbly sandstones where normal grading is typically marked. **h** Normally graded pebbly sand with a bed base marked by shale clasts. **i** Fine- to coarse-grained, planar to low-angle cross-bedded sandstone. Granule horizons along horizontal bedding are common



The sandstone–mudstone couplets facies (thin- to thick-bedded) account for 10% of the total section. These outcrop on the north side of Jebel Sebaâ. The sandstone parts are commonly thin- to thick bedded. Grain size ranges from fine

sand to silt, and shows moderate- to poor sorting. In some cases, the bases of sand bodies exhibit excellent sole markings with flute casts (Fig. 8g) indicating a current direction to the W. The mudstone facies occur between SUA and SUB

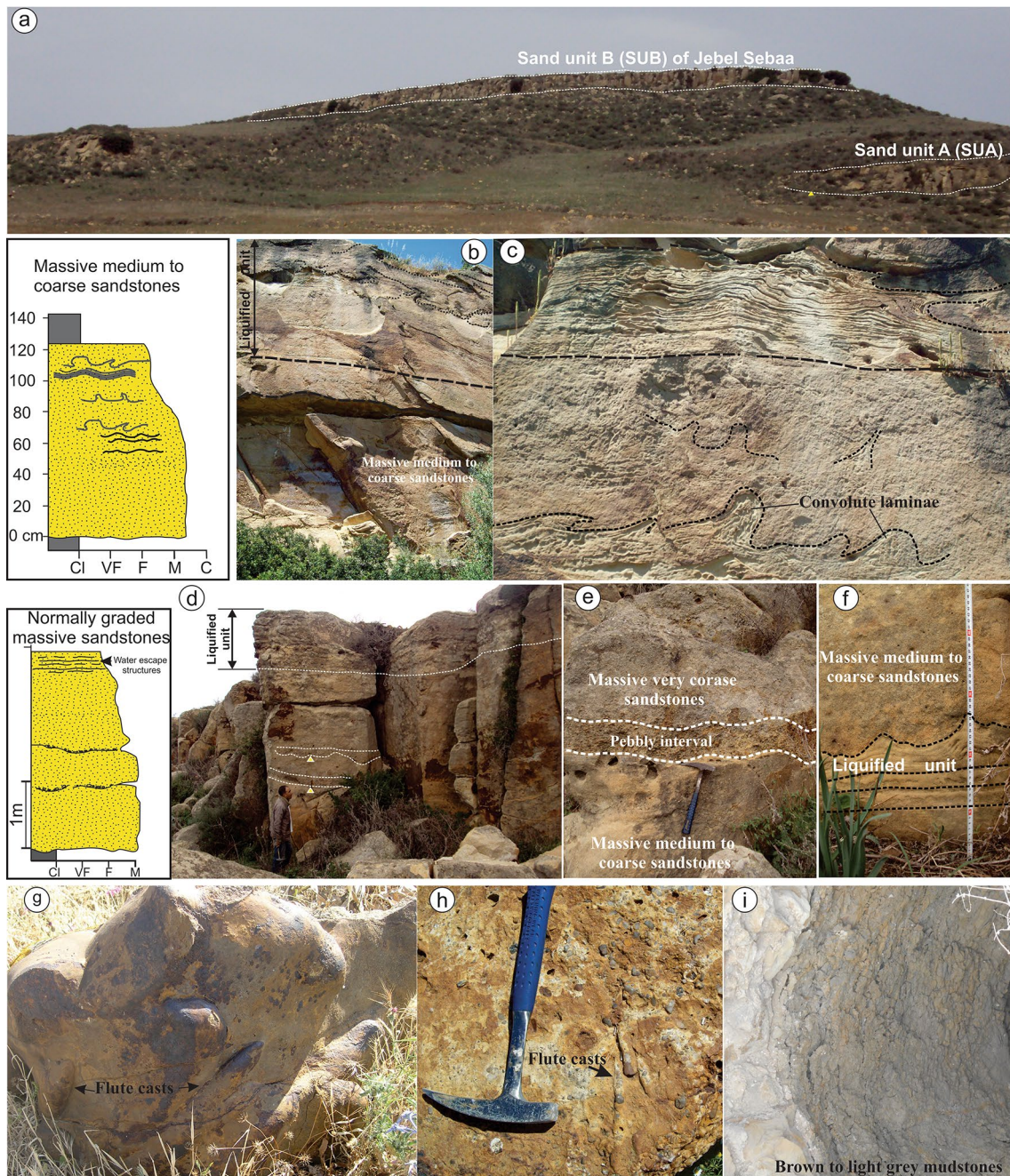


Fig. 8 a Panoramic view of Jebel Sebaâ succession: view toward North. Two sandstone ridges recorded on the southern flank of Jebel Sebaâ which overlies Eocene Souar Formation claystones. The upper sandstone unit (SUB) comprises four massive beds of fine to grit size quartz sand grains associated with iron cemented sandstone clasts up to 7 cm across. Subrounded quartz pebbles up to 3 cm across are also recorded at certain intervals. The lower unit (SUA) is mainly conglomeratic to gravelly quartz sized with frequent reworked elements (pectinid bivalves and Cretaceous to early Eocene boulders). b Thick-

to-very thick massive sandstones facies displaying extensive water escape structures indicative of syn-depositional dewatering. c Detail of water -escape structures (dishes, convolute laminae and pillars) in the very thick-bedded massive sandstone. d Massive sand unit made up by normally graded and structureless sandstones. e Close view of normally graded sandstones facies. f Dewatering features in the normally graded sandstones facies. g and h flutes casts recorded at bed bases at Jebel Sebaâ. i Brown to light grey hemipelagic mudstones facies well inspected at the base of Jebel Sebaâ succession

of Jebel Sebaâ. They are poorly exposed and field inspection was based on a recently dug water-well (Fig. 8i). They

comprise grey-to-light green mudstones containing planktonic and deepwater agglutinated benthic foraminifera.

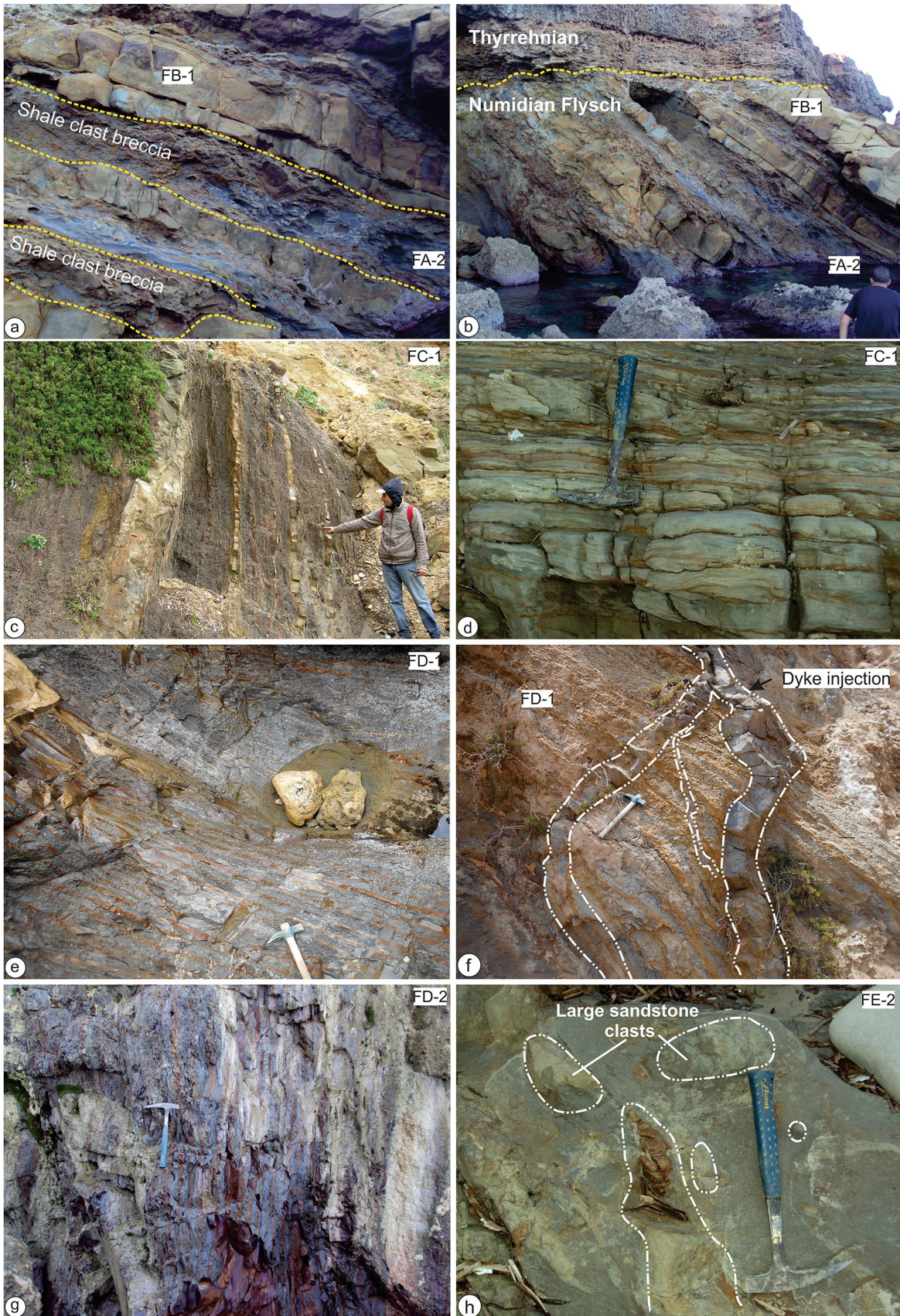


Fig. 9 Lithofacies of the Cap-Blanc succession. **a** Shale clast breccia forming a laterally impersistent zones or as clast 'nests' between sandstone beds and orientated subparallel to sandstone beds. **b** Numidian Flysch deposits made up by massive sandstone interbedded with shale clast conglomerates intervals and overlaid by the quaternary raised beach at the top. **c** Interbedded sandstones and mudstones facies occurring as thin to medium bedded (0.1–0.3 m thick), with an irregular to sheet-like shape. **d** Climbing ripples, cross-lamination and parallel lamination recorded in interbedded sandstones and mudstones facies. **e** Thick irregular silt and mud laminae typified by thin-to-medium beds containing horizontal silt laminae in mud, with some faintly lenticular, indistinct and wispy silt laminae. Silt: mud ratios range from about 2:1 to about 1:2. **f** Horizontal silt laminae in mud affected by dyke injection. **g** Hemipelagic mudstones. **h** Slurry sand facies. Note the sandstone boulders floating within a matrix

Cap-Blanc section

Facies analysis undertaken in the Cap-Blanc section reveals an absence of the matrix-supported conglomerates/pebbly sandstones (FA-1), and rare shale-clast conglomerates (2% of the section). The latter facies occurs either as shale clast 'nests' between sandstone beds (Fig. 9a) or as dispersed mud clasts in the thick/medium-bedded massive sandstone facies. They may contribute up to 60% of the bed with subrounded pebbles of a millimeter-to-centimeter size (40 mm). At the section top, the mud clasts form a lateral impersistent zone, orientated subparallel to bedding (Fig. 9a).

The thick/medium-bedded, structureless massive sandstone facies constitutes 5% of the whole succession. Bed thickness varies between 0.5 and 2.5 m. This facies mainly occurs at the top of the succession and comprises moderate-to-well-sorted sandstones with a fine-to-medium grain size (Fig. 9a, b), interbedded with mudstone and shale-clast conglomerates facies. Beds are ungraded, typically irregular in shape and contain no sedimentary structures.

The sandstone–mudstone units make up some 16% of the succession at Cap-Blanc. They consist of moderately well-sorted to poorly sorted sandstone–mudstone couplets (Fig. 9c, d) showing partial Bouma (1962) sequences (Tbc, Tbcd, Tbcde and Tcde), and occur in units ranging from 1 to 8 m thick. A distinctive form of this facies is noted with thin-to-very thin beds, commonly < 8 cm thick, with sand: mud ratios < 1.0, in which ripples occur with stoss-side erosion and only lee-side preservation, followed abruptly by a silt/mud drape giving the beds a 'form surface' (Fig. 9d). Bed bases are typically smooth and planar, but with minor load and scour structures. The sandstones show parallel and cross-lamination.

The mudstones facies makes up some 73% of the Cap-Blanc sedimentary succession, and occur in units ranging from 5.0 to 40 m in thickness. This part of the succession is characterized by sills and dykes of injected sandstones (Fig. 9f). Silt: mud ratios range from about 2:1 to about 1:2. These include silt-laminated mudstone, with planar,

lenticular, and indistinct laminae (Fig. 9e), and varicolored, structureless mudstones, ranging from dark-grey, light-grey and brown to light green in color (Fig. 9g). The bedding is indistinct to massive, and ellipsoidal ferruginous concretions (septarian nodules) are locally common. The mudstones contain planktonic and benthic foraminifera, although only low-to-moderate CaCO₃ content (< 10–20%). Bioturbation is moderate and specific identification of trace fossils shows *Chondrites* sp. and *Planolites* sp.

Chaotic sedimentary units formed by contorted/disturbed strata, clast-rich mudstones and slurry sands are a minor facies (5%) throughout the examined section. The slurry sands are represented by disorganized sandstone beds, typically up to about 1 m thick (Fig. 9h). These comprise medium-to-fine-grained sandstones (mean size 0.35 mm), and dispersed clasts up to 5 cm in diameter, including sandstone balls, shale clasts and quartz pebbles.

La Baie des Carrières section

The sedimentary succession of the La Baie des Carrières section consists of glauconitic, greenish to bluish mudstones (Fig. 10a) interbedded with thin-to thick-bedded calcareous sandstones (Fig. 10b, c). Five facies are identified, including: (1) very thick/thick-bedded highly glauconitic sandstones; (2) medium-bedded glauconitic sandstone–mudstone couplets; (3) glauconitic, greenish to bluish mudstones; (4) bioclastic lepidocyclinid nummulitid wackestone–packstone; and (5) medium-to-thick sandy calcareous glauconitic sandstones.

The medium-to-thick-bedded sandy calcareous glauconitic sandstones (FF-5) display fish teeth and are commonly interbedded with thick mudstone intervals in the lowermost part of the La Baie des Carrières section. The greenish to bluish glauconitic mudstones (FF-3) form the second most abundant facies, in sequences ranging from 5 to 15 m thick (Fig. 10a). Most of the mudstones are devoid of internal sedimentary structures, and without significant microfossils.

The lowermost bed (30–50 cm thick) of the thick sandstone unit contains bioclastic lepidocyclinid nummulitid wackestone–packstone facies (FF-4). It is parallel laminated (Fig. 10b) and includes larger benthic foraminifera and rare planktonic foraminifera (samples 1–4 in and Fig. 10d, e, f, g, i, j). These are mostly well-preserved, although some are fragmented. The larger benthic foraminifera are characterized by a relatively diverse assemblage of lepidocyclinids (*Eulepidina* and *Nephrolepidina*) and nummulitids (*Operculina* and *Hetorestegina*). Other bioclasts include *Ditrupa*, echinoids and rare planktonic foraminifera (Fig. 10j). The presence of micritic matrix and abundance of *Lepidocyclinidae* and echinoids suggests a low–medium energy open-marine depositional environment situated between the storm wave base and fair-weather wave base.

The highly glauconitic sandstone facies (FF-1) is characterized by high glauconite content and clay-grade sediment (up to 60%). The sandstones range from medium- to fine-grained, with moderate sorting (Fig. 10b). Bounding surfaces are generally clearly defined. Internal sedimentary structures are rarely present, but indistinct parallel lamination occurs. This facies occurs throughout the La Baie des Carrières section and is commonly associated with other Class E deposits.

The medium-bedded glauconitic sandstone-mudstone couplets (FF-2) account for 15% of the section. Bed shape may appear tabular and lensoid (Fig. 10c). The calcareous sandstone beds are structureless except for local flaser-bedding and parallel lamination. Grain sizes are in the range of coarse- to fine-grained sand. The mudstones are rich in glauconite and iron. Thin section analysis shows common benthic foraminifera (*Rotalia*, miliolids, *Amphistegina*) and rare planktonic foraminifera (Fig. 10j, k). Isolated corals and bivalve fragments are also observed.

Beni Aouf section

The Beni Aouf section lies to the NNW of Jebel Sebaâ and overlies the Middle to Upper Eocene Souar Formation (Figs. 3, 11a). The deposits are formed by medium-bedded sandstone–mudstone couplets, mudstones and very thick and thick-bedded calcareous glauconitic sandstone with mudstone partings (Fig. 11b), a rich planktonic foraminiferal assemblage and large echinoderm fragments (Fig. 11c, d).

Petrologically, the sandstone beds are texturally and compositionally mature quartz arenites (Fig. 11e, f), with scarce rock fragments (including Telliian sediments) and feldspars in a calcite cement (Fig. 11g). No large benthic foraminifera are noted, which attests to a more open marine environment than that of the La Baie des Carrières succession. The steeply dipping (45° to the SE) Beni Aouf succession is tectonically overlain by a conglomerate-rich succession of Jebel Sebaâ with more gently dipping strata (5°–15°) (Fig. 11a).

Henchir Ben Naïm section

The Henchir Ben Naïm succession is very poorly exposed and difficult to log. The outcrop chiefly comprises glauconite-rich sandstones embedded within a mudstone facies association (Fig. 12a). The facies include thick-to-very thick sandstones showing linguoid ripples (Fig. 12b), thick-to-very thick calcareous glauconitic sandstones (Fig. 12c), very fine-grained sandstones, mudstones and glauconitic-rich iron mudstones.

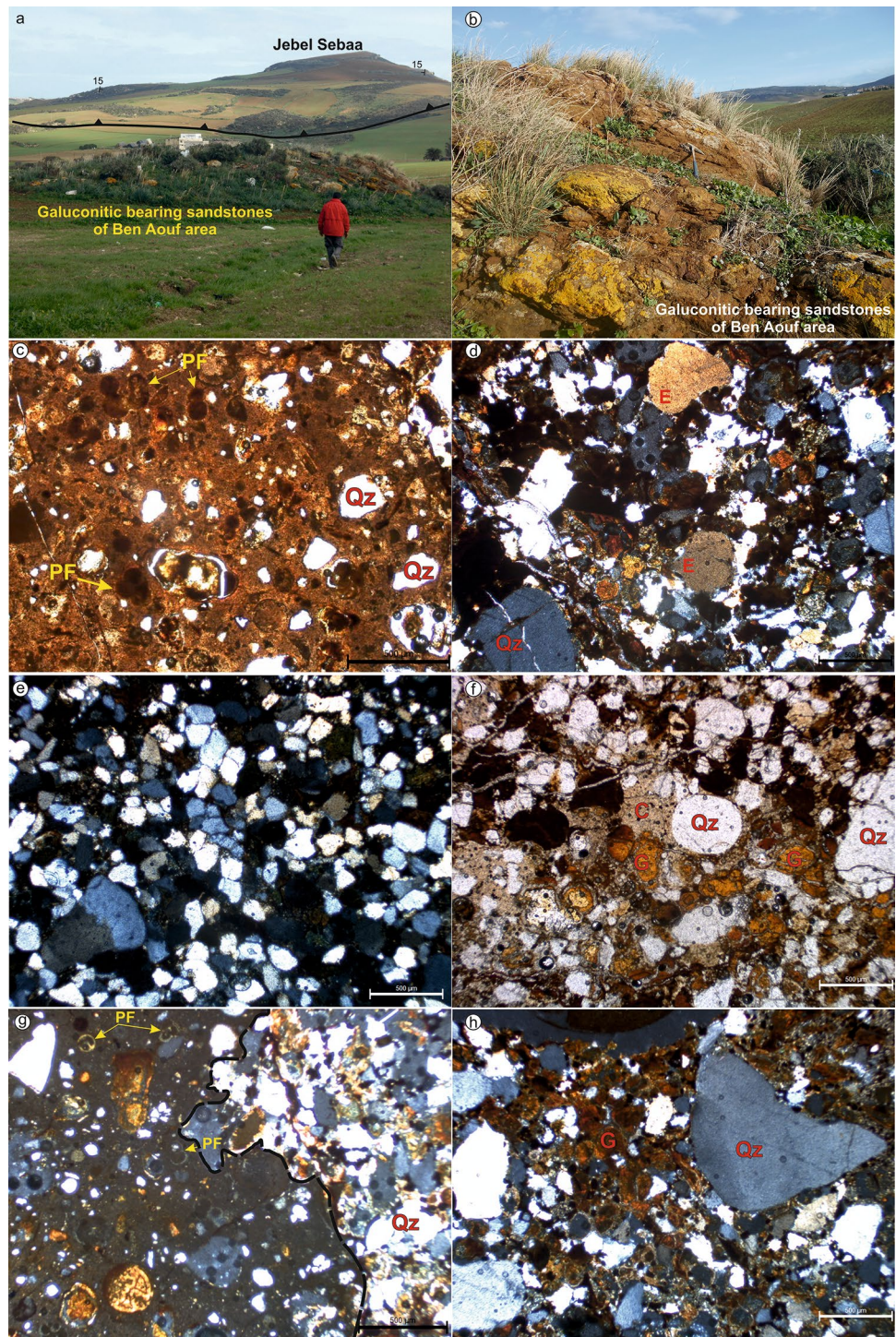
Jebel Zoukar and Ras El Korane sections

Two Numidian Flysch Formation outcrops were selected for study: (1) Jebel Zoukar and (2) Ras El Korane (Fig. 3). These are considered in comparison with the Oligocene–early Miocene deposits of the Jebel Sebaâ, Henchir Beni Aouf and Beni Naïm, Bizerte Town-Sidi Salem, Cap Blanc and La Baie des Carrières sections described above. The Numidian Flysch facies and facies associations have been previously described by Riahi (2011) based on a detailed work carried out in the Kroumirie Mountains in northern Tunisia. Nevertheless, herein we describe additional distinct facies that are not reported in earlier work.

Both Ras El Korane and Jebel Zoukar sections comprise the massive sandstone facies association sensu Stow et al. (2001), together with associated deepwater facies. The facies group A (conglomerates and pebbly sandstones) is relatively the most abundant facies group accounting for approximately 57% of the total section. Of these facies, the graded-stratified pebbly sandstone is the most abundant (35–40%). Beds are medium-to-very thick (typical bed thicknesses from 0.4 to 3 m) and have variable geometry (Fig. 13). They have gradational contacts with both normal and inverse grading (Fig. 13e, f), and coarse stratification of coarser pebbly sandstone medium-grained sandstone (Fig. 13c). In some cases, the facies in this group co-occur as part of megaturbidites (> 10 m thick graded bed). The matrix-supported conglomerate facies accounts for 5% of the section. It consists of thick-to-very thick-bedded, poorly sorted pebble conglomerates to gravel conglomerates (Fig. 13a, b). Clasts of fine-to-coarse pebble grade are most common, with dispersed glauconite-rich cobbles and boulders. Beds range from 0.5 to 3 m thick, with common amalgamation. They can be lensoid in shape, incised into the underlying mudstone and sandstone deposits. The rounded-to-well-rounded pebbly clasts of 7 cm in length may be imbricated throughout the thickness of the bed and are held within a poorly sorted matrix of mud-to-coarse sand (Fig. 13b). Flute marks are present at the bases of many beds (Fig. 14a). Variable oversized glauconite boulders (Fig. 13c), pectinid bivalves, whitish vitreous black cobbles (probably chert nodules), mudstone and grey-to-light grey limestone clasts are common. The shale-clast conglomerate facies makes up around 10% of the two sections and is typically represented by highly lenticular/erosive beds (30 cm to 1.5 m in thickness) (Fig. 13c). The clast population is characterized by dominant very poorly sorted rounded to elongate shale clasts that contribute up to 60% of the bed volume, with a poorly sorted matrix of mudstone and coarse pebbly sandstone. The normally graded pebbly sandstone occurs less commonly (5–10%) and is typically represented by 2–3 m thick sandstone beds which display well-defined normal grading from base to top.

The thick/medium-bedded, massive structureless sandstones of Facies Group B (with < 20% mud and silt

Fig. 11 Lithofacies and microfacies of clastic glauconitic bearing sandstone deposits of Beni Aouf outcropping northward of Jebel Sebaâ. **a** The Oligocene succession of Beni Aouf overlaid by the Numidian structural unit (Jebel Sebaâ). **b** Close view of the very thick and thick-bedded calcareous glauconitic sand with mud parting. **c** Bioclastic planktonic foraminifera wackestone with calcite cement. **d** Sandy lime glauconitic sandstone encompassing frequent Echinoids which indicate an open marine environment. **e** Quartz arenite texture with monocrystalline quartz grains. **f** Glauconite-rich sandstones with calcite cement. **g** Resedimented Tellian facies rich in planktonic foraminifera. **h** Glauconite-rich sandstones with monocrystalline quartz grains



matrix and <5% pebbles-grade material) form the second most abundant facies (16%). Beds are parallel-sided to highly irregular, and locally display water-escape structures (Fig. 13f). Grading is absent or poorly developed as a coarse-tail grading, with small pebbles and granules

concentrated in a thin basal layer and then dispersed throughout the beds. Individual beds range in thickness from about 1–2 m, but are commonly amalgamated into thicker units.

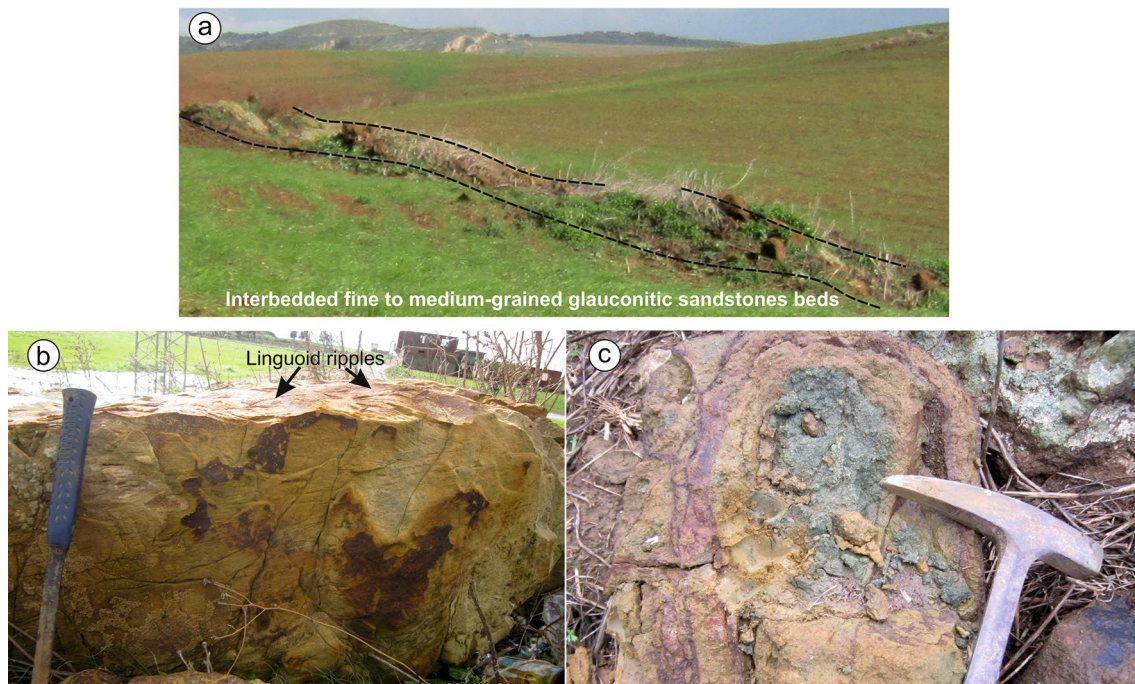


Fig. 12 Photos illustrating the lithofacies and sedimentary characteristics of Henchir Ben Naïm section. **a** Isolated glauconitic sandstones within a mudstone facies association. **b** Thick to very thick, fine-

grained sandstones showing linguoid ripples at the top. **c** Calcareous sandstones glauconitic rich concretions

Associated facies include: (1) thin- to thick-bedded sandstone–mudstone turbidites (Facies Group C, Fig. 14), some with climbing-ripple lamination (Fig. 14c), accounting for 15% of the section; (2) varicolored mudstones (Facies Group D), either structureless or with Stow-division fine-grained turbidites (upper divisions) and some bioturbation traces (e.g. *Chondrites*, and *Trichichnus* sp.), accounting for 5% of the section; and (3) Chaotic or slumped units (Facies Group F, 14% of the section), from < 1 m to > 10 m in thickness (Fig. 14d). These chaotic facies are typically most common within the finer-grained facies, and include extensive packages of clast-rich mudstone. They comprise clasts of all sizes, boulders and contorted soft-sediment clasts, supported in a muddy matrix. Although no ideal debrite sequence was clearly recognized according to the scheme proposed by Stow (2010), their collective characteristics allow a muddy debrite interpretation.

Bizerte Town/Sidi Salem section

The Oligo–Miocene outcrops in Bizerte Town are discontinuous but still accessible adjacent to buildings, in Sidi Salem and along the Bechateur–Jebel Sebaâ road. At Sidi Salem, only two facies were observed, graded pebbly sandstones (Fig. 15a) and greenish-coloured mudstones. The pebbly sandstone beds are medium to very thick (0.45–1.5 m)

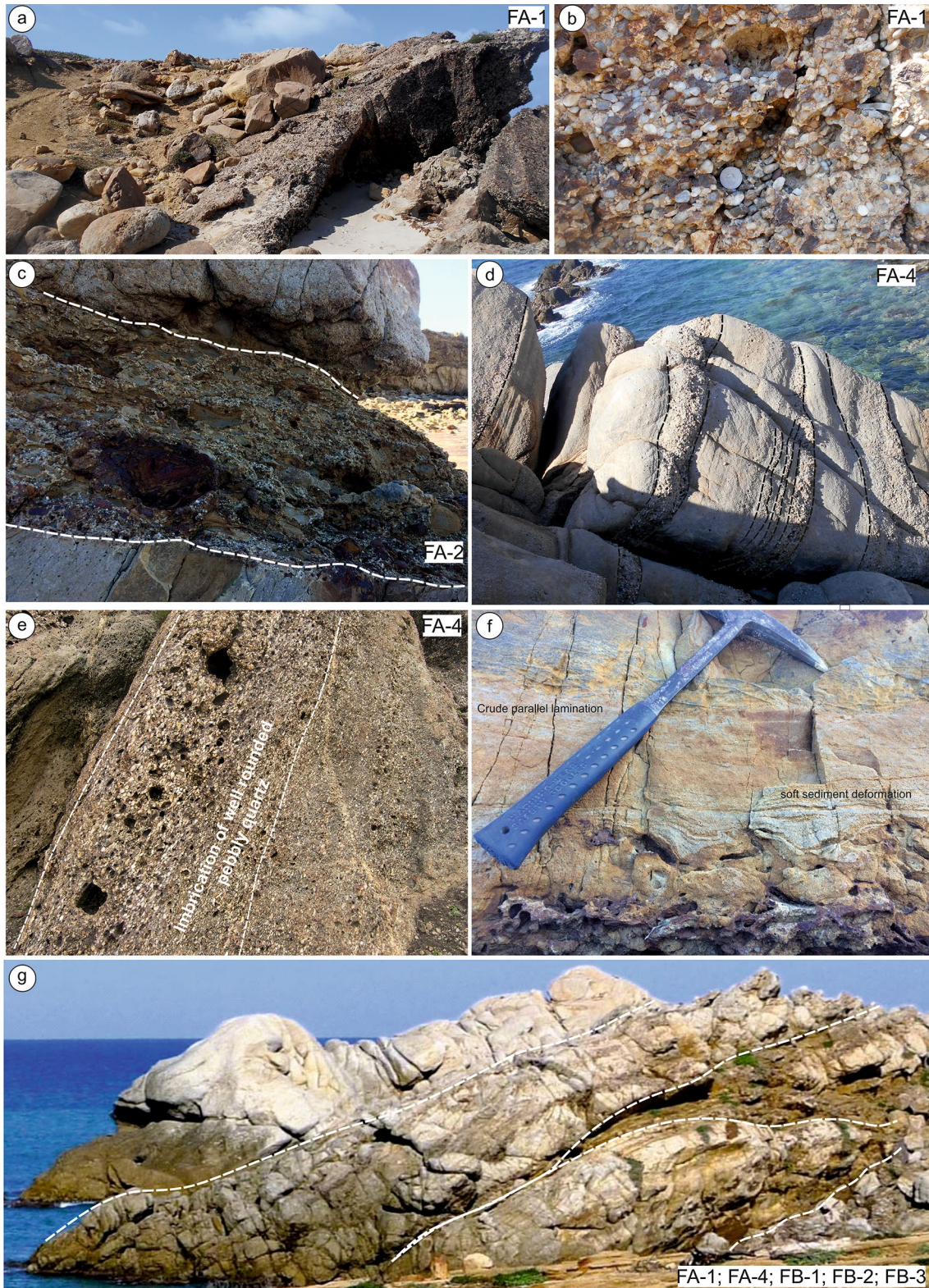
and show an alternation of pebble- and sand-rich layers (Fig. 15a, b). Individual beds have gradational contacts with both normal and inverse grading, and are poorly sorted.

Along the Bechateur–Jebel Sebaâ road (Fig. 15c), the succession is dominated by fine-grained sediment facies (thin-bedded sandstone/siltstone) interbedded with thick/medium-bedded massive sandstones and parallel-stratified sandstones. The massive sandstones are fine- to medium-grained and consist of parallel-sided sandstone beds. Small shale clast horizons tend to occur in the lower or lowest part of the bed (Fig. 15d), whereas more common are isolated shale clasts dispersed throughout the beds. Sandstones with parallel- and cross-lamination are less common (Fig. 15e). The sandstone-mudstone couplets facies group is represented by thin-to-medium beds containing horizontal silt laminae in mudstone, with some slightly lenticular, indistinct and wispy silt laminae. Silt: mud ratios range from about 2:1 to about 1:2.

Discussion

Depositional environment

As stated in the introduction to this paper, there remains uncertainty and controversy surrounding the depositional environments of the Oligocene–early Miocene deposits



of the easternmost Mogod Mountains. Do they represent fluvial deposition (Fortuna Formation), shallow marine deposition (Grès de Bejaoua Formation), or deep marine deposition (Numidian Flysch Formation)? For example,

the deposits of Jebel Sebaâ have been considered as fluvial in origin (Bajanik and Salaj 1972; Melki et al. 1999; Fildes et al. 2010) and representing the Fortuna Formation, whereas an alternative interpretation suggests that they have

Fig. 13 Characteristics of the massive sands facies association of the Numidian Flysch Formation in Ras El Korane-Jebel Zoukar. **a** Matrix-supported conglomerates represented by very poorly sorted pebble conglomerates and including large outsized iron clasts. **b** Close view of photo (a) showing the rounded to well-rounded forms of pebbly clasts of 7 cm in length (although on average are 0.1–3 cm). **c** Large outsized glauconite clasts mixed with matrix-supported conglomerates **d** thick to very thick beds of graded-stratified pebbly sand facies. Beds show an alternation of pebble- and sand-rich layers with extremely variable shape. Both parallel-stratification and large-scale cross-stratification occurs and represented by an alternation of granule sand and pebbles with coarse- to medium-grained sand. **e** Inversely graded matrix-supported conglomerates showing imbricated clasts throughout the thickness of the bed. **f** Graded sandstones. **g** Early Miocene deposits at the top of Ras El Korane succession including 4 storeys filled with interbedded conglomerates, pebbly sandstones and Massive sands. At the base, the storey includes large outsized iron clasts, passing upward to more depositional in the last one

turbiditic affinities and accordingly represent the Numidian Flysch Formation (Biely et al. 1971; Hoyez 1989; Rouvier 1977). The gently dipping Jebel Sebaâ strata (Fig. 3) has lead the adherents of the first assumption to interpret it as stratigraphically discordant upon the Upper Eocene (Souar Formation) and accordingly transgressive over the Telliian series (Crampon 1971; Bajanik and Salaj 1972; Melki et al. 1999). The new mapping and the combination of detailed biostratigraphic and sedimentological data presented herein, allows us to resolve this debate. We have identified two principal depositional environments as follows.

Deep marine environment

The sections at Jebel Sebaâ, Cap Blanc, Sidi Salem, Bizerte, Ras el Korane and Jebel Zoukar are all interpreted as having been deposited in deep marine environments by turbidity current and associated downslope and hemipelagic processes. They can therefore be considered as part of the Numidian Flysch Formation. This interpretation is supported by the faunal content recorded in the mudstone facies that attests to a mid-bathyal depth, and the assemblage of benthic agglutinated foraminifera that is typical of the Numidian Flysch Formation elsewhere (Riahi et al. 2014). It is furthermore supported by the range of sedimentary features typical of deepwater facies, including: normally graded beds, sole marks, fluid-escape structures, thick structureless sandstones, dispersed and nested shale clasts. Both medium and thin-bedded turbidites, with Bouma and Stow turbidite structural sequences, are well represented (Johansson et al. 1998; Stow et al. 2019; Stow and Smillie 2020).

The deepwater massive sandstone assemblage found in several sections, with common water escape features, is typical of rapid deposition from high-density turbidity currents through an active basal layer of hindered settling (Lowe 1975; Stow and Johansson 2000). The massive and

structureless character of such beds has been attributed to the suppression of sedimentary structures and aggradation beneath quasi-steady turbulent flows (Kneller and Branney 1995). The high proportion of conglomerates, shale-clast conglomerates, and very thick-bedded structureless pebbly sandstones in the Jebel Sebaâ, Jebel Zoukar and Ras El Korane successions are compatible with more proximal sections of the Numidian basin. These sediments were most likely deposited by the dense basal part of bipartite turbidity currents characterized by horizontal and vertical segregation of grain-size population (Mutti et al. 1999). The shale clast types and distribution are typical of those described by Johansson and Stow (1995) from deepwater massive sandstones globally. The slurry sandstone facies have been linked to deposition by high-efficiency turbidite systems where flows can travel and erode a large amount of mud (Tinterri and Tagliaferri 2015). The abrupt grain-size breaks noted in some vertical sections may imply flows only dropping coarse parts of their sediment load, with the remaining finer grained



Fig. 14 Photos illustrating the interchannel facies group in Ras El Korane and Jebel Zoukar. **a** Flutes casts recorded at base of coarse-grained facies at Ras El Korane. **b** Mudstones interbedded with fine-grained turbidites. Ripples (Tc) and parallel laminations (Tb) are common with some dewatering structures. **c** Rippled surface (Bouma C-division) of medium-thick turbidite sand (Jebel Zoukar). **d** Indistinctly bedded to unstratified, well-bedded and non-bedded type of chaotic facies. **e** Deformed dykes. Over-pressurisation during deep burial and/or thrust emplacement has further led to sandstone injection from thick sand bodies into the surrounding mudrocks



Fig. 15 Panoramic view and lithofacies of the siliciclastic deposits in Bizerte Town and along Bechateur road. **a** Numidian succession at Sidi Salem. **b** Ta and Tb of Bouma (1962) sequence recorded in the Numidian Flysch succession (Sidi Salem area). **c** Thin-bedded and medium-bedded turbidites forming part of sandstone–mudstones facies association of the Numidian Flysch succession along Bechateur Road. **d** Thick sandstones bed. **e** graded sandstone beds with dispersed shale clast

fractions continuing down-system (Kneller and McCaffrey 2003; Stevenson et al. 2015; Butler et al. 2020).

We interpret the presence of channel architectural elements in the Ras El Korane and Jebel Zoukar (Fig. 16) sections, which provide an excellent exposure along an outcrop belt of 5 km long and ~600 m thick. The evidence for channel interpretation includes (Table 1): the dominance of coarse-grained facies, high sandstone/mudstone ratio, common shale-clast conglomerates, widespread erosional features and incised character of many beds, the block-like to fining-upward vertical sequences of mainly coarse-grained beds, broadly lenticular to incised lateral geometry of sandstone bodies. The paleocurrent orientation recorded from flute marks and cross-bedding, both within and adjacent to the channel bodies (in Jebel Zoukar and Ras el Korane) shows a mainly NNE-SSW and/or E-W orientation, which corresponds well with the main E-W oriented paleoflow trends observed across the Numidian basin (Hoyez 1989; Riahi et al. 2015). The variability of paleocurrent analysis in the SW area (Sejnene, Zouza and Balta) is presumably

related to a transverse structural alignment (N150 Balta fault) at right angles to the Numidian thrust fronts. Such faulting is capable of yielding important morphological barriers that can deflect or reflect the turbulent flows that evolve parallel to the thrust fronts.

The channel architecture observed in this study can be described hierarchically based on Sprague et al. (2002, 2005) and Macauley and Hubbard (2013). The entire 600 m at Jebel Zoukar represents a single complex-set (Fig. 16), made up of two-channel complexes, which are distinguished from one another by a widespread laterally extensive fine-grained unit (mudstones and fine-grained turbidites). Most of the other sections observed show similar channel complexes that are composite features made up of genetically related channel storeys 6–15 m thick. Seven different channel storeys are identified as Ch-1 to Ch-7 from base to top (Fig. 16). The section at Ras El Korane consists of 5th order channel complexes made up of a series of 4th order channel storeys (Fig. 17). These contain individual glauconite-rich clasts up to boulder size. These, together with the silicified carbonate pebbles, shell fragments and limestone boulders recorded in the gravel-rich SUA of Jebel Sebaâ can be interpreted as derived from erosion of older sediments in the uplifted and emergent areas that sourced the Numidian Flysch basin.

Shallow marine environment

The sections at La Baie des Carrières, Ben Aouf and Henchir Ben Naïm are all interpreted as having been deposited in shallow marine environments and influenced by a range of normal marine processes, such as shelf currents, wave and tidal action. They can, therefore, be considered as part of the Grès de Bejaoua Formation as already interpreted by Biely et al. (1971) and Soussi et al. (2012), and not part of the Fortuna Formation as suggested by some authors (Melki et al. 2001). This interpretation is supported by the presence of large benthic foraminifera, rare planktonic foraminifera, and echinoderms, which are characteristic of a shallow marine environment, allied to a recent age determination by Boukhalifa et al. (2020). Furthermore, the sediment facies, sediment structures, and the commonly high glauconite content lead are all compatible with this interpretation.

The Oligocene succession of Beni Aouf shows more open marine conditions, on the basis of faunal assemblage, which would indicate a more outer shelf setting compared to La Baie des Carrières. Also, these deposits correlate well with the Oligocene outcrops of the Nefza Window, the so-called Tellian Oligocene (Rouvier 1977; Boukhalifa et al. 2020). It is worth noting that there is no record of the early Miocene sedimentation in the regions of Bizerte and Nefza, which indicates non-deposition, erosion or non-preservation sediments in the area for this geologic time.



Fig. 16 Aerial photomosaic of an oriented N–NE (20°–200°N) Numidian Flysch outcrop belt of 5 km long and ~600 m thick in Jebel Zoukar, North Bizerte area. The outcrop is made up of coarse-grained, conglomerates to gravely channelized deep-water strata surrounded by fine-grained deposits (mudstones, silts and thin-bedded fine sandstones). The channel complexes are composite features consisted of genetically related channel elements or storey 6–15 m thick named as Ch-1–Ch-7 and this from base to top

Table 1 Evidence of channel interpretation in Ras El Korane and Jebel Zoukar, northern Tunisia

Dominant facies association	Minor facies association	Sand/mud ratio	Shale clasts	Water-escape features	Erosional features	Vertical sequences/bedding:	Lateral geometry
Deep-water and coarse-grained (massive sandstones, conglomerates-turbidites, channel-lag conglomerates), and chaotic (slide-slump units, debris) typically encased in finer-grained turbidite-hemipelagite facies	Fine-grained (mudstone, mudstone-siltstone, mixed sandstone-mudstone), generally turbidites and related deposits; and chaotic (especially injectionite sandstones into surrounding mud-rich facies)	generally sand-rich (dependent on channel type), from 1:1 to > 9:1, more typically > 5:1	Common component of channel-fill sediment and locally abundant; all clast types present (especially erosional A-types and shale-clast conglomerates), with more B-types down-channel	Common feature in channel-fill sands, full and partial water-escape sequences evident (especially larger-scale escape features and convolution)	Clear evidence of marked erosion at base of channel body and common erosion at base of beds within channel-fill (minor irregular scours, flutes and grooves also typical at base of beds)	Meso-sequences commonly blocky, with little internal organization; alternatively thinning-up/fining-up sequences, thick and very-thick beds (commonly amalgamated) together make up > 50% total channel-fill beds	Where exposure permits, channel margins are deeply erosive into finer-grained slope sediments; lenticularity of individual beds common; lateral migration of channel-fill succession is commonly observed. Channel dimensions are derived from the mapping of the channel fill. The term individual channel was used to infer a product of a single cycle of channel cutting, filling, and avulsion or abandonment <i>sensu Sprague et al. (2002)</i> ; two or more channel-fills of similar architectural style are termed Channel Complex

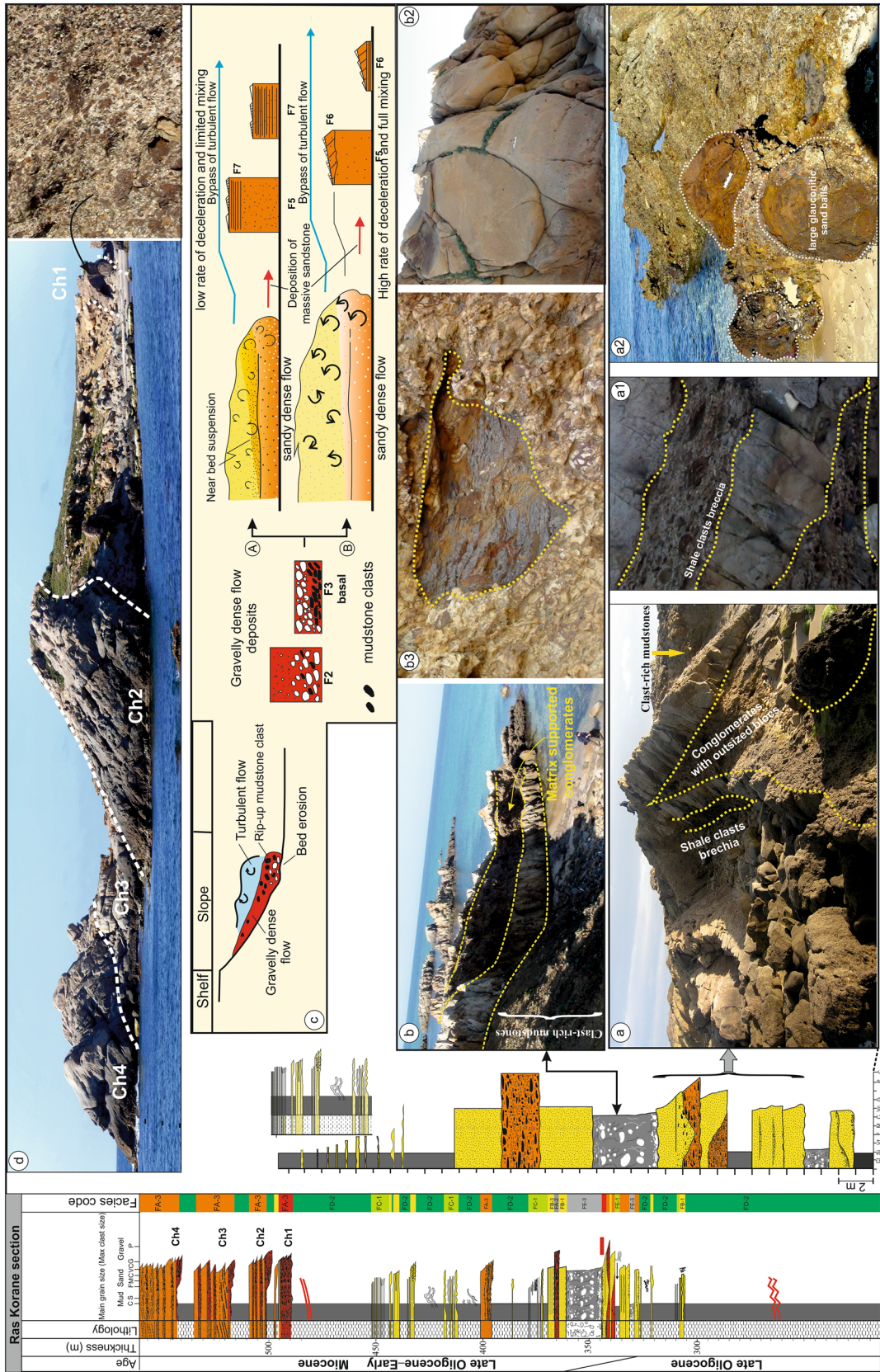


Fig. 17 Lithofacies and architectural elements of the Numidian succession of Ras El Korane; **a** channel storeys characteristic of the sand unit 1 at ras Korane; showing common cut and fill events within storeys. **a1** Very poorly sorted, sub-angular, matrix-supported, chaotic shale clast breccias. The clasts are generally pebble sized (40 mm) and form a laterally impersistent zones or as clast 'nests' between sandstone beds and orientated subparallel to bedding. **a2** Common resedimented glauconitic sand balls at the top of a storey. **b** Channel complex 2 showing common cut and fill events and overlying a clast-rich mudstones (muddy debris). **b1** The shale clast; contains *diplocraterion habichti* which attests the erosion of the underlying layers. **b2** Channel complex 3 showing normal grading and made up by a single channel. **c** Facies types examined upon transformation of a dense sandy flow into a turbulent flow (Mutti et al. 2003). **d** vertical stack of 4th order storey's termed Ch1–Ch4 which are much coarser grained. The base of storey's includes large outsized iron clasts passing upward to more depositional in the last one

New map interpretation and tectonic style for the Bizerte area

The stratigraphic and sedimentological field research presented here for the Oligo–Miocene of the eastern Mogods, allied to further structural field data from the region, have allowed us to refine the geologic map of the Bizerte area (Fig. 18). In short, we agree with Biely et al. (1971) and Rouvier (1977) that the Jebel Sebaâ and outcrops of Bizerte Town are part of the Numidian Flysch Formation and therefore can be interpreted a tectonic klippe (Fig. 19).

The structural style of Bizerte area shows NE–SW striking anticlines and synclines (Fig. 18) affected by NW–SE dextral right strike-slip faulting (i.e. N150 Ras Enngela fault) and NE–SW thrust faulting (Cap–Bizerte fault). These lineaments are presented along the AA' transect (Fig. 19) that show from north to south the following structures: (1) the Jebel Sebaâ Syncline, (2) the Jebel Kebir–Jebel Abiod Anticline, with internal thrust folded tight anticlines and synclines, (3) the Bizerte Syncline, and (4) the Jebel Karrita Anticline. The N150 Ras Engela strike-slip faults, and associated minor NW–SE faults, have induced compartmentalization of the area into independent structural blocks, each one characterized by a specific structural style. The importance of the NW–SE faults has been also demonstrated in the Kroumirie Mountains (the N150 Balta fault).

This compartmentalization allowed to Biely et al. (1971) to distinguish the principal autochthonous unit just west of the Ras Engela fault (Bouzaria area), formed by Upper Cretaceous to Oligocene glauconitic-bearing sandstones of the Grès de Bejaoua (Fig. 19). We contrast this with an allochthonous unit covering the area from Ras el Korane to Jebel Kebir in the south. It is made up of Paleocene–Eocene–Tellian Oligocene of Ben Aouf tectonically overlapped by the Numidian Flysch structural unit. The allochthonous nature of the Numidian Flysch Formation in the Bizerte area can be understood when studying its relationship with time-equivalent deposits (Figs. 20, 21). The terrigenous glauconitic sandstone sequence conformably overlying the Souar Shale in Beni Meslem and Beni Aouf corresponds to the Tellian Oligocene of Rouvier (1977). This suggests a significant juxtaposition of different Oligocene–Miocene units and indicates that the Numidian Flysch succession outcropping in Jebel Sebaâ and Bizerte Town should be interpreted as a tectonic klippe overlying an autochthonous unit formed by the Abiod Formation, El Haria clays, the *Globigerina*-rich chalky limestones of Ypresian age, the Middle to Upper Eocene Souar Formation, and the Oligocene sandstones of the Bejaoua group.

Paleogeographic implications

The published Oligocene–early Miocene paleogeographic maps for northern Tunisia (Salaj and Van Houten 1988; Yaïch 1997) consider that the Bizerte area was either emergent or later uplifted and eroded, and so devoid of Grès de Bejaoua sediments. However, the Grès de Bejaoua Formation is well documented in the northern Beja, Boussalem and Ghardimaou area (Gottis 1962; Rouvier 1977; Yaïch 1997; Boukhalfa 2011). In the present study, it has been demonstrated the missing of the Fortuna Formation, meanwhile the existence of the Oligocene under Bejaoua and Tellian facies in the Bizerte area, so that a revised understanding of the paleogeographic history is needed. The facies distribution of the Fortuna Formation presented here is adopted from the extensive works of Yaïch (1997) and partly refined based on the published several exploration wells in offshore Tunisia (Raja-1, Rod-1, Car1 wells) and in offshore western Sicily (Meccariello 2017). In summary, we propose that the distribution of the Oligocene–Miocene deposits in central and eastern Tunisia (Fortuna Formation), north of the salt dome paleohigh (Grès de Béjaoua Formation), and in northernmost Tunisia (Numidian Flysch Formation) appear to be influenced by various topographic highs and faults that dictated the drainage pattern and sediment distribution.

Oligocene: upper Rupelian–Lower Chattian

As demonstrated by Yaïch (1997), during the Oligocene (Upper Rupelian–Lower Chattian) the Fortuna Formation was characterized by a SW–NE trending facies distribution (Fig. 20). The most proximal deposits (deltaic, lagoon-restricted marine, bioclastic ramp) are located in the central Tunisia at the location of the present north–south axis, while the distal deposits appear towards the Cap-Bon area (El Haouaria, Gulf of Hammamet) and in the offshore domain in the NE. According to Yaïch (1997), such facies differentiation resulted from the progressive deepening towards the east and NE with the development of *Nummulites*-rich limestone bars between Korbous and Zembra Island to the NE. We consider that the northern part of salt dome area (e.g. Thibar) acted as a paleohigh at this time, and guided the dispersion of Fortuna Formation facies along a SW–NE trend. The northeastern extent of this paleohigh is also confirmed in the Raja-1, Rod-1 and Car1 exploration wells (Soua et al. 2016).

North of the salt dome area, the Sidi Mhimech section (near Beja area) is the only one that registers continental deposits (Yaïch 1997). Elsewhere, the Grès de Béjaoua Formation is present but thin and discontinuous, represented by calcareous sandstones, glauconitic sandstones and

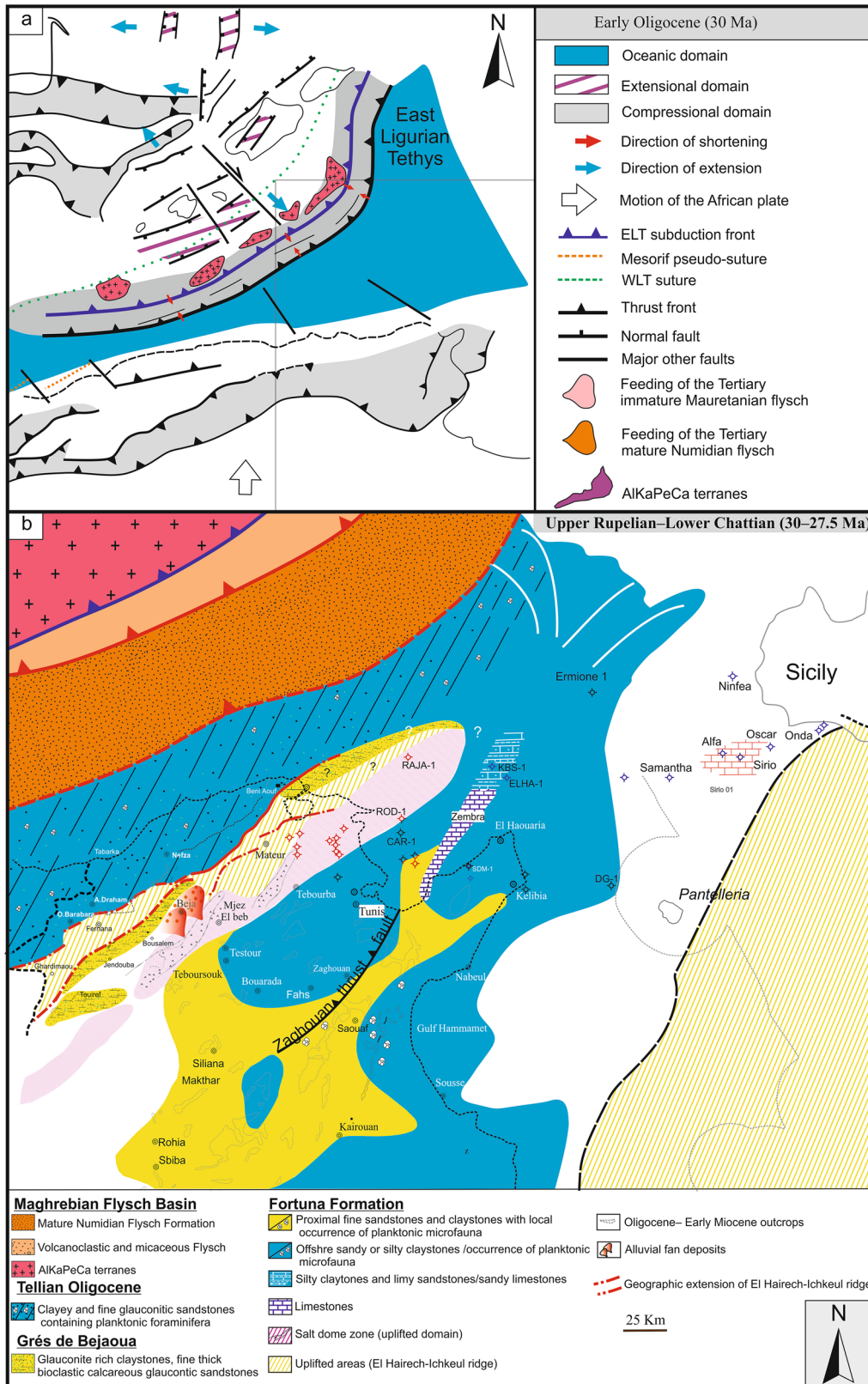


Fig. 20 a Early Oligocene (30 Ma) palaeogeographic map of the western Mediterranean highlighting the location of the Maghrebian flysch basin (Leprêtre et al. 2018). **b** Oligocene (Upper Rupelian–

Lower Chattian) palaeogeographic map showing the distribution of the different Oligocene–Miocene deposits in Tunisia. Facies of Fortuna Formation are slightly modified from Yaïch (1997)

mudstones of foreshore and offshore depositional environments. These deposits deepen northward (Fig. 20) (Henchir Beni Aouf in Bizerte area, Nefza, north of Zahret Madien (Chaabet ez-lazel/Gassaa (Riahi et al. 2007)) and Barbara areas) where the sedimentation becomes mudstone dominated, with rare glauconitic sandstones, and contains pelagic foraminifera (*G. opima* and *G. ampliapertura* zones). The limit between the shallower Oligocene and the deeper one is coincidental with the NE-SW Hairech-Ichkeul ridge (Fig. 20), which corresponds to a submerged high that was clearly in existence from the upper Campanian to the lower Lutetian, as evidenced by reduced thicknesses of the Campanian–Maastrichtian limestones (~150- to 200-m) and missing Lutetian series and lower Eocene limestone (Rouvier 1977; Dlala 1995).

Further north, the Tellian domain evolves into deep-water turbidites (Fig. 20). In this part of the basin, the Oligocene is represented by deposition of deep marine sandstones and mudstones of the Numidian Flysch Formation and more immature sandstones of the La Galite Formation, which is also of turbiditic affinity. Sandstone suites of the Numidian Flysch Formation are exclusively quartzose in composition (Qt92–99 F1–4 L0–3).

According to the eustatic sea-level curves of Haq et al. (1987) (Fig. 4), the early Oligocene period was marked by relative global sea-level high, whereas the late Oligocene saw relatively low sea levels. An early Oligocene transgression is recognized in Tunisia (Yaïch 1997; Boukhalfa 2011) and elsewhere by Thomas et al. (2010). However, the tectonically active nature of this region makes a direct correlation with eustatic sea level less easy to observe, and local variations were almost certainly present. According to the global Cenozoic oxygen isotope curve of Zachos et al. (2001) (Fig. 4), there is a general trend towards global cooling from the Paleocene–Eocene thermal maximum. This may have resulted in a wetter climate and more sediment supply across the North African region.

Early Miocene: Late Aquitanian–Early Burdigalian (N4-to-N5 zones)

A similar paleogeography seems to have persisted from the Oligocene through the early Aquitanian periods, whereas the upper Aquitanian–early Burdigalian (N4–N5 zones) heralds a significant change in facies and depositional environment. The alluvial-fluvial Fortuna Formation facies are much coarser-grained extending along a SW-NE corridor from the El Alaa in the SW to the Cap Bon area in the NE (Fig. 21). The isopaque map of sediment thickness (Burollet 1956) suggests a restriction or confinement in the width of the drainage pathway, which is more or less parallel to the Zaghouan thrust fault. To the north, the upper Fortuna Formation sediments are distributed parallel to the uplifted

salt-walls of Thibar and Lansarine (Figs. 20, 21). This indicates that the fluvial drainage pattern was influenced also by the northern salt dome paleohigh that guided the dispersion facies pattern of the upper Aquitanian. To the NW and north of the salt dome area, the Grès de Bejaoua deposits are transgressive over the Cretaceous to Paleocene series (Jebel Ben Amara) and marked by the deposition of bioclastic limestone and glauconitic sandstones containing *Miogypsina gunteri* and *Globigerinoides primordius* (Hoyez 1989). The local occurrence of fluvial coarse-grained sediments north of the salt dome area is presumably related to local bypass and erosion of the salt wall due to fault cutting (Gaidi et al. 2020). The Sidi Mhimech sector near Beja continued to show continental deposits of alluvial fan affinity (Yaïch 1997).

During the Aquitanian, the occurrence of planktonic foraminifera in some outcrops of the Grès de Bejaoua Formation (Jebel Ben Amara) suggests relative deepening of the paleo-environment (Fig. 21). This applies also to the kasseb Dam, Boussalem and Jantoura areas, which do not show the persistence of an emergent high during the early Miocene. The submergence of the Tellian Oligocene domain is supported by the extensive leaching of the Oligocene deposits in Nefza and the development of vuggy and moldic porosities in thin sections. Northward, the Numidian Flysch Formation continued the infill of deepest and subsiding parts of the Foredeep, while the Grésomiacé Flysch could represent a wedge-top deposition on advancing thrust belt (Critelli 2018).

Basin configuration during the Oligocene–early Miocene

Taking into account the geodynamic evolution of the western Mediterranean, it is accepted that since the Oligocene (30 Ma), the African ocean crust was subducted to the north under the AlKaPeCa domain (Lentini et al. 2002; Golonka 2004; Finetti et al. 2005; Thomas et al. 2010; Roure et al. 2012; Leprêtre et al. 2018; Critelli 2018; Khelil et al. 2019; Henriquet et al. 2020) resulting in the transition from a passive-margin-bounded basin to a compressional foreland basin system (Leprêtre et al. 2018; Guerrero and Martín-Martín 2014; Guerrero et al. 2020). Here, we infer that supracrustal loading by the AlKaPeCa orogens led to the partitioning of the foreland basin into foredeep, forebulge, and back-bulge flexural provinces (Fig. 22a). In northern Tunisia, the variable sediment distribution and depositional environments of time equivalent deposits (Numidian Flysch, Grès de Bejaoua and Fortuna Formations) reflect such partitioning and appear to be influenced by differential basin subsidence (Fig. 22b).

Based on their facies characteristics, we propose that the Tellian Oligocene facies of Late Rupelian–Early Chattian age (regions of Bizerte, Nefza, Oued Barbara and Zahret

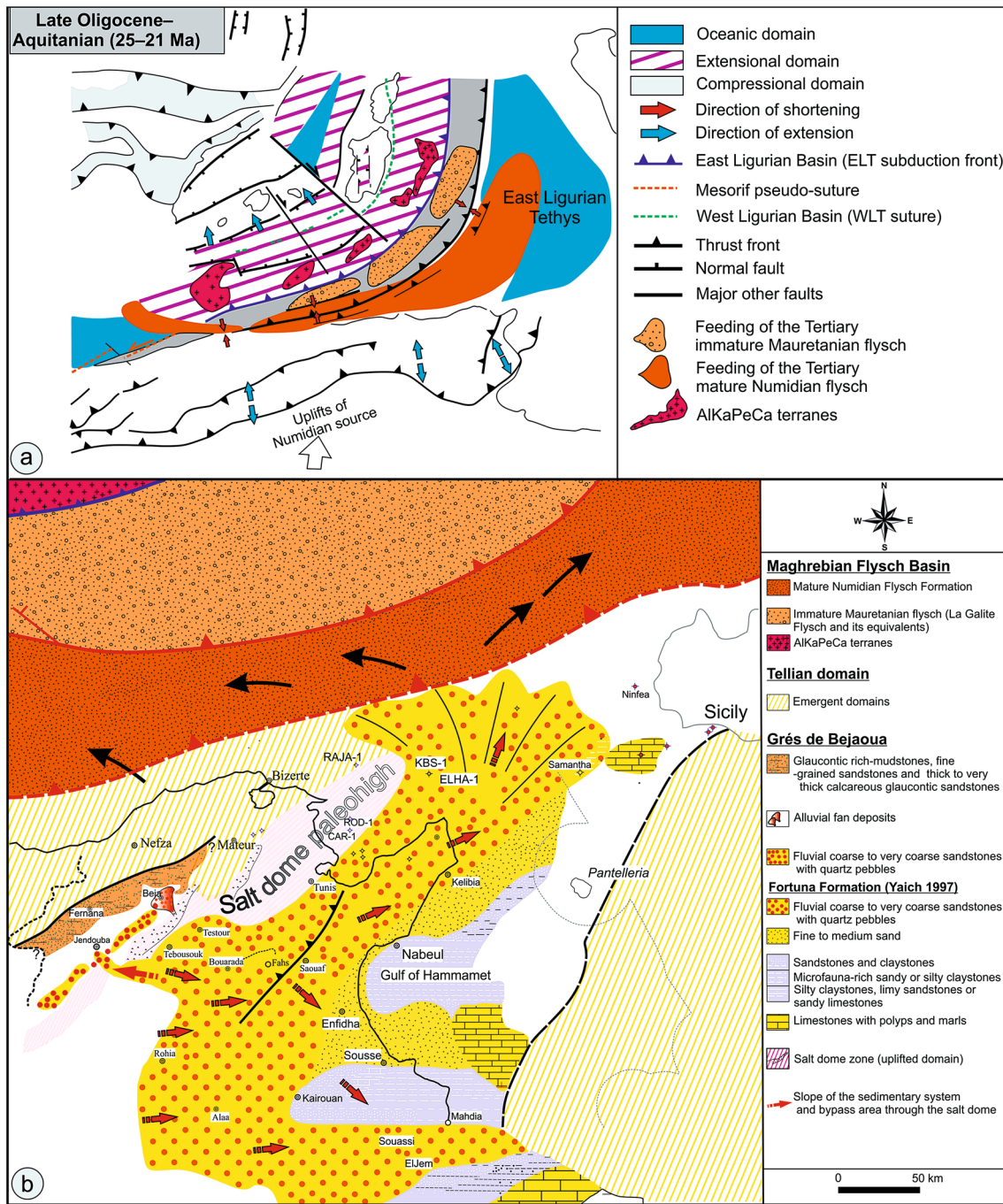


Fig. 21 **a** Late Oligocene–Aquitanian (25–21 Ma) palaeogeographic map of the western Mediterranean (Leprêtre et al. 2018). **b** upper Aquitanian–Burdigalian (21–20 Ma) palaeogeographic map highlighting the relationship between showing the different Oligocene–Miocene deposits in Tunisia (Numidian Flysch Formation, Tellian

Oligocene, Bejaoua facies and Fortuna Formation). The facies of Fortuna Fm are slightly modified from Yaïch (1997), while the facies and age of the “Grès de Bejaoua” were based on Rouvier (1977) and Boukhalfa (2020)

Madien) occupied the hinge zone of a forebulge setting, should represent a transitional or lateral facies of the Oligocene Numidian turbidites that infill the deepest and subsiding parts of the Foredeep. Meanwhile, south of the Hairech-Ichkeul ridge (assumed here to be the forebulge),

the Grès de Bejaoua facies of the SW Mateur, Beja and Boussalem areas were deposited in a back-bulge depozone (Fig. 22b).

During the upper Aquitanian–Burdigalian (21–20 Ma), such domains have evolved in response to tectonic

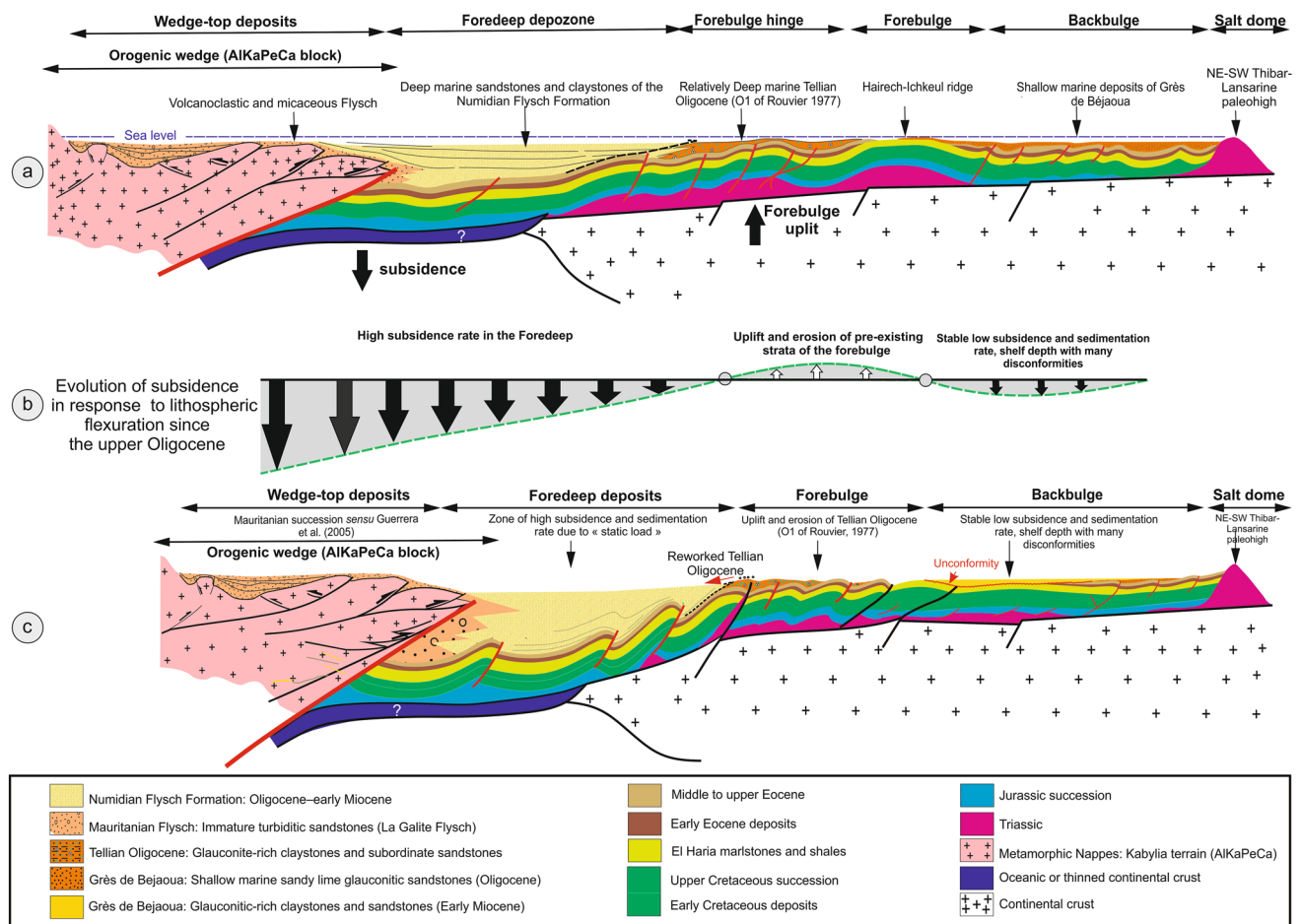


Fig. 22 Oligocene–early Miocene Foreland basin configuration, subsidence and recorded facies

loading and flexuring of the Western Mediterranean foreland (supracrustal load and flexural deflection). The Numidian Flysch Formation continued the infilling of the initial foredeep basin that developed before the Miocene on top of the most distal portion of the North African margin, whereas south of the Hairech–Ichkeul frontal thrusts to the salt dome high, was created a frontal basin recording episode of sedimentation and subsidence, where early Miocene deposits (glauconitic-rich shales and fine-grained sandstones in Jebel Ben Amara) unconformably overlap the top of either Paleocene or Late Cretaceous series (Fig. 22a). Nevertheless, there is no record of late Oligocene–early Miocene sedimentation in the regions of Bizerte, Nefza and Zahret Madien, which is presumably, related to submergence and uplift of these areas (Fig. 22c) in response to the foredeep subsidence and supracrustal load and flexural deflection that led to submergence of Telliian domain which in turn become with the Hairech-Ichkeul as forebulge.

The integration of sedimentological, structural field work (Dlala 1995; Riahi et al. 2010, 2015; Essid et al. 2018) and biostratigraphy/ichnological data (Riahi et al. 2014) on the

Numidian Flysch Formation in northern Tunisia show the intricacy to admit an unconfined deep-sea environment sensu Guerrera et al. (2012) and Belayouni et al. (2010).

The absence of a clear facies differentiation (from proximal to distal) between the Numidian Flysch Formation outcrops straddling the coastline and those confined to the present Numidian thrust front makes this hypothesis contestable. The correlation of various stratigraphic cross sections (Riahi 2011; Riahi et al. 2014) oriented parallel and perpendicular to the main tectonic structures and paleocurrents data (Hoyez 1989) are rather consistent with confined turbidites deposition. The most important evidence supporting this hypothesis is: (1): the Numidian succession of the eastern Mogods (Ras El Korane, Jebel Zoukar, Jebel Sebaâ, Kef Abbed and Ras El Ali) records the coarsest lithofacies locally comprising individual beds of coarse pebbly conglomerates up to 3 m in thickness (Figs. 13, 14), while westwards in the Kroumirie Mountains (Cap-Serrat, Tabarka, Beni Metir), there is a notable grain size decreases (mostly fine-to-medium grain sized fraction). Therefore, we suppose that flows carried out finer grain

sized fraction down system westward. This lateral facies change is well inspected along NE-SW corridors limited by faults (Dlala 1995; Riahi et al. 2015) and the direction of sediment routing is essentially parallel to the trend of thrust-related basins that controlled the Numidian deposition. We infer that confined foredeep was fed by an axial sediment supply. Additionally, the upward increase in the studied stratigraphic succession of the sandstone/mudstone ratio, grain sizes and occurrence of shallow water trace fossils (*Ophiomorpha*) testify the high degree of flow deceleration related to the progressive closure and uplift of the foredeep.

During the late Burdigalian–early Langhian (17–14 Ma), the docking of the Kabylie against the African margin occurred marking the closure of the central part of the Maghrebien Tethys and the onset of the delamination of the sub-continental African mantle (Leprêtre et al. 2018; Roure et al. 2012). The Numidian Flysch Formation is therefore stacked above the external Tethyan units, and a significant juxtaposition of Oligocene–Miocene deposits under different depositional environment is inferred. Paleogeographic back-stripping suggests that deposition of the Numidian Flysch Formation occurred more than 40 km to the north (Rouvier 1977; Carr and Miller 1979).

Conclusion

Integrated facies, microfacies and microfaunal analyses of the Oligo–Miocene deposits in the Bizerte area of the Mogod Mountains in northern Tunisia, has greatly improved our knowledge of the internal architecture, depositional setting and palaeogeographic relationships between different time equivalent deposits (Fortuna, Grès de Béjaoua, and Numidian Flysch formations). The facies observed at Jebel Sebaâ, Cap-Blanc and Sidi Salem are typical of deep marine downslope gravity sedimentation of the Numidian Flysch Formation, which is supported by their deep marine microfossil content. The facies of La Baie des Carrières, Henchir Beni Naïm are characteristic of shallow marine shelf deposits and represent the Grès de Béjaoua Formation, and not the Fortuna Formation as previously proposed. This is supported by a diverse benthic microfossil assemblage.

The variable sediment distribution and depositional environments of the Oligo–Miocene deposits in northern Tunisia can be explained by the partitioning of the Foreland basin system that induced differential basin subsidence (Fig. 22). We propose that the Grès de Bejaoua facies were deposited in a forebulge and back-bulge setting, while the deep marine sandstones and mudstones of the Numidian Flysch Formation occupied the foredeep domain. Since the

upper Oligocene, such domains have evolved in response to supracrustal load and flexural deflection.

The occurrence of these coeval deposits under different depositional environments in the Bizerte area implies a significant thrusting that induced juxtaposition of dissimilar coeval Oligocene–Miocene deposits. Within this framework, the Numidian Flysch succession of Jebel Sebaâ and Bizerte Town may be interpreted as tectonic klippe overlying an allochthonous unit formed by Paleocene–Eocene to Oligocene-bearing sandstones.

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