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ORIGINAL ARTICLE

Biofacies analysis and depositional environments of mid-Eocene larger benthic foraminifera-rich deposits in northern Tunisia

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Abstract

In NW Tunisia, the lateral facies equivalents of the mid-Eocene (Bartonian) "Reineche Limestones" member of the shaley Souar Formation, which constitute a proven reservoir hydrocarbon bearing in Gulf of Gabes, are still poorly known and characterized in NE Tunisia and the Salt Dome zone. Recent sedimentological investigations conducted on: (1) the "Reineche Limestones" member in its type locality in NE Tunisia and (2) three correlative sections, first described herein NW Tunisia, allow improving our knowledge about the Middle Eocene biofacies distribution as well as their depositional environment at a regional scale. Fossil assemblages, rock texture, and fabrics lead to the characterization of eight micro-biofacies (Mf1–Mf8) corresponding to "shoal" inner ramp and middle-to-outer ramp depositional settings. This study demonstrates that the Bartonian carbonates of NE Tunisia bear LBF-dominating assemblages and subordinate planktic and small benthic foraminifera, gastropods, algae, and echinids are indicative of marine ramp context under oligotrophic conditions. However, correlative successions from NW Tunisia are represented by relatively thinner carbonate intervals, including either skeletal limestone facies or phosphorite-rich carbonates. The first facies type, dominated by LBF assemblages, suggests the same depositional conditions as the "Reineche limestones". The phosphorite-rich carbonate facies is characterized by the presence of peloids, bone fragments, lithic components with subordinate nummulitids, planktic and small benthic foraminifers, diversified open marine fauna, and fine siliciclastic grains, all suggesting oxic–sub-oxic conditions favorable for phosphorite genesis. The Bartonian phosphorite-rich carbonate of northwestern Tunisia represents a good example of phosphatic sediment production and accumulation during the latest episode of the Paleogene phosphatogenesis around the paleohigh structures of the Salt Dome zone in the south-Tethyan margin of Tunisia.

Keywords Mid-Eocene · Northern Tunisia · "Reineche Limestones" · Carbonate ramp · Larger Benthic Foraminifera

Introduction

During the Middle Eocene (Bartonian), wide shallow-marine carbonate platforms have been developed under the main control of atransgressive eventwell recorded in the Peri-Tethyan domain (Fig. 1A, B) (Martin-Martin et al. 2021, and references therein). In these broad carbonate shallow-marine environments, large benthic foraminifera-(LBF) facies deposited.

The skeletal component of these facies is dominated by nummulitids, alveolinids, and orthophragminids that required favorable ecological conditions including euphotic and oligotrophic marine habitats and tropical-to-subtropical water temperature (Hottinger 1983; Hallock 1985, 2000; Serra-Kiel et al. 1998). This transitional period with high abundance of K-strategist LBF taxa is dated as Lower Bartonian on the basis of the First Occurrence (FO) of the genus *Heterostegina* (Less et al. 2008; Less and Özcan 2012). It corresponds to the onset of a new global community maturation cycle (Hottinger 2001) and coincides with the transient warming during the Middle Eocene Climatic Optimum (MECO; Bohaty and Zachos 2003; Bijl et al. 2010). In this context, the Bartonian time interval in Tunisia is characterized by the development of a shallow-marine carbonate platform (Fig. 1C) with a remarkable variability of carbonate facies locally bearing diversified LBF assemblages.

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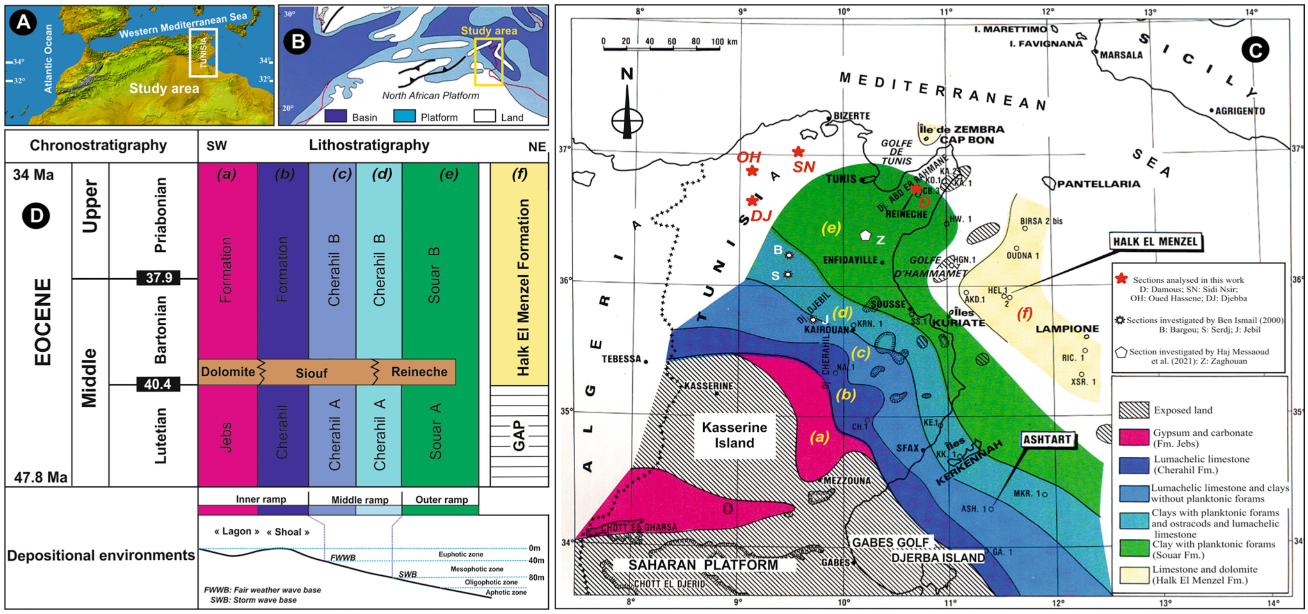

Fig. 1 Geographical and geological settings of the studied area. **A** Location of the study area within the Mediterranean region. **B** Mid-Eocene palaeogeographical map of southern Tethyan margin (Meulenkamp and Sissingh 2003). **C** Location of the main studied sections throughout the different palaeogeographical domains of Tunisia during the Mid-Eocene (Bismuth and Bonnefous 1981). See the same used colors in **D** for stratigraphic attributions. **D** Synthetic lithostratigraphic chart of the Paleogene showing main columnar sections, stratigraphic nomenclature, and main associated depositional environments from southwestern to northeastern Tunisia (Bismuth and Bonnefous 1981)

Three correlative lithostratigraphic units sandwiched within the lower Souar/Cherahil formations are known: the "Reineche Limestones" (Burollet 1956) within the deep-marine shaley Souar Formation, the "Siouf" shallow-marine skeletal limestones of the North–South Axis (Jebel Siouf) within the Cherahil Formation and the "White Dolomite" member (Comte and Dufaure 1973) of the Jebs Formation cropping out in the Gafsa basin and developed in restricted lagoon/sabkha environments were described along an NE–SW trend from the Tunisian Atlas. These carbonate units correspond to regional stratigraphic marker beds sandwiched within a thick shaley unit and therefore used as a seismic marker in subsurface in the Gulf of Gabes by petroleum geologists (Burollet 1956; Comte and Dufaure 1973; Bismuth and Bonnefous 1981; Fournié 1978; Burollet et al. 1978; Ben Ismail-Lattrache and Bobier 1984; Fakhfakh Ben Jemai 2001; Amami-Hamdi et al. 2013, 2014, 2016; Haj Messaoud et al. 2021). The "Reineche Limestones" member consist of thick nummulitid-rich carbonate accumulation considered as good hydrocarbon reservoirs throughout the offshore of Tunisia (Chargui oil and gas field) and Libya (Klett 2001; Taktak et al. 2010; Njahi-Derbali et al. 2017). Previous thematic studies in northwestern Tunisia (Gottis and Sainfeld 1956; Kujawski 1969; Rouvier 1977; Erraoui 1994; Alouani et al. 1996; Boukhalfa et al. 2009; Tlig et al. 2010) did not focus on a detailed biostratigraphic frame and no detailed biostratigraphic data are reported from the coeval deposits of the "Reineche Limestones" marker carbonate levels. Their depositional settings and paleogeographic context are still the object of controversies (e.g., Bonnefous and Bismuth 1982; Ben Ismail-Lattrache 2000; Fakhfakh Ben Jemai 2001).

This work aims at attempting to bring new insights into micro- and macro-facies analyses, regional correlations, and paleoenvironmental interpretations of the middle Eocene deposits from northwestern Tunisia. Beyond regional investigations, our study attempts replacing the Middle Eocene carbonate platform of northern Tunisia in its southern Tethys context and discussing major controlling factors of its development.

Location and geological setting of the study sections

The four studied successions are located in northern Tunisia. The Djebba (DJ) section is situated in the Salt Dome Zone, the Oued Hassene (OH), and Sidi N'sir (SN) sections in the "la zone des écailles" or "Imbrication structural zone", to the south of the folded and thrust domain and the Damous (D) section, in the Cap Bon peninsula (Type locality of the Reineche member). These four Bartonian-aged sections are sampled bed by bed (Fig. 1C). The Damous Quarry section (D section; 20 m) was investigated in the Cap Bon peninsula of NE Tunisia, at the western flank of the Jebel Abderrahman anticline, about 50 m to the west of the road joining MenzelBouzelfa-to-OumDhouil localities. The Sidi N'sir condensed section (SN; 1.20 m) is located to the SE of the structural thrust zone of NW Tunisia, about 500 m to the East of the road deserving Mateur to Beja localities. The Djebba section (DJ; 4 m) is located in the salt Domes zone, at northwestern flank of the Goraa plateau near Djebba village situated at 5.5 km to the South of Thibar and 13 km to the west of Teboursouk town. The Oued Hassene condensed section (OH; 0.60 m) was sampled in the Beja area, ca.10 km to the North-west of Beja town, and 3 km to the West of Amdoun locality.

Our study is focused on the limestone packages intercalated within the Souar (D, SN, and OH sections) and Cherahil shaley (DJ section) formations.

The stratigraphic reference chart of the Eocene corresponds to that published in the International Subcommission of Paleogene Stratigraphy homepage (ISPS; www.paleogene.stratigraphy.org) where the Eocene series (− 56 to − 33.9 My) comprises the Ypresian, Lutetian, Bartonian, and Priabonian stages. For the Bartonian, its base is defined by the abundance of the larger benthic foraminifer species *Nummulites prestwichianus* JONES 1862; its top approximates the base of the Priabonian marked by the successive extinction of large acarininids and the species *Morozovelloides crassatus* COSHMAN 1925.

In Tunisia, the lithostratigraphical chart of the Eocene series (Fig. 1D) shows that marly-to-limestone sequences of middle-to-upper Eocene age in central and northern Tunisia are included in the Souar or Cherahil formations, both considered as lateral equivalents of the Jebs evaporitic Formation (Bishop 1988) toward the South.

Since pioneer works on the middle–late Eocene in Tunisia, the proposed biostratigraphic schemes based on benthic and planktic foraminifers and ostracods have been the subject of controversies and continuous improvements (Burollet 1956; Bismuth and Bonnefous 1981; Bonnefous and Bismuth 1982; Mechmèche 1981; Mechmèche and Toumarkine 1987). The 90s of the last century are characterized by notable advances in approaching a relatively stable age assignments to the reference Souar and Cherahil formations (Ben Ismail-Lattrache 2000; Amami-Hamdi et al. 2013, 2014, 2016 and references therein). These formations are composed of shallow-to-deep-marine clays with thin limestone intercalations, assigned to the Lutetian–Priabonian interval (*Morozovella lehneri* biozone (P12)–*Turborotalia cerroazulensis* (P16/P17) biozones, Ben Ismail-Lattrache 2000). They intercalate carbonate marker levels referred to as the "Reineche" and "Siouf" members within the lower third of the Souar and Cherahil clayey formations, respectively.

Based on nannofossil biozonation and $\delta^{13}C_{org}$ chemostratigraphy, recent improvement of the previous charts by Haj Messaoud et al. (2021, 2023) provides a high-resolution correlation table used here. They confirm that the most part of "Reineche" and "Siouf" members as parts of carbonate platforms lie within the Lower Bartonian (lower CNE 15 Zone of calcareous nannofossils, correlated with the E12 Zone of Planktic Foraminifers and the SBZ 17 of Larger Benthic Foraminifers, LBF). A partly equivalent interval in the reference section of the Souar Formation (Zaghouan area) includes a radiolarian-rich biosiliceous interval encompassing the Lutetian–Bartonian transition.

Materials and methods

Field geological investigations include bed-by-bed sampling with thorough observations of lithological and sedimentological features. Laboratory analyses aimed at defining the petrographic texture of skeletal limestone beds and their micropaleontological content in LBF assemblages. A total of 33 samples were collected for thin-section observations under a "Nikon Eclipse E 200" optical microscope for the identification of main skeletal and non-skeletal components, carbonate grains, matrix, and mineral compounds. Components are divided into three categories, according to the relative abundance estimated under the optical microscope. A given element is considered as: (1) present when it is seen at least once in the whole thin section; (2) common when it appears at least once using an objective × 4; (3) abundant when it appears two-to-four times using an objective × 4. For size evaluation are used the terms large ($D > 1$ cm) and small ($D < 1$ cm). Shape description involves the terms flat ($D/T > 2$) or robust ($D/T < 2$) where D and T refer to the "Diameter" (or wide) and the "Thickness", respectively. Microphotographs were taken by means of a digital camera (Leica M80), transferred to the computer using a Nikon's Digital Sight DS-U3 microscope camera controller and treated with the imaging software Nikon NIS Elements F4. The microfacies analysis and lithology description followed the classification of Flügel (2010) and Dunham (1962). To differentiate microfacies assemblages, all the allochem components and matrix were characterized and visually quantitatively estimated in thin sections. A particular attention has been paid to the Bartonian phosphorite-rich lithofacies which are described and documented here for the first time.

Results

Biofacies composition and occurrences

On the basis of the content in skeletal elements and foraminiferal assemblages, eight main bio-microfacies have been recognized (Table 1).

– *Foraminiferal/red algal biofacies (Mf1)*: occurs only at the middle part of the Damous section. The skeletal assemblage is dominated by alveolinids, associated with micritized nummulitids, small benthic forams, miliolids, amphisteginids, and orthophragminids (Fig. 2A).

- *Ostracod biofacies (Mf2)*: is observed in both Sidi N'sir (Fig. 2B) and Oued Hassene (Fig. 5A) sections. It is dominated by ostracods with subordinate very rare nummulitids, and brachiopods (Figs. 2B, 5A)
- *Nummulitid biofacies (Mf3)*: identified in all studied sections. The foraminiferal assemblage is dominated by large and flat nummulitids. It is associated with common orthophragminids, alveolinids, amphistegina, and small benthic foraminifera at the Damous section (Fig. 2A), while brachiopods, ostracods, echinoderms, and small benthic foraminifera are usually common in Oued Hassene (Fig. 5A) and Djebba (Fig. 5B) sections.
- *Nummulitid and orthophragminid biofacies (Mf4):* described in Damous (Fig. 2A), Sidi N'sir (Fig. 2B), and Djebba (Fig. 5B) successions. It is predominated by large and flat nummulitids and orthophragminids, associated with rare small benthic and planktic foraminifera, brachiopods, and echinoderms (Figs. 2A, B, 5B).
- *Operculina biofacies (Mf5)*: recorded only in Sidi N'sir section (Fig. 2B). The skeletal assemblage is largely dominated by *Operculina* and large flat nummulitids, associated with common orthophragminids, rare planktic foraminifera, echinoderms, and ostracods (Fig. 2B).
- *Orthophragminid biofacies (Mf6)*: observed at the base of both Damous (Fig. 2A) and Sidi N'sir (Fig. 2B) sections. It is dominated by orthophragminids associated with common nummulitids, *Amphistegina* sp., planktic foraminifera and rare echinoderms, bryozoans, brachiopods, and small benthic foraminifera (Fig. 2A, B).
- *Planktic foraminifera (Globigerinid) biofacies (Mf7)*: characterizes the upper part of Damous section (Fig. 2A). The skeletal assemblage is largely dominated by globigerinids. Small benthic foraminifers are usually common and green-glauconite grains can be present (Fig. 2A).
- *Phosphorite microfacies (Mf8)*: characteristic of Sidi N'sir (Fig. 2B), Oued Hassene (Fig. 5A) and Djebba (Fig. 5B) successions. It is mainly composed of peloids, bone fragments, and lithoclasts associated with common small benthic foraminifera, nummulitids, ostracods, brachiopods, and echinoderms fragments and rare globigerinids (Figs. 2B, 5A, B).

Facies distribution

The Damous section

This section is made of 20-m-thick limestone beds of the "Reineche" member intercalated between the clayey "Souar A" member, to the base, and the silty-clay interval of the "Souar B" member, to the top (Fig. 2A). Microfacies, characteristic sedimentological features, and macrofossil content allowed subdividing the Damous section into five intervals (Figs. 2A, 3).

- *Interval M1* (4m; orthophragminid biofacies, Mf6): composed of marls and thin-bedded muddy limestone intercalations. The limestone beds show packstone texture dominated by orthophragminids (Fig. 3A, B) associated with nummulitids, planktic and small benthic foraminifera, echinoids, bryozoans, and *Amphistegina* sp. Rare coral fragments, miliolids, and red algae are also present.
- *Interval M2* (4.5 m; orthophragminid biofacies, Mf6): represented by whitish, fossiliferous nodular chalky limestone showing an irregular base (Fig. 2). It consists of wackestone dominated by orthophragminids and globigerinids (Fig. 3C, D) associated with nummulitids, alveolinids, red algae, and crinoids.

Table 1 Mf1–Mf8 bio-microfacies showing their occurrence sections and main fossil contents and non-skeletal grain components

Bio-microfacies (bmf)	Occurrences (section)	Fossils and non-skeletal grains
Mf1: Foraminiferal/red algea bmf	D	Alveolinids, nummulitids, small benthic forams, miliolids, amphisteginids, orthophragminids
Mf2: Ostracod bmf	SN, OH	Ostracods, nummulitids, brachiopods
Mf3: Nummulitid bmf	D, SN , OH, DJ	Nummulitids, orthophragminids, Small benthic forams, brachiopods, ostracods
Mf4: Nummulitid and orthophragminid bmf	D, SN, DJ	Nummulitids, orthophragminids, planktic and small benthic forams, brachiopods, echinoderms
Mf5: Operculina bmf	SN	Operculinids, nummulitids, orthophragminids, planktic forams, echinoderms
Mf6: Orthophragminid bmf	D, SN	Orthophraminids, nummulitids, amphisteginids, planktic and benthic forams, echinoderms, bryzoans
Mf7: Globigerinid bmf	D	Planktic and small benthic forams, glauconite
Mf8: Phosphorite bmf	SN, OH, DJ	Small benthic forams, nummulitids, ostracods, brachiopods, echinoderms, bone fragments, coprolites, peloids, lithoclasts

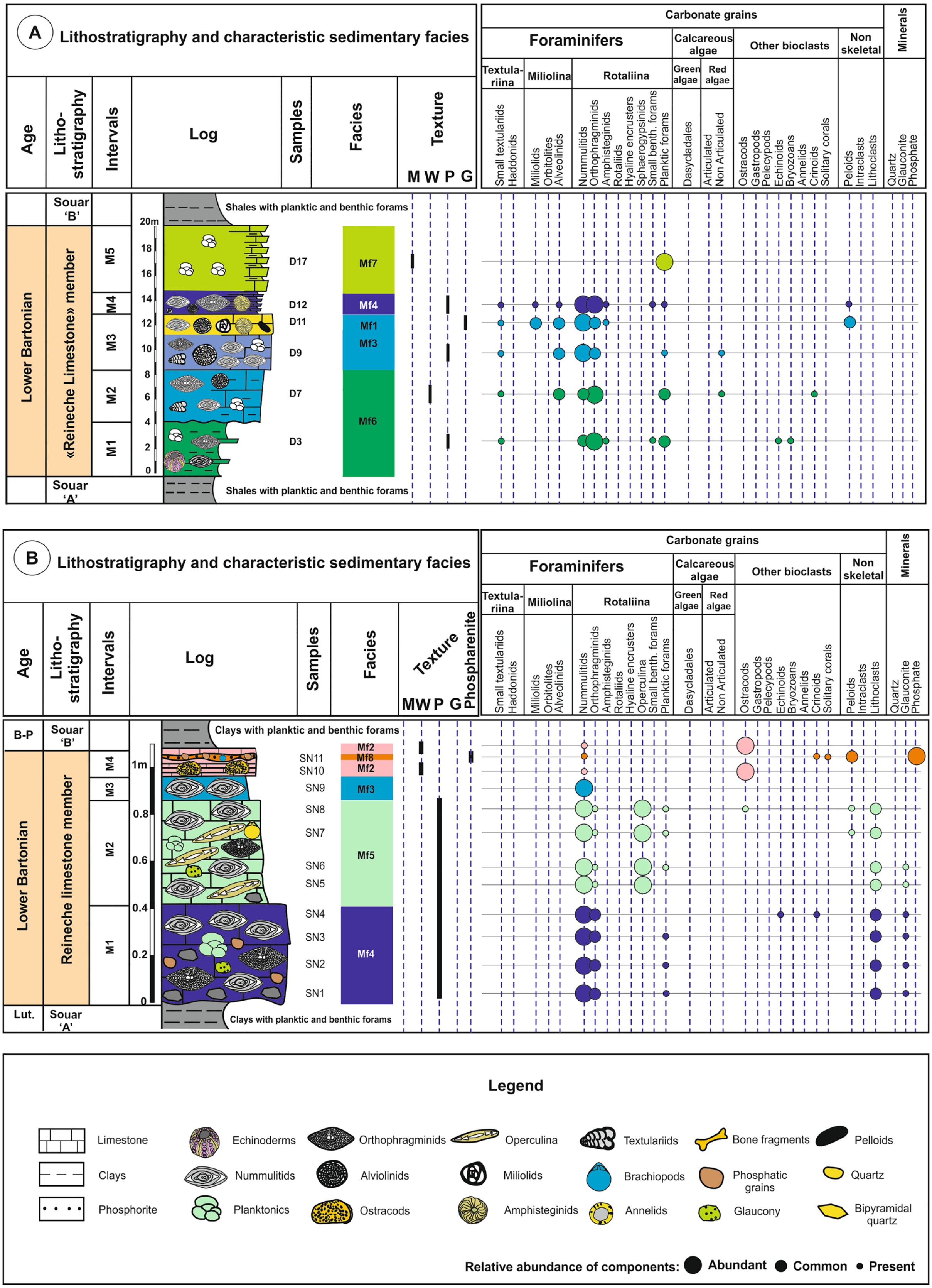

Fig. 2 Stratigraphic logs of Damous (**A**) and Sidi N'sir (**B**) sections with information on facies, texture, and skeletal assemblages

Fig. 3 Skeletal assemblage and microfacies in the Damous section. **A–D** Orthophragminid biofacies (Mf6) associated with small benthic foraminifera (**A, B**) and planktic foraminifera (globigerinids) (**C, D**). **E, F** Nummulitid biofacies (Mf3) associated with alveolinids (**F**). **G–I** Foraminiferal/Algal biofacies (Mf1) showing alveolinids (**G**), Miliolids (**H**), small benthic foraminifera and amphisteginids (**I**). **J, K**. Nummulitid and orthophragminid biofacies (Mf4) associated with alveolinid (**J**) and planktic foraminifera (**K**). **L** Planktic foraminifera (Globigerinid) biofacies (Mf7)

- *Interval M3* (4m; nummulitid biofacies, Mf3): starts with a 3-m-thick massive limestone succession of packstone texture yielding small nummulitids and alveolinids (Fig. 3E, F) associated with common orthophragminids as well as planktic and small benthic foraminifera and red algae. This limestone level is overlain by a 1-m-thick limestone level with a grainstone texture (*Mf1*) displaying abundant small benthic foraminifera, red algae, nummulitids, common alveolinids (Fig. 3G), miliolids (Fig. 3H), and amphisteginids (Fig. 3I).
- *Interval M4* (2 m; nummulitid and orthophragminid biofacies, Mf4): composed of centimeter-to-decimeter thick limestone beds with a thin intercalated clayey layer. The limestones consist of packstone showing nummulitid and orthophragminid-dominating biofacies (Fig. 3J, K). Planktic and small benthic foraminifera, amphisteginids, miliolids, and alveolinids are also present.
- *Interval M5* (5.5 m; planktic foraminifera biofacies, Mf7): represents the uppermost part of the section and consists of limestone/shale couplets. The unit is charac-

terized by abundant planktic foraminifera (Fig. 3L) and overlain by the globigerina-rich shales of the Souar "B" member.

The Sidi N'sir section

The Sidi N'sir section is represented by a 1.1-m thick well to poorly bedded limestone succession of the "Reineche" member, underlain by the clay dominated succession of "Souar A" and covered by silty-clays of "Souar B" (Fig. 2B). As for the Damous section, the Sidi N'sir succession can be subdivided into four intervals (Figs. 2B, 4).

- *Interval M1* (0.4 m; nummulitid and orthophragminid biofacies; Mf4) consists of a 0.4 m-thick packstone dominated by large flat nummulitids and orthophragminids (Fig. 2B). It is underlined by an irregular surface showing poorly sorted polygenic conglomerates (black and light gray lithoclasts). Thin-section analyses indicate that the skeletal assemblage is mainly composed of nummulitids and orthophragminids (Fig. 4A) associated with rare planktic foraminifers, echinoids, and brachiopod fragments. Lithoclasts represent a very significant fraction and glauconite grains are present.
- *Interval M2* (0.4 m; *Operculina* biofacies, Mf5): composed of a 0.4 m-thick limestone bed showing a packstone texture dominated by *Operculina* sp. and large flat nummulitids (Fig. 4B) associated with rare orthophragminids, planktic foraminifera, and ostracods. Lithoclasts are common and green-glauconite grains also occur.
- *Interval M3* (0.15 m; Nummulitid facies, Mf3): composed of a 0.15 m-thick lumachella bed showing big-sized nummulitids up to several centimeters in diameter (Fig. 4C).
- *Interval M4* (0.15 m; ostracod biofacies, Mf1): composed of a 0.15 m-thick massive gray mudstone bed topped by

Fig. 4 Skeletal assemblage and microfacies in the Sidi N'sir section. **A** Nummulitid and orthophragminid biofacies (Mf4). **B** Operculina biofacies (Mf5). **C** Nummulitid biofacies (Mf3). **D** Ostracod biofacies (Mf2). **E**, **F** Phospharenite (Mf8) showing peloids and quartz grains and rare nummulitids (**E**) and molluscan shells (**F**)

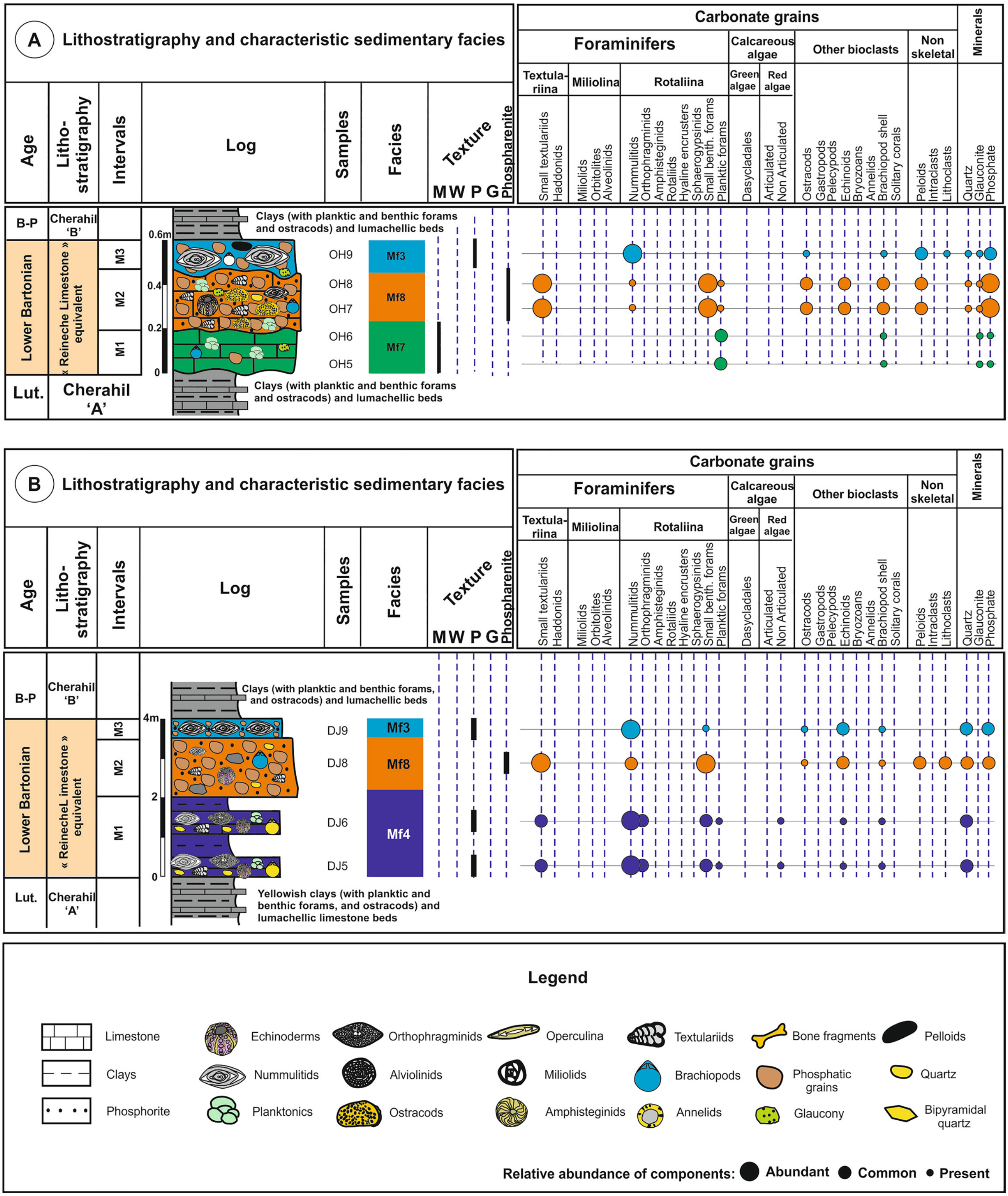

Fig. 5 Stratigraphic logs of Oued Hassene (**A**) and Djebba (**B**) sections with information on facies, texture, and skeletal assemblages

rounded calcareous lithoclasts. The skeletal assemblage includes ostracods and rare small nummulitids (Fig. 4D). This interval comprises a very thin layer (0.01m) showing phosphorite-rich microfacies (Mf8). Thin-section analyses of this phosphorite horizon show peloids, bone and shell fragments, and small nummulitids (Fig. 4E, F).

The Oued Hassene section

This section consists of a 0.60 m-thick condensed fossiliferous limestone bed overlain by "Cherahil B" marl/limestone alternations (Fig. 5A). It represents a lateral equivalent unit of the "Reineche Limestones" of the Souar Formation. These deposits of the "Reineche Limestones" lateral equivalent can be subdivided into three intervals (Figs. 5A, 6).

- *Interval M1* (0.2 m; globigerinids biofacies, Mf7): composed of 0.2 m-thick, muddy limestone of a mudstone texture with rare planktic foraminifera (Fig. 6A, B) associated with brachiopod shells (Fig. 6C).
- *Interval M2* (0.3 m; phosphorite-rich microfacies, Mf8): constituted by a 0.3-m-thick, phospharenite (Fig. 6D) with peloids (Fig. 6E), bone and shell fragments (Fig. 6F) associated with planktic and benthic foraminifera, mollusk fragments, and rare small nummulitids (Fig. 6D).
- *Interval M3* (0.10 m; nummulitid facies, Mf3): composed of a 0.10 m-thick fossiliferous packstone yielding abundant big-sized nummulitids up to several centimeters in diameter. The skeletal assemblage includes nummulitids (Fig. 6G) and rare ostracods and molluscan shell fragments (Fig. 6H). Peloids, lithoclasts, and glauconite grains are also present (Fig. 6G, H).

The Djebba section

The "Reineche Limestone" lateral equivalent of the Djebba section is represented by a 4-m-thick succession made of thin fossiliferous limestones, clays, and phosphorite-rich beds (Fig. 5B). This succession is intercalated between the clay/limestone couplets of "Cherahil A", to the base, and the clays and silty-clays interval of "Cherahil B". This section can be subdivided into three main intervals (Figs. 5B, 7).

- *Interval M1* (2 m; nummulitid and orthophragminid biofacies, Mf4): composed of clays with thin-bedded limestone intercalations. The limestone packstone beds are dominated by nummulitids and orthophragminids (Fig. 7A), associated with nummulitid fragments, red algae (Fig. 7B), and planktic and small benthic foraminifera (Fig. 7A–C). The terrigenous fraction consists of mainly fine subangular quartz grains (Fig. 7A, B).
- *Interval M2* (1.5 m; phosphorite-rich microfacies, Mf8): constituted of a 1.5 m-thick, phospharenite with peloids, bone, and shell fragments (Fig. 7D, E). The skeletal assemblage includes small benthic foraminifera, echinoids, brachiopod fragments (Fig. 7D), and molluscan shells (Fig. 7E).
- *Interval M3* (0.5 m; nummulitid facies, Mf3): consists of a 0.5 m-thick fossiliferous limestone bed yielding very abundant large flat nummulitids (Fig. 7F). The skeletal assemblages include nummulitids associated with rare ostracods, small benthic foraminifera, echinoids and brachiopods, and molluscan shell fragments. Peloids, lithoclasts and quartz grains are also present (Fig. 7F).

Facies interpretation and paleoenvironmental reconstruction

A generalized Cenozoic carbonate ramp model, main depositional environments, and associated faunas were outlined by Buxton and Pedley (1989). Based on modern assemblage analyses, this basic model previously proposed in the ramp profile by Read (1982) has been further refined by several authors (Van der Zwaan et al. 1990; Hohenegger 1994, 2000, 2004; Hohenegger et al. 1999, 2000; Geel 2000; Racey 2001; Pomar 2001; Renema and Troelstra 2001; Beavington-Penney and Racey 2004; Renema 2006, 2018; Mateu-Vicens et al. 2009; Pomar et al. 2017; Boudaugher-Fadel 2018). From outer to inner ramp settings, a diverse array of faunas responds to environmental constraints. Flat and thin large rotaliids (*Operculina* sp., Orthophragminids) dominate lower photic-zone assemblages and are associated with common planktonic foraminifera. Thick and robust nummulitids and amphisteginids (e.g., *Nummulites* sp., *Amphistegina* sp.) thrive in middle-shelf environments, and occupy niches close to the inner shelf. Very robust and large rotaliids (several species of amphisteginids, miogypsinids) dominate "shoal" settings, whereas in shallower waters, miliolids (alveolinids, soritids) are more abundant and can dominate in restricted environments (Martin-Martin et al. 2021; Coletti et al. 2021).

Within this framework, our data on foraminiferal assemblages serve to constrain the depositional environments of identified biofacies. Through the Damous and Sidi N'sir sections, the various vertical identified biofacies characterize a ramp profile with a gradual transition from a depositional environment to another (globigerinids, operculina, orthophragminids, nummulitids, and foraminiferal/red algae biofacies). In the Djebba and Oued Hassene sections, occurrences of phosphorite-rich facies associated with terrigenous input and a decrease in LBF assemblages indicate depositional condition changes between these two studied sectors.

In this study, seven biofacies and one phosphorite-rich microfacies are described from the different analyzed sections (Table 1). For each section, the paleoenvironmental interpretation will be based on the main bio- and microfacies

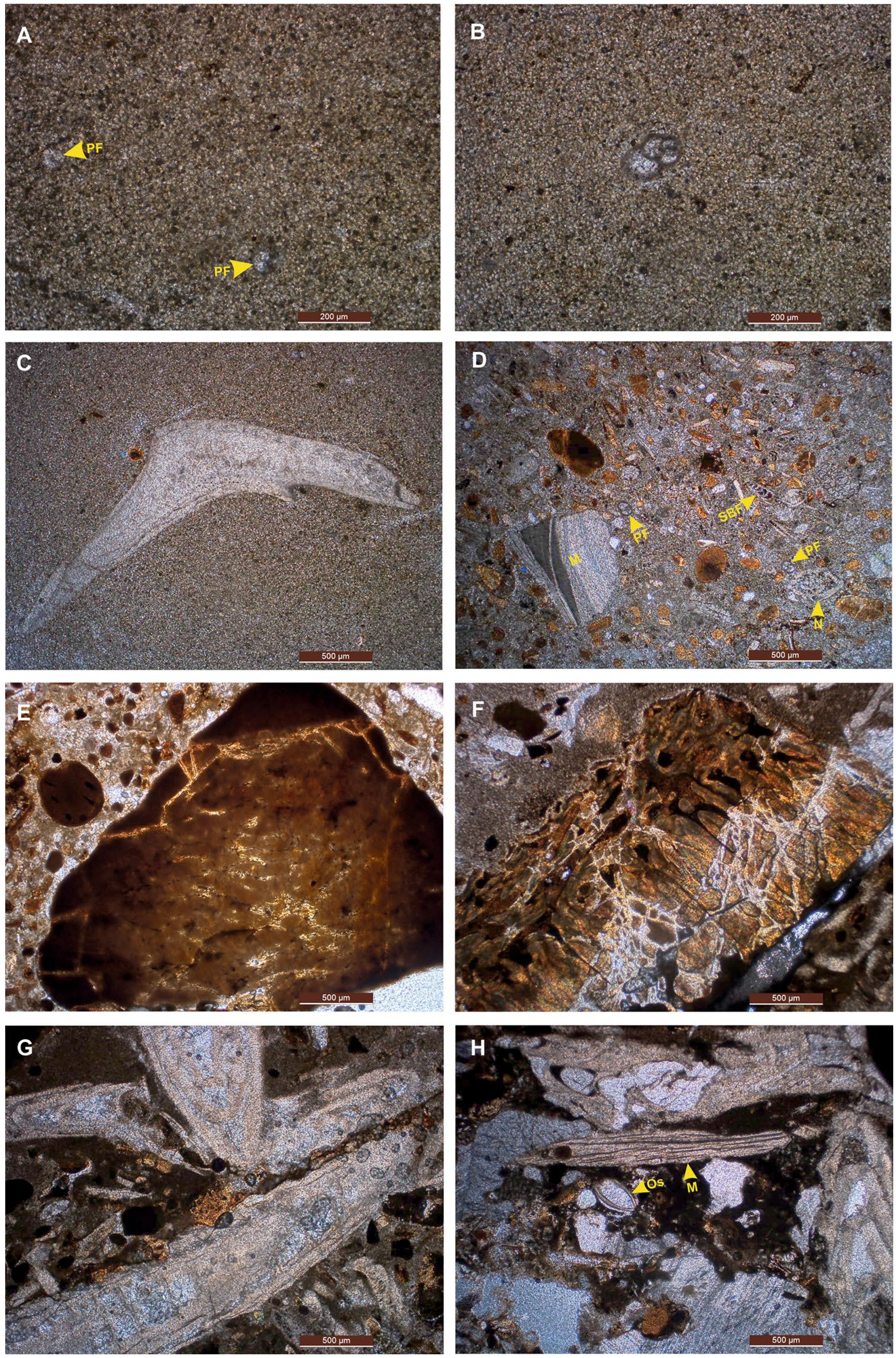

Fig. 6 Skeletal assemblage and microfacies in the Oued Hassene section. **A–C** Planktic foraminifera (Globigerinid) biofacies (Mf7) showing planktic foraminifera (*PF*) (**A**, **B**) and brachiopod fragment (**C**). **D–F** Phospharenite (Mf8) showing planktic (*PF*) and small benthic forams (*SBF*), nummulitids (*N*) and molluscan shells (*M*). **E** peloids. **F** Bone fragment. **G**, **H** Nummulitid biofacies showing large flat nummulitids (**G**) and molluscan shells (*M*) and ostracods (*Os*) (**H**). The matrix contains phosphatic peloids grains

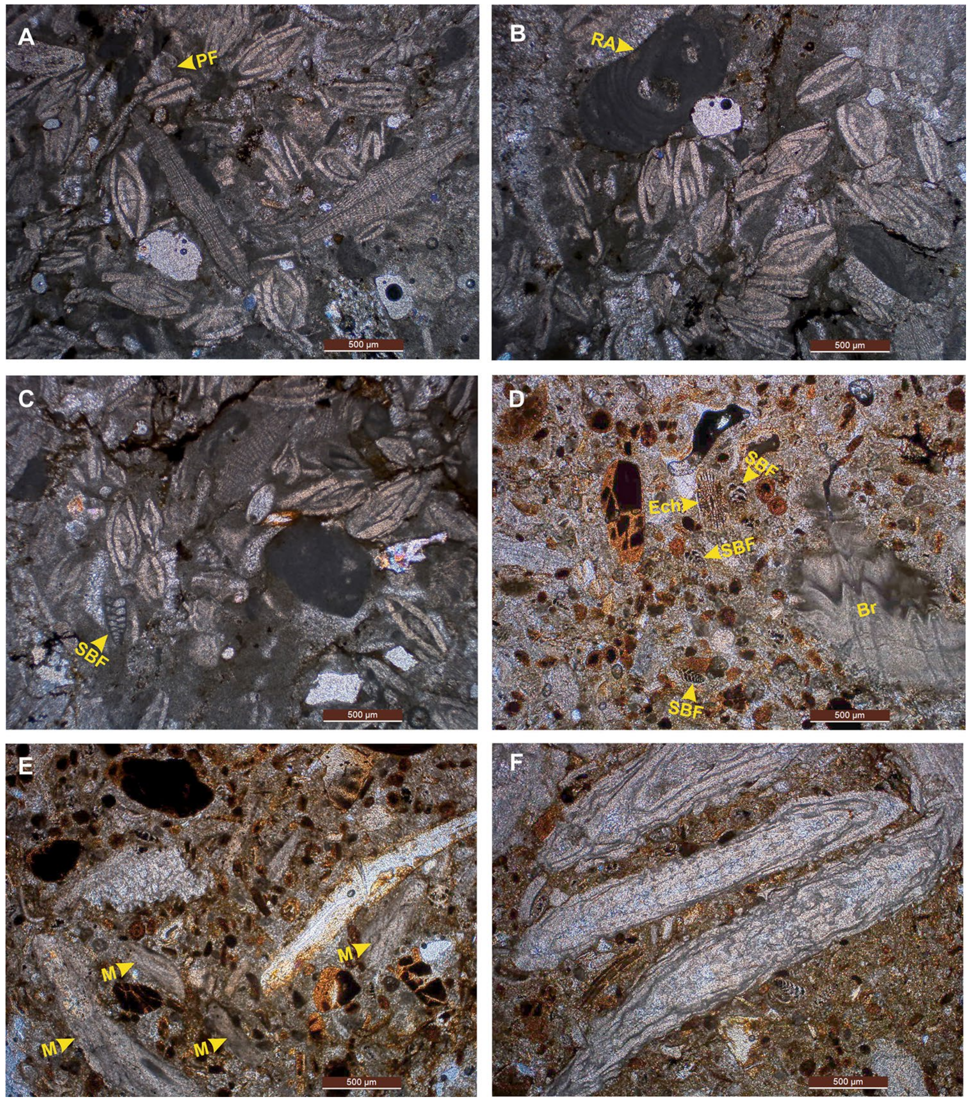

Fig. 7 Skeletal assemblage and microfacies in the Djebba section. **A–C** Nummulitid and orthophragminid biofacies (Mf4) associated with planktic forams (*PF*) (**A**), Red algae (*RA*) (**B**), and small benthic forams (*SBF*) (**C**). **D, E** Phospharenite showing (**D**) small benthic forams (*SBF*), echinids (*Ech*), and brachiopod fragment (*Br*), (**E**) molluscan shells (*M*). **F** Nummulitid biofacies (Mf3) showing large flat nummulites within phosphatic dominated matrix

characteristics from proximal to distal settings as follows (Fig. 8).

Inner ramp

- Mf1: Foraminiferal/red algae grainstone microfacies characterize thin-bedded limestones in the middle part of the Damous section which shows abundant LBF and calcareous red algae with sparitic cement. LBF assemblages, mainly including nummulitids, orthophragminids and alveolinids, calcareous red algae, echinoderm fragments and miliolids also occur. Grainstone texture and fossil content indicates a high-energy shoal environment (Loucks et al. 1998; Flügel 2010; Mateu-Vicens et al. 2012) (Fig. 8).
- Mf2: Ostracod wackestone muddy-limestone is recorded in both Sidi N'sir and Oued Hassene sections. This microfacies is dominated by wackestone with scattered ostracods and subordinate rare nummulitids, and brachiopod shells set in micritic matrix. Ostracods typically occur as major components in stressed brackish, hypersaline, or freshwater environments (Flügel 2010). Ostracods, small nummulitids, and brachiopod fragments are consistent with euphotic protected back-shoal lagoon setting of the inner ramp environment (Loucks et al. 1998; Jorry et al. 2006) (Fig. 8).

Middle ramp

- Mf3: Nummulite-rich packstone microfacies is recorded in all studied sections. This microfacies is characterized by packstone texture dominated by large and flat Nummulites associated with common orthophragminids, alveolinids, *Amphistegina* sp., and small benthic foraminifera. However, brachiopods, ostracods, echinoderms, and small benthic foraminifera are usually com-

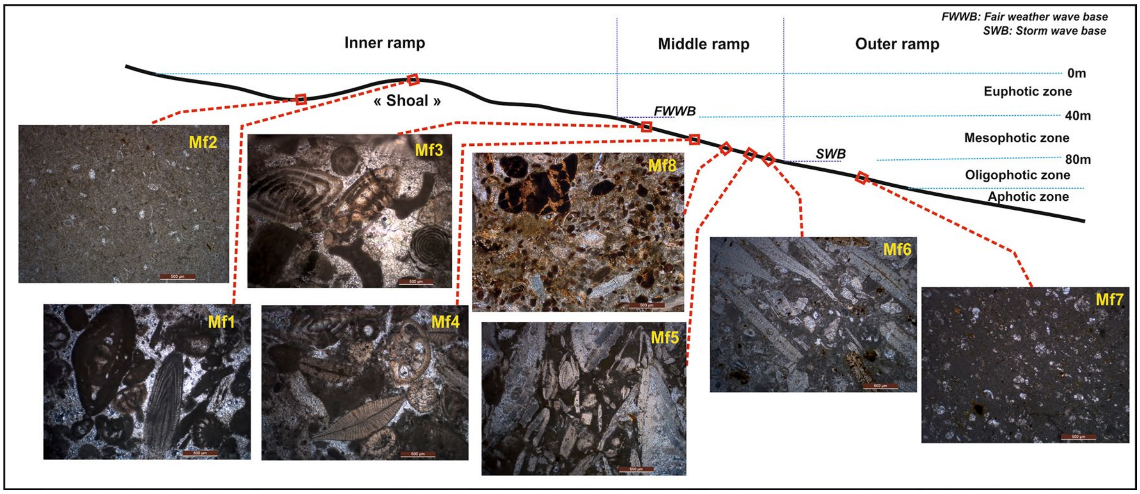

Fig. 8 Environmental microfacies distribution for the Middle Eocene "Reineche Limestones" member and their coeval deposits in northern Tunisia, arranged from proximal to distal depositional environments: Mf1, Inner ramp shoal, Mf2, Inner ramp lagoon, euphotic subtidal environment; Mf3, Proximal middle ramp LBF accumulations (nummulitids), mesophotic environment; Mf4, Mid—middle ramp mesophotic environment; Mf5, Distal middle ramp LBF accumulations (Operculinid), mesophotic environment; Mf6, Distal middle ramp LBF accumulations (orthophragminids), mesophotic environment; Mf7, Outer ramp lacking LBF, planktic foraminifera (globigerinid) microfacies, oligophotic environment; Mf8, Middle ramp, phospharenite microfacies. Ramp subdivision is based on Burchette and Wright (1992), and photic zones are analogous to those described by Hallock (1999) and Pomar et al. (2017)

mon in the Oued Hassene and Djebba sections. Large and flat nummulitids characterize the mesophotic zone (up to 40-m-deepwater mass) with a moderately low energy (Mateu-Vicens et al. 2012; Martin-Martin et al. 2021).

- Mf4: Nummulitid and orthophragminid packstone microfacies is described in the Damous, Sidi N'sir, and Djebba successions. It is dominated by large flat nummulitids and orthophragminids, associated with rare small benthic and planktic foraminifera, brachiopods, and echinoderms. This microfacies indicates a mesophotic zone, within a slightly deeper marine setting than Mf3 (Martin-Martin et al. 2021).
- Mf5: Operculinid packstone microfacies is observed only in the Sidi N'sir section. This microfacies is largely dominated by *Operculina* sp. and large flat nummulitid specimens, associated with common orthophragminids, rare planktic foraminifera, echinoderms, and ostracods. *Operculina* sp. associated with large flat nummulitids indicate the relatively deep part of the mesophotic zone with a moderately low energy (Jorry et al. 2006; Mateu-Vicens et al. 2012; Martin-Martin et al. 2021).
- Mf6: Orthophragminid packstone microfacies is characteristic of the lower part of both Damous and Sidi N'sir sections. It is dominated by orthophragminids associated with common nummulitids, *Amphistegina* sp., planktic foraminifera and rare echinoderms, bryozoans, brachiopods, and small benthic foraminifera. The orthophragminid fauna characterize the deepest part of the mesophotic zone, just above the storm wave base (Özcan et al. 2020; Martin-Martin et al. 2021).

Outer ramp

- Mf7: Planktic foraminifera (Globigerinids) mudstone–wackestone microfacies are observed in both the upper part of Damous section and the lower part of the Oued Hassene section. This microfacies is dominated by a mud-wackestone micritic matrix with scattered planktic and small benthic foraminifers. Green-glauconite grains also occur. This facies indicates an oligophotic zone with relatively low energy, below the storm wave base within the outer ramp setting (Ben Ismail-Lattrache et al. 2014; Özcan et al. 2007, 2020) (Fig. 8).
- Mf8: Phospharenite microfacies is observed in the study northwestern sector including the Sidi N'sir, Oued Hassene, and Djebba successions. It is mainly composed of peloids, bone fragments, and lithoclast grains associated with common small benthic foraminifera, nummulitids, ostracods, brachiopods, and echinoderm fragments and rare globigerinids. In both the Oued Hassene and Djebba sections, large flat nummulitids are characterized by a partial phosphatization of their tests. It is thought that the characteristic faunal assemblage indicates that this phospharenite onset occurs within the mesophotic zone of the middle ramp setting (Garnit et al. 2012; El Bamiki et al. 2020).

Discussion

Ecological considerations and main controlling factors

Through the studied sections, the microfossil assemblages include a mixture of mainly euphotic LBF and coralline/red algae elements, and heterotrophic components (small benthic and planktic foraminifers, ostracods, echinids, mollusks, etc.). These dominating-heterotrophic components suggest oligo- to mesotrophic marine warm waters at low latitudes (Mateu-Vicens et al. 2012). Furthermore, the increase of nutrient supply by continent currents from the SW adjacent areas of the Kasserine Island (and related emerged lands) toward the NE marine environments is also consistent with the described mixture of biofacies elements. In fact, affine associations are also known from other mid-Eocene section in the Tethyan domain (Betic ranges, Geel 2000; Jabaloy Sanchez et al. 2019; Moroccan Rif, Maaté et al. 2000; Pyrenean foreland basin of SE France, Serra Kiel et al. 2003a, b; Anatolian domain, Özcan et al. 2010; Egypt, Tawfik et al. 2016, among others). All these deposits can be included in the "forealgal facies" type of Wilson and Vecsei (2005), mainly characterized by photophile LBF and coralline/red algae. In our study sections, as in coeval levels from the above-cited sectors, LBF associations were identified at different depths, from euphotic to oligophotic conditions, in line with a progressive marine ramp where mainly oligotrophic conditions reign.

Mid-Eocene phosphorite occurrences

The main Tethyan phosphorites onset during the Cretaceous–Eocene interval coincides with Neo-Tethys closure event as a result of the Afro-Arabian and Eurasian plate convergence (Jongsma et al. 1985; Guiraud 1998; Capitanio et al. 2009; Frizon de Lamotte 2009, 2011; Khomsi et al. 2009a, b, 2016; Leprêtre et al. 2018; Guerrera et al. 2019). The appropriate tectonic activities are at the origin of the basin structuring for the major phosphatic settings throughout the Tethys realm (Sassi 1974; Zaier 1984; Chaabani 1995; Baioumy and Farouk 2022 and references therein). In Tunisia, phosphorites are reported in three sectors where the upper Paleocene–lower Eocene Chouabine Fm is well developed. These sectors are referred to as: The Eastern Basins, the Northern Basins, and the Gafsa-Metlaoui Basin (Sassi 1974; Beji-Sassi 1985; Zaier 1984; Kocsis et al. 2013, 2014; Ounis et al. 2008; Garnit et al. 2012, 2017). The similarity between various Tethyan phosphorites in terms of mineralogy (francolite) and constituents (peloids, fish bones, shark teeth, and fossils) suggests that these phosphorite genesis took place in comparable conditions with affine causal mechanisms (Sassi 1974; Beji-Sassi 1985; Zaier 1984, 1999; Ben Hassen 2007; Ounis et al. 2008; Kocsis et al. 2013, 2014; Garnit et al. 2012, 2017): the pristine phosphatic mud had deposited in a relatively deep-marine environment, under the influence of strong upwelling and consequent high productivity. These primary phosphorites have been further reworked landwards by wave actions during marine transgressive phases and then accumulated in shelf environments (Zaier 1984). The mid-Eocene phosphorites of NW Tunisia show various types of grains with arenite-dominating grain-size (less than 2 mm). The main fine-grained components are composed of peloids, coprolites, bone fragments, fossils (large and small benthic foraminifers, echinoids, and mollusks). The origin of the phosphorus of these deposits can be attributed to the microbial breakdown of organic compounds under conditions of marine upwellings that brought nutrient-rich deep ocean water in the Tethys basin, with a subsequent liberation of organic phosphatic compounds into pore waters (Zaier 1984): the abundant fossil content and phosphatized bioclasts being consistent with this interpretation. The distribution of the carbonate factories throughout northern Tunisia domains is mainly controlled by the sea-water temperature (middle Eocene Climatic Optimum, Zachos et al. 2008), nutrient availability (upwelling), and varying terrigenous supply from neighboring paleohighs. Two major carbonate factories, both yielding larger benthic foraminifera, can be distinguished in the study area. In both Damous (Cap bon peninsula) and Sidi N'sir (Imbrication structural zone) sections, the carbonate factory, consistently dominated by LBF, associated with echinoderms, mollusk, small benthic foraminifera, miliolids and algae, is developed under suitable conditions in the mesophotic zone. In turn, this might suggest a situation with limited relief around the basin during the development of the "Reineche Limestones" member. Toward northwestern Tunisia, in both Djebba (Salt Domes zone) and Oued Hassene (Imbrication/Tellian domain) sections, the carbonate factory is characterized by restricted water circulation with sub-oxic conditions. This is consistent with the decrease in LBF skeletal assemblages (mostly nummulitid resisting taxa) and precipitation, formation, and accumulation of phosphorite deposits. The lack of evaporites and presence of abundant small benthic foraminifera indicate that the Mid-Eocene phosphorite rocks were precipitated in the middle ramp (oligotrophic zone) and possibly accumulated by periodic energetic storm currents. The mid-Eocene phosphatic-bearing horizons of northwestern Tunisia (Salt Domes zone and Tellian domain) are thought to be mainly controlled by the halokinetic activities and the phosphorite deposits are accumulated in narrow interdiapiric shaped basins.

Regional geodynamic framework

The above-mentioned descriptions allow us to correlate the study sections with equivalents in central Tunisia aiming at their replacement in a geodynamic context. The W–E correlations of our study sections exhibit an abrupt thickness variation toward higher values in the northeast (Damous section) with an intermediate NE–SW elongated band corresponding to thinner coeval deposits of the Cherahil Formation (sections SN and OH). Works by Amami-Hamdi et al. (2016) and Ben Ismail-Lattrâche (2000) identified a 5-m-thick LBF-rich limestone level of the Siouf member in the J. Jebil section. In the Siliana area (J. Bargou and J. Serj sections), this carbonate marker beds are only 0.3–0.4 m in thickness. These thickness shifts are consistent with the general paleogeography based on the facies distribution (Fig. 1).

This particular regional paleogeography is inherited from a lower Eocene elongated "finger-shaped" distribution of facies that follows the general NE–SW trends of the known major faults of Tunis-Ellès and El Alia-Teboursouk (northern Tunisia). Although still in need of detailed tectonic investigations, our preliminary reconstructions of facies distribution consider that these faults may have acted as transtensive during the Jurassic and Cretaceous continuous opening of the western-Tethys margin of Tunisia. These NE–SW-trending major faults constituted the SE and NW borders of the "Tunisian Trough" of northern Tunisia. In this same line, it is worth of note that these same tectonic deformations have been also recorded in southern Italy (Randazzo et al. 2020a, b, 2021; Vitale and Ciarcia 2022). After the filling of the initial basin by thick Upper Cretaceous-to-Paleocene sediments, the inherited basin architecture still shows the imprints of this fault-bordered structure with a clear facies evolution toward NE, in the context of a ramp setting as reconstructed in this work. To the south-west, in the north-central Tunisia basin, the facies distribution consists of rather NW–SE trending bands, sub-parallel to the direction of ancient major faults that had structured southern Tunisia basins. In this area, during middle Eocene times, the consequent NE extension is still active, but rather limited; the basin polarity remaining constant. This can be explained by the tectonic inversion of these ancient faults with a dextral strike-slip component during the initial stages of the Eocene compression. Further to the eastern Tunisia Pelagian block, signatures of deep subsidence can be followed along an N–S adjacent band, parallel to the N–S major fault that underlines the N–S Axis of central Tunisia. Hence, we interpret the onset of the limestone "Reineche" and "Siouf" members as the product of a major transgressive event (Ben Ismail-Lattrache and Bobier 1984; Ben Ismail-Lattrache 2000; Haj Messaoud et al. 2021) that interplayed with regional tectonics implying mainly N–S, NE–SW, and NW–SE ancient accidents. This regional geodynamic context is to consider in the wider frame of the initial echoes of the Atlassic compressive Eocene event that affected all the south-west Tethys margin of the Maghreb. In this same line, the Paleogene is considered as a time interval when major tectonic activities have taken place throughout the Tethyan domain due to the closing of the Neo-Tethys Ocean as the Afro-Arabian and Eurasian plates converged (Cohen et al. 1980; Ben Ayed 1986; Turki et al. 1988; Bédir et al. 1992; Guiraud 1998; Guerrera et al. 2019). In the Tunisia Tellian domain, the Middle-to-Late Eocene "Atlas event" (Frizon de Lamotte et al. 2000, 2009; El Ghali et al. 2003; Khomsi et al. 2009a, b, 2016; Leprêtre et al. 2018) is further relayed by the overthrust event of the Numidian Flysch sequences (Oligocene-to-Late Burdigalian) over Early Miocene (Burdigalian to Langhian) foredeep sedimentary successions (Khomsi et al. 2009a, b, 2016; Boukhalfa et al. 2009, 2020; Melki et al. 2011; Riahi 2015, 2021).

Conclusion

This study proposes the first reconstruction of depositional environments of mid-Eocene (lower Bartonian) deposits in NW Tunisia. Based mainly on larger benthic foraminiferal assemblages, the Bartonian "Reineche Limestones" and coeval deposits from northern Tunisia consist of eight micro-biofacies sedimented in a progressive shallow-marine carbonate platform, contemporaneous with the Mid-Eocene global transgressive event. Within the study area, two major LBF carbonate factories are distinguished: the first is dominated by LBF and developed in the mesophotic zone (NE Tunisia); the second is characterized by restricted water circulation with anoxic conditions (NW Tunisia). This is consistent with a decrease in the LBF skeletal assemblages, and the precipitation, formation, and accumulation of phosphorite deposits in narrow inter-diapiric shaped basins. In this same context, the onset of the limestone "Reineche" and "Siouf" members is the product of a major transgressive event that interplayed with regional tectonics implying mainly N–S, NE–SW, and NW–SE reactivated faults. This regional geodynamic context remains under-constrained: future works may focus on multidisciplinary investigations of new sections in NW Tunisia aiming at more precise dating by means of nannofossil biozonations, and magneto- and chemostratigraphic calibrations.

Extended regional correlations would provide the necessary improvement regarding spatio-temporal distribution of the various facies and adjacent basin delimitation. This would allow long distance correlations as a relevant support for replacing the mid-Eocene deposits of northern Tunisia in their Tethyan geodynamic context. Eventually, the other controlling events for depositional systems need to be interpreted as interdependent factors with more or less effects. In this line, future paleocirculation models would identify the main gateways at a larger scale considering the whole geodynamic context, and then the part of the middle Eocene Climatic Optimum (MECO) control and related signatures.

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Author contributions A.B.C.D.E.F participated in field surveys, A.C. and E. wrote the main manuscript text, B.C.E and F. prepared figures, and all authors reviewed the manuscript.

Declarations

Competing interests The authors declare no competing interests.

Competing interest The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

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