

ENTOBIA ICHNOFACIES FROM THE MIDDLE MIOCENE CARBONATE SUCCESSION OF THE NORTHERN WESTERN DESERT OF EGYPT

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Abstract: A bed of Middle Miocene (Serravallian) lagoonal facies with well-developed patch reefs is described from a section at the Siwa Oasis, northern Western Desert of Egypt. It is well-exposed in the middle Siwa Escarpment Member of the Marmarica Formation and displays remarkable bioerosion structures that show abundant ichnofossils. Nine ichnotaxa, belonging to four ichnogenera, were identified: two correspond to the clionaid sponge boring *Entobia* (*E. laquea* and *E. ovula*), five to the bivalve boring *Gastrochaenolites* (*G. lapidicus*, *G. torpedo*, *G. cluniformis*, *G. hospitium* and *G. cf. orbicularis*) and two to the annelid-worm boring *Maeandropolydora* (*M. sulcans*) and *Trypanites* (*T. weisei*). In addition, traces of the boring polychaete worm *Caulostrepsis* and the boring acrothoracican barnacle *Rogerella* were recorded. These ichnoassemblages have been assigned to the *Entobia* ichnofacies. The organisms bored into a hard, fully lithified carbonate substrate in a low-energy, shallow-marine environment. The ichnotaxa associations indicate water depths of a few metres (<10 m) and a very low sedimentation rate in a lagoonal setting during a Serravallian regressive cycle.

Key words: Bioerosion, *Entobia* ichnofacies, Lagoonal patch reefs, Serravallian regression, Egypt.

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INTRODUCTION

Hard substrates are special environments that can be characterized by exclusive colonization by macroborers (e.g., Frey and Seilacher, 1980; Bromley and Asgaard, 1993a, b; Taylor and Wilson, 2003; Wilson, 2007; Gibert *et al.*, 2012). In ancient reef environments, endolithic boring organisms are considered important destructive elements that affect primary frameworks and skeletal debris (Jones and Pemberton, 1988; Pleydell and Jones, 1988; Perry, 1996, 2000; Taylor and Wilson, 2003; Tapanila, 2008; Wilson *et al.*, 2010). Mytilid bivalves, clionaid sponges, acrothoracican barnacles, sipunculans and polychaetes are among the most common and important endolithic borers (e.g., Kleemann, 1994; Pickerill *et al.*, 2002). Such borings have a high potential to be preserved as trace fossils, resulting in the development of hard, lithified substrate ichnoassemblages, assigned originally to the *Trypanites* ichnofacies (Frey and Seilacher, 1980).

According to Bromley and Asgaard (1993b), the *Trypanites* ichnofacies includes two different associations, the *Entobia* and *Gnathichnus* ichnofacies. They proposed that these ichnofacies either serve as subdivisions of the *Tryp-*

anites ichnofacies, or as its replacement. MacEachern *et al.* (2007, p. 73) stated that “the ‘*Entobia* ichnofacies’ is broadly similar to the *Trypanites* ichnofacies, in that it corresponds to long-term bioerosion of a lithified surface (typically carbonate), with little or no contemporaneous sedimentation, allowing deep-tier dwelling structures to be excavated and maintained, and superficial borings to be obliterated”. This view is confirmed by Buatois and Mángano (2011) and Gibert *et al.* (2012). In general, the importance of ichnofacies is greatly increased when they are integrated with the sedimentology, palaeontology and stratigraphy of a succession. They are a powerful tool for palaeoecological and palaeoenvironmental inferences (e.g., Seilacher, 1967; Bromley, 1996, 2004).

During their investigations of the Middle Miocene benthonic macro-invertebrates in an outcrop at Siwa Oasis, northern Western Desert of Egypt, the authors identified a spectacular cliff-forming limestone bed with well-developed coral associations. The characteristic feature of the recorded bed is the extensive occurrence of borings, affecting the reef framework. Bioerosion studies on differ-

ent kinds of hard substrates in the Egyptian Cenozoic are extremely scarce (Aigner, 1983; Abdel-Fattah and Assal, 2016). The aim of the present work is to characterize the occurrence of the Middle Miocene bioeroded coral-rich limestone bed in the northern Western Desert of Egypt as well as the ichnoassemblages related to them and thus, to show the relevance of trace fossil analysis for palaeoecological and palaeoenvironmental interpretations.

GEOLOGICAL SETTING

Middle Miocene carbonates form a prominent platform in the northern Western Desert of Egypt (Said, 1962; Gindy and El-Askary, 1969). The southernmost outcrops at Siwa Oasis mark an ancient shoreline, which existed during the peak of the Langhian transgression and resulted in deposition of the Marmarica Formation (Said, 1962, 1990). The main controlling factors on the sedimentation and stratigraphy of this formation were tectonics and eustatic sea-level changes (e.g., Gindy and El-Askary, 1969; Abdel-Fattah *et al.*, 2013; El-Sabbagh *et al.*, 2017).

The Siwa Oasis is located in the northwestern corner of the Western Desert of Egypt, west of the Qattara Depression, between longitudes 25°05' and 26°18' E and latitudes 29°05' and 29°24' N (Fig. 1). The studied section is about 7 km to the north of Siwa City (29°16'24.6"N; 25°31'22.1"E; Fig. 1). In this section, the Marmarica Formation is about 78 m thick. It is composed of alternating carbonate, shale and marl beds. The carbonates comprise mainly bioclast limestone and chalky limestone with cross-bedded coquinas. The abundance of carbonates progressively increases up-section, as the shale and marl content decreases (Fig. 2).

The Marmarica Formation is subdivided into three members (*sensu* Gindy and El-Askary, 1969). The oldest member is the Oasis Member (about 41 m thick). It is overlain by the Siwa Escarpment Member (about 21 m thick) and El Diffa Plateau Member (about 16 m thick). Sediments of the three members are characterized by a highly abundant invertebrate macrofauna (Fig. 2). In addition, the measured section contains a remarkable bivalve coquinoid band, an oyster shell concentration and firmground discontinuity surfaces (see El-Sabbagh and El-Hedeny, 2016; El-Sabbagh *et al.*, 2016, 2017).

MATERIAL AND METHODS

The present work is based on field and laboratory examinations of the coral-rich limestone bed that occurs in the topmost part of the Siwa Escarpment Member and delineates the boundary with the overlying El Diffa Plateau Member (Fig. 2). In the field, the stratigraphical and sedimentological characteristics of this bed were described. To evaluate this bed, the geometry, thickness, lateral extent, packing, sorting, lower and upper contacts and taxonomic composition were investigated. In addition, the taphonomic attributes of the different fossil groups, such as orientation, disarticulation, fragmentation, encrustation and bioerosion, were recorded.

Ten rock samples, representing different parts of the limestone bed, were collected for microfacies analyses using standard petrographic techniques. Dunham's (1962) nomenclature for the textural classification of carbonates was used. Moreover, a total of 140 macrofossil specimens was collected from the bed studied. In the laboratory, the taph-

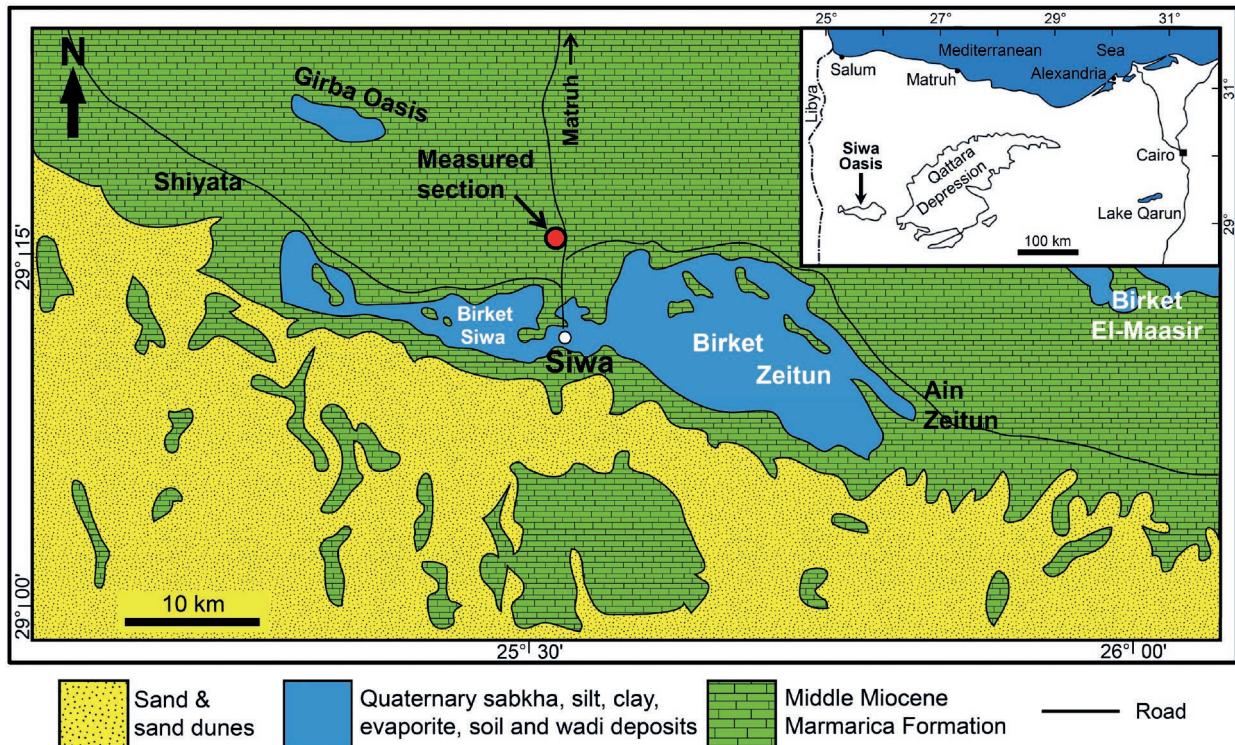


Fig. 1. A simplified geological map of the Siwa Oasis, showing the location of the section studied (modified after CONOCO and EGPC, 1988).

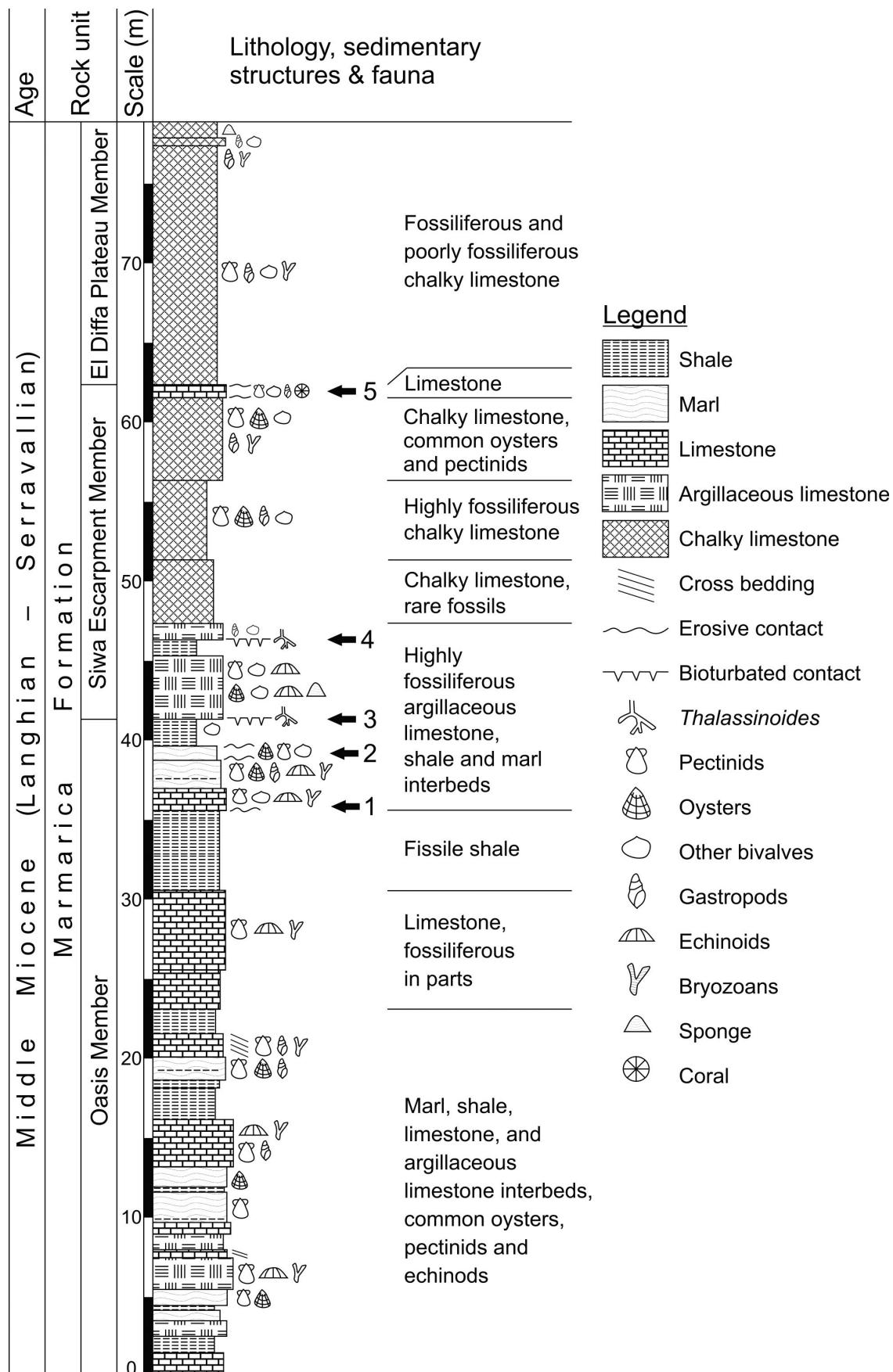


Fig. 2. Lithological descriptions of the north Siwa section. Arrows mark occurrences of (1) the *Placuna (Indoplacuna) miocenica* (Fuchs, 1883) coquinoid band (El-Sabbagh *et al.*, 2016), (2) the *Crassostrea gryphoides* (Schlotheim, 1813) shell lens concentration (El-Sabbagh and El-Hedeny, 2016), (3, 4) the two firmground discontinuity surfaces (El-Sabbagh *et al.*, 2017) and (5) the patch reef bed studied.

nomic attributes of each specimen were carefully examined using hand lens and binocular microscope. Four species of coral, ten species of bivalve and one species of gastropod were identified (Table 1). Identification of coral specimens is mainly based on Rus and Popa (2008) and Vertino *et al.* (2014). For mollusc specimens, the works of Fuchs (1883) and El-Shazly and Abdel-Hamid (2001) have been used. All specimens examined are housed in the Department of Geology, Faculty of Science, Alexandria University, Egypt. Specimen numbers are prefixed by NS33.

To evaluate the boring structures, ten 25 cm² areas of the bed (7 cross-sections and 3 surface exposures) were randomly selected. The bioerosion structures within these areas were identified, counted and measured. The spatial relationships between different bioerosion structures and

encrusting organisms were also recorded. The shape of the borings is distinctive and varies greatly, facilitating identification and classification as well as helping in the estimation of the composition of the ichnocoenoses. Terminology of trace fossil morphology follows that of Häntzschel (1975), Bromley and D'Alessandro (1983, 1984) and Kelly and Bromley (1984). Ichnotaxonomic identification was based on accepted diagnostic characters and comparison with similar specimens in the literature, e.g., Bromley (1972), Bromley and D'Alessandro (1983, 1984) and Kelly and Bromley (1984). The data are expressed as percentages of the total number of bioerosion traces. Aperature size and cavity depth were measured in millimetres, using a digital caliper (accurate to 0.01 mm). The number of *Entobia* borings was counted as the number of apertures visible, omitting the partially eroded ones (Bromley and D'Alessandro, 1984). The density of distribution of each macroboring and embedment structure was determined by counting surface apertures, centred within a 4 cm² grid. Measurements of the length and maximum width of the worm borings were taken with the aid of precision sliding calipers.

Table 1

Macrobenthonic fossils of the Middle Miocene bed studied with information on the corresponding mode of life and feeding strategy. The palaeoautecology of the faunal assemblage studied is recorded on the basis of the Paleobiology Database (<http://paleobiodb.org/#/>). Life habits: ec – epifaunal cemented; em – epifaunal mobile; eb – epibyssate; in – infaunal. Modes of feeding: s – suspension feeders; c – carnivores.

* – bioerosion-bearing taxa

Group/Family	Taxon	Life habit	Trophic group
Corals			
Mussidae	<i>Lithophyllia</i> sp.*	ec	s
Poritidae	<i>Porites</i> sp.*	ec	s
Siderastreidae	<i>Siderastrea</i> sp.*	ec	s
Faviidae	<i>Tarbellastraea</i> sp.*	ec	s
Bivalves			
Mytilidae	<i>Lithophaga lithophaga</i> (Linné, 1758)*	in	s
	<i>Lithophaga</i> sp.*	in	s
	<i>Botula subcordata</i> (d'Orbigny, 1852)*	in	s
Pectinidae	<i>Chlamys zitteli</i> (Fuchs, 1883)	eb	s
	<i>Pecten cristatocostatus</i> Sacco, 1897	em	s
Anomiidae	<i>Anomia ephippium</i> Linné, 1758	eb	s
Lucinidae	<i>Myrtea spinifera</i> (Montagu, 1803)*	in	s
Carditidae	<i>Carditamera hippopea</i> (Basterot, 1825)*	in	s
Cardiidae	<i>Cerastoderma edule</i> (Linné, 1758)*	in	s
Veneridae	<i>Pelecyora (Cordispsis)</i> sp.*	in	s
Gastropods			
Conidae	<i>Conus</i> sp.*	em	c

RESULTS

Description of the bed investigated

The thickness of the bed ranges from about 60 to 80 cm and can be traced laterally for at least 800 m in the outcrop studied. The lower and upper contacts are undulating and erosional (Fig. 3). The bed contains a moderately diverse macrofaunal assemblage that includes corals (27% of the total species identified), pectinids (13%), other bivalves (53%) and gastropods (7%). In addition, the scaphopod *Dentalium* is a rare component (<1%). On the basis of the micro- and macro-fauna identified and the corresponding stratigraphic position, a Serravallian age is suggested for this bed (Abdel-Fattah *et al.*, 2013; El-Sabbagh and El-Hedeny, 2016; El-Sabbagh *et al.*, 2016, 2017).

The sediments consist of light brown, hard, locally dolomitic limestone. They comprise poorly sorted bioclasts (40–50%), embedded in a homogeneous lime-mud matrix (i.e., bioclast floatstone to wackestone). The bioclasts are represented by shells and the internal moulds of corals, molluscs, bryozoans, coralline/green algae and benthonic foraminifera (Fig. 4). Among the latter, the alveolinid *Borelis melo* (Fichtel and Moll, 1798) is the most abundant.

The macrofaunal assemblage is dominated by infaunal species (71.5% of the total specimens collected). Epifaunal species represent 28.5% of the assemblage, of which 18.5% belong to vagile taxa, 7% to cemented and 3% to epibyssate taxa (Table 1). Suspension feeders account for 83% of the total specimens collected. The remainder was represented by predatory, carnivorous, conid gastropods.

The bed is characterized by poorly sorted and loosely packed skeletons (Fig. 3). Hermatypic corals occur scattered throughout the bed in small patches. They are characterized by branched, columnar and massive *Lithophyllia* sp., *Porites* sp., *Siderastrea* sp. and *Tarbellastraea* sp. (Table 1). They have been affected by dissolution. Their identification



Fig. 3. A photograph of the outcrop studied, illustrating the bed studied with erosive, undulating lower and upper contacts.

was mainly based on moulds. The moulds are generally well preserved with surface details preserved, owing to a micritic coating. Some colonies are preserved as hollows, left after dissolution of the corallites (Fig. 5A). Rarely, colonies still exhibit their skeletons.

Most pectinid shells are rotated, disarticulated and highly fragmented (Fig. 5B). However, they are moderately preserved and microscopic surface characters are evident. Gastropods and other bivalves, in contrast, mostly occurred as well-preserved internal moulds. The level of fragmentation in both groups is generally low. Nearly all bivalve moulds are articulated and most specimens are recorded in the life position (see below).

Most types of hard substrate, including the bioclastic limestones and coral fragments, are extensively bored. In addition, some mollusc specimens are locally bored. Endolithic organisms have produced bioerosion structures that appear as cavities, tunnels, grooves and chambers, or systems of these. After abandonment by the trace-making organisms, the borings became passively filled with fine sediments prior to being lithified. During diagenesis, the original aragonitic coral skeletons were leached, leaving natural casts of the borings exposed as three-dimensional structures within the moulds of the former coral heads. In some places, the numerous ichnofossils comprise 85 to 95% of the surface of the bed. Macroborings associated with scleractinian corals are more abundant than those associated with other types of hard substrate. The bed investigated also contains evidence

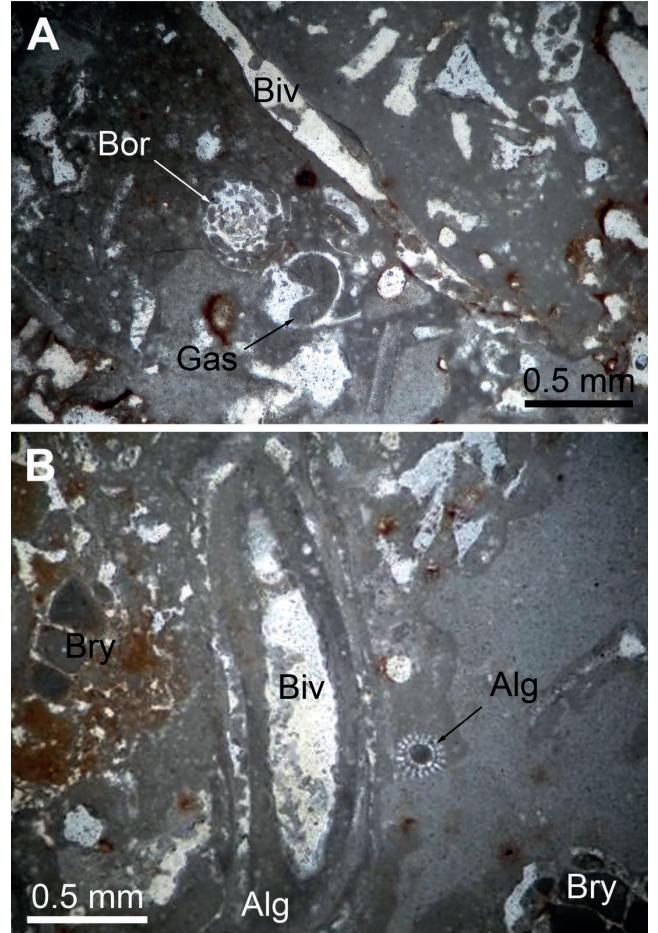


Fig. 4. Photomicrographs of lagoonal facies. **A, B.** Bioclast floatstone/wackestone. The rock is composed of poorly sorted bioclasts, including algae (Alg), alveolinid *Borelis melo* (Fichtel and Moll, 1798) (Bor), bivalves (Biv), gastropods (Gas) and bryozoans (Bry), embedded in a lime-mud matrix. Both photos were taken under plane polarized light (PPL).

of encrusting organisms, such as cheilostome bryozoans and serpulid worms (e.g., *Serpula* sp. and *Protula* cf. *diomedae* Benedict, 1886, p. 547, pl. 20, figs 1–6), which represent *in situ* biota (Fig. 5B–D). Several reciprocal overgrowths were observed between both of these encrusters.

Palaeoichnology

Morphological analysis of the recorded bioerosion structures revealed six ichnogenera (Table 2). These structures were produced by clionaid sponges (*Entobia laquea*, *E. ovula* and *Entobia* isp.), bivalves (*Gastrochaenolites lapidicus*, *G. torpedo*, *G. cluniformis*, *G. hospitium* and *G. cf. orbicularis*), sipunculids and/or polychaetes (*Caulostrepis* isp., *Maeandropolydora sulcans* and *Trypanites weisei*) and acrothoracican barnacles (*Rogerella* isp.). Collectively, they belong to the category domichnia (Seilacher, 1964). The most abundant bioerosion structure recorded is *Gastrochaenolites*, constituting about 50.5% of the total boring structures counted (Table 2), followed by *Entobia* (27.5%), *Trypanites* (13%), *Rogerella* (5%), *Caulostrepis* (2%) and

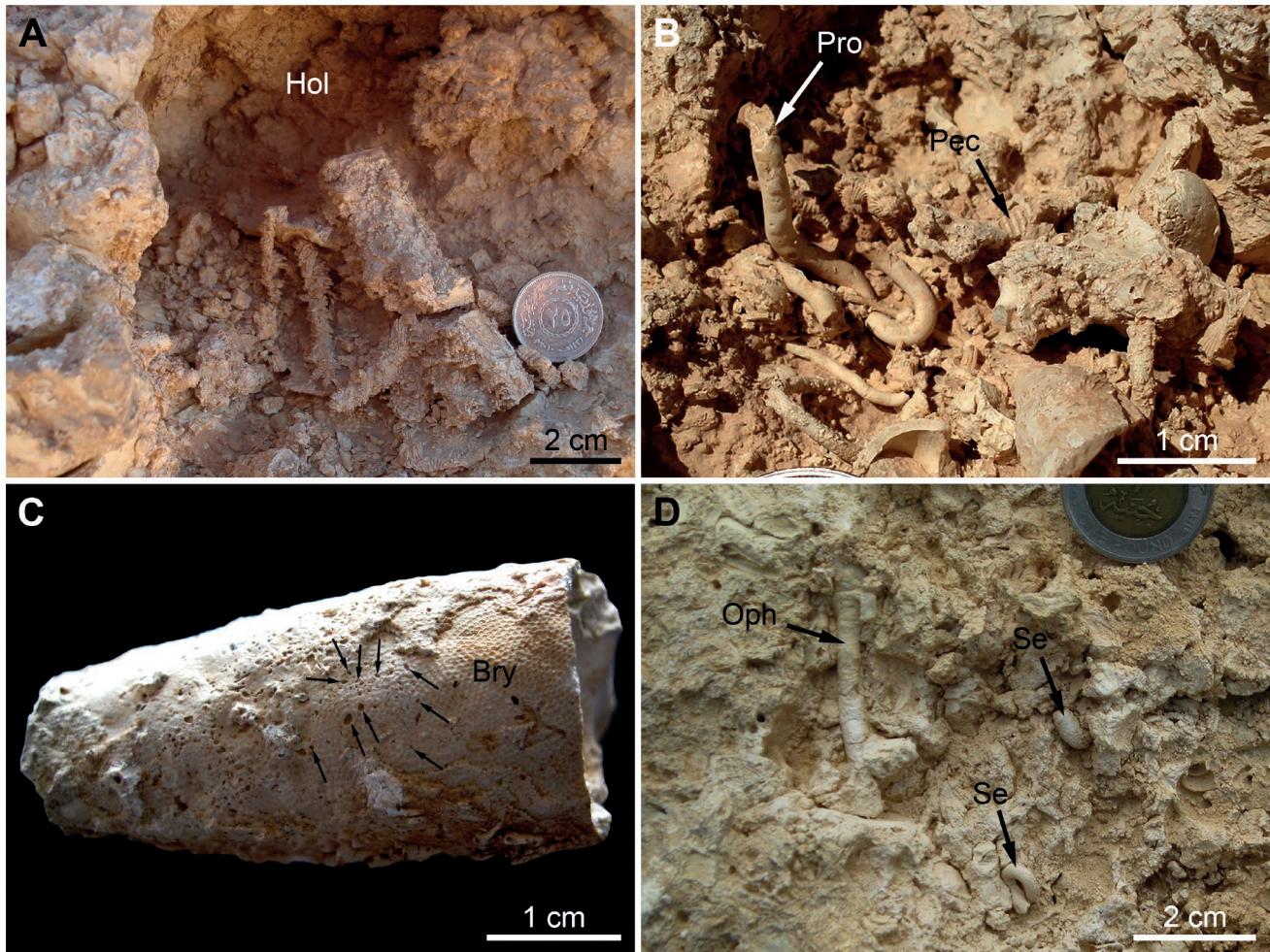


Fig. 5. Some outcrop features of the bed studied. **A.** Cross-sectional view, showing a hollow (Hol) formed after dissolution of a coral colony. **B.** *In situ* serpulid worm *Protula* cf. *diomedae* Benedict, 1886 (Pro). Note the occurrence of a fragment of a pectinid valve (Pec). **C.** A colony of the sheet-like, cheilostome bryozoans (Bry) on a mould of a bivalve *Lithophaga*. Note the *Entobia* isp. perforate the bryozoans (arrows). **D.** Vertical face of the bed, showing the burrow *Ophiomorpha* (Oph) and serpulid worms (Se).

Maeandropolydora (2%). Moreover, *Ophiomorpha* is recorded as very rare traces of peculiarly small size (Fig. 5D). It represents burrows produced in soft sediments.

Gastrochaenolites occurs in randomly distributed clusters. Most borings of this ichnogenus contain moulds of the bivalve tracemaker (Fig. 6). Field counts for all *Gastrochaenolites* showed a maximum concentration of 75 borings per 625 cm² (1200 borings per 1 m²). Within bioclast limestone substrates, some *Gastrochaenolites* are oriented perpendicular to the bedding plane of the bed studied and others are subparallel. In the coral patches, *Gastrochaenolites* are oriented either in the direction of coral growth, or oblique to it (Fig. 6). Some specimens have cup-shaped false floors, being retrusive equilibrium traces that are interpreted as the carbonate layers secreted by a bivalve (Fig. 6D, E). They have been correlated with reduced coral growth and mark individual annual life events of the tracemaker (Blanco *et al.*, 1988; Kleemann, 1994, 2009).

SYSTEMATIC ICHNOLOGY

Ichnogenus *Entobia* Brönn, 1837

Type ichnospecies: *Entobia cretacea* Portlock, 1843.

Entobia laquea Bromley and D'Alessandro, 1984
Fig. 7A

- * 1984 *Entobia laquea* ichnosp. nov. – Bromley and D'Alessandro, p. 244, pl. 17, fig. 2, pl. 19, fig. 2, pl. 23, fig. 1, text-figs 5, 6.
- 2004 *Entobia laquea* Bromley and D'Alessandro – Árpád, p. 45, pl. 2, fig. 2.

Material: Three specimens (NS33 100–102).

Description: Borings appear as tunnel systems and chambers in well-developed growth stages A and C (*sensu* Bromley and D'Alessandro, 1984). The structures of stage A are composed of thin, almost straight tunnels, about 0.5 mm in diameter. Stage C is represented by irregular, oval, and elongate to subangular chambers, 1.5–2.5 mm in diameter.

Table 2

Information on bioerosion ichnotaxa (abundance, substrate, ethology and probable tracemakers) recorded within the Middle Miocene (Serravallian) bed studied.

	Abundance (%)	Substrate	Ethological category	Tracemaker
<i>Entobia laquea</i>	18	Reefal limestone, corals	Domichnia	Clionid sponge
<i>E. ovula</i>	7.5	Reefal limestone, corals	Domichnia	Clionid sponge
<i>Entobia</i> isp.	2	Reefal limestone, corals	Domichnia	Clionid sponge
<i>Gastrochaenolites lapidicus</i>	6	Reefal limestone, corals	Domichnia	<i>Lithophaga</i> sp.
<i>G. torpedo</i>	26	Reefal limestone, corals	Domichnia	<i>Lithophaga lithophaga</i>
<i>G. cluniformis</i>	11.5	Reefal limestone, corals	Domichnia	<i>Botula subcordata</i>
<i>G. hospitium</i>	4	corals	Domichnia	<i>Lithophaga (Leiosolenus)</i> sp.
<i>G. cf. orbicularis</i>	3	Reefal limestone, corals	Domichnia	Endolithic bivalve
<i>Caulostrepsis</i> isp.	2	Reefal limestone, corals	Domichnia	Polychaete annelid
<i>Maeandropolydora sulcans</i>	2	Reefal limestone, corals	Domichnia	Polychaete annelid
<i>Trypanites weisei</i>	13	Reefal limestone, corals	Domichnia	Sipunculid/polychaete annelid
<i>Rogerella</i> isp.	5	Reefal limestone, corals	Domichnia	Acrothoracican barnacles

Remarks: In the Mediterranean Sea, *E. laquea* is produced by sponges of the genus *Cliona* (e.g., *C. vastifica* Hancock, 1849) and/or its close relatives (Bromley and Asgaard, 1993a; Perry, 1996). However, in deep-water corals, the trace of *Spiroxya heteroclita* Topsent, 1896 is correlated to *E. laquea* (Beuck and Freiwald, 2005). According to Higgs et al. (2012), the boring *Osspecus* is similar in morphology to *E. laquea*, particularly in the C or D growth phases. In the bed studied, *E. laquea* is highly abundant, representing about 65.5% of the total *Entobia* specimens identified and about 18% of the total borings recorded (Fig. 8).

Entobia ovula Bromley and D'Alessandro, 1984
Fig. 7B

- * 1984 *Entobia ovula* ichnosp. nov. – Bromley and D'Alessandro, p. 243, fig. 4.3, pl. 4.6a, b.
- 2004 *Entobia ovula* Bromley and D'Alessandro – Blissett and Pickerill, p. 175, fig. 5/4.
- 2007 *Entobia ovula* Bromley and D'Alessandro – El-Hedeny, p. 277, pl. 2, fig. 6.
- 2017 *Entobia ovula* Bromley and D'Alessandro – Gurav and Kulkarni, p. 5, fig. 3E, F.

Material: Three specimens (NS33 110–112).

Description: Camerate system of borings, composed of small spherical to ovoid chambers, with an average diameter of about 3 mm (i.e., phase D), closely spaced and touching one another. In phase C, the chambers are separated by very thin and very short intercameral canals, which are usually reduced to a constriction. The fusion of two or more chambers was observed. Openings are relatively small, numerous and close.

Remarks: The borings described herein coincide with *E. ovula*, described and illustrated by Bromley and D'Alessandro (1984). Gurav and Kulkarni (2017) considered that the globose-to-ovoid chambers, regularity in shape of

chambers, distally tapering apertural canal, and crowding of chambers resulted from the disappearance of necks and presence of bud-like growth system in line of exploratory threads are the diagnostic characters that differentiate *E. ovula* from those of *E. laquea*. In the present study, *E. ovula* is common, representing about 27.5% of the total *Entobia* specimens identified and about 7.5% of the total borings recorded (Fig. 8). In the Mediterranean Sea, *E. ovula* is produced by *Cliona schmidti* (Ridley, 1881), *C. vermicularis* Hancock, 1867 and/or *C. vastifica* Hancock, 1849 (Bromley and Asgaard, 1993a).

Entobia isp.
Fig. 5C

Material: Two specimens (NS33 105–106).
Description: Clusters of irregular, small (<7 mm across) and densely crowded openings with ovoidal to subpolygonal chambers without canals could not be identified specifically. They vary in diameter from 2.5 to 5.0 mm.

Remarks: A stenomorphic character of borings makes identification to the ichnospecies level uncertain in this specimen. It represents about 7% of the total *Entobia* specimens identified and about 2% of the total borings (Fig. 8).

Ichnogenus *Gastrochaenolites* Leymerie, 1842

Type ichnospecies: *Gastrochaenolites lapidicus* Kelly and Bromley, 1984.

Gastrochaenolites lapidicus Kelly and Bromley, 1984
Figs 6B, C, 9C, E, F

- * 1984 *Gastrochaenolites lapidicus* ichnosp. nov. – Kelly and Bromley, p. 797, text-figs 3A, 4A–B.
- 2001 *Gastrochaenolites lapidicus* Kelly and Bromley – Domènec, Gibert and Martinell, p. 104, fig. 7.4.

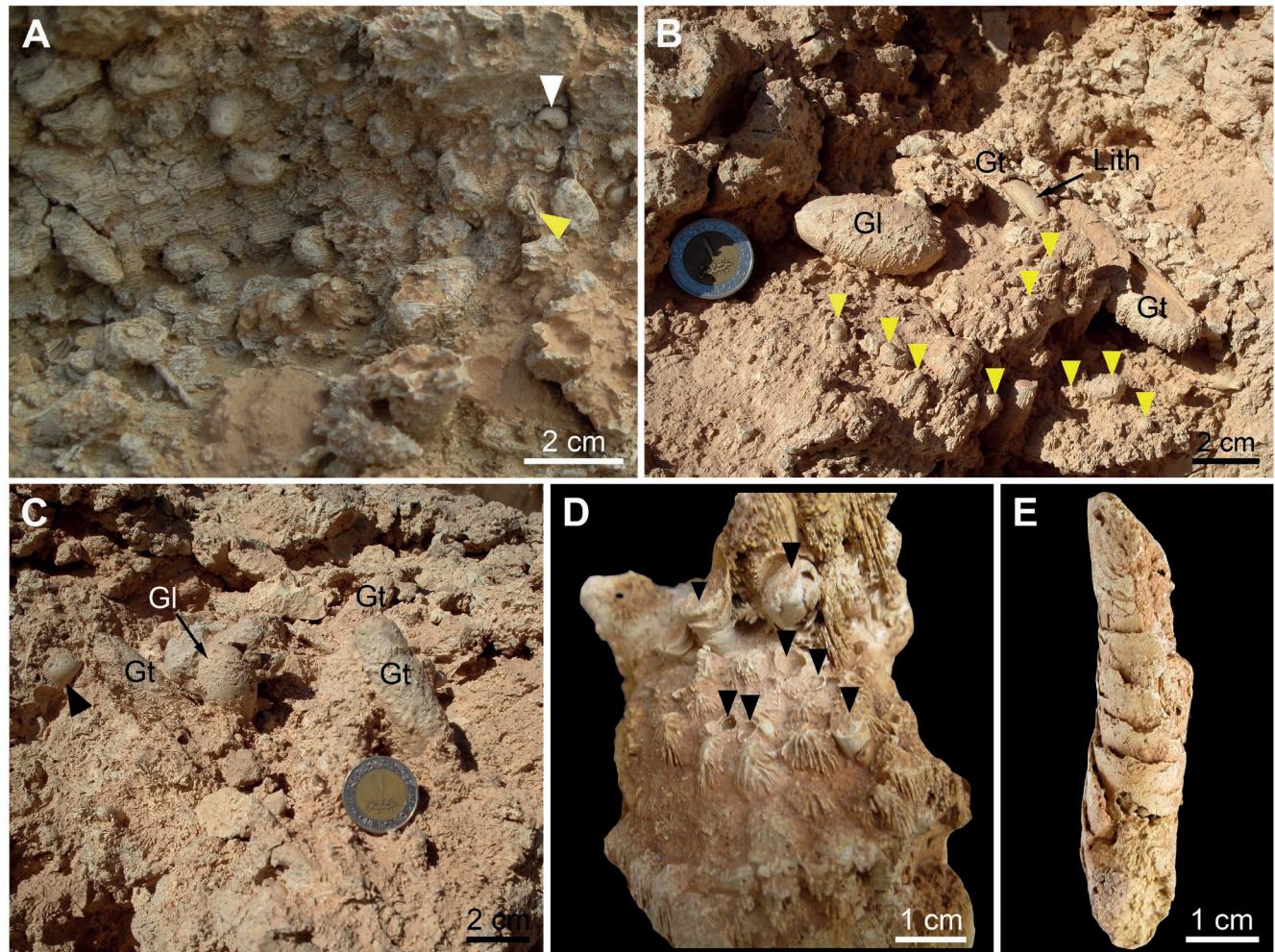


Fig. 6. *Gastrochaenolites* and probable tracemakers. **A.** Cross-sectional view, showing cluster of moulds of *Lithophaga* (the main producer of *Gastrochaenolites*). They bored into the coral fragment, mostly in the direction of coral growth. Note the occurrence of a gastropod mould and a serpulid worm (white and yellow arrow heads, respectively). **B.** Large *G. lapidicus* (Gl) and *G. torpedo* (Gt). *Gastrochaenolites torpedo* (Gt), oriented either in the direction of coral growth (arrow heads) or oblique to it. Note the bivalve *Lithophaga lithophaga* (Linné, 1758) (Lith), still in the boring. **C.** Cross-sectional view, showing *G. lapidicus* (Gl) and *G. torpedo* (Gt) randomly embedded in a coral head. Note the occurrence of a bivalve mould (arrow head). **D.** Coral hand specimen with *G. hospitium* (arrow heads), oriented in the direction of coral growth. **E.** *Gastrochaenolites hospitium* with retrusive equilibrium traces, representing annual events of the tracemaker.

Material: Five specimens (NS33 10–14).

Description: Smooth, clavate-shaped boring with an apertural neck, showing a circular outline with a rounded base in plain view. The widest diameter is located slightly below the centre of the chamber. The neck region is circular in cross-section. The borings vary in size from 20 to 50 mm in length and 5 to 18 mm in width. Internal surfaces of the borings are mostly smooth. Boring walls are commonly ornamented with coral xenoglyphs.

Remarks: The moderately elongated shape, widest at mid-length, and the bluntly parabolic base represent the characteristic features that differentiate *G. lapidicus* from other *Gastrochaenolites* ichnospecies (Kelly and Bromley, 1984). It can be distinguished from *G. turbinatus* Kelly and Bromley, 1984 (p. 803, figs 3G, 8C) in having a well-developed neck region. *Gastrochaenolites lapidicus* may be produced by several bivalve genera, including

Lithophaga, *Hiatella* (Kelly and Bromley, 1984), *Rocellaria* (*Gastrochaena*) *dubia* Pennant, 1777 (Bromley and Asgaard, 1993a), *Parapholas* (Uchman *et al.*, 2017, 2018) and/or *Aspidopholas* (Radwański, 1964, 1969). The total number of *G. lapidicus* was 41 in the measured areas, representing about 11.5% of the total *Gastrochaenolites* specimens identified and about 6% of the total borings recorded (Fig. 8).

Gastrochaenolites torpedo Kelly and Bromley, 1984
Figs 6B, C, 9A, B

- * 1984 *Gastrochaenolites torpedo* ichnosp. nov. – Kelly and Bromley, p. 802, text-figs 3F, 8A–B.
- 2006 *Gastrochaenolites torpedo* Kelly and Bromley – Donovan and Hensley, p. 13, fig. 3.

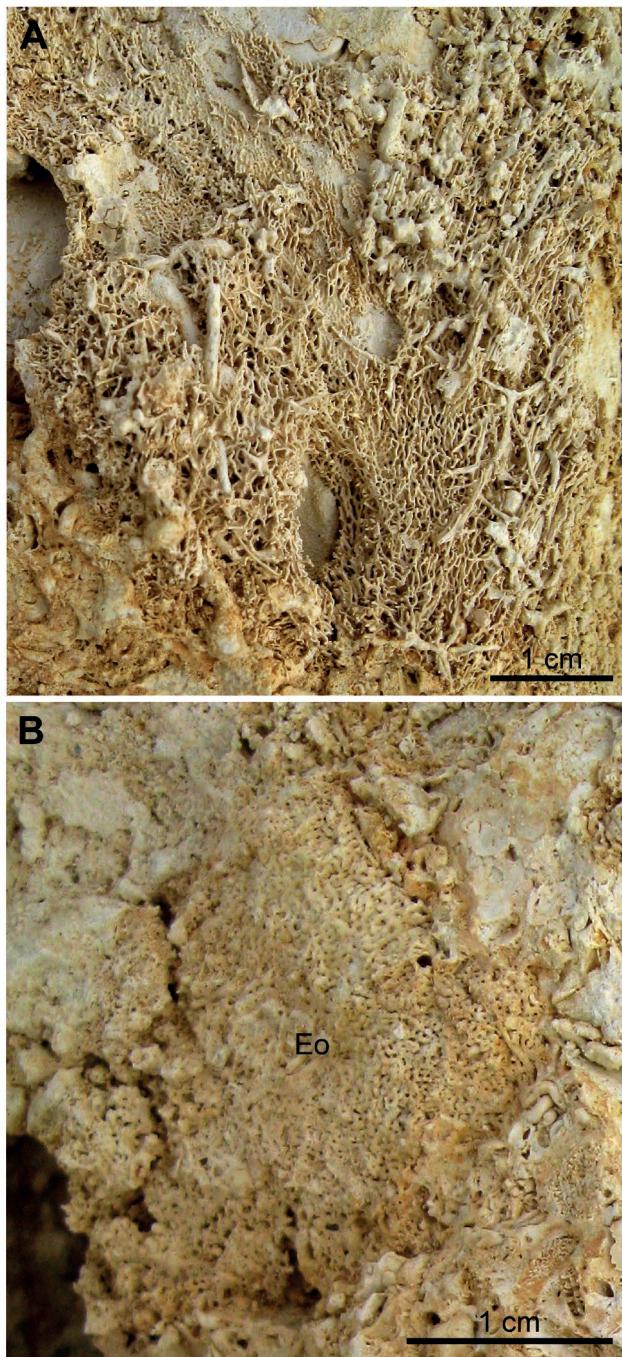


Fig. 7. Sponge borings from the Middle Miocene bed studied. A. Irregular boxwork system of branched, non-camerata galleries of *Entobia laquea*. Note the dendritic nature of this ichnospecies. B. Small, spherical to ovoid chambers of *E. ovula* (Eo).

Material: Twenty-nine specimens (NS33 20–44 and 90–93).

Description: Smooth elongate chamber, with ellipsoidal cross-section and pointed distal end. The maximum diameter (17–25 mm) is located at the centre of the chamber. The neck has a constriction near the aperture. The size of the boring is variable; it is 7–60 mm long and 3–25 mm wide. The internal surfaces of borings are either smooth or display a sculpture of concentric lines.

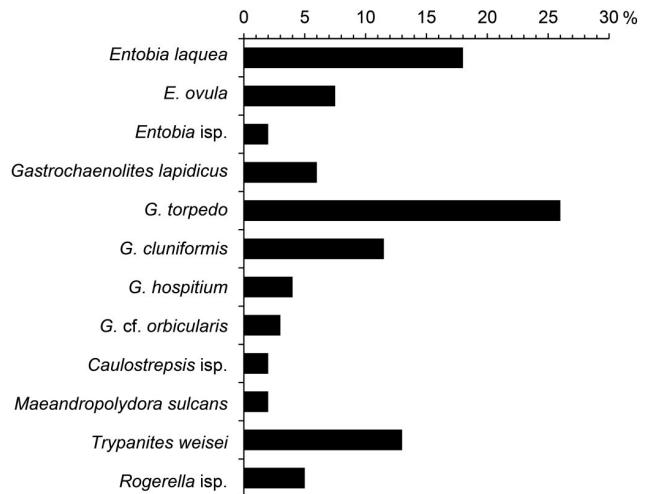


Fig. 8. Relative abundance of different ichnogenera and ichnotaxa, identified in the bed studied.

Remarks: The present ichnospecies shows a close similarity with the diagnostic characters of the boring morphology of *Gastrochaenolites torpedo*, as described and illustrated by Kelly and Bromley (1984, p. 802). However, specimens with oval cross-section or approaching a figure-of-eight were observed in their study. In general, *G. torpedo* may be produced by the bivalve *Lithophaga* (Radwański, 1964, 1969) or *Gastrochaena* (Kelly and Bromley, 1984). Among the *Gastrochaenolites* ichnospecies identified, *G. torpedo* was most abundant. In the measured areas, the total number of *G. torpedo* structures identified was 179, representing about 51.5% of the total *Gastrochaenolites* specimens identified and 26% of the total borings recorded (Fig. 8).

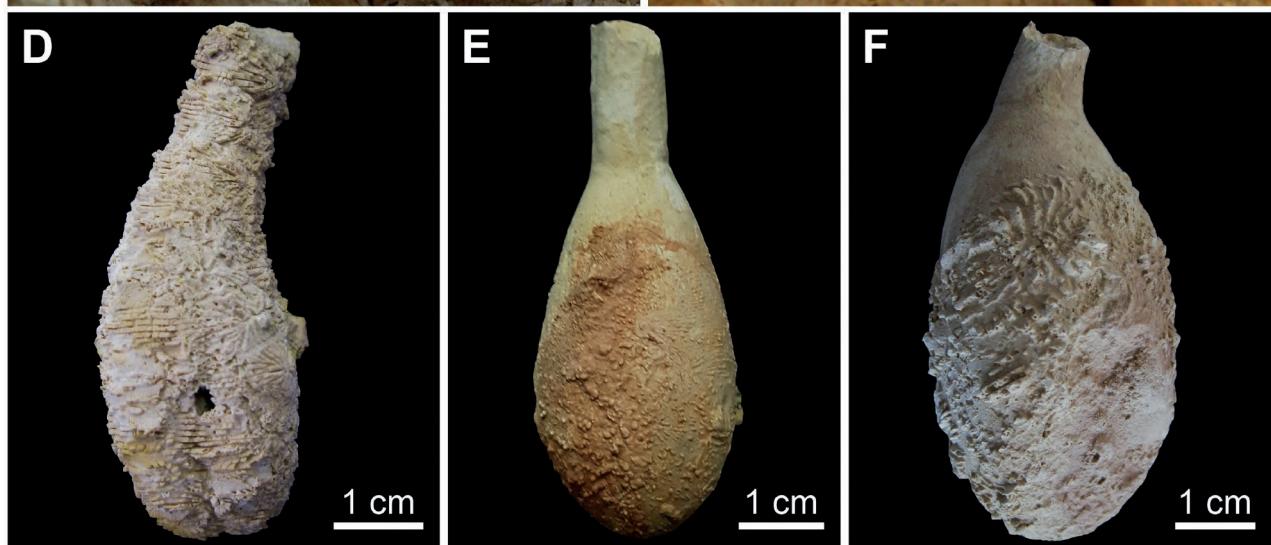
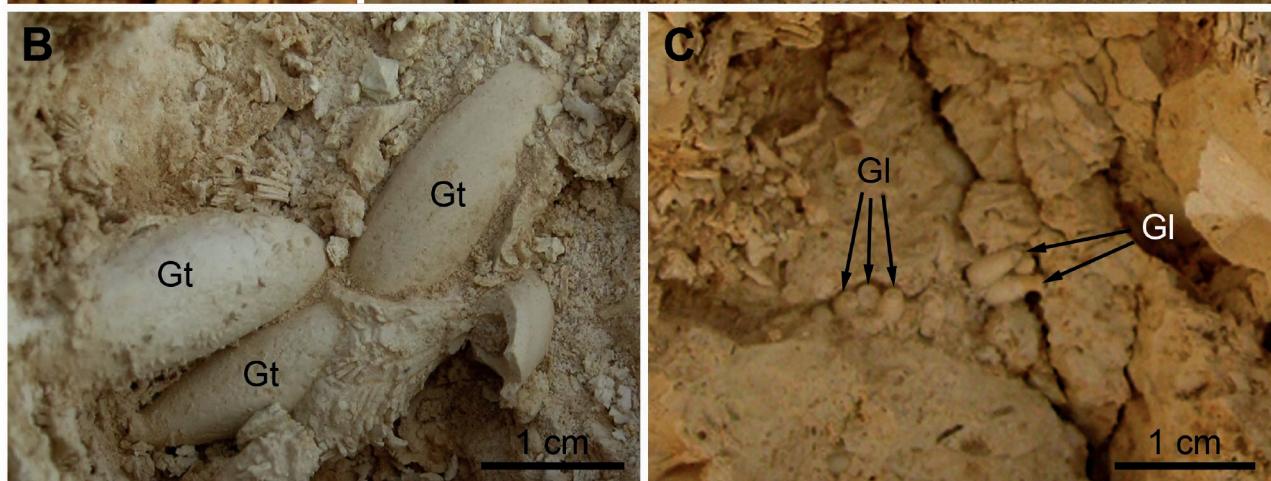
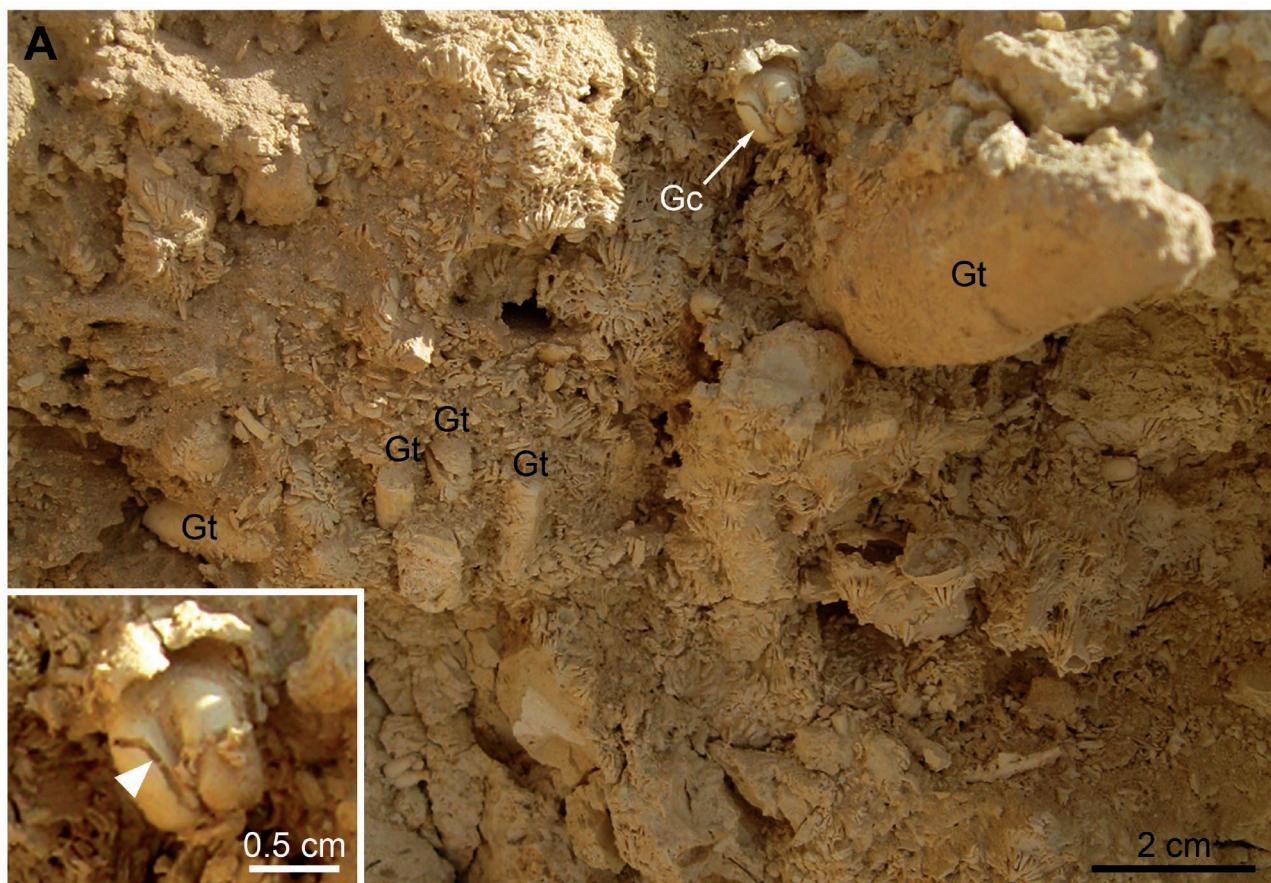
Gastrochaenolites cluniformis Kelly and Bromley, 1984
Fig. 9A, D

* 1984 *Gastrochaenolites cluniformis* ichnosp. nov. – Kelly and Bromley, p. 799, text-figs 3D, 5.

Material: Four specimens (NS33 5–8).

Description: Simple, smooth and unlined clavate-shaped borings; straight to slightly curved, bilobate at the base and circular to ovoid at the aperture. The maximum diameter is located near the centre of the main chamber. The neck and aperture are rounded to oval in cross-section. The boring is 8–44 mm long and 3–18 mm wide. Boring walls often ornamented with coral xenoglyph sculptures.

Remarks: Kelly and Bromley (1984) mentioned that *G. cluniformis* differs from *G. dijugus* Kelly and Bromley, 1984 (p. 800, text-figs 2C–D, 3C, 6A–B) in having the principal ridge in the main chamber and a bilobate form. They agreed that both ichnotaxa have been made by the mytilid genus *Botula* that frequently occurs in corals, a case most similar to the present study. According to Radwański (1969), the bivalve *Gastrochaena* also can produce *G. cluniformis*. In the present specimens, the curvature of some *Gastrochaenolites* may indicate space-limited conditions (Kelly and Bromley, 1984). The total number of



G. cluniformis identified was 80 in the measured areas, representing about 23% of the total *Gastrochaenolites* specimens identified and about 11.5% of the total borings recorded (Fig. 8).

Gastrochaenolites hospitium Kleemann, 2009
Fig. 6D, E

1994 *Gastrochaenolites vivus* ichnosp. nov. – Edinger and Risk, p. 584, figs 9 (far left), 14.

* 2009 *Gastrochaenolites hospitium* ichnosp. nov. – Kleemann, p. 339, figs 2–6.

Material: Eleven specimens (NS33 50–60).

Description: Elongated sub-cylindrical borings, straight to slightly curved, with semi-circular or bow-shaped lines towards the basal end. No neck regions were observed. Borings show slight S-like bending in the basal part. The size of the boring is variable; it is 55–90 mm long and 10–18 mm wide.

Remarks: *Gastrochaenolites vivus* Edinger and Risk, 1994, with arc-shaped laminations parallel to sides and bottom of borehole (Edinger and Risk, 1994, p. 607) is the same trace fossil, but it is regarded as a *nomen nudum* (Kleemann, 2009); therefore *G. hospitium* Kleemann, 2009 is distinguished. In recent representatives of *G. hospitium*, the short siphonal part of the boring becomes the neck of the trace, whereas in the fossil samples, the neck part may be inconspicuous or lost. *Gastrochaenolites hospitium* is produced by mytilid bivalves, belonging to *Lithophaga* (*Leiosolenus*) species (Kleemann, 2009). The total number of *G. hospitium* identified in the measured areas was 30, representing about 8.5% of the total *Gastrochaenolites* specimens identified and about 4% of the total borings recorded (Fig. 8).

Gastrochaenolites cf. *orbicularis* Kelly and Bromley, 1984
Fig. 10A

* 1984 *Gastrochaenolites orbicularis* ichnosp. nov. – Kelly and Bromley, p. 800, text-figs 3H, 6C.

Material: Two specimens (NS33 107–108).

Description: Unlined, slightly shallow depressions with subcircular bases, 3–4 mm in depth. Neck and aperture are not preserved. Depression sides are generally smooth. Rare corrugation and a few *Entobia* isp. have been observed on the walls.

Remarks: The preservation of the specimens is not sufficient to identify them with certainty as the neck and the aperture were not preserved. However, the circular

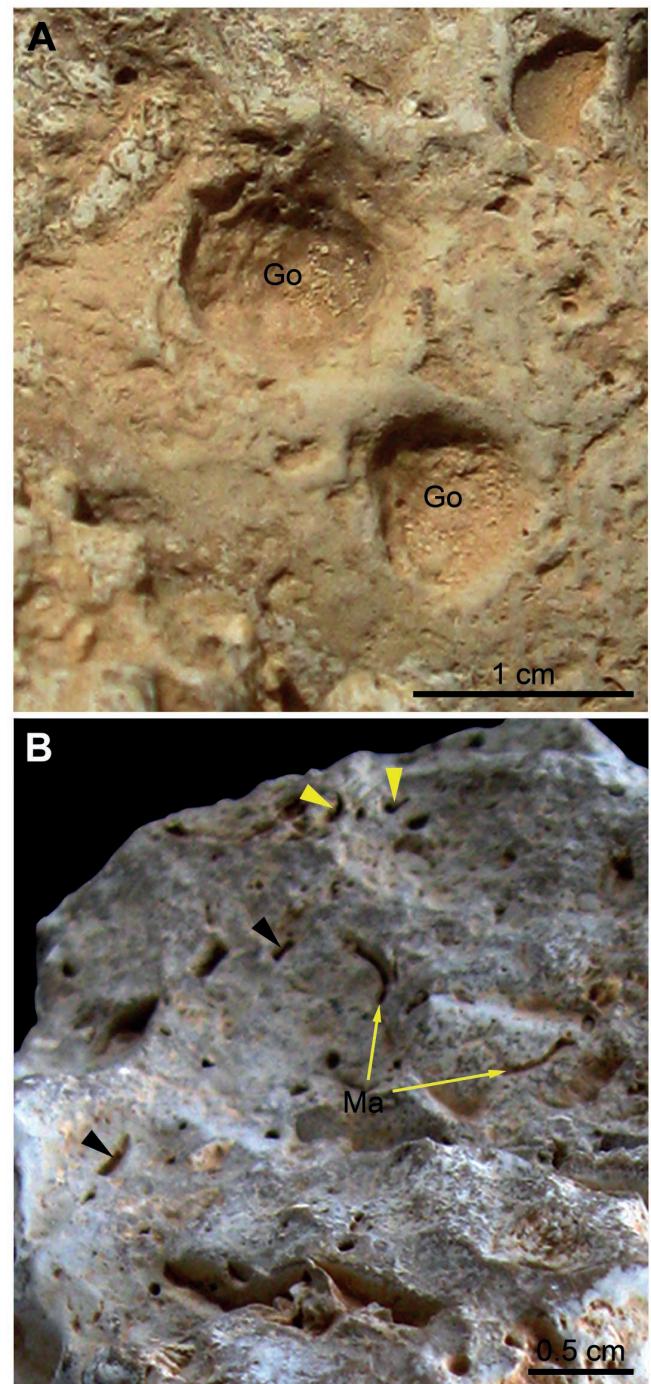


Fig. 10. *Gastrochaenolites* cf. *orbicularis* and other borings. **A.** Plan view of *G. cf. orbicularis* (Go) in reef limestone, showing smooth depressions with subcircular bases. **B.** Reef limestone hand specimen, showing galleries of *Caulostrepsis* isp. (yellow arrow heads), *Maeandropolydora* isp. (Ma) and *Rogerella* isp. (black arrow heads).

Fig. 9. *Gastrochaenolites* from the patch reef bed studied. **A.** Cross-sectional view of the spatial distribution of *G. torpedo* (Gt) and *G. cluniformis* (Gc) within coral heads of the massive coral *Porites* species. Note the worm boring *Maeandropolydora sulcans* (white arrow head in the inset). **B.** *Gastrochaenolites torpedo* (Gt) in a coral head. **C.** Small *G. lapidicus* (Gl) in a coral head. **D.** *Gastrochaenolites cluniformis* exhumed from coral, showing the bilobate base and a circular to ovate aperture. Note the coral xenoglyph sculptures. **E, F.** *Gastrochaenolites lapidicus* exhumed from a coral, showing an ovate chamber with an apertural neck (E) and a parabolic base (F). Note the coral xenoglyphs in (F).

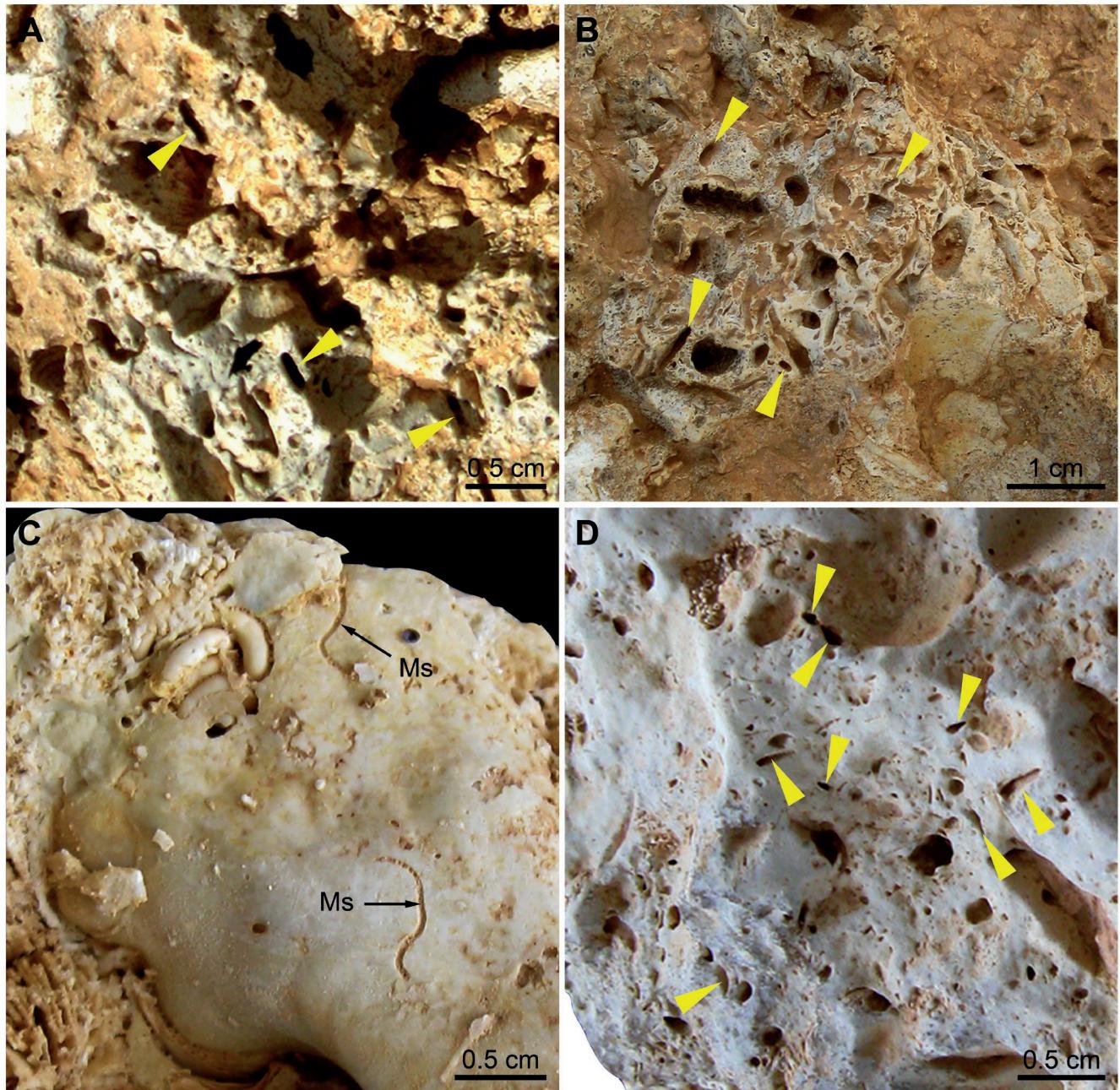


Fig. 11. Examples of some other borings from the bed studied. **A, B.** Plan views, showing *Trypanites weisei* (arrow heads) in reef limestone. **C.** Reef limestone hand specimen, showing *Maeandropolydora sulcans* (Ms). **D.** Limestone hand specimen, showing *Rogerella* isp. (arrow heads).

cross-section distinguishes this ichnospecies from other *Gastrochaenolites* ichnospecies. *Gastrochaenolites orbicularis* is produced by the bivalve *Jouannetia* (Radwański, 1969; Kelly and Bromley, 1984; Uchman *et al.*, 2017). The total number of these structures identified was 19 in the measured areas, representing about 5.5% of the total *Gastrochaenolites* specimens and about 3% of the total borings recorded (Fig. 8).

Ichnogenus *Caulostrepsis* Clarke, 1908

Type ichnospecies: *Caulostrepsis taeniola* Clarke, 1908.

Caulostrepsis isp.
Fig. 10B

Material: Two specimens (NS33 114–115).

Description: Single-entrance borings, having a pouch or earlike shape, smooth, unbranched, U-shaped galleries, with a vane connecting the limbs. The borings ranges are 2–2.4 mm wide and 0.2–1.8 mm long. The cross-section varies from flat-oval to elliptical.

Remarks: *Caulostrepsis* is distinguished from its related boring, *Maeandropolydora*, by its simple U-shaped borings that have a vane connecting the limbs of the U-boring (Bromley, 2004). However, the present specimens are eroded to different degrees, which do not allow proper identification at the ichnospecies level. *Caulostrepsis* is uncommon; it represents about 2% of the total borings identified (Fig. 8). This trace fossil is produced mainly by polychaete annelids of the genus *Polydora* (Radwański, 1964, 1969; Cameron, 1969; Hanken *et al.*, 2012).

Ichnogenus *Maeandropolydora* Voigt, 1965

Type ichnospecies: *Maeandropolydora decipiens* Voigt, 1965.

Maeandropolydora sulcans Voigt, 1965

Figs 9A, 11C

* 1965 *Maeandropolydora sulcans* ichnosp. nov. – Voigt, p. 204, pl. 26, figs 5, 6, pl. 27, figs 3, 5.

?partim 1996 *Maeandropolydora sulcans* Voigt – Mikuláš and Pek, p. 98, pl. 1, figs 3, 5–8, pl. 2, fig. 9; ?pl. 3, fig. 2.

2007 *Maeandropolydora sulcans* Voigt – Blissett and Pickerill, p. 87, pl. 3, fig. 1.

2007 *Maeandropolydora sulcans* Voigt – El-Hedeny, p. 272, pl. 1, figs 1, 2, 4.

Material: Three specimens (NS33 115–117).

Description: Long and cylindrical galleries with two apertures. The borings are either sinuous or irregular. Loose or tight loops may occur. The limbs of the loops are locally connected by a vane, or form a pouch. The size is highly variable; the length ranges from 12 to 28 mm and the width between 0.4 and 2.3 mm.

Remarks: The well-developed cylindrical galleries and lack of pouches and vanes exhibit a strong similarity to *Maeandropolydora sulcans* Voigt, 1965. Like *Caulostrepsis*, *M. sulcans* is uncommon; it accounts for about 2% of the total borings observed (Fig. 8). This trace fossil is produced by suspension-feeding spionid polychaetes (e.g., Bromley and D'Alessandro, 1983, 1987) like recent *Polydora hoplura* Claparède, 1868 (Mikuláš and Pek, 1996).

Ichnogenus *Trypanites* Mägdefrau, 1932

Type ichnospecies: *Trypanites weisei* Mägdefrau, 1932.

Trypanites weisei Mägdefrau, 1932

Fig. 11A, B

* 1932 *Trypanites weisei* ichnosp. nov. – Mägdefrau, p. 151, pl. 5, figs 1, 2.

2007 *Trypanites weisei* Mägdefrau – Blissett and Pickerill, p. 95, pl. 5, fig. 4.

2013 *Trypanites weisei* Mägdefrau – Chrząstek, p. 326, pl. 7, figs 1–8.

Material: Ten specimens (NS33 117–126).

Description: Borings are single, simple, smooth, cylindrical or sub-cylindrical, unlined and unbranched. They have an elongated entrance with a circular aperture. *Trypanites weisei* is straight to slightly curved, mostly oriented perpendicular to the bedding plane. It is 1.2–2.3 mm in diameter and up to 10 mm long. The base of the boring is blind and has a tapered to rounded termination.

Remarks: *Trypanites* is a worm boring, produced by polychaetes, sipunculoids and acrothoracican barnacles (Ekdale *et al.*, 1984). According to Bromley and D'Alessandro (1987), *T. weisei* is mostly oriented perpendicular to the substrate. In the present study, *T. weisei* represents about 13% of the all borings recorded from the bed studied (Fig. 8).

Ichnogenus *Rogerella* Saint-Seine, 1951

Type ichnospecies: *Rogerella lecointrei* Saint-Seine, 1951.

Rogerella isp.

Figs 10B, 11D

Material: Five specimens (NS33 127–131).

Description: Small, rounded to oval-like or comma-shaped depressions, with a slit-shaped aperture extend obliquely to the substrate, varying in length from 0.5 to 2.0 mm. The borings are 1.1 to 2.2 mm deep and 1.2 and 1.8 mm wide. The margins of the boring are smooth.

Remarks: In the present specimens, *Rogerella* is represented by borings eroded to different degrees, which makes identification to ichnospecies level uncertain. Owing to the great similarity between *Rogerella* and *Zapfella*, the latter is questioned by some authors as a possible junior synonym of *Rogerella* (see Pickerill *et al.*, 2002). Barnacles of the Order Acrothoracica are considered to be the tracemaker of this trace fossil (e.g., Mikuláš, 1992; Donovan and Jagt, 2013). In the present study, *Rogerella* isp. is uncommon; it accounts for about 5% of the total borings observed (Fig. 8).

DISCUSSION

Palaeoenvironmental context

Relatively shallow-water, open-marine facies dominate the Siwa Escarpment Member (Abdel-Fattah *et al.*, 2013; El-Sabbagh *et al.*, 2017). They abruptly switch to lagoonal and reef facies in the bed studied, where corals are concentrated in small, scattered patches. The interpretation of the palaeoenvironment of these reefs is based on their shape (e.g., James, 1983). The branched and columnar forms recorded are interpreted as having occupied the flank of a relatively sheltered, lagoonal shoal under low-energy conditions (e.g., Fagerstrom, 1987; Sanders and Baron-Szabo, 2005). The associations of disorganized, slightly abraded and whole-preserved fossils further indicate low-energy conditions, influenced by frequent storm events in a partially protected embayment (Abdel-Fattah *et al.*, 2013; El-Sabbagh and El-Hedeny, 2016; El-Sabbagh *et al.*, 2016). Abun-

dant alveolinids are common in clear, protected lagoons and other quiet, nutrient-rich, normal-salinity environments and on all kinds of substrate (Hallock and Glenn, 1986; Buxton and Pedley, 1989; Murray, 1991; Geel, 2000). The common bryozoans also reflect relatively low-energy, shallow-water conditions (Hageman *et al.*, 2003).

As all bivalve moulds are exclusively articulated and shell breakage is rare, a low degree of reworking is indicated (e.g., Kidwell, 1991). These show that the communities are mostly autochthonous (e.g., Kidwell and Bosence, 1991). However, bioturbation may have resulted in the disturbance and re-orientation of fossils; consequently, some of them are not preserved in their life positions.

Bioerosion ichnofacies

In the section studied, the occurrence of *in situ* epilithobiont fossils, including colonial corals, bryozoans and serpulids, support the existence of a hard, fully lithified substrate (e.g., Taylor and Wilson, 2003; Santos *et al.*, 2010). The high diversity of shallow and deep-tier bioerosion structures recorded represents colonization by different endobionts during periods of reduced deposition (Bromley and Asgaard, 1993b; Perry, 1996; Santos *et al.*, 2010; Pineda-Salgado *et al.*, 2015). Under these conditions, some borings were obliterated by continuous bioerosion (e.g., Bromley and Asgaard, 1993b; Perry, 1996; MacEachern *et al.*, 2007). Further colonization of the substrates studied by polychaete annelids and barnacles resulted in the production of *Trypanites*, *Maeandropolydora*, *Caulostrepsis* and/or *Rogerella* inside *Gastrochaenolites*. In addition, bryozoans and serpulids grew over the borings, indicating later larval settlement (Figs. 5C, 9A). This encrusting epifauna is also affected by borings (Fig. 5C), which represents a further colonization and bioerosion phase. Consequently, this points to a long period (several years) of exposure of the substrates studied before final burial.

The *Trypanites* ichnofacies was proposed by Frey and Seilacher (1980) to characterize boring assemblages in hardgrounds, reefs, rocky shores and omission surfaces (i.e., lithified marine substrates). Bromley and Asgaard (1993b) replaced the *Trypanites* ichnofacies with the *Entobia* ichnofacies (long-term bioerosion of lithified carbonates) and the *Gnathichnus* ichnofacies (bioerosion on clasts and skeletons). The *Trypanites* ichnofacies is recorded from rocks as old as the early Cambrian (James *et al.*, 1977). Bivalve and sponge borings, in contrast, became common only in the Jurassic (Bromley, 1992). Gibert *et al.* (1998, 2007) considered that the *Trypanites* ichnofacies is valid only in Palaeozoic records and the *Entobia* and *Gnathichnus* ichnofacies should be used for Mesozoic and Cenozoic records. MacEachern *et al.* (2007) suggested that *Trypanites* better serves as the ichnofacies, while *Entobia* and *Gnathichnus* serve as expressions of the ichnocoenoses that characterize the ichnofacies as a whole.

In the bed studied, the ichnological suite recorded and its characteristics resemble those of the *Trypanites* ichnofacies of Frey and Seilacher (1980) and those of the *Entobia* ichnofacies of Bromley and Asgaard (1993b). On the basis of the available data, the present authors follow Bromley

and Asgaard (1993b) and Gibert *et al.* (1998, 2007) on the question of ichnofacies. The *Entobia* ichnofacies is proved herein by (1) the high diversity of shallow and deep-tier bioerosion structures, (2) the substrate characteristics, and (3) the increased complexity of marine, benthic hardground communities, compared to the Palaeozoic or Early Mesozoic ones.

Similar occurrences of *Gastrochaenolites* with diverse assemblages of *Entobia*, *Trypanites*, *Maeandropolydora*, *Caulostrepsis* and *Rogerella* were recorded in many Cenozoic reef carbonate rocks, e.g., Oligocene corals, Puerto Rico (Edinger and Risk, 1994), the Oligocene–Miocene Bluff Formation, Grand Cayman (Pleydell and Jones, 1988), the Oligocene–Miocene White Limestone Group, Jamaica (Blissett and Pickerill, 2004), the Middle Miocene Grand Bay Formation, Carriacou (Pickerill *et al.*, 2002), the Middle Miocene of the Carpathian Foredeep Basin in Poland, Ukraine and Moldova (Wysocka *et al.*, 2016), the Miocene reefs of the northwest Red Sea (Abdel-Fattah and Assal, 2016), the Miocene rocky shore of the Mut Basin, southern Turkey (Uchman *et al.*, 2002), the Upper Miocene reefs, Mallorca (Perry, 1996), the Upper Miocene (Tortonian) rocks of Southern Poland (Radwański, 1970), the Lower Pleistocene Manchioneal Formation, Jamaica (Donovan *et al.*, 2001), Pleistocene coral communities, the Falmouth Formation, Jamaica (Perry, 2000), the Pleistocene coral reef, Bahamas (Wilson *et al.*, 1998), the Upper Pleistocene Port Morant Formation, Jamaica (Pickerill *et al.*, 1998) and the Holocene Caribbean reefs (Perry, 1998).

Bioerosion structures as palaeoenvironmental indicators

The ichnoassemblage reported was dominated by *Gastrochaenolites* (Table 2, Fig. 8). Among several boring bivalves (see Uchman *et al.*, 2017, 2018), the mytilid bivalve *Lithophaga* is considered to be the main producer of *Gastrochaenolites* (e.g., Kelly and Bromley, 1984; Bromley and D'Alessandro, 1987), being abundant in carbonate hard substrates. In the present study, the highly abundant *Gastrochaenolites* may point to water depths of a few metres (<10 m), i.e., shallow, euphotic settings (Kleemann, 1973; Bromley, 1992, 1994; Bromley and Asgaard, 1993b). In Mediterranean Neogene successions, areas crowded with individuals of *Gastrochaenolites torpedo* are produced by *Lithophaga lithophaga* (Linné, 1758) and are restricted to depths of 0 to 2 m (Kleemann, 1973). Galinou-Mitsoudi and Simis (1994) considered 2–4 m in depth as the optimum density of *L. lithophaga*.

Among the *Gastrochaenolites* ichnospecies identified, *G. torpedo* predominates over the others (Fig. 8). This predominance may be related to the attitude of the bored surface. In the bed studied, *G. torpedo* is mainly abundant in vertical cliffs, whereas it markedly decreases in horizontal and slightly inclined surfaces. Comparable occurrences have been reported by Bromley and D'Alessandro (1987), Bromley and Asgaard (1993a) and Gibert *et al.* (1998). *Lithophaga lithophaga*, the producer of *G. torpedo*, seems to have a low tolerance to sedimentation (Gibert *et al.*, 1998). Consequently, it tends to live on vertical walls or in

sheltered areas (e.g., Bromley and Asgaard, 1993a; Trigui El-Menif *et al.*, 2007).

The *Entobia* ichnospecies, including *E. laquea*, *E. ovula* and *Entobia* isp., represent the second-most common trace-fossils (Table 2, Fig. 8). In contrast to *Gastrochaenolites*, they may occur in a relatively wide spectrum of depositional settings, ranging from lagoonal patch reefs to fore-reef and offshore sites (e.g., Bromley, 1970; Perry, 1996; Hernández-Ballesteros *et al.*, 2013; Abdel-Fattah and Assal, 2016). However, Perry (2000) showed that coral samples from backreef/lagoon facies are characterized by diverse assemblages of *Entobia* associated with *Trypanites* and *Maeandropolydora*. In addition, clionaid sponges, the producers of *Entobia* (Bromley and D'Alessandro, 1984), prefer to live in nearshore, shallow, relatively low-energy, marine environments (Calcinai *et al.*, 2005). In modern reefs, highly abundant sipunculid/polychaete annelids mark lagoonal to back-reef settings (Bromley, 1978; Macintyre, 1984; Hutchings *et al.*, 1992). These findings further indicate that the ichnoassemblage presented was deposited in a shallow, low-energy environment.

The bed studied here reflects a low-energy, shallow-marine (<10 m water depth) environment, with a very low rate of sedimentation in a lagoon with patch reefs during a Serravallian regressive cycle (cf. Pleydell and Jones, 1988; Bromley, 1992; Seilacher, 1992; Perry, 1996, 2000; Wilson *et al.*, 1998; Abdel-Fattah and Assal, 2016). The recognition of the *Entobia* ichnofacies at the Siwa Oasis may confirm the effect of eustatic sea-level fall in this area during the Serravallian. The Late Miocene, in contrast, was characterized by folding and uplift of the Unstable Shelf of Egypt (Said, 1962; Guiraud *et al.*, 2005). As in most of the northern Western Desert of Egypt, the Late Miocene (Tortonian–Messinian) deposits have not been reported in the Siwa Oasis (Said, 1962, 1990; Gindy and El-Askary, 1969; Abdel-Fattah *et al.*, 2013; El-Sabbagh and El-Hedeny, 2016; El-Sabbagh *et al.*, 2016, 2017).

CONCLUSIONS

A Middle Miocene (Serravallian) lagoonal facies bed with well-developed patch reefs was recorded in a section at the Siwa Oasis, in the northern Western Desert of Egypt. It was described from the topmost part of the middle Siwa Escarpment Member and marks the contact with the overlying El Diffa Plateau Member of the Marmarica Formation. The bed consists of a moderately diverse macrofaunal assemblage of corals, pectinids, other bivalves and gastropods. Cheilostome bryozoans and serpulid worms were also recorded. The bed displays remarkable bioerosion structures, among which six ichnogenera were identified. They correspond to the borings of clionaid sponges (*Entobia laquea* and *E. ovula*), bivalves (*Gastrochaenolites lapidicus*, *G. torpedo*, *G. cluniformis*, *G. hospitium* and *G. cf. orbicularis*), sipunculid and/or polychaete worms (*Caulostrepsis*, *Maeandropolydora sulcans* and *Trypanites weisei*) and acrothoracican barnacles (*Rogerella*). The borings belong to the category *domicinia*. The most abundant ichnogenus is *Gastrochaenolites*, constituting about 50.5% of all borings counted, followed by *Entobia* (27.5%), *Trypanites* (13%),

Rogerella (5%), *Maeandropolydora* (2%) and *Caulostrepsis* (2%). The content of the ichnoassemblage and abundances of borings indicate the *Entobia* ichnofacies, which is typical of a low-energy, shallow-marine (<10 m water depth) environment, with a low sedimentation rate and periods of non-deposition. The depositional environment is interpreted as a lagoon with patch reefs.

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