AN ICHNOFOSSIL-LAGERSTÄTTE FROM THE MIOCENE VILANOVA BASIN (NE SPAIN): TAPHONOMIC AND PALEOECOLOGIC INSIGHTS RELATED TO BIOEROSION STRUCTURES

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ABSTRACT: A new ichnofossil-lagerstätte from the Miocene Vilanova Basin (NE Spain) is described. It is characterized by bioerosion structures that are exceptionally preserved as positive casts, many associated with internal and external molds of mollusk shells (gastropods and bivalves). Five main ichnotaxa were identified: *Caulostrepsis contorta, C. taeniola, Entobia cateniformis, E. geometrica* and *Gastrochaenolites dijugus,* produced by annelids, sponges and bivalves, respectively. Combination of ichnological, taphonomical and systematic data allows the concentration to be interpreted as the result of several storm events that mixed shells from a diverse array of marine environments during the biostratinomical phase. Bioerosive episodes took place before and after storms,

and diagenetic processes produced external and internal shell molds and fine casts of the borings.

INTRODUCTION

Fossil-lagerstätten, in both concentration (konzentrat-) and conservation (konservat-) categories, are mainly characterized by the exceptional preservation of body fossils, either in terms of quantity or quality (Seilacher 1970, 1990; Seilacher and Westphal 1971; Seilacher et al. 1985). The presence of trace fossils as additional components is relatively common within this kind of outcrops and/or sedimentary rocks; however, their preservation is not necessarily exceptional (e.g. Bromley and Ekdale 1986; Gibert et al. 2016; Jensen et al. 2006; Knaust 2010).

Despite its traditional application to body fossils, trace fossil lagerstätten (bioturbation and/or bioerosion) are not uncommon. From the early 1990's (e.g. Bromley and Asgaard 1991) to date, the terms 'Trace fossil-lagerstätte' or 'Ichnofossil-lagerstätte' have become more frequently used. Mángano and Buatois (1995) concluded that the original conceptual framework and classification of fossil-lagerstätten is perfectly applicable to trace fossils. Thus, within the classification of ichnofossil-lagerstätten, two main categories can be distinguished (following Mángano and Buatois 1995 and Savrda 2007, after Seilacher 1990): (1) 'Concentration lagerstätten', where the exceptional abundance of ichnofossils is favored by sedimentological and/or biological processes that promote their concentration or condensation (e.g. Savrda and King 1993; Savrda et al. 2000, 2005; Buta et al. 2005; Hunt et al. 2005); and (2) 'Conservation lagerstätten', where the extraordinary preservation of ichnofossils mainly results from rapid burial, diminished oxygenation, early diagenetic mineralization and/or bacterial activity (e.g. Savrda and Ozalas 1993; Fornós et al. 2002; Hall and Savrda 2008;

Seilacher 2008; Minter and Braddy 2009; Monaco and Checconi 2010; Voigt and Lucas 2015; Savrda et al. 2016).

In the present paper, a new ichnofossil-lagerstätte from the Miocene Vilanova Basin (NE Spain) is described. It is characterized by bioerosion structures (ichnogenera *Caulostrepsis, Entobia* and *Gastrochaenolites*) preserved as positive casts that exhibit the finest details and allow for study of their overall three-dimensional architecture. The casts may appear isolated or associated with mollusk shell molds (mainly bivalves and gastropods). These features suggest its consideration as a conservation lagerstätte, wherein exceptional preservation of trace fossils is mainly due to diagenetic processes. The objectives of this paper are, therefore: (1) to carry out a detailed description of the trace fossils, at both ichnogeneric and ichnospecific levels; (2) to describe the main taphonomic processes; and (3) to discuss the depositional environment and possible tracemakers.

GEOLOGIC AND GEOGRAPHIC SETTING

The studied ichnofossil-lagerstätte is located at the outcrop known as Pi Gros, near the town of Vilanova i la Geltrú, about 50 km southwest of Barcelona (NE Spain) (Fig. 1). The sedimentary rocks here are part of the Miocene infill of the Vilanova Basin, an extensional basin situated over the Mesozoic basement that constitutes the Garraf Massif, which in turn is located within the Catalan Coastal Ranges (Cabrera et al. 2004). The study of terrestrial mammal remains (Agustí and Moyà-Solà 1991; Ramos-Guerrero et al. 1994) and marine mollusks (Batllori and Moreno 2003) suggests a Middle Miocene age (probably Serravallian) for these sediments. Moreover, the Vilanova Basin is part of the onshore section (together with the El Camp de Tarragona Basin, El Vallès-Penedès Basin and the Barcelona Plain) of the Valencia Trough (Fig.

1), an extensional system developed during the latest Oligocene and Miocene between the eastern part of the Iberian Peninsula and the Balearic promontory to the east (Fontboté et al. 1990; Bartrina et al. 1992; Roca and Guimerà 1992; Roca et al. 1999).

Within the infill of the Vilanova Basin, Ramos-Guerrero et al. (1994) differentiated four main units. They are, from bottom to top: (1) Marginal Unit, M_0, consisting of breccia deposits associated with the normal faults bounding the basin; (2) Basal Conglomeratic Unit, M_1, constituted by alluvial conglomerates and whose deposition would be related with the reliefs created by the faults that originated the basin; (3) Intermediate Detrital-Carbonate Unit, M_2, mainly consisting of grey marls with limestone intercalations interpreted as a gradual succession from lacustrine to brackish and marine littoral depositional settings; and (4) Upper Detrital Unit, M_3, constituted by sandstones and calcarenites in the lower part and by siltstones and calcisiltites on top, attributed to shallow marine depositional settings. The succession may be locally covered by Quaternary deposits.

The sedimentary rocks studied herein consist of a mollusk coquina that should correspond with the lower part of the Upper Detrital Unit (M_3) of Ramos-Guerrero et al. (1994). Unfortunately, the Pi Gros outcrop no longer exists; it was destroyed during the construction of an industrial park (over a decade ago), though it was possible to access and sample the outcrop before its total disappearance. The mollusk coquina was some 2 m thick at the site. The matrix of this coquina is composed of a fine- to medium-grained calcarenite, and the molluscan association is highly diverse. Although most are preserved as external and internal molds (*sensu* McAlester 1962), good preservation of some morphologies allowed for identification of gastropod genera such as *Protoma, Turritella, Crepidula, Vermetus, Tudicla, Ancilla, Cancellaria* and *Conus* among others (Batllori and Moreno 2003), as well as bivalves (*Glycymeris, Astarte, Pelecyora,*

Acanthocardia). Associated with the fossil mollusks is a plethora of bioerosion structures preserved as casts. These were mentioned in an abstract (Martinell and Domènech 2005).

All the material related to the present study is deposited in the Ichnological Collection of the Faculty of Earth Sciences of the University of Barcelona, Spain (UB-IC 747 to 887).

SYSTEMATIC ICHNOLOGY

Some parts of the shells in the Miocene coquina show borings produced by different kinds of endoskeletozoans (mainly sponges, polychaetes and bivalves). Five main ichnotaxa were identified: *Caulostrepsis contorta, C. taeniola, Entobia cateniformis, E. geometrica* and *Gastrochaenolites dijugus*. This is not an exhaustive systematic revision; still, descriptions and remarks are provided in order to clarify some aspects. All measurements were carried out using a vernier caliper with a precision of ±0.05 mm.

Ichnogenus *Caulostrepsis* Clarke 1908

Caulostrepsis taeniola Clarke 1908

Description: Cylindrical galleries or tubes bent in a narrow U with an overall morphology that commonly exhibits a rectilinear trajectory or more rarely is slightly curved (14.75 mm of maximum observed length; Fig. 2A, D, G–H). The vane between limbs is poorly developed in width to almost inexistent. Both limbs are always well differentiated along their length except at the vertex area, however. The vertex commonly exhibits tongue-shape morphology with both limbs fused (Fig. 2A, D, G). Subsequently, cross-sections show an 8-shaped perimeter (from 0.6 to 3.45 mm of

maximum observed width), except at vertex where this is flattened-oval. Just once, longitudinal and shallow ridges (bioglyphs; see Ekdale and Gibert 2010 and references therein) were observed along the cast surface (Fig. 2F).

Remarks: In the Miocene Pi Gros outcrop (Vilanova Basin), the specimens of *C. taeniola* occur associated with internal molds of gastropods (mainly *Turritella*, Fig. 2D, H, and more rarely buccinids, Fig. 2G), never as isolated casts. In the case of *Turritella* molds, cluster of borings may occur in the lower part of the body whorl, around the columella (Fig. 2D). Infrequently, they affect infaunal bivalve shells (Fig. 2F). Crystallization may occasionally obliterate the architectural details of borings. Besides *C. taeniola*, specimens of *Gastrochaenolites dijugus* may appear in a single gastropod mold.

Caulostrepsis contorta Bromley and D'Alessandro 1983

Description: Irregular, sinuous and cylindrical tubes which, along its length, are occasionally folded forming tongue- or U-shaped lobes (Fig. 2B, C, E). One tube may form several lobes, which are irregularly distributed and exhibit different dimensions. Depending on the specimens, vanes may be poorly or fully developed; a single tube may bear lobes with or without a developed vane (Fig. 2B, C). Since very complex systems can occur, cross-sections range from 8-shaped to circular/oval-shaped morphologies. A gradation of boring sizes is seen in several specimens, the maximum width varying between 0.45 and 2.5 mm.

Remarks: As with *C. taeniola*, borings are always associated with internal molds of gastropods, never isolated, and in particular with *Ancilla* molds (often clustered in the apex area; Fig. 2B, C), *Turritella* molds (occasionally together with *Gastrochaenolites dijugus*) and more rarely with undetermined bivalve shells (Fig. 2E).

Ichnogenus *Entobia* Bronn 1837

Entobia cateniformis Bromley and D'Alessandro 1984

Description: Simple to complex networks or systems of long cylindrical galleries and sub-circular chambers interconnected among themselves and to the surface by several apertures. The simplest systems consist mainly of a single cylindrical gallery (1.5 mm and 25 mm in maximum observed width and length, respectively) with Y-shaped branching points (Fig. 3A, C, E, G); in turn, secondary and small cylindrical tubes (less than 0.5 mm in diameter) along the length of the main gallery connect it to the surface (Fig. 3A, C). Additionally, sub-circular chambers may be associated with these simple systems at their supposed original area of larval fixation or 'initial point of entry' (following Bromley and D'Alessandro, 1984; Fig. 3A). By contrast, most complex networks comprise cylindrical galleries and sub-circular chambers (3 mm maximum observed diameter) with multiple Y-, L- and/or T-shaped branching points and secondary tiny tubes connecting the main galleries to each other and with the surface (Fig. 3B, F, H), resulting in very complex three-dimensional mazes. Unlike the simpler systems, transitions between cylindrical galleries and sub-circular chambers may be totally chaotic or disordered (Fig. 3F, H).

Remarks: In the Vilanova Basin, *E. cateniformis* was found to be associated both with gastropod (mostly *Turritella* sp.) and bivalve internal molds. In the case of bivalves, borings commonly occur anywhere in the shell, and occasionally are abundant in the umbonal area (Fig. 3A, C, D, E). In gastropods, borings are frequently located in the inter-whorl areas, forming very complex and probably the most delicate three-dimensional structures observed in the studied material (Fig. 3F–H). No other ichnotaxa were observed accompanying *E. cateniformis*.

Entobia geometrica Bromley and D'Alessandro 1984

Description: Three-dimensional networks constituted by sub-circular to polygonal chambers that may be fused together and then separated by annular constrictions, and/or non-fused and interconnected by small secondary cylindrical tubes or galleries. These small tubes are abundantly disposed around the whole perimeter of chambers and also connect the overall system with the surface (Fig. 4). The diameter of main chambers ranges from 0.8 to 3.5 mm, and that of secondary tubes ranges from less than 0.1 to 0.7 mm.

Remarks: This ichnospecies is probably the most abundant one in the Miocene Vilanova Basin. It occurs in both gastropods (*Turritella*, *Protoma*) and bivalves (*Pelecyora*), and in both cases can involve the entire shell, resulting in stenomorphic borings (*sensu* Bromley and D'Alessandro, 1984; Fig. 4A–C, F–H). Other ichnotaxa, e.g. *Gastrochaenolites dijugus* and *Caulostrepsis taeniola,* may frequently occur together with *E. geometrica* both in bivalve and gastropod molds (Fig. 4C, D).

Ichnogenus *Gastrochaenolites* Leymerie 1842

Gastrochaenolites dijugus Kelly and Bromley 1984

Description: These ichnofossils are characterized by a clavate or flask-shaped chamber (0.85 to 22 mm long) with a circular to oval cross-section (0.8 to 12.8 mm wide), connected with a narrow neck region (up to 18.85 mm long and 5 mm wide) that exhibits an 8-shaped aperture (Figs. 5, 6). The neck region has two fused cylindrical elements (Figs. 5B, M–O, 6A). Additionally, up to four annular constrictions are present, affecting the basal part of the neck region (oval in section), as well as the beginning of the two fused cylindrical elements (Fig. 5A, B, P). Evidence of a dissolved

calcareous lining (with a smooth internal surface and a knobby outer surface) surrounding the whole structure is occasionally observed (Fig. 5B). A gradation of very likely ichnogenetic stages (*sensu* Belaústegui et al. 2016) is seen in several specimens (Fig. 6A–C).

Remarks: In the Miocene Pi Gros outcrop, specimens may appear as isolated positive casts (alone or forming clusters; Fig. 5K–P) or else associated with internal molds of gastropods (*Turritella*, *Protoma*, *Conus*) and bivalves (*Glycymeris*, *Pelecyora*) (Figs. 5A–J, Q, 6). The size of *Gastrochaenolites* casts associated with gastropod internal molds often exceeds the probable thickness of the shell (Fig. 5D–J, Q). In addition, bivalve shells (cf. *Gastrochaena*, presumably belonging to the tracemaker) are preserved within some of the casts.

DESCRIPTIVE TAPHONOMY

The marine Miocene of the Eastern margin of the Iberian Peninsula is represented by a variety of facies, from the most marginal (conglomerates and breccias) to those of open marine conditions (calcisiltites, clays or marls) (e.g. Gibert et al. 1995, 1996; Domènech et al. 2011a; Belaústegui and Gibert 2009, 2013; Belaústegui 2013; Belaústegui et al. 2014a, 2014b, 2015). Coral bioconstructions of carbonate facies also appear (e.g. Zamora et al. 2010; Domènech et al. 2011b). The preservation style of the fossils in these deposits is diverse (e.g. Belaústegui et al. 2011, 2012a, 2012b, 2013). The open marine fine-grained facies usually yield quite well preserved invertebrate skeletons, especially in the small fraction. In contrast, the carbonate levels and the more detritic ones tend to be affected by diagenetic processes that led to the dissolution of most shells.

Within this context, the Miocene Pi Gros outcrop allows one to differentiate between biostratinomical and diagenetic aspects (Figs. 7, 8): (1) With respect to biostratinomy, most of the studied material is part of a coquina with a well-sorted matrix that is mainly composed of highly fragmented bivalve and gastropod shells (up to 1.3 cm in size); indeed fact, most of the sedimentary rock corresponds to this matrix (approximately 85%). In contrast, larger bioclasts (greater than 1.3 cm) mainly consist of slightly fragmented to complete bivalve and gastropod shells with abundant bioerosion structures. The preserved ichnofossils are always filled by sediment; the sedimentary infill has the same composition as the host sediment, though generally lacking large bioclasts, which is a consequence of the filtering action of the narrow apertures of the borings. Some bivalve specimens are preserved with shells that are complete and articulated. (2) In reference to diagenesis, all the marine fossils are preserved as internal and/or external molds (rarely, as casts; following the terminology proposed by McAlester 1962) and the cavities previously occupied by the shells are now empty spaces. All ichnofossils are moreover preserved as positive casts promoted by a cementation process that not only favored casting but also hardened the host sediment. Rarely, some of these casts and even the empty spaces generated after shell dissolution are slightly crystallized. Manganese dendrites are common in the outer perimeter of molds and casts.

Comparable examples were described by Fürsich et al (1994), Marcinowski and Radwański (2009) and Radwański et al. (2011) in the Upper Jurassic of southern England, in the Lower Cretaceous of Poland, and in the middle Miocene of Ukraine, respectively. In all these cases, these authors identified (among others) the ichnogenera *Entobia, Gastrochaenolites* and *Maeandropolydora* preserved as positive casts very

248 similar to those described herein. In no case was the designation of ichnofossil-
249 lagerstätte utilized.
250
251 ## DISCUSSION
252 ### *Tracemakers*
253 As stated, bioeroders in the Miocene of the Pi Gros outcrop mainly consist of
254 endoskeletozoan sponges, polychaetes and bivalves. The following paragraphs offer a
255 review of these producers and describe their activity in the studied coquina.
256 *Caulostrepsis* is attributed to the boring activity of polychaete annelids, mainly
257 Spionidae (genus *Polydora*; see Häntzschel 1975; Bromley 2004; Domènech et al.
258 2008), Eucinidae (species *Lysidice ninetta*; see Bromley 1978; Martinell and Domènech
259 2009 and references therein) and Cirratulidae (genus *Dodecaceria*; see Bromley and
260 D'Alessandro 1983); *Entobia* is interpreted as borings produced by Clionaidae sponges
261 (Bromley 2004 and references therein); and *Gastrochaenolites* is widely accepted as the
262 result of the activity of boring bivalves (Bromley 1970; Kelly and Bromley 1984;
263 Fischer 1990; Savazzi 1999).
264 With respect to *Gastrochaenolites dijugus*, evidence of a calcareous lining
265 around some of the largest studied casts has been observed (Fig. 5B). In fact, in many
266 specimens one sees (despite being internal molds) that the size of casts clearly exceeds
267 the expected thickness of shells (mainly in gastropods, Fig. 5D–J). Additionally,
268 isolated casts of *G. dijugus* were recorded. Part of these casts are hence designated as
269 the 'intraskeleton clavate borings' or the 'semi-endoskeletal dwellings' defined by
270 Belaústegui et al. (2013; see also Rahman et al. 2015).
271 A gradation of ichnogenetic stages is manifest (Figs. 6, 7): (1) the initial stages
272 are smaller (most likely related to larval fixing and juvenile ontogenetic stages of the

tracemaker; Fig. 8E, I), confined and adapted to the thickness of the shells, corresponding to intraskeleton clavate borings; and (2) the largest borings with the neck region totally developed (i.e. final ichnogenetic stages; Figs. 7, 8F), with or without evidence of a calcareous envelope (or crypt *sensu* Savazzi 1982) and clearly exceeding the thickness of the shells (both internally and externally), are semi-endoskeletal dwellings.

Finally, isolated *Gastrochaenolites* casts could be the result of soft-substrate colonization (generating a crypt) or the detachment from molds after erosion. Nowadays it is known that tube-dwelling bivalves belonging to the superfamily Gastrochaenoidea are able to secrete full-body enveloping calcareous crypts and colonize soft-substrates (see Belaústegui et al. 2013 and references therein), and the identification as cf. *Gastrochaena* of the bivalves preserved within the casts is compatible with this interpretation.

Ichnologic, taphonomic and paleoenvironmental implications

From the studied material of the Pi Gros outcrop (Vilanova Basin), an ideal (or most likely) and general sequence of chronologically-ordered events (Fig. 7) can be deduced by combining paleobiological and taphonomical information.

The already known malacological content (Batllori and Moreno 2003), together with the new identifications, provide for key paleobiological data to interpret the formation of the studied coquina. Although some alteration of the association could stem from taphonomical processes, the identified taxa shed light on some paleobiological considerations. First of all, it should be noted that the gastropod species correspond to a diverse array of marine environments, both from bathymetrical and substrate conditions. Bathymetrically, they inhabit from supralittoral (*Patella, Gibbula*)

298 to circalittoral environments (*Cassidaria, Athleta*), with examples of meso- (*Nerita,*
299 *Olivella*) and infralittoral (*Nassarius, Natica*) typical taxa. Moreover, rare continental
300 gastropods (helicids) were observed within this coquina. From substrate, there are taxa
301 inhabiting rocky bottoms (*Patella, Gibbula, Nerita*), located under submerged rocks
302 (*Hadriania, Fusus*), on sands (*Strombus, Nassarius*) or muds (*Terebralia, Turritella*),
303 and burrowing in soft substrates (*Protoma, Strioterebrum*).

304 Regarding bivalves, all molds correspond to infaunal species. There are no
305 fossils from epifaunal taxa. Identification, even at a generic level, is problematic owing
306 to the absence of basic morphological characters in many specimens. Deserving
307 mention nevertheless is the presence of *Glycymeris* and *Pelecyora* of remarkable size
308 (12.6 mm of anteroposterior length), *Lutraria, Astarte, Dosinia, Acanthocardia,*
309 *Cerastoderma* and, presumably, corbulids. In all cases, there are common infaunal
310 suspension-feeder taxa of littoral marine environments, which excavate shallow into the
311 sediment. They inhabit at different depths, from the meso- to the infralittoral, occupying
312 gravel (coquina), sandy or muddy bottoms.

313 Taphonomy constitutes the second source of data to deduce the formation of this
314 ichnofossil-lagerstätten. Biostratinomic and fossildiagenetic processes can be discerned.
315 The studied coquina exhibit a bimodal distribution of components: a well-sorted matrix
316 composed of molds of fragmented unidentifiable shells and molds of complete-to-
317 slightly-fragmented mollusk skeletons larger than 1.3 cm.

318 At the beginning of the biostratinomic phase, the finest fraction (i.e. the matrix)
319 would have originated in a shallow marine setting, probably a littoral environment
320 subjected to continuous wave action that generated this well selection and high
321 fragmentation of shells. Subsequently, the well-sorted and highly fragmented material
322 would have been transported by sporadic energetic episodes (storms) to more sublittoral

environments. The storm events could have been strong enough to transport complete or almost complete shells from the most littoral environments to a deeper setting. In turn, the sublittoral autochthonous fauna would have been *in situ* removed and even exhumed in the case of infaunal organisms. In view of the thickness of the studied level (around 2 m), the final accumulation was probably the result of multiepisodic events rather than a single one.

Following the biostratinomic processes, within this sublittoral depositional setting sporadically affected by storms, some proportion of the accumulated and exhumed shells was colonized by different kinds of endoskeletozoans (sponges, polychaetes and bivalves; Fig. 7) as explained above. The different occurrences of *Gastrochaenolites dijugus* give clues to interpret the bioerosive sequence. Thus, while these intraskeleton clavate borings could be perfectly simultaneous with the colonization of polychaetes and sponges (both in time and place, and corresponding to a typical *Entobia* ichnofacies), the presence of semi-endoskeletal dwellings (and maybe also of isolated casts) would imply episodes with higher sedimentation rates, thus ruling out the occurrence of these other organisms, especially boring sponges; during episodes when common boring bivalves became burrowers, it would be more adequate to include their traces in an *Skolithos* ichnofacies rather than within any of the other ichnofacies related to hard substrates. Moreover, those clusters of *G. dijugus* in which the constituent specimens intersect each other (Fig. 5K, L), again demonstrate the occurrence of different boring/burrowing episodes, even within the sediment.

Following probable successive processes of removal and colonization, the infilling of shells and borings, and the subsequent burial and definitive concentration of skeletons and bioclasts (Fig. 7), first diagenetic processes took place (respectively, compaction, cementation and dissolution). The dissolution processes affected all the

shells in the rock, whether mainly composed of aragonite (most part of the molluscan species identified in the Pi Gros outcrop) or the calcitic ones (e.g, gastropod genus *Gyroscala*). In addition, the bivalve-dwelling crypts and tubes were dissolved. External and internal molds were generated (very rarely casts) and the place previously occupied by shells was preserved as empty spaces. An earlier process of cementation of shell and boring infills as well as of the englobing sediment promoted the exceptional preservation of bioerosion structures as three-dimensional trace fossils (Fig. 7). The shell dissolution no doubt took place in an advanced phase of cementation and could contribute to the hardness of the rock.

Particular cases

In the previous section an overall interpretation (ichnologic, taphonomic and paleoenvironmental aspects) of the Pi Gros outcrop (Vilanova Basin) was presented. As there are always exceptions and/or particularities, four specific examples are provided below to shed further light on the processes leading to the final association (Fig. 8):

1. Several specimens of *Gastrochaenolites dijugus* associated with the internal mold of a complete and articulated infaunal bivalve (genus *Pelecyora*) (Figs. 6, 7, 8A–D, L). This internal mold exhibits borings only in the area corresponding to the ventral margin of both valves. Related to the borings, a gradation of ichnogenetic stages is observed. The deep and highly-protruding impressions of the umbonal area and the adductor muscle scars (Fig. 8 C, D) indicate that the valves of this specimen would have had a substantial thickness; consequently, all the bioerosion structures could be considered as intraskeleton clavate borings. In addition, this internal mold allows one to distinguish that its valves were slightly open (Fig. 6C) during or after its exhumation and/or exposure on the seafloor; the presence of borings restricted exclusively to the

most ventral region of valves would be a sign that probably only that part was exposed (Fig. 8A, B). The resulting microhabitat, protected from predators and environmental disturbance, was ideal for the fixing, colonization and development of boring-bivalve larvae.

2. *G. dijugus* associated to *Conus* internal molds (Figs. 5D–J, 7, 8E–H, L). In these cases, bioerosion structures very likely consist of intraskeleton clavate borings during larval fixing and juvenile ontogenetic stages of tracemakers. However, over time, they became clear semi-endoskeletal dwellings (see above) as can be confirmed with preserved material.

3. Clusters of *G. dijugus* isolated in the coquina (Fig. 5K, L). Casts of *Gastrochaenolites* also appear free in the rock, unrelated to skeletal molds. Some are composed by several intersecting specimens.

4. *Entobia, Caulostrepsis* and *Gastrochaenolites* associated with internal molds of turritellid shells (Figs. 2H, 3F–H, 4I, J, 5Q, 7, 8I–K, L). As commented above, the tracemakers of the three ichnotaxa could have coexisted and simultaneously colonized the same shell; however, among the recollected material, only associations of *Entobia-Caulostrepsis*, *Entobia-Gastrochaenolites* and *Caulostrepsis-Gastrochaenolites* were observed. Frequently, these associations clearly correspond to different temporal episodes of colonization. *Entobia-Gastrochaenolites* associations were occasionally observed associated with bivalve internal molds (Figs. 4C, 5A).

CONCLUSIONS

1. The fossil assemblage of Pi Gros outcrop is the result of: (1) the multiepisodic accumulation of marine mollusk shells; (2) the bioerosion effect in the skeletons and the substrate; and (3) the diagenetic processes affecting them all. Taxonomic, ichnologic

and taphonomic approaches allow one to interpret the depositional environment and the fossilization sequence.

2. Five main ichnotaxa were identified: *Caulostrepsis contorta, C. taeniola, Entobia cateniformis, E. geometrica* and *Gastrochaenolites dijugus*.

3. The identified mollusks correspond to several marine environments, whereas the shell accumulation and successive exhumation/burial episodes presumably took place in the sublittoral zone. Bioerosion traces due to different kinds of endoskeletozoans give clues regarding the bioerosive sequence. The intraskeleton clavate borings (produced by bivalves) were simultaneous with the colonization of polychaetes and sponges, but the presence of semi-endoskeletal dwellings and isolated casts implies episodes with higher sedimentation rates that ruled out their occurrence, in particular that of boring sponges. Clusters of intersecting *G. dijugus* prove the occurrence of different bioerosive episodes.

4. Due to diagenetic processes, body-fossils are preserved as internal and external molds and trace-fossils as positive casts.

5. The Vilanova Basin provides a fine example of how destructive (dissolution) and constructive (cementation of boring casts) diagenetic processes may result in the exceptional preservation of bioerosion trace fossils which, in this case, clearly constitute an ichnofossil (konservat)-lagerstätte.

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659
660
661 **FIGURE CAPTIONS**
662 FIG. 1.–Geological and geographical setting of the studied area. **A**) Geological map of
663 Catalan Coastal Ranges and Valencia Trough, showing their location in the
664 Iberian Peninsula (modified from Roca and Guimerà, 1992); main Miocene basins
665 are indicated, including Vilanova Basin. **B**) Simplified geological map of
666 Vilanova Basin (modified from http: //www.icgc.cat/).

667

668 FIG. 2.–*Caulostrepsis*. **A**) *C. taeniola* and *C. contorta* associated with an internal mold
669 of a gastropod. **B**, **C**) *C. contorta* associated with an internal mold of a gastropod,
670 two views of the same specimen. **D**) *C. taeniola* associated with internal mold of a
671 turritellid gastropod. **E**, **F**) *C. contorta* and *C. taeniola* (respectively) associated
672 with external molds of infaunic venerid bivalves. **G**, **H**) *C. taeniola* associated
673 with internal molds of buccinid and turritellid gastropods, respectively. Scale bar
674 is 5 mm.

675

676 FIG. 3.–*Entobia cateniformis*. **A**–**C, E**) Several specimens associated with D. **D**)
677 Internal mold of a complete *Pelecyora* shell showing the displacement of the
678 valves. **F**–**H**) Several specimens associated with internal molds of turritellid
679 gastropods. Scale bar in D is 10 mm, in the rest 5 mm.

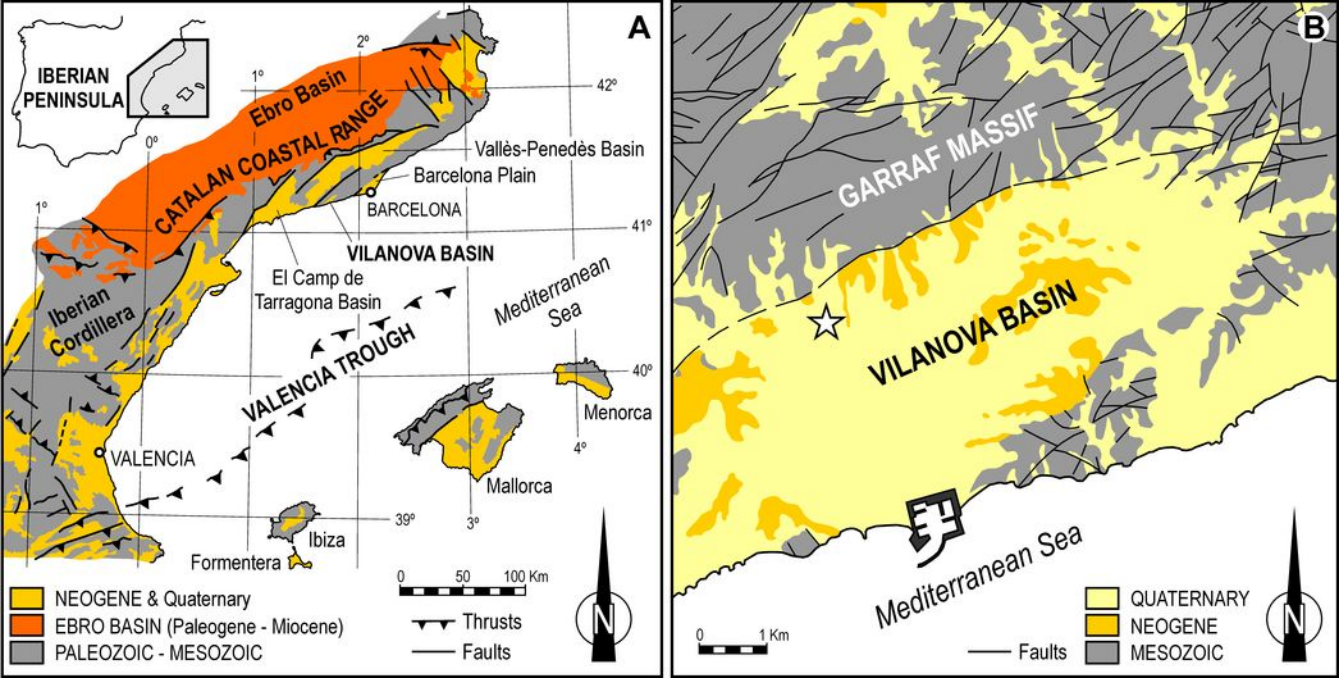
680

681 FIG. 4.–*Entobia geometrica*. **A**, **B**) Specimens associated with C. **C**) Internal mold of an
682 infaunal *Lutraria*-like bivalve. **D, F, G**) Specimens associated with external molds
683 of turritellid gastropods. **E**) Specimen in which it is possible to clearly distinguish
684 between the sub-circular to polygonal main chambers and the small secondary
685 cylindrical tubes or galleries. **H**–**J**) Specimens associated with internal molds of
686 turritellid gastropods. Scale bar in C is 10 mm, in the rest 5 mm.

687

688 FIG. 5.–*Gastrochaenolites dijugus*. **A**) Specimens, together with *Entobia* borings,
689 associated with the internal mold shown in Fig. 4C. **B**) Specimen associated with
690 an internal mold of a *Glycimeris* bivalve; evidence of a dissolved calcareous
691 lining or envelope is observed around the boring. **C**) At least four specimens

692 associated with an internal and external mold of a turritellid gastropod. **D**–**F**)
693 Specimen associated with an internal mold of a conid gastropod; three views of
694 the same specimen. **G**–**I**) Specimen associated with an internal mold of a conid
695 gastropod; three views of the same specimen. **J**) Two specimens associated with
696 an internal mold of a conid gastropod. **K**, **L**) Cluster of at least ten casts. **M**–**P**)
697 Different examples of isolated casts. **Q**) Specimens associated with a turritellid
698 internal mold. Scale bar is 5 mm.
699
700 FIG. 6.–*Gastrochaenolites dijugus* associated with the internal mold of a complete and
701 articulated bivalve (*Pelecyora*). **A**, **B**) Two details of borings shown in C and D;
702 different ichnogenetic stages are observed. **C**, **D**) Ventral and general view
703 (respectively) of the bivalve internal mold. Scale bar in A-B is 5 mm, in C-D 10
704 mm.
705
706 FIG. 7.–Taphonomic diagram showing an ideal succession of biostratinomical and
707 diagenetic processes from the Miocene Pi Gros outcrop (Vilanova Basin).
708
709 FIG. 8.–Taphonomic diagrams of particular cases observed in the Miocene Pi Gros
710 outcrop (Vilanova Basin). **A–D**) Several specimens of *Gastrochaenolites dijugus*
711 associated with the internal mold of a complete and articulated infaunal bivalve
712 (*Pelecyora*). **E–H**) *G. dijugus* associated with *Conus* internal molds. **I–K**)
713 *Entobia, Caulostrepsis* and *Gastrochaenolites* associated with *Turritella* internal
714 molds. **L**) Final result: positive and internal cast of shells and borings.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IBERIAN PENINSULA
Ebro Basin
CATALAN COASTAL RANGE
Vallès-Penedès Basin
Barcelona Plain
BARCELONA
VILANOVA BASIN
El Camp de Tarragona Basin
Iberian Cordillera
VALENCIA TROUGH
Mediterranean Sea
Menorca
VALENCIA
Mallorca
Ibiza
Formentera
0° 1° 2° 42° 41° 40° 39° 4° 3°
0 50 100 Km
NEOGENE & Quaternary
EBRO BASIN (Paleogene - Miocene)
PALEOZOIC - MESOZOIC
Thrusts
Faults
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Mediterranean Sea
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Faults
QUATERNARY
NEOGENE
MESOZOIC
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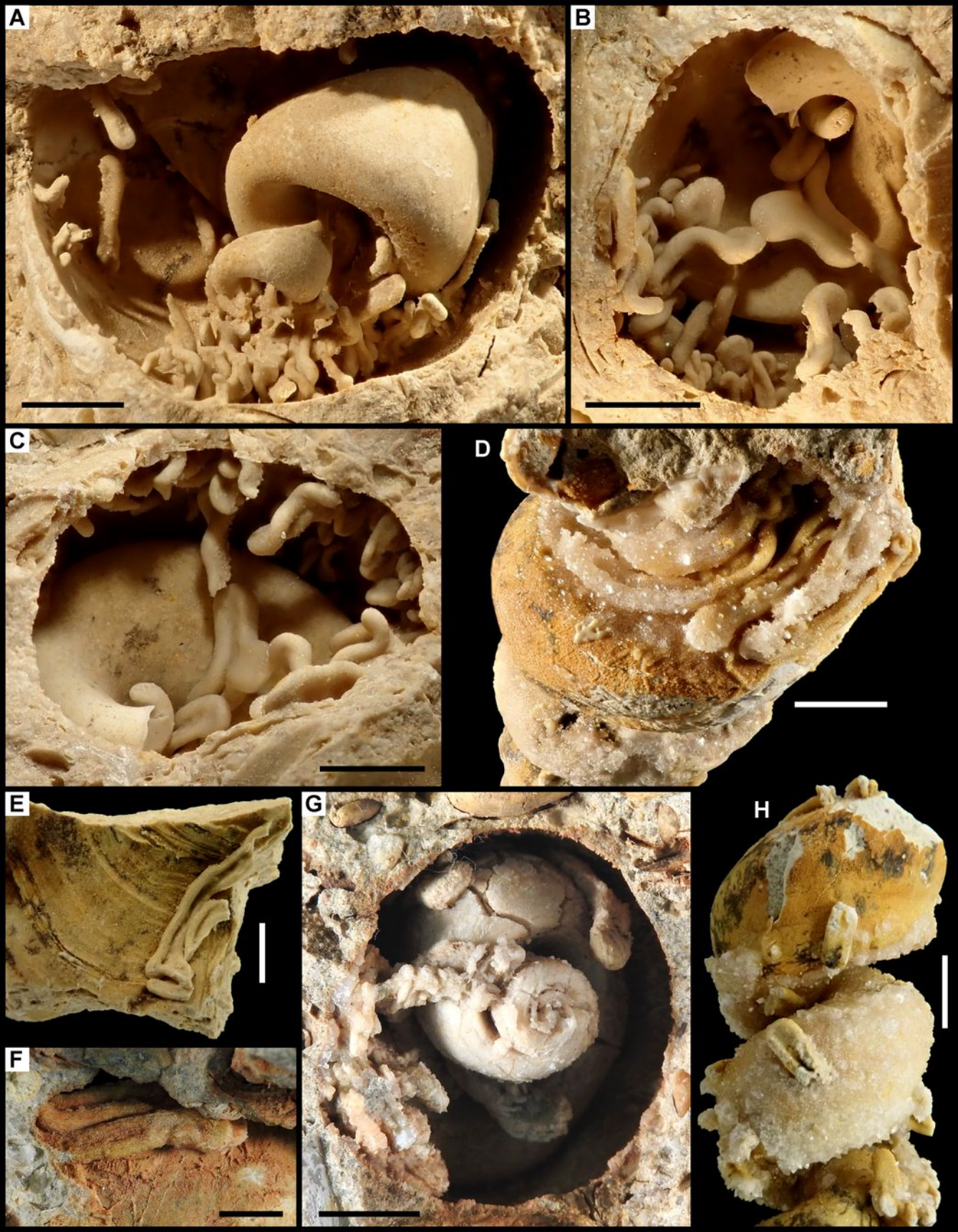
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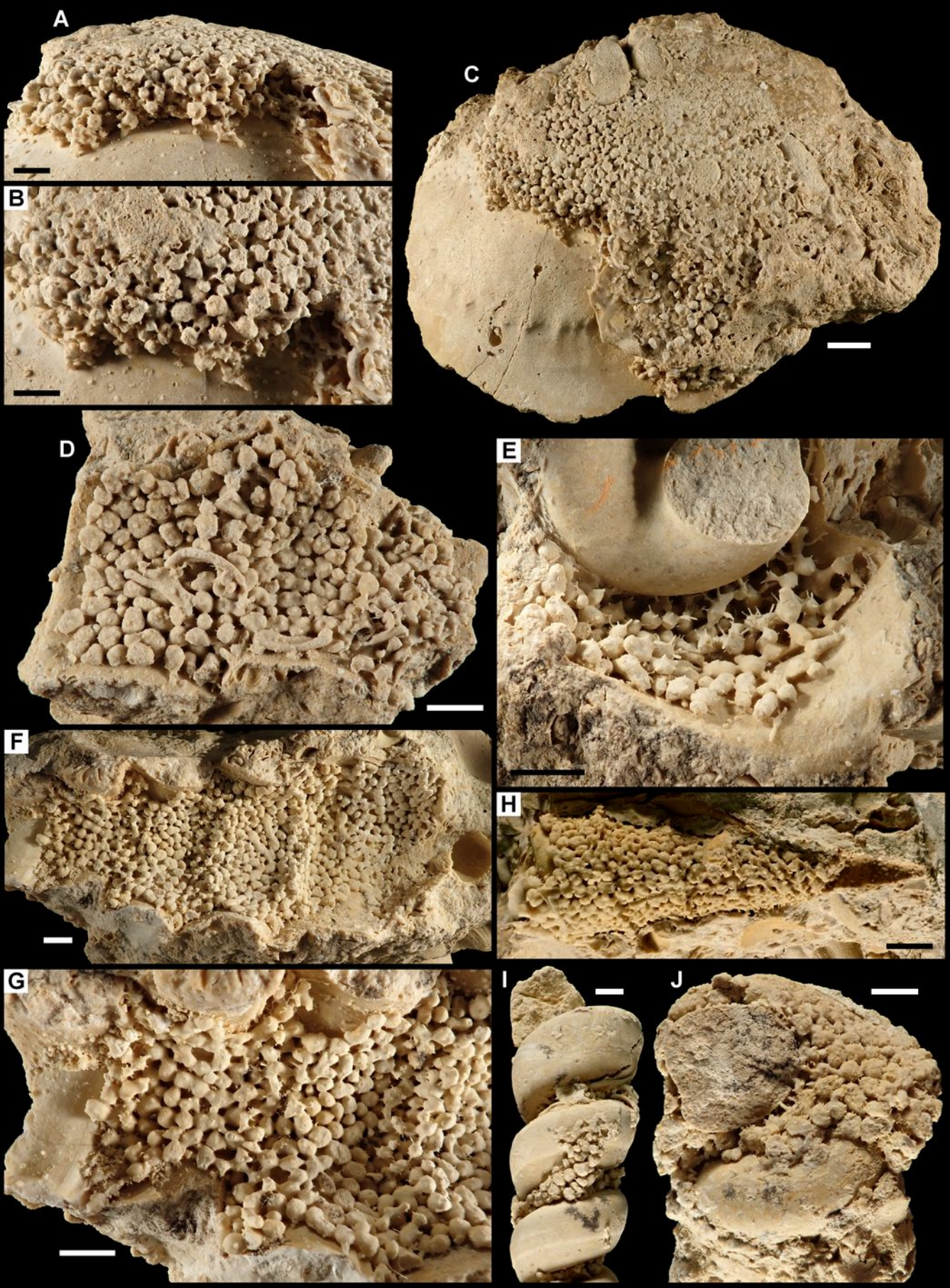
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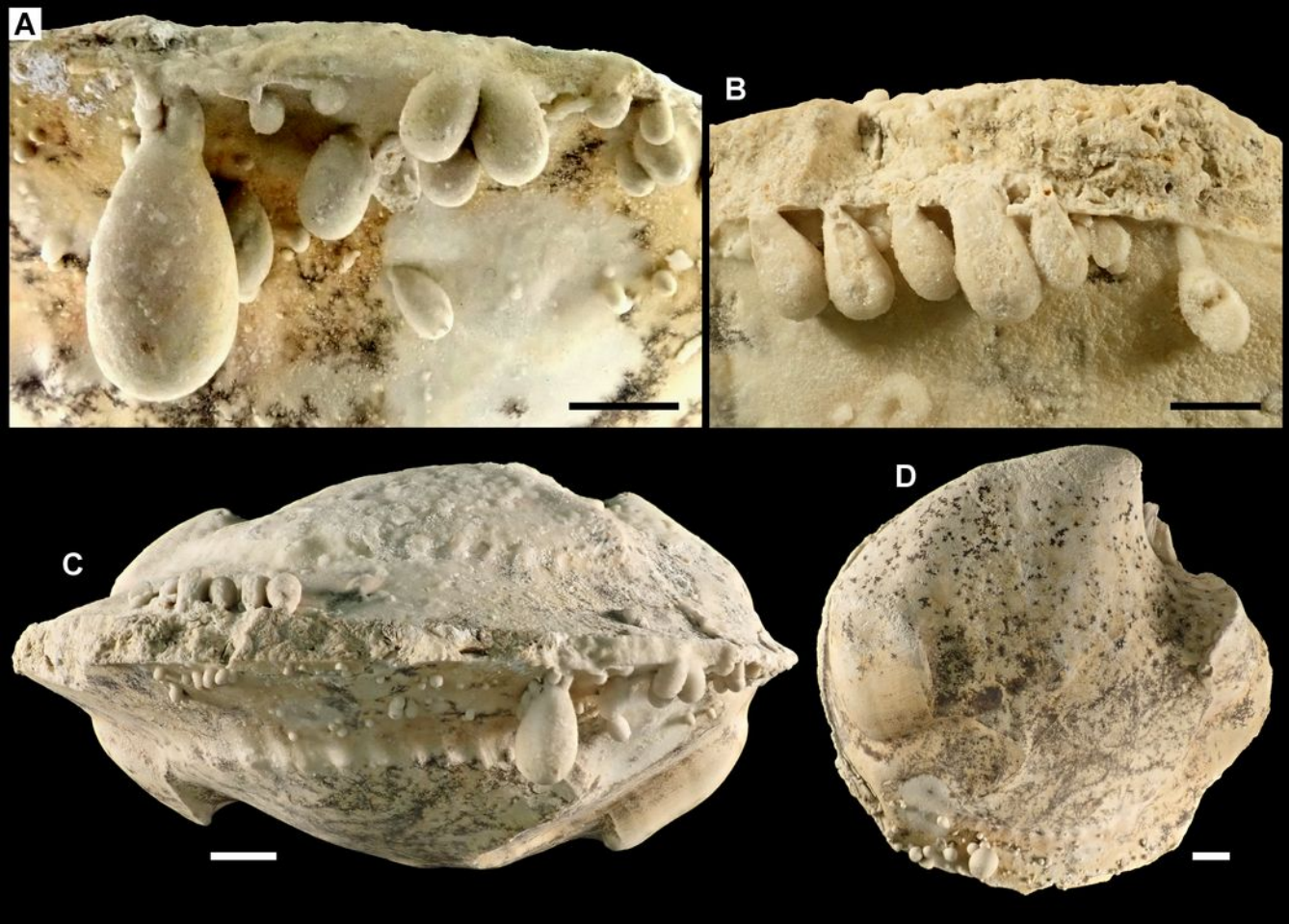
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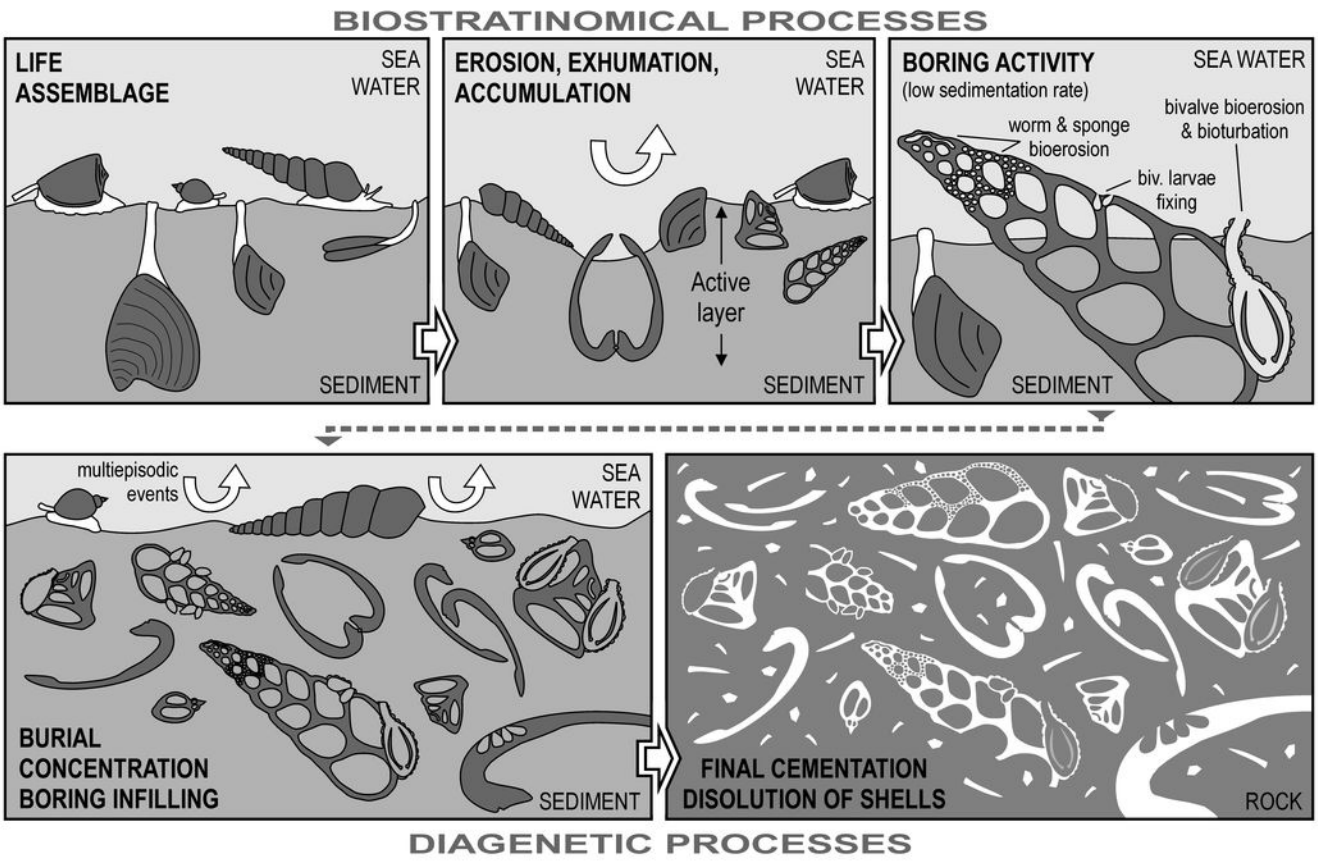
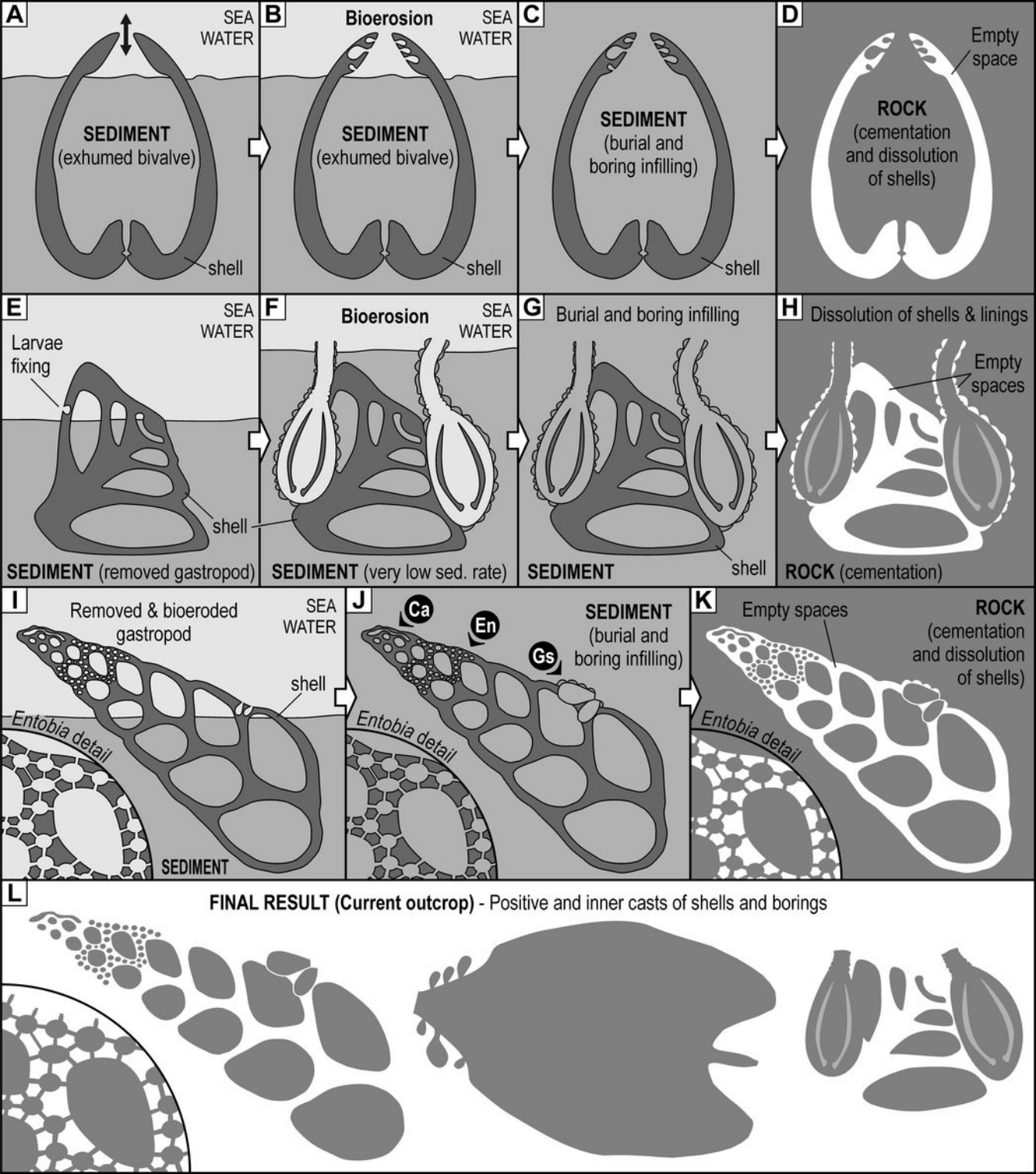

BIOSTRATINOMICAL PROCESSES
LIFE ASSEMBLAGE
SEA WATER
SEDIMENT
EROSION, EXHUMATION, ACCUMULATION
SEA WATER
Active layer
SEDIMENT
BORING ACTIVITY
(low sedimentation rate)
SEA WATER
worm & sponge bioerosion
bivalve bioerosion & bioturbation
biv. larvae fixing
SEDIMENT
multiepisodic events
SEA WATER
BURIAL
CONCENTRATION
BORING INFILLING
SEDIMENT
FINAL CEMENTATION
DISOLUTION OF SHELLS
ROCK
DIAGENETIC PROCESSES


A
SEA WATER
SEDIMENT (exhumed bivalve)
shell
B
Bioerosion
SEA WATER
SEDIMENT (exhumed bivalve)
shell
C
SEDIMENT (burial and boring infilling)
shell
D
Empty space
ROCK (cementation and dissolution of shells)
E
SEA WATER
Larvae fixing
shell
SEDIMENT (removed gastropod)
F
Bioerosion
SEA WATER
SEDIMENT (very low sed. rate)
G
Burial and boring infilling
SEDIMENT
shell
H
Dissolution of shells & linings
Empty spaces
ROCK (cementation)
I
Removed & bioeroded gastropod
SEA WATER
shell
Entobia detail
SEDIMENT
J
Ca
En
Gs
SEDIMENT (burial and boring infilling)
Entobia detail
K
Empty spaces
ROCK (cementation and dissolution of shells)
Entobia detail
L
FINAL RESULT (Current outcrop) - Positive and inner casts of shells and borings