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BICHORDITES MONASTIRIENSIS ICHNOFABRIC FROM THE PLEISTOCENE SHALLOW-MARINE SANDSTONES AT LE CASTELLA (CROTONE), IONIAN CALABRIA, SOUTHERN ITALY

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Abstract. The analysis of *Bichordites* ichnofabric has been performed in laminated calcarenites of Upper Pleistocene marine terraces of the Crotone Peninsula, Ionian Calabria, outcropping in the coast nearby the village of Le Castella (southern Italy). These calcarenitic deposits show an intense and pervasive bioturbation, preserved mainly as endichnia s.s., exposed endichnia (false epichnia with hyp- and epireliefs) and crossichnia, dominated by *Bichordites monastiriensis*. Other forms (more rare) are *Cardioichnus* isp., *Ophiomorpha nodosa, Planolites beverleyensis* and ?*Macaronichnus*-like trace fossils. This shallow-water ichnofabric, that is recurrent in many sandy shallow water marine terraces of Pleistocene, exhibits hundreds of *Bichordites monastiriensis* (meniscate burrows) that are studied in cross sections and plane views. A detailed taphonomic study shows many differences in the central core of *Bichordites monastiriensis* that varies in shape, length and dimension, from the outer meniscate envelopment, following the burrowing action of spatangoid echinids in sandy substrate. The rhythmical arrangement in shape and density of *Bichordites* in foreshore sandy bars with megaripples, with a regressive trend in the stratigraphic section, likely reflects variations and the strength of current along coast.

Introduction

The sea-urchin burrows (Spatangoida, Echinoidea, Echinodermata) of the ichnogenus *Bichordites monastiriensis* Plaziat & Mahmoudi, 1988 is widely known in many shallow-water deposits of Pleistocene in many sandy marine terraces (or sand ridges, Nara 2014) of the world: e.g. in the Tyrrhenian littoral of Tunisia (Plaziat & Mahmoudi 1988), the Rhodos Formation of Rhodes, Greece, (Bromley & Asgaard 1975), the Tursi Sandstone of the Lucania Basin, southern Italy (D'Alessandro & Uchman 2007), in eastern Spain close to Alicante (Giannetti pers. communic.), in Japan (e.g. the Boso Penisula and other nearby places; Nara 2004; 2014, or in Tsuruga Bay, Kanazawa 1995), in Jamaica (Old Pera Beds, Coastal Group, Pickerill et al. 1993) and in New Zealand (Ward & Lewis 1975). Other descriptions of more ancient shallow water deposits with *Bichordites monastiriensis* are described in the Oligocene of Valsugana (Trento area, Northern Italy, Bernardi et al. 2010), the Bateig Limestone of Miocene of Spain (Gibert & Goldring, 2008), the shallow marine Upper Miocene molasse of Austria (Uchman & Krenmayr 1995, 2004) and the Paleogene deposits of the Richmond Formation of the eastern Jamaica (Donovan et al. 2005). Similar ichnotaxa in Cretaceous shallow water deposits of the Sácaras Formation (Sierra Helada, Alicante, eastern Spain, Monaco et al. 2005) are still doubtful and still under study.

In Le Castella (Crotone Peninsula, Ionian Calabria, Fig. 1A) the ichnofabric analysis (sensu Taylor & Goldring 1993; Gibert & Goldring 2007; McIlroy 2007; Aguirre et al. 2010) shows that shallow water laminated sandstones (Seike 2009) exhibit intervals rich in *Bichordites monastiriensis* that occurs in hundred specimens. This ichotaxon consists of an inner core and the outer meniscate large tunnel (named "menisci" in Gilbert & Goldring 2008 that correspond to former "*Laminites*", used in Bromley & Asgaard 1975; Plaziat & Mahmoudi 1988; Bernardi et al. 2010; Uchman 1995, Demírcan & Uchman 2012). *Bichordites* occurs as endichnion, exposed epichnion and also crossichnion (see Martinsson

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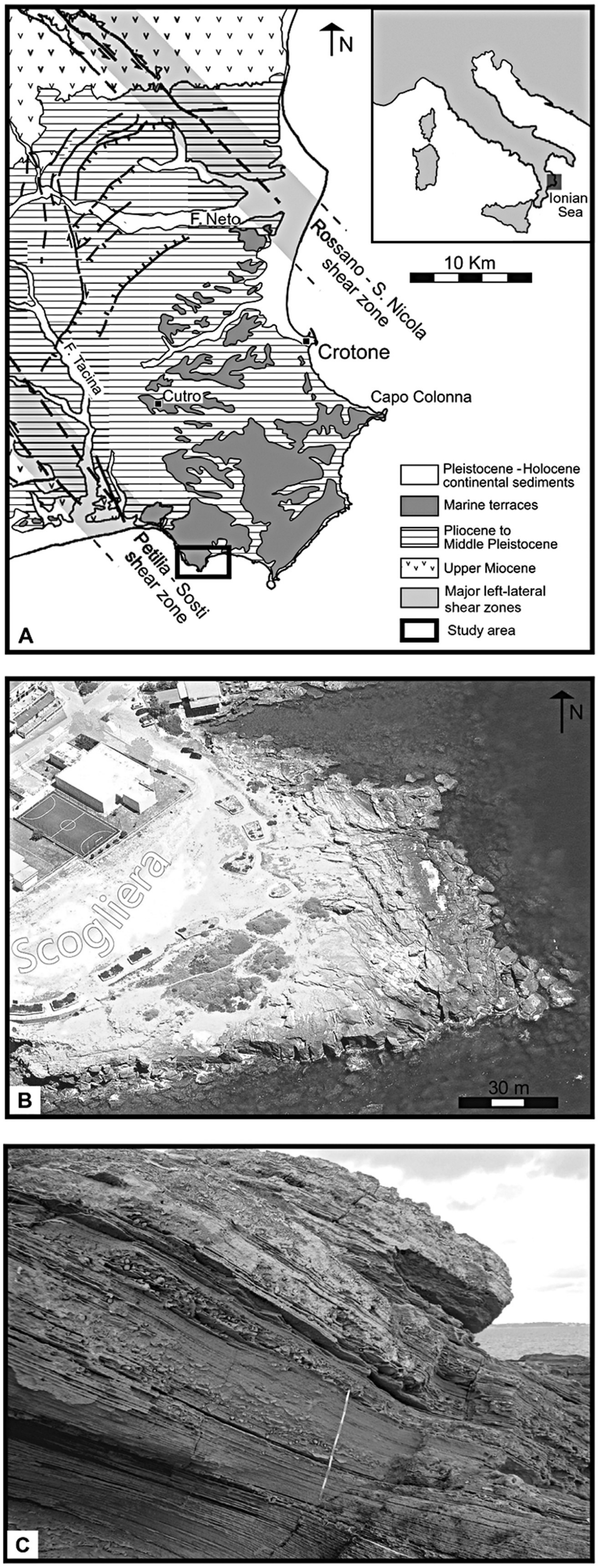


Fig. 1 - A) Geological sketch map of the Crotone Basin (Ionian Calabria, modified by Zecchin et al., 2004) with Le Castella studied section (see rectangle). B) Study area (modified by www.bingmaps). C) Partial outcrops of Le Castella section.

1970; Monaco & Caracuel 2007; Monaco & Checconi 2008 and references therein). The Le Castella section consists of decimeter-thick sands strongly bioturbated by spatangoid urchins alternated with laminated m-thick sands without or with very scarce bioturbation index. This situation is common in other Pleistocene marine terraces of Mediterranean (Bromley & Asgaard 1975; D'Alessandro & Uchman 2007). Usually, the shallow-water ichnofabric at Le Castella exhibits other different trace fossils, such as rare *Rosselia socialis* Dhamer, 1837 (found in the Austrian Molasse and Ionian Calabria; Uchman & Krenmayr 2004; D'Alessandro & Uchman 2007, respectively), *Planolites beverleyensis* Billings, 1862, *Cardioichnus* Smith & Crimes, 1983 (described in assemblage with *Bichordites* in northern Italy, Bernardi et al. 2010), ?*Macaronichnus*-like traces (may be ?*M*. cf. *segregatis* Clifton & Thompson, 1978; or different ichnospecies, see Pearson et al. 2013) and *Ophiomorpha nodosa* Lundgren, 1891. This assemblage can be found commonly together with urchins in many coastal to shallow water deposits (Plaziat & Mahmoudi 1988; Uchman & Krenmayr 2004; Goldring et al. 2007).

The aim of this paper is devoted to make a new composite analysis (taphonomy of ichnofabric) of spatangoid traces in the Pleistocene calcarenitic beds at Le Castella (Crotone area, Fig. 1A-B); the paper intends to characterize variations in constructional model of *Bichordites* in shallow-water conditions, under current changes and trophic variations. Another purpose is to show that concentrations of trace fossils of heart urchins – with a lacks of body fossils as observed in Jamaica in *Scolicia prisca* (Pickerill et al. 1993; Donovan et al. 2005) – change cyclically following the energy of currents to form strongly bioturbated deposits preserved in marine terraces in the Crotone Peninsula (Zecchin et al. 2004; Caruso 2014).

Geological setting

The study area is located nearby the Le Castella village (Crotone, Ionian Calabria, Southern Italy). The outcrop in which trace fossils are discovered belongs to the youngest (V order) Upper Pleistocene marine terraces of the Crotone Peninsula (Gliozzi 1987; Palmentola et al. 1990; Bonardi et al. 2001; Massari et al. 2002; Zecchin et al. 2004, 2012, 2014; Ietto et al. 2008; Fig. 1A).

The study outcrop belongs to the "Crotone Basin", Miocene-Pleistocene in age, that developed on the Calabria-Peloritani Arc (Bonardi et al. 2001; Barone et al. 2008; Zecchin et al. 2012). The Crotone Basin is fault-bounded and it was formed as result of the southeastward migration of the Calabrian Arc (Zecchin et al.

2004, 2005; Zecchin et al. 2012 cum bibliography). The development of the terraces was controlled by Pleistocene sea-level changes (Zecchin et al. 2004, 2012) and by the Middle Pleistocene uplift of the Calabrian Arc (Zecchin et al. 2004), at a rate of 0.40 m/ky for the Crotone Peninsula (Palmentola et al. 1990).

The Plio-Pleistocene part of the Crotone Basin succession is exceptionally well preserved, and consists of a suite of continental, paralic, shallow-marine and moderately deep-marine deposits (Barone et al 2008; Zecchin et al. 2012). The terrace deposits, typically a few metres thick, are dominated distally by carbonate sedimentation consisting of algal reefs, whereas mixed siliciclastic and bioclastic deposits are present landwards (Zecchin et al. 2004, 2012). In particular, the terraces are constituted by marine sedimentary deposits, consisting of mixed carbonate and siliciclastic bodies organized in meter-scale cycles (Zecchin et al. 2004); the cycles are represented by rhythmic alternations between shell-rich intervals (dominated by storm structures or large-scale cross sets) and burrowed shell-poor sandy beds (in which stratification is obliterated by the bioturbation). Zecchin (2005) recognizes in these cycles a fining-upward trend and hypothesizes that the deposition of large-scale cross sets is due to some fault scarps, which led to tectonic confined area (probably a half-graben basin), in which tidal currents were enhances and large subaqueous dunes migrated. On the other hand, the above-mentioned cyclicity is related to the sediment input into the basin that is controlled by sea level variations and climatic changes (Massari et al. 2002; Zecchin 2005).

The outcrop in which ichnological observations have been focused in this paper belongs to the Le Castella-Capo Rizzuto Terrace (Gliozzi 1987); it is situated southward to Le Castella village (N 38°54'22,81"; E 17°01'28,88"; ~ 5 m a.s.l.), in the locality "La Scogliera" (Fig. 1B). Here, the sedimentary sequence is composed by calcarenites and it is tilted seaward (SE).

Gliozzi (1987) describes an intense tectonic activity in the Le Castella sector (fault striking system NNE-SSW), which affected the terraces, causing the tilting of the sedimentary succession seaward (SE); in addition, several fractures (NW-SE and E-W) affected the Le Castella biocalcarenites (Gliozzi 1987), and some of them are filled by laminated sandstone (sedimentary dykes). Furthermore, the presence of submarine canyons (Ceramicola et al. 2009), a submarine megaslide over a buried viscous salt layer (Minelli et al. 2013) and mud diapirism (Capozzi et al. 2012) may have produced strong deformations of the sedimentary succession of the study area.

The palaeoecological analysis carried out on malacofaunas records a marine infralittoral environment (*Posidonia* biocenosis), which confirms the sedimentary structure typical of upper shoreface to foreshore zone, with a trangressive-regressive trend, and a warm-temperate climate (Gliozzi 1987).

The marine terraces are Pleistocene in age, belonging to the "Ionian-Upper stages" MNN21a *H. huxleyi* and MPL8c (referring to the calcareous nannofossil and planktonic foraminifera biostratigraphic schemes; Zecchin et al. 2012). Le Castella terrace is a synthem (Zecchin et al. 2014) related to Marine Isotope Stages (MIS) 3.3 (Zecchin et al. 2012, 2014) and has an age of 62-86 k.y. B.P. based on U/Th analysis and isoleucine epimerization, using corals and molluscs (Gliozzi 1987).

Until now, the sequence was studied (Gliozzi 1987; Zecchin et al. 2004, 2014; Zecchin 2005) only from the sedimentological and stratigraphic point of view; in these papers the authors quote the general presence of bioturbation and burrows, but no detailed ichnological studies were conducted.

In this paper, a detailed stratigraphic section has been measured (Figs. 1C, 2) and ichnological studies are conducted (Fig. 1B-C) in a strongly cemented sedimentary succession (informally named "Le Castella Calcarenites - Cal-LeCast", Caruso 2014), consisting of very coarse- to medium-grained biocalcarenites (Fig. 1C; Fig. 2); from the bottom, is clearly distinguishable a lithofacies (about 0.80 m thick) made by planar beds (N 10° E - 27° dip), followed by sets (3.50 m in total) of laminated beds alternated to totally bioturbated layers (N 5° E - 27° dip), which evolve upsection into a cross-bed lithofacies (with asymptotic layers); this facies (0.50 m thick) is eroded on the top (unconformity); the succession ends with a cross-bed and festoon lithofacies (1 m thick, N 22° E - 5° dip).

Methods

The analysis of spatangoid urchin trace fossils involved hundreds specimens that are preserved in sandy levels of Pleistocene terraces of Le Castella (Isola Capo Rizzuto, Crotone, Ionian Calabria, Figs 1, 2). Sampled specimens, named informally "Cal-LeCast" (followed by numbers) are stored in the IchnoLab of the DiBEST (Department of Biology, Ecology and Earth Science of the Calabria University) and in the BiosedLab of the Physic and Geology Department of Perugia University.

The ichnofabric analysis follows methods of Taylor & Goldring (1993), Gibert & Goldring (2007), McIlroy 2007; Aguirre et al. (2010), Pearson et al. (2013), and in particular the *Bichordites* ichnofabric in Gibert & Goldring (2007, 2008) and D'Alessandro & Uchman (2007). It consists of two basis philosophies: those that used semi-quantitative approach (Miller & Smail 1997; Droser & Bottjer 1986, 1991) and those based on descriptive methods (Wetzel & Uchman 1998; Monaco & Checconi 2010). The semi-quantitative method change slightly from that used by Droser and Bottjer (1986) and Monaco et al. (2010) because in shallow water deposits of Le Castella the endichnial *Bichordites* shows very long specimens that can be observed, in epichnial view, only in bed surfaces of more than 2 m^2 (in plain view); in cross view *Bichordites* specimens are very concentrated, then is possible to analyse

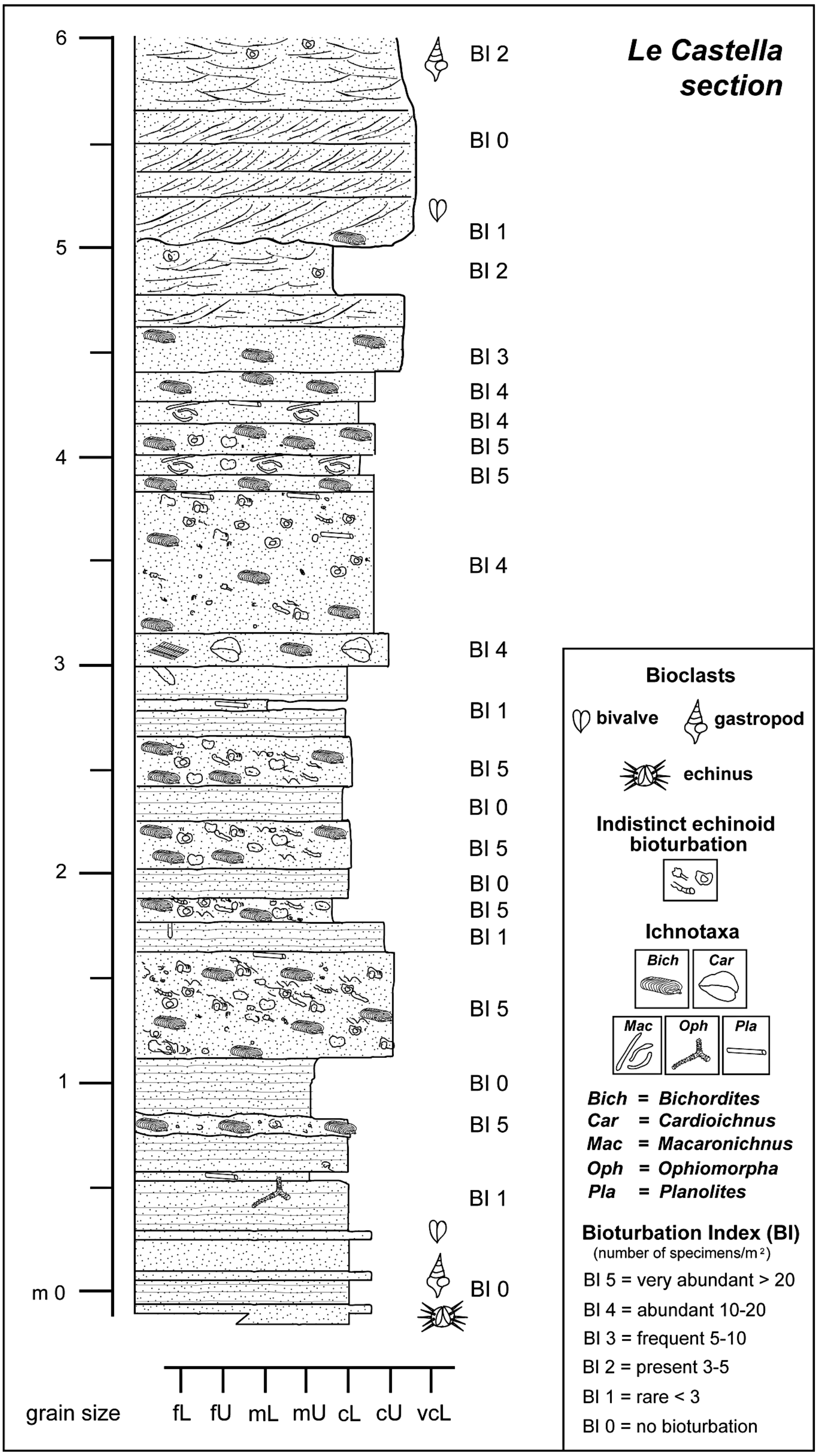
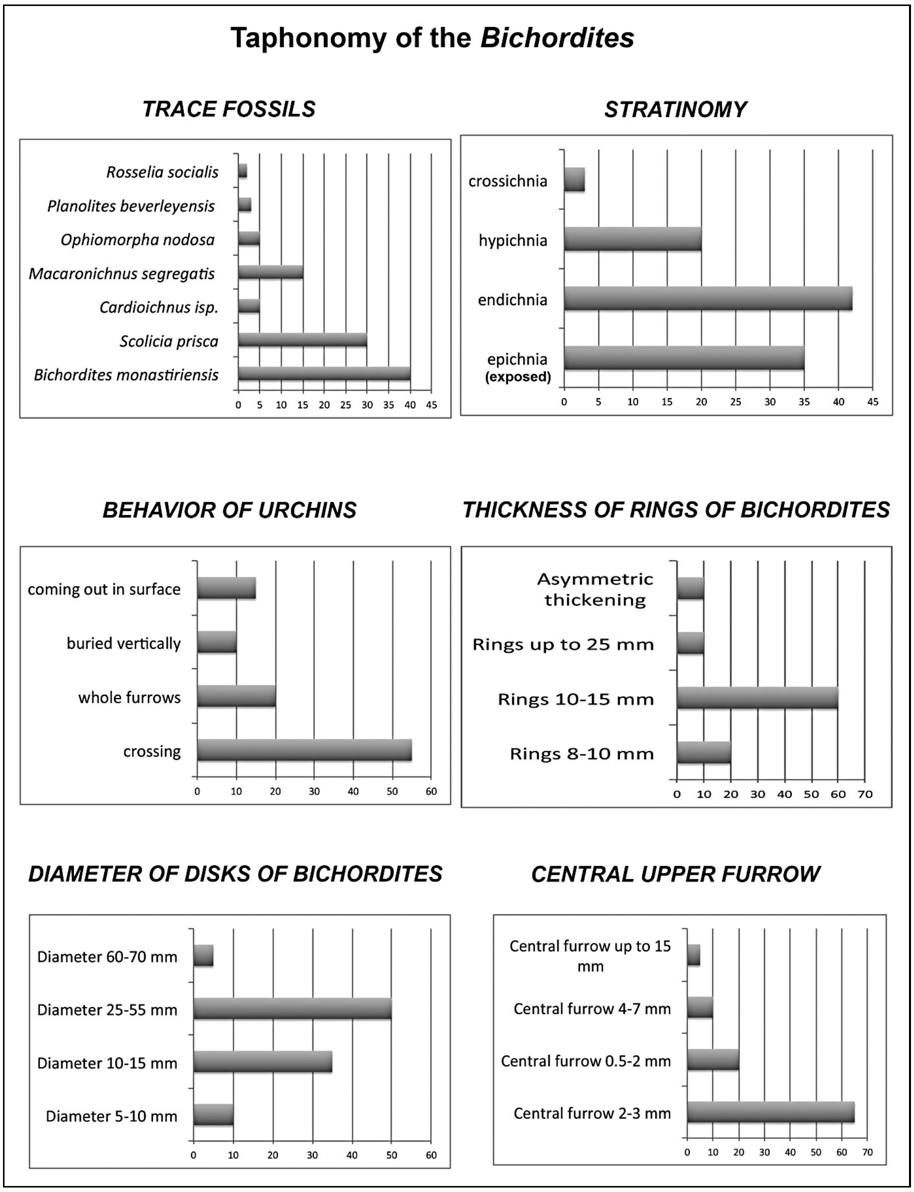


Fig. 2 - Stratigraphic section of Le Castella calcarenites, with ichnotaxa and ichnofabric distribution with Bioturbation Index (see legend).

them in a 1 m^2 surface. In cross view *Bichordites* exhibits shape and dimensional changes (see also Seilacher 1964; Monaco et al. 2005; Monaco & Checconi 2010); data are summarized in diagrams (Fig. 3). The bed-by-bed taphonomic analysis has been made in field analysing stratinomy (Savrda 2007; Monaco & Checconi 2010) and in thin section, using microscope and DinoLite digital camera from 9 to 100 magnifications (Fig. 4). The inner chord (core) and outer menisci of *Bichordites monastiriensis* are analysed (Fig. 5). Menisci are counted and measured in many longitudinal specimens (usually straight or meandering specimens) and cementation has been observed. In cross sections, the inner core has been measured, as well as the outer meniscate envelopment, observing the variability of shape and menisci for cementation. The ichnodensity has been based on the Bioturbation Index (BI, Fig. 2). We used five types of BI (from 0 = absent to 5 that represents a number of specimens/m^2 >20). This method is more useful than that used by Gibert & Goldring (2008), to quantify the energetic parameters of the substrate and paleoenvironment (Fig. 2). Grain size follows the Standard Scale of Wentworth (fine, medium, coarse and very coarse sand,

Fig. 3 - Graphics concerning main taphonomic features (see text for explication).



from lower (L) and upper (U) ranges, respectively). Other preservational features have been considered, such as the presence of *Cardioichnus* preservation close to *Bichordites* (Figs 6, 7).

Descriptive Ichnology

A) Ichnocoenosis

The ichnocoenosis in the Le Castella section consists of: a) 70% of endichnial or exposed in epichnial view *Bichordites monastiriensis* (see Figs 3, 6, 7, 8B), b) 5%, of endichnial *Cardioichnus* (Figs 3, 6C), c) 15% of endichnial ?*Macaronichnus*-like structures (although also branched, Fig. 8A), d) 5% of scattered and rare crossichnial *Ophiomorpha nodosa* (Figs 3, 8D), e) very rare (3%) endichnial-epichnial *Planolites beverleyensis*, and f) very rare (2%) crossichnial *Rosselia* isp. (mainly *Rosselia socialis*). For a detailed description of all these well-known forms, not reported here to avoid a repetition, see many papers (Książkiewicz 1970, 1977; Smith & Crimes 1983; Plaziat & Mahmoudi 1988; Pickerill et al. 1993; Uchman 1995, 1998; Uchman & Krenmayr 1995; Mayoral & Muñiz 2001; Uchman & Krenmayr 2004; Donovan et al. 2005; D'Alessandro & Uchman 2007; Gibert & Goldring 2007, 2008; Demírcan & Uchman 2012; Pearson et al. 2013). For discussion about problems of stratinomy introduced by Martinsson (1970) see discussion of variants in Monaco and Caracuel (2007).

The *Macaronichnus*-like forms (we have difficulties to recognize specimens which often show a false branching) was reported in foreshore environments but also in shallow marine sandy sediments (Clifton & Thompson 1978; Seike 2009; Pearson et al. 2013), deposited in a subtidal palaeoenvironment and affected by high hydrodynamic energy (Seike 2007, 2009; Seike et al. 2011; Nara 2014). It has been discovered both in

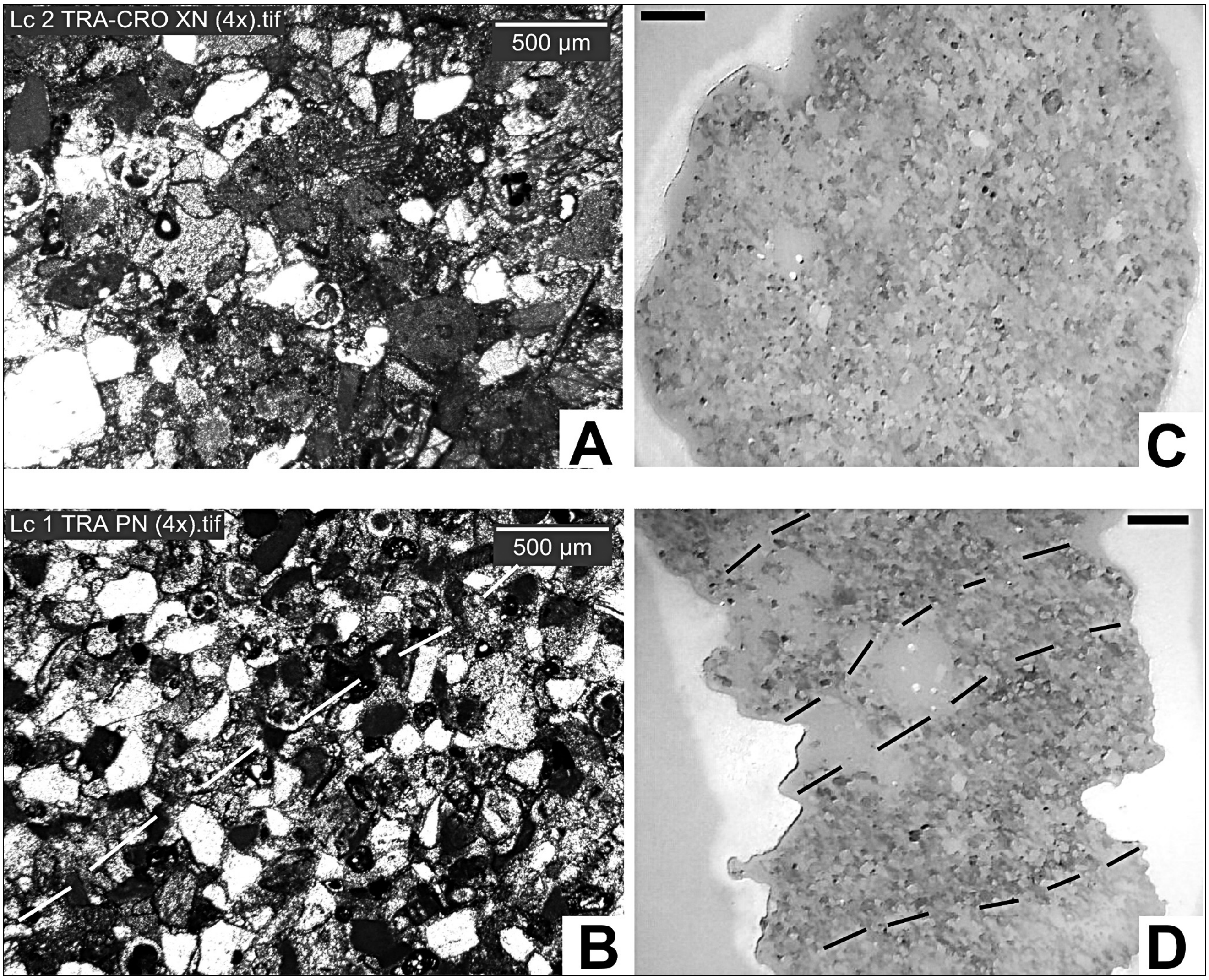


Fig. 4 - A-B) Thin sections showing siliciclastic grains and foraminifers. C-D) DinoLite digital camera photographs (C cross section of *Bichordites monastiriensis* central core and D longitudinal section of outer meniscate envelopment); note the different disposition of grains in C and D along belts (bar is 2 mm).

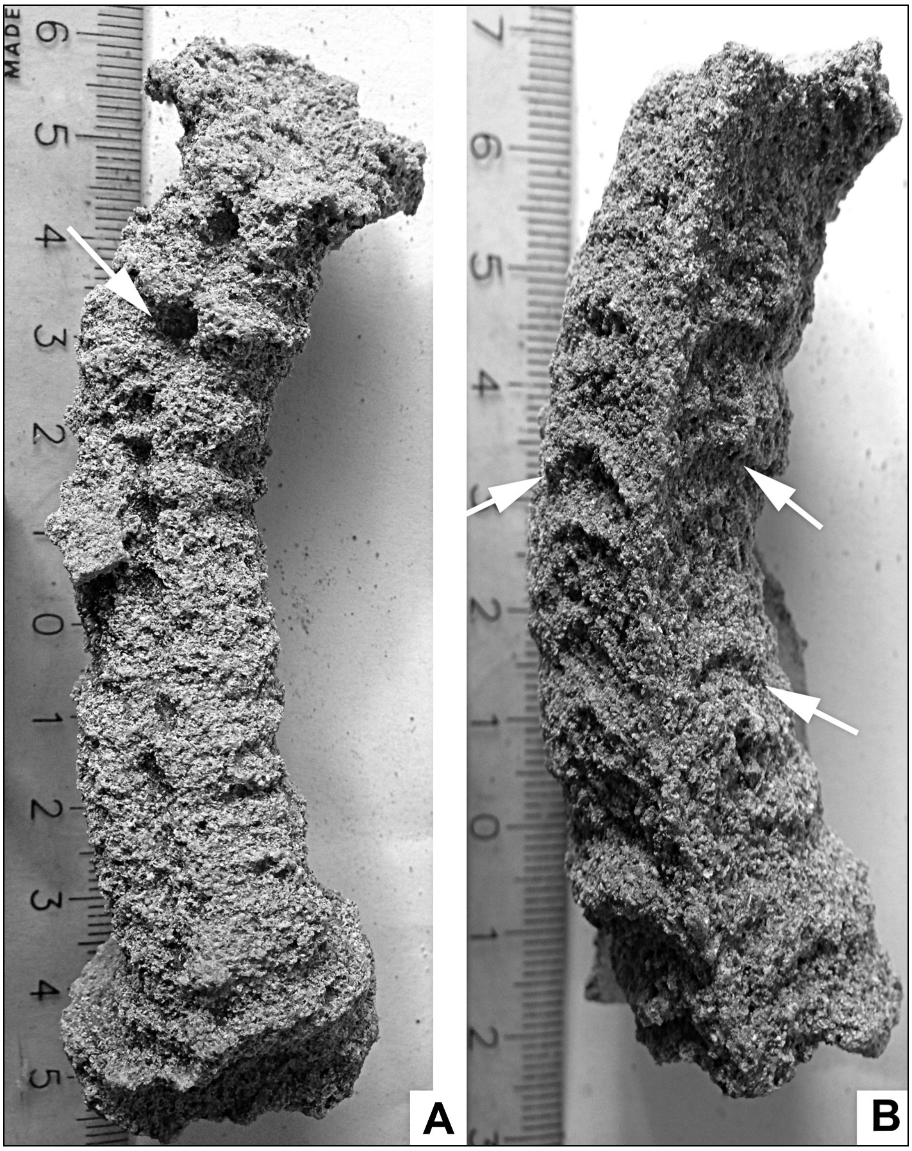
tropical environments, and also in medium-high latitude intertidal deposits (especially in present-day environments). Probably, its presence is linked to seasonal upwelling of food rich cold waters. So ?*Macaronichnus* cf. *segregatis* may be a good palaeoclimatic indicator (Quiroz et al. 2010; Caruso et al. 2013).

This ichnocoenosis may confirm the palaeoenvironment interpretation of foreshore sandy bars with megaripples (along shore of Zecchin et al. 2004), providing also new data about the ecology and ethology of the benthic organisms, which lived in that area; these data are closely related to the edaphic factors of the marine terraces. The study of Le Castella trace fossils allows to recognize several cyclic microenvironments, characterized by less or more hydrodynamic energy and food concentration: the finer calcarenite beds are dominated by ?*Macaronichnus*-like structures, while the coarser intervals are dominated by *Bichordites monastiriensis* and locally also by *Cardioichnus* (Caruso et al. 2013; Caruso 2014).

B) The *Bichordites* ichnofabric

In the studied outcrop, the ichnofabric is composed by pervasive, winding to straight *Bichordites monastiriensis*, usually concentrated in discrete levels with menisci and central chord (see Gibert & Goldring 2008); the semi-quantitative analysis in cross view shows up to 30 *Bichordites* specimens in 1 m^2 (Figs 2, 3). In plain view this ichnotaxon occurs in epirelief or hyporelief, forming exposed endichnia (false epichnia) or shallow endichnia (maximum depth up to 25 cm) that reach up to 6 specimens/m^2 (Fig. 3). Specimens with inner cores and outer menisci dominate almost all coarse-grained calcarenites; both are scattered in cycles, or rhythms, and alternated with no bioturbated laminations (Fig. 8B). Both preservations are grazing-crawling

Fig. 5 - Sand cemented chord of *Bichordites monastiriensis.* A) Dorsal view. B) Lower view. Note in A the central furrow (arrow), while in B the disposition of arcuate laminae (arrows) and the central continuous ridge in the lower part.



burrows, belonging to repichnia- pascichnia, produced by irregular spatangoids in loose sand.

Grains inside *Bichordites* burrows are rounded to angular quartz, carbonate, lithic grains, algal fragments, and plaktonic foraminifera (Fig. 4A-B). Using the DinoLite microscope to show grain disposition, the inner core of *Bichordites monastiriensis* is uniform in cross view (Fig. 4A, C), showing a more regular distribution of grains (Fig. 4C), than the outer meniscate envelopment, which exhibits belts of more concentrated grains along ridges (Fig. 4B, D). Unfortunately, in Le Castella section, body fossils of such echinoids are lacking for a classification of tracemakers (e.g. *Echinocardium cordatum*), as observed in other places (e.g. Tunisia, Plaziat & Mahmoudi 1988; Rhodes, Bromley & Asgaard 1975; Jamaica, Donovan et al. 2005).

In the finer calcarenitic intervals, few cm below the *Bichordites*-bearing level, the ichnotaxon ?*Macaronichnus* cf. *segregatis* is the only small burrow and forms a typical maze of fine strings (Fig. 8A arrows). It is present always in clusters, and it is identifiable from the host rock thanks to its mantle, constituted by mica grains. *Macaronichnus* is a probable fodinichnion, produced by polychaetes (Clifton & Thompson 1978; Seike 2007).

The ichnogenus *Cardioichnus*, always associated to *Bichordites* is less common (Fig. 6C). *Cardioichnus* appears as a bilobate resting trace (cubichnion) with a heart-shaped outline and a central furrow related to a stopping phase during the vertical work of repichnion activity of a wedge-shaped irregular echinoid of the spatangoid group (Mayoral & Muñiz 2001).

In the Le Castella outcrop, *Bichordites monastiriensis* dominates and represents an r-selected ichnospecies. It follows the bedding and completely obliterates layers from 4 to 40 cm thick, destroying the physical primary structures (usually planar laminae, Fig. 8B). Vertically oriented burrows are rare (Fig. 8C). Because

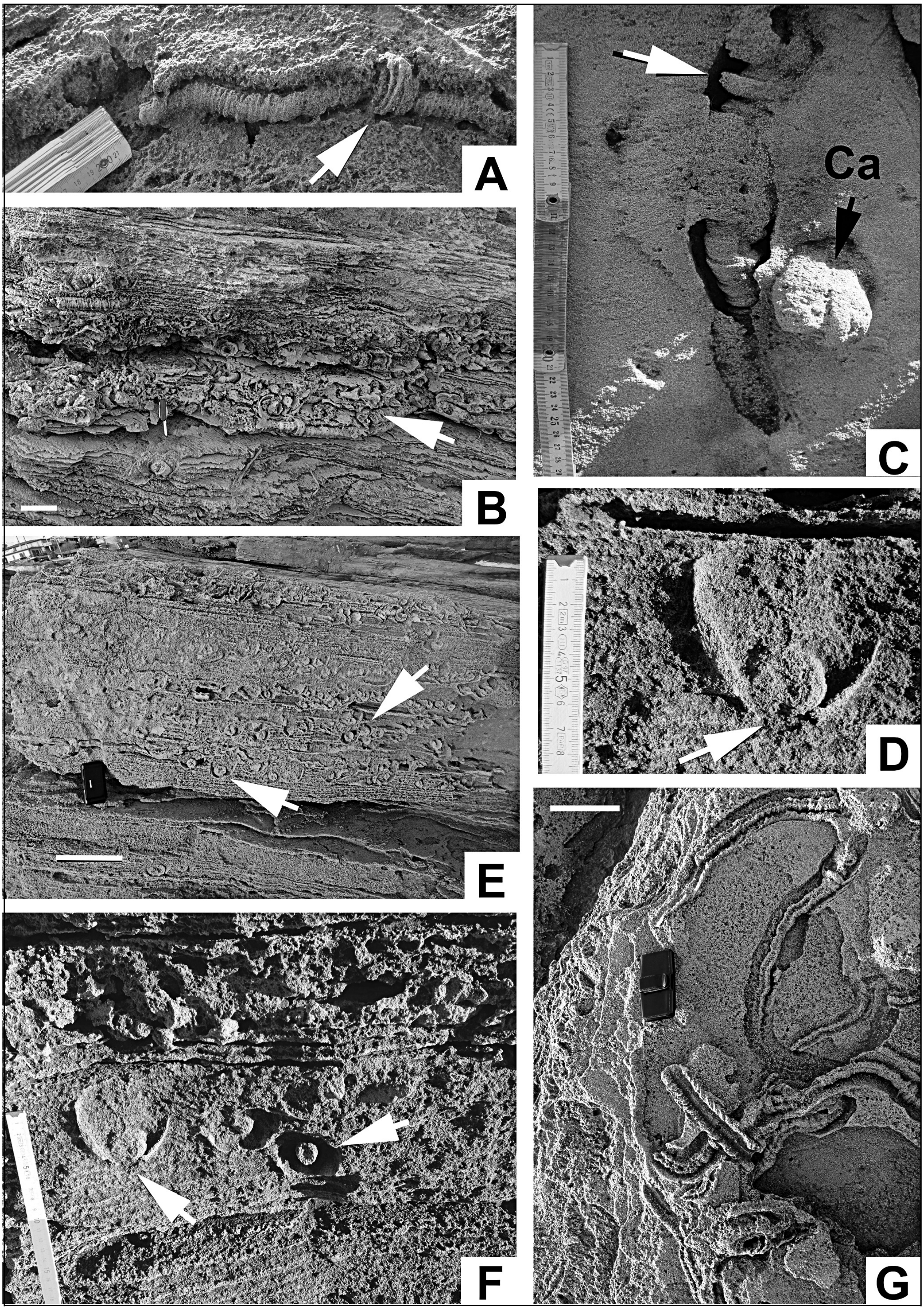


Fig. 6 - The *Bichordites monastiriensis* ichnofabric. A) The horizontal distribution of chord of *Bichordites monastiriensis* showing sharp enlargement of the diameter of rings that destroys outer menisci envelopment (arrow). B-E, F) Alternations of shallow spatangoid burrow (arrow) and few burrow-bearing levels below and above. Note in E and F the disposition and shape of specimens that are mainly oriented towards the open sea (arrows). C) *Cardioichnus* closes the *Bichordites monastiriensis*. D-F) Details of *Bichordites monastiriensis* with different position of internal fecal chord (arrows) respect to the outer meniscate envelopment; note the lacking of the bottom of envelopment that frequently occurs (arrow in D). G) Upper view of meandering *Bichordites monastiriensis* with different types of preservation (see text for explications).
The scale bar is 10 cm.

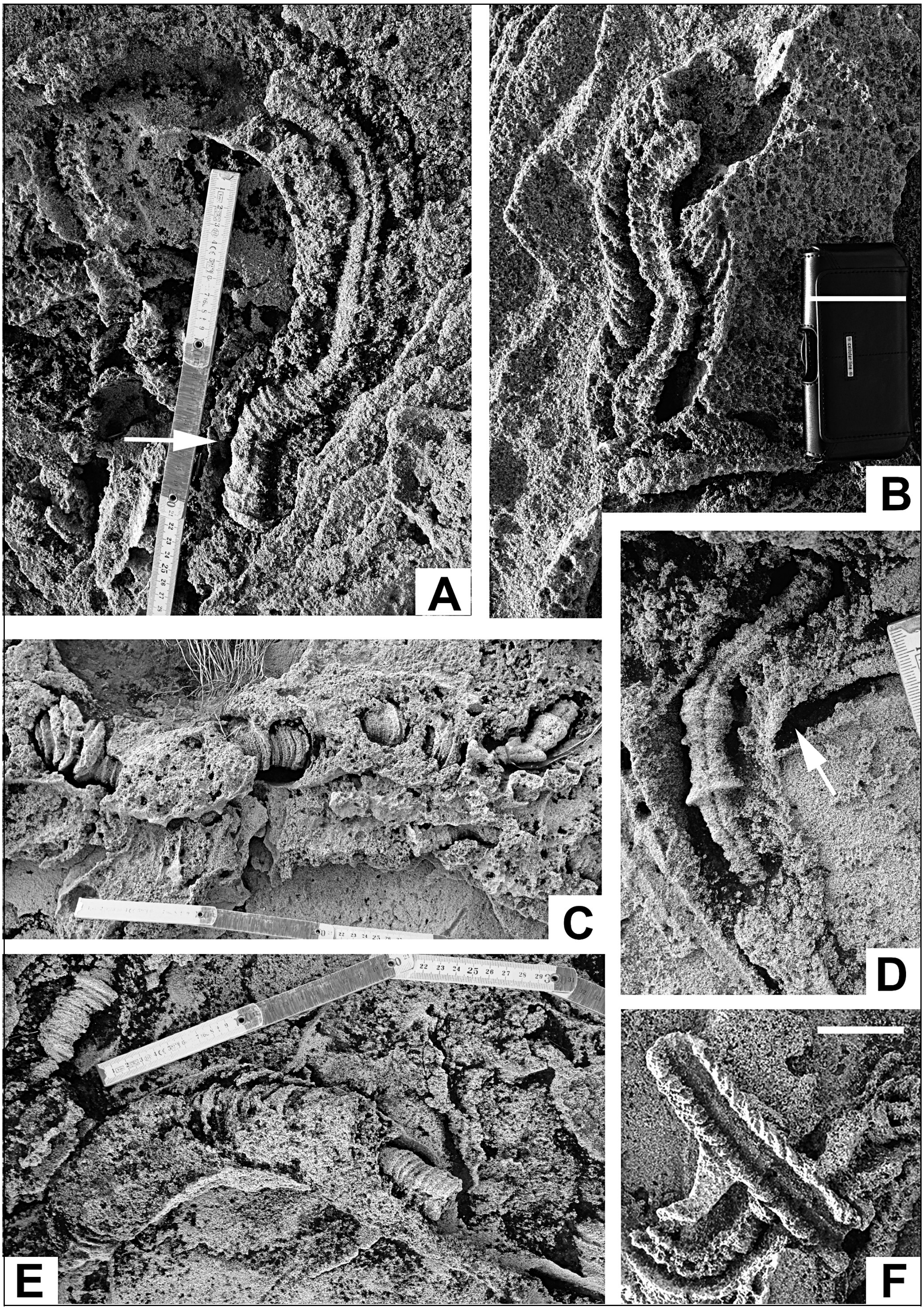


Fig. 7 - Different views of *Bichordites monastiriensis*. A) Irregular distribution of the rings of inner chord; note the enlargement and full cementation of rings that obliterates the central furrow (arrow). B) A complete specimen with internal fecal chord and outer meniscate laminae; note the top with enlargement of central furrow probably due to dissolution, and well preserved inclined laminae of outer part (white bar on cellular bag is 6 cm). C-D-E) Three different view of *Bichordites monastiriensis*, with dissolution of outer menisci and, conversely, the well cementation of the fecal, white inner chord. F) Detail of outer menisci with inclined laminae (bar = 10 cm).

of the dominant presence of this ichnospecies (Figs 6, 7, 8B), the primary sedimentary fabric is almost transformed into a new one, called the *Bichordites* ichnofabric (D'Alessandro & Uchman 2007; Caruso et al. 2011); this fabric is related to a brief colonization window between rapid progradations of the foresets of sandy dunes in the marine terrace (Gibert & Goldring 2008). Cross stratifications (CSs) have also been found (Fig. 8B, arrow). Here trace fossils of spatangoid echinoids are absent (Fig. 8B arrow). The CSs have sharp contacts on planar laminae indicating a shallow marine environment with variable high energy of currents (Colella & D'Alessandro 1988; Uchman 1995; Uchman & Krenmayr 2004). According to Mutti (person. commun.) Le Castella outcrop represents a system of prograding marine bars that evolves to tidal environment toward the top of the succession; when the bars were active and migrated with the megaripples, no bioturbation was recorded, while when the bars stopped, *Bichordites* and other traces could develop in lower energy layers.

C) Taphonomic aspects

Main taphonomic aspects are: 1) *morphological variation*; 2) *relative depth of burrowing;* 3) *enlargement of Bichordites's rings*; 4) *direction of movement;* 5) *dissolution.*

1) *Morphological variation*. The morphological variations of *Bichordites monastiriensis* are poorly recognized (Bromley & Asgaard 1975). Another question is the presence of menisci ("*Laminites*" sensu Plaziat & Mahmoudi 1988). Some authors have been included the ichno(sub)genus *Laminites* in the *Scolicia* group (more precisely in *Scolicia prisca,* see Uchman 1998, fig. 57 A-B and Uchman & Krenmayr 1995; 2004; Donovan et al. 2005) but the question is still open. The main interest of these authors was addressed to define shape (in longitudinal to transversal sections) and disposition in beds showing preservational variants and changes in depth of urchin burrows (Bromley & Asgaard 1975; Pickerill et al. 1993). Especially, a clear distinction of the morphology, based on quantification of types of preservation of *Bichordites* has been little debated. Bromley & Asgaard (1975) emphasized the spatangoid bioturbation and type of burrower organisms (e.g. *Echinocardium cordatum*, *Spatangus* spp. and others) in the Rhodos Formation, focusing to the vertical funnels that connect deep burrow to the surface. Theses funnels (shafts?) can reach a considerable depth at Rhodos (up to 50-60 cm), they are thin in diameter and are depicted in many sections of the Rhodos Formation (Bromley & Asgaard 1975, figs 16-19). Vertical funnels cannot intersect, as highlighted by Pequignat (1970). Moreover, the horizontal drainpipe from the anal part of the animal, which contributes with vertical shaft to ventilation and recirculation of water in the complex depth system of *Echinocardium cordatum* in the scheme of Bromley and Asgaard (1975, fig. 28) has been reported without variations also by other authors (Kanazawa 1995; Bromley 1996; Nara 2004), but with a poor discussion about different causes. If it is the role for Pleistocene Mediterranean deposits rich of *Echinocardium cordatum*, needs to find it also in Le Castella section with the same characteristics. A detailed analysis of specimens from Le Castella highlights that a different behaviour can be found for these spatangoid urchins. In fact, no vertical funnels have been found in this section, suggesting a shallow endichnial activity of spatangoids. This has been observed in the Lower Cretaceous of Spain where different sea urchin types occur with their complete tests inside their epichnial traces (*Epiaster, Holaster, Discoides, Nucleites, Toxaster*, Monaco et al. 2005).

2) *Relative depth of burrowing*. The analysis of almost a hundred of specimens reveals many variations in the depth of *Bichordites monastiriensis* burrows (Figs 2, 3). Usually it can be found as exposed epichnia (35%; Fig. 3) or shallow endichnia (42%), developed a few centimetres, usually 3 to a maximum of 10 cm, below the top of beds (several specimens, Figs 3, 6 C, G; 7A-F). On the contrary, ?*Macaronichnus*-like structures occur only in discrete levels as exposed endichnia (Fig. 8A). Usually, the *Bichordites monastiriensis* cross each other horizontally (up to 55% of specimens) and some sea urchin burrows display whole furrows (20%); in some cases (10%), they are buried into the sediment vertically (Fig. 8C) or come out on the surface as isolated bulges (15%, Figs 3, 6C). Commonly *Bichordites* produces long meandering structures (Fig. 6G), which extrude at the top of sand with short asymmetric bulges, up to 5 cm long and 4 cm wide, that form different morphologic variation of *Cardioichnus* (Fig. 6C). Meanders are usually long and regular (75%) but sharp changes in direction can occur horizontally in the same bed (25%). A strong reworking of laminated sandy intervals, up to 40 cm thick, has been observed cyclically (Fig. 8B). The convex to concave reliefs of many specimens is enhanced by the weathering and dissolution of finer sand between cemented trace fossils (Fig. 7B, C). Shallow depth of bioturbation is also well visible in transversal sections (Fig. 6D, F) where the outer menisci and internal core show different preservation, appearing the core at various position respects to the lower margin of menisci (Fig. 6D, F). The lower pavement is lacking or very thin at bottom as showed by Bromley & Asgaard (1975) for *Echinocardium cordatum* (Fig. 6D, F, arrows). In all cases the strong bioturbation destroyed practically up to 90% of laminae produced by currents (Fig. 8B). In the Le Castella section there are many cycles of levels rich in burrows, which alternate with unbioturbated and laminated sands (Figs. 2, 8B). In 95% of cases the transversal section of *Bichordites* indicates a

depth from 2 to 7 cm exhibiting a filled central drainage hole (Bromley & Asgaard 1975).

3) *Enlargement of Bichordites rings*. Usually many parallel menisci (transversally are rings, from 5 to 35 mm thick, see among others Figs 7A, C, D, E) compose the inner chord of *Bichordites monastiriensis*. They constitute the typical shape both in transversal and in upper views and are well cemented and whitish in colour (Fig. 7A, C-E). In the upper view a central longitudinal furrow occurs along the chord (Figs 5A, 7A, B, D), while in the lower part a thin and continuous convex ridge is present (Fig. 5B), as figured at the base of many specimens of Plaziat & Mahmoudi (1988).

To better understand the menisci, three features have been measured: i) the thickness variation, ii) the diameter variation, iii) the central furrow variation.

i) *The thickness of menisci*. Menisci of the inner chord change from 10 to 15 mm in 60% of cases and from 8 to 10 mm in 20% (exceptionally up to 25 mm in 10% of specimens, Figs 3, 5A-B; 7A, C-E). The thickness of outer menisci of the envelopment ("*Laminites*") is slightly different due to strong cementation and usually they are bended (Fig. 7D). The early cementation of inner chord (about 10% of specimens, Fig. 3) produces bundles and fusion of the menisci that coalesce each other producing an asymmetric thickening (Fig. 7C, arrows). In the lower part some arcuate meniscate structures can be observed at both sides of the central ridge (Fig. 5B, arrows).

ii) *Diameter of menisci*. The diameter of menisci can be extremely variable: most of those of the inner chord are from 10 mm up to 15 mm (35%); in the majority of other cases, diameter of inner chord changes clearly from 25 to 55 mm (60%, Figs 3, 7A, D, E); exceptionally (about 5%), the enlargement of diameter can reach 70 mm. The outer menisci ("*Laminites*"), conversely, can reach 120 to 160 mm. In many cases menisci are poorly developed (or absent) and diameter remains constant for great length, indicating a regular forward movement of the animal (Fig. 7A, arrow). In all these specimens menisci are well developed and an abrupt increase in diameter can be noted; usually, when the diameter increases, also the thickness doubles, due to cementation (Fig. 7A, D, E). Also the outer menisci are deformed or destroyed when *Bichordites* chord enlarged (Fig. 6A arrow). In a few cases when the central furrow or ridge is very narrow, the outer menisci can thin externally and assume a sigmoidal shape, assuming the aspect of some deep-water ichnotaxa (e.g. *Scolicia vertebralis* variation of *S. prisca*, Książkiewicz 1977, Uchman 1998, fig. 58 A-B).

iii) *The central furrow*. This important feature of inner chord, as reported by Bromley & Asgaard (1975) and Plaziat & Mahmoudi (1988, figs 6, 9) represents a typical aspect of the upper part of *Bichordites monastiriensis* and it was observed in Rhodos, Spain and Tunisia. At Le Castella all specimens exhibit this feature; usually in 65% of cases the central furrow is long and continuous, 2 to 3 mm wide, that separates the two lateral parts of the trace, below the outer envelopment, as figured in Plaziat & Mahmoudi (1988, fig. 9). But some changes of wideness has been noted in many specimens (20%), mainly when large menisci are present. They exhibit a marked reduction, from 2 to 0.5 mm, in according to cementation and growth of the trace. Some types of enlargement of the central upper furrow were due to dissolution (10%), enlarging furrow from 4 to 7 mm (exceptionally up to 15 mm, in 5% of specimens) and diameter of menisci remains constant. Also weathering can contribute to this type of dissolution of sand due to a poor cementation during fecal emission.

4) *Direction of movement*. The direction can be found analysing *Bichordites* chord and meniscate envelopment as two cemented products of the same horizontal movement. Densely packed menisci at the bottom are usually concave and produced by locomotion organs of the producer. The concavity of menisci can be strong in internal *Bichordites* chord (Fig. 5 arrows) while is well developed in external menisci when different movement occurred (Fig. 7B, F). Concavity indicates the direction of the movement of the hearth urchins in their horizontal feeding activity (Bromley & Asgaard 1975). The backfill features produced by hearth urchins *Spatangus* spp., and *Schizaster* spp. has been described also as meniscate burrows in the Rhodos Formation with some differences in drainage core disposition, a hearth shaped subanal fasciole with double drain in spatangoids and a lacks of subanal fasciole and drain in schizasterids (Bromley & Asgaard 1975, p. 255). The presence of a few heart urchins in situ in Rhodes (5 tests of *Echinocardium cordatum* in several km of burrow length) demonstrates the rarity of preserved body fossils (Donovan et al. 2005), but, at the same time, is great the importance of this genus to produce an oval sub-anal fasciole. Similarly, in the Le Castella section, there are many metres of meandering and oriented burrows but a lack of body fossils and a very few spines (Donovan et al. 2005). The semi-quantitative analysis of direction of movements indicates a random distribution in the case of meandering traces due to horizontal vagal behaviour (40%), but with a slight prevalence (60%) of direction towards the open sea during the feeding activity, as indicated by the disposition of vertically sections of spatangoid burrows (Fig. 8B). The concavity evidenced by some parts of *Bichordites* chord is the same of outer meniscate envelopment that are strongly inclined (Fig. 7D, arrow). Many cases (40%) of only outer envelopment have been observed without core and vice versa (60%).

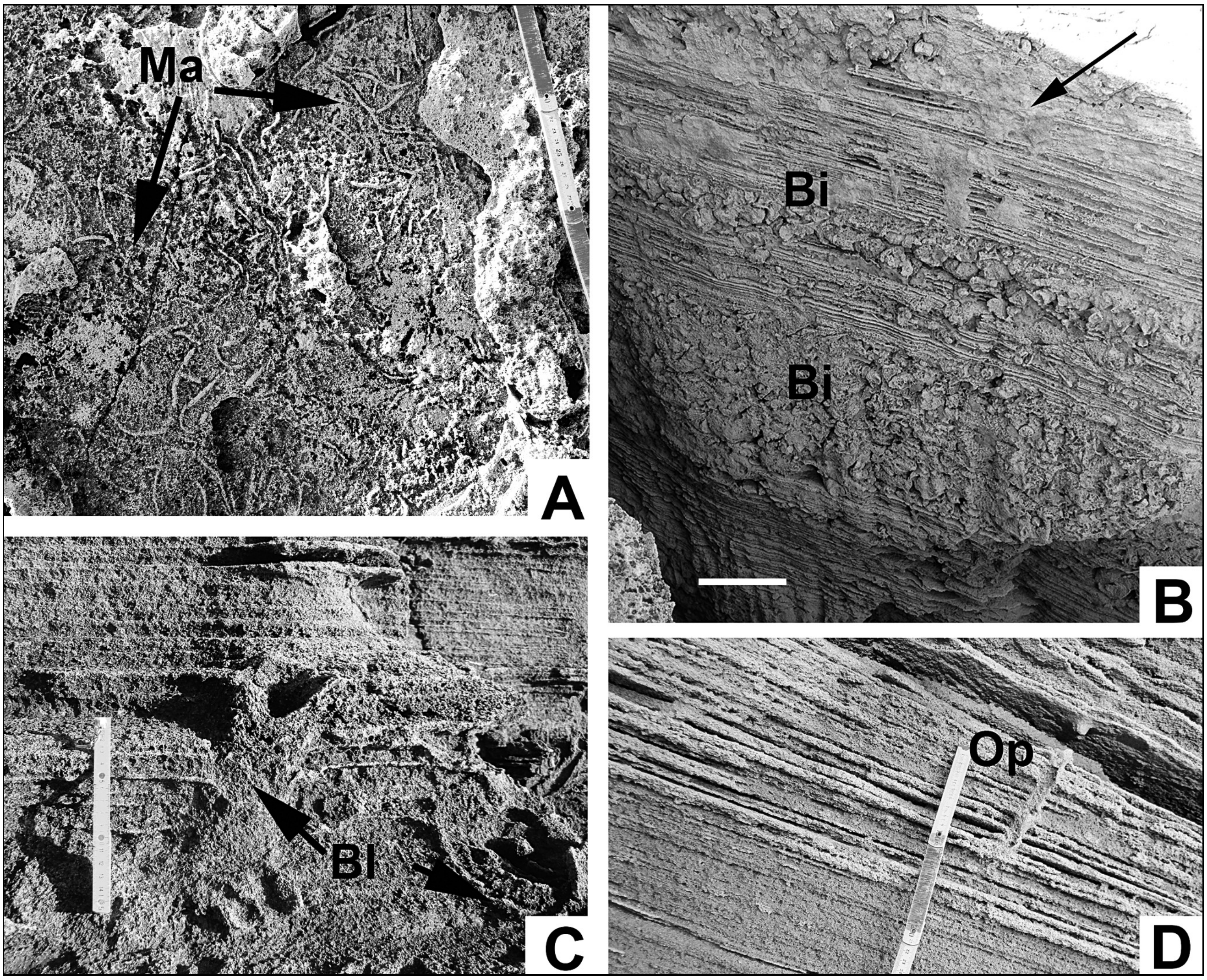


Fig. 8 - A) The ?*Macaronichnus*-like ichnofabric with many specimens (MA) branched or with false branches, few cm below the layer rich in *Bichordites monastiriensis*. B) *Bichordites monastiriensis* (Bi) ichnofabrics alternated with laminated sandstones also with cross laminae due to high energy of prograding sands (megaripples, arrow). Bar = 10 cm. C) Vertical burrow into the laminated calcarenites, destroying and folding laminae downwards (arrow). D) Vertically-oriented *Ophiomorpha nodosa* and sand laminae without spatangoid echinoid burrows.

5) *Dissolution*. The dissolution of *Bichordites monastiriensis* is a very interesting feature. The upper part of this trace surrounding the central empty canal (the lumen of the central chord is 2 to 4 mm in diameter) is dissolved, contrarily to some cases of Japan (Nara 2004) and slightly lighter in colour respect to the sand of menisci that is yellowish to light brown. In about 70% of analysed specimens the dorsal middle part of lower envelopment is dissolved or disposed towards the central core (Fig. 6F, left arrow); in other specimens it can be both collapsed and weathered (Fig. 7B). Weathering produces a strong elimination of half of cemented structure (Fig. 7B). Rare specimens show a whole central cord that is not collapsed and fully cemented (30%, see Fig. 6E). In this case, when a furrow can be preserved and not collapsed, it can reach up to 2 mm in width and depth and follows longitudinally the centre throughout the structure (Fig. 6E).

Discussion

In upper and lateral views, *Bichordites* can display abrupt changes in shape and dimensions of menisci of inner chord and outer envelopment that are backfill structures. As indicated by Bromley & Asgaard (1975) the richness of sub anal spines of spatangoids can help to distribute the mucus and all liquid fecal products, expelled backward, into the sediment by the urchins during their burrowing activity. All this fecal material was distributed in the coarse sand and caused an early strong cementation that characterizes *Bichordites* and distinguishes it from finer sand coprolites (e.g. cololites, Baldanza et al. 2013; Monaco et al. 2014). Therefore, each meniscus of inner chord can be an expression of inter-pore cementation produced by the back-oriented spines placed near the anus, used to distribute the fecal material, essentially composed of liquid excrements, behind the organism. Feces were expelled posteriorly and distributed by long anal spines during the backfilling. All menisci may maintain the same diameter if there is a balance between forward movement of the animal and expulsion of the fecal material posteriorly. Rings of inner chord can enlarge abruptly their diameter if the animal stops or moves backward, compressing the sand posteriorly. Therefore, the fecal material and mucus can be distributed widely also for the change of direction of anal spines and tends to enlarge posteriorly also by the expulsion of feces, producing an abrupt change in thickness of chord due to enhanced cementation. For this reasons many contiguous menisci can double or triple their diameter. It is very probable that the early cementation of fluids into the sand of *Bichordites* was induced by bacterial activity (symbiotic microorganisms, e.g., sulphate-reducing bacteria), as indicated in many other types of coprolites and cololites (see the Pleistocene deposits of Umbria Apennines, Monaco et al. 2014) or shallow-water trace fossils (e.g. Paleozoic *Zoophycos* of South China and Australia, Zhang et al. 2015). These features have been observed very frequently at Le Castella (up to 80% of *Bichordites*). Some other levels immediately below *Bichordites* levels contain many "maccheroni"-like burrows belonging to ?*Macaronichnus*-like structures that appear with up to hundred specimens for a square metre (Fig. 8A).

Several issues continue to remain open. Some of these include: A) the rule of central open core that is generally closed, B) the absence of vertical funnel.

A) The central chord (core) of *Bichordites* observed in Le Castella specimens is commonly empty and, when is open (10% of total cases), their lumen is 5 to 12 mm wide. The collapse of the structure can produce the closing and consequent also the hardening of the tube and, consequently, also of the central core. The functional characteristics of the central hole in the core, as drainage tube of water from surface to backfilling, are discussed (Kanazawa 1995; Nara 2004), but the real function of the hole in the core is not clear and where it ends in the sand behind the advancing of spatangoid it appears completely occluded. Moreover, the role of internal anal spines is poorly explained, maybe different from those that produce *Bichordites*, to maintain open this drainage tube. Nara (2004) presented a circulation pattern of water within the burrow of spatangoids, but this model is poorly explained.

Another interesting feature is the cementation of the backfilled structure of *Bichordites*. Observing the hundred specimens at Le Castella, the backfilled chord can be considered a cemented expulsion of fluids that may be considered as a coprolite, in the sense that the sand behind the body was subjected to an immediate hardness of the mucus and fecal material (partly liquids) that induced an early cementation of the sediment. In this sense, it is slightly different in respect to a particular type of well-cemented coprolites of large marine mammals (Clarke 2006; Monaco et al. 2014). These authors discuss about cementation of different mass types by action of bacteria (e.g. the cololite of sperm whales *Ambergrisichnus alleronae*, Monaco et al. 2014) that can be included or extruded by the body of marine mammals. In the case of spatangoids, as many others producers of fecal deposits (Bromley 1996; Miller 2007; Seilacher 2007), the fecal material distributed by anal spines when expelled by the anus, has been subjected to an early cementation and its size and diameter can be adjusted to the speed of the forward movement of the body animal. In fact, when the animal stops or change vertically the direction (Bromley & Asgaard 1975), also the diameter and cementation of rings changed. In many cases observed at Le Castella outcrop, if the animal moved back – probably due to the food concentration into the substrate or for other unknown reasons – also the menisci were widened and thickened. These features were poorly debated in previous works and are recognized here for the first time.

B) Another issue poorly clear is the lacking at Le Castella of the vertical shaft that can produce funnel and collapsed vertical structures, indicated by some authors (Bromley & Asgaard 1975; Kanazawa 1995; Nara 2004). Observing many vertical sections of laminated-bioturbated layers (Figs 6E, 8B), the vertical shaft of ?*Echinocardium cordatum* has not been found. Although the shape, dimension and structures of *Bichordites monastiriensis* at Le Castella are exactly the same figured by Bromley & Asgaard (1975), Plaziat & Mahmoudi (1988), Pickerill et al. (1993), all the structures of Le Castella are preserved as exposed shallow endichnia (in epichnial view), differing from those illustrated by Bromley & Asgaard (1975), Kanazawa (1995), Bromley (1996), Nara (2004). Therefore, a vertical shaft used to breathe and to favour the circulation of water inside the burrow can occur exclusively in some cases. Unfortunately at Le Castella we have not found fossilized bodies of sea urchins and therefore we do not know whether this is indeed of *Echinocardium cordatum* or other types of echinoids (e.g. different types of Spatangoids or Schizasterids), as observed in Bateig Limestone of Spain by Gibert & Goldring (2008) and by Monaco et al. (2005) in the shallow sediments of a Cretaceous inner platform in the Alicante area (Serra Helada, Spain), where many types of sea urchins can produce superficial or shallow trace fossils with their fossilized test preserved inside their trace fossils (Monaco et al. 2005).

Conclusions

Three types of ichnofabric levels can be recognized in shallow water deposits at Le Castella Pleistocene terraces: 1) The multilevel *Bichordites monastiriensis* ichnofabric with inner core and/or outer menisci with or without *Cardioichnus*; 2) the cm-laminated coarse sands with very few and always scattered small *Bichordites monastiriensis*; 3) the ?*Macharonichnus*-like ichnofabric in finer sand.

1) The typical ichnofabric with *Bichordites monastiriensis* and *Cardioichnus* developed when current action was reduced and constant, and food and organic matter (e.g. fitodetritus) can be abundant and exploited by spatangoid sea urchins on the sea floor or in shallow tiers near the surface. Where the nutritional accumulation was higher, also trace fossils are strongly concentrated and ichnofabric shows different tiers of *Bichordites monastiriensis,* in similar manner than in the other cases of the Mediterranean area (e.g. Rhodos and Bateig Limestone of Spain).

2) The laminated sandstones that show parallel to low angle cross laminations due to migrant megaripples exhibit alternations of coarse and finer grains producing dm-thick stratigraphic cycles with erosional base. In the case of rippled levels and cross-laminations, bioturbational structures are very rare (rare vertical *Ophiomorpha*) or absent. This laminated fabric may be produced by the action of alongshore currents and onshore/offshore prograding sands (e.g. ocean current-generated sand ridge complex of Nara 2014) that were accumulated in high-energy regime, producing the main parts of the Pleistocene terraces at Le Castella. On the contrary, according to Mutti (person. commun.) these laminated and not bioturbated beds may represent the prograding active marine bars with migrating megaripples.

3) The ?*Macaronichnus*-like ichnofabric is dominated by random placed trace fossils of ?*Macaronichnus*-like tubular thin tunnels (locally with *Planolites,* rare *Rosselia* or *Ophiomorpha*). These tubular tunnels (locally branched) occurs with hundreds of over imposed specimens in some discrete layers immediately below *Bichordites* without crossings between these ichnotaxa; they probably occur in very high density of specimens (up to 100 in 1 m^2) as opportunistic behaviours that developed as fodinichnia-pascichnia during low energetic phases of currents.

Probably, rhythmic alternation of laminated and strongly bioturbated intervals indicate a change of energetic conditions in foreshore conditions affecting coastal sediments of marine terraces of Le Castella area. Sedimentary structures evidence a regressive trend upwards with increase of the energy, as indicated by cross stratifications without bioturbation and erosional surfaces. As indicated by ichnofabric development, in all section there was a balance between energetic parameter of longshore to onshore/offshore currents (more strength) and bioturbation activity (minor strength).

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