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Spatangoid-produced ichnofabrics (Bateig Limestone, Miocene, Spain) and the preservation of spatangoid trace fossils

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ABSTRACT

A spatangoid-produced ichnofabric is described from the Miocene Bateig Limestone, SE Spain. This ichnofabric is characterized by the dominant presence of large meniscate burrows (*Bichordites*) produced by irregular echinoids. This constitutes an unusual mode of occurrence for spatangoid bioturbation, as their traces are most typically preserved in bases and tops of sandstone event beds. In fact, despite their important role as burrowers in modern settings (that can be extended back to the Early Cretaceous based on their body fossil record), spatangoid trace fossils (*Scolicia* and *Bichordites*) are comparatively rare. Several factors play an important role in their preservation: mechanism of burrowing, sediment characteristics, early diagenesis and presence/absence of deep-tier burrowers. Spatangoid-produced ichnofabrics, such as those from the Bateig Limestone, characterize depositional settings with intermittent deposition of event beds where there is an absence of deeper-tier bioturbation.

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1. Introduction

Spatangoid echinoids (popularly known as heart urchins or sea potatoes) are among the most active and widespread bioturbators in Modern marine environments. Their burrowing activity results in very distinctive large meniscate backfill burrows commonly bearing one or two drains. These traces are well known from the fossil record and they have been assigned to the ichnogenera *Bichordites* and *Scolicia* according to the presence of a single drain or a pair of drains, respectively (Uchman, 1995). Spatangoid body fossils are known and have been abundant since the earliest Cretaceous, but their trace fossils are less commonly reported and it is not uncommon to find well-preserved tests of infaunal echinoids, apparently in or close to life position, but with no preserved associated trace fossils.

Additionally, spatangoid-produced ichnofabrics, which could be expected to be common considering the burrowing capabilities of Modern representatives, are reduced to a handful of examples in the fossil record. Recently, Bland et al. (2001) reported one such occurrence in an unusual setting: the walls of Brent Cross Shopping Center in North London (Fig. 1). The stone was tracked down to its source in southern Spain and this resulted in a paper describing the ichnology of the Miocene Bateig Limestone (Gibert and Goldring, 2007). The purpose of the present article is to focus on the so-called Bateig Fantasia variety of facing stone, which corresponds to a fully bioturbated *Bichordites* ichnofabric and, in the light of the new

findings, to analyze the situations that lead to the preservation of spatangoid traces and the ecological–taphonomic conditions needed for the formation and preservation of spatangoid-produced ichnofabrics.

2. Spatangoid burrows and ichnofabrics from the Bateig Limestone

2.1. Geological and stratigraphical setting

The Bateig Limestone is quarried in the surroundings of Novelda (Alicante province, SE Spain) (Fig. 2A). This Middle Miocene calcarenite is part of the fill of one of the so-called Eastern Prebetic basins located in the External Zones of the Betic Cordillera (Sanz de Galdeano and Vera, 1992). These small Neogene basins were controlled by folding and diapirism related to the evaporitic mudstones of the Keuper (Cater, 1987; de Ruig, 1992).

This study has been based on quarry sections displaying vertical and bedding-parallel faces and also on serially slabbed and polished material available in the quarry factory at Novelda. The Bateig Limestone is a fine-grained sandy biosparite. Grains are dominantly globigerinid foraminifera with only a limited amount of quartz. A 97 m-thick composite section was measured (Fig. 2B) including a lower bioturbated unit that accounts for most of the succession (84 m) and an upper slightly coarser-grained unit where physical sedimentary structures are dominant over biogenic traces. Four different ichnofabrics were recognized in the succession, which are fully reported in Gibert and Goldring (2007): *Bichordites*, *Palaeophycus*-mottling, *Ophiomorpha*-mottling, and *Ophiomorpha*-primary

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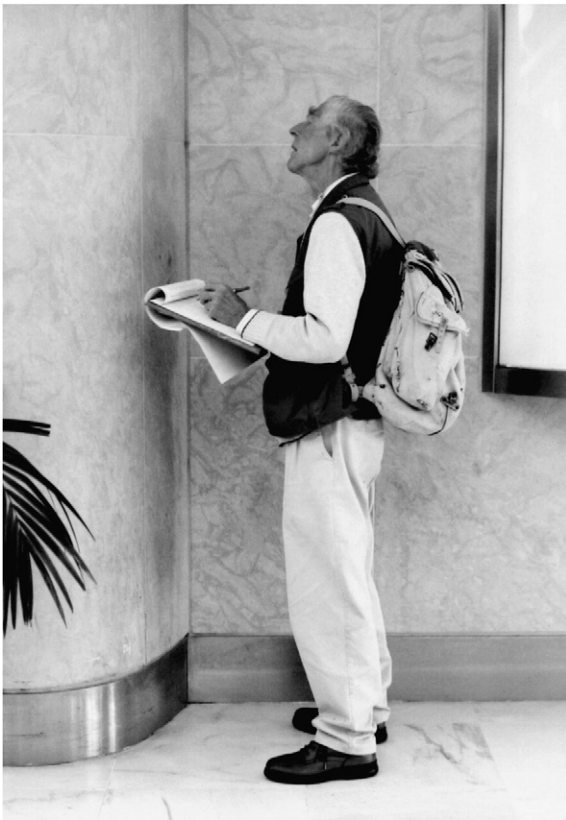[1] Deceased, August 30th 2005.

Fig. 1. Roland Goldring studying the Bateig Limestone (Bateig 'Fantasia') with spatangoid-produced ichnofabrics in the facing stone of Fenwick department store in Brent Cross Shopping Centre (London).

lamination. The latter characterizes the upper unit, while the other three are arranged in several cycles *Bichordites* to *Palaeophycus*-mottling to *Ophiomorpha*-mottling (Fig. 2). Ichnofabrics correlate with the different commercial varieties sold.

2.2. Spatangoid burrows

2.2.1. Modern spatangoid burrows

The burrowing activity of modern spatangoid echinoids is well known from natural observations and aquarium experiments (Nichols, 1959; Chesher, 1963; Howard et al., 1974; Bromley et al., 1997). Large meniscate traces are the typical product of their backfilling activity when ploughing through the sediment (Fig. 3). The animal excavates sediment in the front, which is transported to the posterior part where it is packed with mucus. The open burrow is limited to the volume immediately surrounding the test of the echinoid. One or two open drains are kept behind by action of the subanal tuft spines and the corresponding tubefeet, while periodically, a respiratory shaft may be constructed for aeration purposes or to feed upon surface detritus. Spatangoids produce distinct traces that can be easily recognized in the fossil record (Smith and Crimes, 1983; Plaziat and Mahmoudi, 1988). They are assigned to two different ichnogenera: *Scolicia* when bearing two sanitary tubes and *Bichordites* with only one (Uchman, 1995). Plaziat and Mahmoudi (1988) and Uchman and Krenmayr (1995) pointed out, that among modern spatangoids, the so-called *Spatangus* group are responsible for those traces with two drains, while traces produced by those belonging to the *Echinocardium* group bear only one.

Detailed analysis of fourteen living spatangoid species by Kanazawa (1992) led him to recognize three basic burrowing mechanisms related with test morphology, burrowing depth and sediment grain size: a) backfilling, typical of globular urchins that live deep in sand (e.g., *Echinocardium cordatum* and *Moira lachenisella*); b) pushing-away, characteristic of flat echinoids living close to the sediment
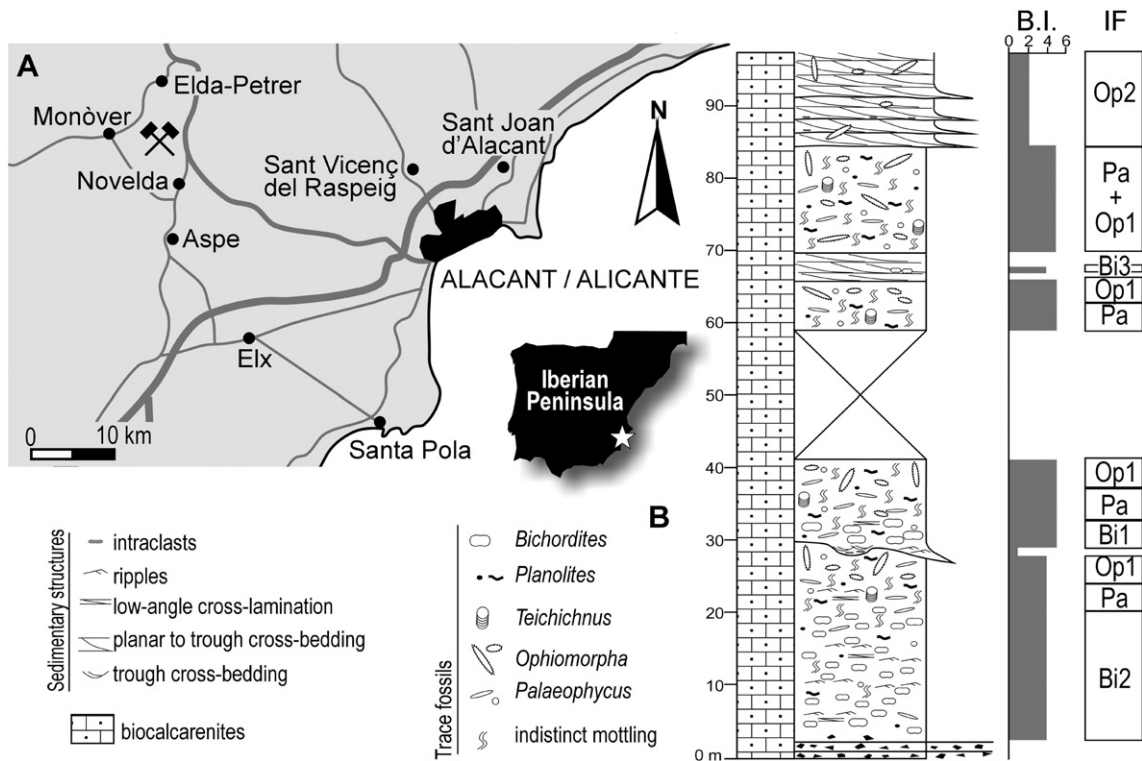

Fig. 2. (A) Geographic situation of the Bateig quarries near Alicante in SE Spain. (B). Synthetic stratigraphic section of the Bateig Limestone with indication of the Bioturbation Index (BI) and the distribution of ichnofabrics (IF). Bi1, Bi2, Bi3, *Bichordites* ichnofabric (varieties 1, 2 and 3); Pa, *Palaeophycus*-mottling ichnofabric; Op1, *Ophiomorpha*-mottling ichnofabric; Op2, *Ophiomorpha*-primary lamination ichnofabric. After Gibert and Goldring (2007).
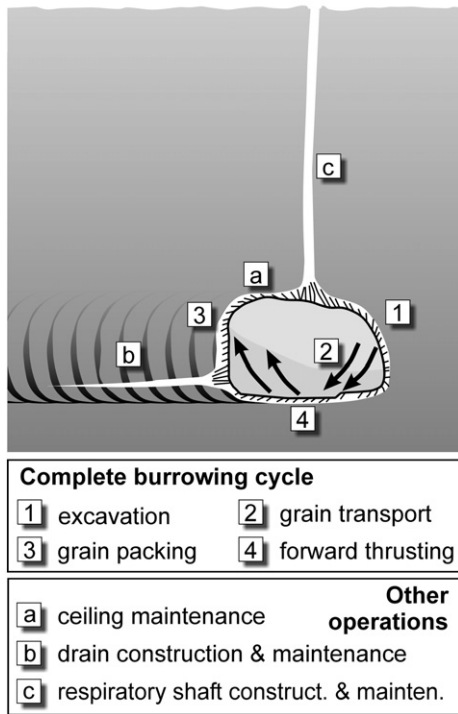
Fig. 3. Burrowing activity of spatangoids (backfilling mode). Based on figures from Bromley and Asgaard (1975) and Kanazawa (1995).

surface (e.g., *Lovenia elongata*); and c) rocking, typical of spatangoids with wedge-shaped tests living in soft, cohesive mud (e.g., *Brisaster latifrons* and *Schizaster lacunosus*). Only the first of these burrowing

modes produces meniscate traces such as those described by previous authors (Kanazawa, 1995). Nevertheless, Asgaard and Bromley (2007) point out that some of these aquarium experiments may result on anomalous behaviors and thus, they consider the rocking style as an artifact due to laboratory conditions.

2.2.2. Bichordites in the Bateig Limestone

Trace fossils from the Bateig Limestone exhibit diagnostic features typical of spatangoid burrows. They are broad, gently curving, horizontal traces with ovoidal morphology in cross-section (Figs. 4 and 5). Widths range between 2 and 11 cm. The internal backfill is distinct with menisci better preserved in the lower and lateral sides where darker grains accumulate (Fig. 4A, B, D). Grain selection was described by Kanazawa (1995) in experiments with Recent echinoids as a result of passive accumulation of finer grains in the floor of the burrow. Nevertheless, lower, darker parts of Bateig traces are not finer-grained but richer in angulose quartz grains. The significance of this is not clear. Quartz grains are denser than carbonate grains (mostly foraminiferal tests, not always completely filled) and thus, accumulate in the lower part. Concentration of heavier grains in lower parts of spatangoid traces was described by Fu and Werner (2000). The upper part of the Bateig traces is usually truncated by overlying bioturbation but when preserved is much less distinct than the lower part (Fig. 4D), another feature described by Kanazawa (1995) in modern traces. Only occasionally, a single central tube in the lower part of the trace can be identified as the record of the drain (Fig. 4C). This feature allows one to assign the traces to the ichnogenus *Bichordites*.

In quarries located in the eastern part of the studied area, partial silicification of the traces has been seen (Fig. 5). This selective cementation seems to originate in the position of the drain, giving rise to a fabric of dark spots (in vertical section), sometimes referred to
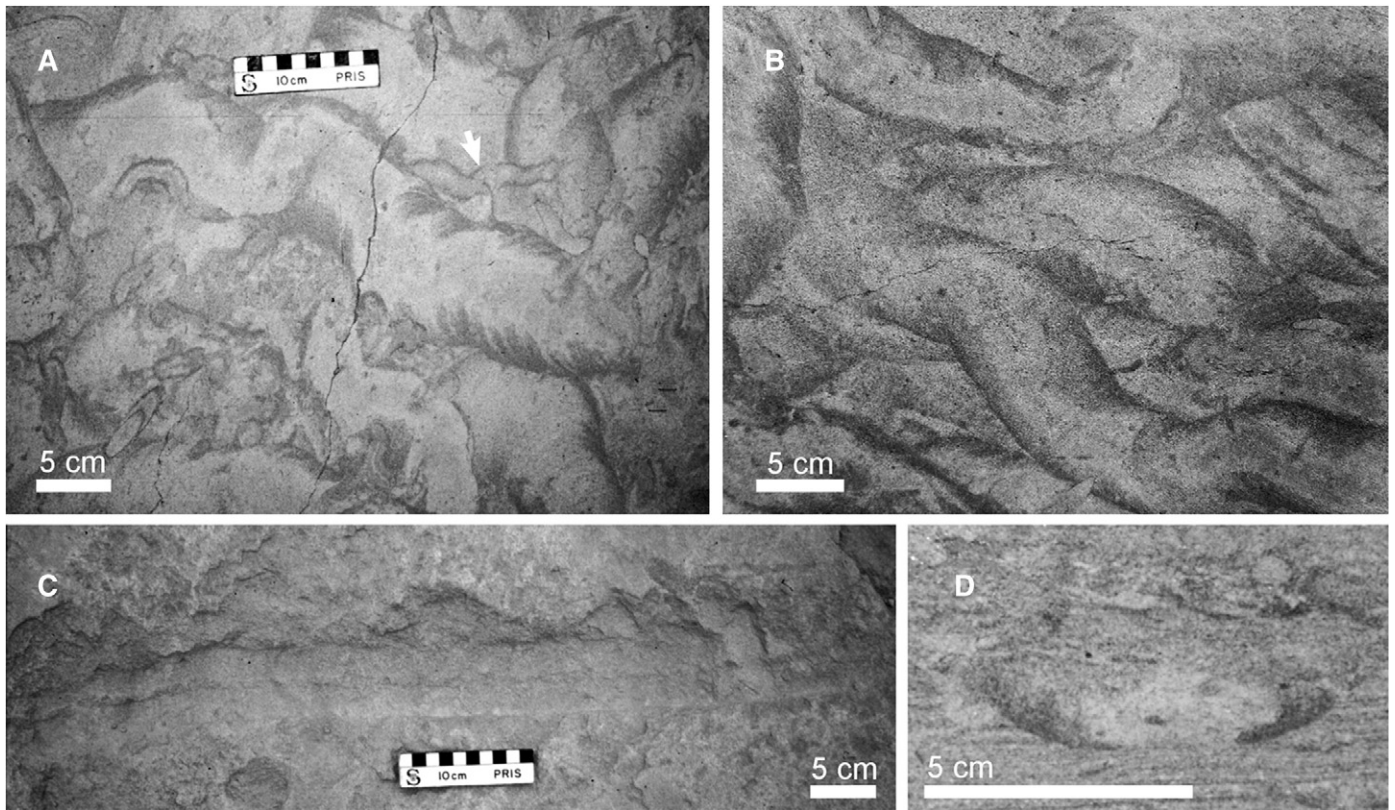
Fig. 4. (A) Horizontal section of *Bichordites* displaying its characteristic meniscate structure and grain selection. Note smaller *Bichordites* (arrow). (B) Horizontal section of numerous *Bichordites*. (C) Weathered-out bedding plane showing a *Bichordites* preserved as a negative epirelief bearing a distinct central chord. (D) Vertical section of *Bichordites* showing the grain selection in the menisci and the indistinct upper part.
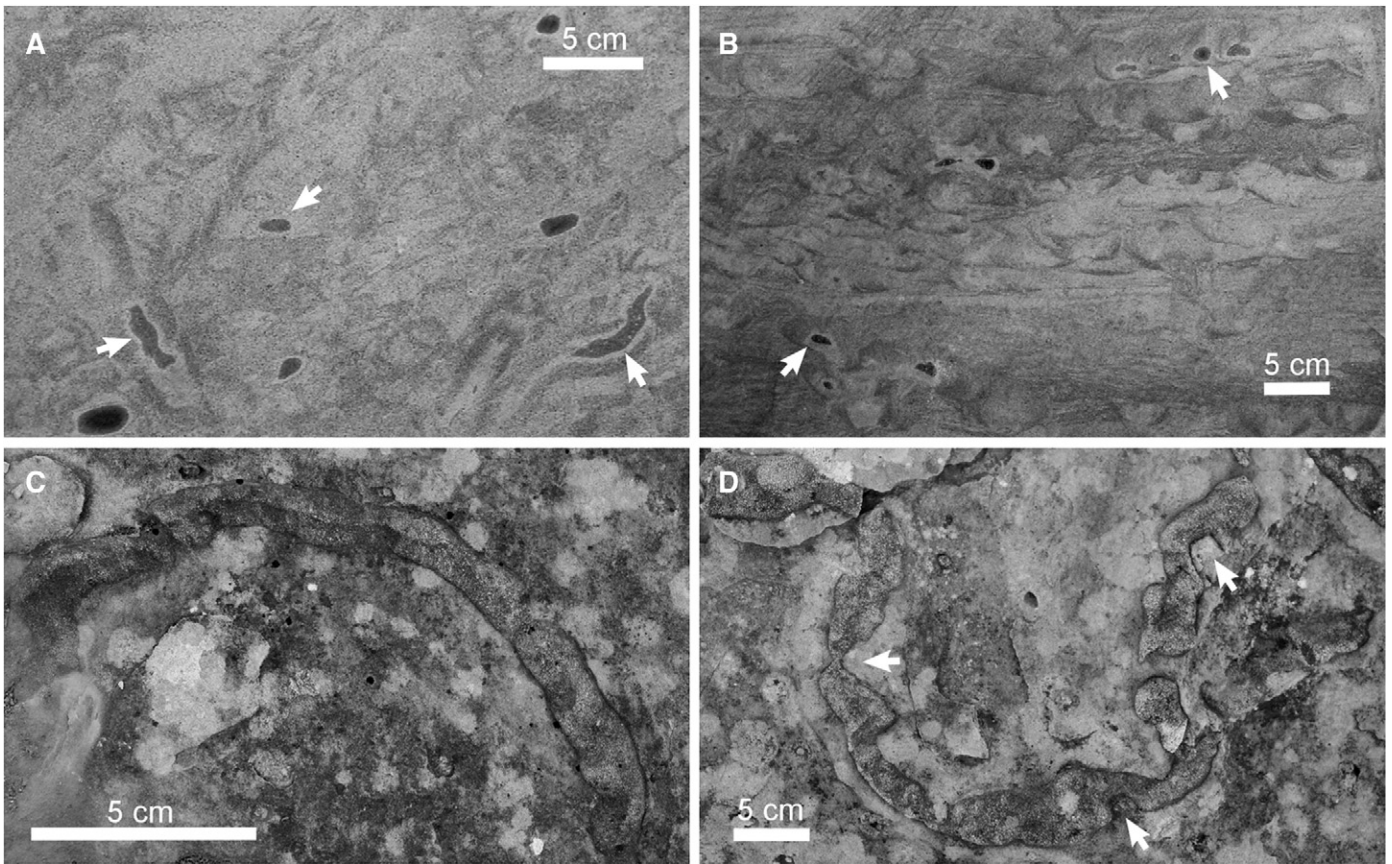
Fig. 5. Silicification in *Bichordites*. (A) Horizontal section showing silicification strings (dark areas indicated by arrows) through the centre of the echinoid burrows. (B) As in A but in vertical section. (C) Natural exposure of a bedding plane with fully-silicified *Bichordites*. (D) Another weathered-out silicified specimen on a bedding plane. Arrows indicated non-silicified burrows cross-cutting *Bichordites*.

informally by quarrymen as their "Dalmatian" variety (Fig. 5A, B). In a few cases, silicification of traces is complete and then, specimens are weathered-out in natural exposures (Fig. 5C, D).

2.2.3. Tracemaker

Well-preserved, complete spatangoid body fossils are among the most common macrofossils in the Bateig Limestone (Fig. 6). They have been assigned to the genus *Maretia* (Gibert and Goldring, 2007),

which is represented in modern seas by several species inhabiting depths from 0 to 150 m (Mortensen, 1951). No other echinoid body fossils have been found and thus, it seems reasonable to consider *Maretia* as the likely producer of the abundant *Bichordites*. *Bichordites* is commonly assigned to the activity of echinocardiidae and Asgaard and Bromley (2007) consider this family to be unique in having a single drain. Nevertheless, *Maretia* (Fam. Maretidae) bears a well-developed shield-shaped subanal fasciole rather than a bilobed
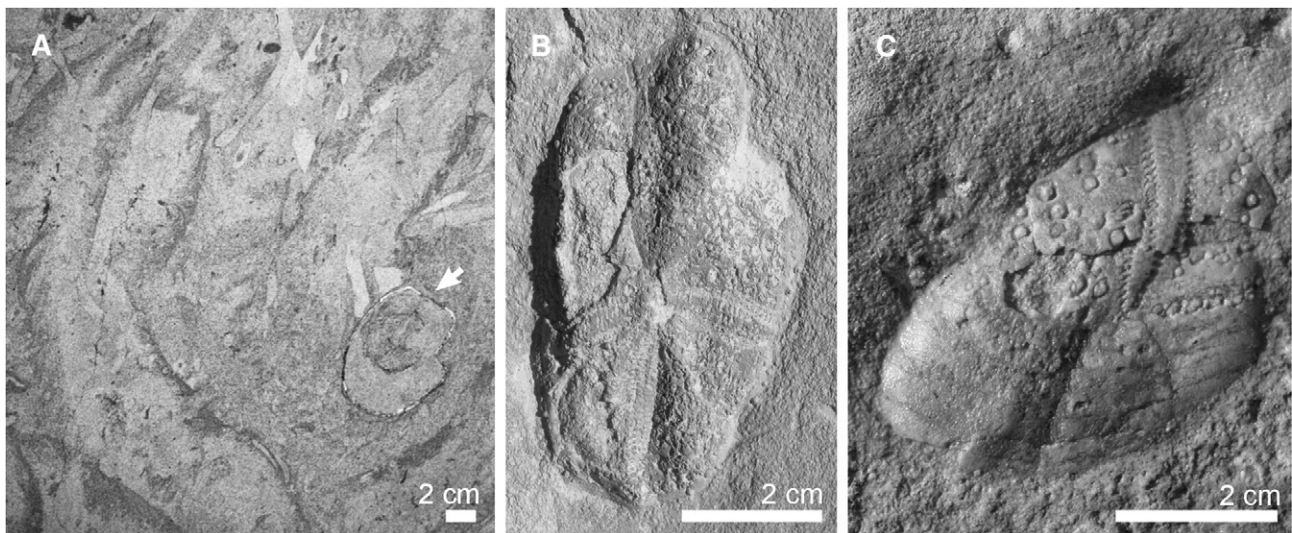
Fig. 6. Spatangoid body fossils (*Maretia* sp.) from the Bateig Limestone. (A) Horizontal cross-section displaying an echinoid (arrow) in a fully bioturbated *Bichordites* ichnofabric. (B) and (C) Two specimens of *Maretia* sp.
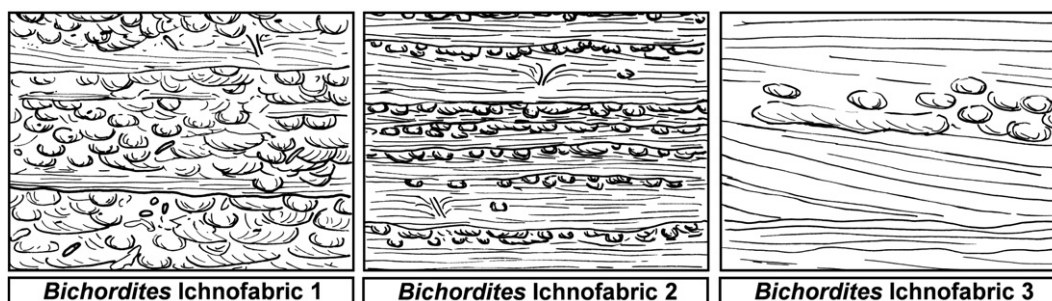
Fig. 7. The three varieties of *Bichordites* ichnofabric found in the Bateig Limestone.

one such as that of typical *Scolicia*-producers (Spatangidae, Brissidae, Lovenidae).

Maretia is found not only in facies bearing the *Bichordites* ichnofabric but also in other bioturbated facies where spatangoid traces are absent or very rare. In any case, preservational features of body fossils are very similar. This suggests that spatangoids did also burrow in those facies although their traces were not preserved.

2.3. Spatangoid-produced ichnofabrics: Bateig Fantasia

Bateig calcarenites with *Bichordites* ichnofabric are sold under the commercial names 'Fantasia' and 'Galaxy'. Both are identical from a sedimentological and ichnological point of view but their color is different (white/yellow and grey/blue, respectively) due to later diagenetic processes. The aesthetic attraction of these varieties is the peculiar pattern of entangled meniscate trails resulting from pervasive echinoid bioturbation. *Bichordites* accounts for 60–90% of the bioturbation. Three varieties of this ichnofabric can be recognized (Fig. 7):

Bichordites ichnofabric 1 (Figs. 4A–B and 8A–D) is the most typical, best represented and the one that is most clearly identifiable as the "Fantasy" and "Galaxy" commercial varieties. It is characterized by large (5 to 11 cm wide) *Bichordites* and by an almost complete bioturbation (Bioturbation Index, BI, 5–6 of Taylor and Goldring (1993). In sections parallel to bedding, the ichnofabric consists of broad curving meniscate bands (Figs. 4A–B and 8B), while in vertical section the *Bichordites* give rise to a pseudo-stratification of semi-meniscate backfills due to truncation by overlying burrows (Fig. 8A, C). Other trace fossils present are *Palaeophycus*, small *Planolites*, poorly defined horizontal burrows and, even more rarely *O. nodosa* and cf. *Dactyloidites*. Primary lamination is preserved rarely as centimetre-thick layers with erosive bases scouring the underlying ichnofabric and horizontal to low-angle cross-lamination which is truncated by over-lying burrows. Escape structures may cross through these beds (Fig. 8D).

A second variety (*Bichordites* ichnofabric 2) occurs in the lower-most part of the measured section (Figs. 5A–B and 8F). It differs from the previous in the smaller size of the *Bichordites* (1–3 cm wide) and a greater preservation of primary lamination. Thus, highly bioturbated *Bichordites* horizons (BI 5–6) are intercalated with almost unbiotur-bated intervals (BI 1–2). The first are truncated by the erosive surface of the latter. Laminated intervals bear planar to low-angle cross-lamination and an irregular wavy lamination produced by current ripples. Escape traces are common.

Bichordites ichnofabric 3 occurs only very locally and corresponds to small clusters of *Bichordites* associated with the bottom set and foreset of a sand dune within a laminated interval intercalated in a unit with *Ophiomorpha*-mottling and *Palaeophycus* ichnofabric (Fig. 8E). Some of the silicified *Bichordites* seen in natural exposures, located stratigraphically below the measured section, occur in the same sedimentological setting, but a detailed analysis of the ichnofabric has been prevented by the absence of quarry sections in this zone.

The interpretation of these *Bichordites* ichnofabrics is given below after discussing some more general aspects on the factors controlling preservation of spatangoid bioturbation.

3. Preservation of spatangoid trace fossils

3.1. The Goldring and Stephenson's Micraster paradox

Spatangoids are very important members of modern benthic communities in marine environments ranging from intertidal flats to abyssal plains (Ghiold, 1988; Lohrer et al., 2005). Their bioturbation activity plays a very important role in the ecology of those communities (Lohrer et al., 2004; Thompson and Riddle, 2005). They are fast, although shallow, burrowers that may be responsible for very rapid reworking of the upper tier of sediment (Table 1) and thus, they can be considered as 'key-bioturbators' (Bromley et al., 1997). For example, Lohrer et al. (2005) described how a natural population of *Echinocardium* was able to rework the five upper centimetres of sediment every three days.

Spatangoids are known in the fossil record since the earliest Cretaceous (Villier et al., 2004) and their body fossil record is abundant and diverse. The oldest occurrence of true *Scolicia* is from the Tithonian (latest Jurassic, Tchoumatchenco and Uchman, 2001), predating the oldest spatangoid body fossils and either produced by an unknown spatangoid or by a member of one of the other irregular echinoid groups that are known since the Early Jurassic. In any case, it is reasonable to believe that since the advent and diversification of spatangoids, the upper tiers of shallow and deep marine sediments must have been subject to intensive and rapid bioturbation on a scale previously unknown.

Nevertheless, spatangoid trace fossils are not as common as could be expected and spatangoid-produced ichnofabrics are reduced to a handful of described examples. This paradox was considered by Goldring and Stephenson (1970) who discussed the reasons for the absence of trace fossils assignable to *Micraster* in the Upper Cretaceous European chalk, despite the abundance of its well-preserved (auto-chthonous) body fossils. They concluded that it was a problem of preservation due to the shallow depth at which *Micraster* burrowed. Bromley and Asgaard (1975) in an inspiring paper on preservation of echinoid burrows, accepted the *Micraster* paradox and provided another comparable example. They pointed out the absence of spatangoid burrows in the Miocene Globigerina Limestone from Malta despite the presence and abundance of several spatangoid species. More examples can be added such as the Pliocene of the Baix Llobregat basin in NE Spain (Gibert, 1996; Gibert and Martinell, 1999) where some localities are rich in spatangoids; particularly the species *Brissopsis papiolensis*, occasionally preserving some spines in situ, but no definitive echinoid traces are recognized in the homogenized mudstones where the body fossils are found. Thus, the absence of spatangoid traces in sediments bearing autochthonous body fossils seems to be the rule rather than the exception. This was already stated
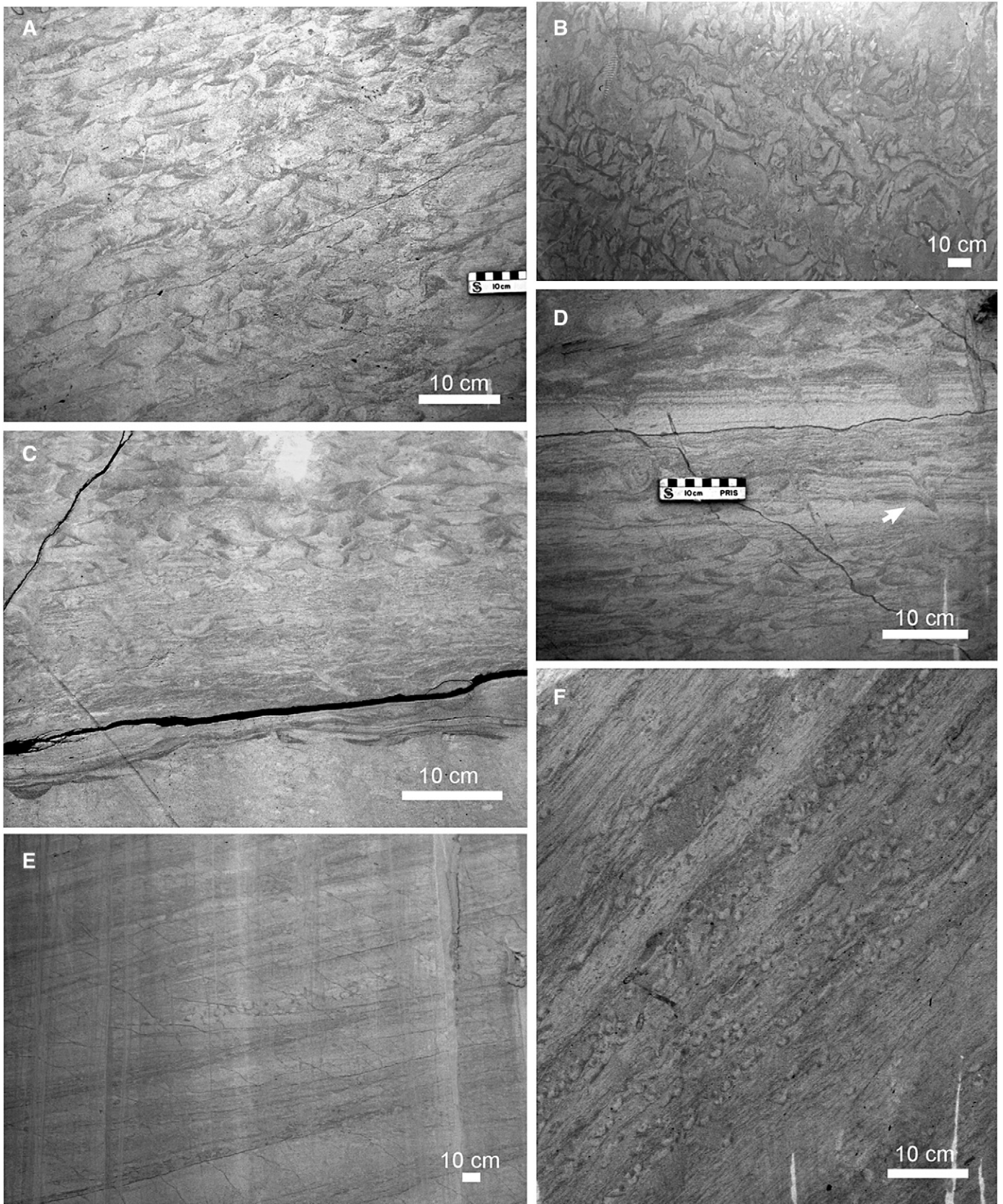
Fig. 8. *Bichordites* ichnofabrics from the Bateig Limestone. (A)–(D) *Bichordites* ichnofabric 1, intensely-burrowed ichnofabric with only local preservation of primary lamination. (A) Vertical section. (B) Horizontal section. (C) and (D) Vertical section with intervals preserving primary lamination with some escapement structures (arrow). (E) *Bichordites* ichnofabric 3, local clusters of *Bichordites* in a vertical section of large-scale cross-bedded grainstones. (F) *Bichordites* ichnofabric 4, vertical section of horizons of small *Bichordites* interbedded with laminated intervals.

by Bromley and Asgaard (1975) and here it is reanalyzed in the light of new fossil findings and new advances on the knowledge of spatangoid biology.

3.2. Taphonomic controls

The reasons for the apparent scarcity of spatangoid traces in the fossil record can be found in the taphonomic factors that intervene in their production and subsequent fossilization history in relation to the burrowing activity of other organisms and their diagenetic modification. The main factors playing a role in the preservation potential of spatangoid bioturbation are: burrowing mechanism used by the echinoids, texture of the burrowed sediment, presence and intensity of deep-tier burrowing in the benthic community and degree and timing of partial or complete lithification (summarized in Fig. 9).

a) Burrowing mechanism. As mentioned above, Kanazawa (1992) was able to reveal the existence of three major types of burrowing among Modern species of spatangoids: backfilling, pushing-away and rocking. Later experiments by the same author (Kanazawa, 1995) to analyze in detail the features of echinoid traces made it clear that only those species that use the first of these three mechanisms are able to produce large back-filled burrows such as those typically assigned to spatangoids in the fossil record (Scolicia and Bichordites). Kanazawa (1992) observed that backfiller species are commonly globular in shape and burrow deeper than others. Other burrowing modes would probably be recorded as indistinct mottling or poorly defined trails.

On the other hand, the other diagnostic feature of spatangoid-produced ichnogenera is the presence of one or two ventral chords corresponding to the drain(s). Nevertheless, a few species (probably shallow burrowers in well aerated sediments) do not construct this feature (Ridder and Lawrence, 1982).

b) Sediment texture. In his experiments, Kanazawa (1995) compared spatangoid burrowing traces in poorly- and well-sorted sediments. No visible traces were formed in the latter substrate, and only the drain tube(s) were detectable. In contrast, the same echinoids when burrowing in poorly-sorted sediments (with different sediment color depending on grain size) produced a clear pattern. In all cases, finer-grained sediment accumulated in the lower part of the trace and in back-filled burrows the smaller grains also accumulated in the lower and outer parts of the menisci, resulting

Table 1
Data obtained from the literature on the burrowing activity (speed and/or rate) and bioturbation depth of several modern spatangoids

Author	Species	Burrowing speed and/or rate	Burrowing depth	Comments
Family Brissidae				
Brissus				
Kanazawa (1992)	*agassizii*	–	30–50 mm	Up to 200 mm
Clark (1921)	*brissus*	–	30–50 mm	Up to 150 mm
Takahashi (1938)	*latecarinatus*	–	75–100 mm	Up to 200 mm
Meoma				
Chesher (1969)	*ventricosa*	80 mm h^{-1}	–	
Kier and Grant (1965)	*ventricosa*	–	30–50 mm	
Family Brissidae				
Brissopsis				
Chesher (1969)	*alta*	20 mm h^{-1}	–	
Kanazawa (1992)	*luzonica*	–	30–50 mm	
Hollertz and Duchêne (2001)	*lyrifera*	14 ml h^{-1} (7 °C) 22 ml h^{-1} (13 °C)	20 mm	Temperature variation
Family Echinocardiidae				
Echinocardium				
Lohrer et al. (2005)	sp.	50–60 mm h^{-1} Up to 20,000 cm^{-3} m^{-2} day^{-1}	Up to 50 mm	
Kanazawa (1992, 1995)	*cordatum*	50 mm h^{-1}	100–300 mm 50–100 mm (aq.)	Shallower in aquarium
Buchanan (1966)	*cordatum*	60–80 mm h^{-1}	–	
Bromley et al. (1995)	*cordatum*	–	30–50 mm	
Nichols (1959)	*cordatum*	–	150–200 mm	
Bromley et al. (1995)	*mediterraneum*	–	20–40 mm	In sand
Bromley et al. (1997)	*mediterraneum*	–	40–50 mm	In muddy sand
Family Loveniidae				
Lovenia				
Kanazawa (1992, 1995)	*elongata*	200 mm day^{-1}	10–20 mm (aq.) 20–30 mm	Shallower in aquarium
Family Maretiidae				
Pseudomaretia				
Kanazawa (1992)	*alta*	–	Up to 100 mm	
Family Schizasteridae				
Abatus				
Thompson and Riddle (2005)	*ingens*	30 mm h^{-1}–2.76 cm^3 h^{-1} 195 mm h^{-1}–17.93 cm^3 h^{-1} (aq.)	Partly buried	More active in aquarium
Brisaster				
Kanazawa (1992)	*latifrons*	Few cm day^{-1}	20–50 mm	In aquarium
Moira				
Howard et al. (1974)	*atropos*	–	Up to 150 mm	
Kanazawa (1992)	*lachesinella*	50 mm h^{-1}	100–200 mm	In aquarium
Schizaster				
Schinner (1993)	*canaliferus*	20 mm h^{-1} (12 °C) 50 mm h^{-1} (20 °C)	–	Temperature variation
Kanazawa (1992)	*lacunosus*	few cm day^{-1}	20–50 mm	In aquarium

in very distinctive traces. Kanazawa (1995) suggested that finer grains slipped down through the spines during backfilling to produce this characteristic pattern. Grain selection has also been observed in Holocene *Scolicia* from deep-sea cores by Fu and Werner (2000), but in this case the geopetal structure resulted from accumulation of darker denser sediment in lower and outer parts of the menisci. Bateig *Bichordites* also display a clear selection of grains in menisci (Fig. 4A–B, D), having lower parts darker due to a higher presence of translucent quartz grains. This seems to agree better with the Fu and Werner's scenario as quartz grains were presumably heavier than empty or partly filled foraminiferal tests of similar size. Thus, although the type of grain selection may probably vary among different sea urchin species and texture of burrowing media, it is clear that their traces would have a very low preservation potential in homogeneous sediments.

c) Lithification. Kanazawa (1995) observed that drain tubes were normally absent in unlithified sediments but well-preserved in lithified sediments. This is because they are empty tunnels that will eventually collapse under sediment pressure unless they are preserved by early diagenetic processes. In fact, drain tubes are commonly recognized as solid strings of well-lithified sediment in fossils (e.g., Bromley and Asgaard, 1975; Smith and Crimes, 1983; Plaziat and Mahmoudi, 1988). Bromley and Asgaard (1975) and Asgaard and Bromley (in press) suggested that mucus-saturated sediment of the drain walls becomes preferentially lithified and thus, they act as nucleus for cementation that may involve the surrounding menisci. They also pointed out preferential cementation of individual menisci in their lower part in specimens from the Pleistocene of Rhodes. Among the specimens of *Bichordites* found in the Bateig Limestone some display silicification. These specimens may be completely silicified and in this case it is easy to recognize how other traces cross-cutting *Bichordites* are not affected by silicification (Fig. 5C–D). In specimens where sediment has not been transformed completely, it can be seen that silicification starts in the lower and central part where the drain is located (Fig. 5A–B).

In those cases, where early cementation around the drain(s) did not take place, the tunnel(s) would collapse and the resulting trace would lack that diagnostic feature. The ichnogenus *Bolonia*, corresponding to large meniscate traces with a medial upper groove (Schlirf, 2002) might include some of these traces.

d) Tiering. Table 1 shows the burrowing depths known for some species as described in the literature. It can be seen that most of them burrow very near to the surface and only a few reach deeper than 10 cm. The maximum depths are recorded for *Moira lachenisella* and *Echinocardium cordatum*, which may reach 20 or even 30 cm. Thus, the preservation potential of the activity of such shallow burrowers is very low in ichnofabrics fully bioturbated by complex tiered benthic communities. In this situation deeper-tier bioturbation typically overprints shallower traces as the sediment–water interface moves upwards due to deposition (Bromley, 1990; Gibert and Martinell, 1996). Overprinting by deeper-tier traces was the main reason invoked to explain the absence of *Micraster* burrows in the Cretaceous chalk (Goldring and Stephenson, 1970; Bromley and Asgaard, 1975) as has been pointed by others (e.g. Fu and Werner, 2000). On the other hand, shallow traces can be easily destroyed by hydrodynamic processes in high energy settings.

3.3. Scenarios of preservation

Considering the taphonomic controls described above, it is easy to understand the limited preservation potential of traces produced by sea urchins. Deposits that did preserve spatangoid bioturbation can be explained in the light of these factors and several scenarios, one more typical and the others rarer, can be depicted:

a) As semireliefs (more rarely full reliefs) in event beds. Traces that can be confidently ascribed to spatangoid activity are very common trace fossils close to the top, within, and on the soles of Cretaceous and Cenozoic deep-sea turbiditic sandstones (Fig. 10A–B). Predepositional echinoid traces may be readily exposed by erosion and cast by turbidite deposition, while postdepositional echinoid bioturbation can be preserved both in the soles or in the tops of beds. In the latter case, they are seen as negative epireliefs found more or less in the level along which the bed may split, or weather
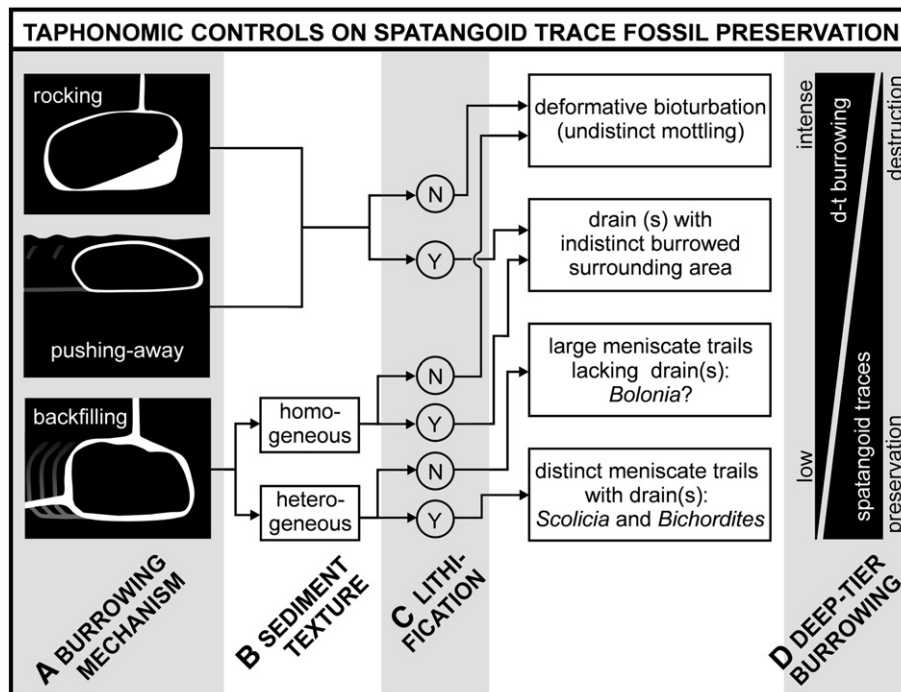

Fig. 9. Taphonomic controls on spatangoid trace fossil preservation. Further explanation in the text.

out, between the sand/silt and finer grade layers (Tc–Td Bouma layers). When preserved on the sole, bed thickness is a limiting factor for such shallow burrowers. This was demonstrated by Seilacher (1962) in the Cretaceous–Paleogene turbidite series in Zumaya where most *Scolicia* are found in beds not thicker than 4 cm and none occurs in beds thicker than 8 cm. These values (we may need to add an unknown amount of mud to know the position of the colonization surface) are consistent with the burrowing depths known for modern spatangoids (Table 1). Thus, echinoid burrows can be preserved as predepositional casts or as postdepositional positive hyporeliefs or negative epireliefs. This led to the definition of different ichnogenera that Uchman (1995) considered as preservational variants. This aspect has received a lot of attention by several authors (Smith and Crimes, 1983; Plaziat and Mahmoudi, 1988; Uchman, 1995) and needs no further discussion here.

The common preservation of sea urchin traces in deep-sea turbidites is favored by the existence of a textural (sand/mud) contrast and by the absence of deeper-tier burrowers. These may inhabit the substrate during background sedimentation but have their activity temporarily inhibited by the episodic sedimentation of a thick blanket of sediment. Meanwhile, spatangoids seem to have a capacity to survive and recolonize substrates after catastrophic events. Thus, Wetzel and Uchman (2001) pointed out that modern *Scolicia* was apparently unaffected by the deposition of 5–10 cm of ash by the eruption of Pinatubo in 1991 in the South China Sea. Rodrigues et al. (2001) also showed how echinoids resisted well to disturbance experiments performed in a deep-sea area in the Central Indian Basin. While other taxa exhibited significant reduction or even disappearance after disturbance, sea urchins and other vagile animals experimented an increase in their abundance.

Spatangoid traces occur also in turbiditic or tempestitic event beds in shallow marine settings (Fig. 10C). The taphonomic factors that allow for preservation in these settings are the same as those described above for deep-sea turbidites. Nevertheless, they do not seem to be so ubiquituous and abundant as in deep marine settings probably because of the higher variation of certain paleoenvironmental parameters in shallow marine settings, such as salinity.

b) As an accessory element in intensely-bioturbated ichnofabrics. Intensely bioturbated ichnofabrics are typically the result of complex equilibrium benthic communities that are commonly vertically organized in tiers. In this scenario, under normal background sedimentation tiers migrate upwards and this leads to the destruction of shallow bioturbation and to the dominance of deeper-tier traces in the final ichnofabric (Bromley, 1990). The typical example of this situation is found in the ichnofabrics of the Upper Cretaceous chalk (Bromley and Ekdale, 1986; Bromley 1990) where *Zoophycus*, *Chondrites* and *Thalassinoides* among other deep-tier burrows prevent the preservation of the shallower traces that might have been produced by the abundant *Micraster*.

Nevertheless, there are some examples where *Scolicia* or *Bichordites* have been described from such intensely-burrowed ichnofabrics, as in shoreface deposits from the Miocene of Argentina (Carmona et al., 2004), and the Pliocene of France (Fig. 10D; Gibert,
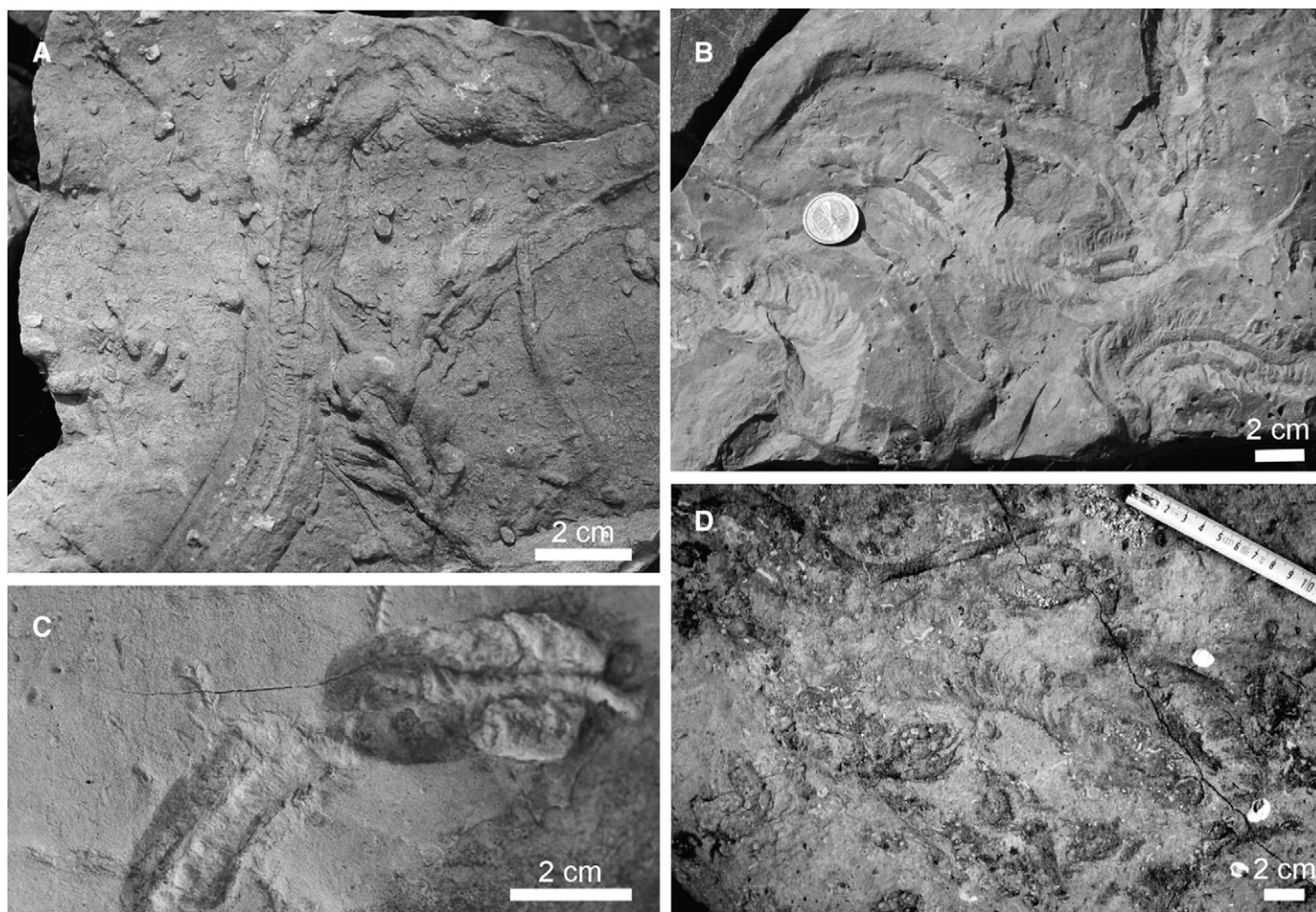
Fig. 10. (A) Hyporelief *Scolicia* from Paleocene deep marine turbidites of the Swiss Alps. (B) Epirelief *Scolicia* from Eocene deep marine turbidites of the Jaca Basin in the Spanish Pyrenees (picture provided by Pau Arbués). (C) Epirelief *Bichordites* from shallow marine sandstone beds in the Miocene Penedès Basin (NE Spain). (D) Spatangoid burrow in highly bioturbated ichnofabric with *Thalassinoides*, *Planolites* and other traces from shoreface facies in the Pliocene Roussillon Basin (SE France).

1996; Gibert and Martinell, 1998) or in Pliocene deep-sea deposits of Ecuador (Miller and Vokes, 1998). In these cases, only partial bioturbation at deep-tier levels allowed for occasional preservation of spatangoid traces.

A peculiar case was briefly referred to by Goldring et al. (2002) from the Globigerina Limestone of Malta where Bromley and Asgaard (1975) failed to find echinoid traces despite the abundance of spatangoid body fossils. Goldring et al. (2002) described the ichnofabric of this unit as dominated by bow-form burrows (cf. *Cylindrichnus*) responsible for very intense bioturbation. Nevertheless, they were able to find *Scolicia* (*Bichordites*) below the base of a sharply based and graded event bed as part of a frozen profile, as this was the only position where deeper-tier burrows did not destroy them.

c) Spatangoid-produced ichnofabrics. This third scenario is typified by the Bateig 'Fantasia' (and 'Galaxy') ichnofabrics that are characterized by intense bioturbation dominated by spatangoid activity. A few other examples of similar ichnofabrics have been recorded in the literature from Oligocene and Neogene rocks (Bromley and Asgaard, 1975; Radwanski et al., 1975; Ward and Lewis, 1975; Colella and D'Alessandro, 1988; Kanazawa, 1995; D'Alessandro and Massari, 1997; Fu and Werner, 2000; D'Alessandro et al., 2004). An account of the ecological and taphonomic setting in which this type of ichnofabrics are produced is given in the next section.

4. Spatangoid-produced ichnofabrics: the Bateig Fantasia scenario

The most typical *Bichordites* ichnofabric (type 1) in the Bateig Limestone is characterized in vertical section by its pseudobedded appearance resulting from the vertical repetition of *Bichordites* horizons, each one truncated by the overlying one (Fig. 8A, C). This feature suggests stacking of successive colonization events rather than random cross-cutting and records the episodic nature of sedimentation. Primary lamination, when preserved, confirms this interpretation as it is characterized by planar-laminated to rippled beds with erosive bases that may be interpreted as deposited by grain flows or turbiditic currents. The tops of these laminated beds are truncated by overlying bioturbation and internally, only a few escape structures cross these intervals (Fig. 8D). Thus, ichnological and sedimentological evidence supports pulsed sedimentation. Intervals between depositional events ('colonization windows' in the sense of Pollard et al., 1993) were probably relatively short-lived as evinced by the absence of background mud sedimentation. High sedimentation rate prevented the development of a complex equilibrium community, while rapid bioturbators with a certain capacity to survive to the depositional events, such as the spatangoids, were able to keep pace with such sedimentation. Colonization by echinoids probably took place by lateral or vertical migration. Because spatangoids are shallow burrowers rarely bioturbating below a few centimetres (Table 1), the almost complete absence of laminated intervals indicates that the thickness of the event beds was only of a few centimetres, probably more or less equivalent to that of the *Bichordites* horizons. The absence of deep-tier bioturbation due to the immaturity of a benthic community affected by frequent and continuous disturbances, allowed opportunistic spatangoids to exploit the resources and the preservation of their burrowing activity.

The scenario for the second type of *Bichordites* ichnofabric is very similar but in this case, sedimentation took place at an even higher rate. This led to a greater preservation of primary lamination and to a greater separation between successive colonization events by spatangoids (Fig. 8F). This ichnofabric records a succession of laminated to bioturbated deposits recording event deposition and subsequent colonization. *Bichordites* are smaller than in type 1, which also supports the less favorable conditions for benthic life. Thus, brief colonization windows and thicker sediment accumulation made the vertical relocation of infaunal organisms more difficult.

Both types of *Bichordites* ichnofabric are found occupying a certain position within a repeated succession of ichnofabrics in the Bateig Limestone (Fig. 2; Gibert and Goldring, 2007). *Bichordites* ichnofabrics overlie surfaces with strong erosional features sometimes covered by a variable thickness of unbioturbated sediments with structures indicating rapid deposition (hydroplastic deformation, climbing ripples) and grades upwards to a *Palaeophycus*-mottling ichnofabric that passes to an *Ophiomorpha*-mottling ichnofabric. Considering the geological context of the region, Gibert and Goldring (2007) interpreted the erosive events that initiate the cycles as caused by diapiric activity of the Keuper (Upper Triassic) evaporites, which today are found in extensive areas of the surrounding Miocene outcrops. The influence of halokinetic tectonics in Miocene sedimentation in the Eastern Prebetic Zone has been demonstrated by several authors (Cater, 1987; de Ruig, 1992). The generation of a relief due to diapir activity and subsequent erosion led to the rapid sedimentation of turbidites at the foot of local faults. It is envisaged that this was the setting for the formation of the *Bichordites* ichnofabric. Interestingly, in a comparable scenario (filling small depressions adjacent to bounding faults), Krautworst and Brachert (2001) described one facies (Facies 4) from the Late Miocene Brèche Rouge de Carboneras of Almeria (SE Spain) comprising limestones with meniscate back-filled burrows (possible *Bichordites*). Differences between the two varieties (1 and 2) of *Bichordites* ichnofabric in the Bateig Limestone might be related to different positions with respect to the sediment source or with different intensity of tectonic processes. Eventually, buildup of sediment on the fault apron would lead to the gradual cessation of turbidite depositional events and the bottom would begin to be influenced by currents moving across the shelf. This change in hydraulic regime would cause ecological changes allowing for the installation of a different benthic community responsible for the *Palaeophycus*-mottling and *Ophiomorpha*-mottling ichnofabrics. Spatangoids were probably part of this community as evinced by the presence of *Maretia* in these facies, but their role was probably not so important and their traces were only rarely preserved due to the overprinting by deeper-tier bioturbating activity. Intercalated in facies with these ichnofabrics, in one large-scale, cross-bedded unit the third type of *Bichordites* ichnofabrics occurs very locally (Fig. 8E). Thus, in this new setting dominated by shelf currents, spatangoid traces are only preserved in those beds with higher sedimentation rate such as those formed by migrating sand dunes.

Hence, the *Bichordites* ichnofabric records the activity of a spatangoid-dominated community in a depositional setting dominated by continuous deposition of small turbiditic beds. The instability of this environment only allowed for the colonization by rapid and resistant burrowers, such as spatangoids, and the absence of deep-tier bioturbation favored the preservation of their activity. The few examples of spatangoid-produced ichnofabrics known from the literature are described from sedimentary settings with very similar depositional, ecological and taphonomic constraints.

The best reported example is from the Pleistocene Cape Arkangelos Calcarenite of the Rhodes Formation in the Eastern Mediterranean (Bromley and Asgaard, 1975; Bromley and Ekdale, 1986; Hanken et al., 1996). This occurrence is associated with clinoform stratification recording migration of an inner shelf mega-bedform into deep water. The avalanche units are highly bioturbated by the activity of the irregular echinoid *Echinocardium* and only in thicker units is a sharp base of a slip unit preserved. Similar occurrences associated to clinoform stratification have been described from the Lower Pleistocene 'Calcarenita di Gravina' (D'Alessandro et al., 2004) and the Middle (?) Pleistocene 'Calcarenita della Casarana' (D'Alessandro and Massari, 1997), both in southeastern Italy. In the Bateig Limestone, there is no evidence of big clinoforms and so its *Bichordites* ichnofabrics are probably more similar to those reported by Colella and D'Alessandro (1988) from bathyal turbiditic units in the Pliocene/Pleistocene Monte Torre Paleostrait (southwestern Italy) or by Fu and

Werner (2000) from Holocene deep-sea cores in the NE Atlantic. The latter authors pointed out that high sedimentation rates (>10 cm/ka) seem to promote the occurrence of *Scolicia*.

Other comparable ichnofabrics have been briefly described or figured from the Pleistocene Hamada Formation in Japan (Kanazawa, 1995), the Upper Oligocene Arno Limestone of New Zealand (Ward and Lewis, 1975) and the Lower Miocene of Denmark (Radwanski et al., 1975). More details on the sedimentology and ichnofabrics of these occurrences would probably led to find the similarities pointed above with other occurrences.

5. Conclusions

The advent of infaunal echinoids represented a revolution in sediment bioturbation, and potentially introduced a new dimension into ichnofabrics. However, the distinct preservation of burrows of such large and rapid, but shallow-tier bioturbators is dependent on the mechanism used to burrow, the sediment texture, the effects of early diagenesis, and the extent to which the burrows can avoid being overprinted by deeper bioturbators as sediment accumulates. These preservational controls are consistent with the most typical taphonomic scenarios in which *Scolicia* and *Bichordites* are found in the fossil record, which is as predepositional or postdepositional traces in thin sandstone event beds in deep and shallow marine settings. Spatangoid traces are rare in fully burrowed ichnofabrics where deeper-tier worm and crustacean bioturbation obliterate shallow biogenic structures. In these settings, echinoid traces can only be preserved when deep-tier burrowing is incomplete or in frozen profiles.

An additional, but distinctive setting may be typified by the *Bichordites* ichnofabric of the Miocene Bateig Limestone. Such spatangoid-produced ichnofabrics are characteristic of a depositional setting where successive sedimentary events (turbidites or grain flows) accumulate cm to dm thick sandy beds. Brief colonization windows between events prevented the establishment of a background equilibrium complexly-tiered benthic community but allowed colonization by rapid burrowers such as spatangoids. Other Oligocene and Neogene examples of spatangoid-produced ichnofabrics described in the literature share the essential ecological–taphonomic setting interpreted for those in the Bateig Limestone.

Acknowledgements

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