Trace fossils from the Lower and Middle Jurassic marginal marine deposits of the Sorthat Formation, Bornholm, Denmark

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The Lower to Middle Jurassic Sorthat and Bagå Formations of the Baltic island of Bornholm, Denmark, are a predominantly fluviatile unit. On the south coast of the island at Korsodde, however, an interval within the Sorthat Formation contains a diverse trace fossil assemblage indicating a marine incursion. Study of this interval revealed 15 ichnotaxa, among which one is new: *Bornichnus tortuosus* nov. igen. et isp. Several of the trace fossils present are generally considered characteristic of the lower shoreface to offshore environments (e.g. *Teichichnus* and *Asterosoma*). However, the low degree of bioturbation and ichnodiversity, and sedimentological features, indicate an environment influenced by salinity fluctuation, probably a tidally influenced delta. Five ichnofabrics are defined that describe this setting and which may be indicative of marginal-marine environments that are influenced by salinity fluctuations.

Key words: Ichnofabrics, trace fossils, palaeoenvironmental analysis, Jurassic, Denmark, *Bornichnus, Diplocraterion, Asterosoma.*

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Trace fossils are valuable tools in the study of marginal marine deposits. For example, they help to determine changes in salinity, bathymetry and energy of the environment, or position of the coast (e.g. Ekdale *et al.* 1984; Bromley 1996; MacEachern & Burton 2000; Gingras *et al.* 2002). These aspects of trace fossils have been applied to Jurassic shallow-marine deposits by several authors (e.g. Farrow 1966; Fürsich 1975, 1981, 1998; Pieńkowski 1985; Goldring *et al.* 1998b; Gibert & Ekdale 1999; Schlirf 2000), but effective studies of palaeonvironments must involve ichnofabric analysis (Pollard *et al.* 1993; Martin & Pollard 1996). For Jurassic shallow marine environments, ichnofabric analysis has been under-utilized, and most such analyses have been based on well cores. Trace fossils have also been used to identify brief marine incursions that are not obvious from the sedimentological record alone (Taylor & Gawthorpe 1993).

Because of the narrow diameter of the core material, good field exposures are to be preferred for effective analysis of environments. The Pliensbachian – Aalenian Sorthat Formation of Michelsen *et al.* (2003) is well exposed on the south coast of Bornholm (Fig. 1). The sediments are poorly lithified and allow free sectioning with spades and knives; this reveals the three-dimensional morphology of the trace fossils and produces serial sections of ichnofabrics. The sediments of the formation were deposited mostly in a marginal marine environment (Michelsen *et al.* 2003), but at only one level are trace fossils abundant (Hoelstad 1985; Hamann 1989; Koppelhus & Nielsen 1994; Pedersen & Surlyk 1999). These trace fossils are comparable to those described from, for example, the Middle Jurassic Brent Formation of the North Sea (Taylor & Gawthorpe 1993).

The aim of this study is to describe trace fossils from the Sorthat Formation in their sedimentological and ichnofabric context. The trace-fossil assemblage contains about 15 ichnotaxa, including the new ichnogenus *Bornichnus*.

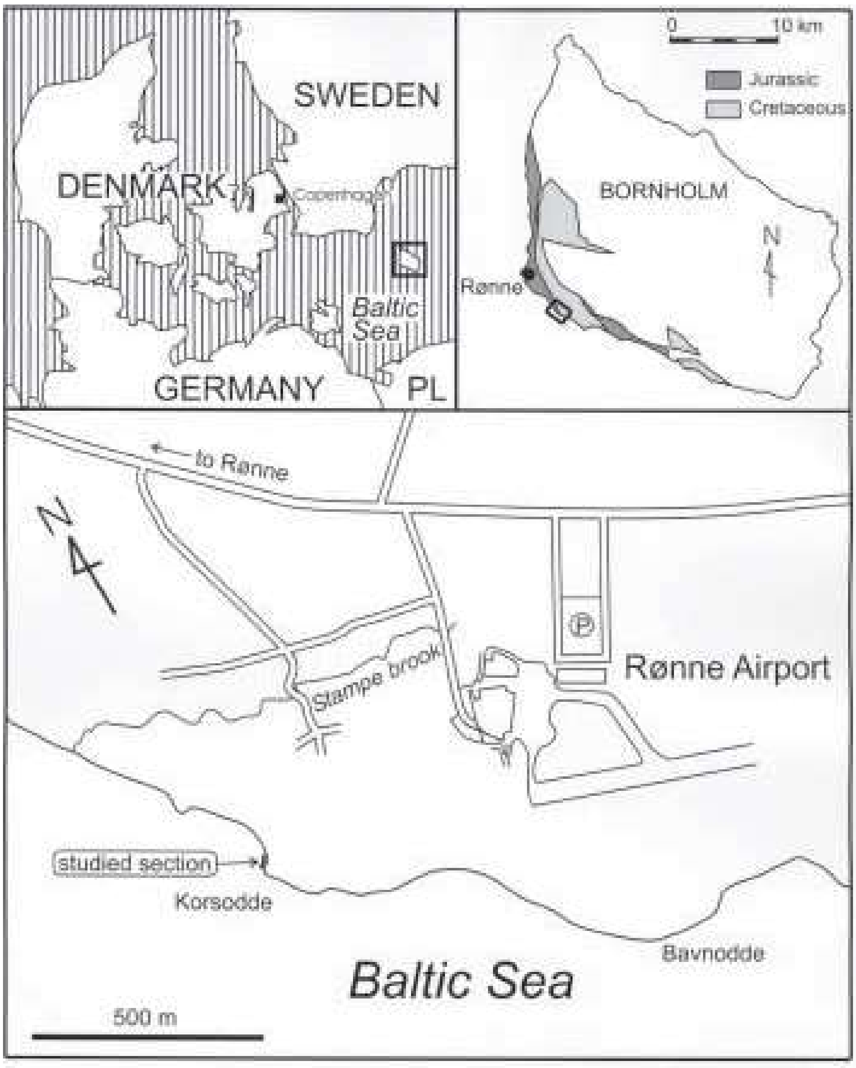


Fig. 1. Map indicating the location of the section at Korsodde on the island of Bornholm.

Stratigraphic background

The investigated section comprises part of the reference section of the Sorthat Formation of Michelsen *et al.* (2003). Sedimentology and environmental interpretations of these sediments have been discussed previously, while they were considered part of the Bagå Formation, by Graversen *et al.* (1982) and Pedersen & Surlyk (1999). The Sorthat Formation consists mainly of fine to coarse grained cross-laminated sands (locally lithified), heteroliths and clays. There is a single rooted coal seam. Most of the deposits are arranged in fining-upward cycles. The Sorthat Formation overlies the ferruginous marine sandstones of the Hasle Formation (Pliensbachian).

The Sorthat Formation is dated to the late Pliensbachian – Aalenian (Nielsen & Koppelhus 1991; Koppelhus & Nielsen 1994). The investigated section at Korsodde is referred in large part to the Upper Pliensbachian to Toarcian (Koppelhus & Nielsen 1994). It is regarded as a 'strongly regressive' unit (Gravesen *et al.* 1982). In the type section, it is interpreted as deposits of a lower delta plain, where fining upward "sand-clay-coal cycles were deposited in a system of meandering channels, levees and backswamps. Marginal marine conditions with clay deposition were developed in interdistributary bays formed by compaction following channel avulsion" (Gravesen *et al.* 1982, p. 46). Coeval deposits, interpreted in a similar way, occur in the Meriedal formation (informal unit)

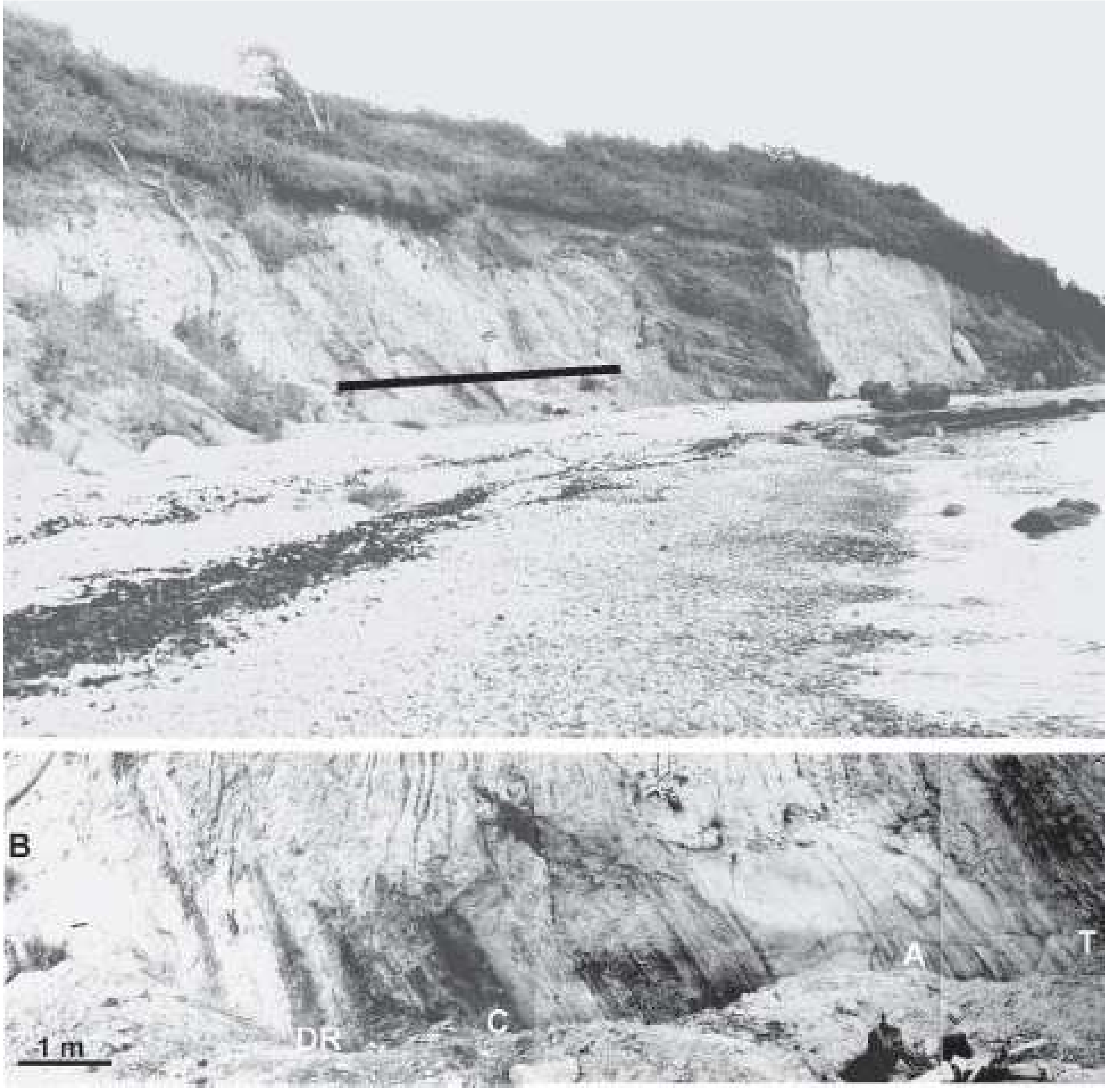


Fig. 2. The locality at Korsodde as exposed in 2000; winter storm erosion changes the section annually. The bar in the upper photograph shows the studied section. This is shown below in cleaned condition. A, horizon of abundant *Asterosoma*. B, area of occurrence of the *Bornichnus-Diplocraterion* ichnofabric. C, the coal-like, organics-rich muddy bed. DR, horizon of the *Diplocraterion*-root structure ichnofabric. T, horizon of the *Teichichnus-Asterosoma* ichnofabric.

in southern Sweden (Norling *et al.* 1993). Lower Jurassic deposits investigated in the Helsingborg railway tunnel between Sweden and Denmark contain tidal heterolithic facies with *Diplocraterion parallelum* (Ahlberg 1990). The Upper Triassic to Lower Jurassic Gassum Formation, which is known from boreholes on Sjælland, Denmark, and interpreted mainly as tidal deposits (Nielsen *et al.* 1989), displays similar facies containing *Diplocraterion parallelum*.

The studied locality at Korsodde (Figs 1, 2) has been described by Hamann (1989), Koppelhus & Nielsen (1994) and Pedersen & Surlyk (1999), and mentioned by Bromley & Uchman (1999). The locality is situated in the sea cliff on the southern flank of an anticline. The succession, about 100 m thick (Fig. 3), is dominated in the lower part by upward-thickening fluvial cycles. The middle part chiefly contains marginal-marine deposits. Fluvial cycles occur again at the top

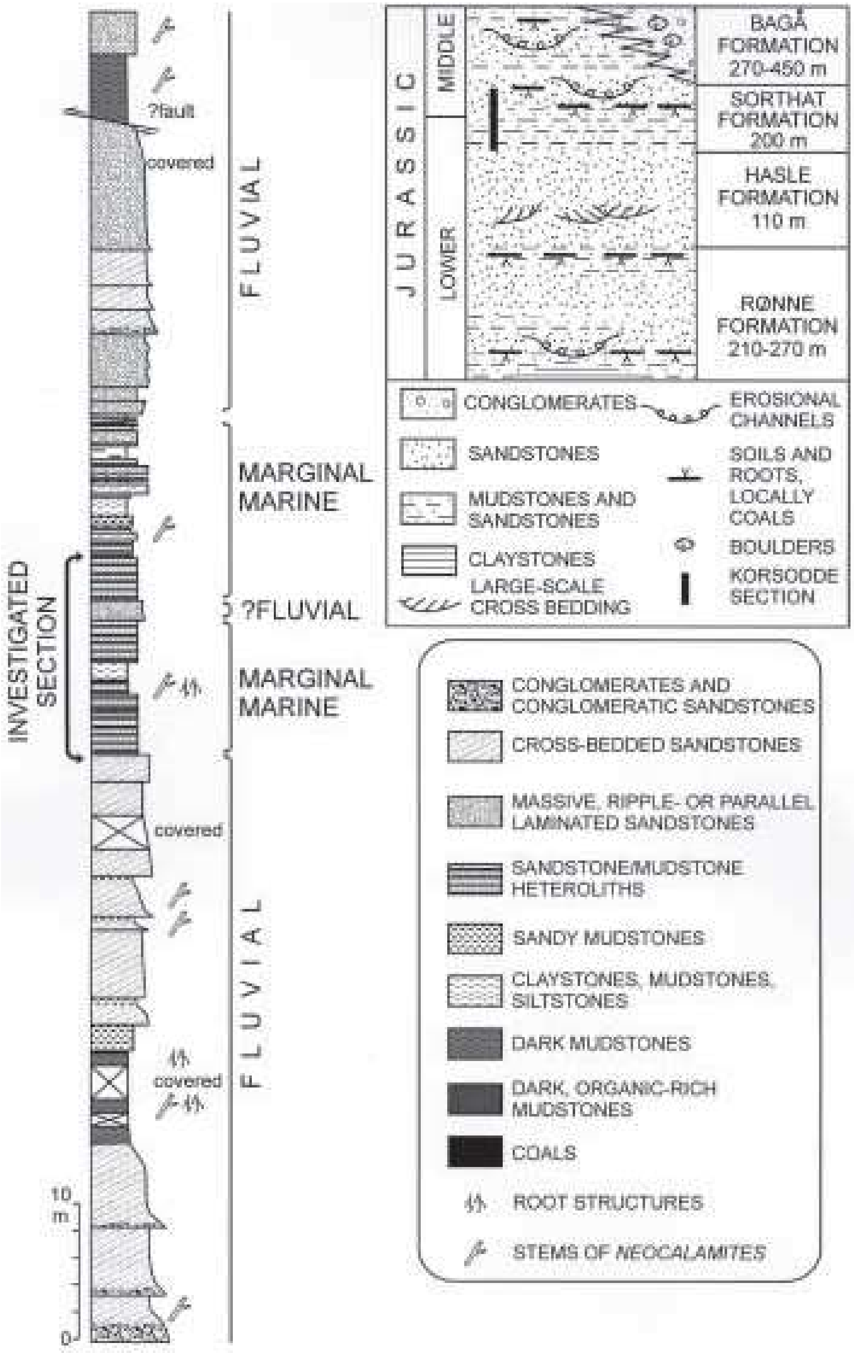


Fig. 3. General stratigraphic scheme of the Lower Jurassic deposits in Bornholm, modified after Hamann (1989), and general section of the Sorthat Formation at Korsodde, showing the location of the investigated section.

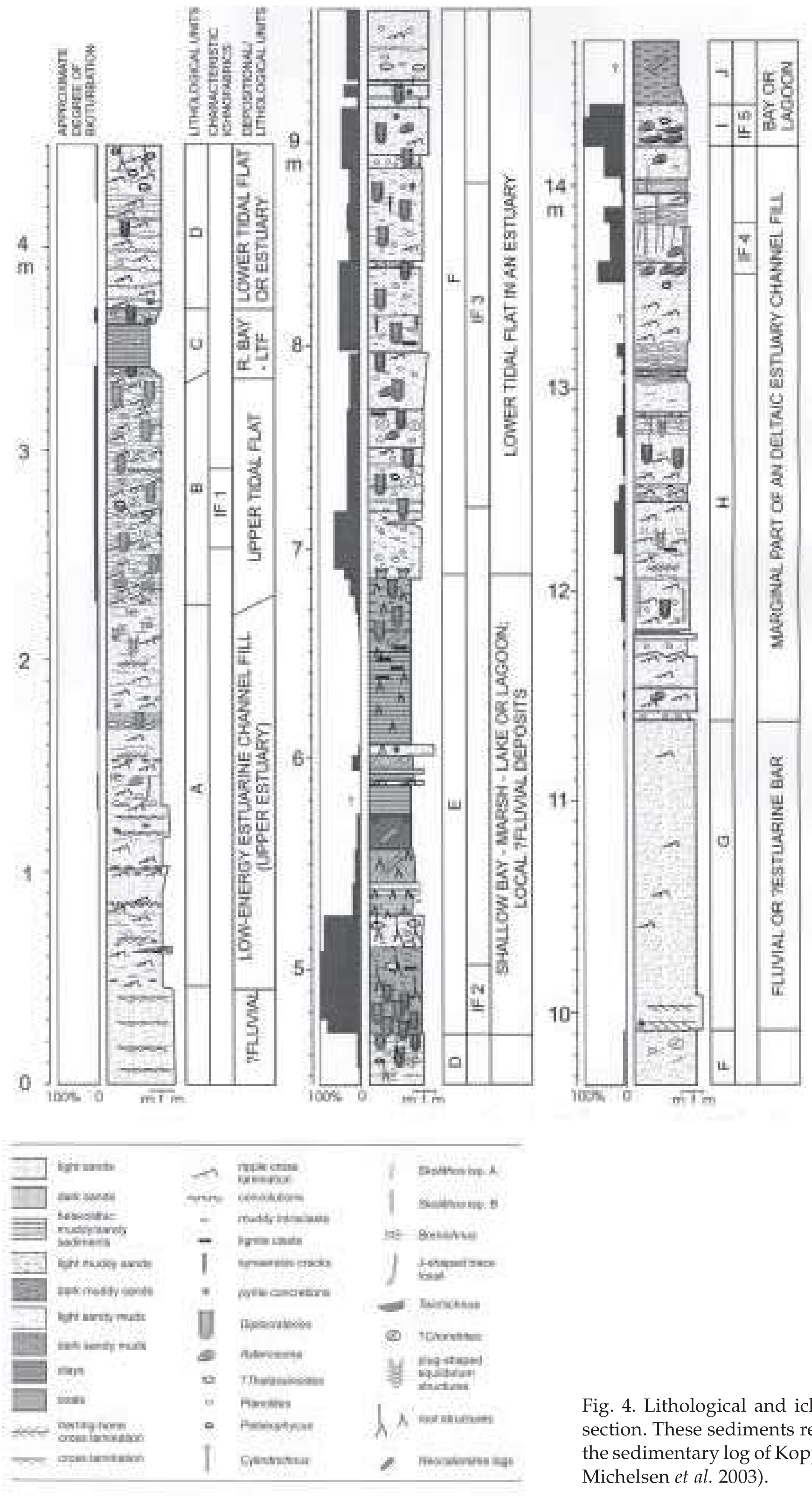


Fig. 4. Lithological and ichnological log of the investigated section. These sediments represent the segment 117–133 m of the sedimentary log of Koppelhus & Nielsen 1994, fig. 17b and Michelsen *et al.* 2003).

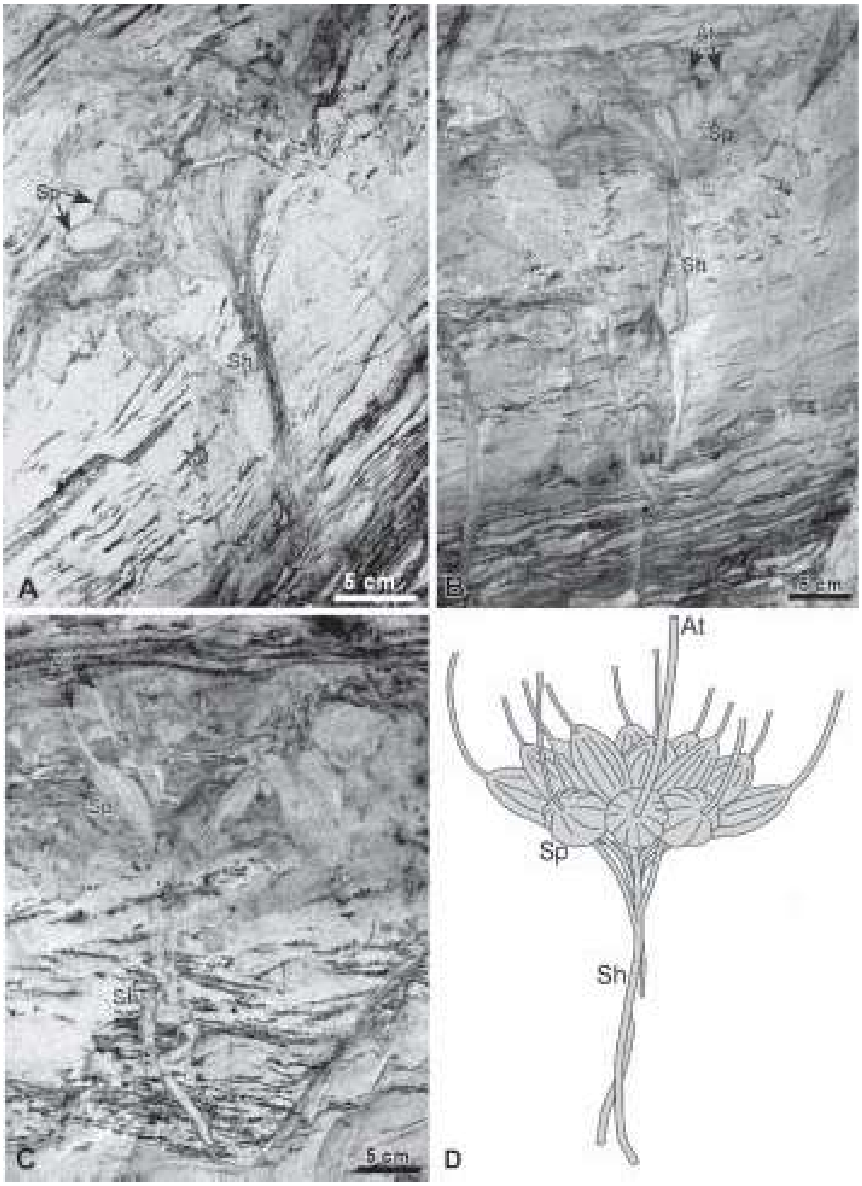


Fig. 5. *Asterosoma* isp. at 13.6 m, seen in vertical sections. A. Specimen showing the shaft (Sh) leading up to a fan-like group of intersecting, steeply inclined spindles. Above and to the left, an array of more horizontal spindles, two of them arrowed (Sp). These probably belong to a different individual. B. Specimen showing a splaying bunch of spindles (Sp), several showing the central tube emerging as an ascending tube, two arrowed (At). C. Another example showing similar features, the ascending tubes nicely sectioned, two arrowed (At). The spindle at left (Sp) shows its concentric structure in longitudinal section. D. Reconstruction of the anatomy of the Korsodde *Asterosoma* based on serial sections of many individuals.

of the section. The ichnology of the lower part of the marine-influenced segment of the section (Fig. 4), which is about 14.5 m thick, was studied in detail.

The palaeoenvironmental interpretations are based on earlier general sedimentological analyses and palynological work (Koppelhus & Nielsen 1994; Michelsen *et al.* 2003). However, an attempt is made here to specify more detailed sedimentary environments as indicated by ichnological data.

Trace fossils

Apart from *Bornichnus*, no trace fossils were collected, because the host rock is soft to poorly lithified. Most can be determined only at the ichnogenus level because of the state of preservation. Some trace fossils can be observed in detail in three dimensions after scraping the cliff surface to produce a series of parallel serial sections.

Asterosoma isp.

Fig. 5

Vertical or oblique complex trace fossil composed of a bunch of spindle-shaped structures and associated tubes (Fig. 5). Each spindle is a bulb-like swelling having concentric internal structure around a central tube. The spindles taper downward and coalesce in a single concentrically layered, vertical or oblique, narrow basal shaft. Around the shaft, the spindles are crowded and older spindles are truncated by younger. The upper parts of the spindles diverge from the vertical axis and become separated. The central tubes extend from the upper end of each spindle and continue upward as 'ascending tubes'. In vertical cross-section, the upper part of the trace fossil is visible as a group of separated concentrically laminated ovals. The central tube of the latest spindle prolongs downwards through the basal narrow part of the spindle and continues beneath as a narrow shaft.

Total length of this trace fossil attains about 35 cm (the uppermost parts of the tubes are always eroded), and its total width approximately 30 cm. The diameter of a single spindle is commonly 3 cm but may exceed 4 cm. The central tube is about 5 mm in diameter. The total number of spindles per trace fossil was not easy to estimate; in horizontal sections, overlap of spindles within and between individuals confuses the picture. However, in least crowded situations, number of spindles was estimated as falling between about 12 and possibly 25, numbers varying between individuals. The trace fossil is filled with muddy fine sand.

Our morphological model based on serial sections (Fig. 5D) might be translated into a three-dimensional structure such as was illustrated by Farrow (1966, pl. 6, figs 1–2) and Fürsich (1974a, fig. 31b) from the British and French Middle Jurassic. Those occurrences, however, seem to have smooth spindle surfaces. The irregular cross sections of the walls of the Korsodde spindles indicate that the walls had the longitudinal grooves depicted in some Late Cretaceous (Otto 1854; Rehnelt 1956; Müller 1971) and Jurassic (Seilacher 1997) examples. The observation of the upward continuation of the central tube of the spindles as ascending tubes appears to be new, although Pemberton *et al.* (2001), in their reconstruction of *Asterosoma*, indicated horizontal extension of the tube from horizontal spindles. Also, Altevogt (1968) illustrated a Cretaceous specimen showing a pair of upward-turned processes that appear to represent proximal parts of two ascending tubes. Miller & Knox (1985) illustrated a Carboniferous specimen that has somewhat upturned spindles but the further extension of the central tubes was not mentioned.

The trace fossil is similar in design to *Parahaentzschelinia surlyki* Dam (1990a) from the Lower Jurassic of East Greenland. The latter, however, is smaller, lacks bulb-like swellings, and has more numerous concentric cylinders. These differences may be considered of accessory significance, and *P. surlyki* possibly should be referred to *Asterosoma*.

This trace fossil is interpreted as having been produced by a small deposit-feeding animal living in a tube communicating with the sea-floor. Sediment was reworked around the upper part of the tube by radically shifting the position of the tube (cf. Chamberlain 1971). In this way, the tracemaker avoided re-exploitation of the same sediment (phobotaxis), however, in the studied specimens, older spindles are truncated by the younger ones.

The ichnogenus *Asterosoma* is in need of taxonomic revision, the results of which will impact our interpretation of this form as a palaeoenvironmental indicator. However, a brief summary of its palaeoenvironmental distribution is included here.

Asterosoma has occurred in several different environments since the Lower Palaeozoic (e.g. Seilacher & Meischner 1964), but it is most common in shallow-marine settings. For instance, in the Carboniferous, it is an opportunistic trace fossil in marginal marine facies, especially in tidal flats (Chamberlain 1978; Miller & Knox 1985; Pollard 1988; Martino 1989). It has been described as a constituent of several ichnofabrics. Howell *et al.* (1996) distinguished Jurassic *Asterosoma* ichnofabrics, dominated by *Asterosoma* and small *Teichichnus*, typical of a restricted environment (?estuarine/lagoonal). Less numerous occurrences of *Asterosoma* have been noted in deeper-water deposits, for instance in Silurian turbidites (Rindsberg 1982), Triassic open-marine carbonate claystones (Droser & O'Connel 1992), Turonian offshore siliciclastic sediments (Vossler & Pemberton 1988, 1989), or Upper Cretaceous – Paleocene turbidites (Powichrowski 1989). *Asterosoma* has been reported from softground substrates, mostly siliciclastics, and rarely from carbonates (e.g. Gibert 1996).

Bornichnus *nov. igen.*

Derivation of name. *Born* – from Bornholm; *ichnus*, latinized Greek – trace.

Type ichnospecies. *Bornichnus tortuosus* Bromley & Uchman.

Diagnosis. Small trace fossil composed of a crowded tangle of lined tubes in millimetre scale that are closely and tortuously branched. The whole trace fossil oc-

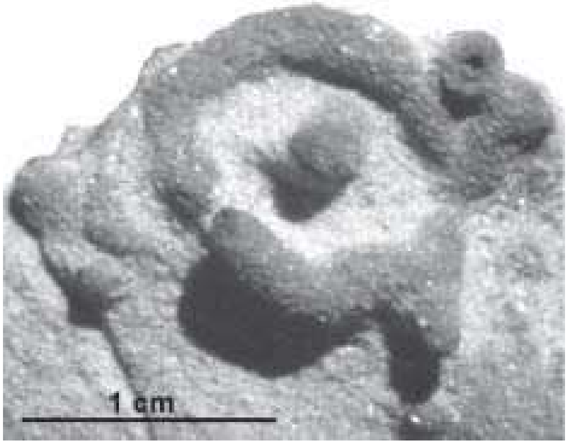


Fig. 6. Holotype of *Bornichnus tortuosus* showing a small portion of the tangled trace fossil. A circular length surrounds another tunnel and a branch leaves this toward lower right. At upper right a cross section shows the thick lining.

cupies an ovoid region of sediment a few centimetres in size.

Remarks. Bornichnus differs from *Palaeophycus* Hall in its tangled, contorted morphology and abundant branching. In section, individual *Bornichnus* occur in small, isolated patches, whereas *Palaeophycus* most commonly forms unbranched or little-branched lined tubes or more extensive, branched systems (Pemberton & Frey 1982).

Bornichnus tortuosus *nov. isp.*

Figs 6, 7

Derivation of name. tortuosus – tortuous in Latin.

Material. About 30 specimens and numerous observations in the field.

Types. MGUH 26859 (holotype, Fig. 6); MGUH 26860 and 26861 (cotypes). The specimens are housed in the Geological Museum, University of Copenhagen.

Type horizon and locality. Bagå Formation (Bajocian), Korsodde, Bornholm.

Diagnosis. As for the ichnogenus.

Description. The tubes are 1.5–3 mm in diameter and display characteristic bends and loops in all spacial orientations, producing a loosely tangled ball. The thick wall comprises about a quarter or more of the width of the tube and is impregnated with ferruginous material. In most cases, T-branches occur after less than 12 mm of tube course. No intersections have been noted. This trace fossil is distributed within the sediment as ovoid bodies 20–60 mm in diameter. In cross section it has the appearance of a patch of dots and short lines (Fig. 7).

Discussion. Bornichnus tortuosus was found only in the lower part of the section dominated by repetitive heteroliths, and interpreted as tidal flat deposits (Fig. 4). The trace fossil occurs in fine-grained sand and locally cross-cuts muddy drapes.

This trace fossil can be interpreted as a complicated system of small open burrows produced by possibly farming, worm-like animals (probably polychaetes). Similar complicated burrow systems are produced by the polychaete *Capitomastus* cf. *aciculatus* in the Georgia coast, at water-depths of 2–10 m, up to 50 cm below the sea floor, especially in fine sand and silt (Hertweck 1972).

?*Chondrites* isp.

Minute, winding and branched trace fossils, less than 1 mm in diameter, filled with mud. This form occurs in impure sands deposited on a tidal flat. This trace fossil may have been produced by a polychaete similar to recent *Heteromastus filiformis*, which is widely known from the North Sea tidal flats (e.g. Schäfer 1962; Hertweck 1994). Taxonomic reviews of *Chondrites* are provided by Fu (1991) and Uchman (1999).

Cylindrichnus isp.

Vertical or subvertical, straight or slightly curved cylinder having a distinct muddy wall. The fill displays internal concentric structure. The cylinder becomes slightly thicker upward. Its upper termination in some specimens is enlarged in a shallow cone-like concentric structure. This trace fossil is as much as 24.5 cm long, and 5 mm in diameter at the mid point.
Cylindrichnus isp. was found only in the uppermost part of the section. It may represent the truncated lower part of specimens of *Asterosoma* isp., which occur in the underlying layer. Dimensions as well as structure of examples of *Cylindrichnus* and the lowermost part of *Asterosoma* isp. are comparable. Frey & Howard (1970) illustrated similar, concentrically layered tubes as *Asterosoma* (their fig. 2a) or as '*Asterosoma* form *Cylindrichnus*' (their fig. 7b), but no further description was provided. The same trace fossil was described by Frey (1970) as '*Asterosoma* form *Cylindrichnus concentricus*'. A similar form was described from a Quaternary fan delta as *Cylindrichnus*

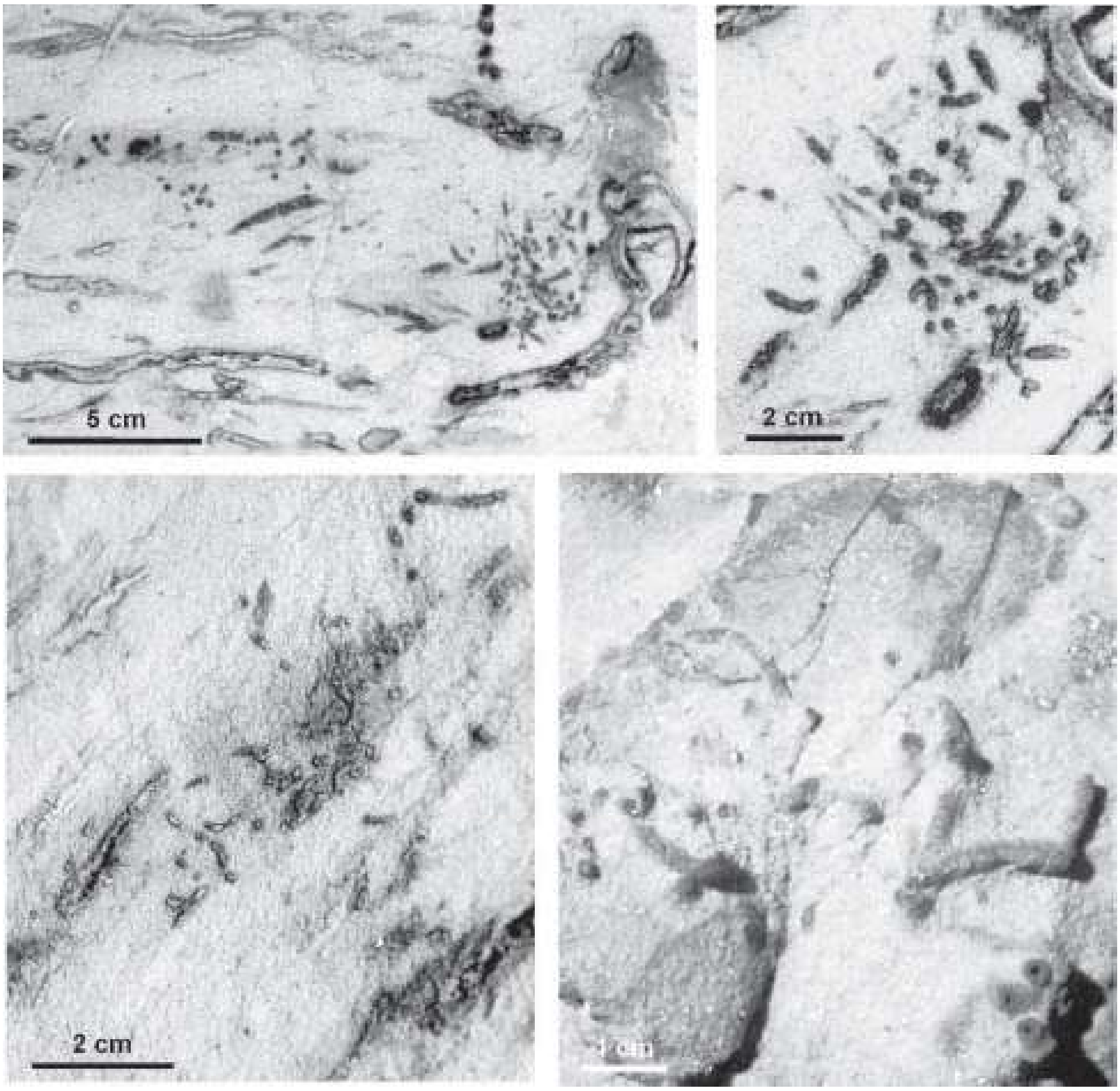


Fig. 7. Four field photographs at 2.2 m of *Bornichnus tortuosus*, showing its general appearance in section.

concentricus by Ekdale & Lewis (1991), who also suggested an affinity to *Asterosoma* (the latter ichnogenus occurs in the same ichnofacies). We cannot prove such a relationship, and therefore these trace fossils are described separately. The ichnogenus *Cylindrichnus* was discussed by Goldring (1996) and, similarly to *Asterosoma*, this ichnogenus needs revision.

Diplocraterion parallelum Torell, 1870

Fig. 8

Vertical or oblique, straight or contorted trace fossil comprising a U-shaped, lined cylindrical tube, connected with a spreite structure. The trace fossils are up to 7.5 cm wide and 30 cm long. The diameter of the tube is about 1 cm. The limbs and vertex are lined with clayey sediment and abundant plant debris and filled with less muddy sediment. The spreite is composed of muddy sandstone and plant detritus. In

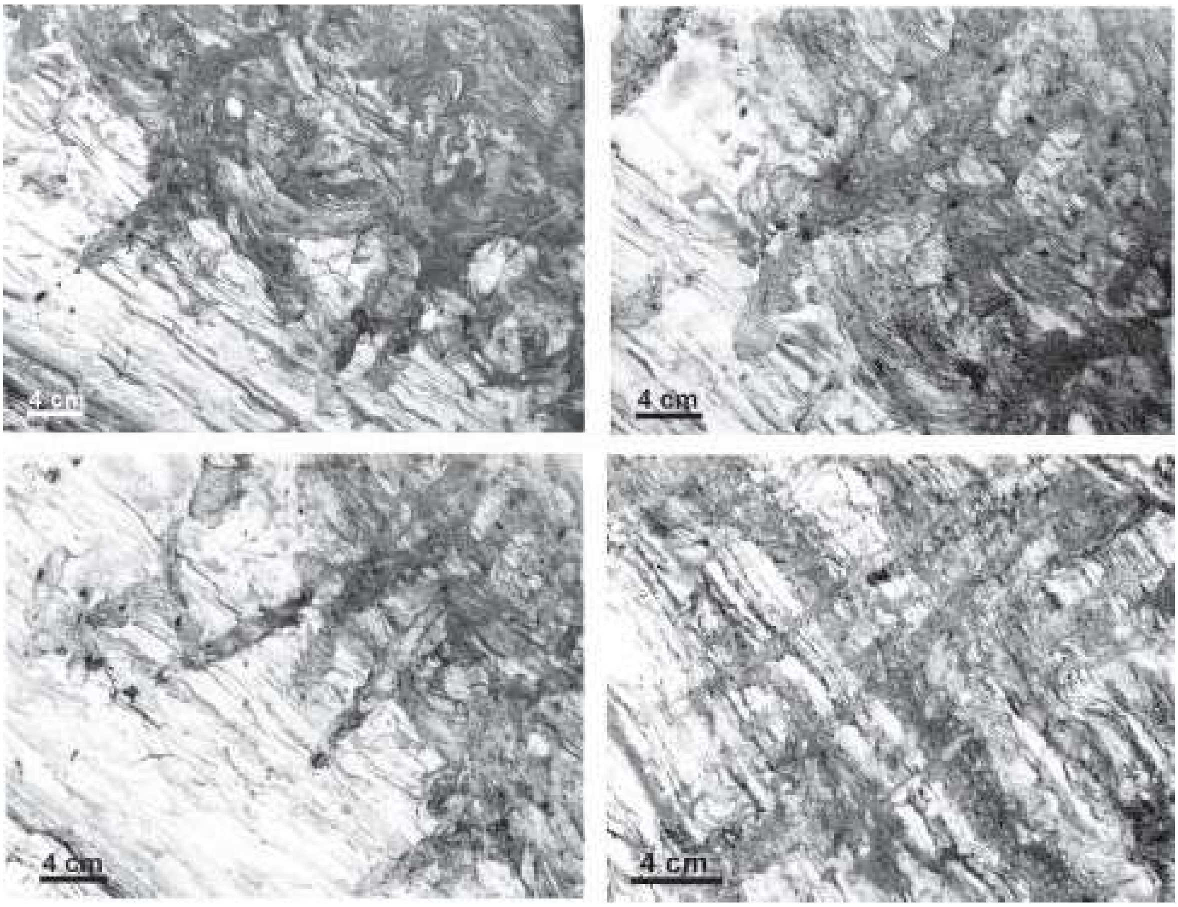


Fig. 8. Four examples of the *Diplocraterion*-root structure ichnofabric from 4.8 m.

cross-sections perpendicular to the limbs, the outline of the spreite is somewhat irregular in most cases. Protrusive, protrusive/retrusive and retrusive spreiten occur, *sensu* Goldring (1962). Intersections are common between the *D. parallelum* individuals where crowded, as is usually the case with this trace fossil (Bromley & Hanken 1991; Goldring *et al.* 1998b).

In Jurassic shallow-marine siliciclastics, *Diplocraterion parallelum* occurs commonly in very shallow subtidal to intertidal facies (e.g. Fürsich 1974b, 1981). In the Jurassic, at least, this trace fossil also characterises transgressive surfaces (e.g. Mason & Christie 1986; Dam 1990b; Taylor & Gawthorpe 1993; Goldring *et al.* 1998b). Horizons rich in *D. parallelum* in the Kimmeridgian of Spain have been used by Olóriz & Rodríguez-Tovar (2000) for the identification of more energetic and physically unstable environments (a transition from the Cruziana ichnofacies to the mixed Cruziana-Skolithos ichnofacies) in relation to sea-level fall, and used to delineate sequence boundaries. In the Upper Jurassic of Portugal, *D. parallelum* chiefly occurs in coarse sands, less commonly in medium sands (Fürsich 1981). Similarly, *D. parallelum* occurs in medium-grained to coarse foreshore sandstones in the Boulonnais region of France (Schlirf 2003). In the Middle Jurassic deposits of Kutchchh, India, *D. parallelum* indicates colonization events in sandy shoals (Fürsich 1998). The Korsodde examples also occur in muddy substrates (Fig. 9), as in the Upper Jurassic of Dorset (Goldring *et al.* 1998a). The absence of a correlation with grainsize presumably reflects the tracemaker having been a suspension-feeder (Fürsich 1974a; 1981). An environment of lowered salinity was implied for *Diplocraterion parallelum* from the Bathonian of Kutchchh, India, on the basis of associated macrofauna (Fürsich *et al.* 1994).

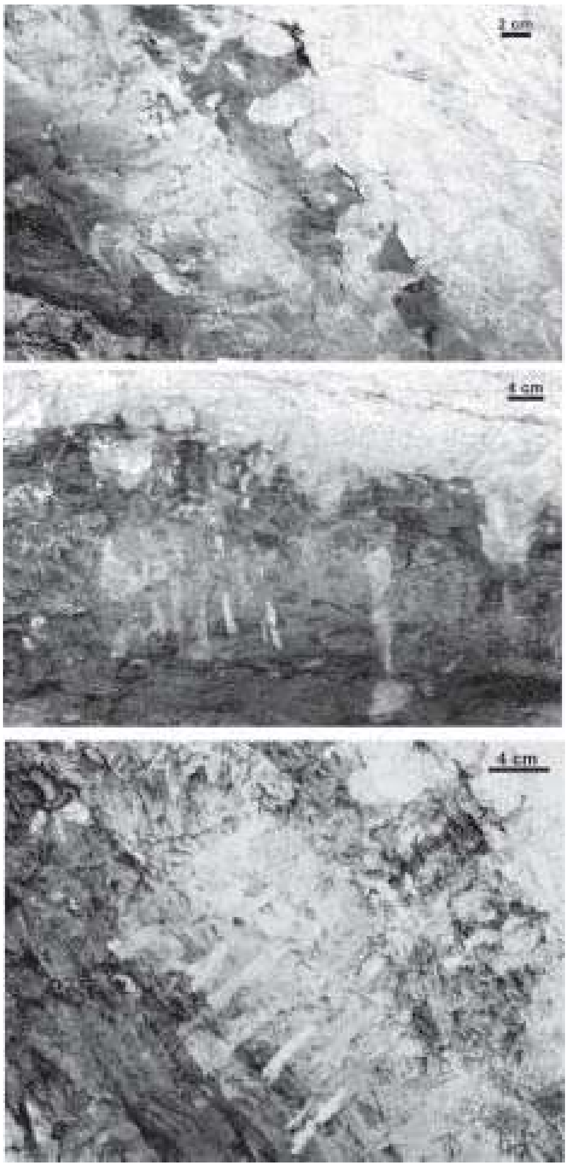


Fig. 9. The lignitic top of the muddy organics-rich bed at 6.9 m has a castellated morphology consisting of small mesas separating depressions. The pale, vertical structures within the mud bed are *Diplocraterion parallelum*. Many of these originate within the depressions.

Palaeophycus isp.

Horizontal or subhorizontal, straight to curved sandy cylinders having a distinct muddy wall. They occur in different size classes, 3, 5 and 10 mm in diameter. The ratio of the diameter of the lumen to the thickness of wall varies between specimens. There are also specimens that have a particularly thick wall. In one case, the lumen was 3 mm in diameter, the wall 2 mm thick; in another, 5 and 3 mm respectively. For discussion of *Palaeophycus* see Pemberton & Frey (1982) and Keighley & Pickerill (1995).

Planolites isp.

Figs 10D, 11A

Horizontal or subhorizontal, straight or curved unlined cylinders, having a different fill lithology from the surrounding sediment. They occur in different sizes from 1 to 15 mm in diameter, but individual size-classes were not separable. *Planolites* (mostly 3–7 mm in diameter) is most abundant (or most conspicuous) within muddy drapes, where they are filled with sand.

Skolithos isp. A

Very narrow, vertical or subvertical, slightly winding unlined shafts filled with mud. These are 1.5 mm in diameter, and as much as 60 mm long.

Skolithos isp. B

Relatively wide, vertical or subvertical, straight or slightly bent and distinctly lined shaft filled with sand. This form is 3–7 mm in diameter, and as much as 60 mm long.

Teichichnus isp.

Fig. 10A

Teichichnus is represented only by a characteristic ichnofabric within a single bed of muddy sandstone in the uppermost part of the section studied. This ichnofabric (IF 5 in this study) is composed of abundant fragments of spreite lamination, produced by the intersection of numerous *Teichichnus*. Similar ichnofabrics composed of *Teichichnus* have been published by Birkelund & Pedersen (1980) and Beynon *et al.* (1988, fig. 7).

?*Thalassinoides* isp.

Fig. 10A

The identification of *Thalassinoides* in vertical cross-section is difficult. The characteristic branching pattern cannot be demonstrated. However, we tentatively refer horizontal or subhorizontal unlined tunnels at several horizons, 5–20 mm in diameter, filled with sand, to this ichnogenus.

At 13.3 m, in association with *Teichichnus*, unquestionable *Thalassinoides* was observed, having dark clay

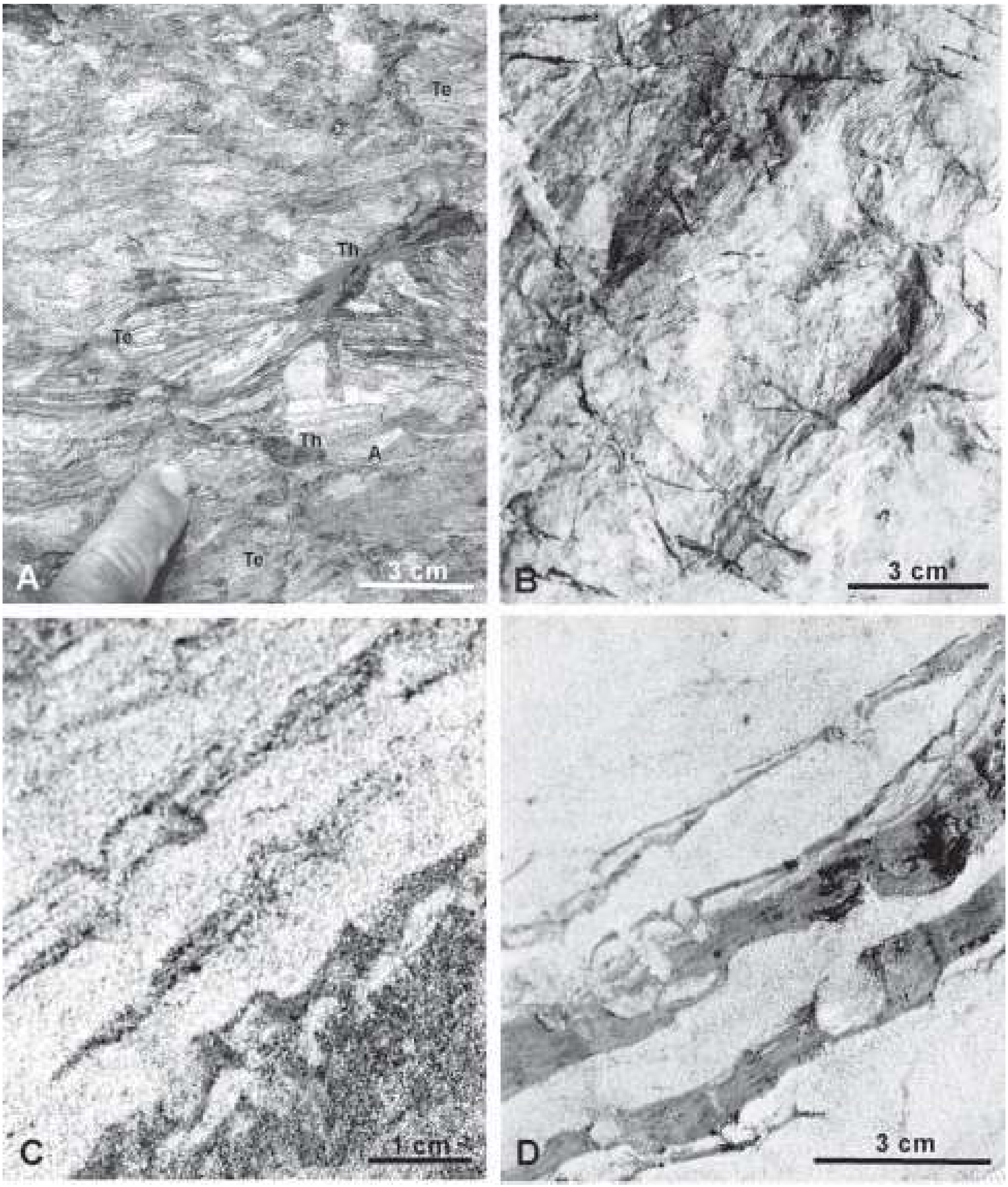
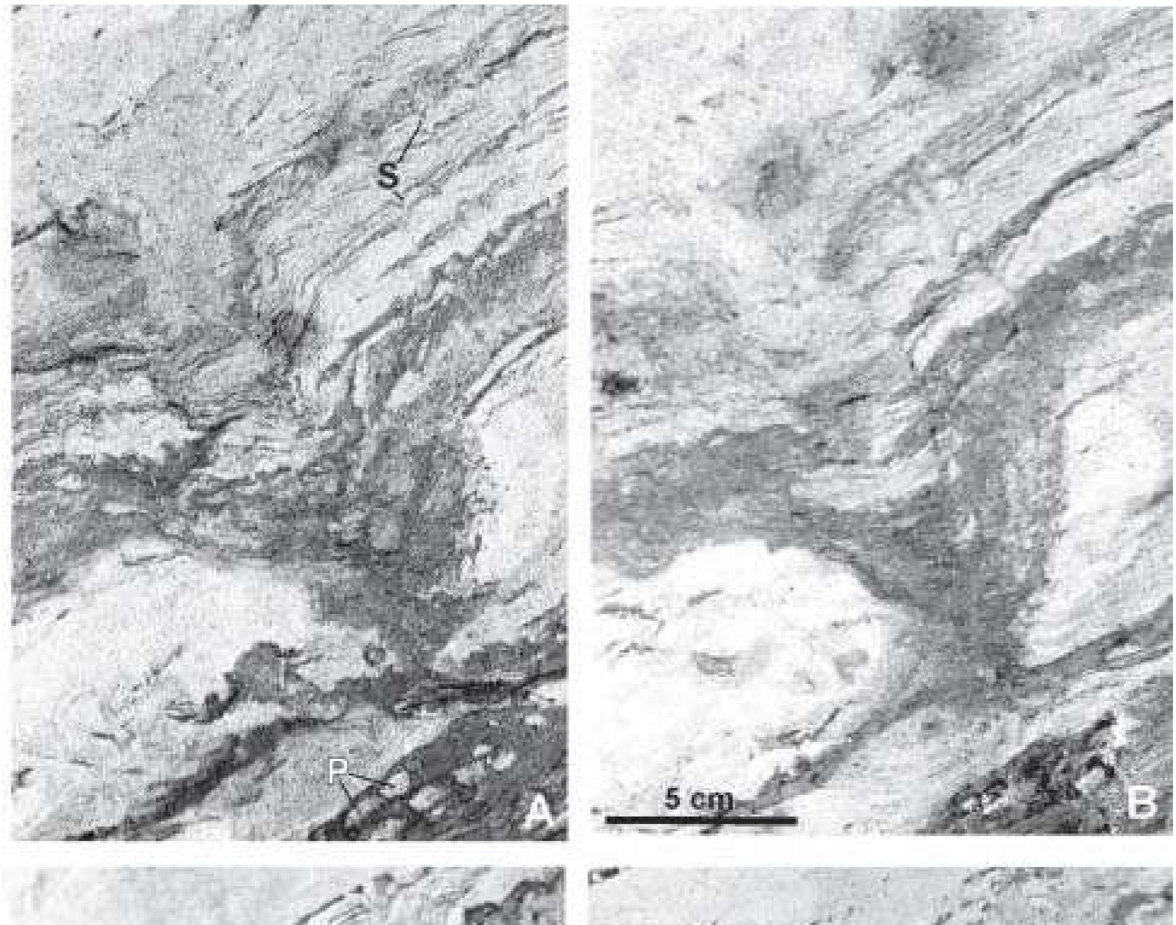


Fig. 10. A, *Teichichnus* dominating the *Teichichnus-Asterosoma* ichnofabric at 14.2 m. *Teichichnus* spreiten occur throughout much of the sediment but are most clearly distinguishable at Te. Dark mud-filled *Thalassinoides* are seen at Th and a part of an *Asterosoma* at A. B, plant root structures cutting poorly visible pale *?Thalassinoides* at 5.2 m. C, small-scale disturbance of laminae at 2.0 m. D, mud drapes penetrated by sand-filled *Planolites* at 13.2 m.

Fig. 11. Plug-shaped equilibrium structures at 12.8 m. Two structures are shown in A–B and C–D respectively, in parallel vertical sections about a centimetre apart. Small, biogenic disturbance structures (S) and *Planolites* (P) are also seen.


S
P
A
5 cm
B
S
C
5 cm
D

fill (Fig. 10A). For discussion of *Thalassinoides* see Frey *et al.* (1984) and Bromley (1996).

J-shaped trace fossil

Vertically oriented J-shaped trace fossil, 7–10 mm in diameter, and up to 7 cm long. It occurs in sand, has a sand filling but is visible because of its ferruginous colouration.

Plug-shaped equilibrium structure

Fig. 11

Vertically-oriented, conical structures, pointed downward centrally and having an irregular margin. The conical angle differs between specimens. The structure is filled with poorly laminated sandy mud that still preserves the texture of the primary lamination. Down-warping of the overlying sediment appears to have taken place. This fill is commonly slightly bioturbated, mostly containing *Planolites*. Laminae of the host sediment are deflected down as they approach the trace fossil. This structure penetrates through several depositional rhythms and therefore shows some vertical repetitions.

The trace fossil is between 7 and 20 cm deep, and 2.5 and 8.5 cm wide at the broadest part of the structure. The repetitions indicate upward adjustment of the tracemaker correlated with depositional increments.

The more conical forms resemble *Conichnus conosinus*, from the Lower Cretaceous of Bornholm (Nielsen *et al.* 1996), but *C. conosinus* is more dish-like in the uppermost part.

Minor disturbance of laminae

Figs 10C, 11

The colour contrast produced by dark and light laminae in heterolithic intervals allows very small biogenic structures to be seen. Many of these are downward warping of laminae, some of them conical in shape, that resemble footprints of epibenthic arthropods (Fig. 10C; Schäfer 1962).

Plant roots

Fig. 10B

Generally vertically oriented, thin, branched tubes, 0.5–2 mm in diameter, filled with carbonized plant material. The central vertical tube is long and straight, and the rare side branches are commonly thinner and short. In most cases, only first-order branches are present. For discussion of root structures, see Bockelie (1994).

Lithological units and ichnofabrics: descriptions and interpretations

Ten lithological units (from A to J) are distinguished. Their metric ranges are shown in Fig. 4. They are described together with their trace fossil content and characteristic ichnofabrics. The latter are considered only where the trace fossil assemblages are sufficiently distinctive and appear to approach discrete communities (ichnocoenoses) rather than community replacement series. The method for ichnofabric definition described by Bromley (1996) is used (Fig. 12). In much of the succession, trace fossils occur too sparsely or sporadically to allow ichnofabrics to be defined.

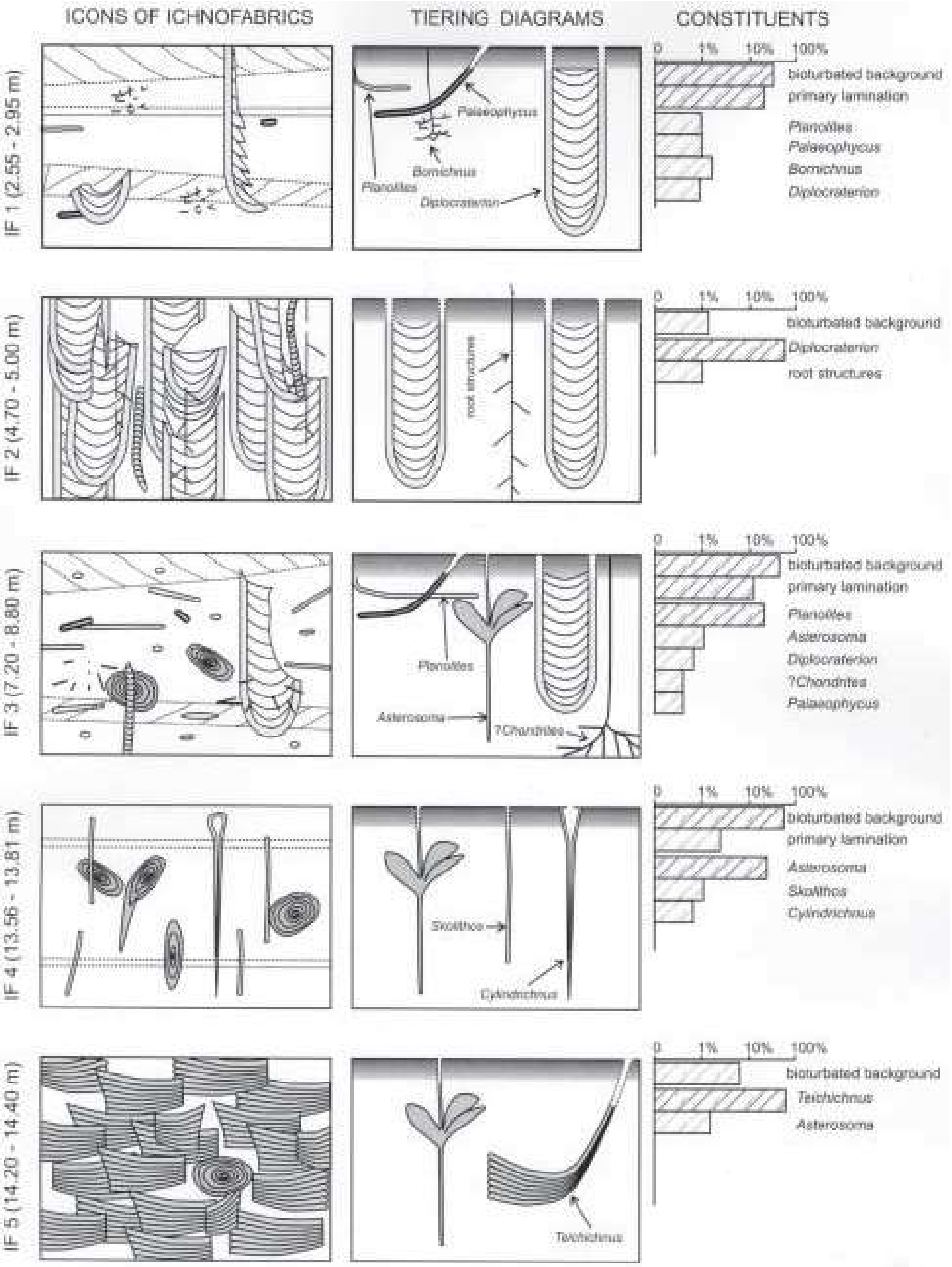
Unit A

Description. Unit A (0.45–2.3 m) is composed of yellow, weakly cemented muscovite quartz sandstone, which is medium- and fine-grained in the lower part, and fine-grained in the upper part. Most beds show current ripple and some herringbone cross lamination, discontinuous dark mudstone drapes, mostly up to 0.5 cm thick (flaser bedding *sensu* Reineck & Wunderlich 1968), and mudstone intraclasts. Ferruginization is common around the mudstones. A thin horizon showing convolute lamination up to 1 cm thick occurs at about 85 cm of the section (Fig. 4). A single minor erosional surface covered with mudstone intraclasts occurs at 1 m. At level 1.65–1.75 m, a layer of heterolithic deposits occurs, composed of alternating laminae of fine-grained, ripple-laminated sandstones and mudstones (wavy bedding *sensu* Reineck & Wunderlich 1968).

Trace fossils are absent in the lower part of unit A and relatively scarce in the remaining part. Only *Planolites* is common in the mudstone drapes, and *Bornichnus* occurs locally in the sandstones in the upper part of the unit. *Asterosoma*, J-shaped trace fossils, and plug-shaped equilibrium structures occur rarely. A single *Diplocraterion* was observed in the heterolithic layer. The degree of bioturbation does not exceed a few percent.

→

Fig. 12. Definition of the 5 ichnofabrics using thumbnail sketches of the fabric (icons), tiering diagrams summarizing the depth of tier of individual ichnotaxa, and the percent of bioturbation at each discernible tier.


ICONS OF ICHNOFABRICS
TIERING DIAGRAMS
CONSTITUENTS
IF 1 (2.55 - 2.95 m)
Palaeophycus
Bornichnus
Planolites
Diplocraterion
0
1%
10%
100%
bioturbated background
primary lamination
Planolites
Palaeophycus
Bornichnus
Diplocraterion
IF 2 (4.70 - 5.00 m)
root structures
0
1%
10%
100%
bioturbated background
Diplocraterion
root structures
IF 3 (7.20 - 8.80 m)
Planolites
Asterosoma
?Chondrites
0
1%
10%
100%
bioturbated background
primary lamination
Planolites
Asterosoma
Diplocraterion
?Chondrites
Palaeophycus
IF 4 (13.56 - 13.81 m)
Skolithos
Cylindrichnus
0
1%
10%
100%
bioturbated background
primary lamination
Asterosoma
Skolithos
Cylindrichnus
IF 5 (14.20 - 14.40 m)
Teichichnus
0
1%
10%
100%
bioturbated background
Teichichnus
Asterosoma

Interpretation. Unit A is interpreted as estuarine channel fill (Michelsen *et al.* 2003). The thin layer of heteroliths may represent deposits of a short-lived upper tidal flat. Ripple cross-bedded sandstones and common mudstone drapes indicate low-energy current deposition interrupted by slack-water deposition. The currents were capable of eroding mud drapes as indicated by the presence of intraclasts. Herringbone laminations suggest bidirectional flow related to tidal currents. All these features allow us to interpret unit A as the upper or marginal, less energetic part of an estuarine channel fill.

Low diversity of trace fossils and low degree of bioturbation indicate strong environmental stress, which may be related to low salinity, probably in the upper part of an estuary.

Unit B

Description. Unit B (2.3–3.41 m) is a heterolith composed of intercalations of thin layers of yellow fine-grained muscovite quartz sandstones and dark mudstone drapes. The sandstone layers are lenticular in vertical section, and up to 3 cm thick, and the mudstone drapes are 0.5 cm thick (wavy lamination). Some sandstones layers display ripple cross lamination and rarely herringbone lamination. The former is emphasized by the mudstone drapes. Most of the mudstone drapes are composed of few, very thin laminae separated by thicker, coarser, mainly silty laminae. Ferruginous cementation is common around the mudstone drapes. A layer of muddy sand 6 cm thick occurs at the top of unit B. It represents a transition to the overlying unit C.

Planolites is common in the mudstone drapes, and *Bornichnus* in the sandstones. *Diplocraterion* cross-cuts sandstone and mudstone layers. It is most abundant at the top of the unit. *Palaeophycus* occurs locally. *Asterosoma* was found in the lower part of the unit. A *Bornichnus-Diplocraterion* ichnofabric (IF 1) is defined in the middle part of unit B (Figs 4, 12). It represents a low bioturbation index (BI = 1 or less than 10%).

Interpretation. Unit B is interpreted as upper tidal flat deposits surrounding an estuary. It overlies unit A (estuarine channel deposits) without a break in sedimentation. Heterolithic deposits containing a high contribution of mudstones, common current ripples and herringbone lamination, are typical of the upper tidal flat (e.g. Reineck & Singh 1980).

The trace fossil assemblage contains vertical forms referred to suspension feeding (*Diplocraterion*) or deposit feeding (*Asterosoma*) and various horizontal forms (*Planolites*, *Bornichnus, Palaeophycus*). It can be determined as the impoverished mixed Skolithos-Cruziana ichnofacies, which is typical of tidal flats (Ekdale *et al.* 1984, p. 179).

Unit C

Description. Unit C (3.41–3.7 m) consists of two layers: 20 cm thick, horizontally laminated dark mudstone with very thin silty laminae, and dark heteroliths, 9 cm thick, dominated by dark mudstones intercalated with ripple-laminated siltstone.

Planolites is more common in the heteroliths than in the mudstones. Rare *Diplocraterion* occurs only in the heteroliths. Degree of bioturbation in the mudstones is no more than 1%. It increases slightly in the heteroliths.

Interpretation. This unit is interpreted as a restricted bay passing into upper tidal flat deposits. The laminated mudstone suggests a low energy environment, while feeble, shallow-tier bioturbation (*Planolites* only), together with the dark colour of the sediments may witness low oxygenation. The layer of mud-dominated heteroliths containing *Diplocraterion* and abundant *Planolites* is typical of the upper tidal flat.

Unit D

Description. Unit D (3.7–4.7 m) consists of fine-grained, yellowish, muscovite-rich quartz sandstone beds, up to 10 cm thick, interbedded by continuous and discontinuous dark, organics-rich, composite mudstone drapes, up to 1 cm thick (flaser to wavy lamination). The sandstones display ripple cross lamination. Small pyrite concretions are present in the lower part.

Planolites is present in mudstone drapes, whereas *Palaeophycus*, *Bornichnus*, and root structures occur in the upper part of the unit. *Diplocraterion* is rare in the middle part of the unit, and it becomes common at the top, where it penetrates the top 20 cm from the overlying unit. No more than 1% of the lower part of unit D is bioturbated. In the upper part, the degree of bioturbation increases gradually up to about 10%.

Interpretation. Unit D is dominated by rippled sandstones and probably represents a lower tidal flat within an estuary. *Diplocraterion*, *Palaeophycus* and *Planolites* can be ascribed to impoverished Skolithos-Cruziana ichnofacies, typical of tidal flats. The colonization surface for the roots and abundant *Diplocraterion*, which descend from the top of the unit, is located within the overlying unit E. Nevertheless, the presence of roots in unit D indicates the proximity of a terrestrial environment.

Unit E

Description. Unit E (4.7–6.9 m) is composed mostly of very variable organics-rich fine-grained sediments. A 55 cm thick muddy sandstone to sandy siltstone occurs at the base. It is dark in the lower and middle parts and light-coloured in the upper part. The sandstone is capped by a dark mudstone bed 5 cm thick, which is followed by three thin and uneven layers of fine-grained sandstones (2, 1 and 3 cm thick, respectively) interbedded with dark siltstone-mudstone. The uppermost sandstone layer contains ripple cross-lamination and scarce pyrite concretions. Above this occurs an indistinctly laminated, dark sandy mudstone containing transported *Neocalamites* stems, 15 cm thick, followed by a massive coal layer of similar thickness containing horizontal, somewhat co-oriented *Neocalamites* stems. Pyrite concretions are common at the top of the coal.

This is overlain by a dark, massive mudstone (15 cm). It is followed by two very thin, fine-grained sandstone layers intercalated with dark sandy mudstones (17 cm), and this is overlain in turn by a medium-grained, poorly sorted, yellow, ferruginous, massive sandstone layer, 5 cm thick, having an uneven base, and containing pyrite concretions. The top 85 cm of Unit E are composed of dark mudstones containing allochthonous *Neocalamites* stems and lignite clasts, especially in the middle part, where they form a layer a few centimetres thick. Below this layer, the mudstone is laminated, becoming massive above. An erosion surface is present at the top.

The muddy sandstone at the base of the unit contains, in its lower part, only root structures and abundant *Diplocraterion parallelum*. Accordingly, a *Diplocraterion*-root structure ichnofabric (IF 2) has been defined on the basis of sediments from 4.7–5.0 m above the base (Figs 4, 12). Degree of bioturbation is high (BI = 4–5 or about 90%, locally 100%). *Planolites* and ?*Thalassinoides* are present in the upper part of this sandstone. Above, root structures occur everywhere except in the coal and the overlying mudstone layer. Above the sandstone at the base, the degree of bioturbation drops markedly, although it should be noted that it is difficult to estimate bioturbation in the mudstones and coal. *Planolites* is present in the first mudstone bed, and ?*Thalassinoides* below the medium-grained sandstone beds just below the 6 m level. The top of the unit is penetrated as far as 30 cm by sand-filled *Diplocraterion parallelum* from the overlying erosional surface bounding the unit.

Interpretation. Michelsen *et al.* (2003) proposed a generally lagoonal environment above a coal bed, which is specified in greater detail in this paper. The lowermost part of the unit probably represents deposition within a shallow bay. The overlying mudstone and coal probably represent a marsh environment whereas the organics-rich mudstones could have been deposited in a low-energy lake or lagoon. The common root structures in the mudstones indicate a subsequent terrestrial or semiaquatic environment, the sediments of which were eroded at the base of unit F, where remnants of a lignite layer occur. The isolated sandstone beds (5.85–6.05 m) may be fluvial sediments related to floods.

The bay sediments at the base containing abundant *Diplocraterion* display ichnofabric IF 2. Proximity of terrestrial environments is indicated by the root structures, which cross-cut *Diplocraterion*. This trace fossil was formed rather in the upper intertidal zone in an organics-rich environment. Ichnofabric IF2 corresponds to the subfacies B3 of Ahlberg (1990) from the Lower Jurassic deposits between Sweden and Denmark in the Helsingborg region, which were referred to supratidal palaeosol sediments, but *Diplocraterion* could have been produced prior to the formation of soil, in the intertidal zone, as in Bornholm.

?*Thalassinoides*, *Planolites* and roots were found in the marsh sediments. ?*Thalassinoides* disappears first, then *Planolites* and, finally, roots become more abundant. ?*Thalassinoides* was probably produced by crustaceans and *Planolites* by polychaetes, which are common in the Holocene and recent marshes along the Georgia coasts (Edwards & Frey 1977; Frey & Basan 1981).

The lake or lagoon mudstones are not laminated. This can indicate that they are totally bioturbated, but ichnofabric is not preserved owing to low sediment cohesion. Total bioturbation, on the other hand, would indicate an oxygenated environment.

Unit F

Description. Unit F (6.9–9.9 m) is composed of pale, fine-grained, muddy sandstone beds and pale, fine-grained sandstones, mostly 20–30 cm thick, separated by thin (up to 8 cm) layers of pale, sandy mudstones or thin mudstone drapes (flaser bedding). Ripple cross lamination is common and locally, sparse pyrite concretions and lignite clasts occur in the sandstones. Synaeresis cracks were noted at levels 8.15 m and 8.75 cm. Ferruginization is common, especially at the top of the unit.

Planolites is the commonest trace fossil, occurring in all lithologies of the unit, but especially in the mudstones. *Diplocraterion* is also common and the most eye-catching trace fossil. At the base, *Diplocraterion parallelum* penetrates downward from the erosional pot-like depressions excavated in the organic mud.

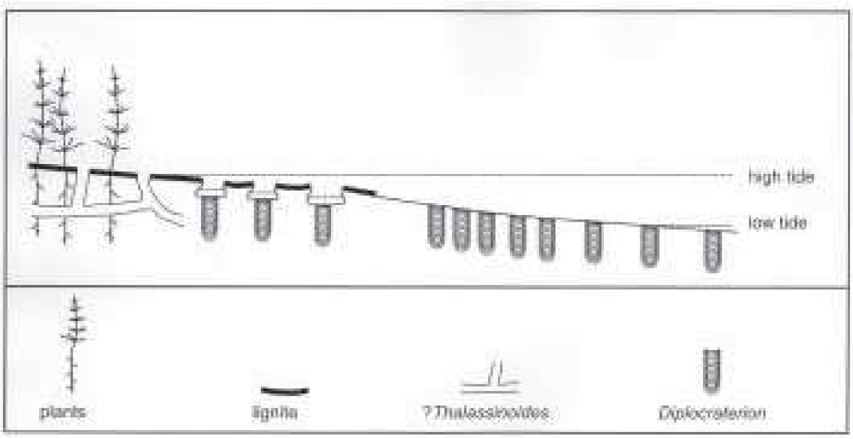


Fig. 13. Distribution of root structures, ?*Thalassinoides* isp. and *Diplocraterion parallelum* in the transition from marsh to upper tidal flat environments.

These depressions have overhanging walls and flat floors and are up to 5 cm deep (Fig. 9). The small mushroom-like or crest-like mesas between the depressions are capped by a lignite layer.

Asterosoma, ?*Chondrites* and *Palaeophycus* occur locally, and ?*Thalassinoides* is present about 50 cm below the top of the unit. The first 30 cm of the unit is totally bioturbated. Above this, the degree of bioturbation in sandstones oscillates around 30% but drops markedly in some mudstone layers. A *Diplocraterion-Planolites* ichnofabric (IF 3) was defined in the interval between 7.2 and 8.8 m (Figs 4, 12). Diversity rises here to 5 ichnotaxa while the degree of bioturbation is about 20–50% (BI = 2–4), corresponding to the abundance of *Planolites*.

Interpretation. Unit F represents relatively low-energy current sedimentation interrupted by deposition of muds in slack water conditions. The unit may be interpreted as lower tidal flat deposits in an estuary. Synaeresis cracks suggest changes of salinity.

The uneven surface at the base (Fig. 9) is probably a local transgression surface between a swamp and a lower tidal flat. The pot-like depressions can be the washed-out bases of older *D. parallelum* possibly produced on an eroded upper tidal flat. (Some of these depressions are broader than wide but these did not appear to be dinosaur footprints.) The producer of *Diplocraterion parallelum* was probably able to survive during low tides because of the retention of seawater within the depressions (Fig. 13).

The trace fossil assemblage once more contains vertical forms referred to suspension feeding (*Diplocraterion*) or deposit feeding (*Asterosoma*) and various horizontal forms (*Planolites*, *Palaeophycus*). This can be determined as the impoverished, mixed Skolithos-Cruziana ichnofacies, which is typical of tidal flats (Ekdale *et al.* 1984, p. 179).

Unit G

Description. The base of Unit G (9.9–11.35 m) is an erosional surface. It is composed of yellow, muscovite-quartz medium-grained (basal 20 cm) grading upward into fine-grained sandstones. These are cross laminated at the base and show indistinct current ripple cross lamination in the remaining part of the unit. Thin, organics-rich laminae locally emphasize the cross bedding. Pyrite concretions occur above the base. Neither trace fossils nor bioturbation occur in this unit.

Interpretation. This unit is interpreted as fluvial deposits (Michelsen *et al.* 2003). Its middle and upper part with ripple cross lamination was deposited by relatively stable lower energy currents. It is possible that it represents an estuarine bar.

Unit H

Description. Unit H (11.35–14.2 m) consists of pale, fine-grained sandstone beds and pale, fine-grained muddy sandstones, mostly 20–40 cm thick. These are separated by thin layers of pale, sandy mudstones up to 3 cm thick or mudstone drapes up to 2 cm thick. Layers of mudstone-sandstone heteroliths that are 10–15 cm thick (flaser bedding) also occur. Some of the beds change thickness within a distance of 1–2 m. Most of the sandstone beds display ripple cross lamination and rare lignite clasts. Herringbone lamination occurs at level 12.1 m. Some of the laminae are rich in organic matter. Ferruginization is common around the mudstones.

Trace fossil distribution in unit H is variable. *Planolites* is abundant, especially in the heteroliths. *Diplocraterion*, well-developed plug-shaped equilibrium structures, *Skolithos*, *Palaeophycus*, *Cylindrichnus* and *Asterosoma* are also present. An *Asterosoma-Cylindrichnus* ichnofabric (IF 4) is present around 13.6 m above base of the section (Figs 4, 12). The degree of bioturbation varies from bed to bed from 0% to 30%, but the appearance of abundant *Asterosoma* in IF4 increases the degree of bioturbation to about 40% (BI = 3).

Interpretation. Unit H probably represents a marginal part of an estuary channel fill. The heterolithic beds may have been deposited on short-lived tidal flats at the margin of a migrating channel. This interpretation corresponds well with the underlying fluvial or estuarine bar sediments of unit G.

The trace fossil assemblage contains vertical forms referred to suspension-feeding (*Diplocraterion, Skolithos,* and possibly *Cylindrichnus*) or deposit feeding (*Asterosoma*), as well as variable horizontal forms (*Planolites*, *Palaeophycus*). It can be determined as the mixed Skolithos-Cruziana ichnofacies, which is typical of tidal flats.

Units I and J

Description. Unit I (14.2–14.4 m) is a layer of totally bioturbated muddy sandstone. It contains abundant *Teichichnus*, together with rare *Asterosoma, Planolites* and *Palaeophycus.* The *Teichichnus-Asterosoma* ichnofabric (IF 5) is defined here. Small *Teichichnus* account for some 40% of the bioturbation, cross-cutting sparse *Asterosoma*. Locally, *Thalassinoides* occurs, filled with dark mud (Fig. 10A).

Unit J (14.4–14.7 m) is a dark, massive siltstone passing upward into plastic mudstone containing *Neocalamites* logs. The siltstone is totally bioturbated in the lower part and probably also in the upper part.

Interpretation. These units may represent a short-lived bay or lagoon. The ichnofabric IF 5 is comparable to a fabric termed *Teichichnus zigzag* ichnofabric by Martin & Pollard (1996). However, it should be pointed out that, while the fabric may present a zigzag appearance, the trace fossil *T. zigzag* is not present. *T. zigzag* has a broad spreite produced by lateral migrations of the causative burrow (Frey & Bromley 1985) and is easily distinguished from the present fabric. IF 5 is also comparable with a fabric defined by Nielsen *et al.* (1996) containing small *Teichichnus* in a restricted coastal lagoon environment in the Lower Cretaceous of Bornholm.

In particular, however, the *Teichichnus-Asterosoma* ichnofabric appears to resemble the *Asterosoma* ichnofabric of Howell *et al.* (1996), in which *Asterosoma* is associated with small *Teichichnus* in an overall low diversity. This combination was considered to represent a restricted, nearshore setting. The similarity is increased by the close proximity of the *Asterosoma*-dominated ichnofabric (IF 4) in the studied section.

The presence of *Teichichnus,* which normally is a deeper-water form, in lagoonal settings was observed by Fürsich (1981) in the Upper Jurassic of Portugal, Nielsen *et al.* (1996) in Lower Cretaceous of Bornholm, and Petersen *et al.* (1998) in the Middle Jurassic of the Danish Central Graben, North Sea. Also Pemberton *et al.* (2001, p. 324) indicated that *Teichichnus* is common in "lagoon/bay facies characterized by brackish-water".

Above 14.7 m no trace fossils were found, indicating that these sediments are non-marine.

Distribution of trace fossils

The distribution of the trace fossils and degree of bioturbation are summarized in Figure 4. *Bornichnus* occurs only in the lowest part of the section, interpreted as a tidal flat deposit. It does not occur higher in the section, even though lithologically similar sediments are present.

Diplocraterion parallelum occurs at several horizons and in different densities. It penetrates a wide variety of different substrates, from pale-coloured sands to organics-rich mudstones. It is a dominant component of ichnofabrics in the middle part of the section.

Through most of the section, *Asterosoma* is rare and its occurrences are scattered. It occurs abundantly at one horizon only, in the uppermost part of the section, above which *Skolithos* isp. A and *Cylindrichnus* isp. occur. *Planolites* occurs throughout the section, but varies in abundance. It is especially common in some sets of mudstone drapes. ?*Thalassinoides* appears in dark sandy mudstones with roots, interpreted as marsh deposits. The plug-shaped equilibrium structures occur in the uppermost part of the section. *Teichichnus* occurs only at the top of the section in totally bioturbated sandy mudstones, together with unquestioned *Thalassinoides*. The remaining trace fossils do not appear to show any characteristic distribution.

A few cross-cutting relationships were observed. *Diplocraterion parallelum* cross-cuts *Bornichnus tortuosus*. It also cross-cuts roots, but reverse situations occur. Roots penetrate also into the fill of ?*Thalassinoides*. *Planolites* cross-cuts the plug-shaped equilibrium structures. *Asterosoma* is cross-cut by *Cylindrichnus*. It cannot be demonstrated whether the cross-cutting relationships resulted from within-community tiering or by community replacement, although the latter is probably the more likely.

The degree of bioturbation varies from place to place, ranging from unbioturbated sediments to totally bioturbated sediments. The intensity of bioturbation in individual beds probably was controlled by several factors, and was not simply related to substrate. It is possible that salinity changes considerably influenced biological reworking of the sediment. Diversity of trace fossils is very low in the upper part of the marginal-marine section (Fig. 4), above the section illustrated in Figure 3, which is probably related to possible back-barrier environments. Degree of bioturbation is very low there, and trace fossils are represented mainly by *Planolites*.

Discussion

Most of the described trace fossils are common in fossil tidal flats of different ages. These trace fossils are produced by non-vagile suspension-feeders (e.g. *Diplocraterion, Skolithos*) and deposit-feeders (e.g. *Asterosoma*). Vagile deposit-feeders are represented mainly by *Planolites*. Plug-shaped equilibrium structures and *Palaeophycus* possibly were produced by carnivores. It is possible that *Bornichnus* is a gardening structure.

Diplocraterion parallelum is generally considered a result of initial colonization of flooding surfaces (e.g. Fürsich 1975; Dam 1990a; Goldring *et al.* 1998b). Dam (1990b) emphasized the depositional hiatus at *Diplocraterion parallelum* events, and the presence of coal at these transgressive surfaces.

The presence of *Asterosoma* in such a proximal setting is interesting, as this ichnogenus is typically considered as a classic open-marine shelf form (e.g. Pemberton *et al.* 1992). However, in the present case this interpretation does not fit the model. Our highly dominant occurrence of *Asterosoma* in association with very small *Teichichnus* (IF 4 and IF 5) has a close similarity with an occurrence in the North Sea Upper Jurassic Humber Group, where Howell *et al.* (1996) interpreted this association as related to a restricted setting adjacent to environments of decreased salinity (Bromley 1993 unpublished, in Howell 1996). Fürsich (1975) also noted a twofold occurrence of *Asterosoma* in the Upper Jurassic, both in the lower intertidal and in the shoreface.

Generally, the trace fossil assemblage can be determined as the mixed Skolithos-Cruziana ichnofacies, which is typical of tidal flats (Ekdale *et al.* 1984, p. 179). However, absence of *Ophiomorpha* is remarkable, especially in the more sandy deposits. Moreover, a dominance of deposit-feeders would be expected in the muddy tidal flat sediments. The reduced abundance of such trace fossils, therefore, may be connected with brackish waters in the deltaic environment proposed for the Sorthat Formation. For the same reason, but also because of coastal proximity, the fully marine Jurassic deposit-feeder trace fossils such as *Rhizocorallium irregulare, Phoebichnus trochoides, Gyrochorte comosa, Phycosiphon incertum* and *Phycodes bromleyi* all are unrepresented. Indeed, the low diversity itself is probably indicative of lowered salinity levels in the coastal area (e.g. Dam 1990b; Pemberton & Wightman 1992; Howell *et al.* 1996).

Diplocraterion occurs in the upper tidal flat up to the range of high tides, as indicated by the association with small pools in depressions (Figs 9, 13). ?*Thalassinoides*, *Planolites* and roots were found in the lower marsh. In the higher marsh ?*Thalassinoides* disappears first, then *Planolites* and, finally, roots became more abundant. Horizons yielding allochthonous *Neocalamites* stems are present in the upper marsh. ?*Thalassinoides* was probably produced by crustaceans and *Planolites* by polychaetes, which are common in the Holocene and recent marshes along the Georgia coasts (Edwards & Frey 1977; Frey & Basan 1981).

Above 14.7 m, Michelsen *et al.* (2003) suggest that the sediments represent shoreface to offshore transition environments. However, the complete lack of bioturbation of these deposits does not support this interpretation. The sediments above this level are considered fluviatile and lacustrine.

The ichnofacies problem

Ichnoassemblages containing horizontal trace fossils related to deposit feeding, and vertical forms related to suspension feeding are generally considered as representing a mixed Skolithos-Cruziana ichnofacies, or proximal Cruziana ichnofacies (e.g. Ekdale *et al.* 1984). The studied ichnoassemblage shows these features. According to the classical scheme of ichnofacies (Seilacher 1967; Frey & Seilacher 1980; Pemberton *et al.* 1992), the bathymetric range of the Cruziana ichnofacies is from reserved fair weather wave base to storm wave base. The Korsodde assemblage is mostly from intertidal to supratidal settings, locally subtidal.

Occurrence of the mixed Skolithos-Cruziana ichnofacies in tidal flats was reported by Ekdale *et al.* (1984, p. 179). These authors ascribed the elements of the Skolithos ichnofacies to sand flats and tidal channels, and the elements of the Cruziana ichnofacies to mixed sand mud or mud flats. Occurrence of the Skolithos ichnofacies in sand waves and the Cruziana ichnofacies from intertidal mixed sandy mud deposits has been well documented for the Lower Palaeozoic (e.g. Bjerstedt & Erickson 1989; Mángano *et al.* 1996; Mángano & Buatois 1998; Astini 2001). Younger examples are not obvious, but the present example establishes a similar situation from the Jurassic period.

Within single horizons in the studied section it is possible to distinguish examples of the Skolithos and Cruziana ichnofacies respectively. For instance, IF5, dominated by *Teichichnus,* represents the Cruziana ichnofacies, and IF4 generally indicates the Skolithos ichnofacies. The problem of distinguishing ichnofacies depends on the scale of observation, i.e. at the scale of individual beds or larger units. Both scales of observation have their value; certainly for high-resolution studies, consideration of ichnofacies relationships at bed scale is necessary. Occurrence of the mixed Skolithos-Cruziana ichnofacies at the scale of a single bed can result from community replacement. For example, IF3 has features that suggest a replacemnt of Cruziana ichnofacies forms by Skolithos ichnofacies trace fossils.

Conclusions

1. The ichnology of a trace-fossil-rich interval is described within the Sorthat Formation (Lower – Middle Jurassic) of Bornholm. The trace-fossiliferous interval indicates a marine incursion within a succession that was dominantly deposited in a fluvial deltaic environment.
2. The following 15 ichnotaxa were found: root structures, *Diplocraterion parallelum*, *Asterosoma* isp., *Thalassinoides* isp., *Planolites* isp., *Palaeophycus* isp., *Cylindrichnus* isp., *Skolithos* isp. A., *Skolithos* isp. B, *Bornichnus tortuosus*, J-shaped trace fossils, *Teichichnus* isp., ?*Chondrites* isp., a plug-shaped equilibrium structure, and a conical structure.
3. Degrees of bioturbation and ichnodiversity are generally low.
4. At the most suitable horizons, where the assemblages appear to represent ichnocoenoses, five ichnofabrics have been defined. These are (1) *Bornichnus-Diplocraterion* ichnofabric, (2) *Diplocraterion*-root structures ichnofabric, (3) *Diplocraterion-Planolites* ichnofabric, (4) *Asterosoma-Cylindrichnus* ichnofabric and (5) *Teichichnus-Asterosoma* ichnofabric.
5. Although several ichnotaxa present have been recognized in lower shoreface and offshore settings, the low diversity and degree of bioturbation indicate a nearshore restricted environment. The presence of a coal and root bed within the succession supports this interpretation and further support is to be had from the literature.
6. A new ichnotaxon, *Bornichnus tortuosus* nov. igen. et isp., is erected.
7. The studied ichnoassemblage represents impoverished, mixed Skolithos-Cruziana ichnofacies. Occurrence of such a mixed ichnofacies has been characteristic of intertidal deposits since the Lower Palaeozoic. In most cases it is possible to distinguish between ichnofacies within a single bed (assemblage). Mixed assemblages at some horizons can be the result of community replacement.

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Dansk sammendrag

Sporfossiler i Sorthat Formationen (Nedre – Mellem Jura) på Bornholm, afslører et marint indslag indenfor en lagserie, der ellers er domineret af fluviatile aflejringer. Sporfossilet *Diplocraterion parallelum* har længe været kendt i blotningen ved Korsodde på øens sydkyst. Et nærmere studium af dette interval har afsløret tilstedeværelsen af 15 ichnotaxa med *Bornichnus tortuosus* nov. igen. et isp. som nyt sporfossil. Flere af disse sporfossiler (f. eks. *Teichichnus* og *Asterosoma*) menes at karakterisere ydre strandplan- og shelfmiljøer. Den lave bioturbationsgrad og ichnodiversitet i det undersøgte interval indikerer imidlertid et kystnært 'restricted' aflejringsmiljø påvirket af salinitetsændringer. Fem ichnofabric typer optræder i intervallet og disse vil muligvis vise sig at være indikative for kystnære 'restricted' aflejringsmiljøer.

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