# The Miocene Hagenør-Børup sequence at Lillebælt (Denmark): its biogenic structures and depositional environment

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The paper presents the results of chemical, mineralogical and trace-fossil analyses of the lower Miocene sequence exposed at Hagenør and Brørup at the Lillebælt Coast in southern Jylland, Denmark. The section comprises a 20 m thick series of clastic deposits that is subdivided into 6 units that vary in lithology and sedimentary structures, both physical and biogenic. The major biogenic structures are burrows that are attributable to the life activity of sea anemones, polychaetes, echiuroids, ?haustoriid amphipods, callianassid decapods, gastropods, pelecypods, holothurians and echinoids. The investigated ichnocoenose reflects a diversified pattern of bottom consistency and hydrodynamic conditions that prevailed in the eastern part of the Miocene North Sea. The sedimentary environment in this area was highly comparable to that of some regions of the present-day North Sea.

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Exposures in the cliff sections at Hagenør and Børup in Jylland along the Lillebælt Coast (fig. 1) have been examined as part of investigations of Neogene deposits being carried out by the Department of Exogene Geology, University of Aarhus. The investigation of the Børup exposure was initiated as a sedimentological training project. This preliminary work has been followed up by a more detailed study of both the Hagenør and the Børup exposures.

The Hagenør exposure has not previously been mentioned in the literature. The geological map-sheet of the Fredericia area (Nordmann 1958) shows the existence of a Tertiary sequence at Børup without describing it, and it has been briefly mentioned by Sorgenfrei (1961), Andersen (1973) and Friis (1973).

## Description of localities

The localities are situated at the eastern limit of preserved Neogene deposits in Denmark (fig. 1). The distance from Hagenør to Børup is approximately 1.2 km. The two sections overlap stratigraphically, Børup representing a well

exposed lower part, while at Hagenør younger sediments are preserved (fig. 2).

According to Sorgenfrei (1949, 1951), a local doming of the pre-Quaternary deposits occurs at Hindsgavl (fig. 2) exposing Upper Oli-
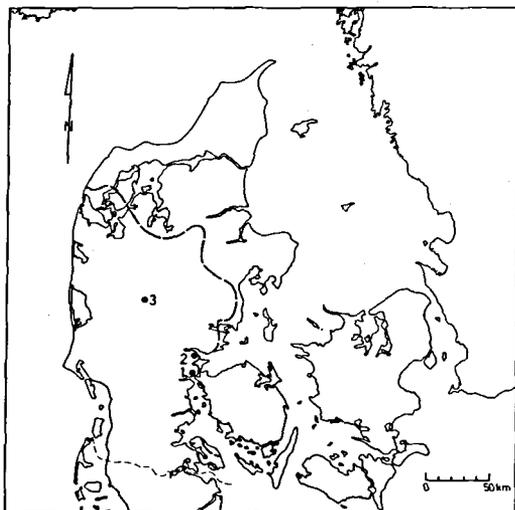


Fig. 1. Location map. 1: Hagenør-Børup, 2: Brejning, 3: Søby-Fasterholt. (Dotted line indicates eastern limit of preserved Miocene deposits according to Sorgenfrei 1954).
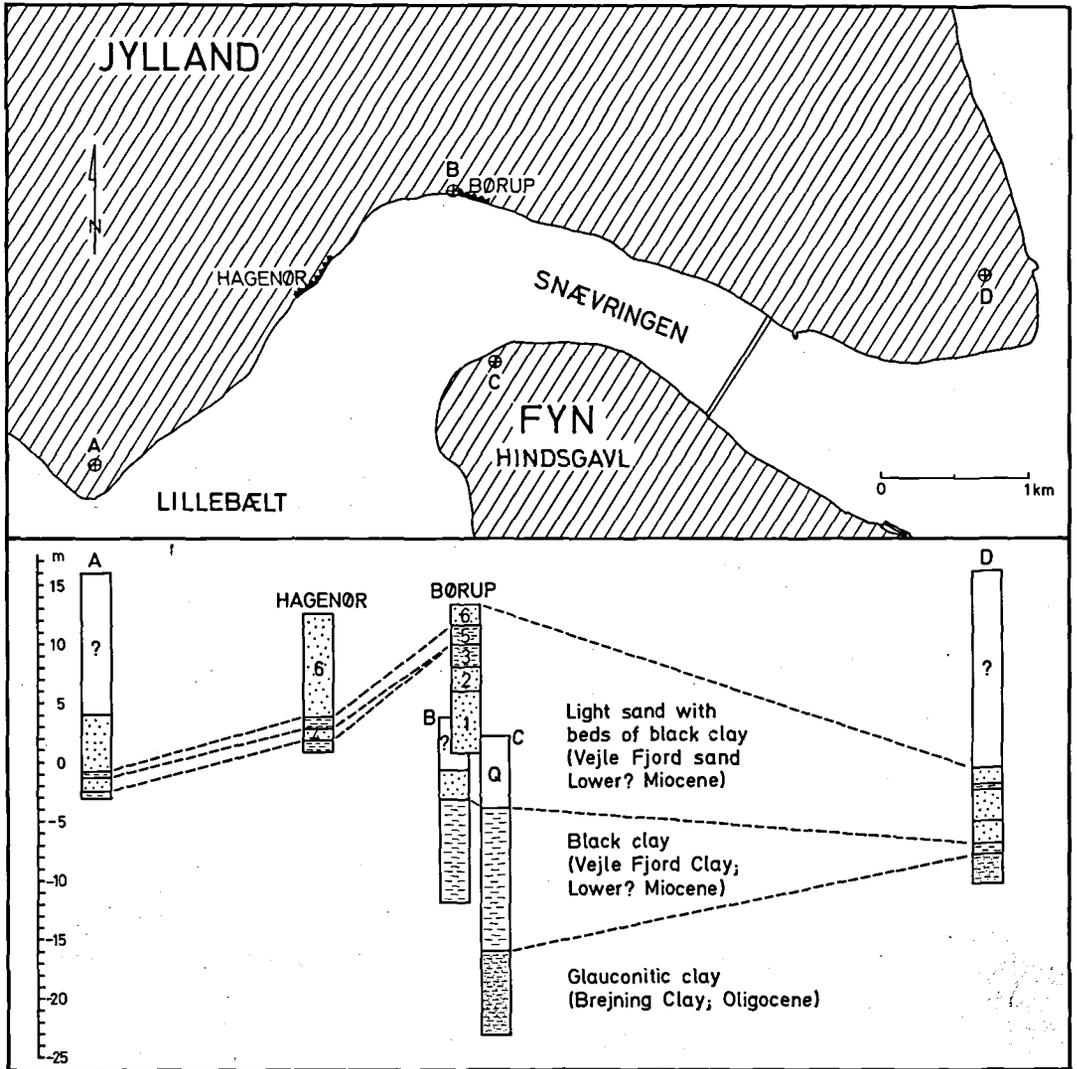
Fig. 2. Sketchmap of the Hagenør-Børup area and lithological correlation of exposures and borings A (D.G.U. file no. 134–599), B (D.G.U. file no. 134– 207), C (D.G.U. file no. 134–226) and D (D.G.U. file no. 134–224).

gocene glauconitic clays at the southern coast of the Hindsgavl peninsula. The examined exposures are situated on the NW side of this dome, and it is supposed that the sequence represents a part of the Lower Miocene. This suggestion has not yet been confirmed by biostratigraphic investigations, but it is supported by information given by water-supply borings in the immediate surroundings (fig. 2) as compared to the Vejle Fjord Formation (cf. Larsen & Dinesen 1959). In the Lillebælt area Oligocene glauconitic clays at the southern coast

gocene glauconitic clay is superposed by brownish-black clay of varying thickness followed by sandy deposits with clay intercalations. The sections at Hagenør and Børup represent parts of this latter sandy sequence (fig. 2). At Brejning (fig. 1), 15 km north of Børup, a lithostratigraphical subdivision has been established (Larsen & Dinesen 1959). Compared to the Brejning exposures, the glauconitic clay is referred to the Brejning Clay Member, the overlying dark clay is referred to

the Vejle Fjord Clay Member, and the sandy sequence, including the Hagenør and Børup exposures, is referred to the Vejle Fjord Sand Member. From investigations of the sequence at Brejning it was suggested that the Vejle Fjord Sand Member most probably belongs to the Lower Miocene (Larsen & Dinesen 1959), and the deposits at Hagenør and Børup are presumed to be of this age (fig. 2).

## General lithology

The Tertiary sequence is overlain by approximately 5 m of Quaternary deposits; however, the sections appear to be unaffected by glacial tectonics. The exposed Tertiary has a total thickness of approximately 20 m and is divided into six major lithological units (figs 2 and 21).

*Unit 1.* In the Børup cliff section (fig. 3), 6.5 m of fine sand, light grey in colour, with predominating parallel lamination are referred to this unit. Small-scale cross lamination occurs at several horizons. At a few spots burrows

are abundant. In the westernmost part of the exposure the parallel lamination is horizontal. In the easternmost part a lower, horizontally laminated sub-unit is unconformably overlain by another with slightly (3°) easterly inclined lamination.

*Unit 2.* At Børup this unit attains 2.0–2.5 m in thickness and increases eastwards along the cliff section. Coarse sand with two gravel horizons, one at the base of the unit, the other 0.5–0.8 m below the top. Above the upper gravel horizon the sand is more fine grained. The unit is rusty brown in colour and strongly bioturbated. To the west, the burrows are so abundant that the primary bedding is almost obliterated. Within and just below the upper gravel horizon pelecypod valves are preserved as limonitic crusts (fig. 4). The convex-upward orientation of the valves indicates influence of traction currents (Schrock 1948, pp. 314–320; similar occurrence is also noted in the Oligocene/Miocene Kölner Schichten of North Germany – Gliese 1971).

Above the uppermost gravel, badly preserved internal moulds of a myoid pelecypod are bur-



*Fig. 3. General view of the exposure at Børup. The numbers denote the units described in the text. (Willy Høi phot.).*

*Fig. 4. Limonitic crusts of current-strewn valves of pelecypods in gravelly coarse-grained sands of Unit 2. (Søren Priisholm phot.).*

ied in a vertical, life position (fig. 5) with valves gaping upward. The general shape of this myoid pelecypod is of the *Panopea* type. The shell morphology, with the valves rather slightly gaping, the outline of commarginal growth
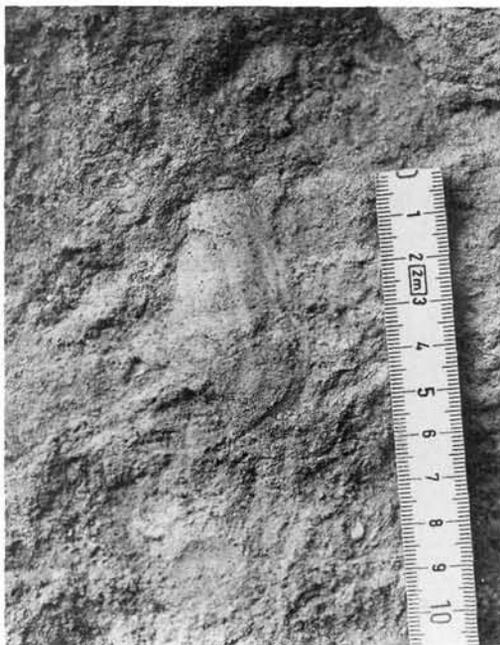


*Fig. 5. Mould of pelecypod shell, attributable supposedly to the genus* Panomya, *buried in life position in sands of the uppermost part of Unit 2. (Rud Friborg phot.).*

rugae, some of which are distinctly swollen, and the presence of an indistinct median depressed area (fig. 5) suggest the genus *Panomya*.

The boundary between Units 1 and 2 is erosional, but gradational due to bioturbation. It is situated in a higher position in the eastern than in the western part of the exposure (fig. 3).

*Unit 3.* At Børup it attains 2.0–2.4 m, and thickness is greatest in the western part of the exposure. The lithology is clay, silty to fine sandy, with a brownish black colour. The boundary against Unit 2 is sharp. In the lower part, the clay is very firm and dark, grading upwards into silty fine sand of lighter colour. At the top, coarse sand occurring as diffuse lenses is found. From these lenses undeterminable burrows filled with coarse sand extend into the fine sand. In the eastern part of the exposure a few gypsum crystals have been found.

*Unit 4.* This unit, consisting of fine sand, which is dark brown from organic carbon and strongly bioturbated, is developed only at Hagenør (fig. 6); it attains 0.6–1.0 m, and its thickness increases to the southwest. In the topmost part, patches of primary lamination and ripples are preserved. Unit 4 in the Hage-

Fig. 6. General view of the exposure at Hagenør. The numbers denote the units described in the text. (Rud Friborg phot.).
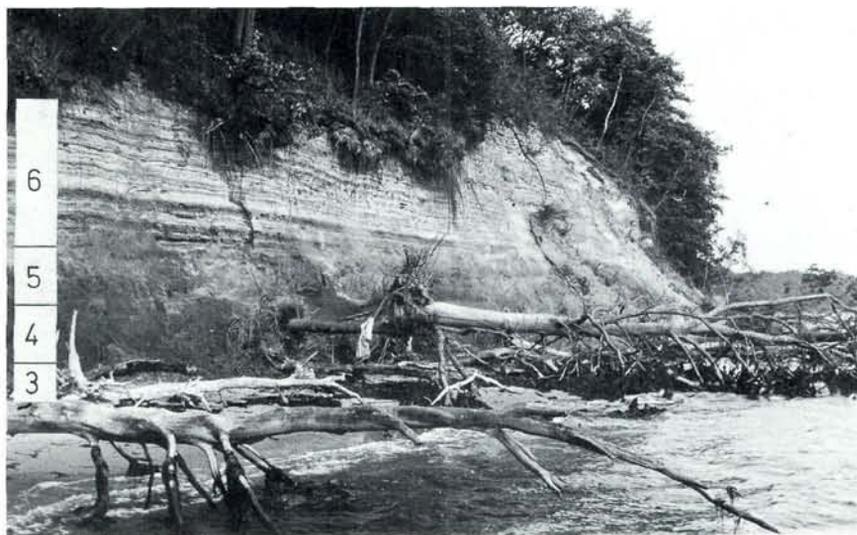


nør exposure corresponds to the coarse sand terminating Unit 3 at Børup.

*Unit 5.* The thickness of this unit varies at Børup from 0.5–1.8 m (at Hagenør 1.0 m) and is thinnest where the substrate is at its highest position. It is composed of clay, which is silty to fine sandy and brownish black in colour.

*Unit 6.* Very little of this unit has been preserved at Børup. At Hagenør the maximum thickness is 8.7 m. The unit is composed of light grey sand. Clay/silt intercalations are common, especially in the lowermost part (fig. 19). Locally cross-bedding, erosional troughs and ripples are found. In several horizons burrows are common.

## Biogenic sedimentary structures

The biogenic sedimentary structures in the sequence, represented mostly by burrows, allow the recognition of the activity of a series of benthic animals that have moved, dwelled or fed on and/or below the sediment surface, and left distinct and coherent traces of their activity. As all the calcareous shell material has been completely leached out during diagenesis or weathering, these traces are almost the only evidence of organic life in the sedimentary basin. Nevertheless, those traces that have per-

sisted demonstrate the presence of marine animals of various kinds and therefore are a valuable key for the recognition of environmental conditions.

The assemblage of recorded trace makers comprises sea anemones, polychaetes, echiuroids, ?haustoriid amphipods, decapods, gastropods, pelecypods, holothurians and echinoids. Their trace fossils are discussed below in that order, which is not necessarily that of their relative importance in the ichnocoenose.

### Sea anemones

The burrows attributable to sea anemones occur commonly in fine, even-parallel bedded sands in Unit 6, just above the clay interlayers (fig. 19). The burrows are better preserved in the lower parts of the laminae sets, as here dark clay interlaminae give the burrows a distinct outline; in the higher, more homogeneous parts, the burrows are hardly discernible. Usually they appear in groups of a few, and the groups are sparsely distributed along the layer. Within a group, the burrows are scattered at distances of 3–5, maximum about 10 cm apart. Their structure is demonstrated by the two successive sections obtained by peeling off the exposure wall (fig. 7).

The burrows are characterized by a disruption and pressing down of parts of the laminae, and they continue upward almost vertically, giving an appearance of irregular convex down menisci or cones (fig. 7 a, b). Their
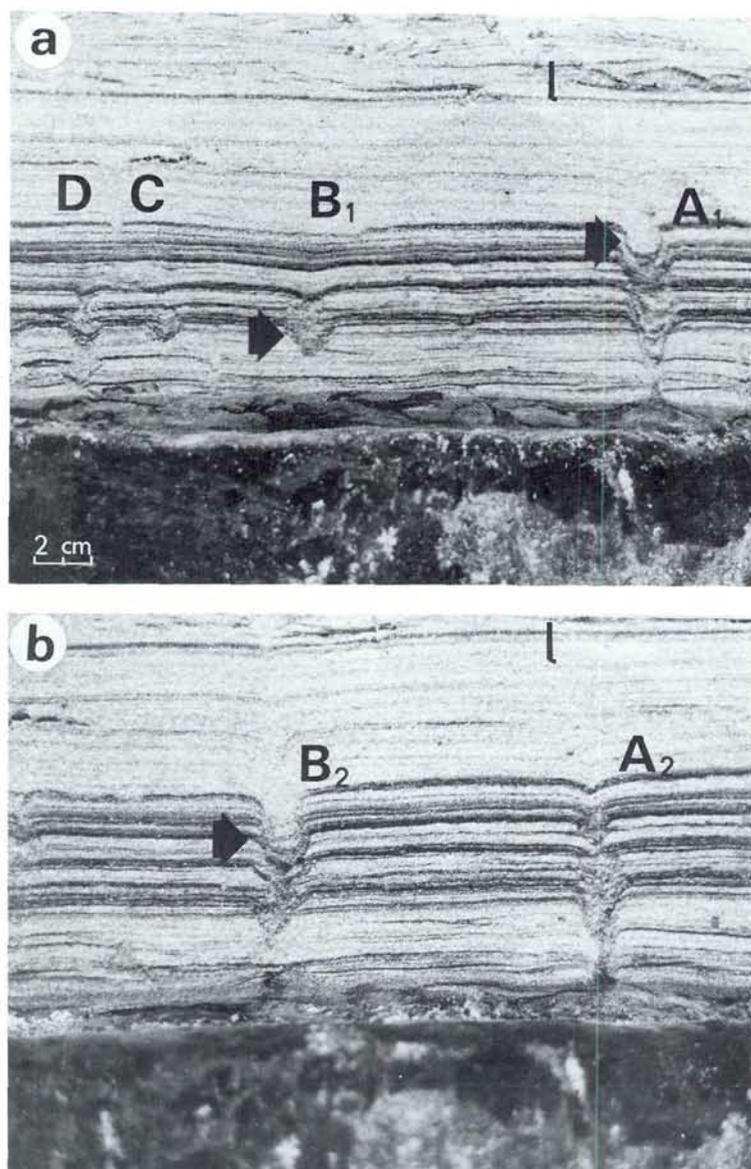
Fig. 7. Burrows of sea anemones in laminated sands of Unit 6: two successive sections (a, b – distance 8 mm) demonstrate the shape variability of the four burrows (A,B,C,D). The burrows A and B are visible in both sections. In burrows A and B, their lower part constructed in laminated sediment, is preserved better than that in the overlying more homogeneous deposit (up to the level marked by l). In burrow B, both the initial (arrowed in $B_1$) and the final (arrowed in $B_2$) positions of the physa chamber are descernible; in burrow A, only the final position of this chamber (arrowed in $A_1$) is observable in the section. (Rud Friborg phot.).

length is up to 12–15 cm, but usually only smaller fragments are preserved distinctly. One of the pressed-down segments of the burrow, usually situated at the half-length, (fig. 7 a, b), is more pronounced and bulb-shaped.

The bulb-shaped part of the burrows suggests a sea anemone as the trace maker, this part being produced by the lower part of the body (physa) when it was spherically expanded to anchor the animal securely in the soft bottom. The upper part of the body (scapus)

with tentacles was stretching up to the water interface. The bulb-shaped chamber marks the final position of the animal before its burial. The structure beneath was left by the animal during successive withdrawal from the sediment to reach the rising level of the bottom (Shinn 1968); it is therefore a "retrusive" form sensu Goldring (1962) (cf. also Schäfer 1956; and Goldring 1964, fig. 1). This lower part of the burrow is better pronounced as it is developed in sands with clay interlamination;

the upper part that cuts more homogenous sandy material is rather diffuse. The mode of formation of the burrows is referrable to that presented by Shinn (1968, pl. 112) for *Phyllactis conguilegia* common in agitated waters of the Bahama Banks.

The burrows produced by other sea anemones, mostly by stubby *Cereus* or elongated *Cerianthus* and *Ceriantheopsis* are known from present-day shallow sublittoral and intertidal environments (Lessertisseur 1955, Schäfer 1956, 1962; Reineck et al. 1967; Frey 1970 a, b; Hertweck 1972). In a fossil state, apart from the Pleistocene burrows discussed by Shinn (1968), which are regarded as being left by sea anemones, are various forms in which successive traces of contraction and expansion of the body are recognizable. These forms, usually preserved as hyporeliefs on the layer undersides, are represented by older Palaeozoic forms *Bergaueria* (Prantl 1945; Howell & Hutchinson 1958; Häntzschel 1958, 1962; Radwanski & Roniewicz 1963; Arai & McGugan 1968, 1969; Alpert 1973; the ichnogenus has recently also been recorded by Fürsich 1974, from the Upper Jurassic of England), and by *Conostichus* of Carboniferous age (Chamberlain 1971; Pfefferkorn 1971; Alpert 1973). In the former, no migration traces have so far been observed; they appear in *Conostichus*, and Alpert (1973) therefore postulated that the sea anemone's ability to migrate upward to keep pace with rapid sedimentation evolved at some time between the life periods of sea anemones producing these forms. In sections alone, only a few structures have hitherto been attributed to see anemones, e. g. *Kulindrichnus* from the Jurassic (Hallam 1960), and a recently illustrated burrow from the Muschelkalk (Trammer 1974).

## Polychaetes

The burrows attributable to onuphid polychaetes are the infillings of dwelling tubes, usually straight and almost vertical, that occur in sandy layers of Unit 6 (fig. 19). The largest burrows attain 15–20 cm in length, and a few are up to 5–6 mm in diameter. Usually, these burrows display the outline of the tube wall, and they are filled with sand containing a dark clay admixture.

Most of the burrows, represented only by straight tubes (fig. 8 a, 9 b, 10 b and 13 a), may be compared to those produced by *Onuphis microcephala,* a common dweller inhabiting the Georgia offshore (cf. Hertweck 1972; Howard & Frey 1973, fig. 5 b; Howard et al. 1973, fig. 20 D).

A few fragmentarily preserved burrows, surrounded by a bushy collar of irregular, brown-coal containing flakes (fig. 8 b, c) may furthermore be interpreted as produced by a *Diopatra* type of polychaete. In the present-day environments of the Georgia offshore the species *Diopatra cuprea* incorporates, in the upper quarter of its tube, small current drifted shells or plant debris (Frey & Howard 1969, 1972; Myers 1970, 1972; Hertweck 1972; Howard & Frey 1973; Howard et al. 1973). The latter portion ('the plume') is often the only part of the tube preservable in deposits (Myers 1970, fig. 1 b), and this is believed to be represented in the material under study. The plant material was either selectively bound by the polychaetes, or it became the residuum left after dissolution of any associated shell material.

In present-day environments a similar structure of tubes is also displayed by *Owenia fusiformis* which incorporates smaller shell fragments along the full length of the tube (Frey & Howard 1969; Hertweck 1972); no comparable burrows are however present in the investigated deposits.

## Echiuroids

The burrows attributable to echiuroids are fairly common throughout all the clay/sandy intercalations, mostly of Unit 6 (fig. 19), but usually they are individually scattered in the deposit. They also occur in some pure sandy layers. Most of the burrows as visible in the exposure (fig. 9) represent the lower part of a broad, U-shaped loop with distinct traces of animal motion. The burrows, in transverse section (figs 9 a, b, 12 and 13 a), are therefore recognizable as a group of several variously bent, excentric, clay crescents, separated or overlapping each other and arranged around the central canal. The canal is usually filled
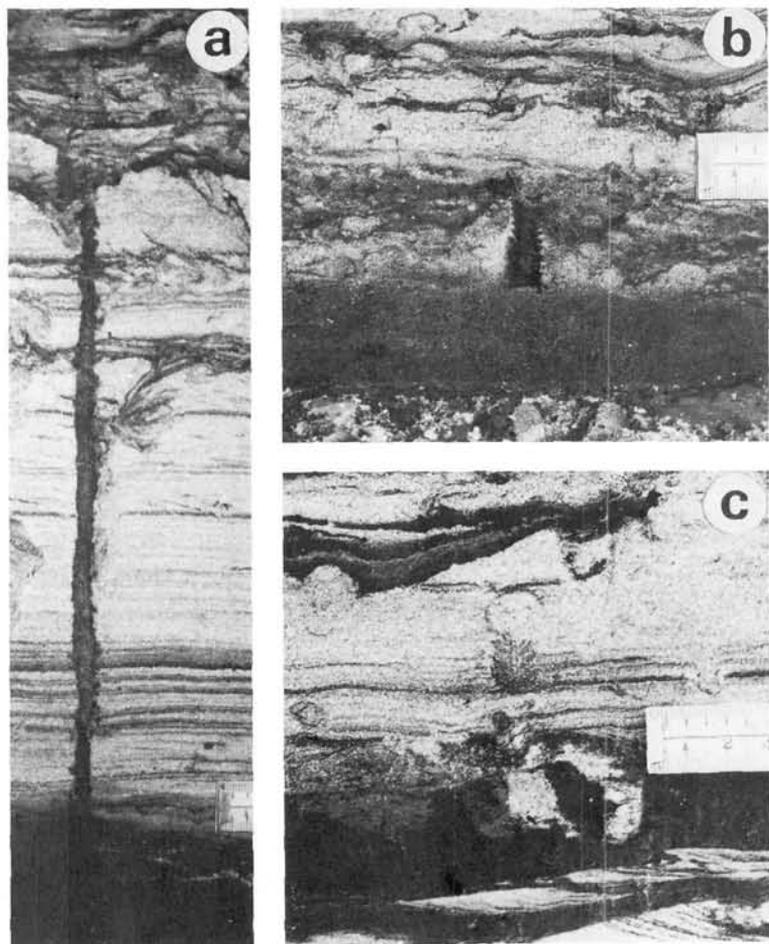
Fig. 8. Burrows of polychaetes in sandy deposits of Unit 6: a – dwelling tube comparable to that of present-day Onuphis, b, c – upper parts ('the plumes') of dwelling tubes comparable to those of present-day Diopatra; in b, a tube stretching through the plume is visible. (Rud Friborg phot.).

with sand similar to that outside it, and only in a few cases it is filled by clay, becoming then better contrasted against the background (arrowed in fig. 9 a). When the burrows appear in clay/sandy intercalations (e. g. layers A, C in Unit 6 – fig. 12), they are either collapsed or synsedimentarily disturbed, and as a result the structure is less discernible. Longitudinal sections, due to such a collapse, are much less easily recognizable (fig. 9 b).

The investigated burrows are identical with those reported by Hertweck (1968, 1970) for present-day Echiurus echiurus from the North Sea which densely populate the area southeast of Helgoland, on a muddy bottom at a depth of 15–35 m, the bottom community being dominated by Echiurus itself whose adult individuals produce burrows up to twice as

large as those investigated here (Hertweck 1968, figs 11–12). It may therefore be concluded that the sequence studied was deposited in an environment distinctly less favourable (mostly sandy bottom) for biological requirements of echiuroids which are smaller and appear much more sparsely.

In the fossil state, there is apparently no report on similar trace fossils, except of that by Fürsich (1974) who pictured in schematic drawing some sections from the Upper Jurassic of England. Their outline (Fürsich 1974, fig. 26) is analogous to that of the Miocene forms, but the photographs (Fürsich 1974, fig. 27 a) do not offer good evidence, as is also the case for the forms put by Fürsich into their synonymy.
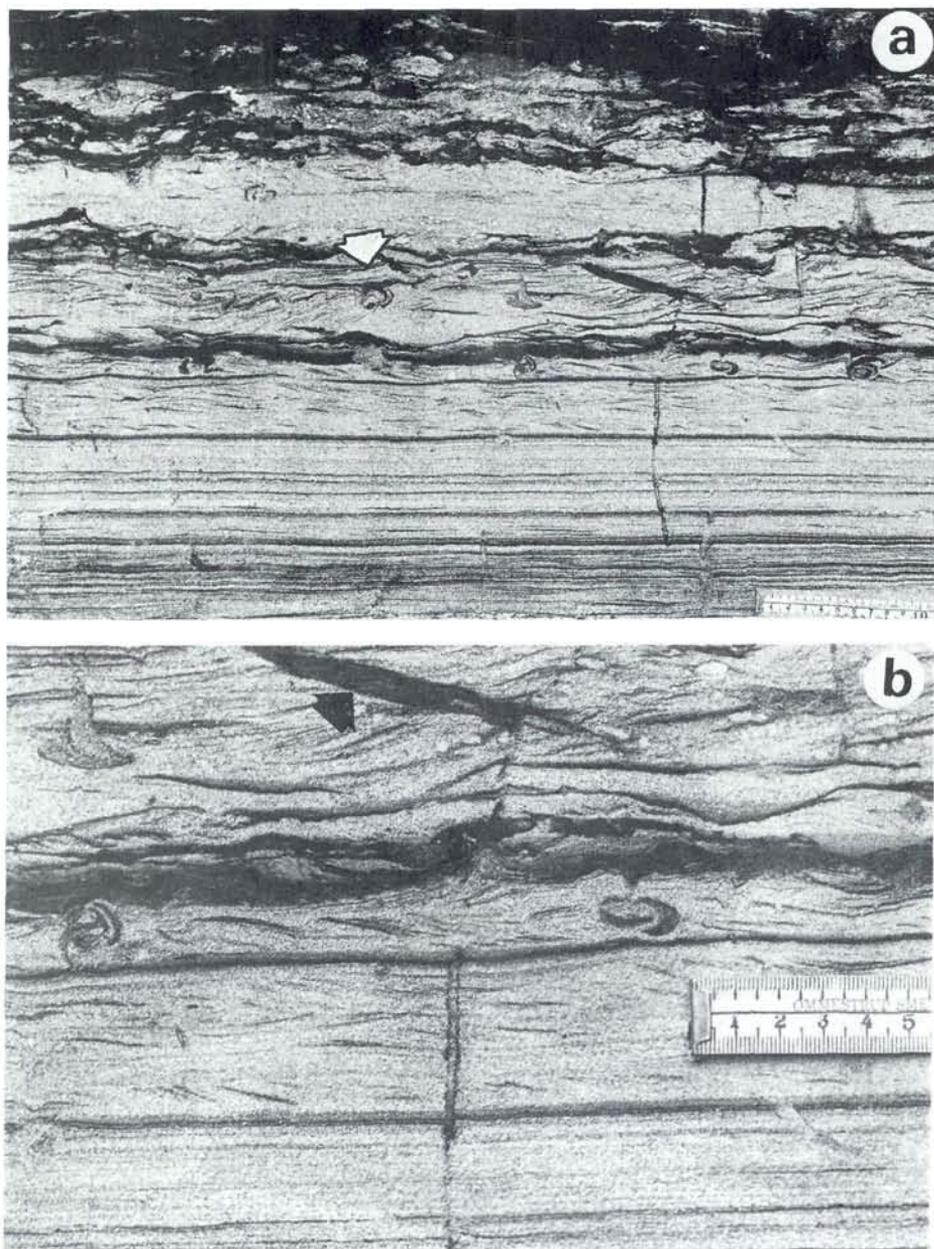
*Fig. 9. Burrows of echiuroids in sandy deposits of Unit 6: a: general view of cross- and ripple-laminated sands containing burrows (arrowed is the burrow with preserved central canal), b: close-up view to show the burrows both in oblique-tangential (arrowed) and transverse sections; down the centre, a polychaete burrow of the* Onuphis *type is visible. (Rud Friborg phot.).*

### ?Haustoriid amphipods

The burrows that may presumably be attributed to haustoriid amphipods are the most common trace fossils throughout the sequence studied. They occur in almost all the clay/sandy intercalations of Unit 6 (fig. 19) giving them a mottled appearance. Within such intercalations, the burrows are confined to sandy laminae, either even parallel, or discontinuously wavy bedded. In some sandy laminae they oc-
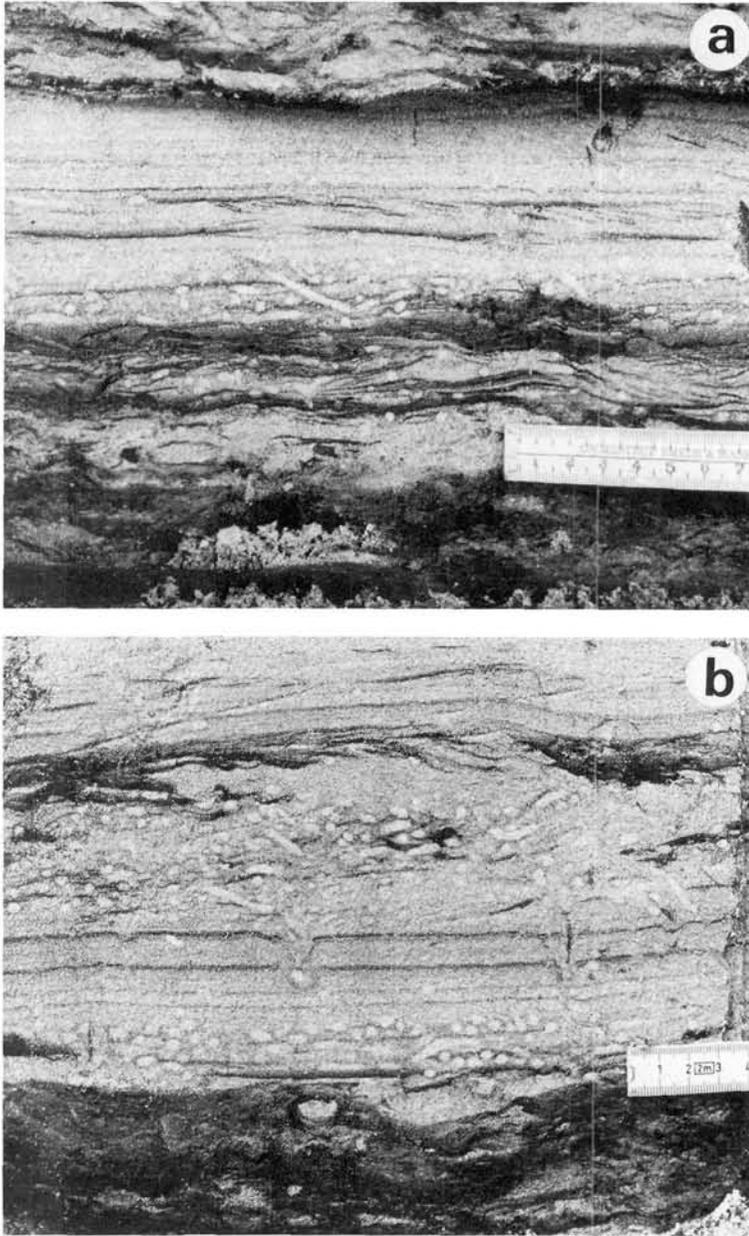
*Fig. 10. Burrows of ?haustoriid amphipods in sandy deposits of Unit 6: a - the burrows grouped at one level; one of the burrows penetrates obliquely through the successive laminae, b - the burrows predominantly at two levels, and dispersed in the adjacent layers; polychaete burrows of the Onuphis type are also visible. (Rud Friborg phot.).*

cur in greater quantitites and occupy the space almost completely (fig. 10). The burrows are filled with sand, usually slightly lighter in colour than the matrix, so that they are weakly discernible. Burrow fills in darker layers are better contrasted, being free of dark clay admixtures.

The burrows have the shape of a single, very short and stubby tube, slightly bent or arched; some forms are weakly sinuous and resemble a vertically much elongated letter S. The length of the largest forms is up to 3.5–4.0 cm, but most of the burrows are about half that size. Tube diameter is equal along the length, being about 2.5–2.8 mm in average forms. Smaller forms occur in all the layers in minor numbers. The cross section is circular, and the tube boundaries are smooth. In many

burrows indistinct traces are observable that indicate the former presence of a mucus wall to which clay particles adhered.

The nature of the burrows cannot easily be recognized as their shape and morphological details are very limited. In the sequence studied, these burrows are mostly confined to clay/sandy intercalations deposited by currents of a tranquil flow, and they are absent in clay layers. On the other hand, the burrows do not display any escape structures, and they do not gather along the layer interfaces that correspond to temporary breaks in sedimentation. It may therefore be inferred that the burrowing animals were not the permanent inhabitants of the sedimentary area, but that they were introduced together with sediment by currents. The burrows, being neither restricted nor attached to any sedimentary surface seem to be produced by active vagile animals that penetrated rapidly through the sediment. Consequently it is supposed that the trace makers were not the sedentary worms or worm-like animals to which many similar tube-shaped burrows are commonly referred.

These trace makers may be related to the amphipods, especially the haustoriid amphipods, the burrowing activity of which has recently been studied in aquaria (Howard & Elders 1970). Some burrows, especially of *Protohaustorius deichmannae* (Howard & Elders 1970, pl. 1), and of *Haustorius* sp. (Howard & Elders 1970, pl. 3), have a general appearance similar to the investigated forms. A selection of some laminae during the burrowing for food, and final bioturbation effect (Howard & Elders 1970, pl. 8) are also similar to those in the sequence studied (fig. 10 b). The difference is only in the presence of backfilled structures in haustoriid burrows, but this feature may not be detectable in fossil material if the burrow-filling sand was homogeneous enough. There is also a problem with environmental circumstances since the haustoriid amphipods studied by Howard & Elders came from the intertidal zone to which they are confined. In aquaria, however, they were fully active for as long as a week under permanently submerged conditions of a flowing water system. It appeared in these experiments that the burrowing activity of haustoriid amphipods was very fast, e. g., that by *Haustorius* sp. led to strong bioturbation in a period of 48 hours.

The data presented by Howard & Elders (1970) (cf. also Frey & Howard 1972; Howard & Frey 1973) show that the burrowing activity of haustoriid amphipods is comparable to that inferred for the Miocene forms. Nevertheless, further investigations are needed, especially of bathymetric range of present-day haustoriids and other burrowing amphipods. In the sequence studied, an intertidal source of the amphipods supplied to the sedimentary area by currents is not impossible, but it may perhaps be regarded as too extreme.

Decapods

Attributable to callianassid decapods are the burrows *Ophiomorpha nodosa* which occur to a limited extent in a sandy layer just beneath the second gravel horizon of Unit 2 (fig. 21).

The burrows, rather poorly preserved here, start from the sand/gravel interface and penetrate through the layer down to about 60–70 cm. Their diameter is about 1.5–2.0 cm, in some specimens even 2.5 to near 3.0 cm. In places, a warty sculpture of the external surface of the burrow wall is pronounced (fig. 11 c); this wart-like covering is comparable to the pellets of faecal material used by callianassids to stabilize and reinforce the burrow walls (cf. Hester & Pryor 1972, fig. 11). Most of the burrows are almost vertical or slightly oblique (fig. 11 a), some are moderately oblique (fig. 11 b) and a few are horizontal (fig. 11 c). These horizontal segments and local Y-shaped branching are characteristic features, comparable to those revealed by *Ophiomorpha* burrows from the Søby-Fasterholt area in central Jylland (cf. Asgaard & Bromley 1974, fig. 2).

The ichnospecies *Ophiomorpha nodosa* is one of the best recognized trace fossils (Häntzschel 1952, 1962; Kennedy 1967, 1970; Fürsich 1973; Bromley & Frey 1974) and the ghost shrimp *Callianassa major* has been shown by Weimer & Hoyt (1964) to produce such burrows today. Nevertheless, it has subsequently been shown that other species of *Callianassa* can also make structures of this same type (Frey & Howard 1972; Hertweck 1972;
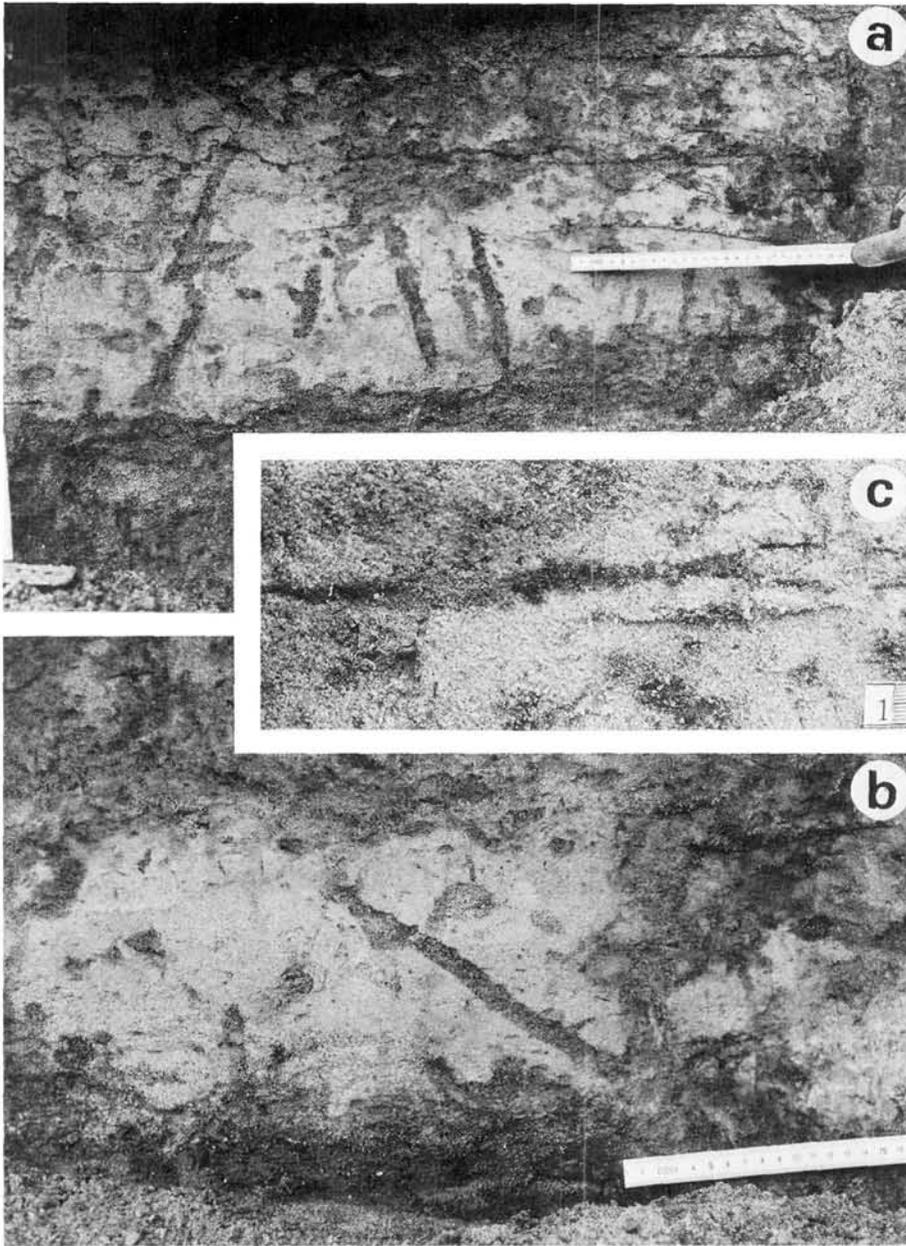
Fig. 11. Ophiomorpha nodosa, *the burrows of callian-*
*assid decapods in sandy deposits of the median part of*
*Unit 2: a - group of almost vertical burrows, b - oblique*
*burrow, c - close-up view of a horizontal burrow to*
*show the wartlike structure of the burrow wall (sup-*
*posedly having been reinforced by faecal material).*
*(Rud Friborg phot.).*

Howard & Frey 1973; Howard et al. 1973; cf. also Asgaard & Bromley 1974). It is therefore recommended to attribute *Ophiomorpha nodosa* only generally to the callianassid decapods.

Extensive studies on the distribution of *Callianassa major* and its burrowing activity (Weimer & Hoyt 1964; Hertweck 1972), amply demonstrate its environmental requirements and limitation to intertidal and shallow subtidal

conditions. In a fossil state the *Ophiomorpha nodosa* burrows are correspondingly generally regarded as an extremely shallow marine, nearshore indicator. Their frequency and mode of occurrence in the deposits have been successfully used for a reconstruction of the facies sequence and bathymetry, e. g. in the Purbeckian/Weald of Bornholm in Denmark (Gry 1968; Jux & Strauch 1968), Upper Cretaceous of South Dakota (Waage 1968; Rhoads et al. 1972), Cretaceous and Palaeogene of England (Kennedy 1967, 1970; Kennedy & Macdougall 1969; Kennedy & Sellwood 1970; Dike 1972), and Miocene of southern Poland (Radwanski 1970, 1973). They also occur in similar nearshore facies in the Oligocene/Miocene of the North Sea Basin (Häntzschel 1952; Jux & Strauch 1967; Radwanski 1970, p. 386; Gliese 1971; Martini & Mentzel 1971). In the Søby-Fasterholt area in central Jylland the common *Ophiomorpha* burrows appear at the transgressive base of the marine Hodde Clay that overlies non-marine sands of the Odderup Formation (Koch & Christensen 1973; Asgaard & Bromley 1974).

Gastropods

Gastropod burrows are represented by spiral-shaped escape traces recorded in one sandy layer in the lowermost part of Unit 6 (fig. 19). The burrows start here from a clay lamina and pass upwards more or less vertically, through the sandy layer, 3–5 cm thick, and capped with a ripple-laminated portion and ripplemarks (fig. 12). Their infillings consist of sand with clay admixtures.

The traces are almost identical with escape structures produced by *Hydrobia ulvae* and reported by Hertweck (1968) from the North Sea at a depth of 10–15 m to which living *Hydrobia* were transported from tidal flats during heavy storms. The shape, size, distribution and frequency of the traces in sediments are well comparable in both discussed occurrences; the only differences are in more clayey material through which *Hydrobia* escape in the North Sea (cf. Hertweck 1968, fig. 13 = Reineck & Singh 1973, fig. 478; also Hertweck 1968, pl. 2, fig. 2).
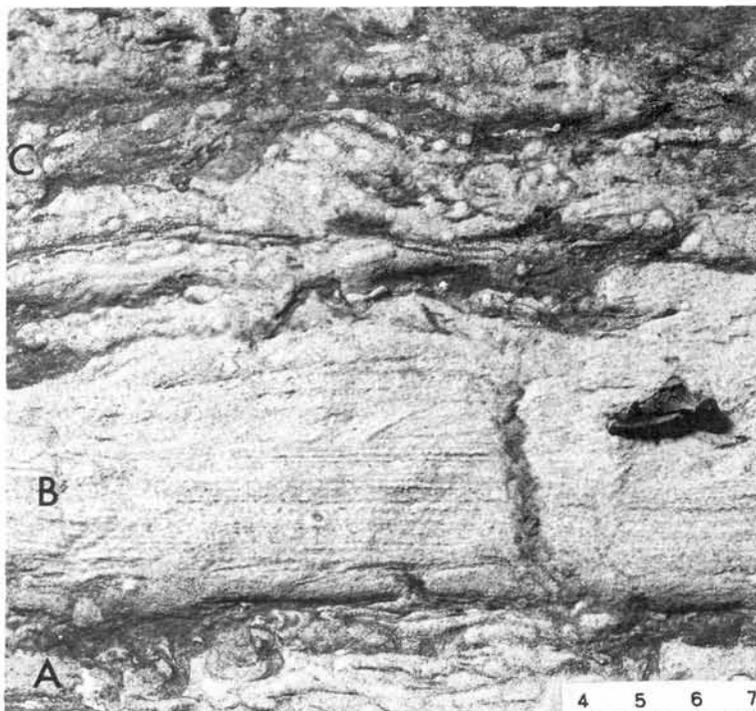


Fig. 12. Escape trace of a gastropod at the bottom part of Unit 6. The structure of the sediment (B), which the gastropod escaped through, is complex: lower part is parallel laminated (rapid flow), upper part is ripple laminated (tranquil flow). A piece of wood and indistinct escape trace of a pelecypod are preserved near the trace. The under- and overlying clay/sandy deposits (A, C) are strongly bioturbated by gregarious ?haustoriid amphipods and single echiuroids. (John Sommer phot.).
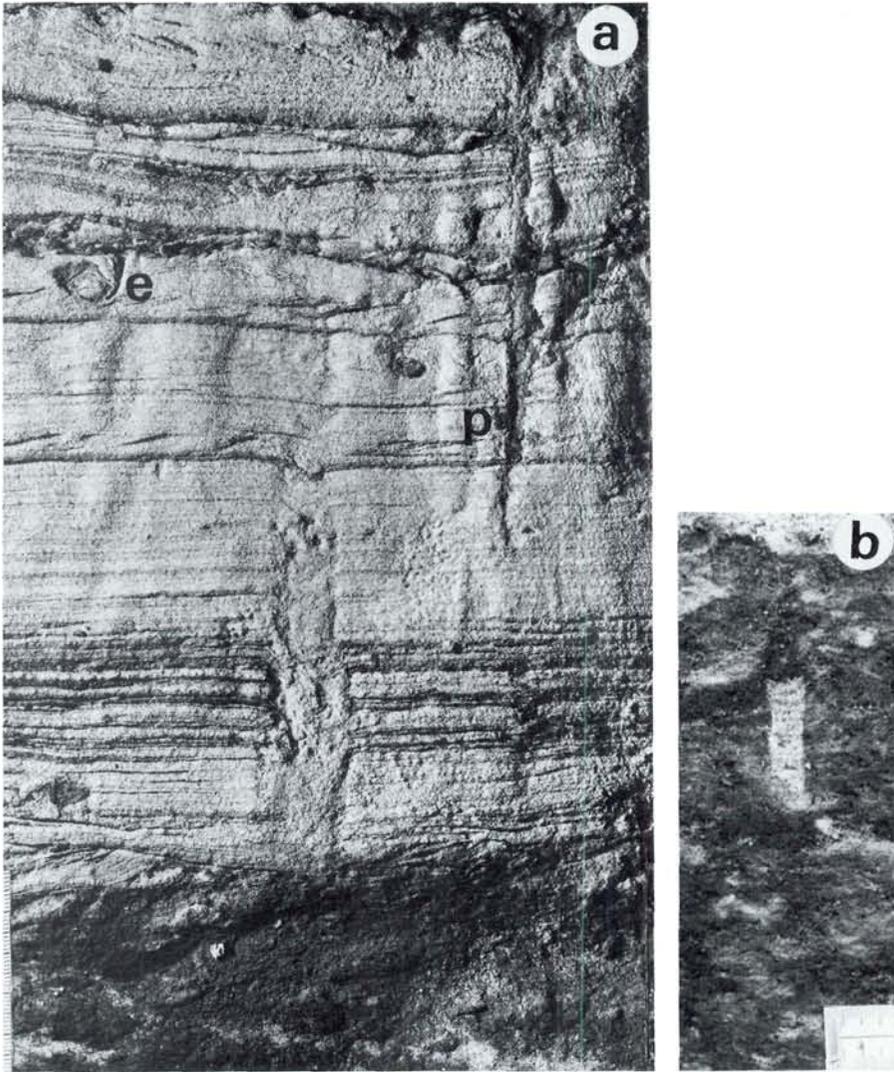
Fig. 13. Escape traces of pelecypods: a - in laminated sands of Unit 6 (echiuroid burrow - e - and polychaete burrow - p - of the Onuphis type are also visible), b - in clayey sands of Unit 4, strongly bioturbated by holothurians. (a: John Sommer phot., b: Rud Friborg phot.).

Pelecypods

The burrows attributable to pelecypods are escape traces produced by animals living at a certain depth beneath the bottom surface. As deposition progresses, pelecypods move upward to escape from inconvenient conditions beneath thicker sediment cover. Particular burrows of this kind vary in shape, internal structure and size, being dependant on the nature of the pelecypod and its dwelling habit, behaviour, and on the consistency of bottom material.

In the deposits studied, two types of pelecypod escape traces are distinguishable. The first appears if a monotonous sandy material was supplied. The burrows then did not have sharply defined boundaries, and they were filled with loose sand without lamination; internally only a collapse of laminae at the burrow boundaries is observable (fig. 13 a). Such burrows, common enough in the sandy layers of Unit 6 (fig. 19 and 21), and attaining 12–15 cm in length, are comparable to those produced by present-day Macoma, illustrated by
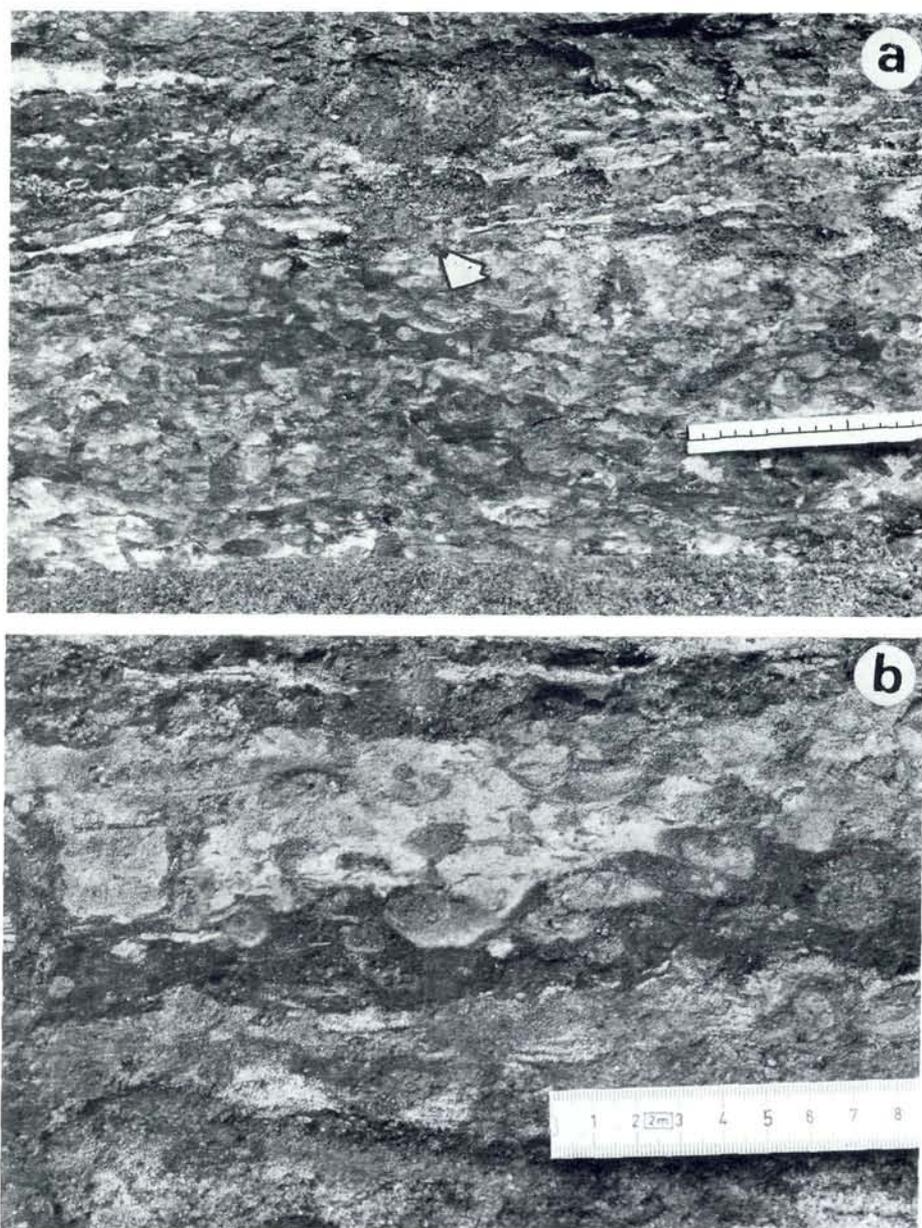
Fig. 14. Burrows of holothurians in clay/sandy deposits of Unit 4: a - general view of the middle part of Unit 4 (arrowed are the burrows displaying shapes comparable to those of the present-day genus Thyone (cf. Frey & Howard 1972, fig. 5), b - close-up view of the upper part of Unit 4 to show another burrow comparable to that of Thyone. (Rud Friborg phot.).

Reineck & Singh (1973, fig. 224) from tidal flats of the North Sea. Similar but less distinct forms were obtained for *Mulinia* in aquaria (Frey & Howard 1972).

When the bottom material was firm and more coherent the burrow boundaries are sharper, and an internal lamination left by the pelecypod moving upward may be preserved. Such burrows are met with rarely in brown clayey sands of Unit 4 (fig. 21), and they are comparable to present-day forms produced by *Mya,* as illustrated by Reineck (1958, fig. 2;

16*

cf. also Goldring 1964, fig. 1, and Reineck & Singh 1973, fig. 234) from the North Sea. In some burrows of this type, a final life chamber is recognizable (fig. 13 b); it is filled with clay material at the top of the retrusively laminated canal.

Holothurians

The burrows attributable to holothurians occur abundantly in brown clayey sands of Unit 4, (fig. 21), and here they are responsible for an almost complete bioturbation of the layers. Individual burrows vary in shape and size, being broadly U-shaped, near sack-shaped, either stubby or elongated with their ends turned up. The average length is up to 5–6 cm, and height up to 2–3 cm. All the burrows are filled with coarse-grained sand, light in colour and usually well contrasted against the dark clay background (fig. 14; also fig. 13 b).

The only comparable forms are some of the feeding burrows produced by holothurians *Thyone* that have recently been investigated in aquaria (Howard 1968; Frey & Howard 1972). These are of similar size and shape as the Miocene forms, but both these features are dependant on the animals' behaviour, and its contraction or elongation during the dwelling and feeding activity (Howard 1968; Frey & Howard 1972). As Howard (1968) and Frey & Howard (1972) noticed, the burrow walls are usually not very distinct and smooth, and the shape of the burrows may additionally be disturbed by gradual migration of the animal. There are also some burrows of tubular, more or less irregular shape. Such a set of shapes is also discernible in the investigated burrows, and a full gradation of boundaries is here recorded – from well defined ones to a blurred and diffuse boundary against the clay background (fig. 14 a, bottom). The better preserved burrows, having more definite sacklike shapes, appear mostly in the uppermost part of Unit 4 (fig. 14 b).

As seen from the structure of the whole Unit 4, the holothurians must have dwelled here gregariously, and they supposedly fed on organic remains contained in new supplies of clay sediments. The burrows show a very slight tendency to migrate up through the deposit as it accreted. On the other hand, the burrows are filled with coarse-grained sand, the supply of which presumably smothered and buried the holothurians. The latter returned and colonized the bottom again when inconvenient conditions of sand flooding, and thus of scouring the bottom by currents had ceased. It may consequently be concluded that all the burrows distributed more or less uniformly through this unit, were produced not by one holothurian community, but by a number of successive communities.

Echinoids

Burrows produced by spatangoid echinoids commonly occur in Unit 1 (fig. 21), especially in some of its cross-bedded parts. The burrows are present here in great quantities and almost wholly fill the space (figs 15–17). In the higher part of the sequence, they are met with singly in the clay/sandy intercalations of Unit 6 (fig. 18, also fig. 19). All the features of these burrows are almost identical with those of the present-day heart urchin *Echinocardium cordatum*, the burrows of which are well recognized and have satisfactorily been illustrated (Schäfer 1956, 1962; Reineck 1963, 1968; Reineck et al. 1967; Reineck & Singh 1973; Bromley & Asgaard 1975). The most typical feature is a conspicuous backfill composed of meniscus-shaped portions arranged along a central canal, and left behind the animal when it has passed through the sediment (Reineck 1968, pl. 2, fig. 3; Bromley & Asgaard 1975).

In the sequence studied, all types of these elongated burrows are recognizable, from ideally transverse (fig 16 above – cf. Reineck 1968, pl. 2, fig. 4; Reineck & Singh 1973, fig. 219) to a more or less longitudinal (fig. 17 a, b – cf. Reineck 1968, pl. 1, fig. 1). Nevertheless, it seems that a kind of orientation in the burrowing activity is revealed here: within the most gregarious occurrence (layer A in fig. 15 b), displaying about 100 sections, only 2 are longitudinal. In another, much shorter and lenticular layer (B in fig. 15 b), the proportions are however different and 4 longitudinal sections are present out of a total of 11. In both these layers the burrows belong to a few generations, and in many places younger burrows truncate or pass through older ones (figs 16 below, 17 a).
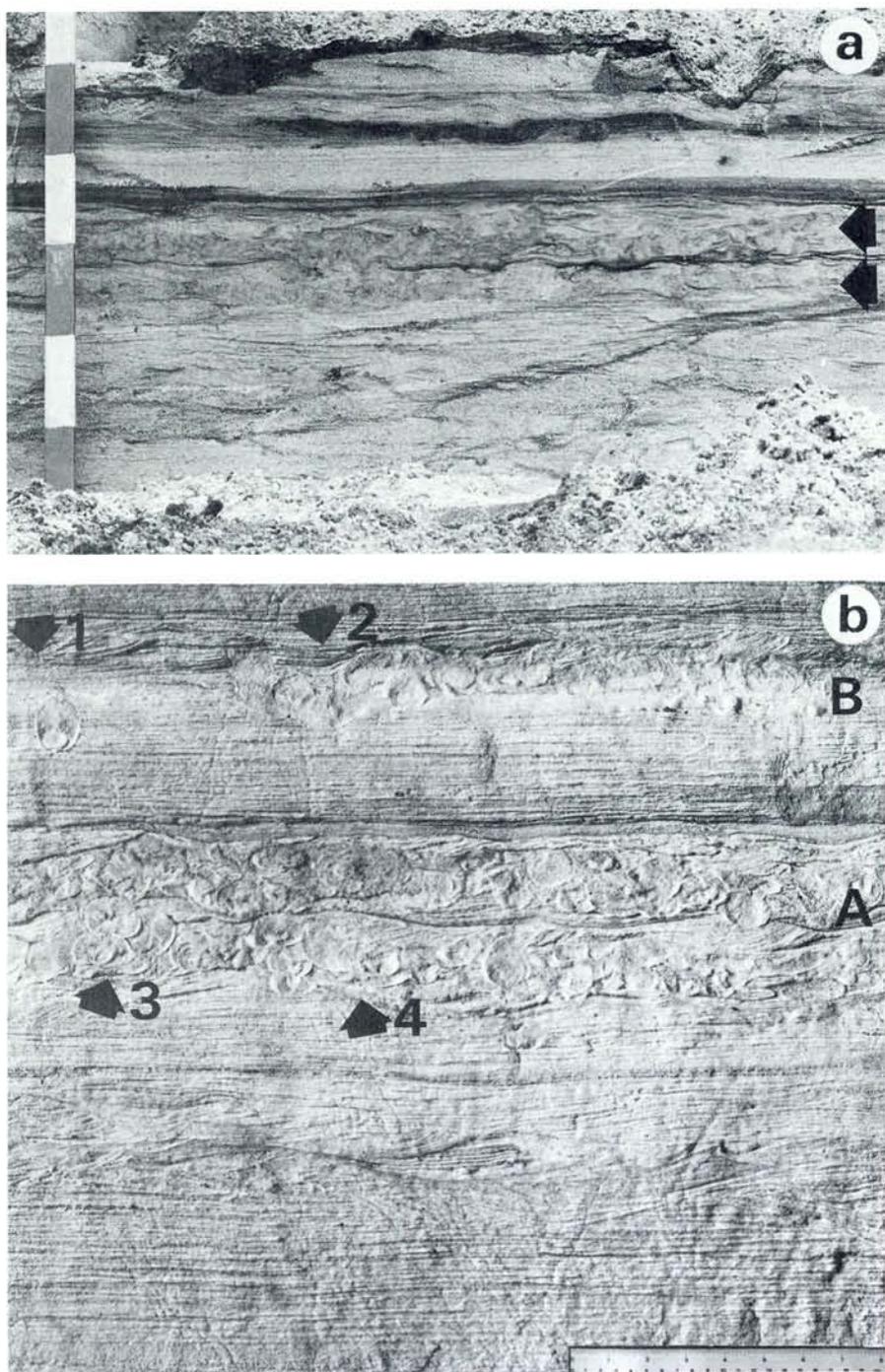
Fig. 15. Bioturbation by spatangoids in the median part of Unit 1: a - general view of the section to show the state of preservation of burrows in freshly cleaned exposure: the burrows are hardly discernible in two sandy layers (arrowed), b - lacquer peel of another fragment of the exposure displaying two horizons (A, B) crowded with echinoid burrows. Arrowed are the parts enlarged in figs. 16–17 as follows: 1 - fig. 16 above, 2 - fig. 17 b, 3 - fig. 16 below, 4 - fig. 17 a, (a: Rud Friborg phot., b: John Sommer phot.).
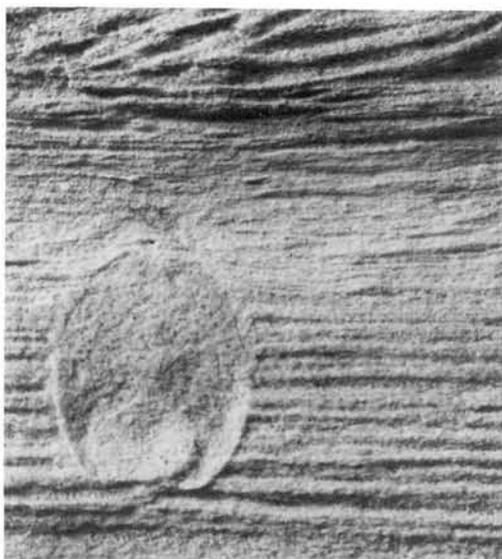
Fig. 16. Echinoid burrows from sandy deposits of Unit 1 (cf. fig. 15 b); nat. size: above - transverse section displaying two minisci (one preserved fragmentarily) of the backfill, below - transverse sections of the burrows of a few generations. (John Sommer phot.).

All the occurrences of echinoid burrows in the sequence studied are confined to cross-bedded layers or to the sets partly cross-bedded. Where the burrows are numerous, younger burrows truncate older ones and fill the layer tightly in a way comparable to that shown by present-day urchins (cf. Reineck 1968, pl. 1, fig. 2). There are no premises to calculate how many individuals were burrowing here, and it may only be presumed that their number was considerable. Confinement of the burrows to cross-bedded layers may result either from the feeding activity in food-containing deposits freshly supplied by currents, or from transportation of living urchins by these currents.

The same type of echinoid burrows has recently been reported by Asgaard & Bromley (1974) from the Søby-Fasterholt area in central Jylland; their mode of preservation is here similar to that in clay/sandy intercalations of Unit 6 (fig. 18 and Asgaard & Bromley fig. 4).

The reader is referred to Howard et al. (1974) and Bromley & Asgaard (1975) for a thorough discussion of other fossil occurences of spatangoid burrows.

## General features of the ichnocoenose

Problems of nomenclature

The investigated ichnocoenose from the Hagenør-Børup sequence represents a relatively rich assemblage of burrows that are attributable to 9 taxonomic groups of animals.

All the recognized burrows belong to the realm of trace fossils that commonly are termed with special ichnological names (ichnogenera and ichnospecies). It seems that such a procedure is reasonable only for those trace fossils that have been reported earlier than their trace makers. For those trace fossils however that are attributable to well-known present-day producers, special names seem to be unneccessary. This is really a kind of nomenclatural philosophy, since all the trace fossils should generally be named with specific names to persist (Osgood 1970), i. e. to be recorded in any references and indexes. The investigators of the present-day traces – Schäfer, Reineck, Hertweck, Frey and others – do not however introduce new names for the results of animal activities they have studied. Such a procedure has been followed in this paper which attributes the Miocene traces to
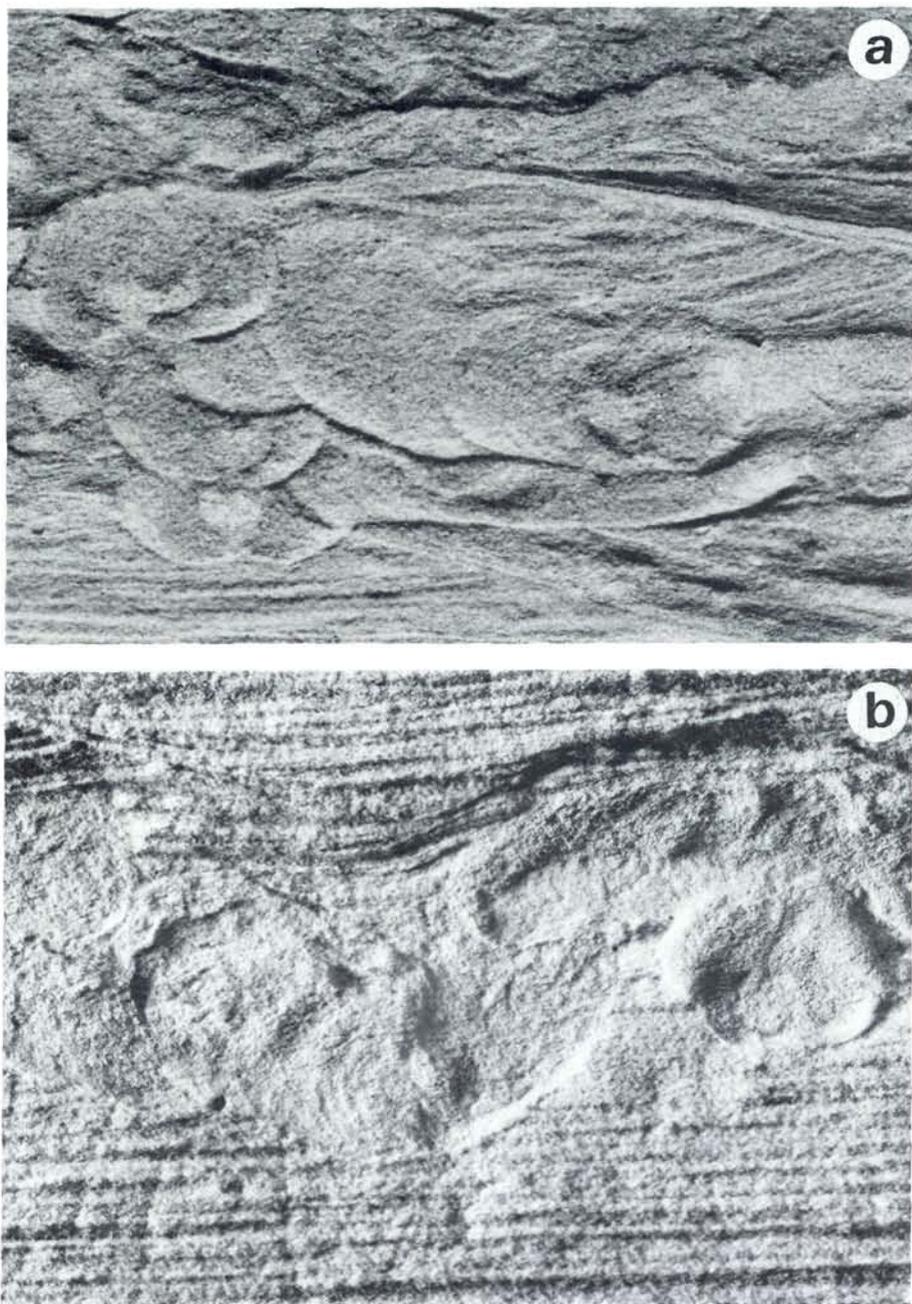
Fig. 17. Echinoid burrows from sandy deposits of Unit 1 (cf. fig. 15 b); nat. size: a - burrows of a few generations; both transverse and longitudinal sections are visible, b - another group of burrows, one of them arching downward (section near longitudinal). (John Sommer phot.).

present-day producers. An exception is made only for the *Ophiomorpha* burrows, which were first described from the fossil record, and their present-day makers recognized much later; this name is therefore retained and kept in common use.
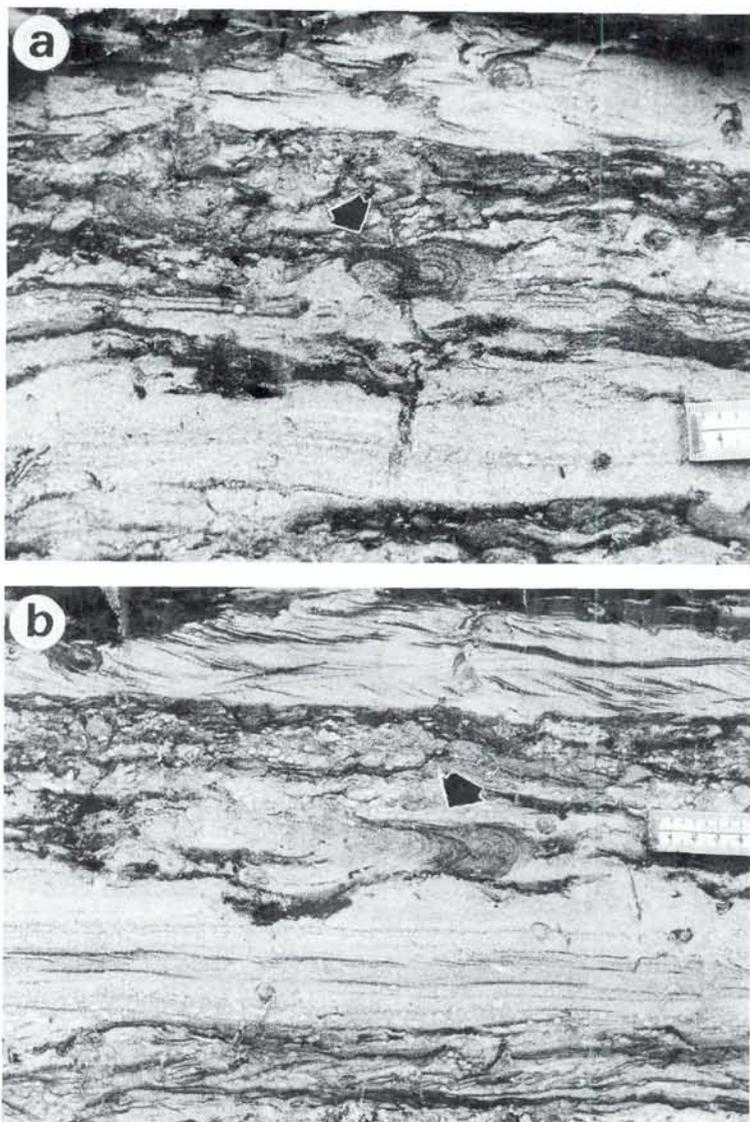
*Fig. 18. Echinoid burrows (arrowed) in clay/sandy deposits of Unit 6: a - transverse section with several minisci of the backfill, b - longitudinal, near tangential section. (Compare with those from Fasterholt, illustrated by Asgaard & Bromley 1974, fig. 4). (Rud Friborg phot.).*

Ichnocoenose/biocoenose relationship

Any ichnocoenose undoubtedly offers a better insight into the composition of the organic community than body fossils can do. This largely results from a record of various activities of soft-bodied animals that only exceptionally may be preserved in ancient deposits, and secondly, from in situ burial of the trace fossil assemblage (Lawrence 1968; Radwanski & Roniewicz 1970). In the investigated deposits, some traces are also attributable to shell-bearing animals that either escaped from the sedimentary area after leaving the traces,

or whose shells if primarily preserved in the deposit, have subsequently been removed.

The recognition of particular systematic groups of animals that are a part in the investigated ichnocoenose does not however explain their quantitative role in the biocoenose that settled in the area. The vagile burrowers, like amphipods and echinoids, might have produced many traces during their life. Escape traces were produced only occasionally, being dependant on the sedimentation rate, and they represent animals (sea anemones, gastropods and pelecypods) that moved upward

only during their temporary burial. The same animals might however have been covered by a new portion of sediment and then produced new traces. The tubes made by onuphid polychaetes were certainly the result of only a single burrowing. As discussed previously, the structure of the holothurian burrows, and their filling up with periodically introduced coarse sandy material, presumably evidences the life and burial of successive communitites rather than a successive upward migration of one biocoenose. It is therefore apparant that the number of traces does not correspond exactly to the number of trace makers, being presumably much smaller than the latter. An almost total bioturbation of some layers may, in turn, result from the activity of a community not denser than the one that lived during deposition of layers yielding few burrows.

## Rate of burrowing

Another variable problem is the rate of burrowing. It is obvious from their nature that all the escape traces must have been produced rapidly, and this is confirmed for sea anemones, haustoriid amphipods and holothurians, the activity of which has been investigated in aquaria. The sea anemone *Phyllactis conguilegia,* adapted to life within migrating oolite banks on the Bahamas, and therefore to a rapid sedimentation, escapes overnight through a 30 cm coverage (Shinn 1968). Some haustoriid amphipods bioturbated a layer almost completely in a few days, others in a week (Howard & Elders 1970). The holothurian *Thyone,* referred to burrows in Unit 4, produes well defined burrows in $12^h$, and a further change of their shape, resulting from feeding behaviour and addition of new sediment, takes place in about $18^h$ (Howard 1968, fig. 2 A, B). It is therefore apparent that for the two latter animal groups a few days are sufficient to bioturbate a layer lying on a temporary sea bottom, and it was presumably the same in the Miocene invironment. In other animals, the rate of bioturbation was certainly slower, as is evidenced by Hertweck (1970) for the *Echiurus* communities of the North Sea; these have inhabited a previously bare muddy bottom and burrowed during one generation that ranged about 4 years. The

observations by Hertweck (1970) demonstrate also that the trace-maker communities, and consequently the rate of burrowing of the seafloor, may change as a result of inconvenient seasonal temperature conditions.

## Characteristics of the ichnotope

The deposits in which the investigated ichnocoenose occurs, i. e. the ichnotope, are generally characterized by diverse clastic materials, ranging from gravels to clays. A set of physical sedimentary structures displayed in sediments of fractions coarser than clay is indicative of current action of diverse velocities. The distribution of particular burrows in the sequence is therefore non-uniform, and it sensitively reflects changes in the nature of deposits (figs 19 and 21). In a spectacular way, it is well demonstrated by the lowermost part of Unit 6 (fig. 19), in which through a 1 m thick series most of the physical and biogenic variants in structures are revealed.

A distinct pattern of facies recognizable in the lowermost part of Unit 6, and realized in a vertically repeated array of structures attributable successively to rapid flow→tranquil flow→stagnant conditions (sub-units B→E, F →J; fig. 19) is interpreted as resulting from periodical stormy agitation in the adjacent areas, This involved rapid flow into a stagnant sedimentary area, and subsequently a tranquil flow when the current velocities decreased. If the current vanished, the stagnant conditions appeared and stabilized in the area. The higher cycles of Unit 6 lack the period of stagnation, the products of which might however have been removed during a temporary scouring of the bottom material (sub-units K→L, erosion, sub-units M→N, fig. 19). The sedimentary area of this part of the Hagenør-Børup sequence is therefore thought to have been situated in a stagnant area influenced by temporary supplies of clastic material from nearshore zones.

The discussed part of Unit 6 (fig. 19) offered especially good conditions for preservation of burrows, as the clay admixture was present for almost the whole time of sedimentation. It penetrated inside the burrows, marking most of them with a distinct lining that was conducive to better preservation. This is well evidenced e. g. in burrows of echiuroids

SECTION AT HAGENØR

(lowermost part of Unit 6 – vide Fig. 21)

(fig. 9), gastropods (fig. 12), and of some echinoids (fig. 18). The clay admixture is furthermore responsible for lamination of the deposits due to which the structure of the escape traces, e. g. of sea anemones (fig. 7) is better discernible.

Some parts of the ichnotope are disturbed by post-depositional processes. These processes are primarily realized in thin clay/sandy intercalations when sandy laminae, most often ripple-marked and therefore being of uneven weight, have either sunk in a simpel load-cast mode, or they display a stronger advance of deformations due to instability in density stratification. Such deformations usually obliterate burrows of echiuroids and ?haustoriid amphipods which are usually confined to the discussed intercalations (sub-units A, C in fig. 12; the same and sub-unit N in fig. 19).

### Dependence of the ichnocoenose upon sedimentary conditions

The presented features of the ichnotope and discussion of the rate of burrowing show that the periods of active work by trace makers upon and into the bottom material was probably very short in comparision to the intervals when the trace makers were absent in the sedimentary area, or when the deposits were slowly scoured away. The greatest changes in the composition and structure of the biocoenose, and consequently of the investigated ichnocoenose were here controlled by the hydrodynamic conditions responsible for the nature and rate of deposition.

Some burrows are confined to slow-current deposited layers, usually either ripple-bedded

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*Fig. 19. Compilation of the sedimentary (physical and biogenic) features and inferred regimes of the lowermost part of Unit 6 at Hagenør. Lithologically the sequence is divided into sub-units A–N, characterized as follows: N - clay/sand intercalations w/ larger lenticular sandbodies. M - sand, laminated, filling an erosional trough. L - sand w/ small-scale cross-bedding. K - sand, laminated (plane bed). J - clay, silty. H - clay. G - sand w/ small-scale cross-bedding; w/ local troughs in the bottom boundary. F - sand, laminated (plane bed). E - clay, silty. D - sand w/ clay intercalations, ripple bedded. C - clay/sand intercalations. B - sand, laminated (plane bed), w/ ripple bedding and ripples in upper part. A - clay/sand intercalations w/ larger sand body; w/ clay seams at top. The photo of the section (by John Sommer) is of a lacquer peel.*

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or cross-bedded. Their makers, ?haustoriid amphipods and echinoids (e. g. in Units 1 and 6 – figs 19 and 21), are therefore thought to have dwelled, certainly searching for food, in an organic-enriched, fresh material transported from zones of higher biogenic productivity. It is even possible that these animals were carried into the sedimentary area by these very currents. Other animals, like gastropods, have evidently been stirred up from their biotopes by storm currents and deposited within or beneath the sediment through which they tried to escape. The escape traces of both the gastropods, and of the sea anemones and pelecypods, being confined to horizontal, parallel-laminated layers (e. g. sub-units B, F, K in fig. 19), evidence formation of the layers by rapid sedimentation from high-energy currents. The *Diopatra*-type of polychaetes streched with their plumes out of the clay deposits in which they dwelled during slower sedimentation. The clayey, sandy bottom, typically of Unit 4 was, otherwise, preferably occupied by Holothurians that had found there the best trophic contitions.

Generally, it is concluded that the trace-making communities were confined to definite hydrodynamic conditions and bottom character, and there are no layers in which all the different types of trace makers occurred together. The trace-making communities were changing in the area with the appearance of new hydrodynamic conditions. Nevertheless, through the entire sequence the same type of facies variety dominated, and most of the discussed trace makers could presumably return in any part of the vertical succession. The ichnocoenose is therefore regarded as being the same for the whole sequence studied.

### Bathymetric requirements

The bathymetric conditions under which this ichnocoenose formed may be estimated only roughly. As it is inferred from the present-day requirements of some communities, these conditions changed at least once through the sequence. The shallowest depths are evidenced by the *Ophiomorpha* burrows beneath the gravel deposits of Unit 2; these depths were certainly very extreme, as confirmed by an erosional truncation of the topmost parts of

the burrows (cf. Weimer & Hoyt 1964). This is the only horizon where decapod burrows occur (fig. 21), and more distinct erosion of the deposit is pronounced. All the other trace makers that are recognized in the investigated sequence range in present-day environments from very shallow subtidal, sometimes even intertidal zone, to a depth of about 30–50 m. Nevertheless, in this sequence there are also depositional premises, viz. an absence of any intertidal and shallowest subtidal sedimentary structures. All the deposits were laid down by currents, most of them stably oriented, and of variable velocity. The deposited material appears not to have been remodelled by waves or stirred up in larger quantities. Deposition is therefore postulated as having taken place at some depth below the wave base.

The frequency of particular trace makers and the set of physical sedimentary structures is referable to those occuring at a range of 10–20 m, at most 30 m in the North Sea (Reineck et al. 1967, 1968; Hertweck 1970; Reineck & Singh 1973). The secondary differences in the trace-fossil frequency and variability are here interpreted as dependant on variable bottom conditions that have controlled the settling and activity of organic communities.

Composition of the communities

The ichnocoenose occuring through the Hagenør-Børup sequence demonstrates an extensive development of organic life that however is recorded mostly by biogenic structures in the sediment. The extreme paucity of body fossils is attributable to subsequent dissolution, the role of which has recently also been evidenced in other Tertiary sequences (Lawrence 1968; Beu et al. 1972; Radwanski 1973). On the other hand, of the trace fossils constructed in the environment, some were certainly better suited for preservation than others, and their present-day frequency in the section is therefore laden with further information loss. The preserved ichnocoenose thus evidences the development of only a part, supposedly a very small one, of the communities that must have been dominated not only by the soft-bodied macrobenthos, but also by the profuse microbenthos that supplied food for larger ani-

mals. The importance of microbenthos, both floral and faunal, was here supposedly similar to that in present-day benthic ecosystems, as demonstrated for example by Fenchel (1969) for Danish waters in northern Øresund and Isefjord. It may generally be concluded that the organic communities that inhabited the Lower Miocene sea of Denmark were of a composition very similar to that of the present-day North Sea.

It should be stressed, however, that in the present-day North Sea the benthic communities comprise trace makers of much greater diversity. Apart from those to which the studied trace fossils are attributable, there occur also other burrowers, e. g. various vagile polychaetes, and crabs, scaphopods, starfish (Schäfer 1956, 1962; Reineck 1958; Reineck & Singh 1973). Any traces of life activity of these animals are not however evidenced in the Hagenør-Børup sequence, and this may result either from their absence in the investigated sedimentary area, or from their having little potential for preservation of traces. The recognition of their traces seems however to be highly possible in this formation. At the section studied, several, usually small burrows, still remain unrecognizable as to their makers, and they may enlarge the trace-fossil spectrum in the future.

Palaeogeographical application

It is noticeable that the investigated sequence is highly comparable to some areas of the present-day North Sea to the predecessor of which, the Neogene North Sea Basin, the investigated region belonged. Nevertheless, when analysing the organic communities, recorded as the ichnocoenose in this sequence, some extraneous elements are also recognizable. These, represented mostly by ?haustroriid amphipods and holothurians, are typical of the Atlantic coast of the southern United States (Frey 1970 b; Howard & Elders 1970; Frey & Howard 1972). Their presence in the Miocene North Sea Basin is therefore suggested to be indicative of warmer climatic conditions at that time. It is instructive that the Miocene mollusk communities in Denmark contain more philothermic forms than are found in the present-day North Sea (Sorgen-

frei 1958, pp. 414–415; Rasmussen 1966, pp.
331–333). The warmer climatic conditions are
also recognizable if the composition of Mio-
cene communitites of the Mediterranean regi-
ons is taken into consideration. In these com-
cunities many subtropical and tropical ben-
thic animals appear that lived there until a
temperature drop at the Neogene decline.
They indicate that in the Miocene Mediterra-
nean basins (both Tethyan and Paratethyan) the
climate was much warmer than it is at pre-
sent in the Mediterranean Zone (Radwanski
1974 a, b, 1975). Similar climatic conditions
are also indicated, within terrestrial floral as-
semblages, by various tropical and subtropi-
cal elements, including the zingiberacean *Spi-
rematospermum wetzleri* which thrived on the
land area surrounding the marine basin in
which the Hagenør-Børup sequence developed
(Koch & Friedrich 1970, 1971; Koch et al.
1973).

## Mineralogical and chemical analyses

Samples selected for laboratory investigations
were all taken from the Børup exposure. A
standard section through the sequence at Bø-
rup is represented by 23 samples (fig. 20).

Mineralogical analyses
The analyses have been restricted to the grain-
size fraction from 74–250 μm. After removal
of organic carbon by $H_2O_2$ this grain-size frac-
tion was separated by wet sieving (fig. 20).

The grain-size fraction 74–250 μm was sep-
arated into a heavy and a light fraction using
bromoform. The heavy fraction was mounted
in Clearax (R. I. = 1.666), the light fraction
in canada balsam (R. I. = 1.54). The mineral-
ogical composition was estimated quantitative-
ly by grain counting. From the light fraction
100 grains were counted, and the quartz/
feldspar ratio was estimated counting a total
of 100 of these mineral grains. From the
heavy fraction the contents of opaque grains
and mica were estimated by counting 100
grains. The mutual proportions of non-opaque
minerals (except mica) were determined by
counting 200 grains (fig. 20).

Chemical analyses
Eleven samples from the clayey part of the
sequence (Units 3 and 5, and lower part of
Unit 6) were analysed for C, Fe and Ca (fig.
20). The C-analyses were made by combustion
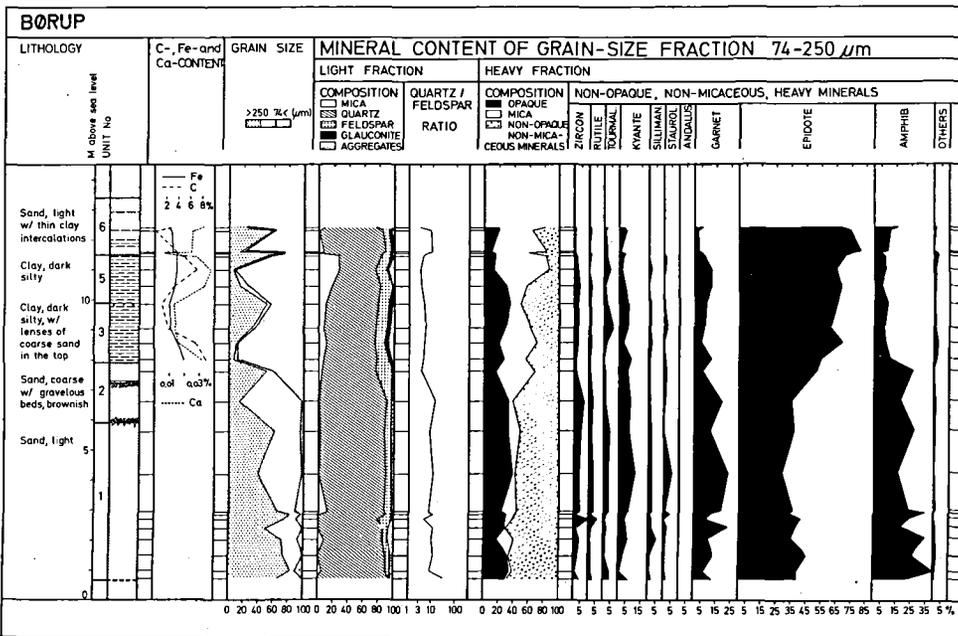


Fig. 20.

(LECO induction furnace), whereas the Fe- and Ca-analyses were made on totally dissolved samples using an atomic absorbtion spectrophotometer (Perkin-Elmer 303 equipment).

## Discussion of mineralogical composition

The light fraction is composed mainly of quartz and feldspar. Most of the feldspars have R. I. $<$ 1.54. Of these (alkalifeldspar and Ca-poor plagioclase), alkalifeldspar predominates. The individual feldspar-grains seem to be unaffected by chemical dissolution processes. The quarts/feldspar ratio ranges from 3–30 (fig. 20). Glauconite is present in low but rather constant proportions throughout the sequence, except Unit 1, where glauconite was not found.

The heavy-mineral association is dominated by epidote and green hornblende, both of which are generally considered to be unstable during chemical weathering (Füchtbauer & Müller 1970, p. 35). In all samples hornblende appears to be quite fresh and unaffected by chemical weathering. Concerning the mutual relation between these two minerals, epidote dominates in the most fine-grained parts of the sequence while hornblende is relatively more abundant in the coarse-grained parts. In the sandy part of the sequence the content of garnet is inversely related to grain-size.

Comparison between the mineralogical composition of the Børup sequence and the Vejle Fjord Formation at Brejning discloses a striking similarity of mineral associations. The relation between grain size and hornblende percentages was previously demonstrated from Brejning (Larsen & Dinesen 1959).

Investigations of other Neogene deposits in Denmark and Schleswig-Holstein show that marine deposits generally contain hornblende while in non-marine deposits hornblende is absent (Bøggild in Harder 1913, pp. 15–30; Weyl 1952; Larsen & Dinesen 1959; Larsen & Friis 1973).

This unstable hornblende-epidote association is presumably the result of a rapid production of detrital material in the source area, rapid transportation to the area of deposition and subsequent superposition of younger sediments

to prevent exposure to weathering processes during the Tertiary.

This assumption is supported by investigations of other Neogene deposits from Denmark which demonstrate that deposits exposed to weathering during the Tertiary have suffered from dissolution of such unstable heavy minerals as hornblende (Friis 1974; Friis & Johannesen 1974). A similar destruction of unstable minerals should have taken place if during transportation the material had temporarily been deposited and subsequently exposed to weathering, and finally reworked.

## Discussion of chemical analyses

The chemical analyses are restricted to the clayey part of the sequence. It is recognizable (fig. 20) that percentages of C and Fe are positively correlated, a large content of C being associated with a large content of Fe. An exception from this correlation are sandy samples from the upper part of the exposure; the high Fe-content of these samples is explained by limonitic segregations due to exudation from ground water. As to the other samples it is supposed that the contents of C and Fe reflect conditions during deposition. The carbon seems to be organically bound as no carbonates have been detected. The Fe-content is presumably represented by pyrite which has been found during macroscopic examination. The content of C and Fe is correlated to the amount of fine grained material ($<$ 74 $\mu$m – fig. 20). In the sequence high contents of C and Fe are found in the dark coloured clayey sediments of Units 3 and 5 with only very few burrows. These circumstances are jointly evidence that these parts of the sequence were deposited in a stagnant evironment with reducing bottom conditions.

Throughout the sequence, the content of Ca is very low (fig. 20). As no carbonates have been found, Ca probably occurs in silicate minerals or in secondary gypsum.

The occurrence of rusty crusts after pelecypod valves (Unit 2) indicates a primary content of $CaCO_3$. Furthermore some of the burrowing organisms, as echinoids, pelecypods and gastropods had a $CaCO_3$-skeleton. This primary content of $CaCO_3$ must have been removed by secondary dissolution, either during

early diagenesis (syndiagenetic initial stage of Fairbridge 1967) or during weathering of the exposed section. Such weathering has not been intensive enough to influence the heavy-mineral association.

## The sedimentary environment

The sequence at Hagenør and Børup (figs 19–21) represents a part of the supposedly Lower Miocene Vejle Fjord Sand Member of the Vejle Fjord Formation. The presented results of mineralogical and chemical analyses together with the biogenic structures are discussed below to give a few notes on the origin of the sediments.

### Succession of environments

*Unit 1*. Unlike the other parts of the sequence, the sandy deposits of Unit 1 have proved to be barren of glauconite. However, related to the occurrence of horizons with echinoid burrows, the absence of glauconite is not indicative of a non-marine origin of the unit. These horizons, which are of undoubtedly marine origin, are found in an otherwise homogeneous sequence, so it is concluded that the whole of Unit 1 was deposited in a marine environment. Since during deposition of Unit 1 the burrowing activity was restricted to rather few episodes, it is supposed that the accumulation was too rapid to allow the establishment of a burrowing fauna within the bottom sediments. Vigorous burrowing activity of echinoids only took place when accumulation was slower.

*Unit 2*. Numerous burrows as well as imprints of pelecypod valves and the content of glauconite prove the coarse, gravelly sands of Unit 2 to be of marine origin. The coarse-grained character of the deposits, together with the convex-upward orientation of the pelecypod valves indicate the current or wave influence of a high-energy environment. The abundant *Ophiomorpha* indicate that deposition took place in an extremely shallow subtidal environment.

The erosional character of the boundary against Unit 1 suggests that conditions chan-

ged rather abruptly to the high-energy environment of Unit 2.

*Unit 3*. This unit consists of brownish-black clay with a considerable amount of organic material and pyrite. Only very few burrows are referred to benthic organisms feeding in the sediment during deposition of this unit. Burrows at the top of Unit 3 are related to changes in the environment refelcted by the deposition of Unit 4. From these properties it is inferred that Unit 3 was deposited in a restricted environment with only temporary water circulation at the bottom.

*Unit 4*. The brown, sandy deposits of Unit 4 show a very high degree of bioturbation. Primary structures are almost obliterated, but the bioturbation indicates a marine environment with oxygen present in bottom waters.

*Unit 5*. The characteristics of Unit 5 correspond to those of Unit 3, and a restricted depositional environment is similarly inferred.

*Unit 6*. In the lower parts, the sandy sequence of Unit 6 contains numerous clay intercalations. Burrows are abundant and indicate a marine depositional environment with well circulating bottom waters. Most of the physical sedimentary structures displayed by this lower part of Unit 6 are indicative of the lower flow regime, or the tranquil flow (Reineck & Singh 1973, fig. 2). However, some of the sandbeds contain only few burrows that are mainly escape traces, indicating rapid accumulation (fig. 7). Accordingly, these parallel laminated beds are interpreted as the plane beds sensu Reineck & Singh (1973) that originate from the upper flow regime, or rapid flow. This indicates that current velocities at the bottom changed rather abruptly several times during deposition of the lower part of Unit 6.

All the structures reported from the lower part of Unit 6 demonstrate a remarkable similarity to those found in the south-eastern part of Recent North Sea. However, it should be emphasized that the present knowledge of sedimentary conditions in the Miocene North Sea is too limited to allow a close comparison of depths and distances to shore line with those of the Recent North Sea.

### Concluding remarks
All parts of the sequence were deposited in a
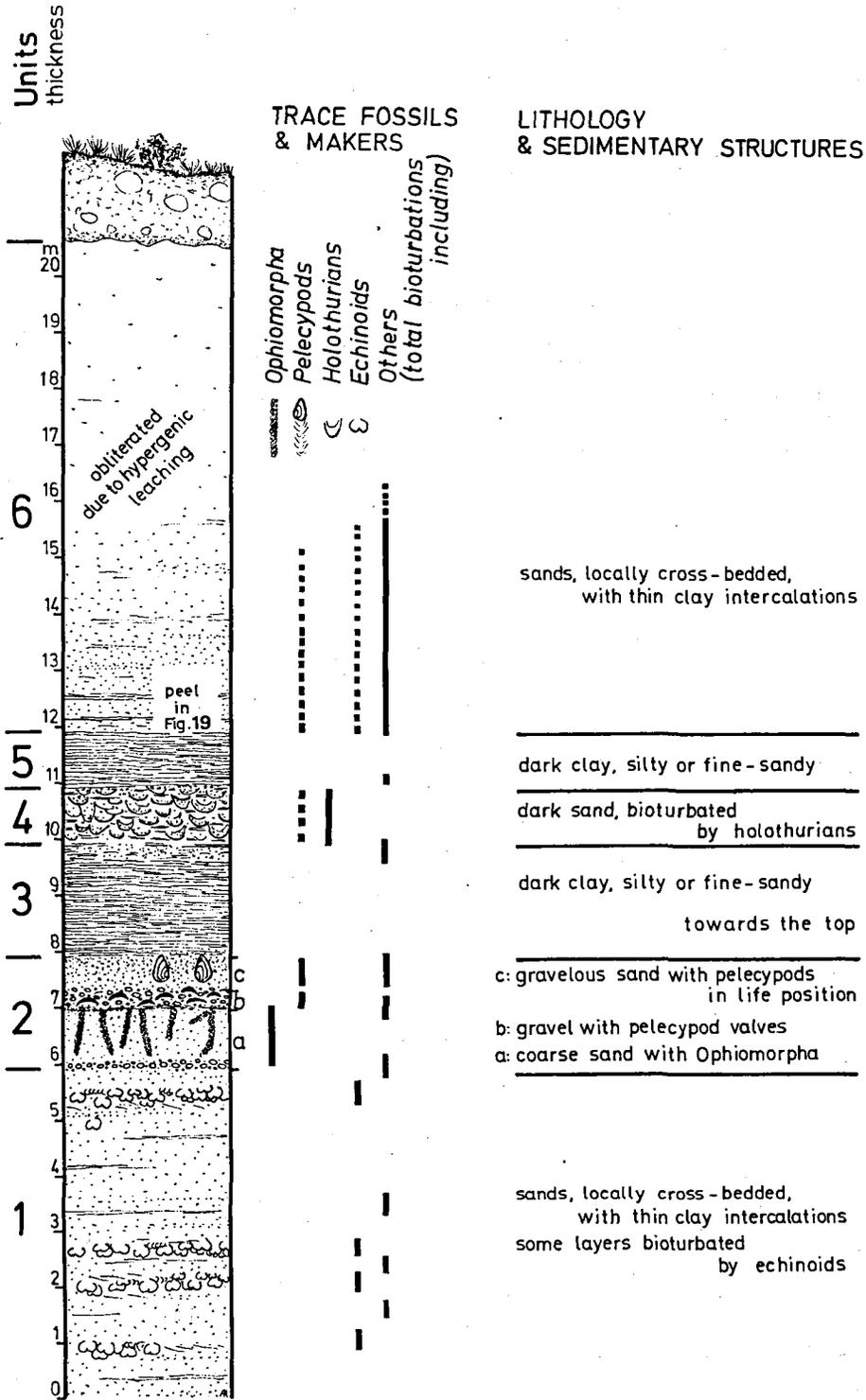
Fig. 21. Generalized sequence exposed at Hagenør and Børup (cf. fig. 2).

marine environment with periods of open, high-energy conditions changing with low-energy, more or less restricted conditions. The exposures are situated at the easternmost limit of Neogene deposits in Denmark (fig. 1), and it is inferred that the changing marine conditions represent the environmental conditions in the marginal parts of the Miocene North Sea.

Previously Larsen & Dinesen (1959) discussed the palaeogeographical development of the eastern margin of the Oligocene/Miocene North Sea as it appeared from investigations of the Vejle Fjord Formation at Brejning. The depositional environment of the Vejle Fjord Clay Member was compared to Recent Præstø Fjord where black muds are deposited, sheltered by a marine sand bar (Hansen 1944; Larsen & Dinesen 1959, fig. 20). Similar conditions are found along the present-day North Sea coast of Jylland, and it was concluded that during deposition of the Vejle Fjord Clay Member, conditions were very much like those of present-day North Sea.

From the exposures at Hagenør and Børup (referred to the Vejle Fjord Sand Member) further details on palaeogeographical conditions may be added. In the Vejle Fjord Sand Member, the rapid deposition of sand in Unit 1 is believed to represent the growth of a sand bar, capped by the decapod burrowed gravel deposits of Unit 2. The dark clays of Units 3 and 5 were deposited in a protected area, maybe of a lagoon type, which was restricted from the open North Sea by a bar, similar to that exposed at Børup. The rapidly changing lithology of Unit 6 may be a reflection of strongly changing current influence in more open waters, below the wave base. Such conditions may have existed within the coastal zone, protected by bars, or they may have been found at greater depths, as for instance in the present-day North Sea near Helgoland.

It is concluded consequently that the deposition of the parts of the Vejle Fjord Sand Member, exposed at Hagenør and Børup, took place in the coastal region of the Neogene North Sea, environmental conditions of which were very similar to those of the Recent North Sea coast, where lagoons, restricted by bars,

alternate with areas of open marine conditions.

## Dansk sammendrag

Der fremlægges en undersøgelse af en ca. 20 m mægtig ungtertiær lagserie blottet i klintprofiler ved Hagenør og Børup på den jydske Lillebælt-kyst (fig. 1 og 2). Støttet på oplysninger fra boringer er lagserien søgt korreleret med Vejle Fjord formationen ved Brejning; resultatet heraf er, at aflejringerne ved Hagenør og Børup øjensynlig udgør en del af det formodede nedre miocæne Vejle Fjord sand.

På lithologisk grundlag kan den undersøgte lagserie opdeles i flg. 6 enheder (fig. 3 og 6):

   6: lyst sand, nedre del indeholdende mørke lerlag og talrige gravegange.

   5: sort ler

   4: brunt sand, stærkt bioturberet

   3: sort ler

   2: brunt sand, groft gruset, stærkt bioturberet, med aftryk af pelecypoder (fig. 4 og 5).

   1: lyst sand, med enkelte horisonter indeholdende gravegange.

For enhed 4 gælder, at den kun er udviklet i Hagenør-profilet.

Feltundersøgelserne har foruden almindelig lithologi især omfattet studier over biogene sedimentstrukturer. I laboratoriet er der foretaget analyser af mineralindhold og kemiske komponenter i en prøveserie fra Børup-profilet (fig. 20).

Undersøgelsernes hovedemne er de biogene sedimentstrukturer frembragt af bundlevende organismers aktivitet i havbunden. Der er påvist spor efter flg. taxonomiske grupper:

   søanemoner (fig. 7)

   polychæter (fig. 8)

   echiuroider (fig. 9)

   ?haustoriide amphipoder (fig. 10)

   callianasside decapoder (fig. 11)

   gastropoder (fig. 12)

   pelecypoder (fig. 13)

   holothurier (fig. 14)

   echinoider (fig. 15–18)

Disse sporfossilers optræden i lagserien (fig. 19 og 21) fortæller om ret betydelige ændringer i bundmiljø og hydrodynamiske tilstande under lagseriens udvikling. Eksempelvis må enhed 2 ifølge forekomsten af spor efter callianasside decapoder være dannet på meget lavt vand; enhed 6 indeholder sedimentstrukturer svarende til dem, man møder i de sydlige dele af den recente Nordsø på vanddybder fra 10 til 30 m. For enhederne 3 og 5 må man ifølge sortfarvning, stort C-indhold og mangel på sporfossiler antage stagnerende muligvis lagunære miljøforhold.

Forekomsterne ved Hagenør og Børup er lokaliseret nær den østlige grænse af ungtertiærets udbredelsesområde (fig. 1). Hele den undersøgte lagserie er øjen-

synlig marin. Det er således miljøforholdene ud for den danske ungtertiære Nordsøkyst, lagserien belyser. På væsentlige punkter synes de at svare til forholdene ved nutidens danske Nordsøkyst.

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