Sedimentary history of the island Læsø, Denmark

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Coastal sections on the island Læsø in the northern Kattegat, Denmark, expose many well-preserved sedimentary structures. These structures have been studied in order to gain information about the postglacial sedimentary history of the island. Furthermore, numerous beach ridges make it possible to reconstruct the size and shape of the island at all stages of its development. During early postglacial transgressions and alternating regressions the island was represented by a shoal. During the transgressions the shoal was inhabited by the heart urchin *Echinocardium cordatum*, whereas it was inhabited by the lugworm *Arenicola marina* during regressions. Heart urchin-burrowed layers are found in three horizons with lugworm-burrowed beds below and above the upper heart urchin-burrowed horizon. The burrows of the two animals are found in different sedimentary facies, thus also suggesting different hydrographic conditions by means of physical sedimentary structures. In places the lugworm-burrowed horizons are characterized by irregular erosion surfaces. Similar structures are found today at the pseudo-tidal flats south of Læsø, where they are formed by partial erosion of algal mats. The alternation of different sedimentary structures including trace fossils and irregular erosion surfaces is thus believed to reflect postglacial transgressions and regressions.

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The island Læsø in the northern Kattegat, Denmark, was built up mainly during postglacial transgressions and regressions. The sea cliffs provide extensive sections of sedimentary structures including well-preserved trace fossils. Numerous beach ridges make it possible to reconstruct size and shape of the island at all stages of its development (fig. 1). The combined evidence from beach ridges and other sedimentary structures provides a detailed history of the forces and events involved. The cliff at Bansten Bakke (fig. 2), which cuts through an old tongue of land, shows a continuous sequence of sediments from the initial transgressions as far as the maximum extent of series of Subboreal transgressions. In addition, a study of the recent

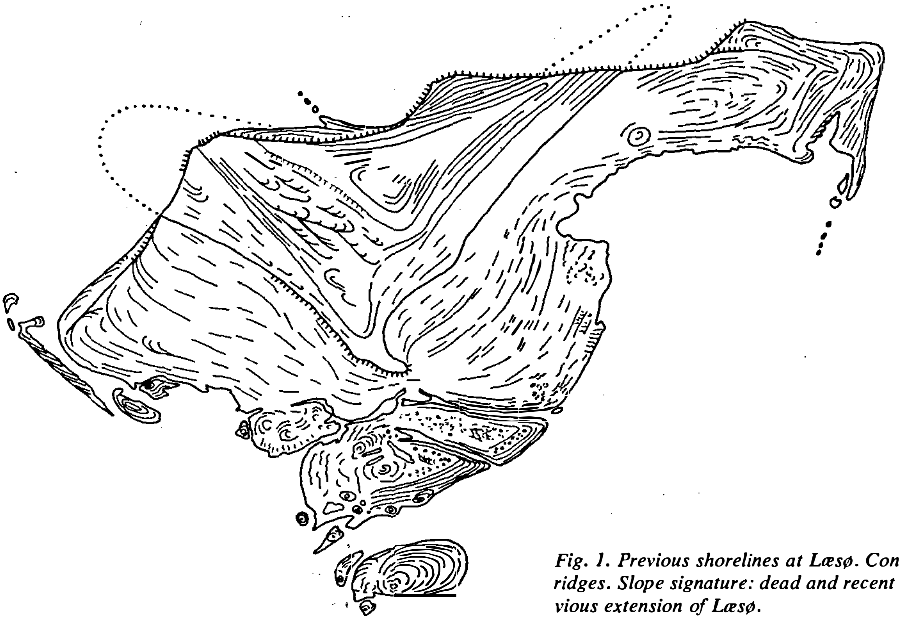

Fig. 1. Previous shorelines at Læsø. Continuous lines: beach ridges. Slope signature: dead and recent cliffs. Stippled: previous extension of Læsø.

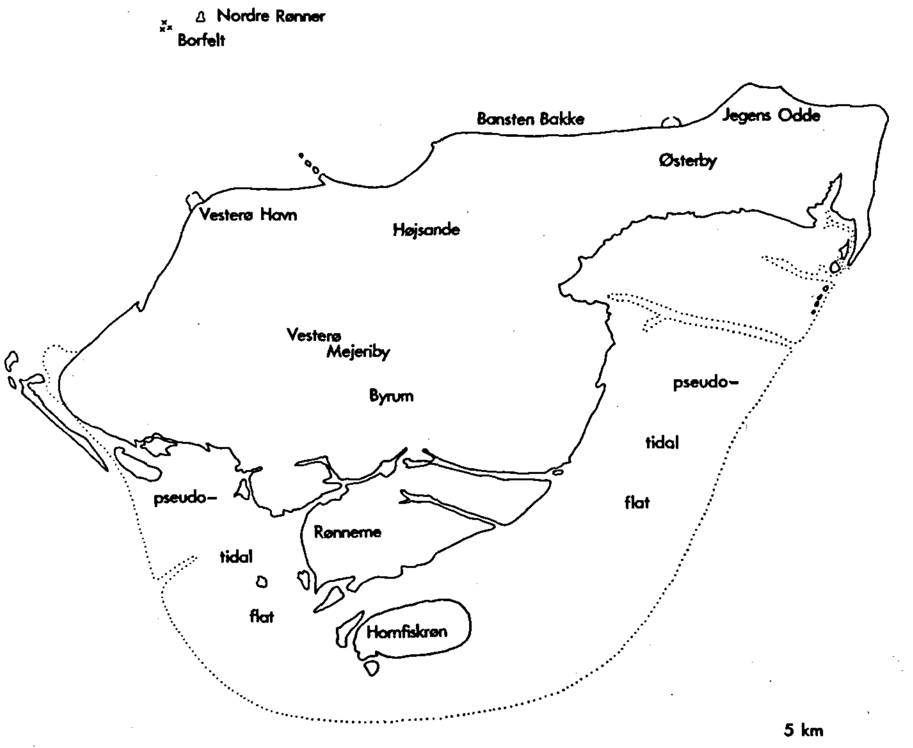

Fig. 2. Locality map.

pseudo-tidal flats south of Læsø provides an explanation of some of the structures involved and adds significantly to the conclusions that can be drawn.

Previous work has been carried out by Jessen (1897, 1920 & 1936), who gave an outline of the general geology. Michelsen (1967) dealt with the Foraminifera from the late glacial Yoldia Clay and from the lowermost part of the sand and gave (1968) a brief outline of the beach ridge sytem. Mörner (1969) visited the island as a part of a major work on the late and postglacial history of the Kattegat.

The island is built up of 5 sedimentary units (mentioned in sedimentary order):

1. The *Yoldia Clay*. Exposed north of Vestrø Havn, at Bansten Bakke and in several clay pits in the southern part of the island. Thickness unknown. Radiocarbon age: 10.960 ± 180 years BC (Tauber 1966).
2. *Residual gravel and blocks* resting on the Yoldia Clay. Thickness 0–0.5 m.
3. *Marine sand*. Exposed in the coastal sections along the north and west coast and in a pit 3 km west of Byrum. Thickness 0–13 m.
4. *Beach sediment*. Exposed in the coastal sections along the north and west coast and in several pits. Thickness 0–5 m. Radiocarbon age: Tooth of sperm whale (*Physeter catodon*) found north of Byrum, 4.5 m above sea level, 980 ± 80 years BC (Tauber, in litt.).
5. *Aeolian sand*. Thickness 0–17 m. Main part formed in the 18th century.

The present paper deals with the Yoldia Clay, laying special emphasis on the overlaying marine sand and beach sediments, which contain the well-preserved sediment structures.

The Yoldia Clay

The late glacial Yoldia Clay underlies the entire northern Kattegat sea and covers extensive parts of northern Jylland, and forms the platform upon which the postglacial sand of Læsø has been

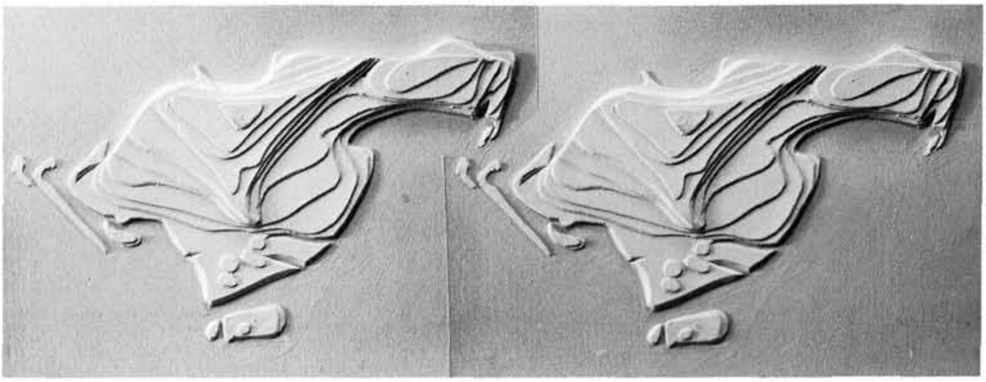

Fig. 3. Model (stereopair) showing the supposed relation between time and shape of Læsø. Each step roughly *corresponds to 500 years. Notice that the steps do not correspond to contours, since the isostatic recovery of the northern part of Læsø has been 2–3 m greater than of the southern part (cf. Mertz 1924).*

built up. It has a variable lithology, ranging from sticky, silty clay to more or less sandy silt or even to muddy and stony sand. In places the Yoldia Clay is very rich in stones and boulders some of which are very large (about 50 tons). In the southern part of Læsø, where the postglacial sand sheet is very thin, these boulders are strewn over considerable areas, probably as a result of outwash during the Ancylus time and during the postglacial transgressions (Michelsen 1967). Jessen (1897) suggested that the boulders were derived from drift ice, an idea that might be supported by the fact that the Yoldia Clay is specifically rich in boulders where it formed highs at the sea bottom. The small islands and shoals north of Læsø (Nordre Rønner and Borfelt) are almost entirely built up of boulders of quite unusual size in spite of the total lack of tills or till-ridges on Læsø and its neighbourhood. Therefore it seems likely that the Yoldia Clay was formed as some kind of drop-till while the late Weichselian ice stood near the Swedish west coast or even farther westwards. Mörner (1969) assumed the presence of a till-ridge running north-south through Læsø. The presence of this till-ridge is speculative and not supported by primary observations. If present, the till-ridge must be buried under several metres of Yoldia Clay.

Locally the Yoldia Clay contains an abundant fauna dominated by *Saxicava arctica, Macoma calcarea* and *Balanus* sp., whereas *Portlandia arctica* is rare. However, fossils are generally few and those that occur are often crushed, probably by boulders as they hit and deformed the sediment or by ice bergs ploughing through the sediment. Both in borings and exposures the Yoldia Clay is overlain by a thin layer of gravel and stones obviously derived from the clay. This layer is equivalent to the boulders strewn on the southern part of Læsø.

The postglacial sand

Briefly the postglacial sand can be divided into an older and a younger part with reference to topography. The older part forms the triangular raised part of the island, which to the south is surrounded by the younger part, and to the north by the sea. The two parts of different age are separated by fossil cliffs and big beach ridges. The older part of the sand formation is up to 13 m thick and elevated 6 to 11 m above sea level, whereas the younger part is much thinner, ranging mostly from 0 to 3 m, and is not elevated more than 4.5 m above sea level. During earlier stages Læsø had a shape much like that of the island Anholt in the middle of the Kattegat. As seen in figs. 1 & 3, the eastern end of this older part of Læsø is cut by the present shoreline. The section at this locality shows the previous exist-

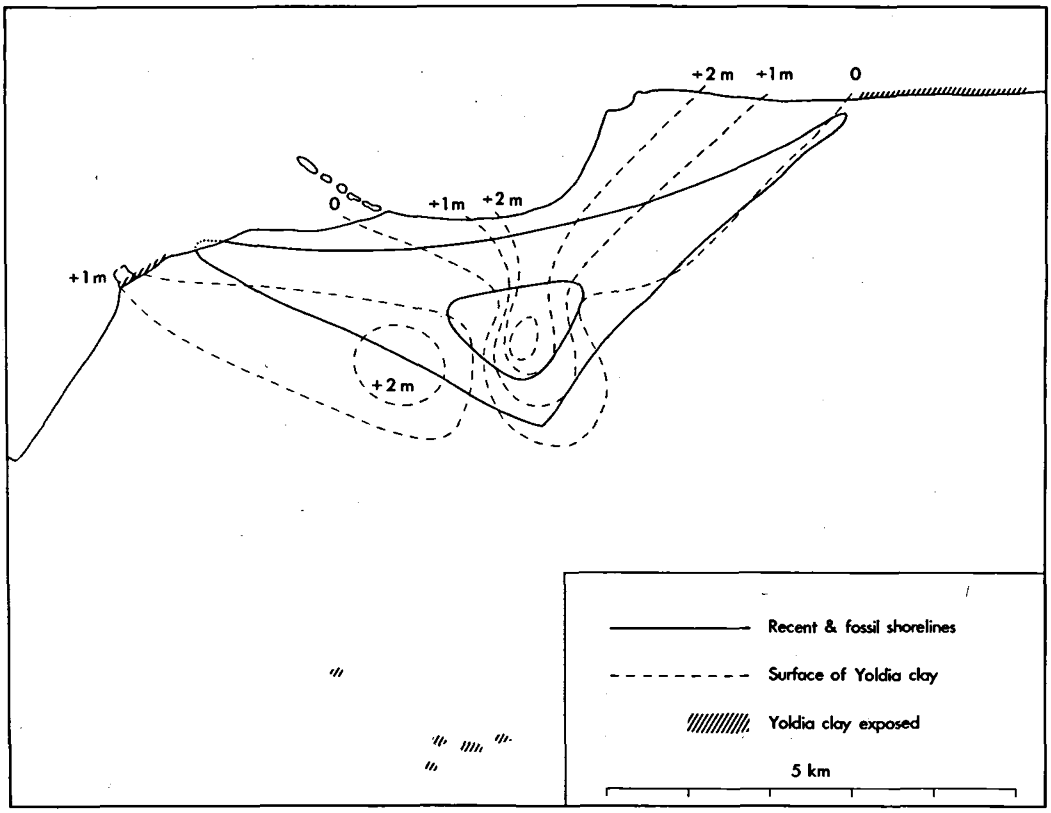

Fig. 4. Surface of the Yoldia Clay and early stages of Læsø's development.

ence of a tongue of land very like the eastern part of Anholt and orientated in the same direction.

The island of Anholt is built up on the lee side of a moraine knoll (Jessen 1897 & Schou 1945). However, no such structure exists or has existed at Læsø. On the contrary, Læsø seems initially to have been built up on the lee side of a high but submerged part of the Yoldia Clay (fig. 4). The triangular "core" of Læsø from which point growth started, is situated immediately east of the highest part of the Yoldia Clay under the sand. From this point Læsø grew northeastwards forming a long tongue of land according to the dominating wind direction, and also west- and southwards in response to the position of the Yoldia Clay platform. As seen in fig. 1 this growth took the form of a succession of recurved spits on the SW side of the island. These recurved spits migrated southeastwards. In contrast, the growth of the tongue of land followed a series of linear beach ridges.

During a postglacial transgression maximum, probably a Subboreal transgression (Iversen 1937 & 1967) (see discussion later), the fossil cliffs and big linear beach ridges surrounding the older triangular part of Læsø were formed. Subsequent shallowing of the sea produced a new regime of currents around Læsø. This is evident from the fact that the recurved spits on the southwestern part of Læsø during these stages migrated northwestwards, whereas they migrated southeastwards during the older stages (cf. fig. 1). It is clear that the sea shallowed considerably after the Subboreal transgression because of the fact that the marine sand surrounding the old triangle is only elevated maximally 4.5 m above present sea level, whereas the old triangle is elevated at least 6 m, except for a very narrow

Fig. 5. Irregular erosion of algal mat; pseudo-tidal flat southwest of Læsø. Notice that the surface is scattered with traces after Corophium volutator.

zone between the old and the young part. By this process the Yoldia Clay platform came so close to the sea level that the wave action at the south coast became of less influence, resulting in a shape completely different from the old triangle.

In addition, the large, younger peninsula on which the village of Østerby is situated was initiated by the occurrence of an island east of the older triangular island. The two islands became probably interconnected by a bar running from the area north of Bansten Bakke to Jegens Odde, where a cliff section shows sedimentary structures including trace fossils similar to those in the cliff at Bansten Bakke.

The southernmost part of Læsø has been formed in a rather different way. The beach ridges are very irregular and low. Here the surface of the Yoldia Clay is very close to the sea level, thus strongly controlling the shoreline, even when minor changes in sea level arise. The area is believed to have been formed by emergence and overgrowth of a pseudo-tidal flat rather similar to that found south of Læsø today. The southern part of Læsø, Rønnerne, is cut by numerous pseudo-tidal channels carrying the water in and out, when the area occasionally is partly submerged. The lower part of the area between the pseudo-tidal channels is covered by halophytes alternating with numerous very shallow ponds. The salt concentration in the pond water varies greatly. During rainy days the water may be nearly fresh, while on hot sunny days the salinity greatly exceeds that of the sea water. The faunal and floral elements in the ponds and the channels are thus restricted to a few species of arthropods and algae. The higher part of the area between the pseudo-tidal channels is dominated by ericaceans.

The topography of channels and ponds at the southernmost part of Læsø has mostly been produced by the emergence of the pseudo-tidal flat through the formation of many small islands that steadily grew by accretion of plant-remains and sand at the borderlines of the islands. Thus the islands as seen from the air (e.g. Hornfiskerøn) somewhat resemble mussel shells with their numerous growthlines.

Pseudo-tidal flats

In the ultimate stages of the history of Læsø the Yoldia Clay platform was raised so much, that on the southern part of Læsø it became very close to the sea level. In this way a wave-cut platform, which soon developed into a pseudo-tidal flat, was formed. In most places the pseudo-tidal flat extends 5 km or more south of Læsø (fig. 2). It should be emphasized that the onshore and offshore currents of seawater on this pseudo-tidal flat are not controlled by normal tidal forces, but rather by wind strength and direction. Thus the flat can be exposed to the air for considerable periods, e.g. a month, and submerged for even longer periods. However, these alternating periods of different hydrographic conditions usually change after a few days, so that the sand only very rarely becomes completely dry.

The sedimentation in this area seems to be partly controlled by algal mats, which cover the entire area. Therefore sedimentary structures other than horizontal lamination and, less common, small scale ripples are rare. The algal mats are usually 1–2 cm thick and not very cohesive. They can be eroded by the pseudo-tidal flow of water to produce irregular erosional surfaces (fig. 5). The structure of these surfaces is treated later. During strong gales the wind may cause erosion of the algal mats because of drying. This has only been observed by the author once (from an aeroplane), but on that occasion an area of about 30 km^2 was covered with numerous small barcan-like aeolian dunes, not more than 1 m high. The dunes were destroyed by the next in-

Fig. 6. Paddling trails of the seagulls Larus argentatus *or* L. fuscus. *The surface is scattered with traces after* Corophium volutator.

cursion of the sea. During such gales stony deflation surfaces can also be formed. At the flats southwest of Læsø, where the sand in places is rather stony because of outwash from the Yoldia Clay, such deflation surfaces are frequent. The pebbles are usually covered and bound together by a peculiar alga, which forms thin parchment-like and very stony sheets, thus stabilizing the deflation surface for considerable periods of time.

Because of these extreme conditions the diversity of the fauna is rather limited. The main constituents are *Arenicola marina, Nereis diversicolor, Corophium volutator* and *Cardium edule,* which all are burrowing animals. In addition rather small amounts of other molluscs are present, e.g. *Mya arenarea,* which also burrows, and a few epifaunal elements dominated by *Littorina littorea* and *Hydrobia ulvae*. The distribution of these animals is somewhat patchy, the lower part of the pseudo-tidal flat being dominated by *Cardium edule,* the upper part by *Arenicola marina*. Small, very shallow depressions, which are not completely dried out during temporary periods of exposure, are dominated by *Corophium volutator*. It is a general rule that the burrowing depth of the animals roughly corresponds to the number of days in which the sand is exposed during a year.

Otherwise the area is inhabited by a great number of birds, which are not without importance for the sand-accumulation.Seagulls are very common in the area and largely feed upon animals from the upper part of the sediment using a special method. With their heads turned into the wind the seagulls 'paddle' rapidly with both legs, thus whirling up the sediment containing their food. Moving foreward against the wind a peculiar kind of trace is formed (fig. 6), which I suggest calling a 'paddling trail'. Hertweck

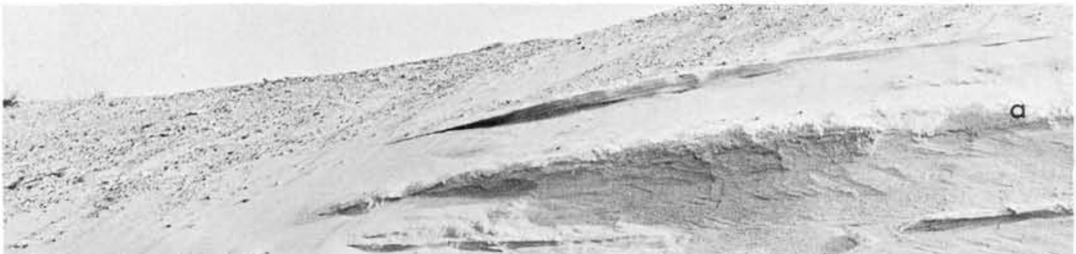

Fig. 7. Central part of the cliff at Bansten Bakke showing the upper (a) and the middle (b) Echinocardium-*burrowed horizon intercallated with sediment of facies 1. In the middle* Echinocardium-*burrowed horizon (b), the primary sedimentary structures are totally obscured in two minor horizons, whereas horizontal lamination is partly visible outside these horizons.*

Fig. 8. Beach sediment from the eastern part of the cliff at Bansten Bakke. Stone-layers dipping southeastwards intercallated with parallel laminted and convex upwards cross-bedded sand-ripples migrating northwestwards.

(1970: 110) called this kind of trail a resting trace. However, this description is considered to be inaccurate, since the paddling trails can be very long (30 m or more), and since this special paddling behavior in seagulls has been observed several times. Furthermore, the paddling trails are preferentially found in the shallow depressions where *C. volutator* predominates. The paddling trail is composed of two parallel rows of U-shaped furrows in the sand, with the open end of the U in the direction of movement. The paddling trail leaves the sand completely loose with most of the algal filamants on the top of it. If the sea-water begins to move before the sand is reinhabited and bound by the algae, the paddling trails will form week points in the algal mat where erosion can start and undermine the mat, which is then easily broken down.

Sedimentary structures

The cliff at Bansten Bakke (figs. 7, 8 & 9), which cuts through an old tongue of land, shows many extremely well-preserved structures, both trace fossils and physical sedimentary structures.

In general the cliff shows the Yoldia Clay at the bottom, overlain by three horizons intensively bioturbated by *Echinocardium cordatum*. These horizons are generally horizonatally laminated or small-scale ripple laminated. The *Echinocardium*-burrowed horizons are interbedded with large-scale cross-laminated or small-scale rippled horizons. In the latter type of sediment the dominating trace fossils are funnels made by *Arenicola marina*. It is remarkable that where the two types of trace fossils are found together, their cross-cutting relationships nevertheless indicate that the two species never inhabited the sediment together: either all *Arenicola* funnels are cut by *Echinocardium* burrows or the *Echinocardium* burrows are cut by *Arenicola* funnels (fig. 10).

In the upper part of the cliff section other structures are encountered. These are very irregular erosional surfaces, which are believed to have been formed by partial erosion of algal mats (see below), and a deflation surface represented by a single layer of partly polished stones.

To the east the section is capped by beach ridges composed of very coarse-grained layers interbedded with cross-laminated sand. The entire section is overlain by aeolian sand, in places developed as small dunes with large-scale low-angle concave upwards cross-laminations.

Physical sedimentary structures

On the basis of physical sedimentary structures alone three major sedimentary facies can be distinguished. These are:

Facies 1: Figs 7, 9, 10, 15, 17, 18 & 20. Large-scale cross-laminated horizons (of which there are four) with rather few trace fossils preserved. These trace fossils are dominated by funnels made by *Arenicola marina*. The large-scale cross-laminations are mostly of two kinds: 1) erosive structures composed of either planar or concave upwards sets and 2) nonerosive planar to convex upwards sets. The convex upwards sets are quite similar to those described under facies 3. The structures of facies 1 commonly are associated, especially in the upper and middle horizons, with irregular erosion surfaces. The uppermost horizon of this type contains a deflation surface, whereas the lowermost horizon

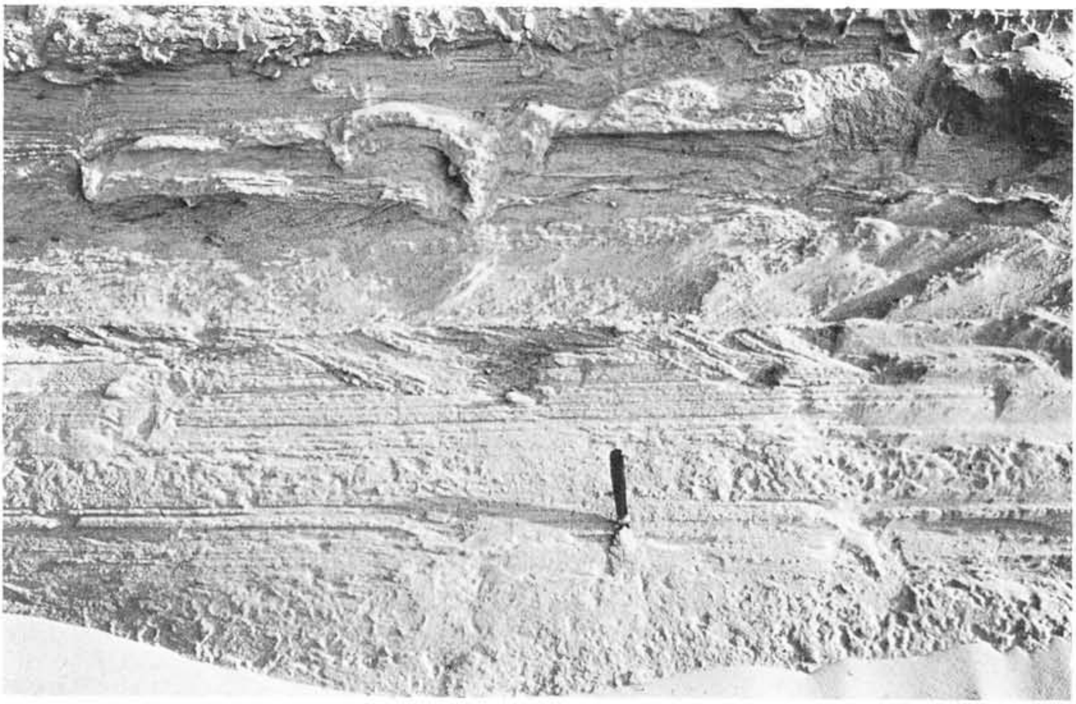

Fig. 9. Central part of the cliff at Bansten Bakke showing sediment of facies 2 containing Echinocardium *burrows and irregularly eroded by sediment of facies 1 containing* Arenicola *funnels.*

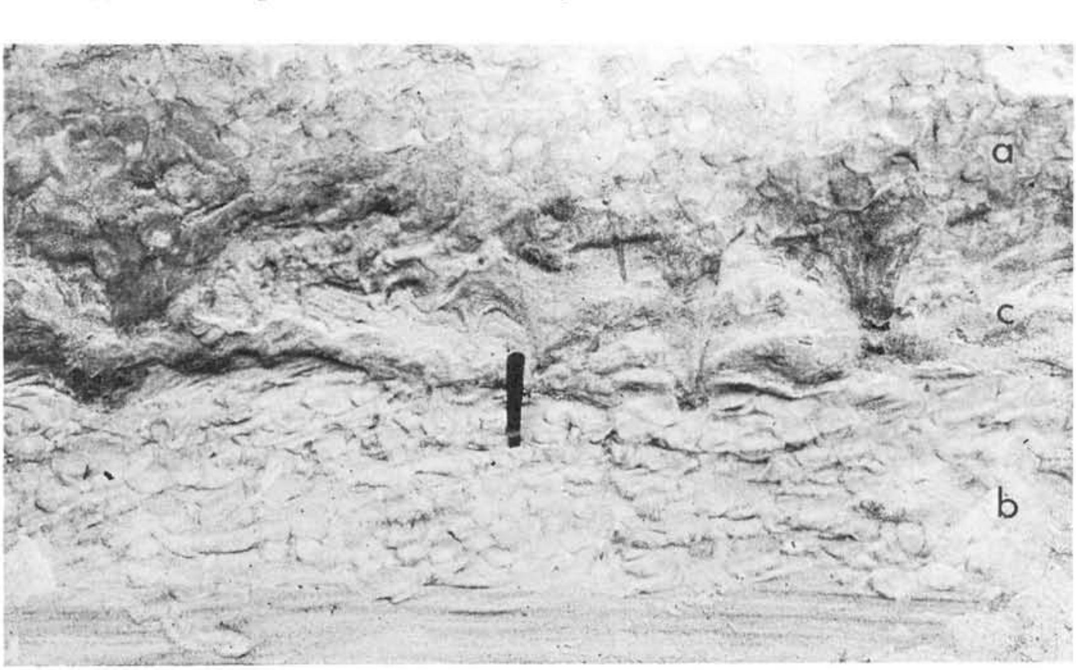

Fig. 10. Echinocardium *burrows from the upper (a) and middle (b)* Echinocardium-*burrowed horizon separated by a thin horizon of facies 1 containing* Arenicola *funnels (c). All the* Arenicola *funnels are truncated by* Echinocardium *burrows from horizon a, while the* Arenicola *funnels cut the* Echinocardium *burrows from horizon b indicating that the two species did not live in the sediment simultaneously. Furthermore,* Echinocardium *burrows from horizon a are found to a depth of c. 10 cm below the upper limit of the* Arenicola *funnels indicating that the burrowing depth of* Echinocardium *could be at least 10 cm.*

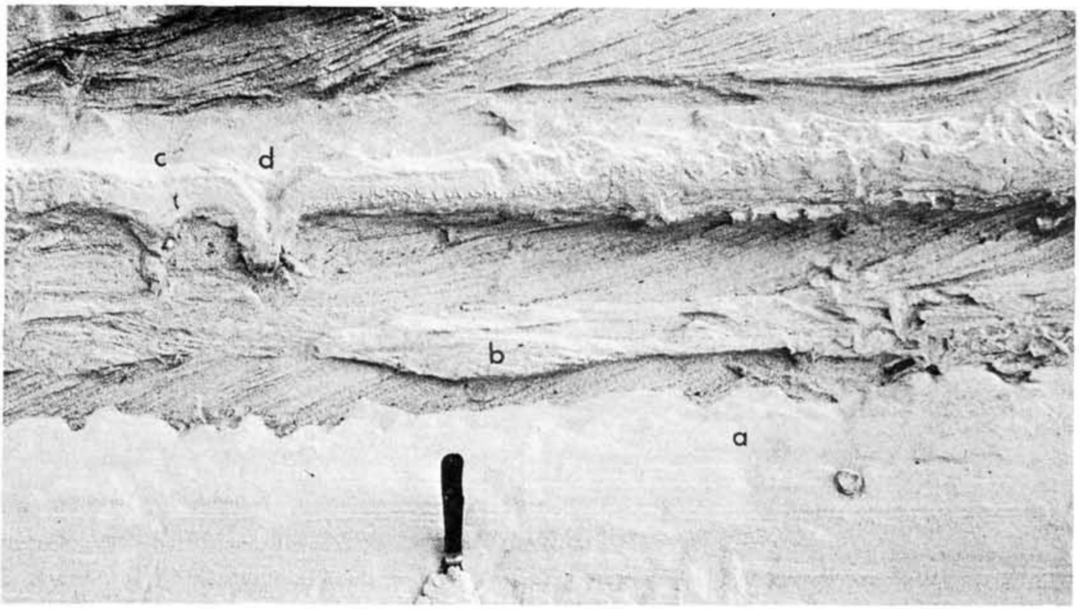

Fig. 11. Sediment of facies 2 (a) without Echinocardium *burrows irregularly eroded by sediment of facies 1 (b) containing* Arenicola *funnels (c, d) cut both laterally and centrally by the cliff-section.*

contains no such structures that would indicate very shallow water or exposure to the air. In addition the lowermost horizon contains numerous horizontally laminated layers. The orientation of the cross-laminations seems to be bimodal to polymodal, which in places gives rise to well developed 'herringbone' structures.

Facies 2: Figs 7, 9, 10, 11, 14, 15, 16, 17 & 20. Horizons (of which there are three) with small-scale troughs, small-scale ripple lamination and horizontally laminated layers. This type of sediment is associated with numerous burrows of *Echinocardium cordatum* that in many places completely have obscured the physical sedimentary structures. The orientation of the small-scale ripples seems to be random.

Facies 3: Fig. 8. In this facies there are three basic structures: 1) 10–100 cm thick, gently SE dipping layers composed of very stony horizons and parallel to them, parallel-laminated sand, 2) scour and fill structures, and 3) convex upwards large-scale cross-laminations. The strike of the stony horizons parallels the beach ridges seen at the top of the cliff. The axes of the scour and fill structures also tend to parallel the beach ridges, whereas the convex upwards cross-laminations tend to show migration towards land. Facies 3 is in direct connection with the beach ridges at the top of the cliff, and represents obvious beach sediments.

Trace fossils

Trace fossils of many kinds are present, but only three kinds will be considered here: burrows of the heart urchin *Echinocardium cordatum,* funnels made by the lugworm *Arenicola marina* and notches produced by *Pectinaria* sp. Besides these structures there are also trace fossils attributable to bivalve and crustacean activity. Specially conspicuous are escape traces of probable bivalves. Most of the traces are visible because of variations in concentration of the rather high proportion of heavy minerals in the sand. But the slightest difference in grain size also makes the trace stand out in the section in windy and dry weather, whereas the structures are almost invisible on rainy days and for many days afterwards. Because of these circimstances the section only rarely is in a satisfactory condition for study.

Lugworm funnels. Figs 9, 10, 11 & 17. Funnels made by *Arenicola marina* are often found in

Fig. 12. The J-shaped domichnion of Arenicola marina.

facies 1. Because these structures have their greatest extension in the vertical plane their appearance is highly dependent on the arbitrary section represented by the cliff (fig. 11). The funnels have a core of more or less structureless sand with or without vertical striations. The core is surrounded by only slightly disturbed sediment, the laminae of the contact zone being gently bent downwards. The depth of the funnels varies considerably, ranging from 5 to 30 cm. This type of funnel is restricted to sediment completely free of mud, as in the cliff. On the pseudo-tidal flat south of Læsø, where the sediment locally is muddy, the structures made by the lugworms are only funnel-shaped in the uppermost part, whereas they form narrow tubes in the lower part . Similar variations were described by Schäfer (1962: 341 & 410). In very rare cases the characteristic J-shaped domichnion of the lugworm is found (fig. 12). This takes the form of a narrow, light fill (the same colour as the sand that the worm feeds upon) coated with a dark layer of heavy minerals.

In general the funnels are largest near horizons of facies 2 and smallest in the middle of horizons of facies 1. Since facies 1 is supposed to have been formed at shallower water depths than facies 2, one should expect the middle part of facies 1 to represent the shallowest condition during a regression. It is wellknown that small lugworms prefer shallow water, and that the worms migrate to deeper water during their growth. Thus the distribution of different sized lugworm traces supports the transgression/regression model presented in the following.

In recent seas *Arenicola marina* lives at water

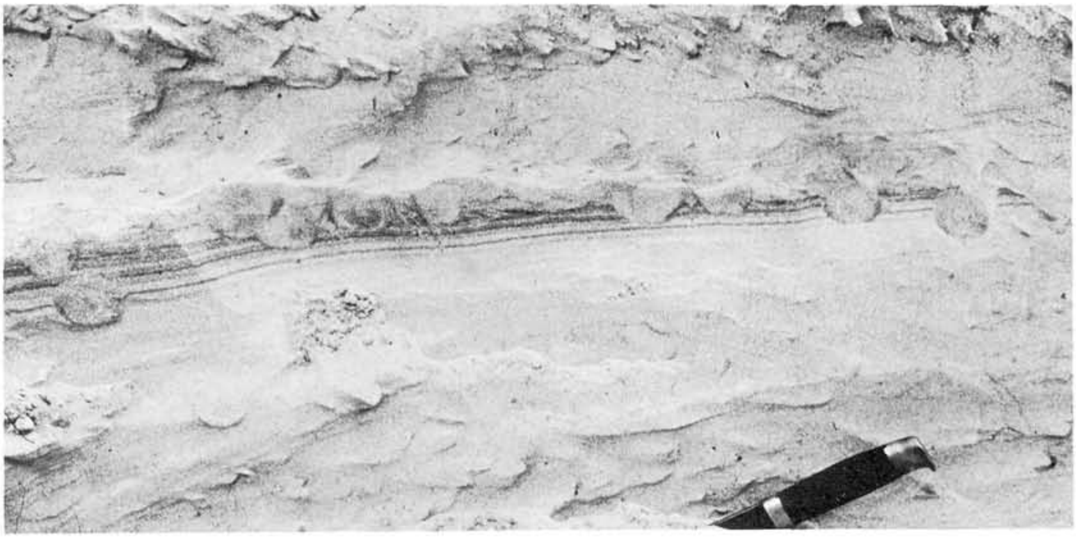

Fig. 13. Cross-sections of Echinocardium *burrows with visible backfilling structures.*

Fig. 14. The lower Echinocardium-*burrowed horizon in the eastern part of the cliff at Bansten Bakke, where the horizon may be more than 1 m thick and very intensively bioturbated.*

depths close to sea level, or more abundant within the intertidal zone. It should be emphasized that *Arenicola marina* has not been reported from bottom communities containing *Echinocardium cordatum.*

Heart urchin burrows. Figs 7, 9, 10, 12, 13, 14, 15 & 17. In association with facies 2 there are usually great numbers of burrows of heart urchins. Typically they are visible in cross-section and rarely identified in longitudinal sections, owing to poor development of the back-filling structure. In cross-section they are seen as circular to semicircular concentrations of heavy minerals corresponding to the outer limit of the locomotion trace. The semicircular cross-section

Fig. 15. Echinocardium *burrows in sediment of facies 2 (a) overlain by sediment of facies 1 containing escape-traces of* Echinocardium *(b).*

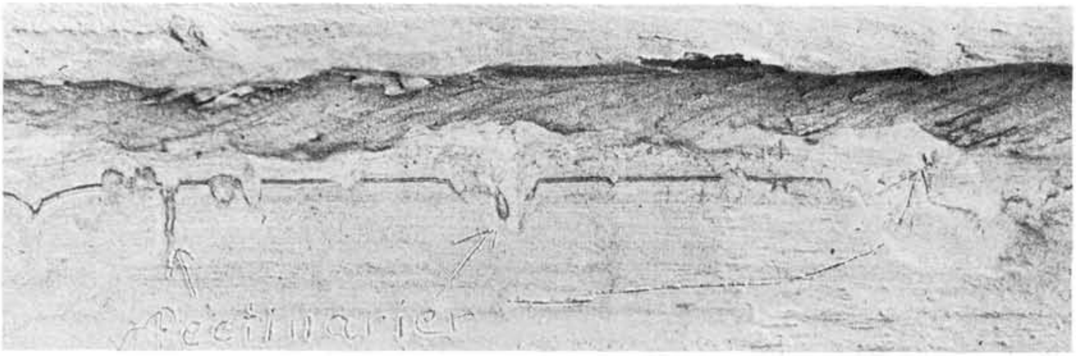

Fig. 16. Notches produced by Pectinaria *sp. in sediment of facies 2 overlain by an irregular erosion surface and sediment of facies 1.*

of most burrows – with the open end upwards – is either due to partial collapse of the roof or more commonly to truncation by a younger locomotion trace. The burrowing depth was c. 10 cm (fig. 9). Usually the animals burrowed in the horizontal plane in a meandering manner, but steeply inclined burrows have also been observed. Escape traces through more than 50 cm thick megaripples have been observed in some cases (fig. 15). These are straight and inclined at an angle of about 45°.

The structures here described resemble strongly those observed in living *Echinocardium cordatum,* by which species they are believed to have been formed: the burrowing depth rules out the possibility of any other heart urchin – see discussion and more complete bibliography in Bromley & Asgaard (1975).

At Bansten Bakke the heart urchins lived at water depths not exceeding 14 m. Concerning the entire triangular area they probably lived at water depths not less than 5 m and not exceeding 16 m (see discussion below). In the recent Kattegat sea Petersen (1893) found living *Echincardium cordatum* at numerous localities outside the 6 m contour, which seems strongly to control the distribution of the animals at localities free of mud, whereas at such localities they seem to have no lower limit at the water depths reaced in the recent Kattegat sea. In the Tyrrhenian Sea Hertweck (1971 & 1973) found that *Echinocardium cordatum* burrows are the most characteristic species of the ichnofacies below the wave-base.

Notches produced by Pectinaria *sp.* Fig. 16. The only body fossils found in the cliff are the agglutinating tubes of the polychaete worm *Pectinaria*. They are mainly found in the living position with the wide end of tube pointing downwards. Above the wide end of the tube a notch in the sediment lamination is commonly observed. These structures are particularly visible when found in connection with thin layers of heavy minerals. In most cases the notches are V-shaped in cross-section, but in many cases a small grabenlike structure is found instead (fig. 16). The borders of the notch then are defined by two or more minute normal faults. Notches after *Pectinaria* are found in both facies 1 and 2, but they are apparently most abundant in facies 1, where also reworked tubes are found.

Composite structures

Partial erosion of algal mats. Figs 5, 9, 11, 16, 17, 18 & 19. The cliff at Bansten Bakke exhibits several surfaces of irregular erosion. In all cases the eroded sediment is horizontally laminated, whereas the superposed layer always exhibits large-scale cross-lamination. The superposed ripples are mostly 10 cm high, but often larger. The ripple foresets are mainly straight, but curved convex upwards or concave upwards foresets also occur. The ridges and furrows of the erosion surfaces are in general weakly parallel (fig. 19). All those observed are more or less perpendicular to the ripple drift direction, but this might be due to the fact that they would be hardly visible if they were parallel to the ripple drift direction. In many cases the ridges have

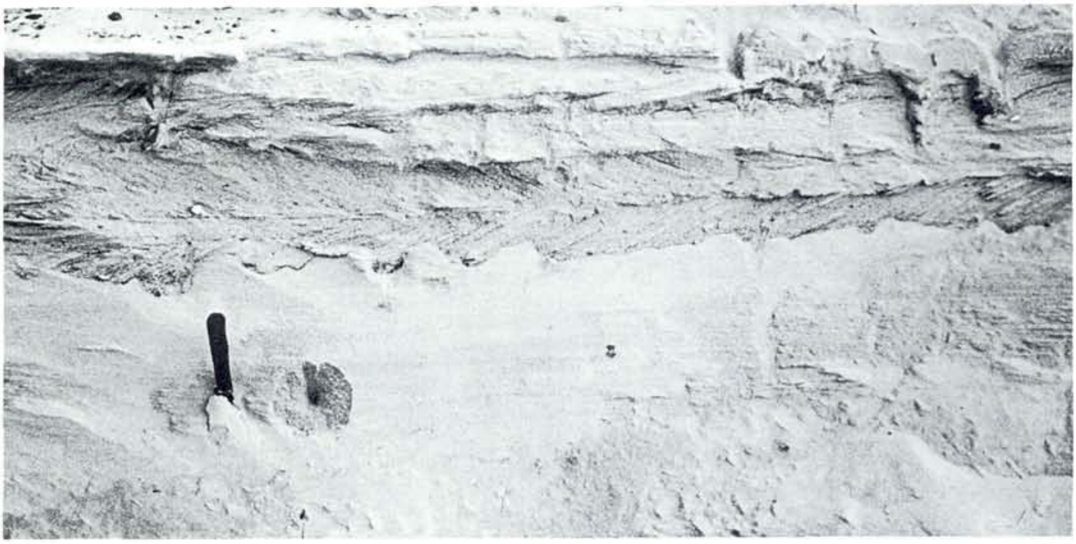

Fig. 17. Sediments of facies 2 and facies 1 separated by typical irregular erosion surface. The facies 2 sediment is intensively bioturbated by Echinocardium *as far as c. 20 cm below the erosion surface. A few* Arenicola *funnels are seen in various sections in the sediment above.*

small overhangs indicating that some binding agent must have been present. This agent is believed to have been sediment-binding algae, since the sediment is absolutely free of mud.

Recent structures similar to the irregular erosion surfaces exposed in the cliff are found at the pseudo-tidal flat south of Læsø (see above). There the structures obviously have been formed by partial erosion of the algal mat, since the ridges of these structures are capped by a greenish layer, 1–2 cm thick, in which numerous algal filaments can be seen when a piece of the sand is carefully broken. Newly formed furrows between the ridges are not capped by such a layer. However, the furrows are rapidly reinhabited by the algae, so the structures can be preserved during the next incursion of the sea.

It is obvious that these structures on the

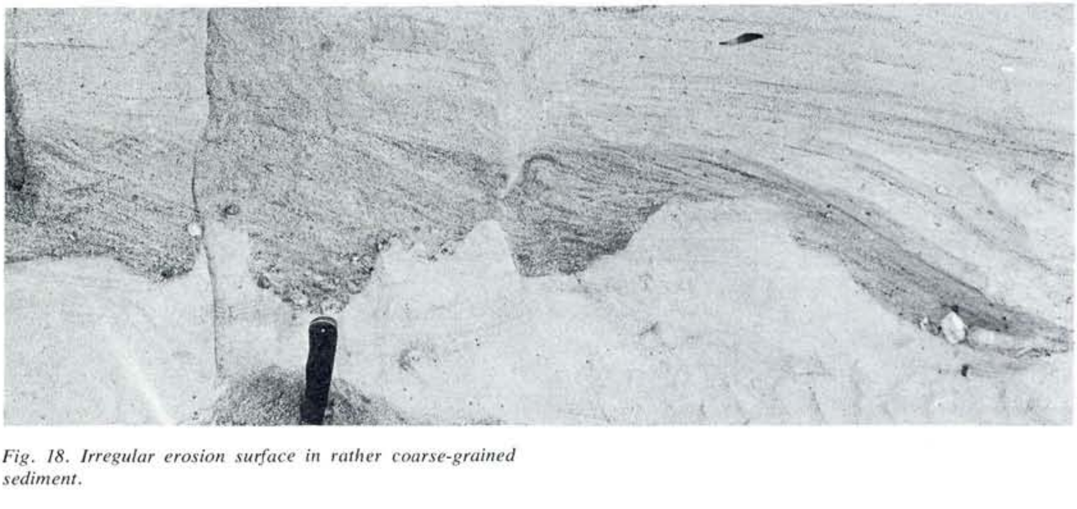

Fig. 18. Irregular erosion surface in rather coarse-grained sediment.

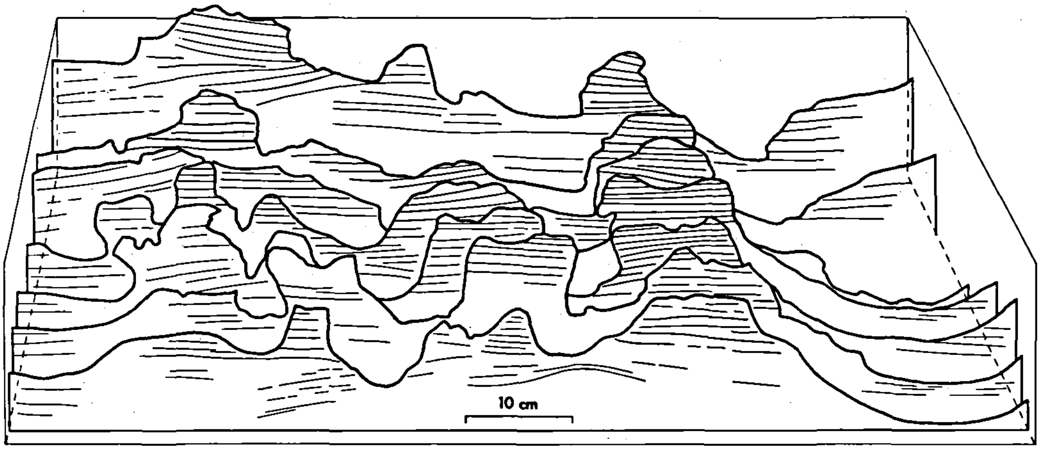

Fig. 19. Diagram showing a series of sections through an irregular erosion surface at Bansten Bakke.

pseudo-tidal flat are formed during very shallow conditions, either as a result of paddle-feeding by seagulls, or purely physically by the interaction between the sand-surface and the water-surface. Erosion occurs commonly at the pseudo-tidal flat, e.g. when the water leaves the flat and numerous small, very shallow ponds are formed. Along the borders of these ponds small waves constantly erode the looser parts of the algal mat, thus forming ridges and furrows more or less perpendicular to the borders of the ponds.

If not formed by partial erosion of algal mats under very shallow conditions, similar to what is found at the pseudo-tidal flat, the irregular erosion surfaces found in the cliff might have been formed by partial erosion of algal mats under stronger current conditions than are known from the present Kattagat sea. Spärck (1926) and Steemann-Nielsen (1939) found faunal indications on the presence of tidal currents during early postglacial time. This hypothesis is supported by the fact that the fossil irregular erosion surfaces generally are better developed than those occurring at the pseudo-tidal flat, and also by the fact that the cross-bedding structures of facies 1 at Bansten Bakke are larger than similar structures at thepseudo-tidal flat, where horizontal lamination and small-scale ripples are the most common structures. Furthermore, the herringbone structures commonly found in the cliff at Bansten Bakke may also indicate stronger tidal current conditions in early postglacial time.

Gas-expulsion structures. Figs 20 & 21. Gas-expulsion structures are commonly found in the western part of the cliff. Structures of this type are in general irregular V or U-shaped, 0.5 to 1 m high and with a piece of algal peat at the bottom. Internally the structures are vertically striated by concentrations of heavy minerals, completely obscuring primary sedimentary structures, while the surrounding sediment is not disturbed.

It is suggested that structures like this are formed by upwards migration of numerous small gas-bubbles developed by decomposition of algae, which in this way are converted to the algal peat found at the bottom of the structures.

Such structures might have been caused by rhythmic changes in the hydrostatic pressure, e.g. under tidal conditions. But the effect of transgressions and regressions should also be considered, since the bottom of the structures mostly are found in facies 2 (transgression) and the top in facies 1 (regression). Förstner & al. (1968) described similar expansion of gas-bubbles in sediment caused by changes in the hydrostatic pressure.

Geological interpretation of the sedimentary structures

Keeping in mind that the cliff represents a cross-section through an old tongue of land, it is clear that the sediment exposed in the lower part

Fig. 20. Gas-expulsion structure. Basis of structure in sediment of facies 2, top in facies 1.

of the cliff represents a cross-section through a submerged shoal. During the postglacial transgressions and regressions such a shoal must have been sensitive to changes in sea level.

The cliff section is composed of three minute fining upwards sequences each followed by a coarsening upwards sequence both in respect to structures and to grain-size. Furthermore, these sequences correspond to particular sedimentary structures so that the transition from fining upwards sequences in each case is linked to facies 2 and the burrows of *Echincardium cordatum*, whereas the transition from coarsening upwards sequences to fining upwards sequences in each case is linked to facies 1 and funnels made by *Arenicola marina*.

It is generally accepted that fining upwards sequences in marine sediments may be formed during transgressions, and coarsening upwards sequences during regressions. Both facies involved belong to the lower flow regime, but facies 1 obviously belongs to a higher energy level than facies 2. This is probably to be correlated to changes in water depth, with the lowest energy level in the deepest water.

Thus the physical sedimentary structures *alone* allow the postulation of three postgacial transgressions intercallated with regressions before Læsø became a stable island. Since the cliff shows no major erosional surfaces (except that immediately above the Yoldia clay, which probably coincides with the Ancylus time) we may also postulate that the transgressions reflected in the cliff section may be the oldest known from the postglacial history of Denmark. Three Atlantic and one Subboreal transgression are known from Denmark (Iversen 1937, Troels-Smith 1942, Krogh 1965). As discussed elsewhere the extensive beach ridges and dead cliffs surrounding the old triangular part of Læsø are related to a late Subboreal transgression and probably may also be related to an earlier Subboreal transgression. Thus the similarity between what is found at Læsø and what is known from other parts of Denmark seems striking. On the other hand Mörner (1969) found a long series of postglacial transgressions at the Swedish west coast. If his hypothesis is correct several transgressions must be included in the same *Echincardium* burrowed layer. This could be so, especially in the case of the lowermost layer, which probably was formed during the deepest water conditions where the magnitude of the regressions would hardly affect the sedimentary structures. According to Mörner the postglacial limit at Læsø should be found 8 m above present sea

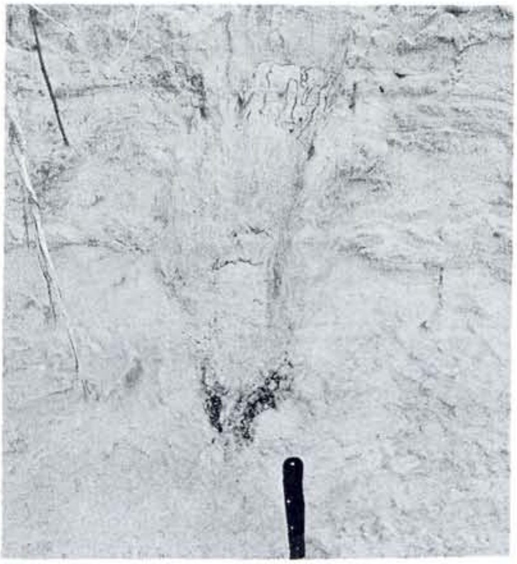

Fig. 21. Gas-expulsion structure. At the base of the structure the algal peat is clearly visible.

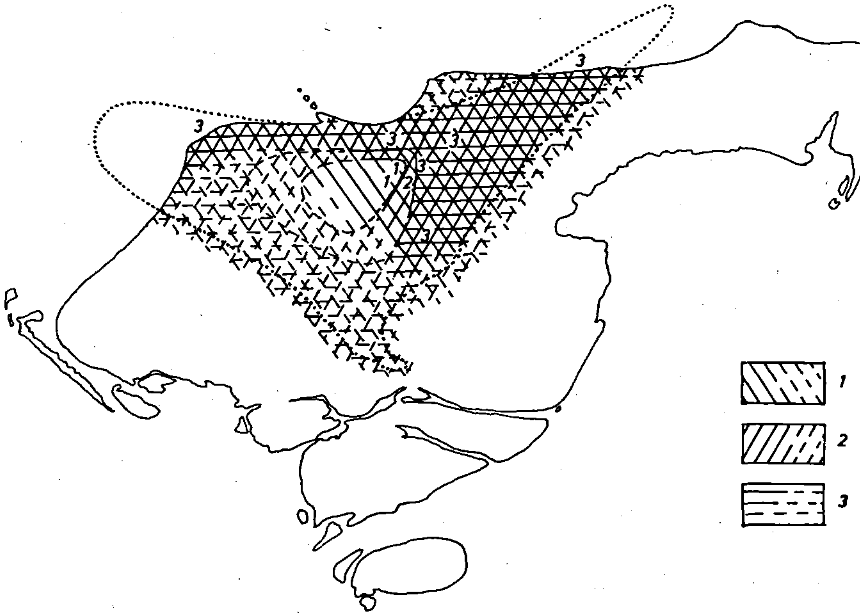

Fig. 22. The distribution of sediments of facies 2. 1: Only one horizon (the lower) present. 2: two horizons (the lower and middle) present. 3: three horizons present. The distribution of the middle and upper horizon may roughly correspond to the shape of the initial growth stages of Læsø.

level. However, at Læsø beach sediments are found up to 11 m above sea level, and since these sediments do not even represent the postglacial limit (Jessen 1897), it seems unlikely that Læsø followed the same pattern of isostasy as the Swedish west coast.

The cliff taken as an entity forms one major coarsening upwards sequence. This corresponds to a regressive tendency in spite of the transgressions. Facies 1 horizons contain irregular erosion surfaces that are believed to have been formed by partial erosion of algal mats under shallow conditions. In the uppermost horizon of facies 1 there is also a deflation surface. But in the lowest part of the cliff no such structures are found that could be interpreted as the result of exposure to the air. The interpretation of the cliff on the basis of physical sedimentary structures alone is therefore that a long-ranging postglacial regression interrupted by at least three transgressions has taken place and thus formed the 'pre-emergence' part of Læsø.

The lateral extension of facies 2 has been investigated by examination of the original descriptions of ten boreholes penetrating the oldest part of Læsø at Højsande. Some of these boreholes have been published by Michelsen (1967). In boreholes 4, 8 and 9 no differentiation can be made between facies 1 an 2 because of very homogehous grain-sizes. In seven boreholes however, one to three fining upwards sequences with intercallated coarsening upwards sequences can be distinguished, thus indicating the presence of one to three horizons of facies 2 in the boreholes. This is supported by finds of shell-fragments and spines of *Echinocardium cordatum* in fine-grained sediment in some of the boreholes.

Fig. 22 shows the supposed extension of horizons with facies 2. The lowermost horizon extends over the whole area, whereas the middle does not occur in boreholes 2 and 6, and the uppermost horizon does not occur in boreholes 2, 3 and 6. Thus the extension of the middle and uppermost horizons roughly corresponds to the shape of the initial growthlines of Læsø.

From the cliff north of Vesterø Havn (Jessen 1897, Michelsen 1967) Mörner (1969) described three fine-grained horizons separated by more coarse-grained shore sediments. Because of poor exposure during the last ten years the cliff has not been studied in detail. However, both

Echinocardium burrows and *Arenicola* funnels have been observed in the cliff, indicating a development of this part of Læsø similar to that found at Bansten Bakke.

Furthermore, in a pit at the southwestern margin of the old triangle near Vesterø Mejeriby *Echinocardium* – burrowed layers are found below shore sediments 4.5 m above sea level (theodolite measurement).

Comparing the cliffs at Bansten Bakke and Vesterø Havn, the ten boreholes and the pit near Vesterø Mejeriby it seems evident that the alternation between sediments formed at shallow water and deeper water respectively is not a local phenomenon occurring only at Bansten Bakke, but rather a feature reflecting events of regional significance.

No horizons in the ten boreholes are characterized by stony horizons similar to those known from beach ridges. It therefore seems unlikely that Læsø emerged as a stable island before the completion of the three transgressions, but rather that the entire area represented a shoal occasionally exposed to the air during the last regression maximum. Mörner (1969 p. 388) mentions the occurrence of eolian sand with structures derived from frost activity in the lowermost fine-grained horizon in the cliff at Vesterø Havn. The present author has not been able to confirm this observation, but is of the opinion that the structures mentioned are bivalve escape traces, which may be confused with ice-wedge structures.

According to Mertz (1924) the Littorina transgressions in Vendsyssel (north Jylland) reached c. 14 m above present sea level at localities along the isobase transecting the cliff at Bansten Bakke. At Læsø the trangressions may be considered to have reached approximately the same level. Facies 2 horizons are found from 2 m below to 9 m above present sea level. Sediment of this type therefore must have been formed at water depths between 5 and 16 m. Further calculations of water depths greatly depend on when precisely the Littorina transgressions reached their maximum in this area. It is believed that this happened during the first of these transgressions since the lowermost horizon of facies 2 seems to cover the entire island, whereas the two upper horizons are limited to lower areas.

In southern parts of Denmark the Littorina transgressions reached their maximum extension during Subboreal time (Troels-Smith 1940, 1942; Krog 1968) or even later (Mikkelsen 1949), whereas the transgression maximum was reached in mid-Atlantic time in Dybvad in Vendsyssel (Iversen 1943). Thus this investigation supports the idea that the maximum of the Littorina transgression took place earlier and earlier the farther northwards one goes, which is simply explained by the difference in magnitude of the isostatic recovery during postglacial time.

In the cliff section at Bansten Bakke the lowest *Echinocardium*-burrowed layer (facies 2) is found between 0 and 1 m above present sea level, while the uppermost layer is found up to 3.5 m above the sea. Therefore it seems reasonable to suggest that *Echinocardium cordatum* in the cliff area lived at water depths of c. 14 m during the first transgression, and at water depths between 10.5 and 5 m during the last transgression maximum.

The interpretation of the physical sedimentary structures is strongly supported by trace fossils and composite structures. However, there seems to be a discrepancy between several earlier authors and the present author concerning the magnitude of the regressions between the transgressions reflected in the cliff. Since *Echinocardium cordatum* in the recent Kattegat sea lives at water depths greater than 6 m, and since *Arenicola marina* is most abundant in the inter-tidal or pseudo-tidal zone (and a little lower) it requires shorelevel displacements of the magnitude of 5 m between each transgression and regression to explain the alternation of *Echincardium*-burrowed and *Arenicola*-burrowed layers in the upper part of the section. Mörner (1969) operated with regressions of the magnitude of not more than 1 m. However, it should be emphasized that studies on beach ridges do not give any direct information about the magnitude of the regressions, since sediments formed during the maximum extension of the regressions are covered by beach ridges or marine sediments deposited during later transgressions. The alternation of *Echinocardium*- and *Arenicola*-burrowed layers may therefore be explained by a much broader inter-tidal zone than known from the recent Kattegat sea. This is supported by the existence of 'herringbone' structures, gas-expulsion structures, a deflation surface, irregular erosion surfaces, and by the faunal investigations by Spärck (1926) and Steemann-Nielsen (1939).

Age of the old part of Læsø

In 1872 a skeleton of a sperm whale (*Physeter catodon*) was found NE of Byrum at an altitude of c. 4.5 m close to the foot of the beach ridge surrounding the old triangular part of Læsø. A tooth of this whale has been C^{14}-dated by H. Tauber. The age of the tooth is 980 ± 80 years BC. The find was described with exceptional care by the local doctor (Jensen 1872). His description makes it possible to state that the whale was contemporaneous with the beach ridges surrounding the old triangular part of Læsø, or slightly younger. Unfortunately it has not been possible to find other fossils which can be used for C^{14} dating.

The beach ridge is complex where the whale was found. This can also be seen in the cliff section at Bansten Bakke, and in the area between Byrum and Vesterø Havn, where the beach ridge splits in two. To the north there is a strong beach ridge running along a straight line from Byrum to Vesterø Havn, and to the south there is a dead cliff at Byrum passing into a beach ridge south of Vesterø. The age of the whale is thus contemporaneous with the dead cliff, or slightly younger, i.e. late Subboreal. The older part of the beach ridge complex then may be related to an earlier Subboral transgression.

By aid of his shorelevel displacement curve Mörner (1969) related this beach ridge complex to postglacial transgression maxima 5B and 6, which he dated to 3.650 BC and 2.100 BC respectively. The age of the whale (980 BC) as well as the presence of beach ridges 11 m above sea level at Læsø, where the postglacial limit according to Mörner should be expected 8 m above sea level, demonstrates that the shorelevel displacement curve calculated by Mörner at the Swedish west coast does not fit to structures and ages found at Læsø.

Conclusions

The sedimentary history of Læsø falls into two distinct stages. During earlier stages Læsø formed a shoal inhabited by the heart urchin *Echinocardium cordatum* during periods of transgression and by the lugworm *Arenicola marina* during periods of regression. During later stages Læsø became a stable island and numerous beach ridges were formed. The oldest beach ridges are found at altitudes of only 11 m above present sea level. This indicates that Læsø remained a shoal until after the maximum Littorina transgression, which in southeastern Vendsyssel took place during mid-Atlantic time. However, since it is a general tendency that the maximum transgression began earlier the farther northwards one goes perpendicular to the isobases, it is to be expected that the maximum transgression at Læsø took place still earlier.

The cliff at Bansten Bakke shows a general lowering of the sea level during early stages of Læsø's history. The lower *Echinocardium*-burrowed horizon is by far the thickest, and above this horizon neither funnels made by *Arenicola marina* nor irregular erosion surfaces have been found as is the case in the upper part of the section. These features seem to indicate that the maximum transgression coincides with the first transgression, which in other parts of Denmark took place during early Atlantic time. Moreover, the alternation of *Echinocardium*- and *Arenicola*-burrowed horizons, the latter containing 'herringbone' structures, gas-expulsion structures, a deflation surface and irregular erosion surfaces, seems to indicate the presence of stronger tidal currents than are known in the recent Kattegat sea.

The shoal sediments in the cliff are capped by beach ridges, which can be traced to the place where the skeleton of a sperm whale was found. C^{14} dating of a tooth of the whale gave an age of 980 ± 80 years BC, i.e. late Subboreal. In the cliff it is obvious that this beach ridge is complex since it is built up in places by two thick stony horizons separated by sand containing bivalve trace fossils. The stony horizons are found from 2 to 7 m above present sea level. The younger part of these stony horizons thus seems to be contemporaneous with the whale, while the older part seems to be contemporaneous with the straight beach ridge north of the dead cliff between Byrum and Vesterø.

Certainly, it is tempting to correlate this older part of the beach ridge with the early Subboreal transgression, and the three *Echinocardium*-burrowed horizons with the three Atlantic transgressions (Iversen 1937 & 1943). However, according to Mörner (1969) that model seems to be inaccurate since he found a large number of postglacial transgressions at the Swedish west coast. Although his shorelevel displacement curves fit very badly at Læsø, it is nevertheless believed that more than four postglacial transgressions have taken place. Before Læsø became a stable island at least three transgressions took place. This is seen in the cliff at Bansten Bakke. Before the completion of the old triangle at least one further transgression took place. This is reflected by a c. 2 km long and 1 m high dead cliff starting from a point c. 2 km east of Vesterø Havn. And finally, before the death of the whale two transgressions took place to form the dead cliffs and beach ridges surrounding the triangle. This means that at least 6 transgressions have taken place between the formation of the Yoldia Clay (10.960 ± 180 BC) and the formation of the dead cliffs and beach ridges surrounding the old triangular part of Læsø (980 ± 80 BC).

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Dansk sammendrag

Læsøs sedimentære historie belyses ved tolkninger af øens strandvoldssystemer og af de ofte meget velbevarede sedimentstrukturer, som kan ses i klinterne langs nordkysten. Gravegange efter sømus og sandorm karakteriserer lag afsat på henholdsvis dybt og lavt vand. De sømus-gravede lag findes i tre horisonter, som anses for at repræsentere havstigninger, der fandt sted endnu inden Læsø existerede som ø. Mellem de sømus-gravede lag findes sandorm-gravede lag, som anses for at være dannet i perioder med havsænkninger. Dette bekræftes af rent fysiske sedimentstrukturer, idet de sømus-gravede lag domineres af sedimentstrukturer, der ofte dannes på forholdsvis dybt vand, mens de sandormgravede lag domineres af sedimentstrukturer, der oftest dannes på lavere vand. Bl. a. forekommer der hyppigt uregelmæssige erosionsflader i de sandorm-gravede lag. Desuden forekommer der en enkelt afblæsningsflade. De uregelmæssige erosionsflader tolkes som opstået ved delvis erosion af algemåtter under medvirken af betydeligt stærkere tidevandsstrømninger end kendt fra det nuværende Kattegat.

En markant diskordans findes mellem strandvoldene på den lavtliggende del af Læsø og de strandvolde, som dækker den ældre, højtliggende del, idet den ældre del omgives af indlandsklinter og særligt veludviklede strandvolde. Indlandsklinterne anses for at være dannet ved erosion under en yngre Subboreal havstigning. Efter Subboreal tid er Yoldialeret, hvorpå Læsø er aflejret, hævet så meget, at dets overflade over store strækninger er næsten sammenfaldende med havoverfladen. Herved blev de vidtstrakte meget lavvandede sandflader (pseudotidale flader) dannet syd for Læsø. Særegne sedimentstrukturer karakteriserer disse sandflader, specielt uregelmæssige erosionsflader opstået ved delvis erosion af algemåtter. Disse strukturer ligner i høj grad strukturerne i de ældre dele af Læsøs sedimenter.

På basis af sedimentstrukturerne, som kan ses i klinterne langs nordkysten, kan det konkluderes, at Læsø under de første tre eller flere havstigninger var fuldstændig vanddækket, og at de største vanddybder opnåedes under den første havstigning. Endelig kan det på basis af bl.a. en kulstof-14 datering af en kaskelothval og på forekomsten af indlandsklinter på den ældre, højtliggende del af Læsø konkluderes, at der i tidsrummet mellem dannelsen af Yoldialeret og kasketlothvalens død har fundet mindst 6 havstigninger sted.

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