DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 1999/52

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Introduction

The succession spans the upper Oligocene - lower Miocene and represents marginal marine deposits, which can be subdivided into three depositional sequences; A to C. The lower sequence boundary is a composite sequence boundary separating middle Eocene deposits from upper Oligocene deposits. Sequence A is very thin and consists of fine-grained glaucony-rich clay. The marine clay is at it's upper boundary dominated by siderite and goethite which indicate a distinct change in depositional environment related to a sea-level fall. Within sequence B, the lateral development of a barrier-complex can be seen in the Vejle Fjord area. Here the sediments include washover fans, lagoonal muds, and tidal-flat deposits. Further south in the Lillebælt area, prominent hummocky cross-stratified beds deposited in shoreface and estuarine environments outcrop. These hummocky cross-stratified beds are inferred to be equivalent to backbarrier/spit deposits at Vejle Fjord. Sequence B is bounded from sequence C by a ravinement surface. This sequence boundary spans most of the Aquitanian and correlates with a detached lowstand delta, recognized on seismic data from South Jutland. The succession of sequence C, outcropping at Lillebælt, shows several steps of spit complex development including lateral and vertical development of shoreface sand, lagoonal muds and washover fans under influence of changing sea level and/or sediment supply.

The deposits illustrate how a thin gravel layer interbedded in marine fine-grained sand can be used to predict isolated and thick, sand-rich deltaic deposits in a basinal setting. The lateral facies development in marine nearshore-lagoonal succession is also prominently illustrated and thus how coarsening/thickening - and fining/thinning upward trends should be interpreted in a sequence stratigraphic framework depending on the position in front of or behind a spit complex. The deposits at Lillebælt and Vejle Fjord may thus be an excellent analogue for Jurassic nearshore deposits within the North Sea area and fundamental in the understanding of shallow marine deposits.

To demonstrate the development of the succession ca. 10 localities will be visited, which corresponds to two full-day program. During the excursion there will be an opportunity to see the Paleocene and lower Eocene succession equivalent to the Lista and Balder formations.

The excursion will start from Billund Airport (fly connections to Oslo, London etc.) about half an hours drive from the first locality.

Route

Day 1

We will start from Billund at 8:30 in the morning. From Billund Airport we will pass through different landscapes formed during the Weischelian glaciation. The area around Billund consists of outwash fans deposited in front of the glaciers. After 10 min of driving we will pass through the moraine landscape, and after Danish conditions, a rather hilly landscape. This landscape is buildup by plateau-moraines, ice-lake deposits, and erosional valleys formed during the deglaciation. After ca. 45 min we will be at the first locality; Øksenrade (locality 1). Within short distances we will visit 2 lokalities; Hindsgavl (locality 2) and Børup (locality 3) and when finished Børup a lunch break will take place at a local Kro (restaurant). After lunch the first locality is Hagenør (locality 4) and when finished this outcrop we will go to the other side of Kolding Fjord where the last locality; Rønshoved (locality 5) is situated.

Day 2

After breakfast we will continue to the Vejle Fjord area where the first locality is Skansebakke (locality 6). Skansebakke is the type locality for the Vejle Fjord Formation (upper Oligocene). After Skansebakke, the Hvidbjerg outcrop will be visited (locality 7) and we will continue to the northern side of the Vejle Fjord, where the first stop is Dykjær (locality 8). After lunch the last locality; Jensgård (locality 9), will be visited and we will return to Billund Airport.

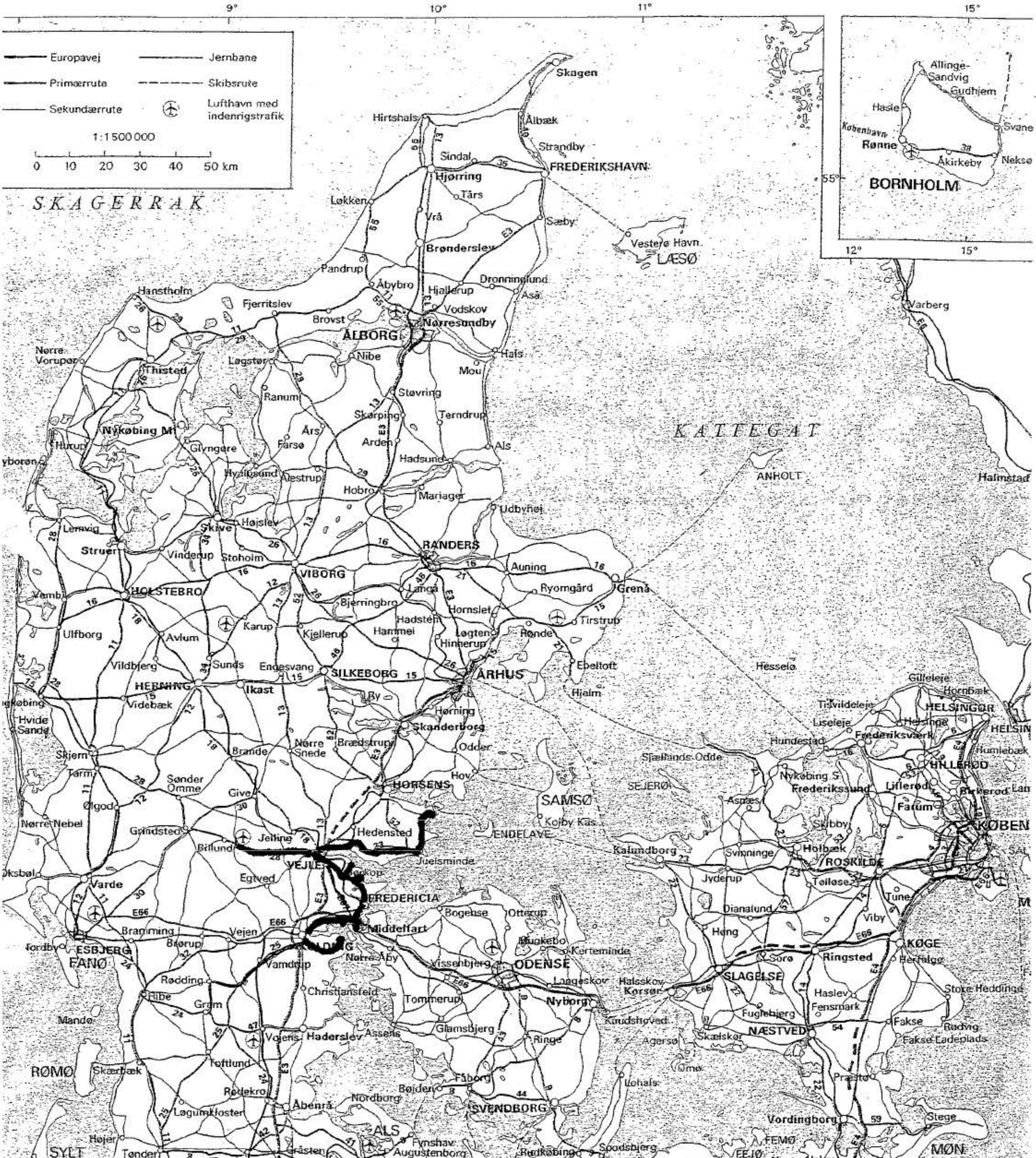

Fig. 1: Map showing the excursion route in Denmark.

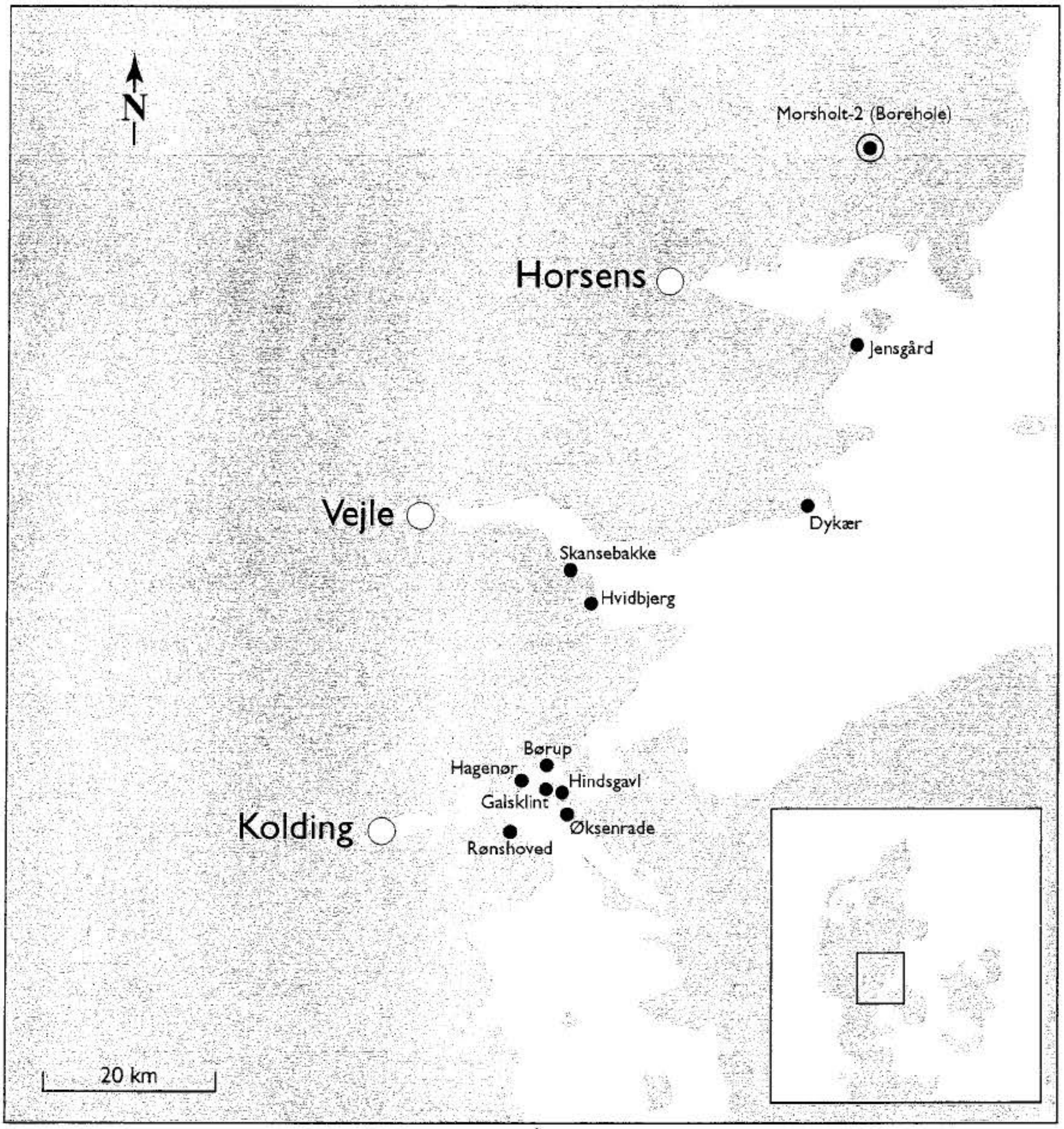

Fig. 2: Localities to be visited at the excursion and the Morsholt-2 borehole.

Regional geology

During the Late Cretaceous and early Palaeogene the North Sea was influenced by inversion tectonics. Former grabens were inverted especially along the Sorgenfrei-Tornquist Zone (Sorgenfrei 1951; Ziegler 1982; Liboriussen et al. 1987; Michelsen and Nielsen 1993; Mogensen 1994). During the Cenozoic a successive infill of the basin occurred (Figs. 3,4). The pattern of the infill was influenced by tectonic phases during the Oligocene and Miocene (Langhian) and glacio-eustatic sea-level changes. Through the Danien the depositional environment was characterized by deposition of cool-water shallow marine carbonates in the Danish Basin (Surlyk 1997). From the late Palaeocene clastic deposition dominated and during the late Palaeocene and most of the Eocene fine-grained sediments accumulated in a marine environment (Fig. 5). The variation in depositional conditions were caused by changes in sea level or circulation patterns in the North Sea (Bonde 1979; Pedersen and Surlyk 1983; Heilmann-Clausen et al. 1985; Rasmussen 1994). Volcanic activity in the northern Atlantic during the latest Palaeocene and early Eocene is reflected by a number of interbedded ash layers. At the end of middle Eocene an increased supply of silt occurred in the southern part of the Jylland and northern part of Germany (Gripp 1964). The upper Eocene and lower Oligocene succession is incomplete in the Danish area. Whether this is due to non-deposition or erosion is uncertain, but evidences of late Oligocene and Neogene uplift of Fennoscandia has been reported by Michelsen and Nielsen (1993) and Japsen (1993). Reworking of older Tertiary sediments during the Neogene has been suggested by Rasmussen and Larsen (1989) and the supply of coarse-grained sediments is documented by Larsen and Dinesen (1959) and Rasmussen (1987). The transition from the Palaeogene to Neogene is an important phase in the sedimentary development of the eastern North Sea Basin. The distinct uplift of Fennoscandia, upto 1200 m in eastern Denmark (Japsen 1993), resulted in a marked increase of coarse-grained clastic in the southwestern part of the Danish area. Minor salt movements also took place during the Oligocene and resulted in some topography of the basin, especially minor silled basins developed north of the Ringkøbing Fyn High. A complex succession of alternating terrestial/near-shore marine and shelf deposits were laid down during the late Oligocene and Miocene and the coast line was occasionally displaced more than hundred kilometres basinwards (towards the west) (Fig. 5). The overall stacking pattern of this correlates to glacio-eustatic sea-level changes (Fig. 6)(Rasmussen 1996). The general sediment supply was from the north and northeast (Fig. 7)(Cameron et al. 1993; Sørensen et al. 1997; Gregersen 1997.)

In the Palaeocene and most of the Eocene the climatic conditions were warm and humid (Buchardt 1978; Bonde 1979; Collison et al. 1981). At the end of the Eocene a cooler period started and continued during most of the Oligocene. Warm-temperate and humid climatic conditions prevailed in the Miocene (Sorgenfrei 1958; Radwanski et al. 1975; Koch 1989).

Lithostratigraphy

The Oligocene and Miocene succession of South Denmark is subdivided into 7 lithostrastigraphic units (Figs. 8 - 10). The formations dominated by marine deposits are the Vejle Fjord (Klinting Hoved), Arnum, Hodde, Gram, and Sæd formations. The Ribe and Odderup formations consists of continental deposits and were laid down in fluvial environments under major regressive events. Only the Vejle Fjord Formation has been subdivided into formal members and these are important for this excursion. The members are: The Brejning Clay, the Vejle Fjord Clay, and the Vejle Fjord Sand.

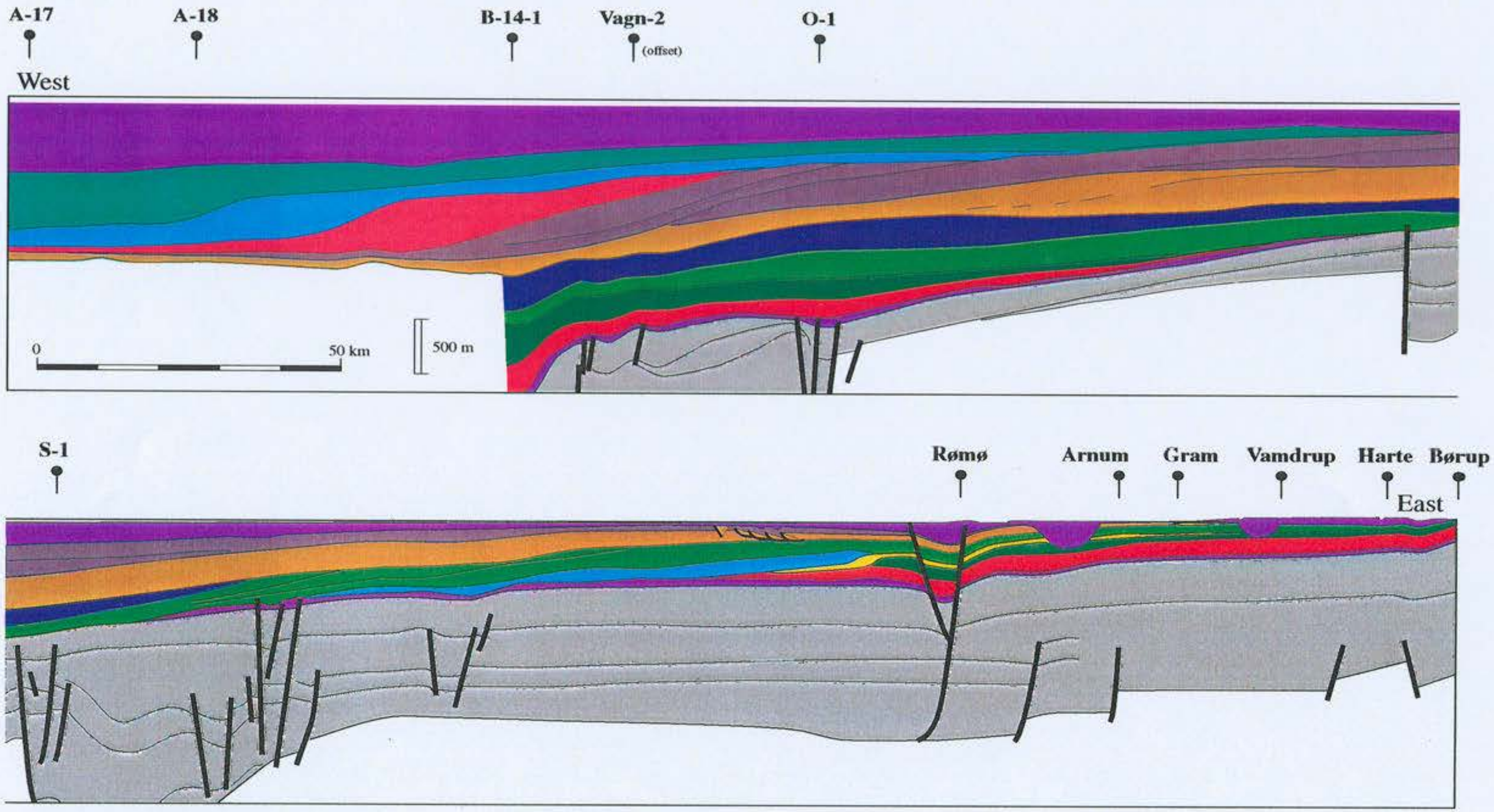

Fig. 3: E-W trending geosection across the North Sea and Jylland.

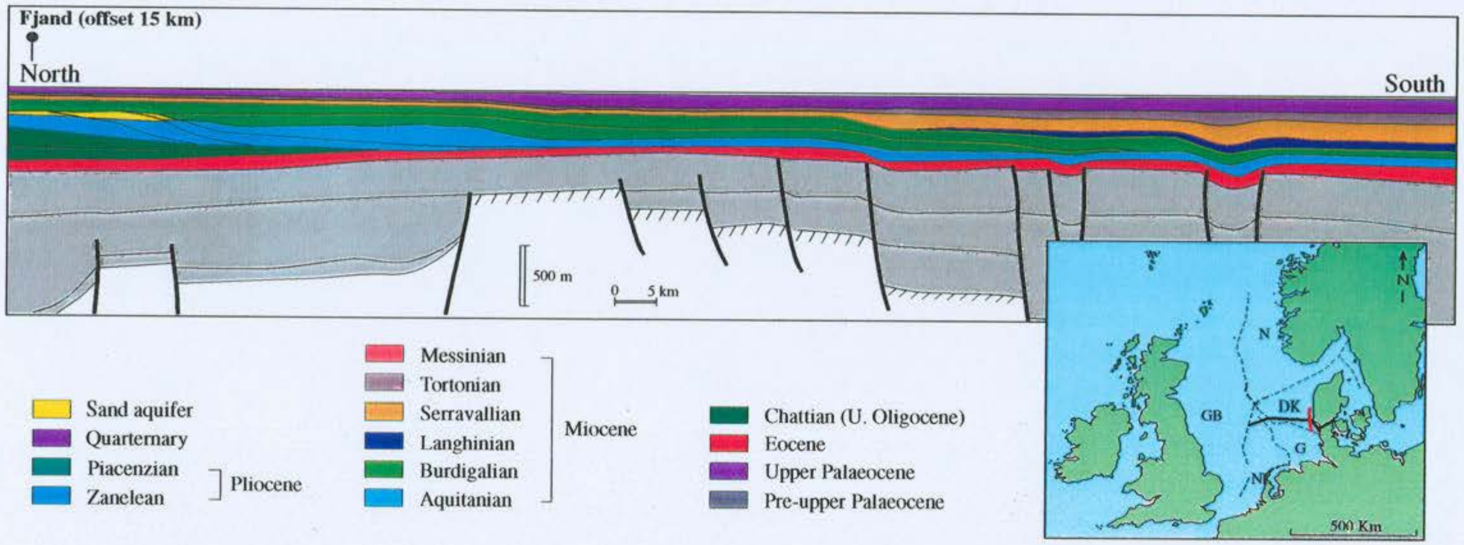

Fig. 4: N-S trending geosection just off Jylland.

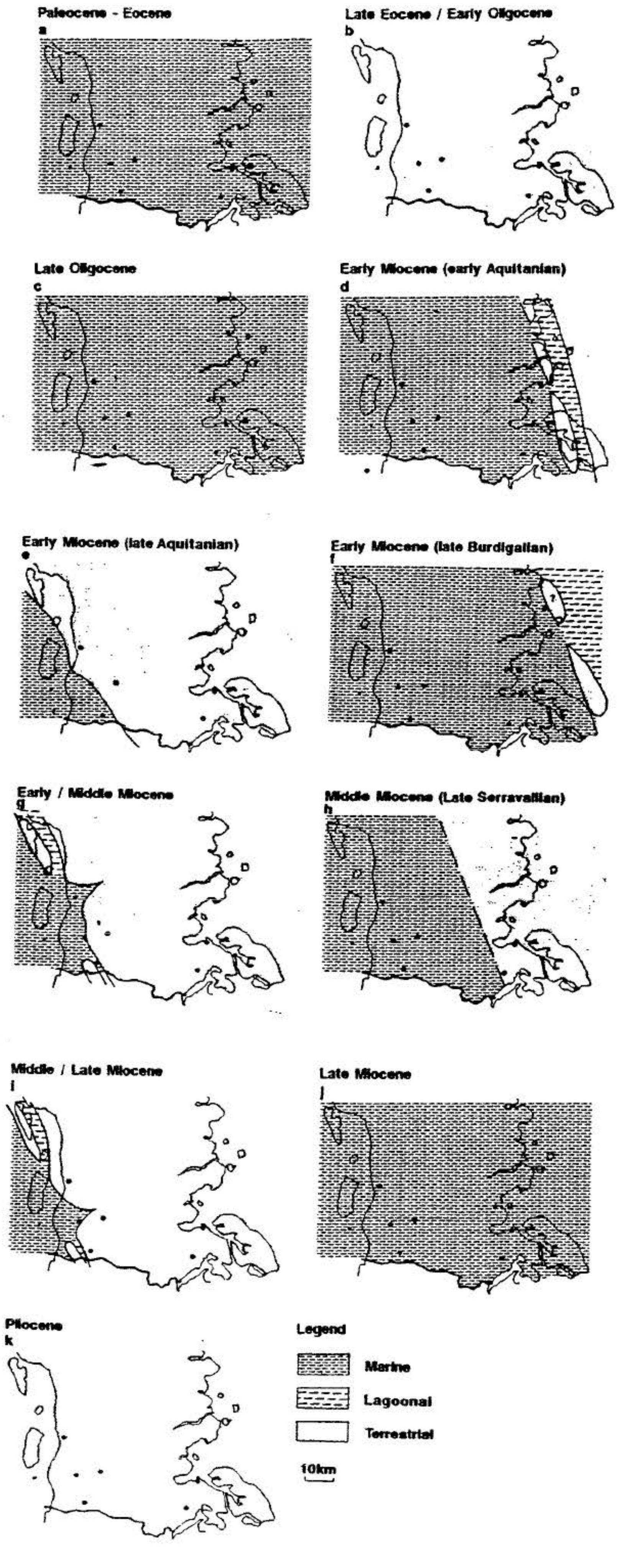

Fig. 5: Palaeogeographical maps of South Jylland showing the development through the Cenozoic.

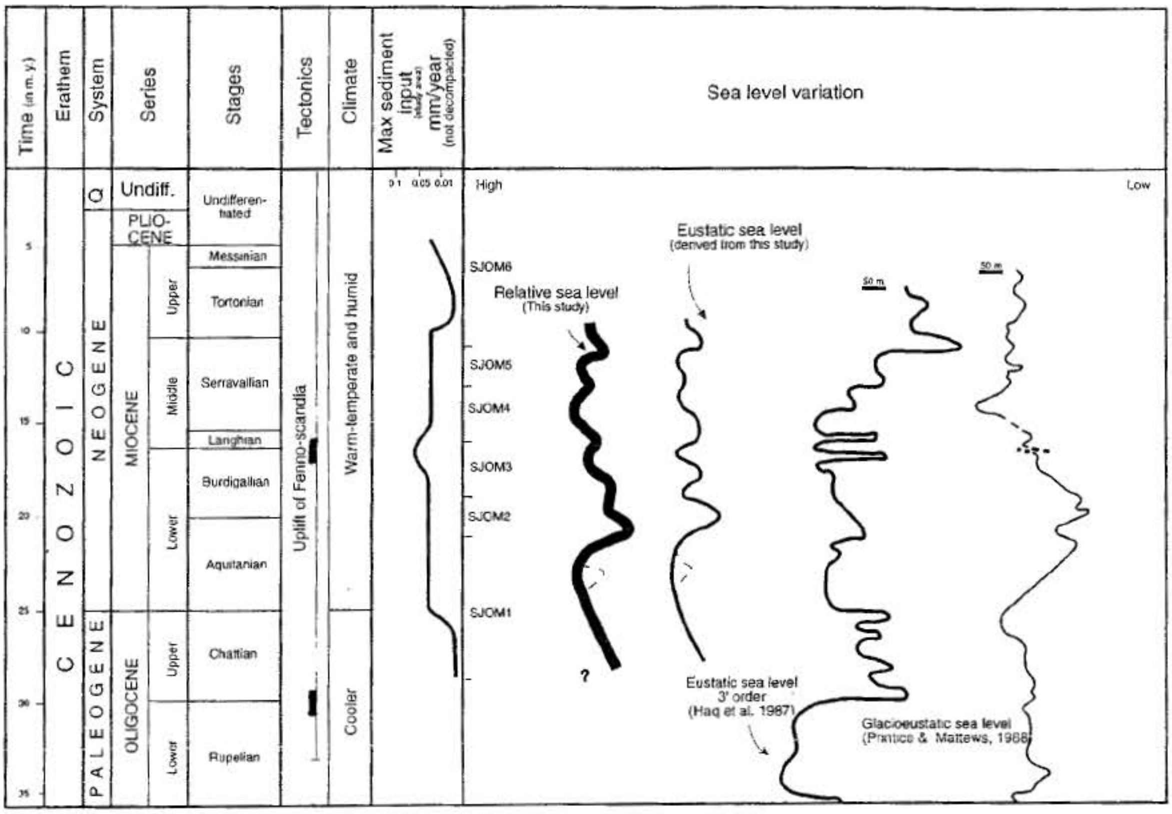

Fig. 6: Various sea-level curves of the Cenozoic. Note the distinct low sea level in the Aquitanian (Early Miocene), which is important for the development of the successions presented on this field trip.

OLIGOCENE - MIOCENE NORTH SEA

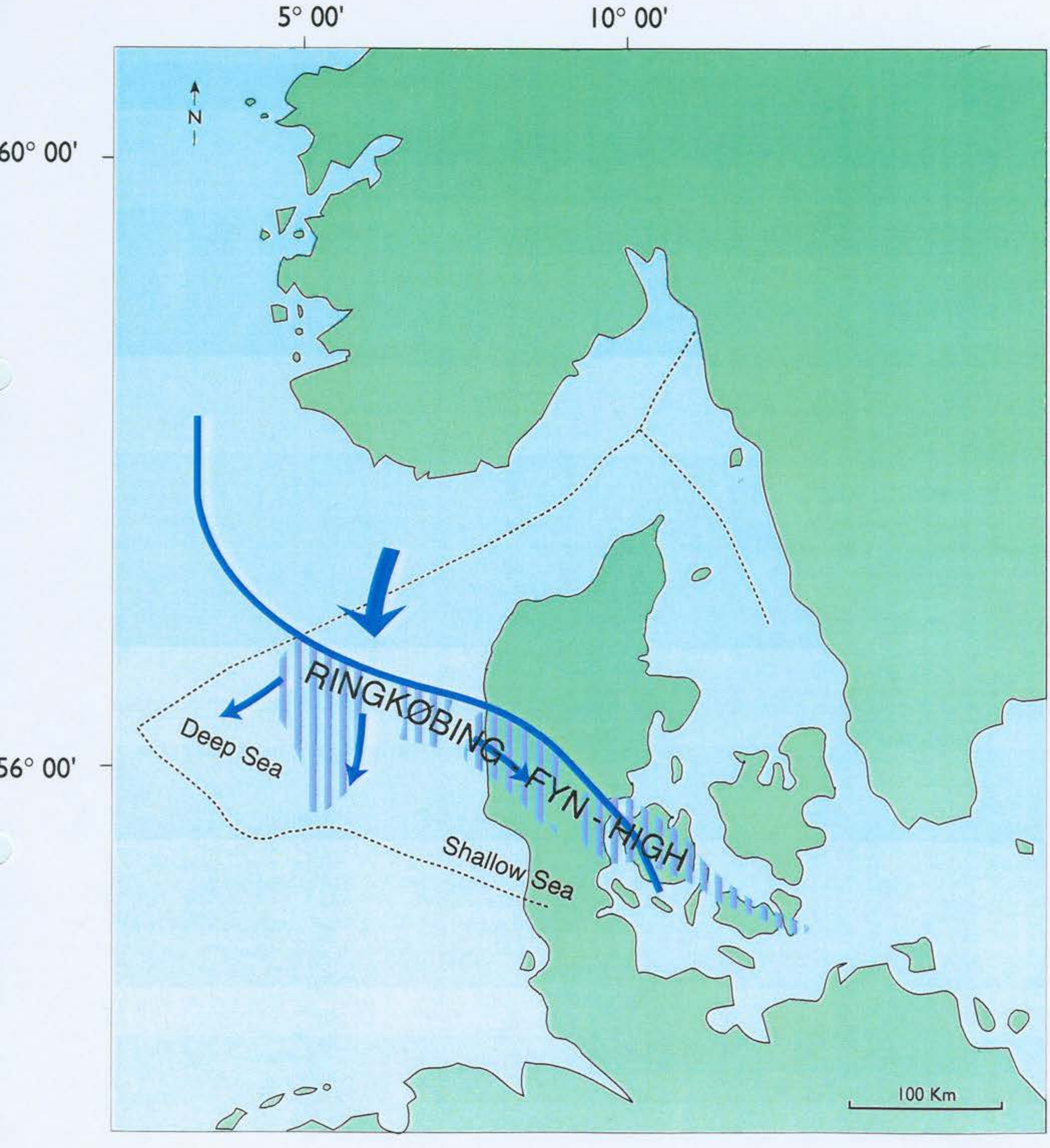

Fig. 7: The blue line indicate the shoreline during highstand of sea level in the Early Miocene. Arrows indicate sediment transport routes.

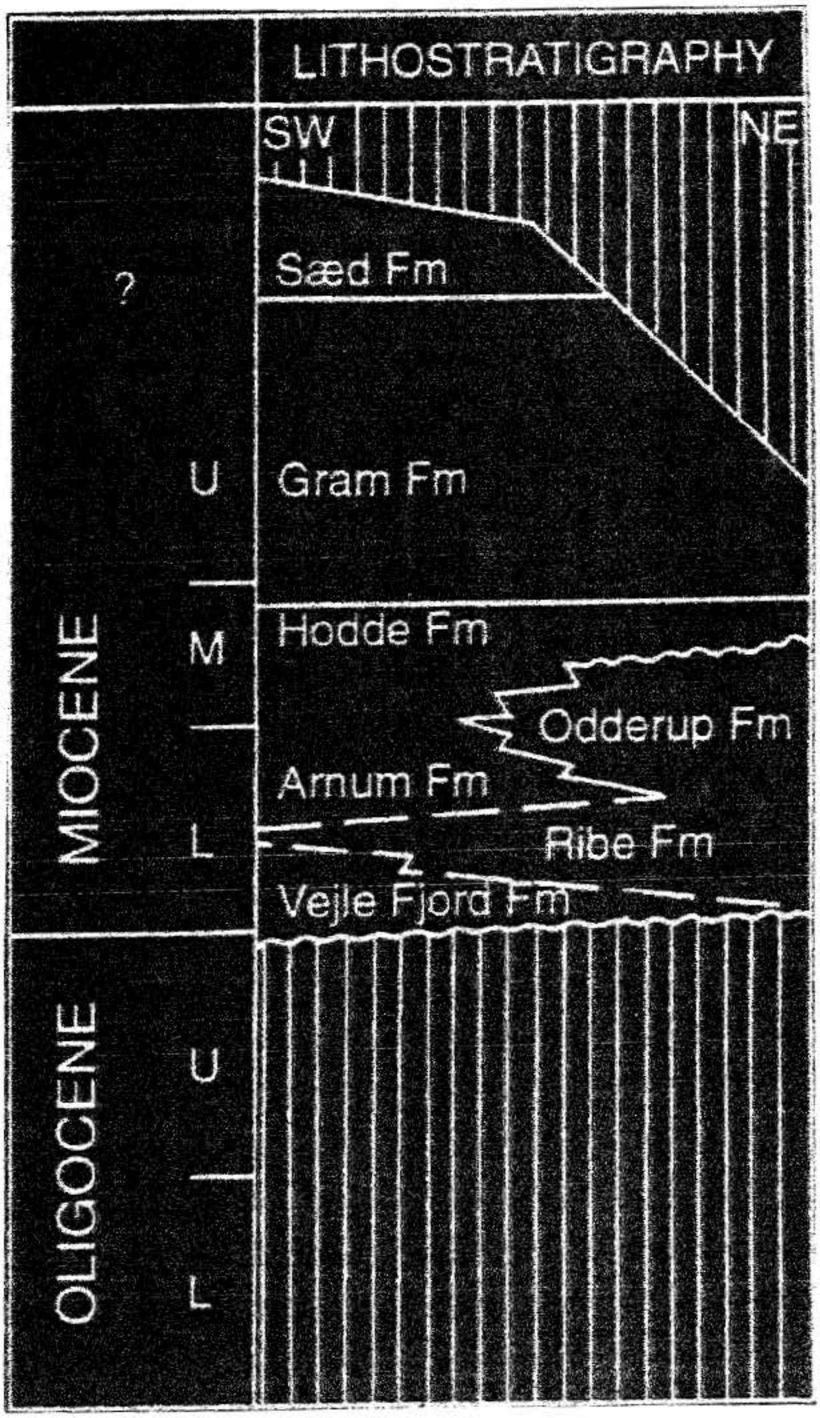

Fig. 8: Lithostratigraphy onshore Denmark.

CENOZOIC

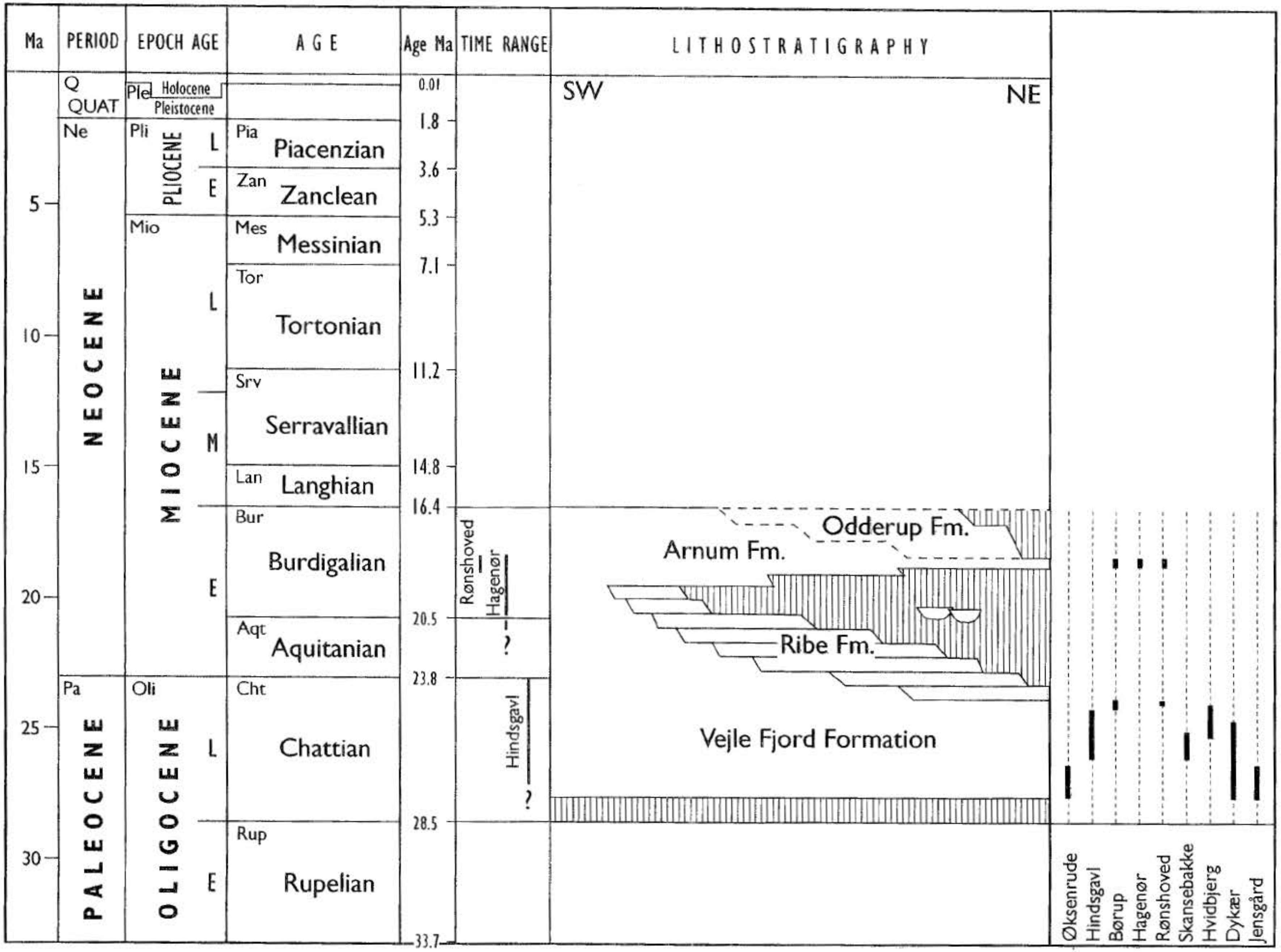

Fig. 10: Proposed lithostratigraphic subdivision of the upper Oligocene – early Miocene succession and the stratigraphic position of localities.

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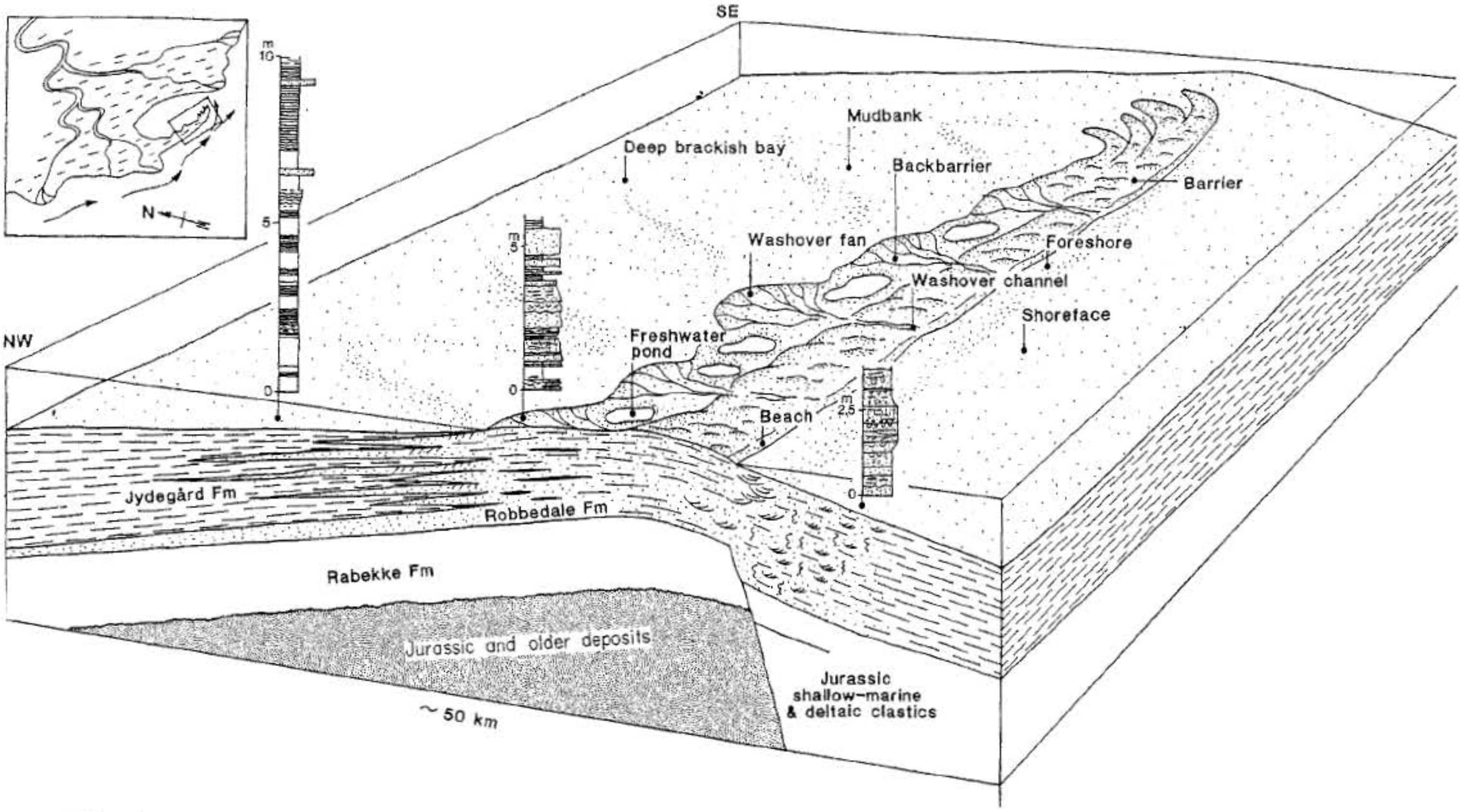


Fig. 11: Environmental reconstruction of the Lower Cretaceous Jydegård Formation, Bornholm. The figure shows the structural control on the location of a spit system. (Noe-Nygaard and Surlyk 1988)

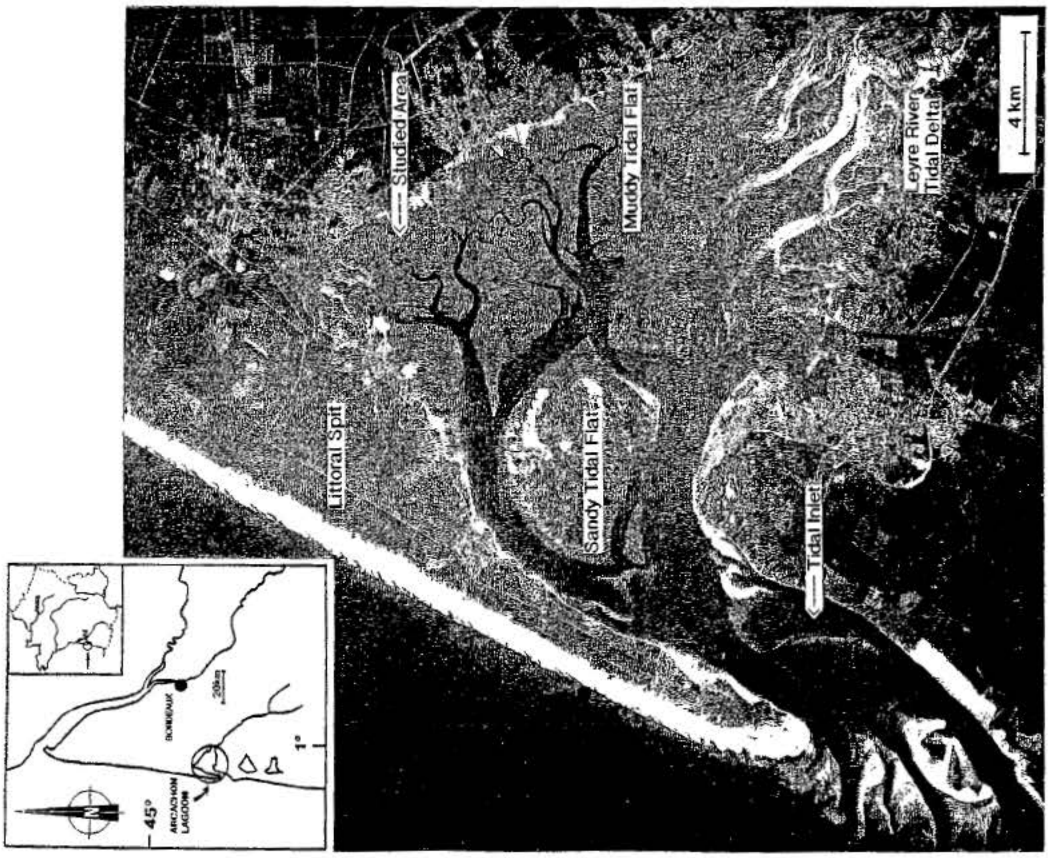


Fig. 12: Aerial photograph of the Arcachon Lagoon, France at low tide (from Fenies and Faugeres 1998).

Palaeogeography

The succession at Lillebælt and Vejle Fjord forms the northeastern limit of the upper Oligocene and lower Miocene North Sea during periods of high sea level. The deposits bear all the diagnostic features of combined storm and tidal processes; hummocky cross-stratification, coarse-grained ripples, washover fans, and diurnal deposition. The depositional environment is therefore interpreted as estuarine with some more restricted conditions behind spit/barrier complexes. The location of spit complexes were strongly controlled by the Ringkøbing Fyn High in a similar way as the Lower Cretaceous spit systems on Bornholm (Fig. 11) (Noe-Nygård and Surlyk 1988). Recent examples of depositional environments related to spit systems is shown in Fig. 12).

There are only a few unequivocal measurements of palaeocurrent-directions in the succession. The SE – wards dipping laminated sand in the upper part of sequence B represent beach lamination formed on a shoreline of a spit complex. These beach deposits were interpreted as back barrier deposits by Friis et al. (1998). However, two observations point against this interpretation; 1) the sand-rich section is very clean and no intercalation of mud has been observed which should be expected in a restricted back-barrier environment; 2) the palynofacies study indicate a distinct environmental change towards more marine conditions that prevailed during deposition of the underlying estuarine deposits. The sedimentary evolution in the upper part of sequence B (parasequences 3 and 4) show many similarities to the recent Skagen Odde spit complex (Nielsen and Johannessen, 1998) where along shore sediment transport supply sand to a major spit system in northern Denmark. The general palaeo-shoreline during the early Miocene trended NW-SE with major sediment input from the north (Fig. 7) (Jordt et al. 1995; Rasmussen 1995; Rasmussen 1997). The southward transport of sand resulted therefore in accretion especially on the southern eastern part of these systems giving the SE dips measured (Figs. 13A, 13B). The climatic conditions were humid and temperated.

The gravel layer at the sequence boundary of B and C, is the result of a displacement of the coast line more than 100 km towards the SW during the Aquitanian (Rasmussen 1998) and a long period, ca. 3 my, during which subaerial deposition occurred (Fig. 13C). In the Lillebælt area gravel was deposited as the result of fluvial activity.

During the subsequent transgression of the area, in the latest late Aquitanian, the fluvial deposits were reworked and a ravinement surface was formed replacing the sequence formed during the lowstand. The resumed marine conditions in the area resulted in deposition of sediments related to spit and barrier complexes (Fig. 13D). Periodically, minor transgressions occurred and open, but shallow marine deposition dominated. Directions of crests of coarse-grained ripples and sedimentary facies development between Hagenør and Galsklint indicate a NW-SE trending shoreline during the latest late Aquitanian and early Burdigalian. This orientation of the shoreline is similar to late Burdigalian deposits found in Central – and West Jylland (Christian Knudsen, personal communication 1998). The presence of the burrows of *Haustoriids* and the dinoflagellate *Hystrichoshaeropsis Obscura* in the late Aquitanian to lower Burdigalian succession indicate that warm climatic conditions prevailed (Radwansky et al. 1975; Dybkjær and Rasmussen in prep.).

Palaeogeography

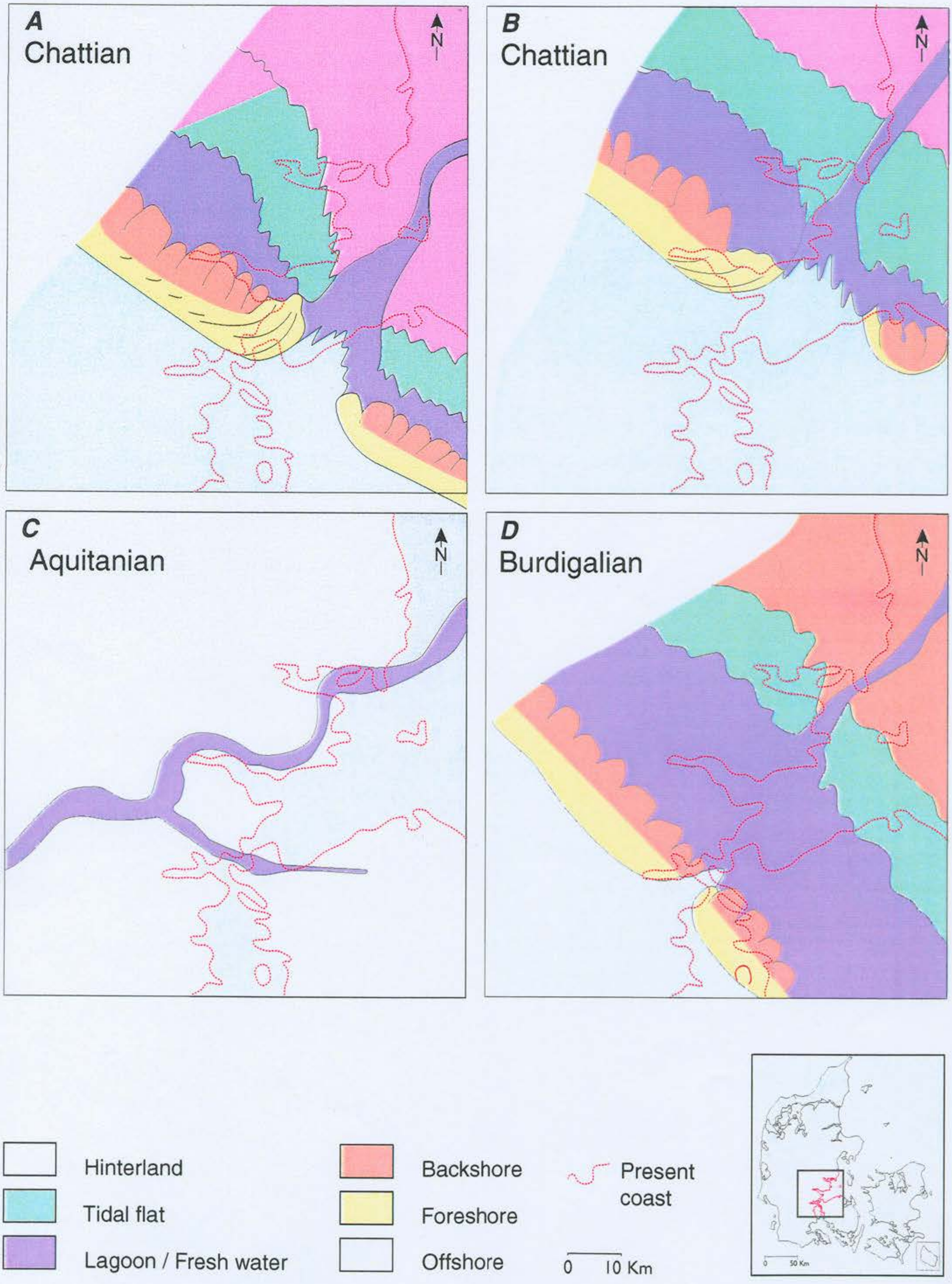


Fig. 13: Palaeogeographical reconstruction during the Late Oligocene transgression **A**, during maximum flooding in the Late Oligocene **B**, during the Aquitanian lowstand of sea level **C**, and early Burdigalian times **D**.

Locality 1: Øksenrade

The locality is situated on the southern part of the Middelfart peninsula in the forest of Øksenrade (Fig. 2). Here an introductory overview of the Upper Oligocene - Lower Miocene deposits of Denmark will be presented.

At this locality the iron-rich Øksenrade sandstone and the glaucony-rich Brejning Clay can be seen. The sediments were deposited in a shallow marine environment; the Brejning Clay was laid down in a sediment starved environment during the late Oligocene. The Øksenrade sandstone was a result of increased supply of coarse-grained sediments into the area. In the Lillebælt area two sand layers of ca. 1 m are interbedded in the silty, organic-rich offshore deposits.

Sedimentary structures

The glaucony-rich deposits at Øksenrade is strongly bioturbated (Fig. 14). However, a few sand lenses are seen sporadically. In the uppermost part of the profile the Øksenrade sandstone is sharply overlying the Brejning Clay (Fig.15). Shell impressions of molluscs occur at distinct levels. The succession probably represents a sequence, Sequence A, with the maximum flooding surface located in the most glaunony-rich interval.

Clay mineralogy and geochemistry

The clay mineral association consists of illite and kaolinite. There is a high content of authigenic glaucony in the lower part of the succession. In the upper part, where the sediments are silty, the glaucony shows clear evidences of reworking. Pyrite and siderite were formed during early diagenesis. The present high content of iron-oxides is due to weathering and concentration within the permeable sand layers.

Fig. 14: The Brejning Clay at Øksenrade. Note the glaucony-rich lower part and the increase in the content of organic matter upwards.

Fig. 15: The Øksenrade sandstone at the type locality.

Locality 2: Hindsgavl

At this locality a general coarsening upward trend of the succession can be seen. The succession represents a development from estuarine clay dominated sediments to sand dominated lower – upper shoreface and beach deposits. Both storm and tidal processes were involved in the deposition of the sediments. The depositional environment was oxic, but the lower part of the succession contain more organic matter due to deposition under low energy conditions. In the sequence stratigraphic framework this part forms the upper part of the transgressive systems tract and the highstand systems tract of sequence B. The sharp transition from the clay dominated part to the sand dominated part marks the maximum flooding surface separating the two systems tracts. A palynological study indicate a Late Oligocene age.

Sedimentary structures (Fig. 16)

Generally the outcrop demonstrate a wide range of hummocky cross-stratification.

The lower part of the succession is characterized by wave rippled sand, climbing ripples, laminated beds showing diurnal inequality, and micro-hummocky cross-stratified sand interbedded with black clay (Fig. 17). Scour and drape of mud is common. Discrete and amalgamated hummocky cross-stratified sand with wave rippled top occurs frequently and both isotropic and anisotropic are present (Fig. 18). This part of the succession is, however, dominated by small scale hummocks interbedded in a wavy-influenced heterolithic clay and sand (Fig. 19). Above this, at ca. 2.5 m, follows a ca 1 m bed of heterolithic clay and silty sand showing wave-rippled top. This bed is overlain, at ca. 3.5 m, by a succession, which is dominated by discrete 25 cm thick hummocky cross-stratified sand beds with wave rippled top (Fig. 20). These beds gives examples of ideal hummocky units with a sharp base, a relatively thick H zone with several second-order surfaces, a thinner F zone and X zone with wave ripples, and finally a M zone. Each HCS bed is separated by a 1 – 2 cm thick clay layer but cut-out of mud is seen and amalgamation occurs. Upwards amalgamation of sand beds become more frequent and only the erosional base (first order surface) and the H zone are present (SCS). The scours are often filled by pebbly sand showing a transition from concave-up laminae to convex-up laminae (Fig. 21). This part is terminated by parallel laminated sand beds with wave rippled top and flaser bedding, at ca. 8 m. The clay layers in this part are brown rather than black, indicating more oxidised conditions in the water column.

The uppermost part of the exposure, from ca 8.5 m, is dominated by laminated sand beds with scattered pebbles and low-angle cross-stratified sand beds. The dip of the cross-stratified sand beds is towards the southeast (Fig. 22).

Palynolfacies

The organic matter in 6 samples representing the black clay is very uniform, being strongly dominated by terrestrially derived palynomorphs (especially bisaccate and non-saccate pollen). The palynofacies results are presented in cirkular diagrams in Figs 23-26. Brown wood also constitute a major part of the organic particles, while amorphous organic matter (AOM) occur in minor amounts only. Marine palynomorphs only occur sporadically.

A distinct change in palynofacies occurs from sample 6 to sample 7 (Figs 24, 26). Samples 7 and 8, representing the brown clay layers, are dominated by brown wood rather than palynomorphs, and among the palynomorphs the marine dinoflagellate cysts dominate strongly. The dinoflagellate cyst assemblage is dominated by one genus, *Homotryblium* (here represented by the species *H. tenuispinosum*, *H. floripes* and *H. vallum*). According to Brinkhuis (1992, his fig. 3.13) high numbers of *Homotryblium* is an indicator for an inner neritic depositional environment

The change in palynofacies from samples 1-6 to samples 7-8 indicate a development from a semi-restricted marine, low-energy depositional environment towards a higher energy environment, possibly combined with a sea-level rise, as indicated by the distinctly higher relative percentages of marine palynomorphs in the upper two samples.

Clay mineralogy and geochemistry

The clay mineral association is dominasted by Illite and kaolinite in the estuarine deposits and smectite rich clay mineral association is typical for open marine deposits. The only authigenic mineral formed in this section is pyrite.

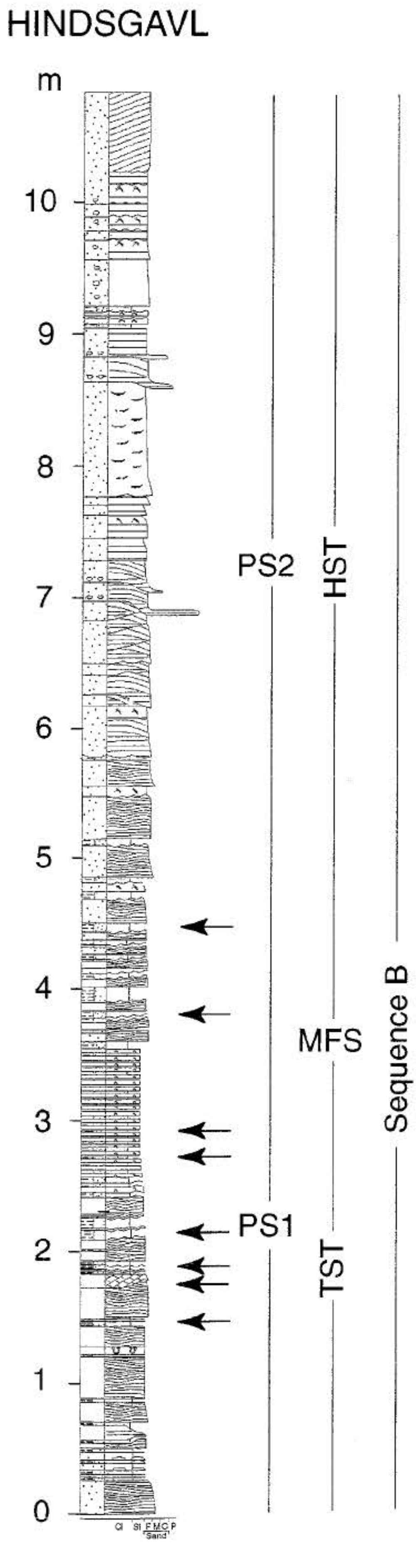


Fig. 16: Sedimentological log of the Hindsgavl section. Arrows indicate samples for palynology. For legend see the last page.

Fig. 17: Photo from the lower part of the Hindsgavl section. Sediments deposited in an estuarine depositional environment. The beds are frequently scoured and often draped by clay. Note the bed showing diurnal inequality.

Fig. 18: Hummocky cross-stratified sand beds interbedded in wave-influenced heterolithic clay and sand. Note the bed in the middle part of the photo shows scour and drape. The drape above the second order scoured surface shows anisotropy indicating combined flow origin. The anisotropic hummocky indicate flow towards the left (east or southeast) and probably caused by geostrophic currents along the coast.

Fig. 19: Hummocky sand body in a wave influenced heteroilthic sand and clay. Some of the hummocky sands are laterally passing into wave ripples.

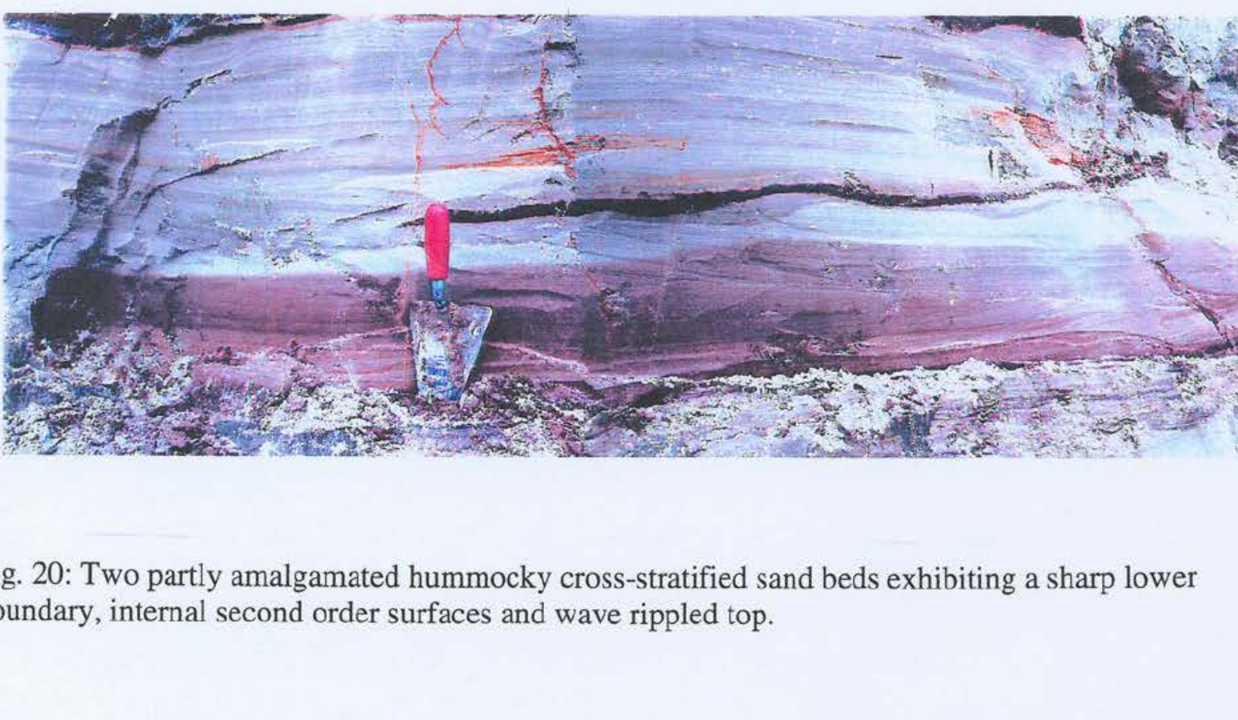


Fig. 20: Two partly amalgamated hummocky cross-stratified sand beds exhibiting a sharp lower boundary, internal second order surfaces and wave rippled top.

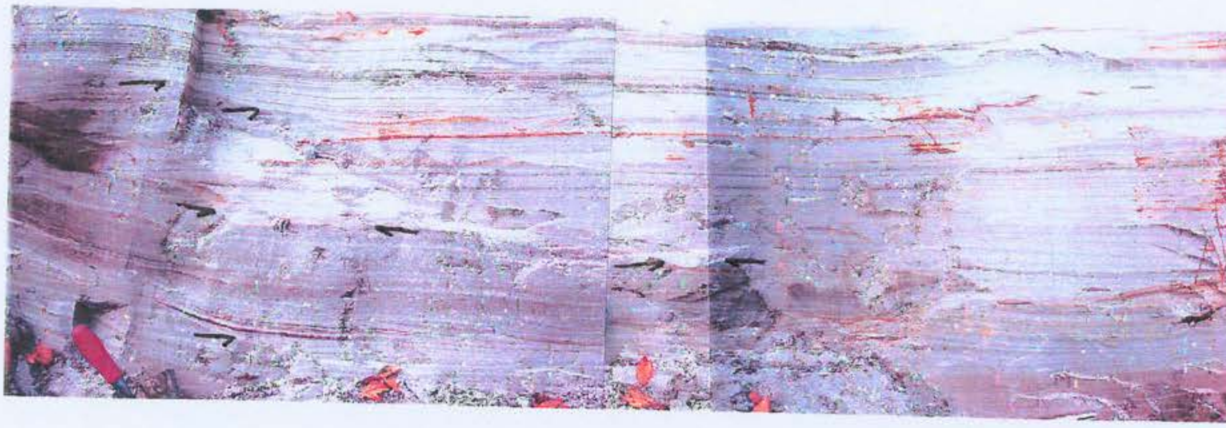


Fig. 21: Swaly cross-stratification. Note that the stratification is relatively flat The swales are indicated by an arrow.

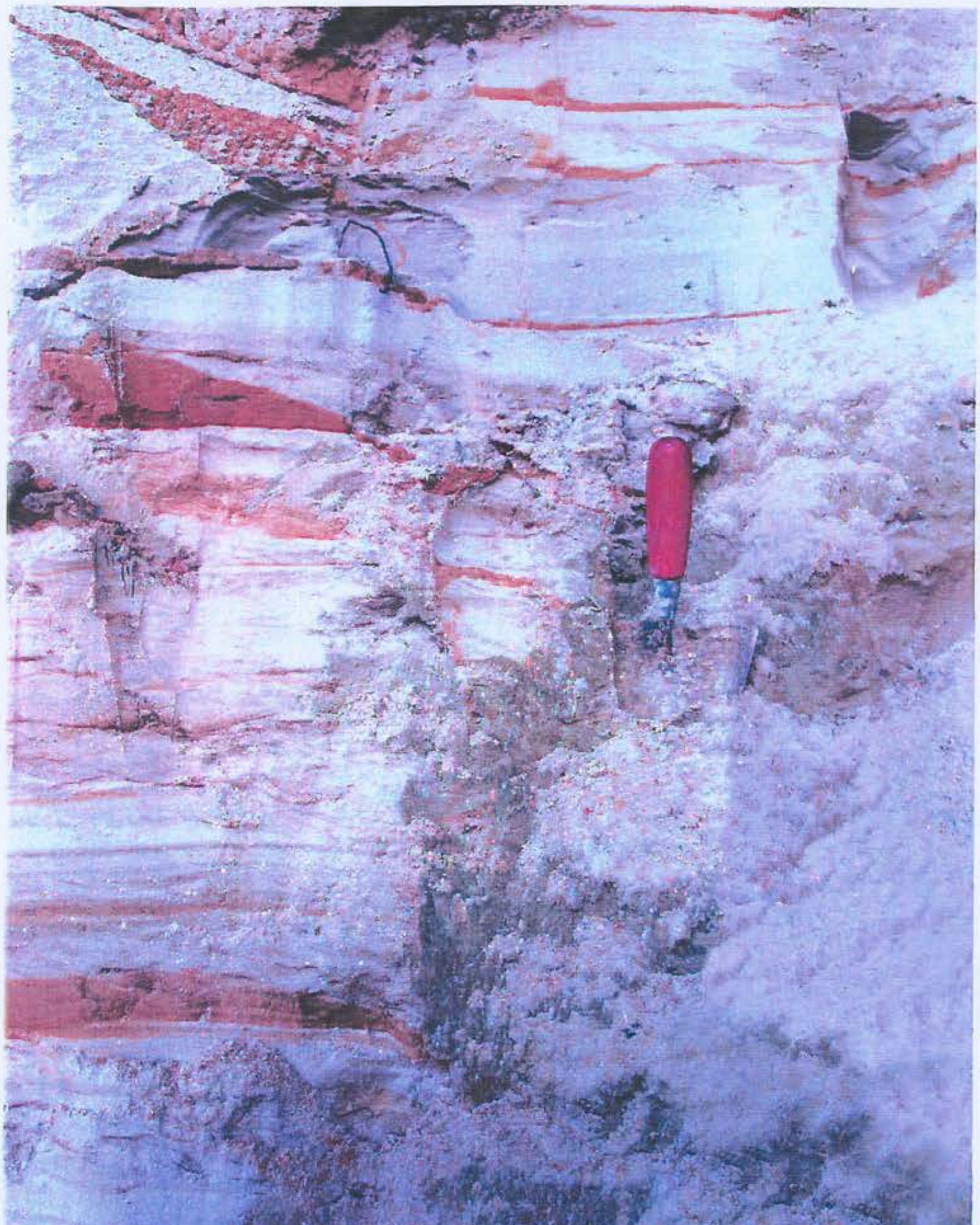
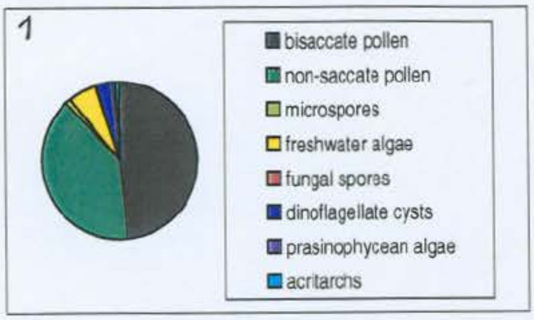
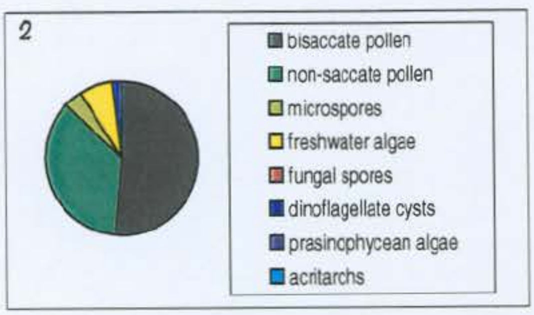


Fig. 22: Sand beds showing flaser and laminated bedding. The laminated beds at the uppermost part of the photo are pebbly.

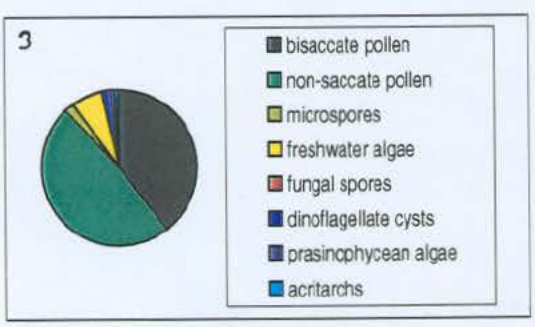
112	92	3	14	1	7	1
49%	40%	1%	6%	<1%	3%	<1%



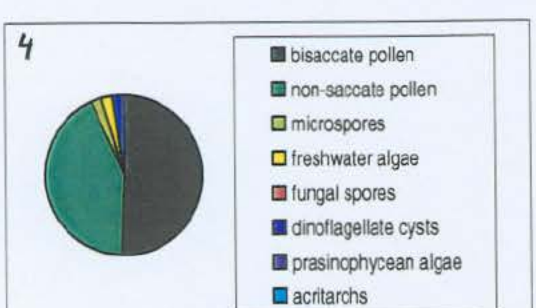
117	82	9	16	0	4	0
51%	36%	4%	7%	0%	2%	0%



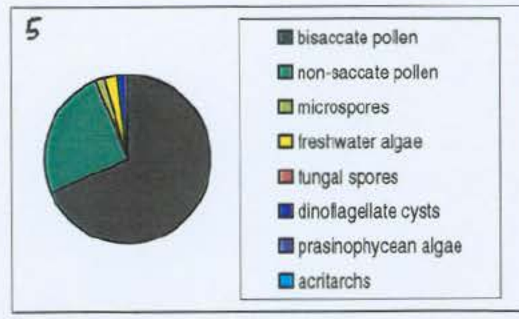
95	117	5	16	0	4	2
39%	48%	2%	7%	0%	2%	1%



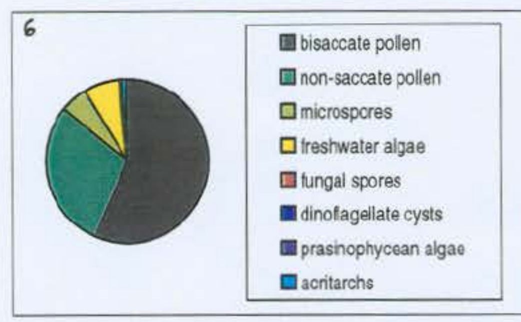
113	96	5	5	0	5	0
51%	43%	2%	2%	0%	2%	0%



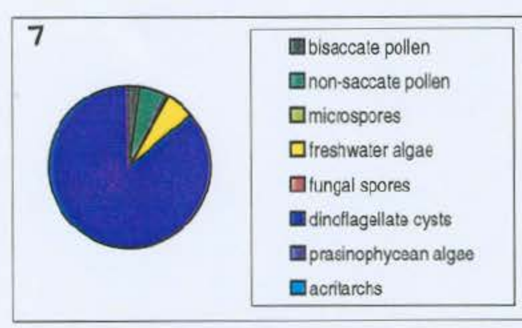
166	62	4	7	0	4	0
67%	26%	2%	3%	0%	2%	0%



130	68	13	17	0	0	1
57%	29%	6%	7%	0%	0%	<1%



5	12	1	13	0	186	0
2%	6%	<1%	6%	0%	86%	0%



39	10	0	5	0	161	0
18%	5%	0%	2%	0%	75%	0%

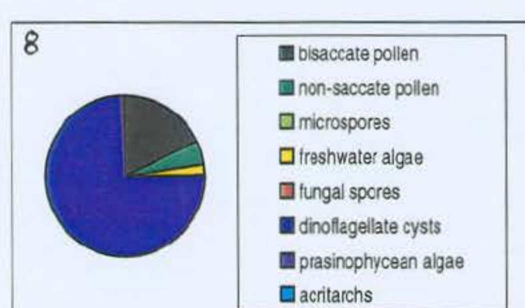


Fig. 23 + 24: Results from the palynofacies study showing the relative percentages of the main categories of organic particles. A relatively uniform composition of the organic matter occur in samples 1-6 , while a distinct change is seen from sample 6 to 7.

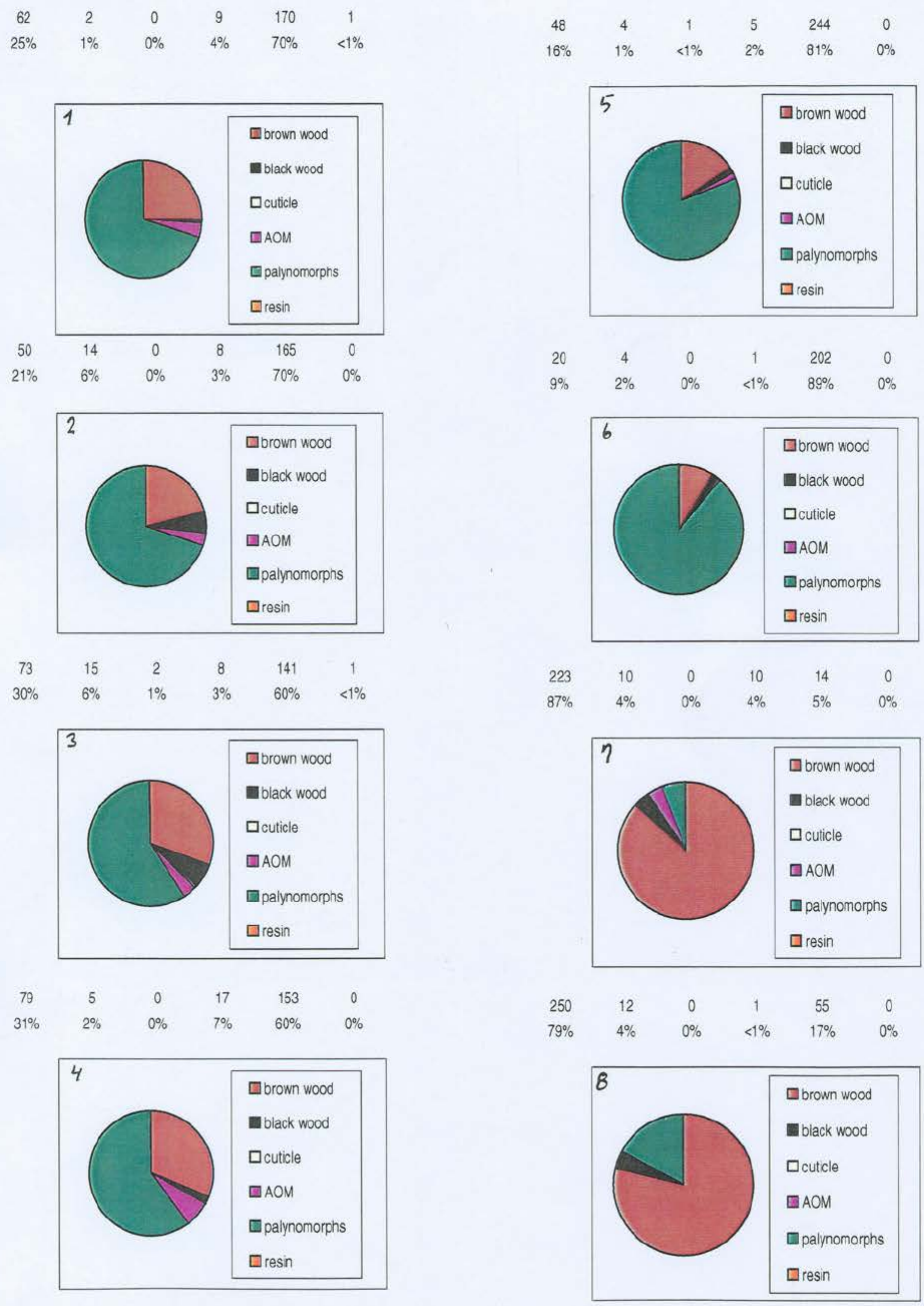


Fig. 25 + 26: Results from the palynofacies study showing the relative percentages of the palynomorph categories. A relatively uniform composition, with a clear dominance of terrestrially derived palynomorphs, was recorded from samples 1-6, while a distinct change occur from sample 6 to sample 7, with samples 7-8 being strongly dominated by marine derived palynomorphs (dinoflagellate cysts).

Locality 3: Børup

The succession here is a continuation of the clean sand in the uppermost part of the Hindsgavl succession. This part of the section is interpreted as shoreface and beach sediments. The deposits are sharply overlain by a bioturbated gravel layer. This layer was laid down in a fluvial environment during lowstand of sea level. Sub-aerial conditions prevailed probably during most of the Aquitanian. During the subsequent transgression in the latest Aquitanian – early Burdigalian, the fluvial deposits were redeposited and strongly bioturbated. Due to accretion of spit/barrier-complexes seaward lagoonal organic-rich sediments were deposited and forms the upperpart of the section. In a sequence stratigraphic framework the section forms the upper part of a highstand systems tract topped by a sequence boundary which later was replaced by a revinement surface (gravel layer). The transgressive systems tract above the sequence boundary is very thin and the lagoonal deposits form the early highstand systems tract? with two flooding events of the succeeding sequence.

Sedimentary structures (Fig. 27)

The lower 4 m of the exposure is characterized by a series of four fining upward cycles consisting of a relatively thick (20-30 cm) laminated sand bed topped by trough cross-stratified sand. This is overlain by alternating laminated to wave rippled sand and bioturbated sand beds separated by a thin clay layer. Scour and fill with pebbly sand occurs sporadically at the base of each cycle (Fig. 28). Above 4 m an up to 2 m thick medium-grained, weakly laminated and trough cross-bedded sand bed is seen (Fig. 29). Sporadically burrows of ophimorpha occur. Erosively upon this layer at ca 6.5 m, a series of two gravel layers topped by strongly bioturbated medium-grained sand beds are seen. The bases of the gravel layers are sharp and characterized by scours (Fig. 29). The layer is very poorly sorted with a grain size distribution between 2 mm and 30 mm. Bioturbation into the gravel layers are common. Each gravel layer show a fining upward trend. The uppermost bioturbated sand bed is at 8 m sharply overlain by black organic-rich silty clay of ca. 1 m in thickness. A new ca. 1 m thick organic-rich silty clay layer is superimposed on a 20 cm totally bioturbated coarse-grained sand bed which separates the two organic-rich layers. The uppermost part of the section consists of alternating sand and mud beds, but these are difficult to study at this locality.

Clay mineralogy and geochemistry

The clay mineral association in the organic-rich sediments is dominated by kaolinite and some illite. Samples from the gravel layer contain only kaolonite. In the sandy deposits, showing a high degree of bioturbation, a distinct increase in smectite and illite have been measured. The authigenic minerals in the black layers are siderite and pyrite.

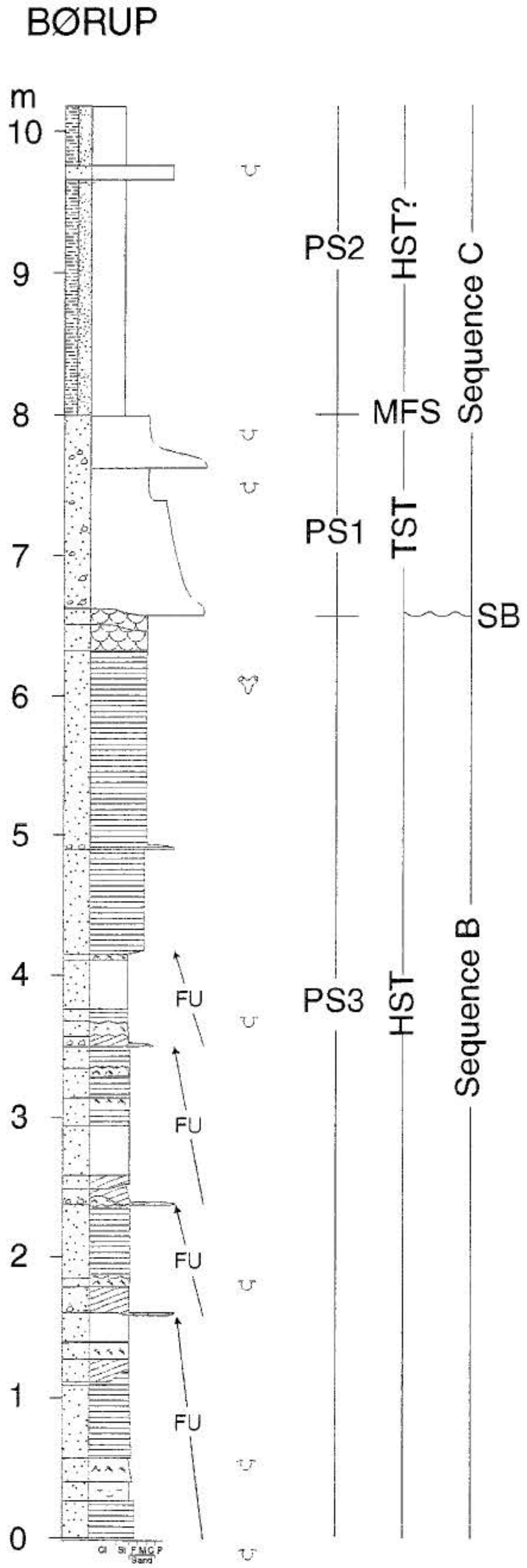


Fig. 27: Sedimentological log of the Børup section. For legend see the last page.

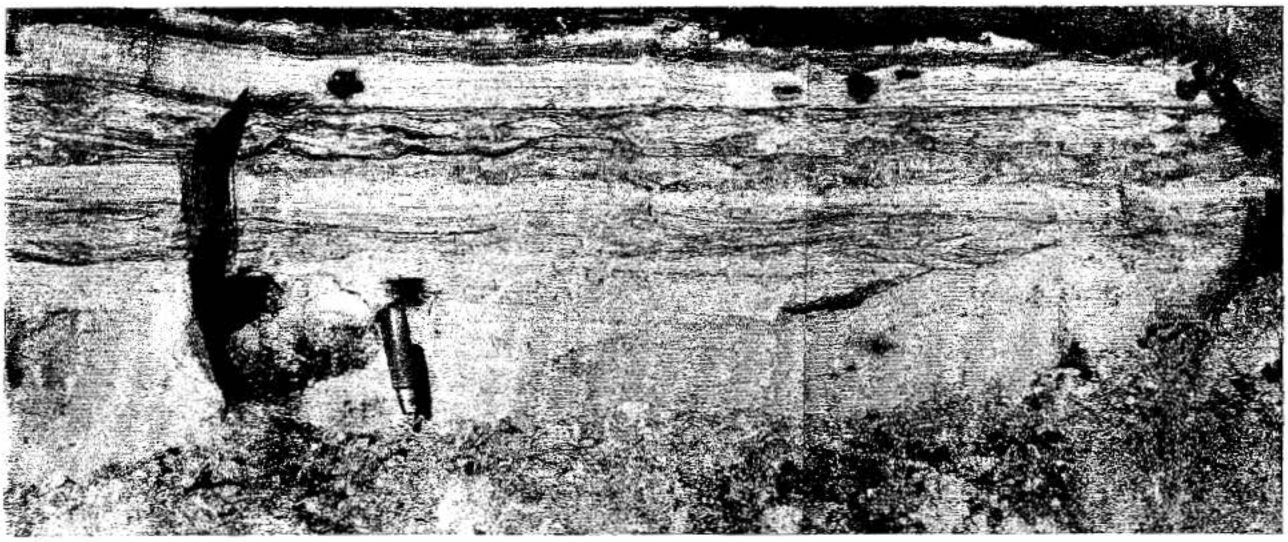


Fig. 28: A relatively thick laminated sand bed topped by wave ripples in the lower part of the photo. Note the upward widening of troughs below the overlying laminated sand bed. The upper part shows thin laminated sand beds with wave-rippled top and bioturbation. Some of the thin bedded sands are totally bioturbated.

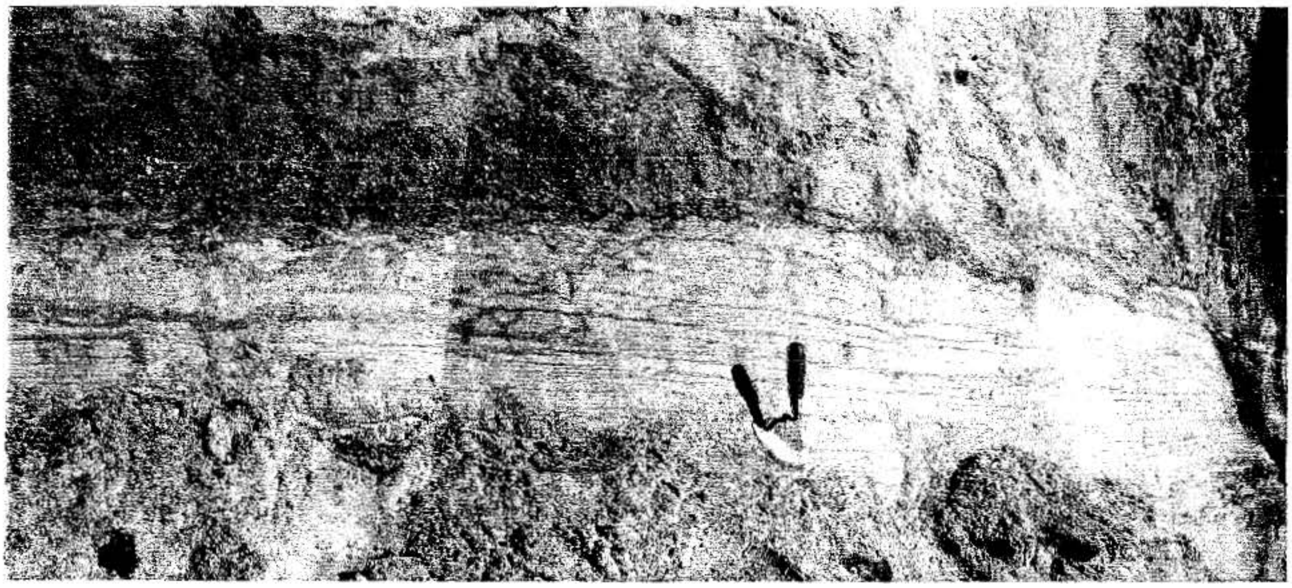


Fig. 29: Laminated to trough cross-stratified shoreface sand cut by a pebble layer. The erosive base forms a sequence boundary.

Locality 4: Hagenør

This locality is a continuation of the Børup profile. The organic-rich deposits seen in the uppermost part of the Børup section can clearly be seen here. It is thus possible to study the lateral development of the organic-rich sediments. The section at Hagenør is interpreted as back-barrier deposits representing lagoonal and upper-shoreface depositional environments. Both storm and tidal processes were involved in the deposition. In a sequence stratigraphic framework this succession forms parts of the transgressive systems tract and early highstand systems tract. The base of the strongly bioturbated sand bed (sporadic wave-rippled coarse-grained sand bed) represent a flooding surface. The age of the deposits is (late Aquitanian?) – early Burdigalian. The dinoflagellate *hystrichosphaeropsis Obscura* has been found in correlatable marine sediments at Rønshoved.

Sedimentary structures (Fig. 30)

In the extreme lower part of the exposure a layer of very dark and organic-rich silty clay is seen (Fig. 31). This is followed, at about 1 m, by brownish, organic-rich sand, which is strongly bioturbated. The trace fossils and markers of *Pelecypods* and *Holothurians* (Radwansky et al. 1975) are excellently exposed here. At ca. 1.8 m this layer is sharply overlain by a rippled coarse-grained sand/gravel layer (Fig. 32). Some ripples are asymmetrical and draped by a thin clay layer which again is overlain by an asymmetrical cross-stratified coarse-grained ripple bed. The foreset laminae of the ripples dip towards the southwest and the crests strikes NW-SE. The thickness of the sand/gravel layer varies laterally. It is overlain by organic-rich silty clay similar to the lowermost clay bed but not as black as this; especially not in the southern part of the locality. At ca. 3 m a gradual increase of intercalated sand beds occur (Fig. 33). The sand beds are characterized by a sharp lower boundary and are either homogeneous or show lamination in the lower part and wavy bedded in the upper part. The top often shows wave-rippled cross-lamination, occasionally bidirectional, but most frequently a southern dip of the foresets are seen. Burrows of ?*haustorid* are common (Radwansky et al. 1975). The exposure is topped by a homogeneous sand layer which is erosively overlain by Quaternary fluvial deposits.

Palynofacies

At this locality 3 samples have been collected (Figs 34, 35). The organic particles in sample 9 from the organic-rich clay is dominated by more or less degraded vitrinitic matter (AOM and brown wood). Non-hardened resin occur commonly. Among the palynomorphs the terrestrial dominate totally while marine palynomorphs occur only sporadically. Most of the recorded dinoflagellate cysts are torn or otherwise physically degraded. The palynofacies results indicate a restricted, low-energy, marginal marine environment with strong oxygen-deficiency at the sea-floor and with a very high terrestrial influence. Most of the dinoflagellate cysts are probably washed in from a higher energy environment, e.g., during storms.

Sample 10, representing the sand-rich deposit interbedded in the organic-rich clay, show a dominance of palynomorphs, distinctly less AOM than in the previous sample and with wood particles constituting only a minor parts. Among the palynomorphs the terrestrially derived also dominates in this sample, but the relative percentage of marine palynomorphs (dinoflagellate cysts) are twice as much as in sample 9. Furthermore, the dinocysts in sample 10 show a higher diversity and are generally better preserved than in sample 9. The palynofacies results indicate a semi-restricted, low-energy, marine environment with some oxygen-deficiency at the sea-floor and with a very high terrestrial influence. A slightly longer distance to terrestrial sources than sample 9 is indicated by the slightly higher relative percentages of bisaccate pollen. Furthermore, the more diverse and more well-preserved dinocyst-assemblage indicate a more open-marine environment than for sample 9.

The organic particles in sample 11, are dominated by brown wood, but also palynomorphs constitute a major part of the sedimentary organic particles. AOM occurs only sporadically. Among the palynomorphs the terrestrially derived dominates strongly (especially the bisaccate pollen). Dinoflagellate cysts occur only sporadically, while the other marine algae (including prasinophycean algae and "large spheres), acritarchs and freshwater algae occur in distinctly higher numbers than in the previous two samples. The palynofacies of this sample indicates a restricted, marginal marine, possibly brackish-water environment with a slightly higher energy-level than sample 10 and a well-oxygenated sea-floor.

The palynofacies results indicate a change from a strongly restricted marine environment with anoxic conditions at the sea-floor (sample 9) to a situation with less oxygen-deficiency and slightly higher marine influence (sample 10) and ends up with a situation with possible brackish water conditions and no oxygen-deficiency (sample 11). Furthermore, the high relative percentages of saccate pollen in sample 11 indicate a longer distance to the terrestrial source than in the two previous samples.

Clay mineralogy and geochemistry

The clay mineral association in the organic-rich sediments is dominated by kaolinite and some illite. In the sandy deposits showing a high degree of bioturbation a distinct increase in smectite and illite have been measured. The authigenic minerals in the black layers are siderite and pyrite.

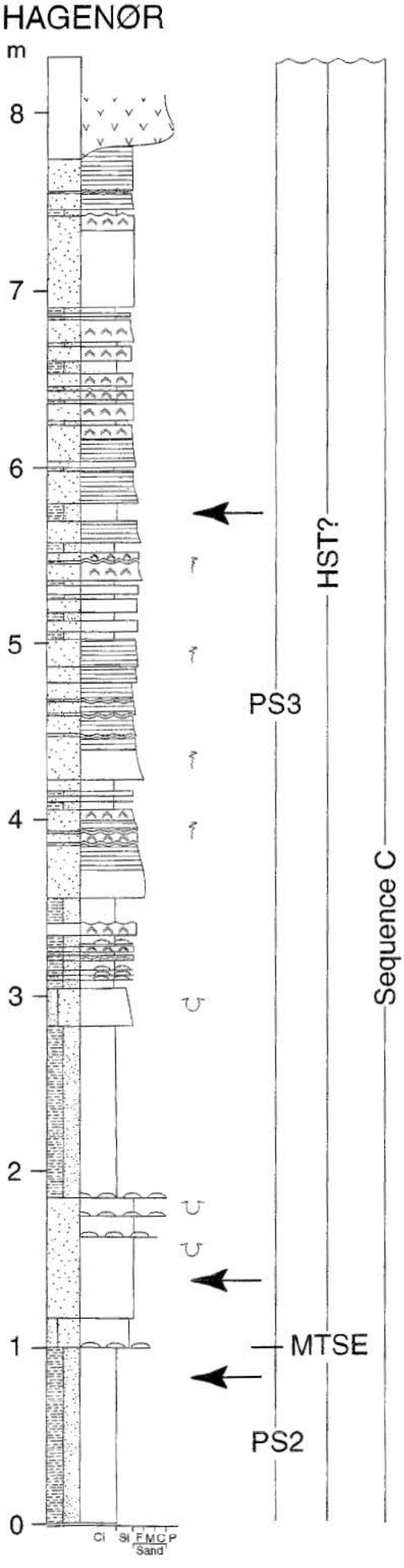


Fig. 30: Sedimentological log of the Hagenør profile. Arrows indicate samples for palynology. For legend see the last page.

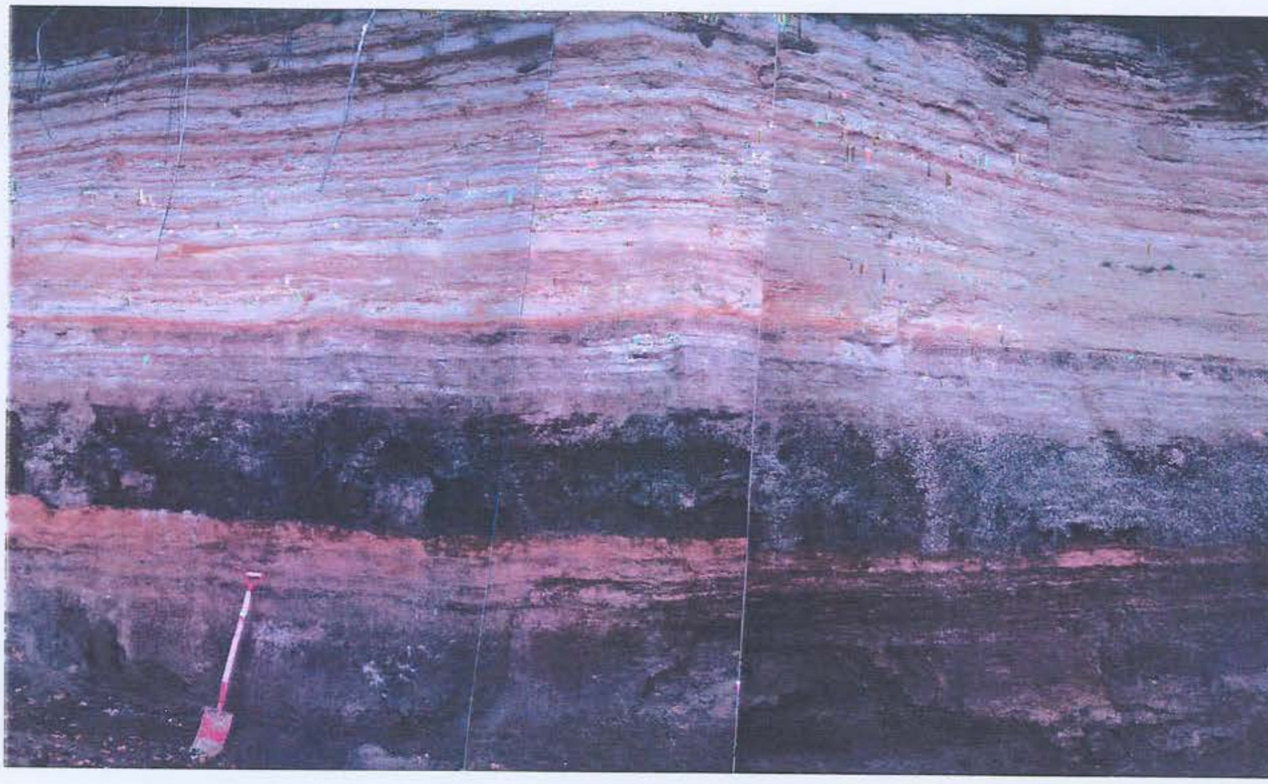


Fig. 31: The out-crop at Hagenør. The section is dominated by back-barrier deposits characterized by lagoonal mud and washover fans. The yellow layer in the lower part of the section is an intensively bioturbated sand bed indicating a period with open marine conditions.

Fig. 32: Intensively bioturbated open marine sand bed interbedded in lagoonal muds (black). Note the bioturbated sand bed is topped by a sharp based rippled coarse-grained sand/gravel layer. This layer correlates laterally with hummocky cross-stratified fine-grained sand beds. The crests of the ripples strikes NW-SE indicating a NW-SE trending palaeo-shoreline.

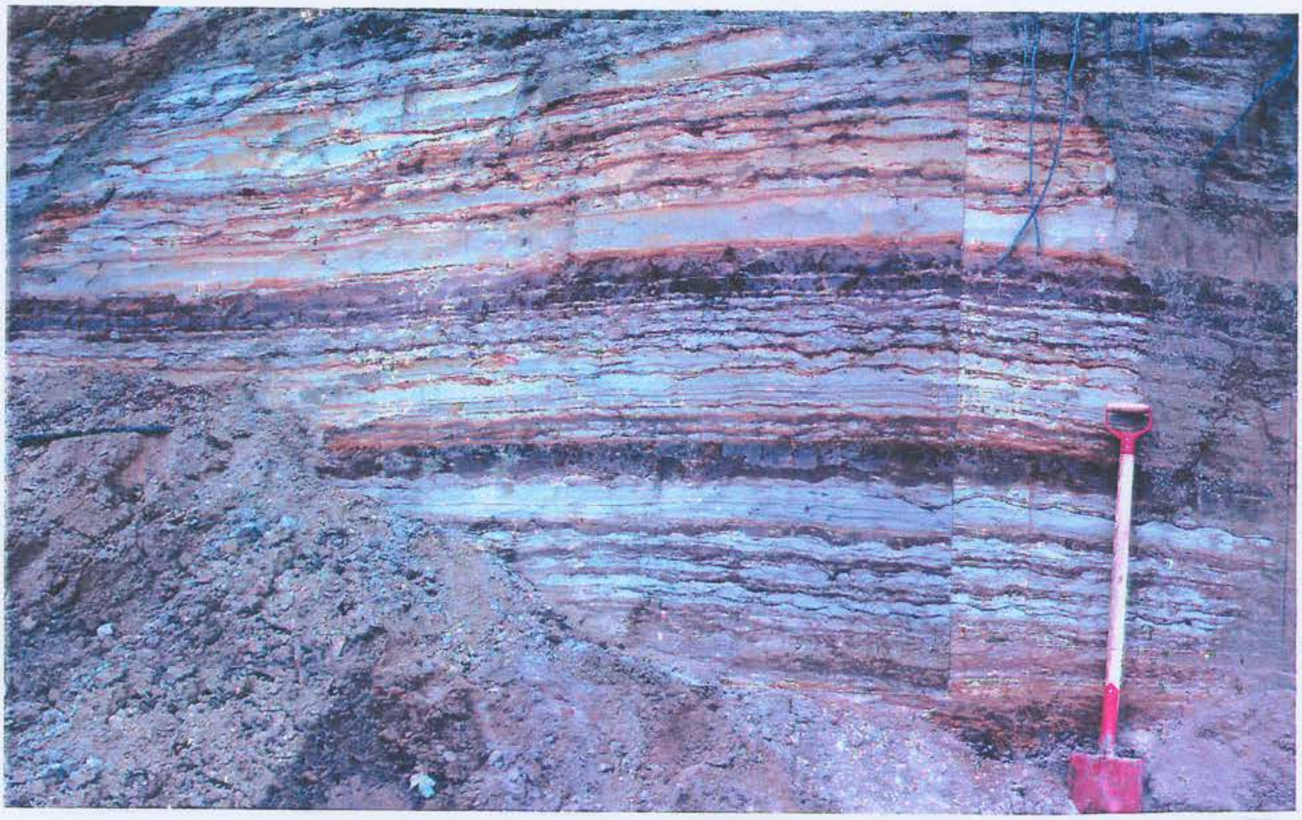


Fig. 33a: Alternating sand and clay beds. The sand beds are often sharp based and laminated with a rippled top. Some of the ripples interbedded in the muds indicate tidal influence, e.g. flame structures and bidirectional cross-bedding.

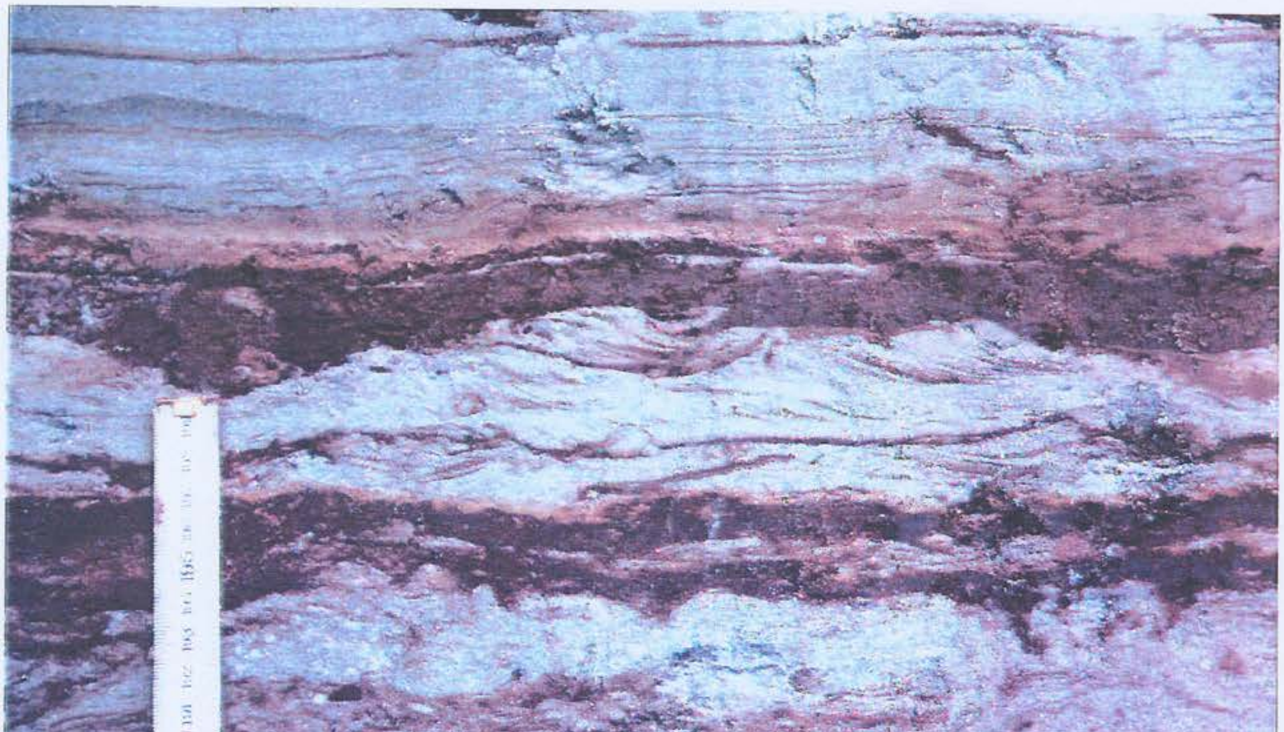
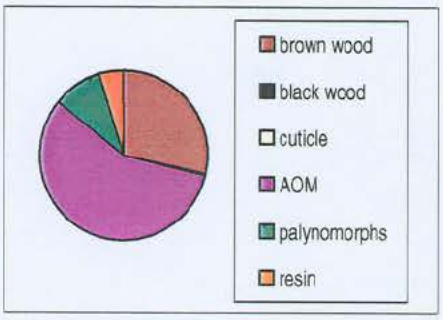
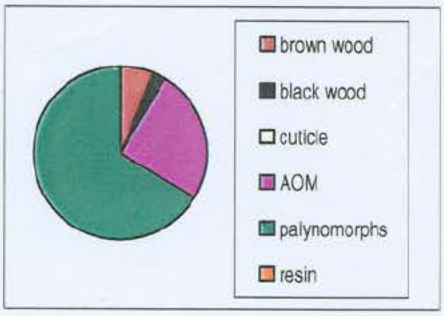


Fig. 33b: Close-up of photo 33a showing wave formed ripples and borrows.

Sample no.	Br. Wood	Bl. Wood	Cuticle	AOM	Palynom.	Resin	Total
9	71	1	0	142	23	12	249
	29%	<1%	0%	57%	9%	5%	100%



Sample no.	Br. Wood	Bl. Wood	Cuticle	AOM	Palynom.	Resin	Total
10	14	6	0	57	153	0	230
	6%	3%	0%	25%	66%	0%	100%



Sample no.	Br. Wood	Bl. Wood	Cuticle	AOM	Palynom.	Resin	Total
11	131	16	7	3	98	2	257
	51%	6%	3%	1%	38%	1%	100%

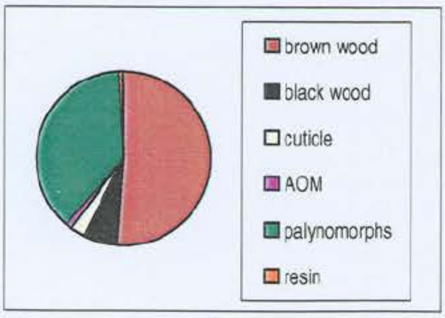
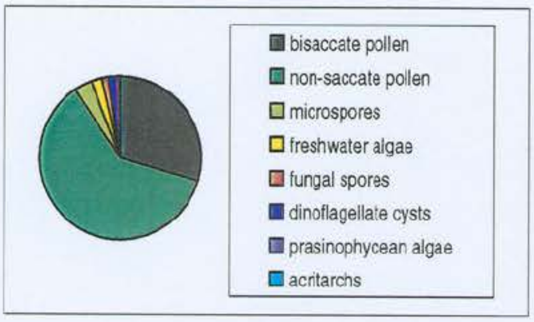
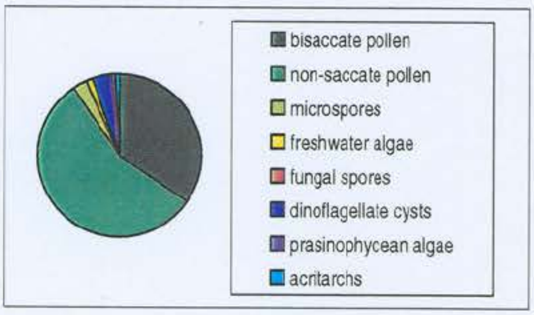


Fig. 34: Results from the palynofacies study showing the relative percentages of the main categories of sedimentary organic particles. Note the gradual decrease in AOM, indicating an increase in oxygen at the sea-floor.

Sample no.	Saccate	Non-sacc.	Spores	Fresh.Alg.	Fungi	Dinocysts	Prasinoph.	Acritarchs	Total
9	66	137	8	5	3	4	0	1	224
	29%	62%	4%	2%	1%	2%	0%	<1%	100%



Sample no.	Saccate	Non-sacc.	Spores	Fresh.Alg.	Fungi	Dinocysts	Prasinoph.	Acritarchs	Total
10	83	135	7	3	0	9	2	2	241
	34%	56%	3%	1%	0%	4%	1%	1%	100%



Sample no.	Saccate	Non-sacc.	Spores	Fresh.Alg.	Fungi	Dinocysts	Prasinoph.	Acritarchs	Total
11	108	43	2	25	1	1	12	12	204
	47%	18%	1%	11%	<1%	<1%	5%	5%	100%

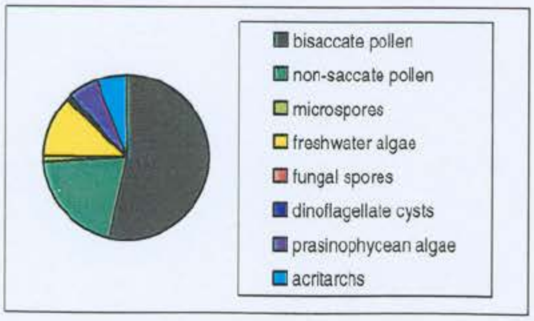


Fig. 35: Results from the palynofacies study showing the relative percentages of the palynomorph categories. Note the relatively high percentages of the marine derived dinoflagellate cysts in sample 10 and in acritarchs and prasinophycean algae in sample 11.

Locality 5: Rønshoved

This locallity consists of two small but important exposures. The lateral development of sequence B at Hagenør and Børup outcrops can be studied here (e.g. Friis et al. 1998). The sediments were laid down in open marine, shoreface, and lagoonal environments. A palynological study of the section indicate a late Aquitanian – early Burdigalian age. In the sequence stratigraphic framework the gravel layer in the lower part of the succession corresponds to the sequence boundary at Børup. Upon this boundary lagoonal sediments were deposited. These are overlain by open marine deposits showing a coarsening/thickening upward trend. The lower boundary is formed by a marine transgressive surface of erosion. In a sequence stratigraphic framework this locality represent the transgressive systems tract of sequence C.

Sedimentary structures

Exposure a (Fig. 36)

The lower part of the exposure consists of weakly bioturbated fine-grained sand ca. 1 m. This is sharply overlain by black, homogenous, organic-rich silty clay which is succeeded by large scale cross- and trough cross bedded clayey sand. Erosionally upon this, at 2.25 m, hummocky cross-stratified and swaley cross-stratified sand and wavy heteroliths occur (Fig. 37). The hummocky bed above the erosional surface show a nice antiform with two second order truncation surfaces. Laterally, this bed correlates with a wave and tidal influenced heterolith. The uppermost part of the exposure consists of a laminated massive and sharp-based sand bed.

Exposure b (Fig. 38)

At the base of the exposure a ca. 25 thin cm gravel layer occurs. This is followed by weakly bioturbated fine-grained sand ca. 2 m. This layer is strongly bioturbated at the top. Above the bioturbated layer, at ca. 2.25 m, a section of interbedded sand and silty clay occurs. This is gradually developed into a 60 cm thick black, organic-rich silty clay. At about 4 m ca 1.5 m thick cross-bedded (HCS?), silty sand is seen (Fig. 39). Just above 5 m a distinct erosional surface separate these deposits from sand dominated sediments characterised by alternation of hummoky cross-stratified beds (sharp erosive base and antiform) superposed by beds showing climbing ripple lamination (Fig. 40). At 7 m low-angle trough cross-stratified clean sand occurs.

Palynology

Three samples were collected at this locality (Figs 41, 42). The two lowermost samples (samples no. 12 and 13) are strongly dominated by AOM while brown wood and palynomorphs only constitute minor amounts of the organic particles. Most of the AOM is probably degraded vitrinitic material. Among the palynomorphs the terrestrially derived dominates totally. Marine palynomorphs occur only sporadically, and the few recorded dinoflagellate cysts are torn or otherwise physically degraded. The palynofacies results indicate a restricted, low-energy, marginal marine environment with strong oxygen-deficiency at the sea-floor and with a very high terrestrial influence. Most of the dinoflagellate cysts are probably washed in from a higher energy environment or during storms.

A distinct change in palynofacies occurs from sample 13 to sample 14. Sample 14 is dominated by palynomorphs but also brown wood constitute a major part of the sedimentary organic particles while AOM only constitute a minor part. The palynomorphs are dominated by terrestrial palynomorphs. The dinoflagellate cysts are, however, much better represented in this sample than in the two previous and are diverse and well-preserved. The palynofacies results indicate a low-energy, open marine but coast-near depositional environment with a well-oxygenated sea-floor and with high terrestrial influence.

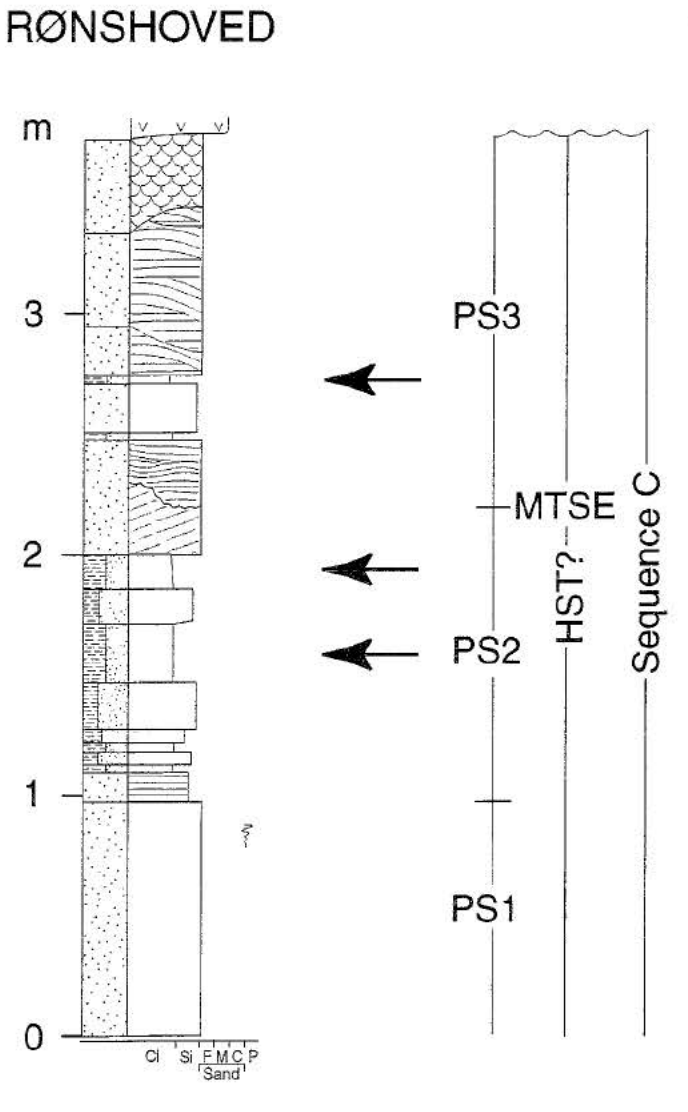


Fig. 36: Sedimentological log of the Rønshoved A section. Arrows indicate samples for palynology. For legend see the last page.

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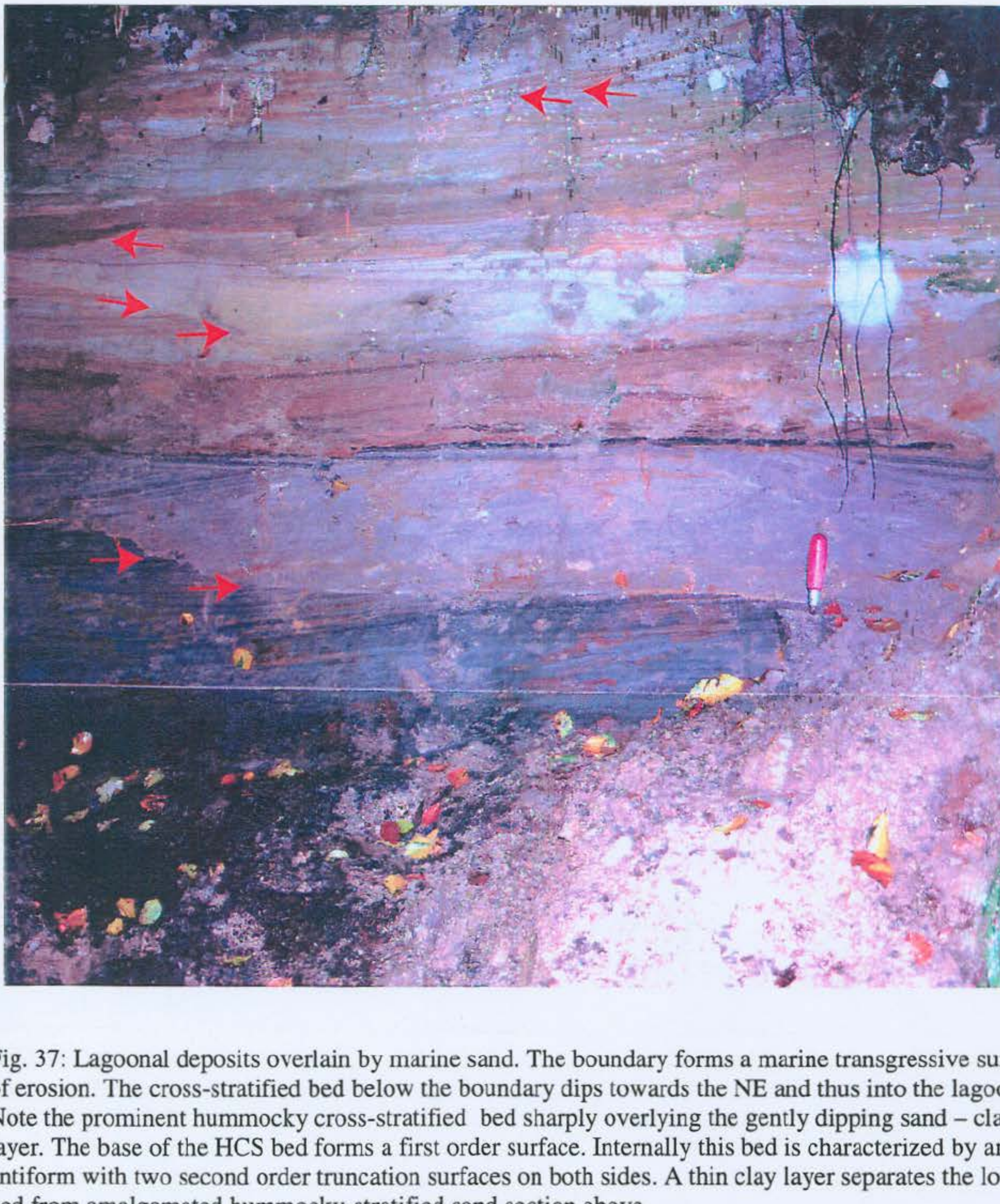


Fig. 37: Lagoonal deposits overlain by marine sand. The boundary forms a marine transgressive surface of erosion. The cross-stratified bed below the boundary dips towards the NE and thus into the lagoon. Note the prominent hummocky cross-stratified bed sharply overlying the gently dipping sand – clay layer. The base of the HCS bed forms a first order surface. Internally this bed is characterized by an antiform with two second order truncation surfaces on both sides. A thin clay layer separates the lower bed from amalgamated hummocky-stratified sand section above.

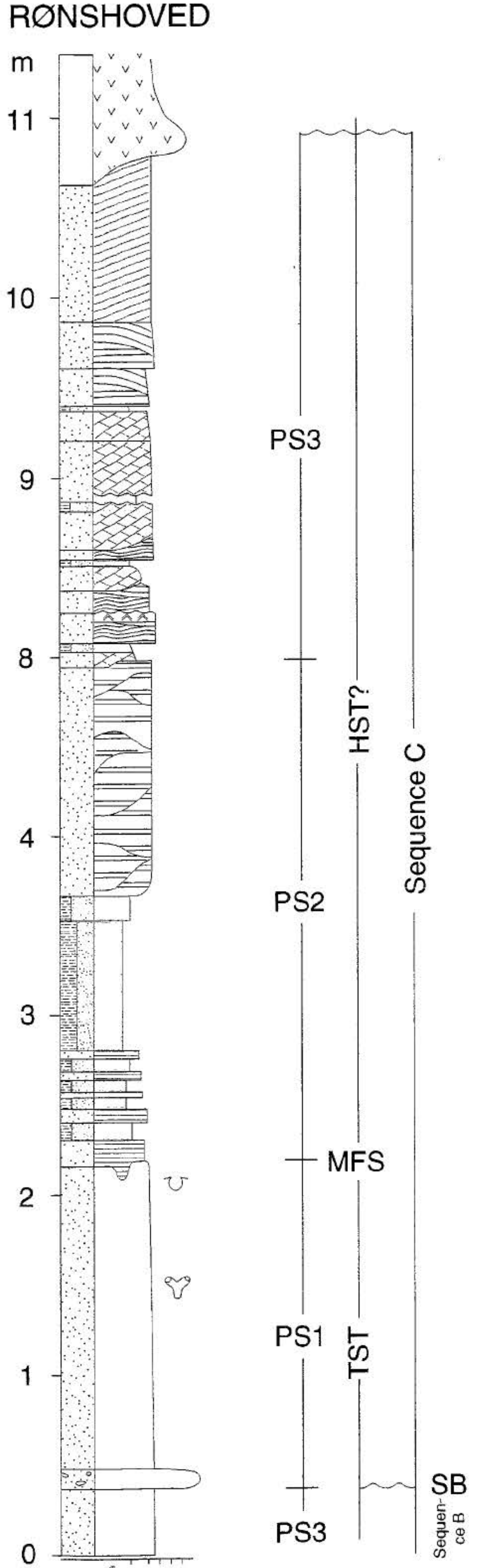


Fig. 38: Sedimentological log of the Rønshoved B section. For legend see the last page.

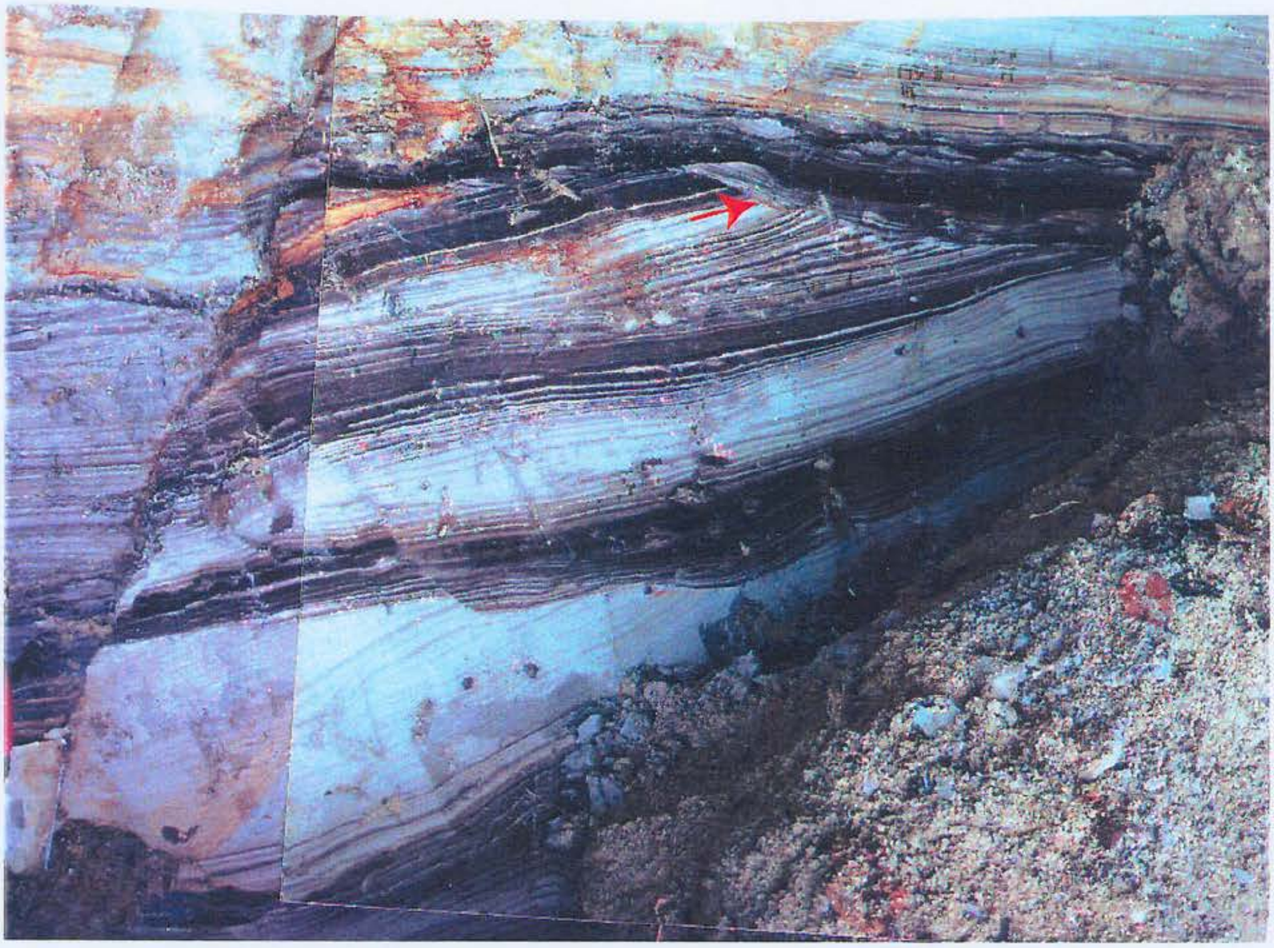


Fig. 39: Tidal influenced bedding is seen in the lowermost part of the photo. The bedding shows both diurnal inequality and neap-spring cycles. Erosionally on top of this laminated mud and sand is seen. This is followed by hummocky cross-stratified beds and climbing ripples.

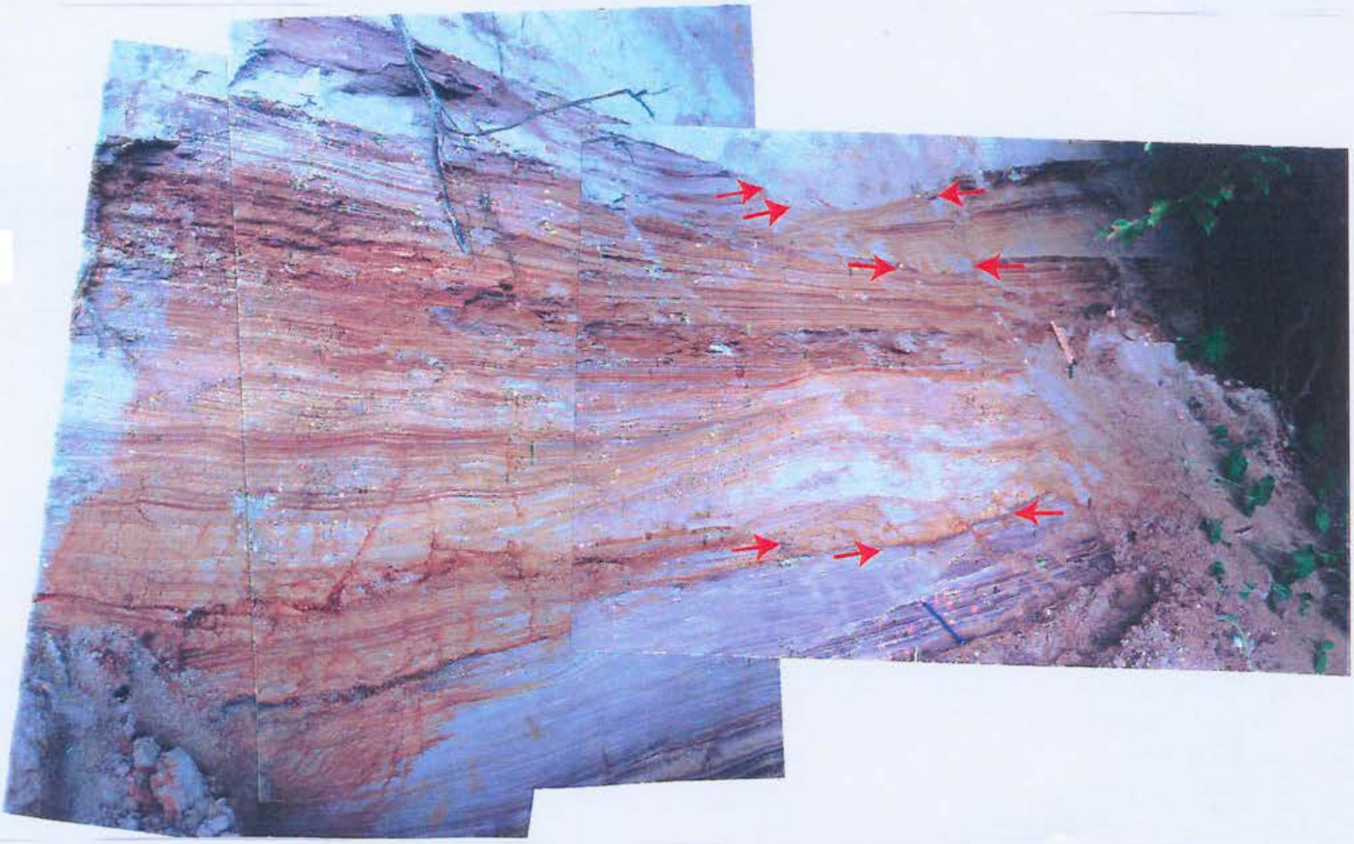
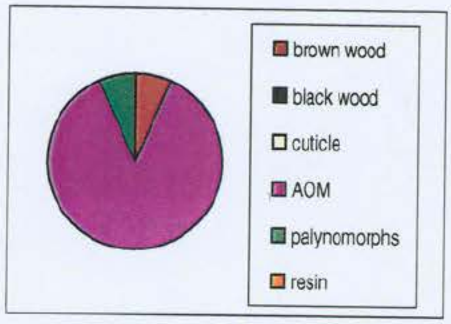
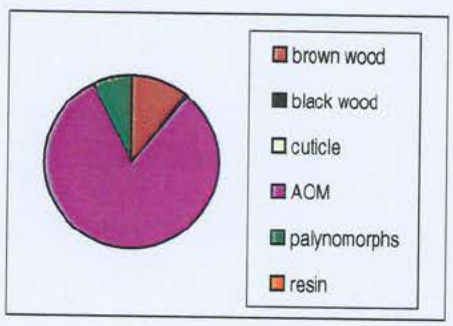


Fig. 40: Alternating hummocky cross-stratified sand beds and climbing ribbles. Each hummucky bed is characterized by a sharp erosional base and internal second order surfaces. The hummocky is gradually developed into climbing ripples and laminated bedding. In the extreme upper part of the photo a scoured sand bed is seen. The sand bed is charactericed by low angle cross-stratification.

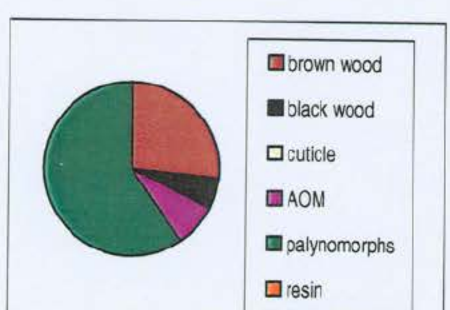
Sample no.	Br. Wood	Bl. Wood	Cuticle	AOM	Palynom.	Resin	Total
12	18	0	0	231	18	0	267
	7%	0%	0%	86%	7%	0%	100%



13	23	1	0	178	16	0	218
	11%	<1%	0%	82%	7%	0%	100%



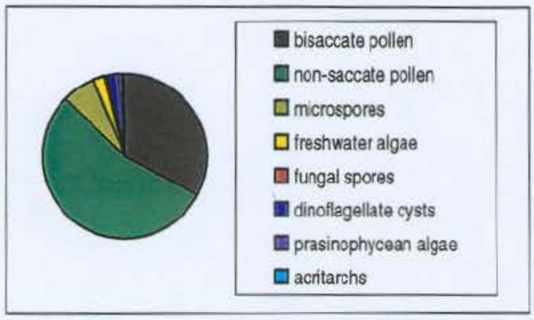
14	71	15	0	21	159	0	266
	27%	6%	0%	8%	59%	0%	100%



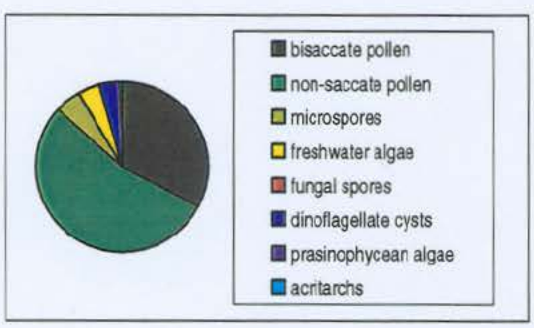
brown woo black wooc cuticle AOM palynomoŋ resin

Fig. 41: Results from the palynofacies study showing the relative percentages of the main categories of organic particles. Note the high relative percentages of AOM in sample 12 and 13, indicating oxygen-deficiency at the sea-floor.

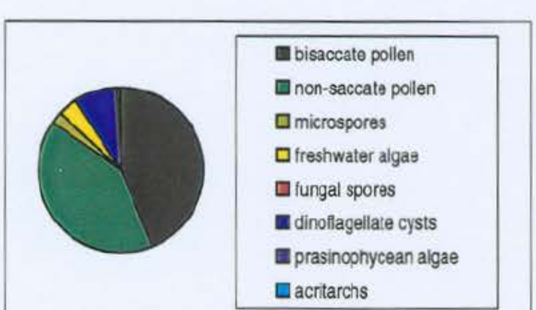
Sample no.	Saccate	Non-sacc.	Spores	Fresh.Alg.	Fungi	Dinocysts	Prasinoph.	Acritarchs	Total
12	70	116	14	5	1	4	2	1	213
	33%	54%	6%	2%	<1%	2%	1%	<1%	98%



Sample no.	Saccate	Non-sacc.	Spores	Fresh.Alg.	Fungi	Dinocysts	Prasinoph.	Acritarchs	Total
13	64	105	10	8	0	7	0	1	195
	32%	52%	5%	4%	0%	3%	0%	<1%	96%



Sample no.	Saccate	Non-sacc.	Spores	Fresh.Alg.	Fungi	Dinocysts	Prasinoph.	Acritarchs	Total
14	91	86	5	8	0	17	1	1	209
	43%	40%	2%	4%	0%	8%	<1%	<1%	97%



bisaccate p non-saccat microspore freshwater fungal spor dinoflagella prasinophy acritarchs

Fig. 42: Results from the palynofacies study showing the relative percentages of the palynomorph categories. Note the increase in the marine derived dinoflagellate cysts from sample 13 to 14.

Locality 6: Skansebakke

The Skansebakke section is the type locality for the Vejle Fjord Formation (Larsen and Dinesen 1959). The outcrop shows a development from dominance of lagoonal mud to increasing occurence of washover fans and gutter casts deposited on a tidal flat. In a sequence stratigraphic framework this part is interpreted to represent the transgressive systems tract of sequence B.

Sedimentary structures (Fig. 43)

At the base of the outcrop homogenous, black silty clay occurs (Fig. 44). This is, at 2 m, overlain by alternating sharp based sand beds and brown silty clay (Fig. 45). The sand beds are characterised by a homogenous lower part and parallel laminated upper part, occasionally with a wave-rippled or scoured top. Some of the sand beds are laminated throughout. Upwards, at ca. 6.5 m, the sand beds become thinner and lenticular (Fig. 46) and gutter casts are seen in the upper most of the section (Fig. 47).

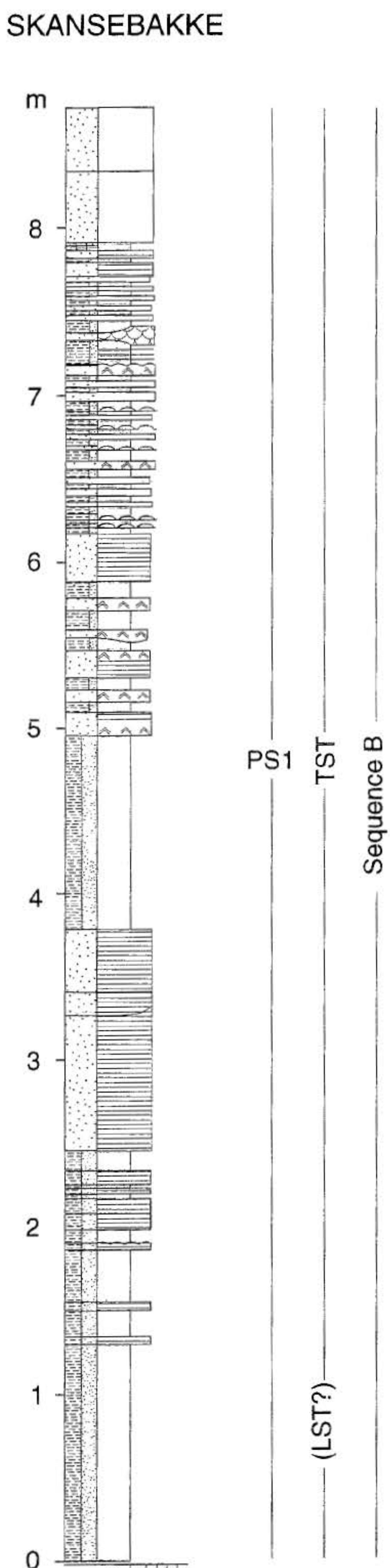


Fig. 43: Sedimentological log of the Skansebakke section. For legend see the last page.

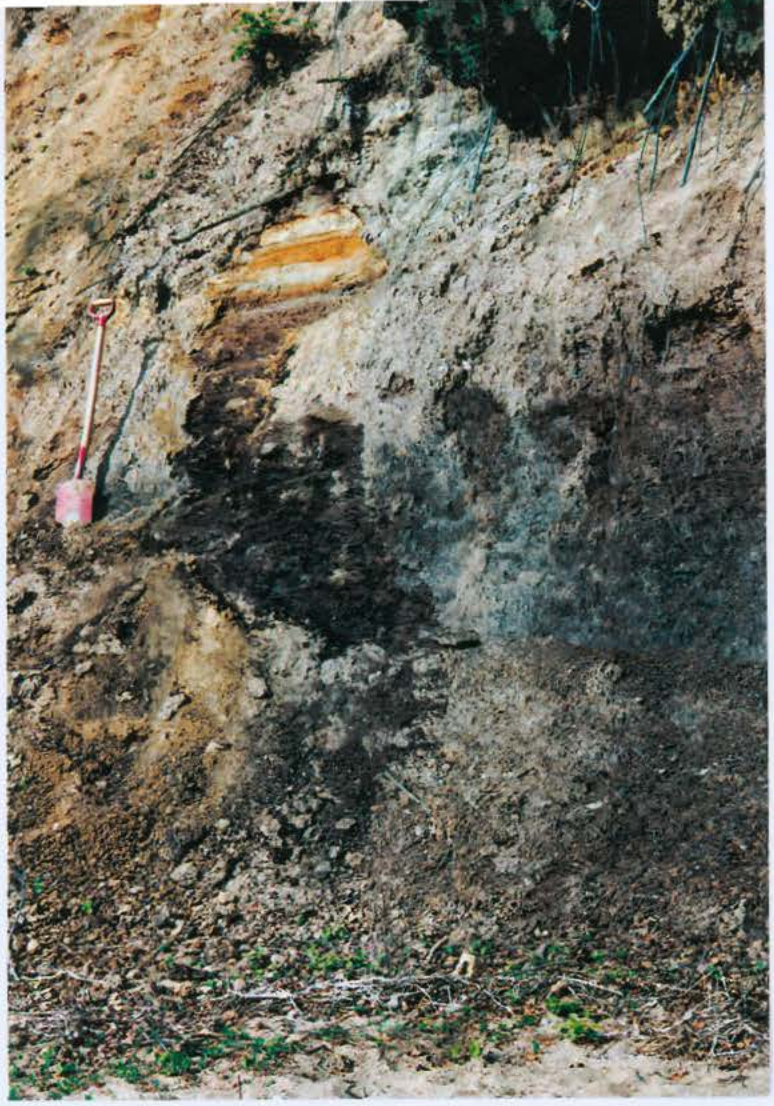


Fig. 44: Lower part of the Skansebakke section showing the transition from lagoonal muds to interbedded washover sand and lagoonal mud.

Fig. 45: Discrete washover fan characterised by a sharp lower boundary and homogenous to laminated internal structures.

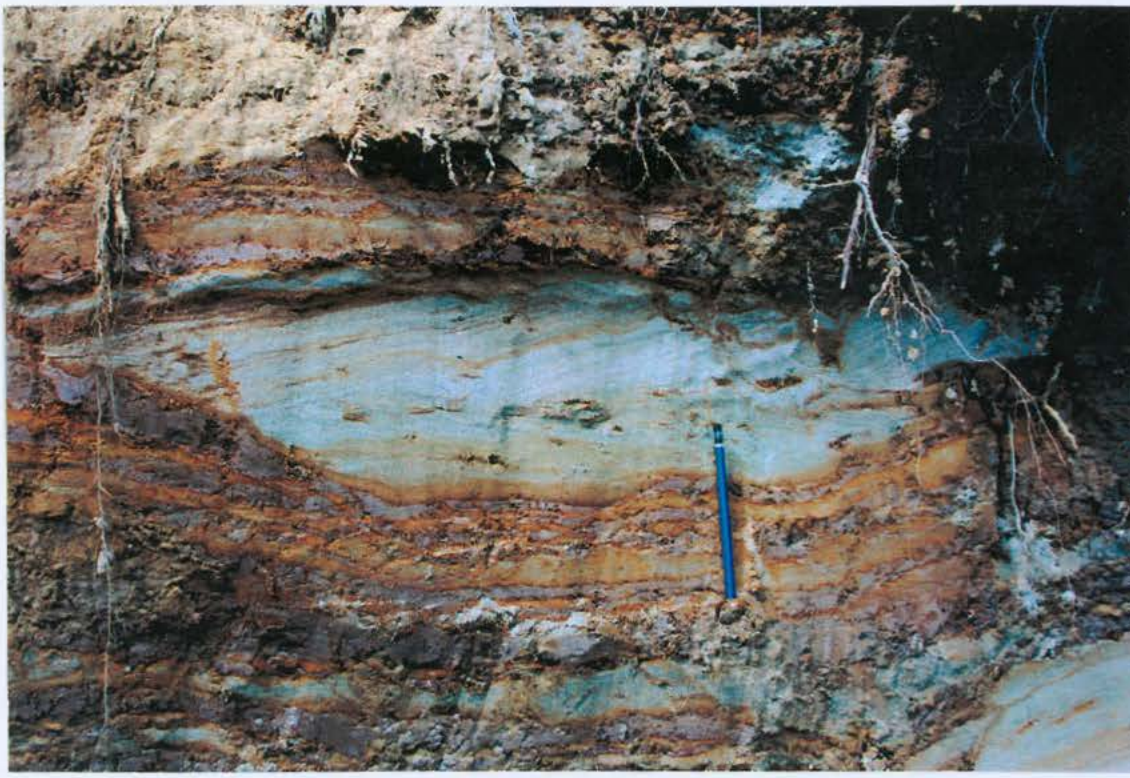


Fig. 46: Gutter casts in the upper part of the Skansebakke profile.

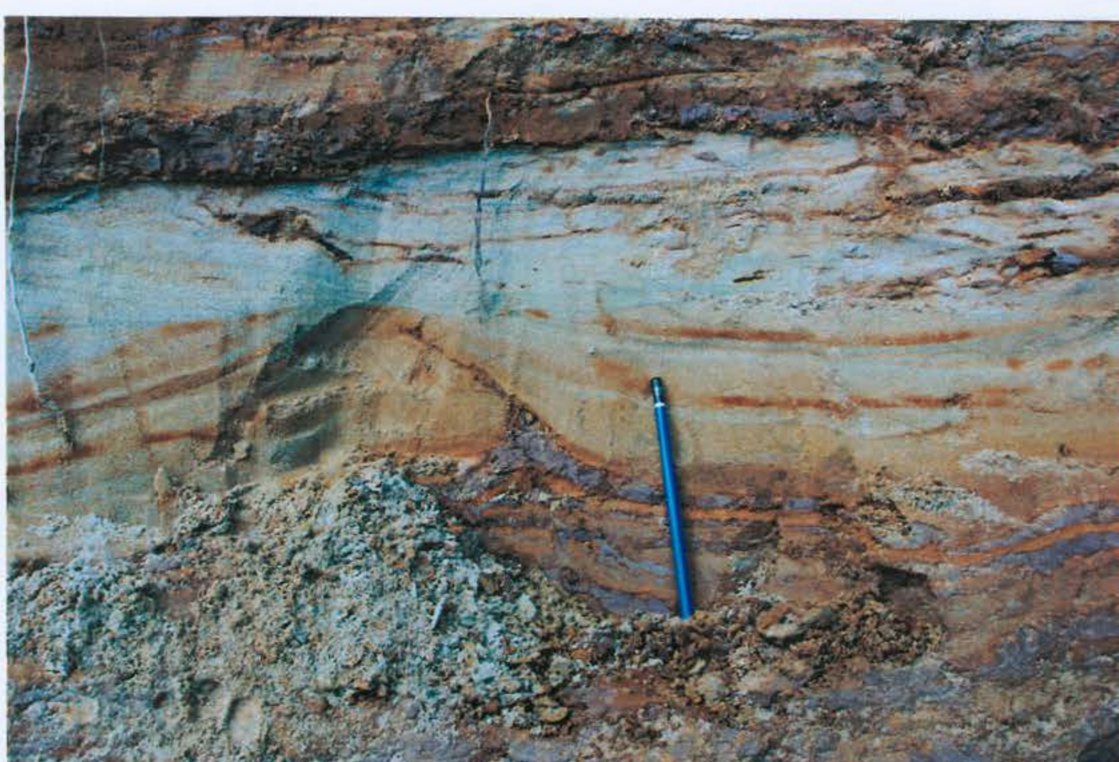


Fig. 47: Details of a gutter cast. Note that the trough is draped by clay indicating tidal influence during deposition.

Locality 7: Hvidbjerg

The outcrop at Hvidbjerg consists of almost 14 metres of white clean sand deposited in the shoreface and beach zone of a prograding spit system. Two coarsening upward sections can be recognized. Based on a regional correlation the succession at Hvidbjerg is interpreted to represent the highstand systems tract of sequence B based by the maximum flooding surface found at Hindsgavl. The highstand systems tract at Hvidbjerg consists of two para sequences like the time equivalent succession at Lillebælt (Hindsgavl and Børup).

Sedimentary structures (Fig. 48)

The lowermost part consists of homogenous black silty clay (Fig. 49). This is erosively overlain by 9 m of laminated and cross-stratified sand beds topped by wave ripples (Figs. 50, 51, 52). Burrows of *ophiomorpha* can be seen. The section show an upward coarsening and thickening of sand beds; pebbly horizons are seen in the uppermost part. This is followed by 6 m of alternating sand and silty clay beds. The sand beds show a thickening upward trend and is characterized by laminated, flaser, and wavy bedding. Burrows of *ophiomorpha* in the upper part of each coarsening and thickening upward section.

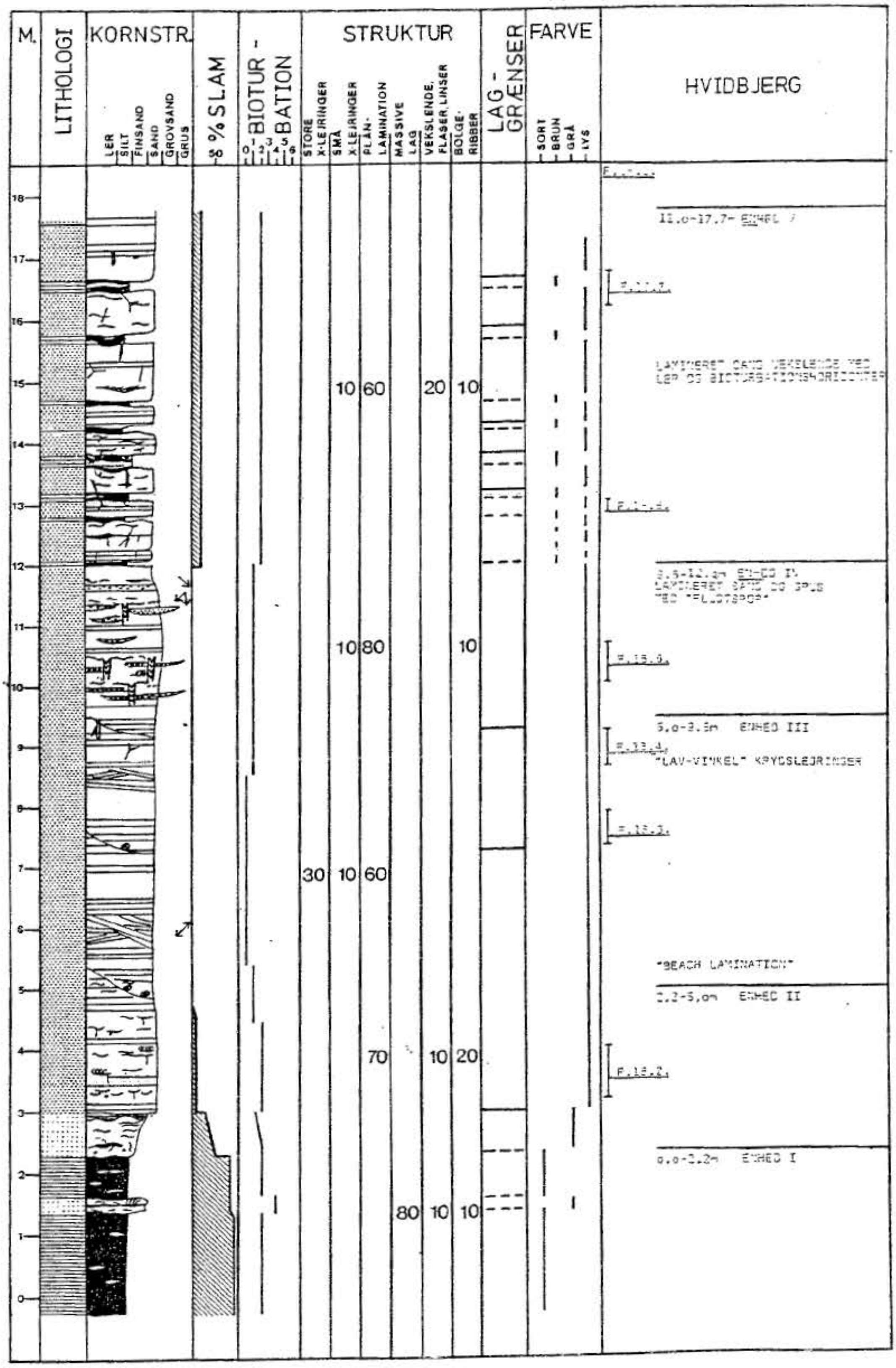


Fig. 48: Sedimentological log from Hvidbjerg (Mikkelsen 1983).

Fig. 49: The boundary between lagoonal mud and shoreface sand at Hvidbjerg. This boundary forms a distinct flooding surface (MFS) which also can be recognized at Hindsgavl.

Fig. 50: Laminated sand from the lower part of the Hvidbjerg section.

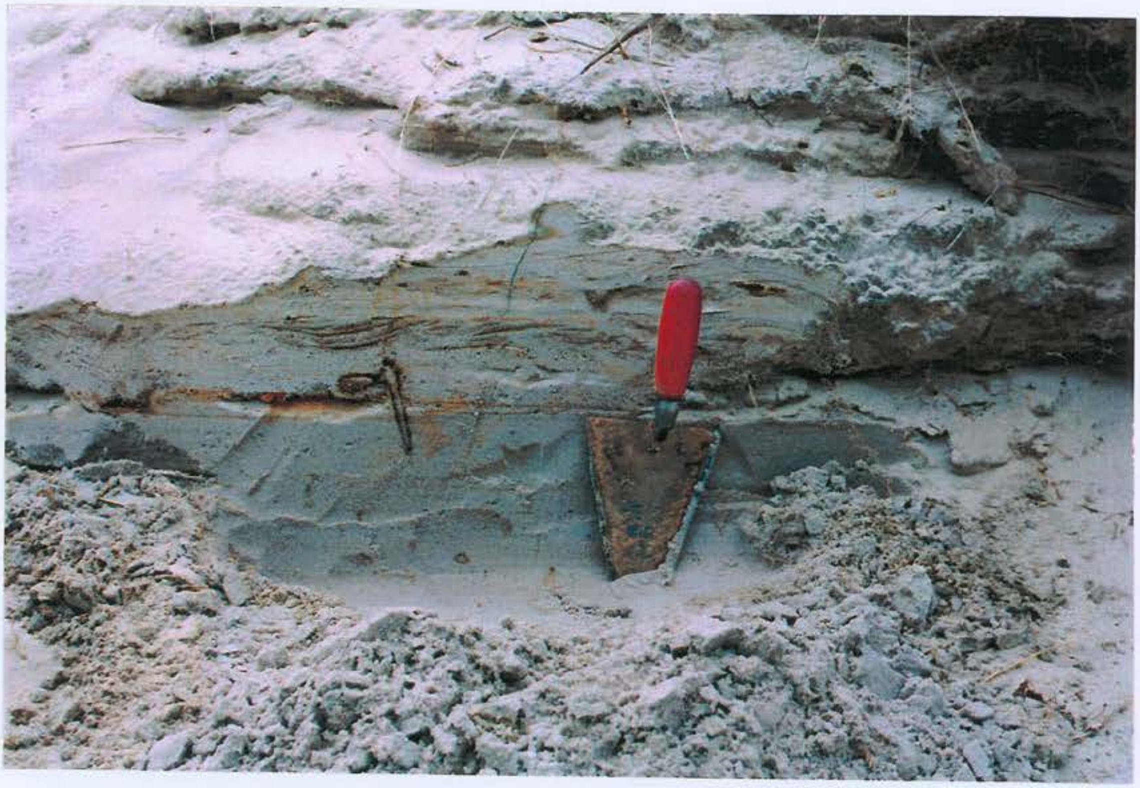


Fig. 51: Homogenous and laminated sand topped by wave rippled sand. Burrows of *ophiomorpha* and *skolithos* are seen in the middle part of the photo.

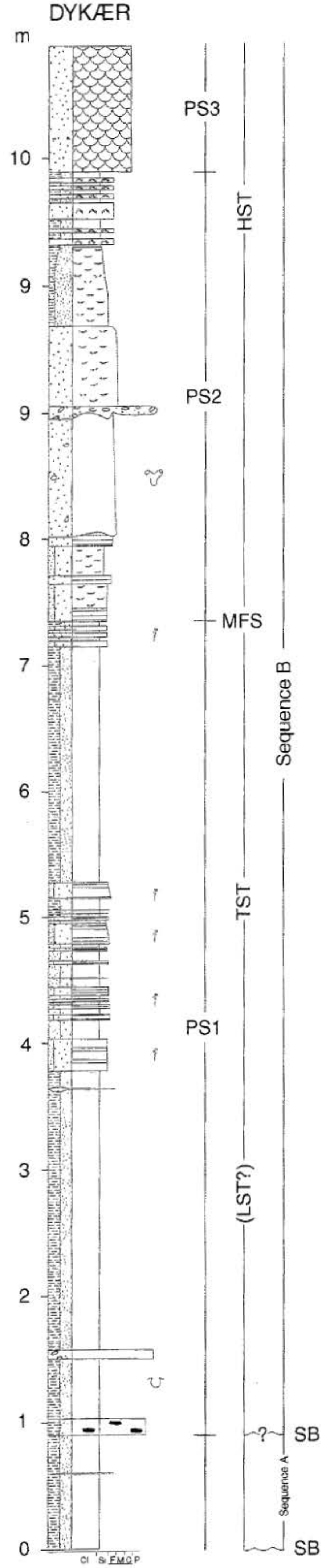
Fig. 52: Flaser bedded and laminated sand beds at Hvidbjerg. Note the horizontal cut of the *ophiomorpha* trace fossil.

Locality 8: Dykær

At Dykær a complete succession of the Vejle Fjord Formation can be seen. At the base the marine glaucony-rich Brejning clay is outcroping. Interbedded in the Brejning Clay both siderite horizons and a discrete gravel layer indicate periods with distinct changes in depositional environments e.g. sub-aerial exposition. Superimposed on the Brejning Clay the muddy lagoonal deposits of the Vejle Fjord Clay is seen. The lagoonal mud is intercalated with silty/sandy tidally influenced beds. Upwards more sand dominated tidally influenced layers are seen and the upper part of the succession show an abrupt change to marine sand. The sequence stratigraphy of the Dykær profile is not straight forward, but the base of the Vejle Fjord Formation forms a sequence boundary. The presence of a siderite horizon and a discrete pebble layer may indicate the existence of two sequence boundaries in the lowermost part of the succession. And thus indicate an additional sequence boundary within the Brejning Clay here named Sequence A. The lagoonal mud is interpreted to represent the lowstand systems tract of sequence B followed by tidal and storm dominated sediments of the transgressive systems tract. Finally, a maximum floooding surface at the base of marine sand beds separate the transgressive systems tract from the early highstand systems tract in the uppermost part of the exposure.

Sedimentary structures (Fig. 53).

The lower part of this outcrop is characterised by a strongly bioturbated glacony-rich clay. A siderite lag and a pebble horizon is seen 2 m and 3 m above the base respectively. At ca 2.5 m, the glaucony-rich clay is overlain by homogenous silty clay with interbedded layers of thinly alternating fine-grained sand and silt showing diurnal inequality. These beds are weakly bioturbated (Fig. 54). In the upper part of the profile, at 7.5 m, sharp-based laminated sands alternating with sand and clay showing strong bioturbation at certain levels are seen (Fig. 55). At 10 m, this is overlain by black silty clay which upwards grade into alternating thinly laminated sand and silt showing diurnal inequality (Fig. 56). The succession is terminated by planar and trough cross-bedded sand with few borrows of *ophiomorpha* (Fig. 57).



DYKÆR
m
10
9
9
8
7
6
5
4
3
2
1
0
Cl
Si
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P
PS3
PS2
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HST
MFS
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Sequence B
Sequence A
?
SB
SB

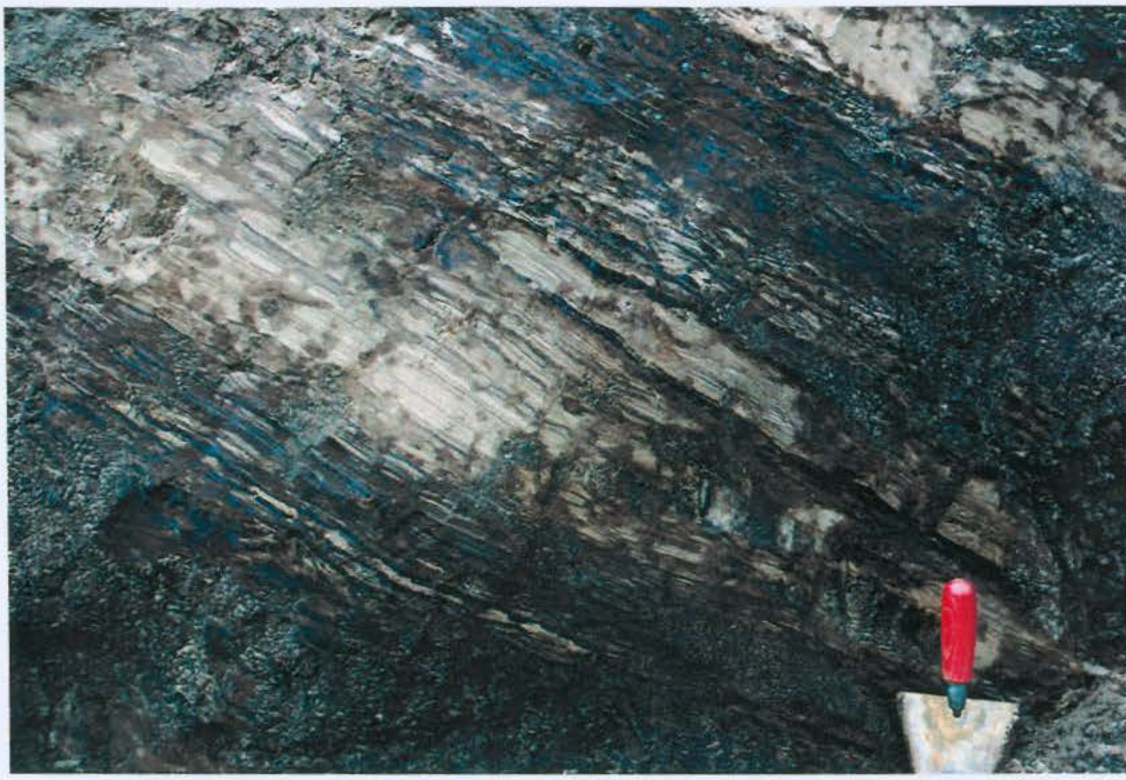


Fig. 54: Weakly burrowed tidal deposits from the lower part of the Dykær profile.

Fig. 55: Alternating sharp based tempestites (storm deposits) and strongly bioturbated sand and mud layers.

Fig. 56: Organic-rich deposits with few intercalated thin sand beds passing upwards into tidally influenced sand.

Fig. 57: Trough cross-stratified sand from the upper part of the Dykær section.

Lokality 9: Jensgård

At this locality Oligocene marine glaucony-rich Brejning Clay alternating with ooid ironstones are exposed. Siderite horizons indicate, however, changes in the depositional environment. Above the Brejning Clay, lagoonal and tidal influenced silty clay and sand of the Vejle Fjord Clay can been seen. The sequence stratigraphy of the glaucony-rich Brejning Clay is not strait forward, but it is believed that the high content of siderite indicate a period with increased influx of fresh water related to a sea-level drop and thus a sequence boundary (sequence boundary of sequence A). A further subdivision of the Brejning Clay into systems tracts is not possible. The lagoonal deposits above is interpreted to represent the lowstand-transgressive systems tract of sequence B.

Sedimentary structures (Fig. 58)

The lower part of the exposure is characterised by strongly bioturbated glaucony-rich clay alternating with sandstones. The burrows are filled with faecal pellets which is iron cemented (Fig 59). The sandstones are weakly bioturbated (Fig. 60) and consist of ooids and show a coarsening upward trend. The ooids have a core of quartz.

Above a section with poor exposure, at 3 m, 2.5 m of alternating laminated sand and silty clay is seen (Fig. 61). The sand show diurnal inequality and scours are frequent (Fig. 62). In the upper part of this section, at ca. 5 m, channelized clean sand occurs. This is overlain by 5 m of black organic-rich silty clay with some thin laminated sandy horizons.

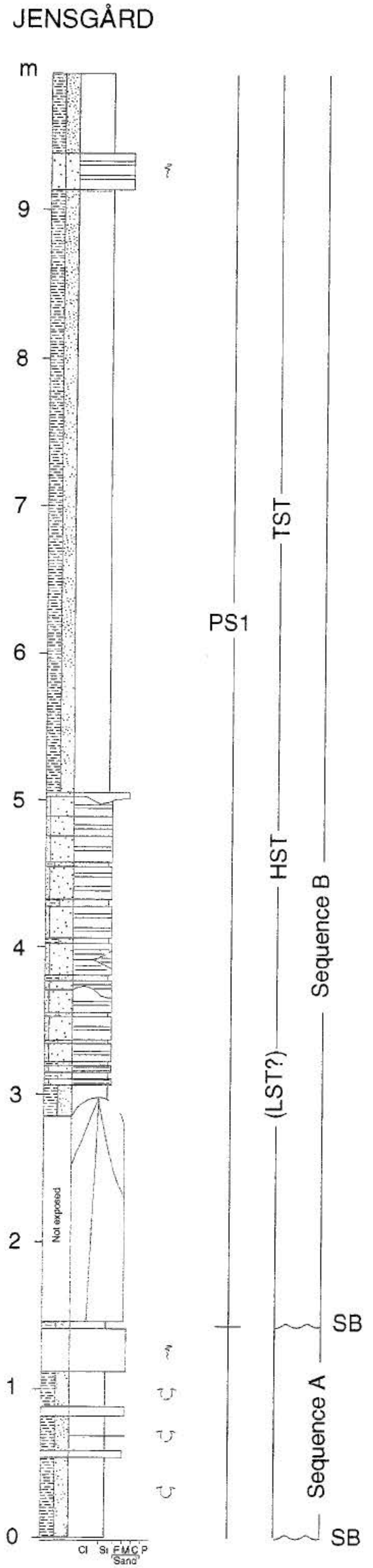


Fig. 58: Sedimentological log from Jensgård. For legend see the last page.

Fig. 59: Intensively burrowed glaucony-rich clay.

Fig. 60: Oolitic sandstone with few, glaucony filled borrows.

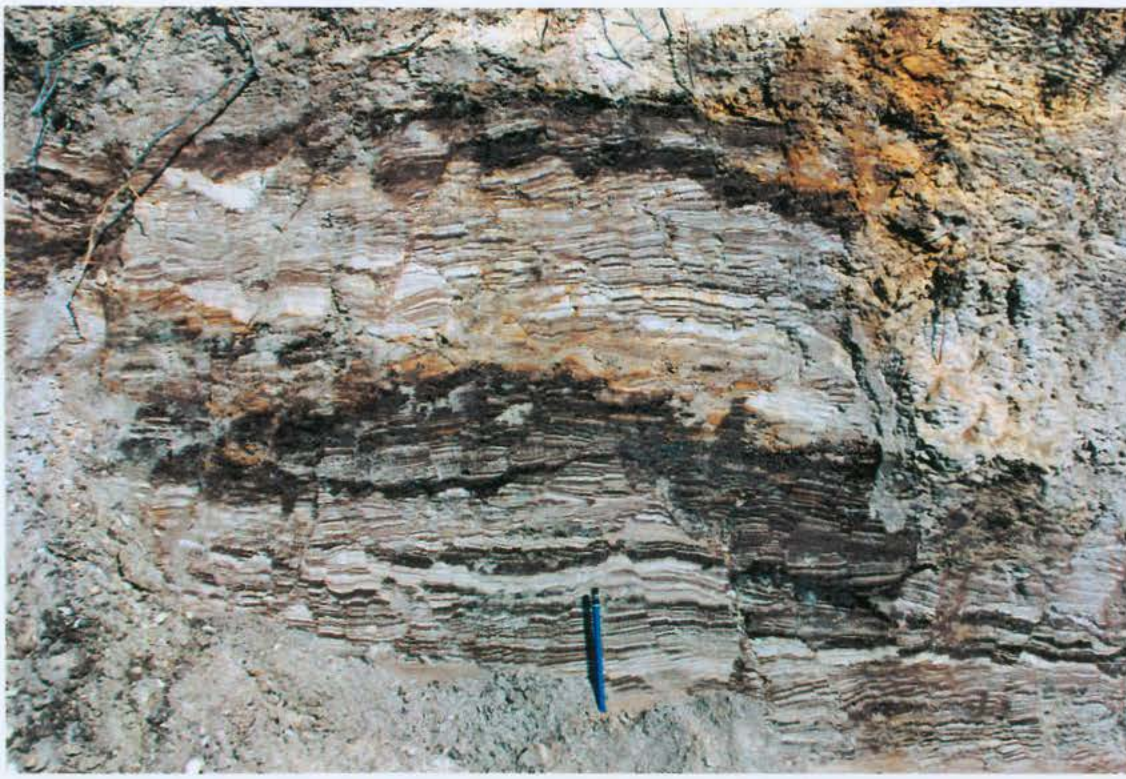


Fig. 61: Tidally influenced laminated sand and mud. Beds showing diurnal inequality and neap and spring cycles can be seen.

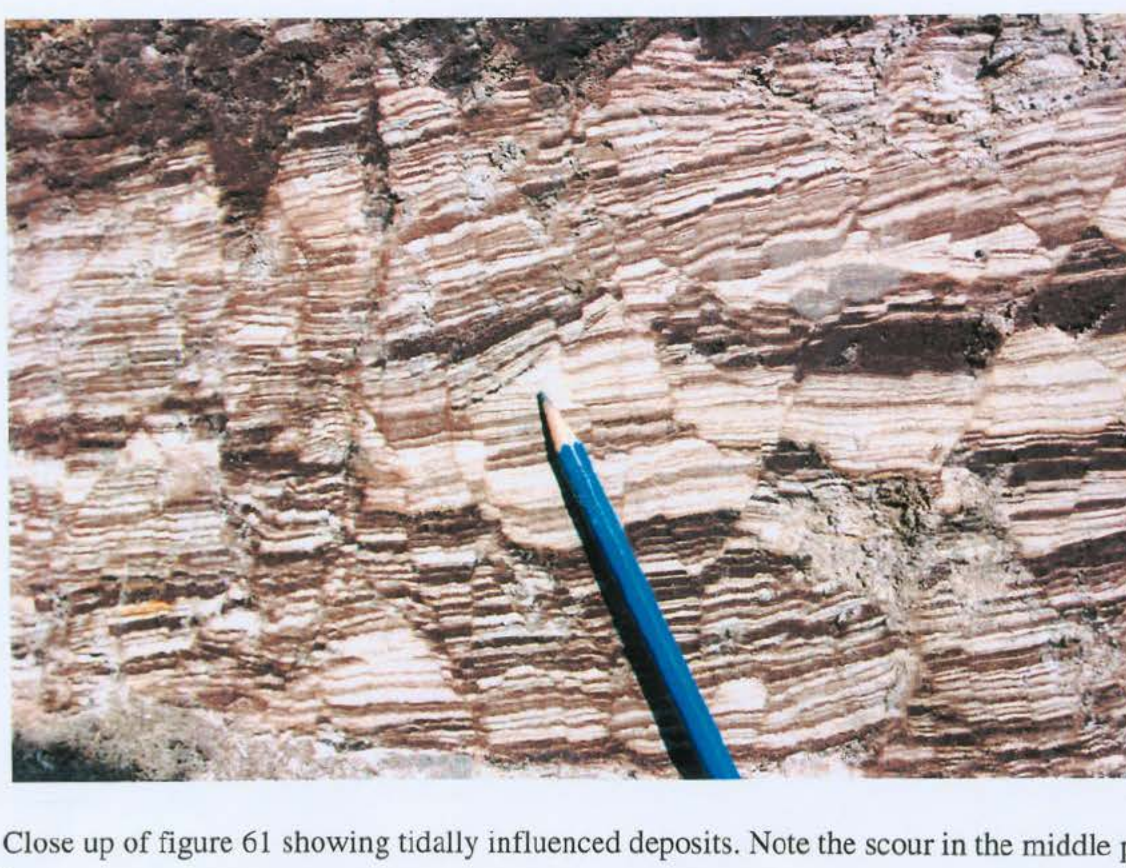


Fig. 62: Close up of figure 61 showing tidally influenced deposits. Note the scour in the middle part of the photo

Pratical use of Sequence stratigraphy as examplified by the succession at Lillebælt and Vejle Fjord

Introduction

Correlation of key-surfaces of the succession at Lillebælt and Vejle Fjord, and in borings distributed around jylland provides the framework for a sequence stratigraphic subdivision (Figs. 9 and 63). Furthermore, seismic data from South Jylland add to the understanding of the sedimentary architecture of the upper Oligocene - lower Miocene succession (Fig. 64). The base of the succession is formed by a composite sequence boundary, separating the middle Eocene Søvind Marl Formation from the Brejning Clay Member of the Vejle Fjord Formation/Klintingehoved Formation. The Brejning Clay represents the regionally correlatable glaucony-rich clay of late Oligocene age. A further subdivision of the Brejning Clay into one or two sequences is indicated by a siderite lag deposit and a distinct pebble layer. The latter, however, is only found at one locality and is therefore not considered to be of regional extent. The high content of siderite and deposition of organic-rich brackish water deposits above the marine Brejning Clay indicate a sea-level drop and the formation of a sequence boundary above the Brejning Clay (Fig. 63). Above the sequence boundary organic-rich mud was laid down in a restricted bay. The first indication of transgression in the area is indicated by deposition of washover fans in Skansebakke and Dykær; at Jensgård lagoonal mud is overlying tidal flat deposits and finally at Hindsgavl, lagoonal muds is superposed by estuarine deposits. The transgressive systems tract is bounded upward by a maximum flooding surface which resulted in a regional flooding in the area and marine deposits are recognised at all localities where a complete Oligocene succession occurs. The overlying highstand systems tract consists of two parasequences which are prominently developed at the Hindsgavl-Børup profiles and Hvidbjerg (Fig. 63). The highstand systems tract is sharply overlain by a pebble layer which has a regional extent. The layer is interpreted as a ravinement surface associated with a sequence boundary. Biostratigraphic data from below and above the sequence boundary indicate a hiatus of ca. 3 m.y. During this period the shoreline was displaced ca. 100 km towards the southwest as shown on the seismic line in figure 64. The section above the ravinement surface (Fig. 63) constitutes a thin transgressive systems tract and a maximum flooding surface is placed at the strongly biotubated level. As a result of increased influx of sediments spit/barrier systems were formed, probably associated with topographically high, and restricted conditions resulted in deposition of lagoonal muds in the area during the early highstand. Resumed flooding is recognised in the Lillebælt area represented by a marine transgressive surface of erosion at Rønshoved and at Hagenør (Fig. 63). This is followed by regression and gradually a new spit/barrier system was formed which resulted in restricted condition behind this system.

Prediction of lithology

The outcrops at Børup, Galsklint, and Rønshoved show a distinct facies succession (Fig. 63); a poorly sorted gravel bed sandwiched in fine-grained sand. The base is highly erosive and forms a sequence boundary separating late Oligocene sediments from late Aquitanian deposits. The gravel bed is interpreted to represent fluvial deposition during falling sea level and/or lowstand of sea level (Rasmussen 1998). Consequently the gravel represent part of a forced regressive systems tract or lowstand systems tract. The period of sub-aerial exposure in this part of Jylland was according to palynological data in the order of 3 millions of years and lasted probably most of the Aquitanian. During this period the coast line was displaced ca. 100 km towards the southwest where it can be correlated to a delta south of the town of Ribe in South Jylland (Fig. 64). During the succeeding sea-level rise the gravel bed was wave reworked so it now forms the basal part of a transgressive systems tract with a ravinement surface at the base (Nummedahl and Swift 1987). The high degree of bioturbation in the sand above the gravel layer and also into the gravel layer indicate a period with sediment starvation. The distinct change in depositional environment is also illustrated in the clay mineral association (Fig. 65). In figure 65 four samples of the clay mineral association from the Børup outcrop is shown (for more details see Rasmussen 1996). The deposits representing foreshore and open lagoonal deposits have relatively high content of smectite in the clay mineral association whereas the reworked fluvial deposits are absent in the contents of smectite. This is interpreted as a result in a different provenance of the clay minerals, where the smectite-rich association is characteristic for marine clays; e.g. South USA (Weaver 1960). The development of the succession presented on this excursion is illustrated in figure 66.

Pitfall in correlation of backbarrier and offshore successions by using sequence stratigraphic concepts.

The exposures at Børup, Hagenør, Galsklint, and Rønshoved permit the study of the development of a spit complex in three dimensions. The evolution was controlled by changes in sea level so both back-barrier and offshore successions and there interrelationship is prominently illustrated.

The sediment supply to the area was from the north by along shore currents. This resulted in accretion of a spit-complex in the area and lagoonal conditions were established for a period (Fig. 67). Resumed transgression reestablished open marine conditions. Therefore, a flooding surface is placed at the lower boundary of the sand-rich sediments interstratified between lagoonal mud. The sand section, which is strongly bioturbated, show several coarse-grained ripple layers arranged in a general coarsening/thickening upward trend. The uppermost coarse-grained ripple bed is very distinct and would, if not overlain by lagoonal mud, be interpreted as a ravinement surface. However, the coarse-grained ripple bed is succeeded by organic-rich lagoonal mud and therefore back-barrier conditions were re-established due to accretion of a new spit/barrier seaward. The succession terminates with a gradual increase in deposition of washover fans within lagoonal muds indicating transgression of the spit/barrier-complex. It is thus assumed that this part of the succession was deposited during rising sea level.

This part of the succession illustrates a more complex development and recognition of a para-sequence. According to Van Wagooner et al. (1990) a parasequence is defined as: " A relatively conformable succession of genetically related beds or bedsets bounded by marine flooding surfaces or their correlative surfaces". At Rønshoved, the lagoonal mud and inlet deposits, of the lower lagoon, were clearly superimposed by marine sediments and bounded by a marine transgressive surface of erosion. This surface constitute the basal flooding surface of a parasequence. The correlative surface in the lagoonal environment is the bioturbated sand bed sharply overlying the lagoonal muds and thus relatively simple in this case. The open marine sand layer is ca. 20 cm thick at Børup and shows a lateral thickening of up to 6 m at Rønshoved (5 km apart). The marine sand section consists of up to five cycles given a general thickening- and coarsening upward trend terminating with lagoonal mud. The sand section and the lagoonal mud forms one parasequence which constitute a shoaling upward succession mainly build-up by offshore progradation. Above, a new parasequence is formed when the progradation is overtaken by a transgression of the barrier complex (base defined by the correlative surface to a marine surface of erosion in this case the first appearance of washover fans). The transgressive barrier complex show a thickening upward trend that on geophysical logs would look similar to the offshore progradation below (Fig. 68) and thus constitute a pitfall in correlation and understanding of the succession.

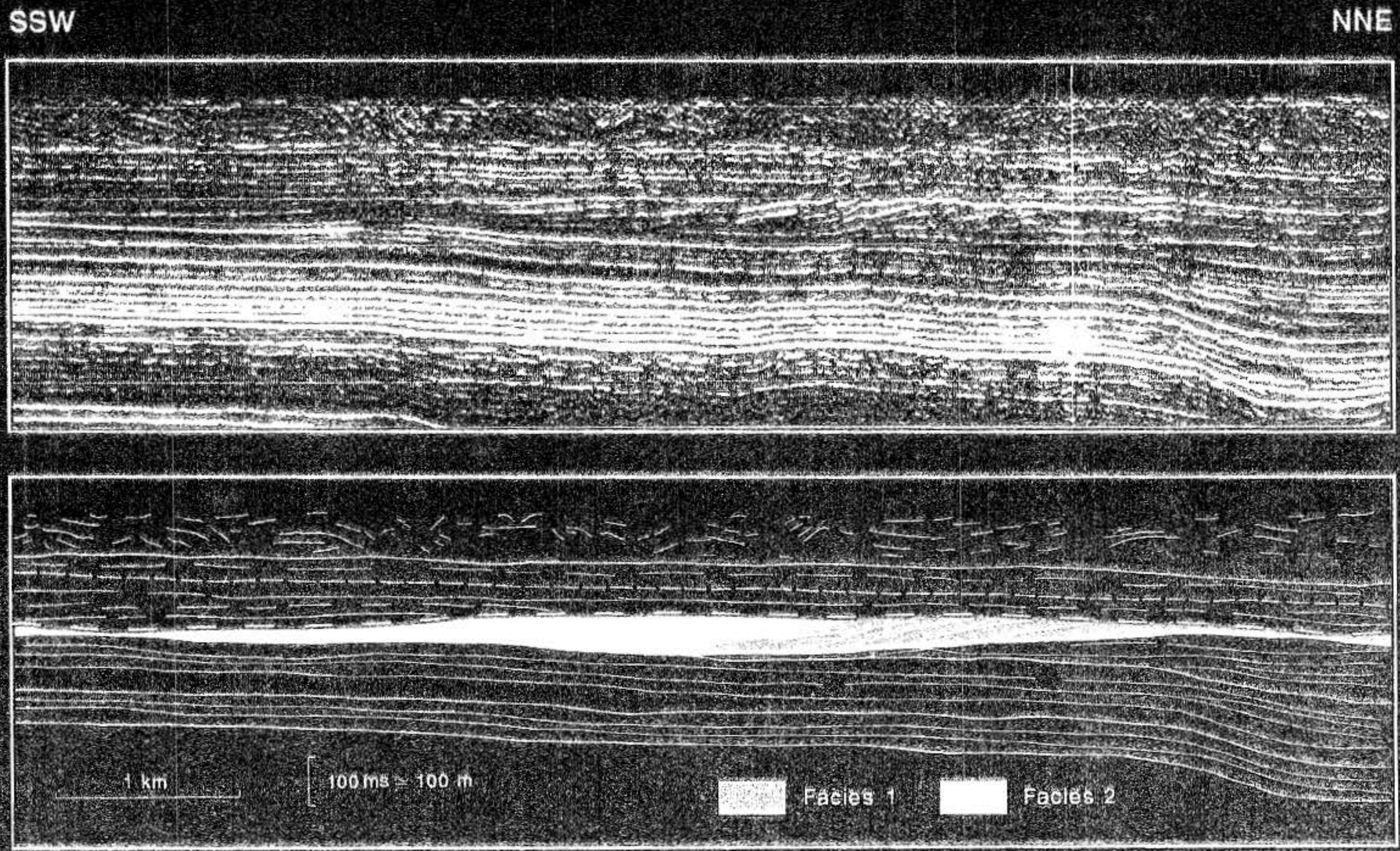


Fig. 64: Southwest-northeast striking seismic line from South Jylland. Progradation of the shoreline during the Aquitanian terminating with deltaic deposition represented by seismic facies 1 and 2 can be seen. The unlapping succession represent late Aquitanian – early Burdigalian transgression which correspond to the transgressive and highstand deposits of sequence B.

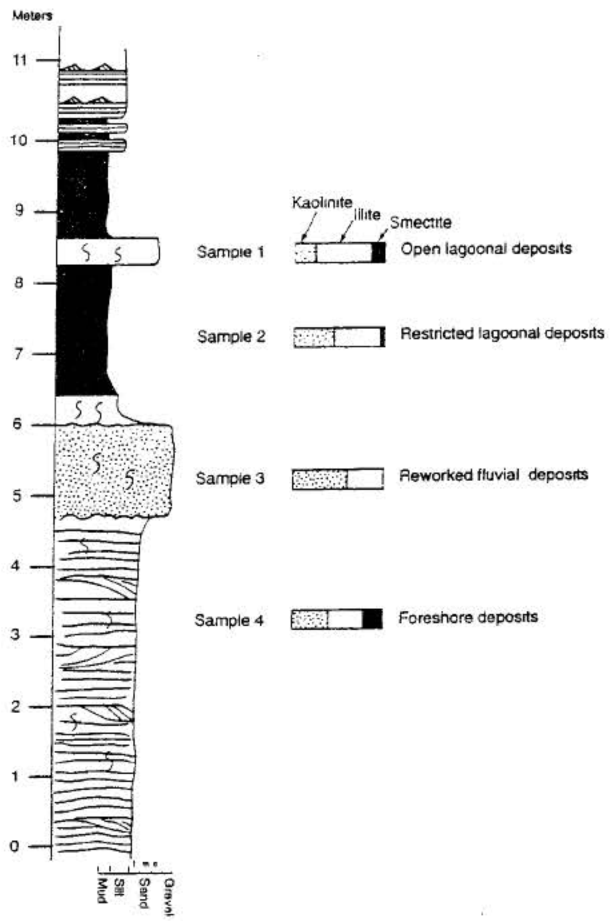


Fig. 65: Sedimentological log from Børup. The relative clay mineral content of four samples are shown. Marine deposits are characterised by high contents of smectite and non-marine by the absence of smectite.

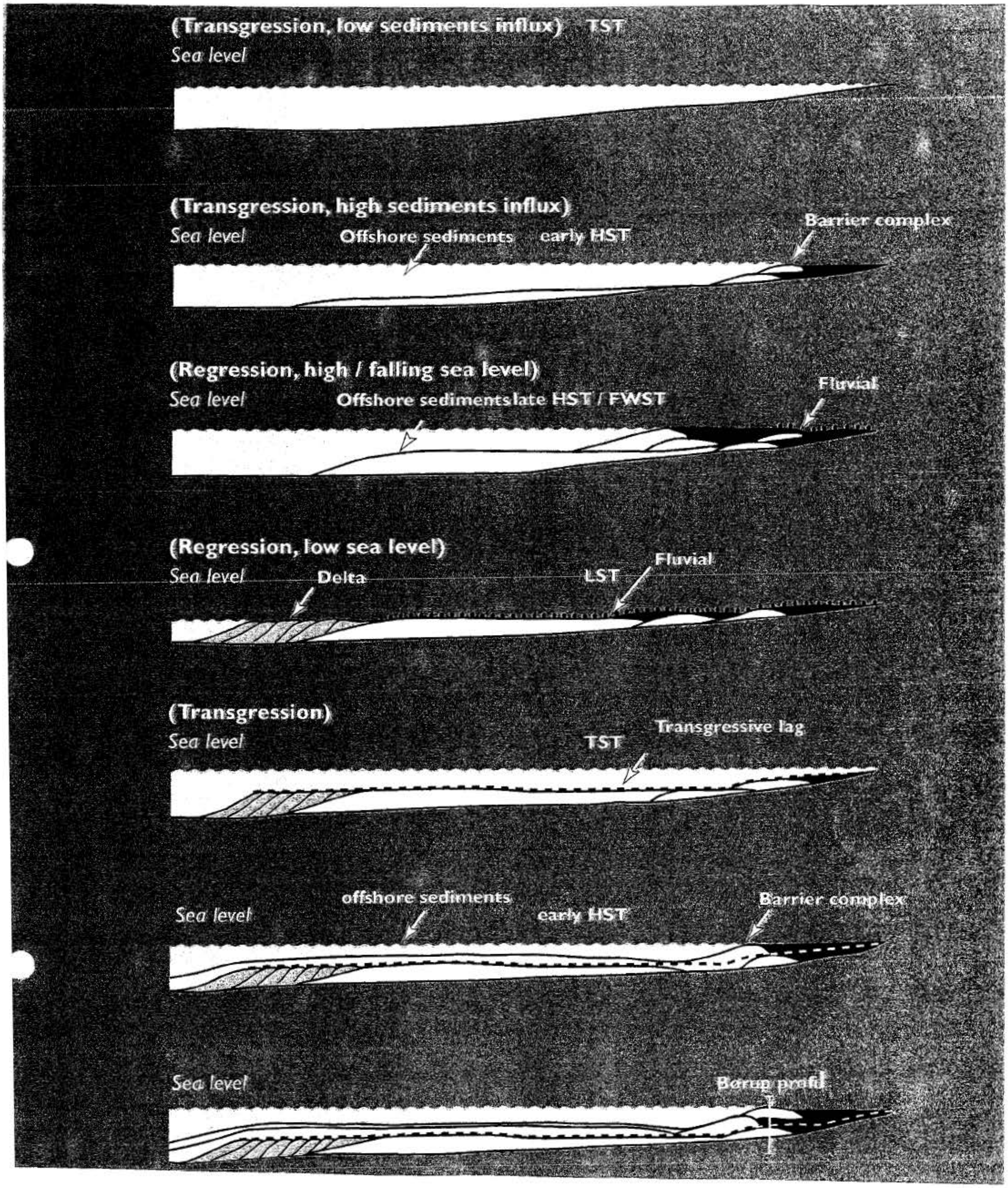


Fig. 66: Schematic illustration of the development of Late Oligocene and Early Miocene succession. During the Late Oligocene (a) the area was transgressed and fine-grained, glaucony-rich marine sediments were deposited. In the marginal areas (Lillebælt) a shoreline was formed by deposition of near-shore sand-rich deposits (b). Increased sediment supply into the area resulted in regression of the shoreline under relative sea-level rise (highstand systems tract). A drop in the relative sea level resulted in a distinct shift of the shoreline towards the southwest and deltaic sediments were deposited in the southwestern part of Jylland and fluvial sediments in East Jylland (d) (Any evidences for forced regression is probably due to a data gab between the outcrops in East Jylland and seismic data from South Jylland). During the subsequent transgression, parts of the fluvial deposits were reworked and a ravinement surface was formed (e). Resumed establishment of a shoreline in East Jylland in deposition within a barrier-complex (f, g).

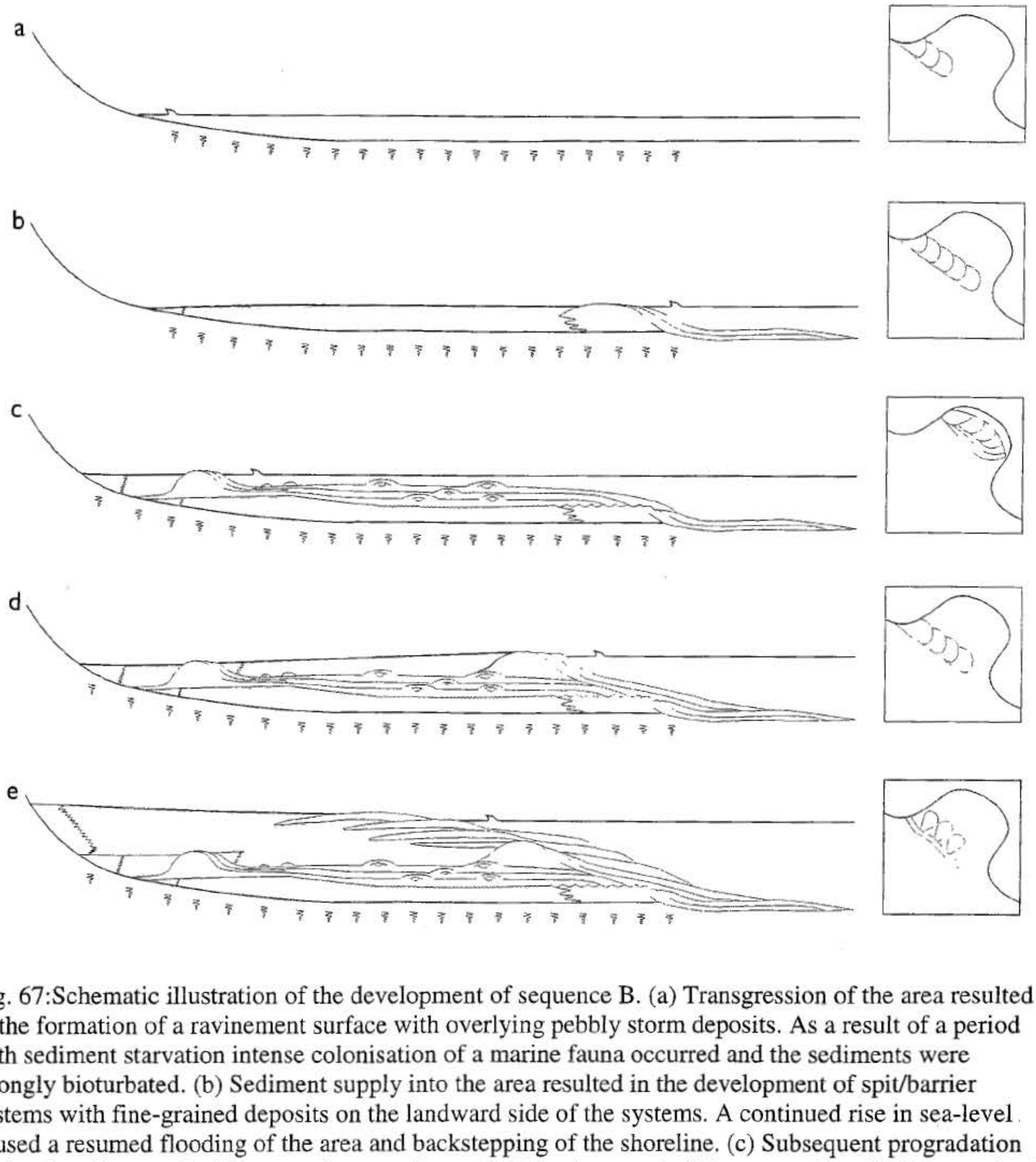


Fig. 67:Schematic illustration of the development of sequence B. (a) Transgression of the area resulted in the formation of a ravinement surface with overlying pebbly storm deposits. As a result of a period with sediment starvation intense colonisation of a marine fauna occurred and the sediments were strongly bioturbated. (b) Sediment supply into the area resulted in the development of spit/barrier systems with fine-grained deposits on the landward side of the systems. A continued rise in sea-level caused a resumed flooding of the area and backstepping of the shoreline. (c) Subsequent progradation of the shoreline resulted in upward coarsening and thickening trend of the succession. (d) As a result of increased sediment supply due to a lower rate of relative sea-level rise during the deposition of the highstand system tract, resulted in the formation of a new spit/barrier system. (e) Slow backstepping of the system as a result of decreased rate of sea-level rise and increased sediment influx during the deposition of the late highstand.

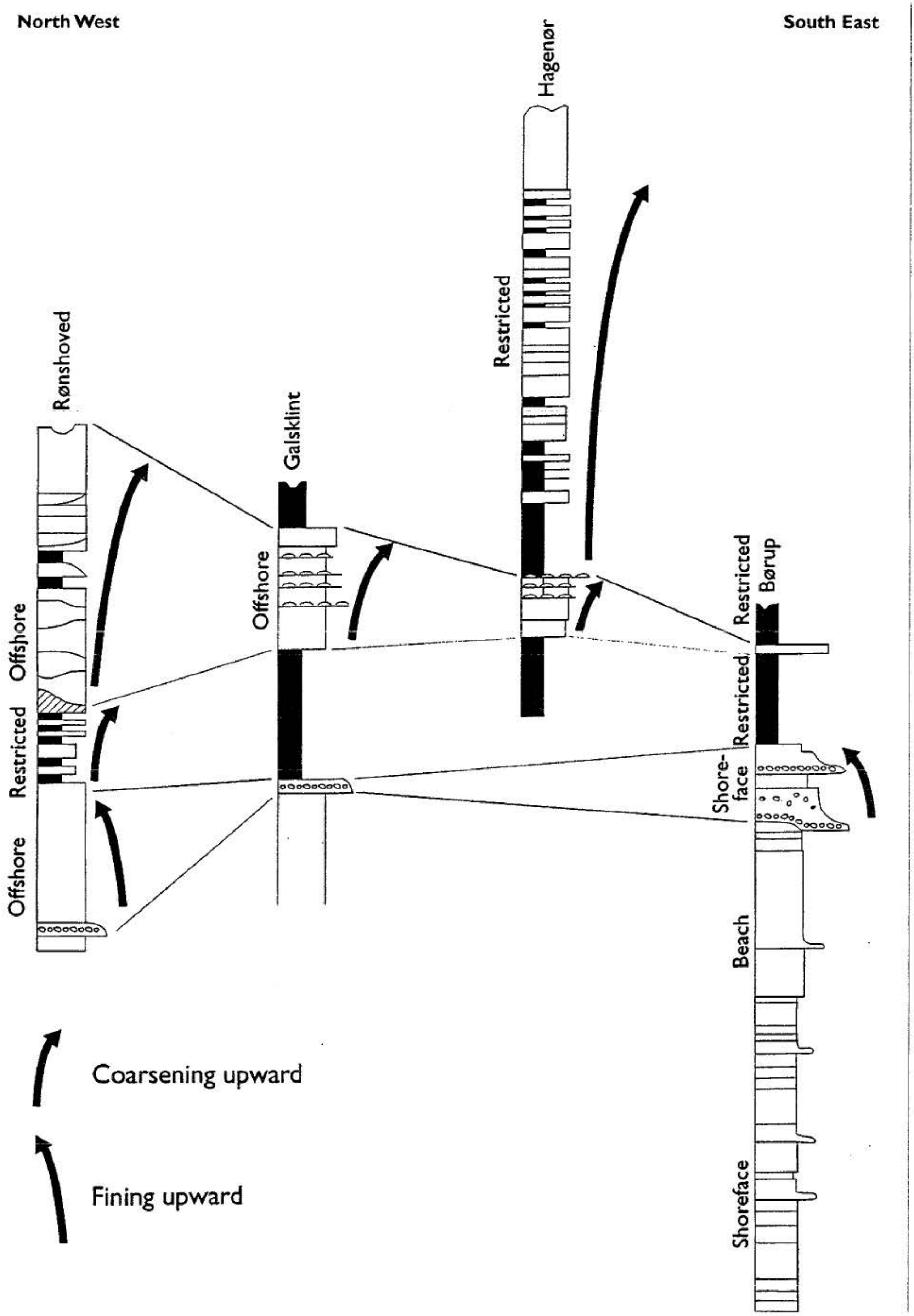
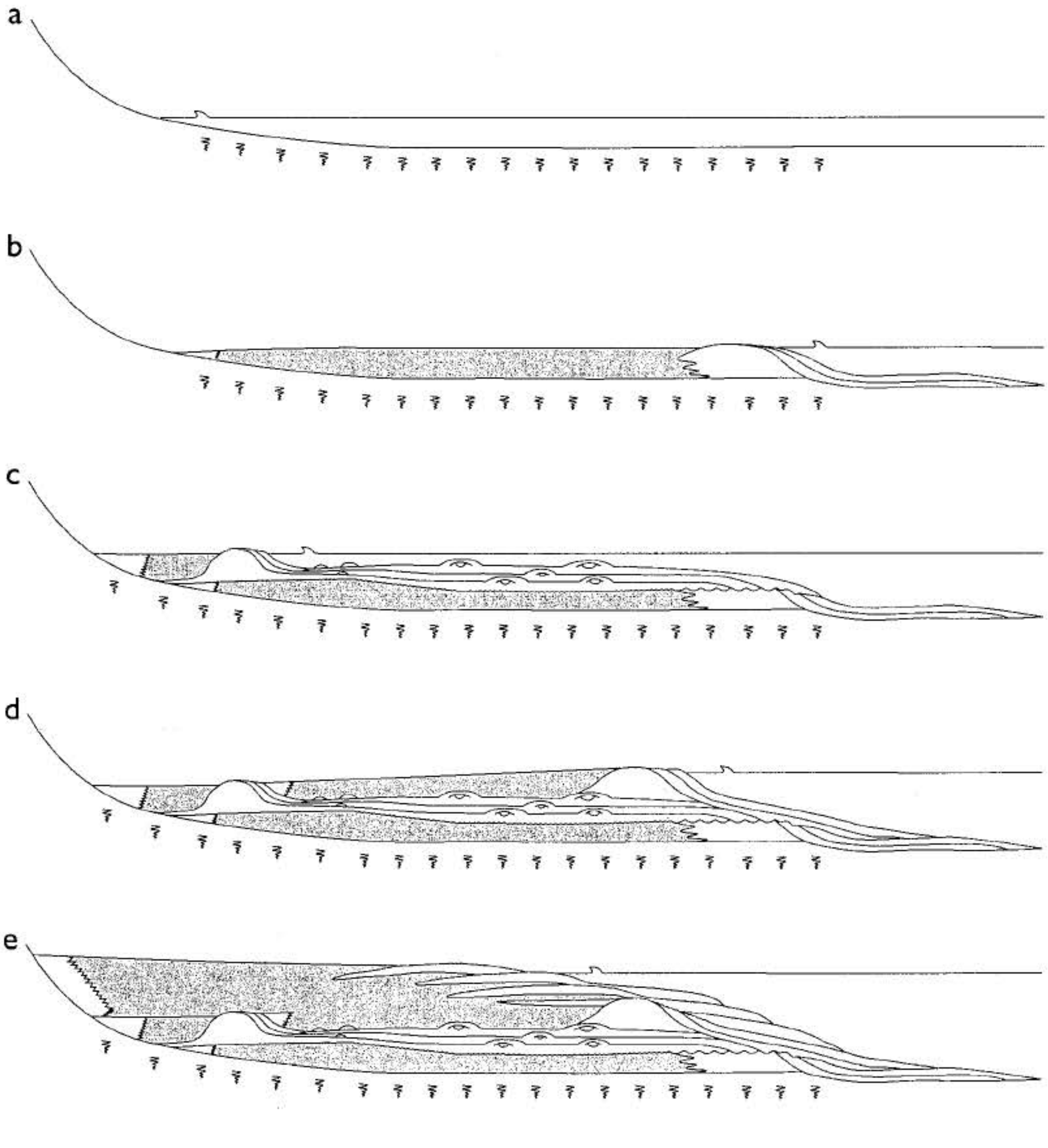


Fig. 68: Coarsening – and fining upward trends at 4 localities and interpreted depositional environments. Note that coarsening upward trends, e.g. the upper part at Rønshoved and Hagenør is a result of progradation and retrogradation respectively.


a
b
c
d
e

Sedimentary structures

1 2D Ribbles
2 3D Ribbles
3 2D Dunes
4 3D Dunes
5 Soft sediment deformation
6 Wave ribbles
7 Climbing ribbles
8 Horizontal stratification
9 Hummocky cross-stratification (Isotopic)
10 Hummocky cross-stratification (Anisotopic)
11 Swaley cross-stratification
12 Low angle cross-stratification
13 Homogeneous
14 Flaser bedding
15 Clay
16 Clay (Sand / silt-streaked)
17 Sand-clay couplets
18 Quaternary

Wavy surface

Erosional surface

Lihtology

19 Clay
20 Silt
21 Sand
22 Pebbles

Biogenic structures

23 Shell
24 Ophiomorpha nodusa
25 Massive bioturbation
26 Weakly bioturbation

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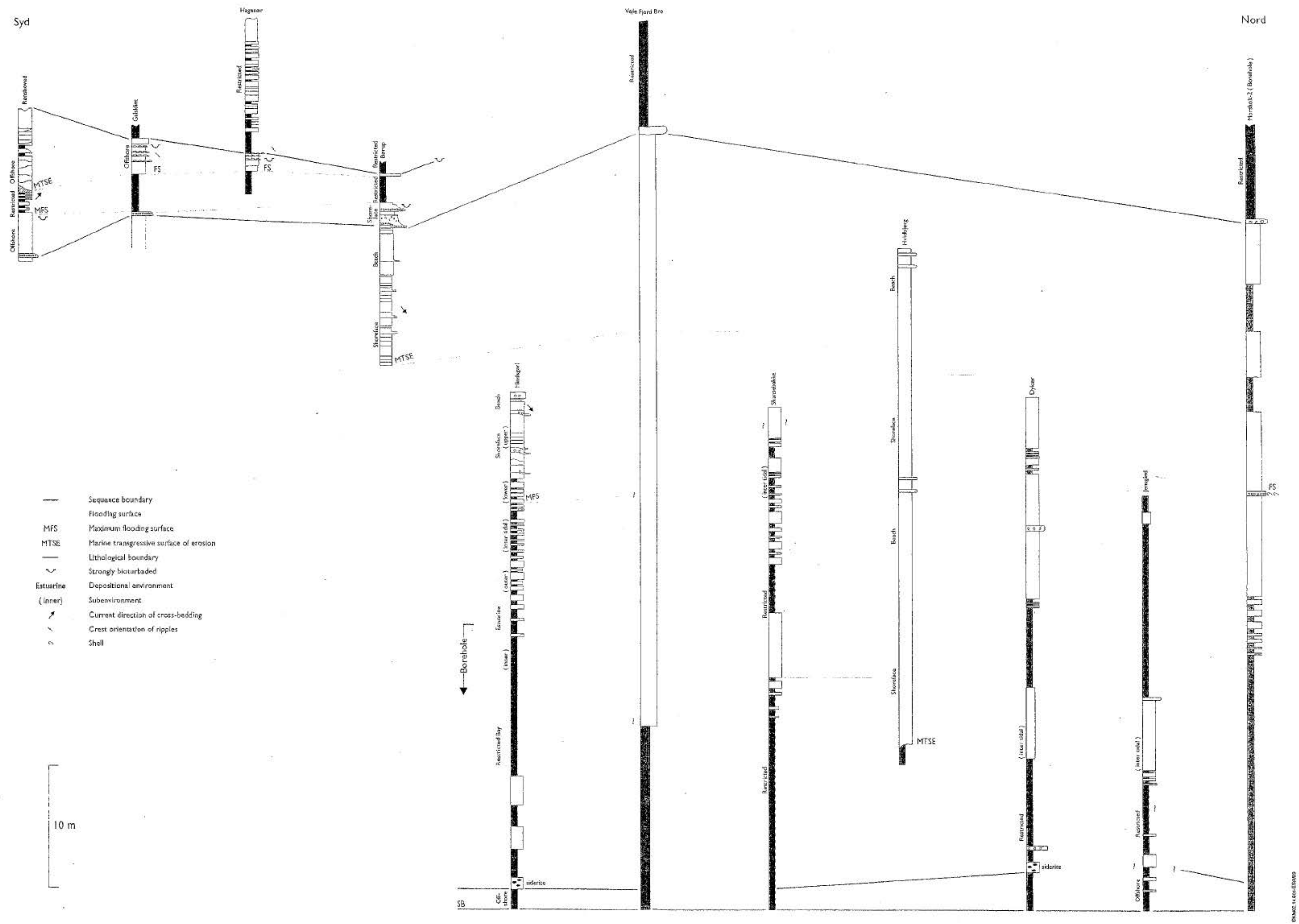
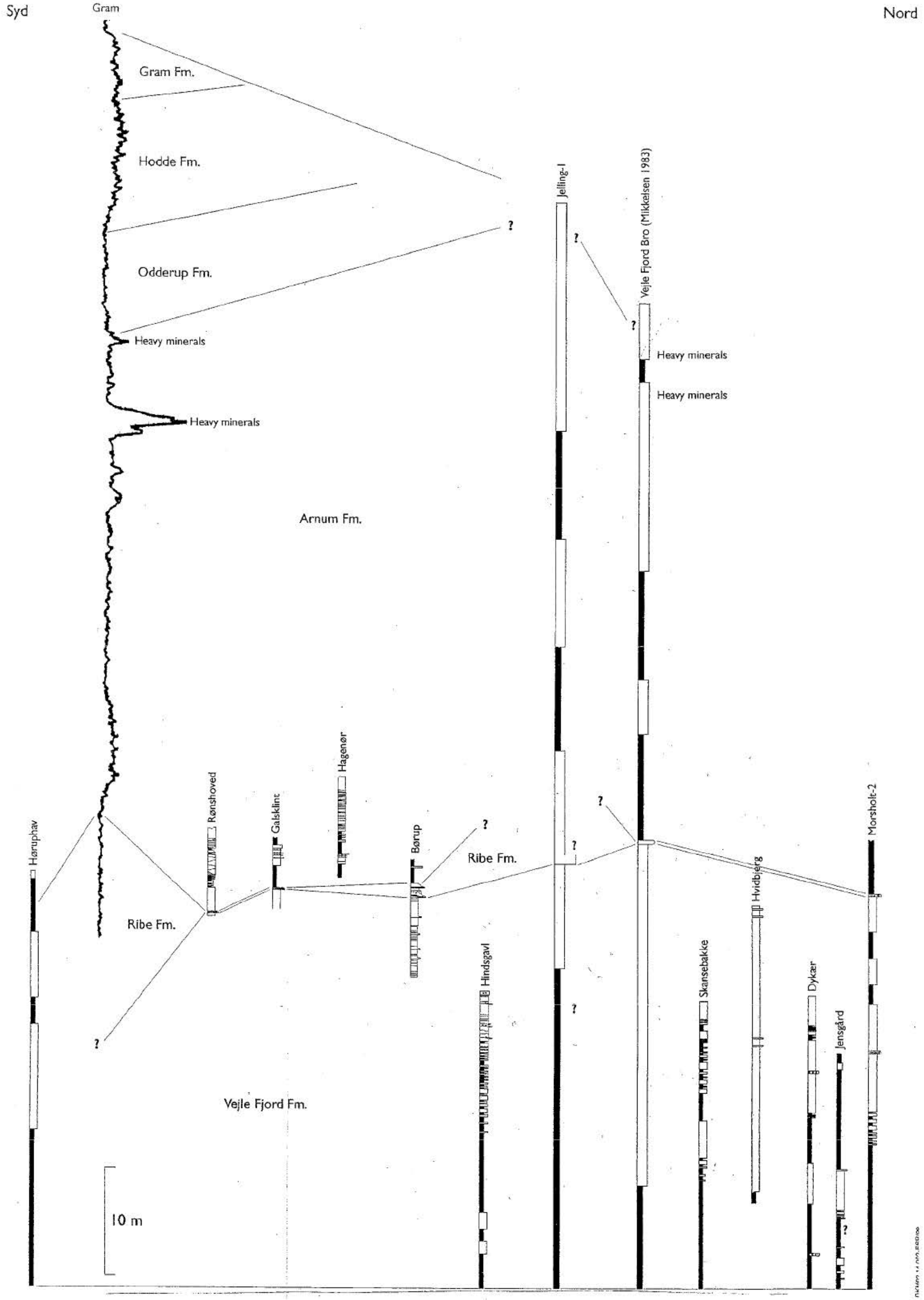


Syd
Nord
Hagenæ
Vejle Fjord Bro
Offshore
Restricted
MTSE
MFS
FS
Shore-face
Beach
Shoreface
Shoreface (upper)
(lower)
(inner tidal)
(outer)
Estuarine
(inner)
Restricted Bay
Off-shore
siderite
SB
Borehole
Hvidbjerg
Jensgård
(inter tidal)
Sequance boundary
Flooding surface
MFS Maximum flooding surface
MTSE Marine transgressive surface of erosion
Lithological boundary
Strongly bioturbaded
Estuarine Depositional environment
(inner) Subenvironment
Current direction of cross-bedding
Crest orientation of ripples
Shell
10 m



Syd
Nord
Gram
Gram Fm.
Hodde Fm.
Odderup Fm.
Heavy minerals
Heavy minerals
Arnum Fm.
Jelling-1
Vejle Fjord Bro (Mikkelsen 1983)
Heavy minerals
Heavy minerals
Høruphav
Rønshoved
Galsklint
Hagenør
Børup
Ribe Fm.
Ribe Fm.
Morsholt-2
Hvidbjerg
Skansebakke
Hindsgavl
Dykær
Jensgård
Vejle Fjord Fm.
10 m