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Early lithification in Danian azooxanthellate scleractinian lithoherms, Faxe Quarry, Denmark

Frühe Lithifizierung in azooxanthellaten Scleractinien-Lithohermen des Danium, Steinbruch Faxe, Dänemark

by

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Abstract

Penecontemporaneous lithification is shown to be a fundamental part of the construction of the Faxe coral mounds. Internal structures and textural features of the rocks of one of the larger coral mounds exposed in the Faxe Quarry are presented. A close correlation between biological processes and early lithification of interstitial muds, controls both the shape and internal structure of the mounds as well as the textures of the coral limestone. This accentuates a close resemblance between the Faxe coral limestone and recent lithoherms as well as "mudmounds" in general.

Zusammenfassung

Syngenetische Lithifizierung ist ein wesenlicher Bestandteil bei der Bildung der Korallen Mounds von Faxe. Internstrukturen und texturelle Characteristika eines der größeren Mounds, die im Faxe-Steinbruch aufgeschlossen sind, werden vorgestellt. Eine enge Beziehung zwischen biologischen Prozessen und früher Lithifizierung von interstitiellen Schlammen kontrolliert die Form und die Internstruktur der Mounds sowie die Textur des Korallenkalkes. Dies betont die enge Beziehung zwischen dem Korallenkalk von Faxe und rezenten Lithohermen bzw. „Mud Mounds" im allgemeinen.

1. Introduction

The coral limestones of Faxe were first described as a fossil reef by STEFFENS (1810, p.117): "Man glaubt vor einer unverändert aus dem Meere erhobenen Korallenbank zu stehen." Since that time they have been treated in a great number of papers, most recently by FLORIS (1980), BERNECKER & WEIDLICH (1990), WEIDLICH & BERNECKER (1991), and WILLUMSEN (1993).

Biohermal, coral-rich carbonates, which contain evidence of early lithification, are exposed in the well-known Faxe Limestone Quarry, (southern Sjælland, Denmark), (JOHNSTRUP, 1864). These classic azooxanthellate coral mounds are of Early Paleocene (Danian) age and developed in the narrow epicontinental seaway that followed the Tornquist–Sorgenfrei lineament (BERTHELSEN, 1992; Fig. 1). Extensive bryozoan mound fields developed in this seaway during the Early and Middle Danian, associated locally with azooxanthellate coral mounds (HÅKANSSON & THOMSEN, 1979; THOMSEN, 1989). Most prominent are the coral mounds at Faxe, where they form a significant part of a coral-bryozoan mound complex (CHEETHAM, 1971; FLORIS, 1972). The mound complex in Faxe is of late Middle Danian age (PERCH-NIELSEN, 1979; THOMSEN, 1989 & pers. comm., 1993).

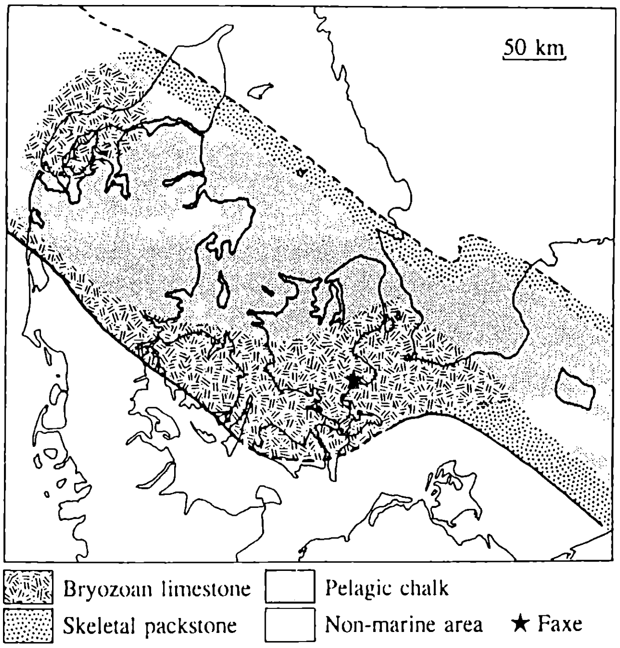

Figure 1: Simplified palaeogeography and facies distribution in the Danish area in late Middle Danian time; asterisk indicating the location of Faxe Quarry (in part based on HÅKANSSON & THOMSEN (1974) and THOMSEN (1989)).

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A complex history, probably related to major relative sea-level changes, is reflected in both fauna and lithology (NIELSEN, 1913 and this study). The quarry at Faxe is dominated by bryozoan bioherms in the stratigraphically lowest parts (below the mound complex investigated here). They are followed by an interval dominated by coral mounds, which is bounded upward by an extensive discontinuity surface with a pronounced topography, which may approach 10 m. In most places this discontinuity surface is developed as a hardground, which at present is well exposed in the quarry. In places, coarse-grained bryozoan grainstone rests directly on the hardground and fills fissures ("neptunian dykes") in the coral limestone. Subsequently, the accumulation of fine-grained bryozoan pack-wackestones interbedded with coral rudstones was resumed but at these levels they contain a somewhat different associated fauna, e.g. more bivalves and larger gastropods than below the hardground. The youngest preserved Danian lithology in the quarry is a partly cross-bedded, flint-free, sorted bryozoan packstone (above the interval considered in this paper).

The distribution of scleractinian corals covers a wide spectrum ranging from isolated colonies and small thickets in the intermound facies to mounds in hundred metre scale (banks, sensu SQUIRES, 1964). The mounds are dominated by phaceloid to dendroid scleractinian corals which, from their branching geometry, are judged to have been azooxanthellate (FLORIS, 1972; BERNECKER & WEIDLICH, 1990). They constitute the primary frame constituents, and they are found exclusively as displaced colony fragments, ranging from centimetres to 0.5 metre in size.

Coral fragments of matrix-deficient subfacies have been additionally broken both prior to and subsequent to growth of fringing cements. Associated with the scleractinians was a highly diverse fauna of bivalves, gastropods, brachiopods, decapods, stylasterines, poriferans, bryozoans and octocorals, including several species restricted to the coral limestone, (e.g. *"Rhynchonella" flustracea*; ASGAARD, 1968). The interstitial space of the coral limestone is partly filled by two types of carbonate mud matrix, and almost all surfaces are covered by fringing cements. Matrices postdating fringing cements are present locally.

1.1. Terminology

Recent years have seen a wealth of terms designated for specific types of mound lithologies on the basis of growth form and constructional function of the primary, in situ framebuilders (e.g. EMBRY & KLOVAN, 1971; CUFFEY, 1985; TSIEN, 1990; WRIGHT, 1992). In the coral limestone of Faxe, the colonial scleractinians are never found in actual life position (FLORIS, 1967; ASGAARD, 1968; this study). They are commonly heavily fragmented prior to burial, and only to a limited extent are they held together by binders (e.g. sponges). Thus, they neither meet the classic definition of an organic framework, nor do they fit the various modified classifications for biohermal carbonates. Yet the sediment is of clear biohermal affinity, forming mounds which had a distinct topography, offered a diverse range of habitats, and exercised an impact on the surroundings. Terminology concerning textural types follows EMBRY & KLOVAN (1971); however, in consequence of the observations presented above, such terms are here applied strictly descriptively, with no implicit interpretations, and the concept of "detrital framework" in the sense of HUBBART et al. (1990) seems highly appropriate here. In accordance with REID et al. (1990), unattached, non-skeletal precipitates that formed and accumulated in cavities are referred to as internal sediment, whereas the term cement is restricted to attached, non-skeletal precipitates.

As a consequence of the prominent role that early lithification played in mound construction, the term "lithoherm" (sensu NEUMANN et al., 1977) is regarded as highly appropriate for at least the mound type described below.

2. Materials and methods

An oblique transverse section through one of the larger coral mounds, exposed in the western part of the northern, subvertical quarry-wall, was investigated in detail (Fig. 2); the section investigated corresponds to "profil M" of BERNECKER & WEIDLICH (1990). The bulk of the information originates from field observation along six vertical transects made using climbing equipment, supplementing work along the bottom of the quarry. Oriented samples were brought back and a total of 42 blocks were prepared to obtain two vertical, perpendicular sections, (a few blocks containing more friable facies were embedded in epoxy prior to the preparation), which were subsequently ground to a fairly high polish. The polished surfaces range in size from about 30 cm^2 to 180 cm^2, and the total excedes 6 x 10^3 cm^2. These surfaces form the basis for qualitative and semiquantitative assessment of the components and their mutual relations. Additional information, in particular on the various types of matrix were obtained from 22 ordinary petrographic thin-sections supplemented by SEM investigation of 10 freshly broken surfaces as well as 18 etched, polished surfaces.

3. Results

3.1. Internal mound geometry and depositional units

The investigated section is approximately 20 m high, subvertical, and slightly curved with an almost east-west orientation (Fig. 3). Toward the west it is terminated in a fairly wide, fault-generated melange zone containing bryozoan limestone and contorted chert bands outside Fig. 3. The eastern limit of the profile is arbitrarily placed in a more or less homogeneous coral limestone showing

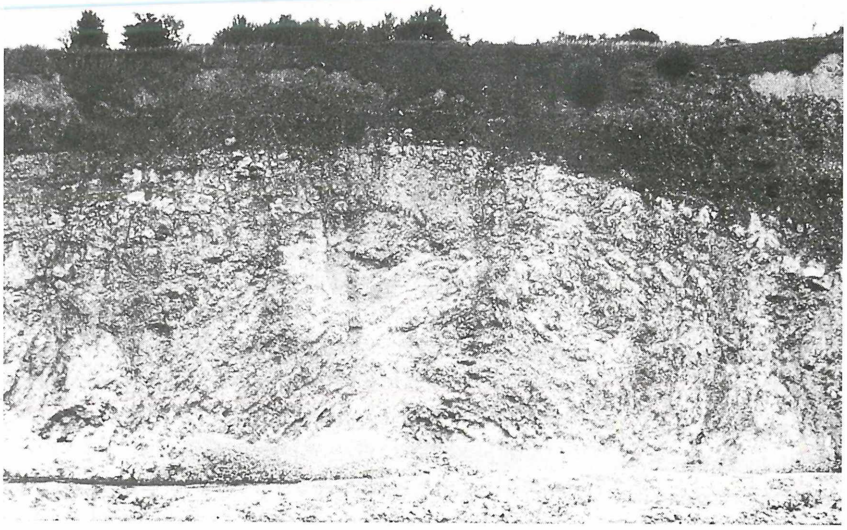

Figure 2: The central part of the investigated section in the northern wall of Faxe Quarry (cf. Fig. 3) displaying the very steep, conformable bedding in the lower mound phase A. The Danian carbonates are covered by Quaternary glacial deposits. Height of exposed limestone wall c. 20 m.

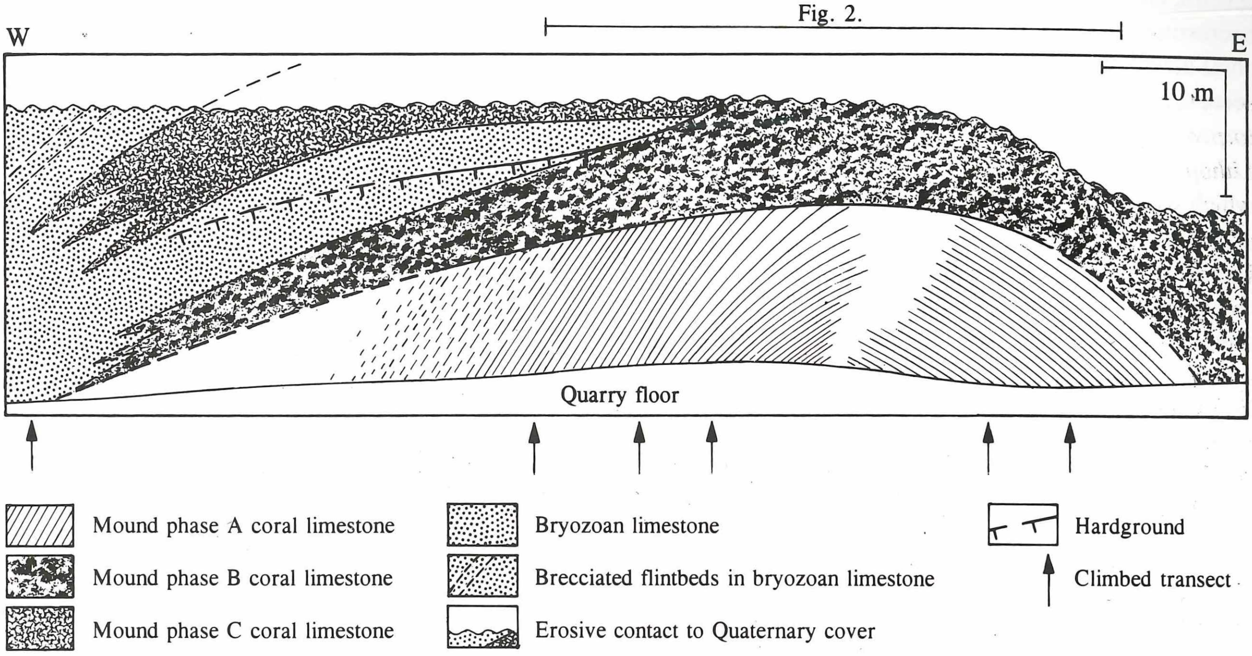

Figure 3: Schematic section illustrating the relation between three major constructional phases and the facies distribution. Mound phase A is characterized by continuous layers of coral limestone representing steep depositional slopes, truncated by a discontinuity surface. The steep layering gradually become less distinct towards the west. Mound phase B is dominated by coral limestone in the lower part, while bryozoan limestone gradually take over from the west. Above the hardground mound phase C is developed as a coral limestone relatively rich in bryozoans interfingering with coral bearing bryozoan facies. During the three phases the local topographic relief is gradually diminished.

only very faint internal structures. Two major discontinuity surfaces divide the profile into three depositional phases.

Mound phase A

The lower unit consists of 40–70 cm thick layers of coral rudstone with steep slopes ranging from 44° to 64°. The layering arises from repetetive shifts between matrix-rich and matrix-poor coral rudstone beds. The lower limit of the oldest unit is not exposed, and the basal part of the mound has therefore not been seen. Upward the unit is terminated in a somewhat irregular discontinuity surface, which truncates the steep bedding. Empty moulds indicate that the discontinuity surface was lithified prior to aragonite dissolution; however, no endolithic borers, encrusters or other biotic indications of hardground formation are present. Mound phase A is suggested to represent a steep, well lithified frontal part of a lithoherm, facing a unidirectional current, while mound phase B in this model represents the lee side, which gradually covers the older frontal part as the lithoherm grows on up-current. Mound phase A is the main subject of this paper, and its lithologies are described below.

Mound phase B

Mound phase B is composed of conformable beds of coral rudstone resembling the matrix-rich parts of mound phase A. This unit attains its maximum thickness over the crest of the underlying lithoherm. Towards the west the coral rudstone is interbedded with a bryozoan-dominated wackestone, which seems partly to fill the intermound area just west of the mound. Towards the top of mound phase B the bryozoan wackestone covers most of the coral rudstone.

The upper boundary of mound phase B is developed as a genuine hardground, which has been traced along most of the northern wall. The hardground itself encompasses a complex history of epi- and endolithic community replacement. Within the profile investigated here, the hardground is mainly developed as a subhorizontal surface in a bryozoan dominated lithology, and here at least three ichnospecies of *Entobia*, a number of encrusting bryozoan species, encrusting serpulids, Thecidian brachiopods and encrusting foraminifers are found. When developed in coral limestones, steep surfaces and even overhangs are seen, supporting dense populations of *Gastrochaenolites torpedo*, (at least partly and probably mainly made by *Lithophaga* sp. (K. KLEEMANN, pers. comm. 1993)), which were subsequently eroded and superseded by the encrusting, stalkless crinoid *Cyathidium holopus*.

From the hardground several fissures, filled with bryozoan-foraminiferal packstones to grainstones with angular fragments of the coral limestone, cut down obliquely into the underlying mound phases A and B. The fracture-filling lithologies are probably derived from coarse bryozoan grainstones that immediately overlie the hardground outside the investigated profile. Fracturing and lithification of in-filled packstones both predate dissolution of aragonite in the coral rudstone fragments, whereas they postdate the isopachous, fibrous cement, which lines the cavities in adjoining coral limestone.

Mound phase C

In the investigated profile the hardground is followed by a bryozoan wackestone, containing burrows of *Thalassinoides*-type, hexactinellid sponges reaching 10 cm in size and sporadic colonial scleractinian corals. The number of corals gradually increase upwards, at first accompanied by heavy bryozoan encrustations of the corals. After a few metres it grades up into a bryozoan-rich coral rudstone, dominated by relatively stout *Dendrophyllia candelabrum*, still accompanied by hexactinellids; this facies is best developed on top of the underlying mound in the central part of the profile. However, along the flanks of the mound the bryozoan rich coral rudstone is interbedded with the bryozoan wackestone which dominates the intermound area, containing allochthonous blocks of the bryozoan-rich coral rudstone. The upper boundary of mound phase C is an erosive contact to Quaternary, glacial deposits.

3.2. Details of mound phase A

Internal structure

Oversteepened bedding is a highly characteristic feature of the coral limestone of phase A. The sediment is a coral rudstone composed of distinct depositional units comprising an upper matrix-rich part and a lower, matrix-poor part (Figs. 4, 5). The boundary between depositional units is placed at the well-lithified upper surface of the matrix-rich coral rudstone; in contrast the boundary between the two subfacies within a unit is gradual and very irregular. The thickness of each depositional unit remains constant when traced from the quarry-floor to the upper limit of mound phase A.

The steep bedding is clearly conformable, and resembles the structure of a sliced onion; however, early faulting and subsequent erosion inhibits actual correlation between the western and eastern flanks. In the westernmost part of

Figure 4: A single depositional unit of mound phase A, steeply inclined towards the left. At the hammerhead the sharp upper surface of the upper matrix-rich part is in direct contact with the matrix-poor lower part of the next depositional unit, which is constituted by virtually matrix-free coral sticks. The highly irregular and gradual change from matrix-rich to matrix-poor coral limestone is characteristic of this mound phase. Length of hammer is 30 cm

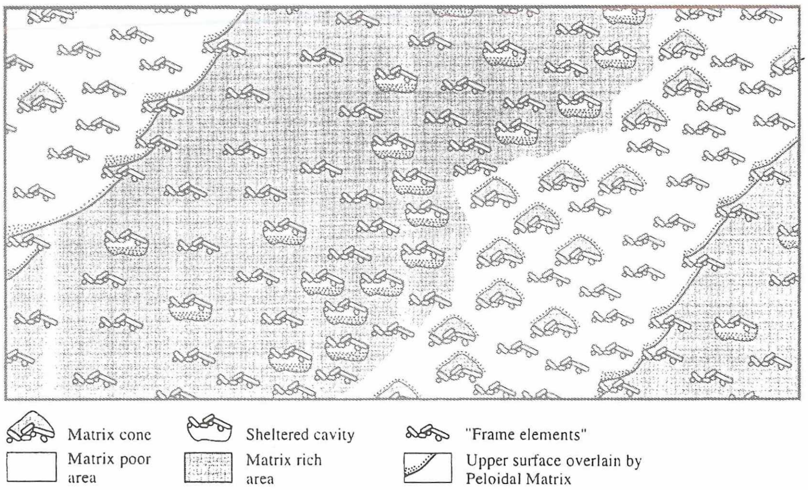

Figure 5: Schematical vertical section through a single depositional unit of mound phase A. Each depositional unit is bounded upwards by fairly regular matrix surfaces; the matrix-rich, upper part shows a marked increase of cavities downwards, ultimately attaining the character of the matrix-poor, lower part across a highly irregular boundary. The matrix-poor part also shows a marked increase in cavity volume, i.e. a decrease in the amount of matrix, downwards. Matrix surfaces are covered by geopetal Peloidal Matrix. The lower limit of coherent matrix area is for the major part supported by coral material, however, to attain clarity the amount of "frame elements" is limited in the figure (cf. Fig. 4). Similarly unsheltered cavities have been left out.

Figure 6: Thin-section showing the two types of matrix, which predate the first isopackous, fibrous cement. Primary Matrix is seen as mottled areas to the left and the right with a high proportion of skeletal material in a dense micritic matrix. Peloidal Matrix is seen as a slightly darker area in the central part of the picture, where it constitutes a geopetal cavity fill with a distinct, highly irregular boundary between the two matrix-types. The peloidal to clotted fabric is visible only just below the smooth cavity-floor. The remaining cavity is now filled by cement. Scalebar: 2 mm.

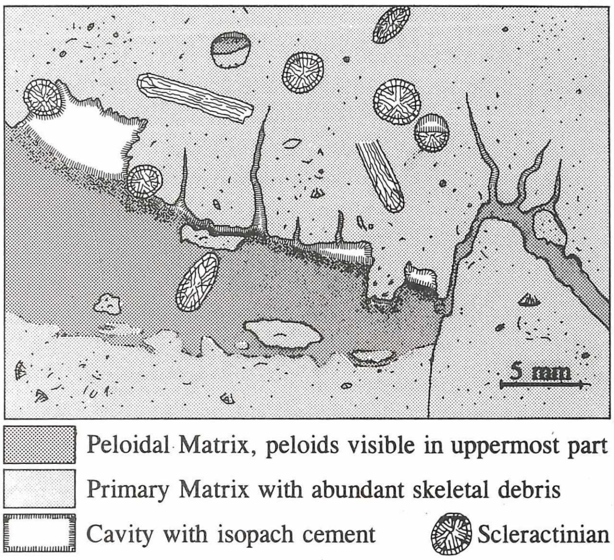

Figure 7: Very early coherence of Primary Matrix is indicated by the presence of unsheltered cavities, micro-fracturing prior to deposition of Peloidal Matrix, and the presence of angular clasts of Primary Matrix or cavity floors.

the lithoherm the layering is hardly discernible. This is partly due to a higher matrix content and a less thorough lithification of the rocks; however, more importantly, the strike of the bedding is nearly parallel to the quarry wall in this part of the profile.

Textural features

The part of sedimentary matrix in the mound, which predates the first isopachous, fibrous cement, comprises two types, which occur in a strict chronological order. The Primary Matrix (Figs. 6, 7, 8), is a bioclastic wackestone to mudstone containing abundant coccoliths and numerous other marine microfossils as well as mm-sized fragments of other faunal elements. The secondary, Peloidal Matrix (Figs. 6, 7) is an intrasediment, predominantly consisting of micrite displaying peloidal to clotted fabrics and containing rare marine microfossils (foraminifera and (?)calcispheres). Locally it contains skeletal clasts thought to have originated from the Primary Matrix.

Peloidal Matrix occurs as up to 1 cm thick internal sediments in cavities (Figs. 6–8), as fracture fill in the Primary Matrix, and as matrix of in situ breccia with clasts of Primary Matrix (Fig. 7). Peloids also occur in isolated, intraskeletal cavities, or more rarely as geopetal fill in the bottom of moulds after scleractinians, deposited prior to precipitation of the later, coarse cement.

The peloidal fabric is conspicuous only in the top few millimetres of Peloidal Matrix, while progressive compaction resulted in blurred peloidal to clotted fabrics below thicker accumulations. Well preserved peloids are composed of sub-micron sized crystals constituting aggregates approximately 40 µm in diameter (range from 10 to 100 µm). Subsequent to initial settling compaction the interstitial space is filled by 10–30 µm equigranular

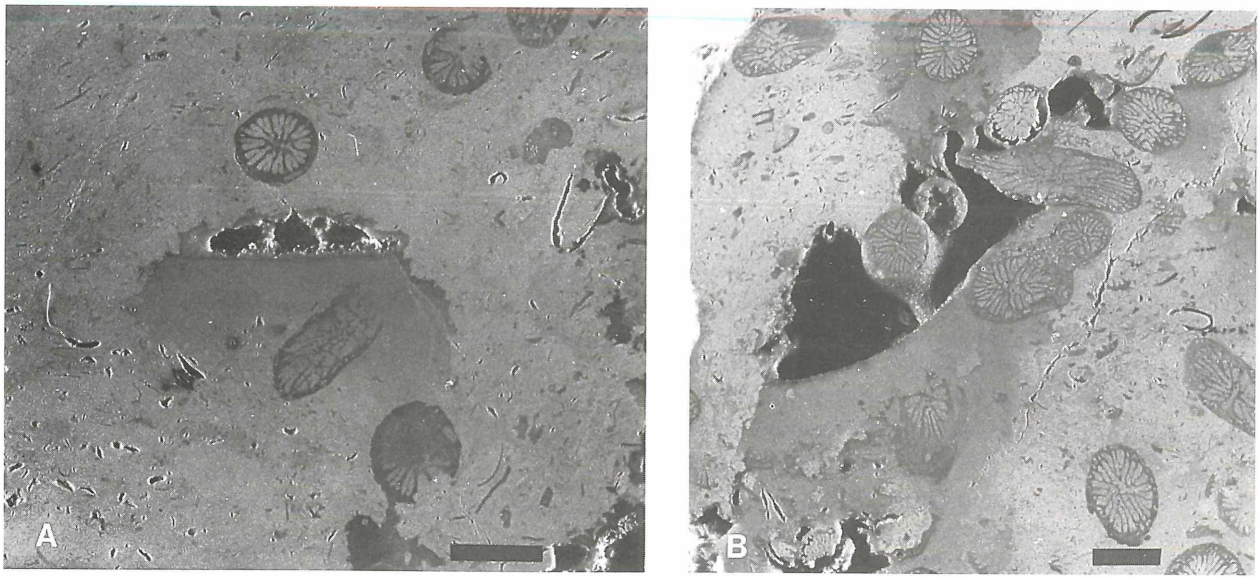

Figure 8: Vertical, polished surfaces on slabs from the matrix-rich sub-units in mound phase A (cf. Fig. 5). Scale-bars: 3 mm.
A) Primary Matrix with a mottled appearance and a multitude of partly dissolved skeletal debris takes up the larger part of the polished surface. An unsupported cavity in Primary Matrix is incompletely filled by Peloidal Matrix (recognizable by the dark, dense appearance), indicating stabilization of the former prior to infilling. In the remaining cavity, on top of the horizontal, geopetal surface, a sparse cement-lining is developed.
B) Frame-supported cavity with evidence of stabilization and internal erosion of Primary Matrix prior to deposition of Peloidal Matrix. Oversteepening of the Peloidal Matrix reflects transport inside the interconnected cavity system as well as penecontemporaneous lithification.

microspar. This preferential lithification is observed even in parts of the rock where the Primary Matrix is still hardly affected by cementation. Single peloids are interpreted to have been precipitated as a result of microbial life-processes (cf. e.g. CHAFETZ, 1986; REID, 1987; SUN & WRIGHT, 1989; PICKARD, 1992). Peloidal Matrix is always found with sharp boundaries to the Primary Matrix, and where Peloidal Matrix does not fill the larger (cm-sized) cavities completely, depositional slopes of 40°–50° are not uncommon (Figs. 7, 8B).

Micro-fracturing of Primary Matrix prior to the precipitation of Peloidal Matrix is most common in the lower part of the matrix-dominated subfacies (Fig. 7). The stability of the Primary Matrix already at this time is indicated by the angularity of the clasts, as well as by a great number of unsheltered cavities and rare examples of foraminifers and bryozoans encrusting cavity roofs.

Numerous examples of sheltering reveal that the sedimentary matrix was filtered into a pre-existing frame. The shelter-cavities are developed both beneath single larger bioclasts, and in association with concentrations of bioclasts caught in the frame along the roof of the cavity. In the matrix-poor areas the picture is reversed, with partly or totally isolated cones (Figs. 5, 9) of matrix-filled rock with smooth upper matrix surfaces resting on highly irregular lower surfaces of exposed bioclasts. Part of the shelter-cavities may very well have originated subsequently to initial infilling of sediment as a result of internal resedimentation (WALLACE, 1987), perhaps in connection with dewatering-induced compaction of the mud and thixotropically governed partial collapse (HECKEL, 1972).

In addition, cavities having apparently unsupported roofs (unsheltered cavities) are a common feature of the coral limestone. Most unsheltered cavities have a stromatactoid appearance with digitate roofs and smooth floors (Fig. 8A); since they are commonly still empty voids lined only with isopachous, fibrous cement, they are not stromatactis sensu stricto (cf. BATHURST, 1982). Most of these cavities are partly filled by Peloidal Matrix, and some contain assumed remnants of sponges, which may have supported the matrix prior to stabilization. A complete preservational suite of sponge remnants have been encountered, ranging from cement casts of delicate hexactinellid (lychniscid) spicules in original geometric arrangement, and assumed micrite casts of internal channel systems, over irregular cement casts of hardly discernable spicules, to the "pure" Peloidal Matrix (cf. BOURQUE & BOULVAIN, 1993). The latter end-member is by far the most frequent.

4. Discussion and conclusions

Mound forming processes

The maintenance of a depositional outer form showing slopes consistently steeper than 40° and having a minimum relief of 16 m, indicates a penecontemporaneous lithification of the sediments. There are several lines of evidence

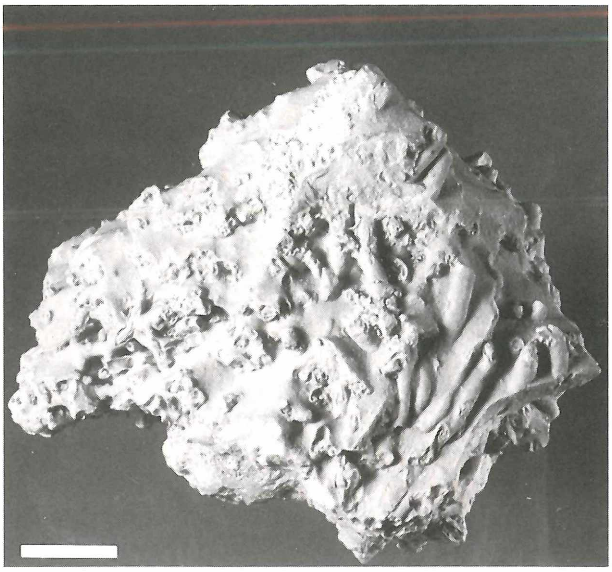

Figure 9: A single, large matrix-cone from matrix-poor sub-unit in mound phase A (cf. Fig. 5). Several frame elements are partly exposed. The marked cone-shape, resembling the sand-cone in an hourglass, indicates that the matrix was deposited subsequent to the deposition of the frame elements, and it suggests that pathways open to the sedimentary matrix were limited in number and size. Smooth, slightly darker surfaces are depositional, while more heterogeneous ones represent fractures. Scale-bar: 4 cm.

for early stabilization and lithification, in the described mound phase A in particular and in the coral limestones of Faxe in general. Timing indications of the observations range from penecontemporaneous processes to redeposition of lithified rock within the upper part of the Middle Danian. As this paper focuses on the constructional phase, it is primarily the earliest part of this spectrum that is considered here.

The fact that each depositional unit in mound phase A is of largely the same thickness across the mound, as well as the nearly constant dip of each unit, clearly suggest an *in situ* development. Deposition of debris transported down the structure would have likely produced wedge-shaped layers with a thicker distal portion expanding over the surrounding sea-floor.

Debris layers containing angular clasts of coral limestone are reported from several of the large, steeply bedded coral structures of Faxe (ASGAARD, 1968; FLORIS, 1979; BERNECKER & WEIDLICH, 1990; personal observations), indicating lithification of the coral limestone during the construction of the coral mounds.

Extensive fracturing of Primary Matrix as well as the unsupported nature of some of the Primary Matrix roofs, suggests coherence and partial consolidation of the Primary Matrix prior to the deposition of Peloidal Matrix. Furthermore, rare encrusting organisms on Primary Matrix surfaces suggest actual lithification prior to the deposition of the Peloidal Matrix. The unbroken connection to the marine biosphere during deposition of Peloidal Matrix, which is documented by the microfossil content, further indicates that lithification was initiated very soon after deposition of Primary Matrix.

It should be noted, however, that neither boring nor encrusting organisms have been found in association with the consolidated matrix surfaces terminating each depositional unit in mound phase A. Thus, these surfaces were probably not directly exposed to sea water, and actual hardground formation was most likely not an integrated part of the mound formation in Faxe.

In addition to very early lithification, any model for the construction of the lithoherm constituting mound phase A in Faxe has also to take into account the following elements: a) the lack of frame elements in growth position, b) the cyclic shift between matrix-rich and matrix-poor lithologies, and c) the matrix-cones and shelter-cavities which indicate infilling of matrix into an existing frame. The first steps in sediment accumulation were most likely comparable to the processes described from patches of azooxanthellate, non-tropic, scleractinians that flourish today on Rockall Bank (WILSON, 1979). In that case inevitable breakage and collapse of all coral material results in a sediment containing no frame-elements in growth position (SCOFFIN et al., 1980). At Faxe the colony fragments were probably retained on the steep flanks of the lithoherm by their entangling in older fragments, which were already "fixed" by lithified mud. The infilling of matrix into a pre-existing frame demonstrates the primary nature of the matrix cyclicity at Faxe, which probably was controlled by a periodic input of carbonate mud. On the basis of enhanced chemical activity during times of low matrix input, it may be suggested that lithification followed a cyclic pattern as well.

In other words, an open framework of reorientated frame-elements was constructed more or less continuously, while in contrast the carbonate sediment seems to have been supplied according to a cyclic pattern. During times of high matrix input the open framework allowed matrix to filter down into the mound, but gradually the interstitial pathways were occluded. This led to incomplete matrix infilling with a gradual, very irregular transition from matrix-filled to matrix-free coral limestone at some distance down into the frame. Similar cyclicity in input of micritic sediment was proposed for Lower Devonian mud-mounds by FLAJS & HÜSSNER (1993), who also acknowledged synsedimentary lithification as an essential part of mound construction.

The primary nature of matrix deficiency in the lower part of each layer at Faxe is corroborated by the regular occurrence of isolated matrix-filled depositional cones. Erosion or redeposition of matrix from the lower unlithified part of each bed, below a stabilized upper crust, can be an additional process, such as was described from recent lithoherms (NEUMANN et al., 1977). However, in Faxe this process must have been of limited importance, since substantial amount of coarser skeletal lag is lacking.

The highly interconnected cavity system inside the mound facilitated a constant flow of water, thus improving the lithification potential (cf. BROMLEY, 1967). Progressive consolidation through dewatering caused the Primary Matrix to react competently on minor dislocations, leading to the observed fracturing and in situ micro-brecciation. In this state, the presence of rich organic material in the cavities and Primary Matrix could have given rise to microbially induced precipitation of peloids, which settled to form the Peloidal Matrix. This secondary matrix filled smaller fractures and covered virtually all internal surfaces, including the top surface of the matrix-rich part of the underlying layer. The texture, and probably also the chemistry, of the Peloidal Matrix led to penecontemporaneous lithification through precipitation of interpeloidal microspar.

NEUMANN et al. (1977) and MESSING et al. (1990) described topographic mounds composed of surface-hardened conformable crusts of submarine-lithified fine grained carbonates off Little Bahama Bank. The term "lithoherm" was applied to these mounds in order to describe "deep, muddy carbonate build-ups formed by the constructive interaction of penecontemporaneous submarine lithification and organism attachment below the photic zone."

Acknowledging the crucial influence of the penecontemporaneous lithification, and the lack of framework organisms in life position contributing to the construction of mound phase A in Faxe, it is concluded that the term **azooxanthellate scleractinian lithoherm** is appropriate for at least this particular mound type in Faxe. Future investigations will reveal the extent to which the term is applicable to other build-ups at Faxe.

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