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Petrographic study of Danian limestone from eastern Denmark (Core Copenhagen TUBA 13)

BY

Erik Broe Nielsen

DANSK SAMMENDRAG:
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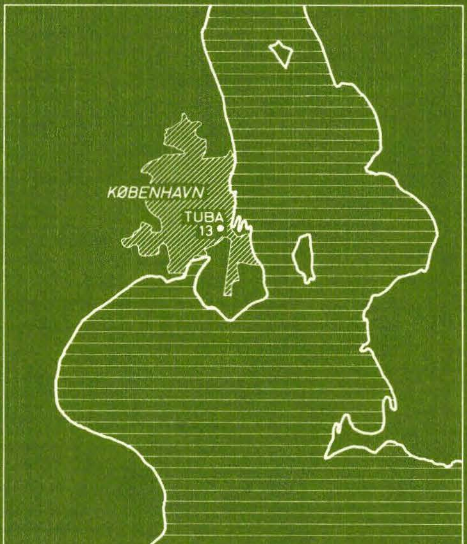

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Contents

Abstract

Based on the investigations of thin sections, peel prints and X-ray radiographs, quantitative and qualitative data on the carbonate constituents of the Danian limestone from København are presented.

The Danian limestone was classified according to both the petrographic nomenclature proposed by Folk (1962) and Dunham (1962) and to the occurrence of microborings.

It is believed that on the basis of the results of the present study the problems concerning the wave and current intensities, as well as the relative depths of the formation of the Danian limestone, might be solved, through future petrographic investigations.

Introduction

The results of a petrographical study of the Danian limestone from the cores of the well TUBA 13, drilled in København, are presented. This study ought to be regarded as a supplement to the lithological description of the Danian limestone in the København area (see Stenestad, 1976).

In the present study it was particularly attempted to elucidate the variations in the composition of this limestone. Different constituents were identified mainly according to the descriptions by Horowitz and Potter (1971) and Bathurst (1971), while the petrographic classification was essentially adopted from Folk (1962) and Dunham (1962).

Earlier works dealing with the Danian limestone in which the emphasis was placed mainly on petrography are those of Rørdam (1897), Hennig (1899) and Larsen (1961). Rørdam (1897) subdivided the Danian limestone from the northeastern part of Sjælland into five groups: coral limestone, bryozoan limestone, foraminifera limestone, coccolith limestone and sponge limestone. The calcite occurring between the skeletal particles in the first four groups was described qualitatively as either coarse grained, fine grained, very fine grained or microcrystalline. In the sponge limestone the calcite was described as sparry. Hennig (1899) adopted, in essence, Rørdam's classification of the Danian limestone, based on the kind of dominating skeletal particles. But the latter author has drawn attention to the fact that the presence, or absence, of e.g. foraminifera in different limestones does not necessarily mean that the original compositions of these limestones were different. Hennig (1899) has furthermore subdivided the bryozoan limestone from the area of Limhamn in southern Sweden into five types based on the sizes and the shapes of calcite crystals in the pores among the bryozoan fragments. Larsen (1961) has described some Danian limestones from Sjælland by means of the percentages of the main constituents and the grain size distribution of the skeletal fragments.

In most studies done on the Danian limestone the emphasis was placed on the palaeontologic, palaeoecologic or biostratigraphic characteristics. Ødum (1926) gave a very comprehensive description of the Danian limestone occurring in Jylland and on the island of Fyn. The same author was also the first to introduce a biostratigraphic subdivision of the Danian. On the island of Sjælland the Danian limestone was investigated in detail by e.g. Milthers (1908), Rosenkrantz (1937), Berthelsen (1962), Asgaard (1968), Rasmussen (1971) and Floris (1972). In southern Sweden the bryozoan limestone was studied by Hadding (1941), Brotzen (1959), Cheetham (1971) and others.

Samples

All samples in the present study originate from the core of the well Copenhagen TUBA 13, D.G.U. (Geological Survey of Denmark) Well Archive no. 201. 3080.

The Maastrichtian – Danian boundary in this well is encountered at −103 m, Bang (1976), and the Danian – Selandian boundary at −11 m, Stenestad (1976). The type locality of the formation the København Limestone, which is of Danian age, is by Stenestad (1976) defined as the interval between −11.1 m and −50.3 m of the core of this boring.

The lithology of the Danian limestone in the well Copenhagen TUBA 13 has been described in detail by Stenestad (1976), who also, on the basis of lithology, divided the Danian limestone of the core of this well into two parts: a lower part from −103 to −50 m consisting of a bryozoan limestone unit and an upper part from −50 m to −11 m consisting of a calcarenitic limestone unit; the København Limestone.

Methods

The petrographic data presented here were obtained through the study of large thin sections, peel prints and X-ray radiographies.

The constituents of the limestones were determined through counting of 400 points in 1 × 1 mm net in each thin section. A magnification of 160 was used in the identification of different limestone constituents. The percentages measured by point-counting are expressed in % grain bulk, since openings and deep indentations in grains were counted as grains instead of as pores (following Dunham, 1962 and Jaanusson, 1972).

The content of dolomite crystals and pellets, which make up a maximum of a few per cent of the rock, was only relatively determined. After counting along a 10 cm long line, the result was recorded as a number/cm.

The determination of the content of dolomite crystals was done by using peel prints, since it is not possible to distinguish between dolomite and calcite in thin sections on the basis of their optical properties alone. By means of peel prints, which bring out the micro relief of an etched limestone surface, the dolomite crystals can be clearly distinguished (for a description of the peel techniques see e.g. Wolf, Easton and Warne, 1967).

The insoluble residues are listed as the weight per cent of the non-carbonate fraction. The carbonate fraction was determined by titration.

The weight per cent of the Mg-ions was measured by means of a Perkin-Elmer 303, Atomic Absorption Spectrophotometer.

The constituents of the Danian limestone

In the present study the following constituents that may form parts of the Danian limestone will be treated: (1) skeletal material, (2) matrix, (3) spar or sparry crystals, and (4) dolomite.

1. Skeletal material

Skeletal material can be recognized as such if morphological features or a characteristic skeletal structure are preserved. The minimal sizes of skeletal fragments which can be ascribed to a certain group of organisms were discussed by Feray, Heuer and Hewatt (1962). These authors suggested that the fragments of echinoderms and bryozoans ought to have minimal sizes of 0.063 mm and those of foraminifera 0.031 mm in order to be identifiable. If, however, the origin of the fragmented materiel were known, the lower size limits for all these three groups of organisms were thought to be ca. 0.031 mm.

The terms skeletal sand and skeletal silt are used for those particles whose longest diameter is longer than and shorter than 0.063 mm respectively. The smallest particles which were determined as skeletal fragments but not ascribed to a certain group of organisms were approximately 0.020 mm large.

In the present study the skeletal material makes up 25 % to 50 % of individual samples. Of this amount only echinoderms, bryozoans, foraminifera, sponge spicules and serpulids make up more than 1 %.

Echinoderms. The skeletons of recent Echinoidea consist of separate skeletal elements which are made up of single high-magnesian calcite crystals. These elements possess mostly a fenestrate structure with a very high porosity that may exceed 50 %. Fossil echinodermal grains, embedded in calcite cement or micrite, are distinguished by their dusty appearence and uniform extinction, even where particle shape is no guide. For an elaborate description of the skeletal material of echinoderms see e.g. Bathurst (1971).

In several samples studied the original skeletal structure can be seen due to the fact that the fenestrate pore space are filled with micrite (pl. 1, fig. 1), glauconite (pl. 2, fig. 4), or silica. Especially in the samples 030 and 120 (pl. 4) many grains were observed where glauconite fills both the original pore space and pore spaces produced later by boring microorganisms (pl. 2, figs. 4, 5). Both of these types of glauconite fillings correspond closely to those described by Rørdam (1897, pp. 81–85) as glauconitized sponge skeletons from the uppermost part of the Danian limestone in the København area, and by Hennig (1899, pp. 34–35) from the Danian limestone occurring at Limhamn in southern Sweden.

In most cases, however, the host skeleton of the fragments of echinoderms is enclosed in a syntaxial crystal of calcite cement and a certain amount of opaque inclusions is characteristic for the echinoderm grains found in the samples. These inclusions occur usually in form of irregular aggregates and, but seldom, as branching filaments (pl. 1, fig. 2).

The echinoderms make up to 25 % grain bulk of the limestones (pl. 4). As a main constituent of the skeletal material echinoderm grains occur only in the upper part of the Danian limestone (pl. 3, fig. 3).

In a textural context two things have to be emphasised when echinoderm grains are considered as sedimentary particles. First that echinoderm grains most often display very irregular shapes (see Cain, 1968) and second that their outlines are indistinct when they occur enclosed within the syntaxial calcite cement. For these reasons the random sections of the fragments of echinoderms in a thin section can give only an approximate impression of the actual size and roundness of these grains.

Bryozoans. The calcareous skeletons of recent bryozoans are polycrystalline and have either a liminated, fibrous or granular wall structure. Their skeletons are built of either high-magnesian calcite, low-magnesian calcite, aragonite or of both high-magnesian calcite and aragonite. For the studies of the skeletal materials of bryozoans see Bathurst (1971), Horowitz and Potter (1971) and Tavener-Smith and Williams (1972).

The fragments of bryozoans found in the Danian limestone may be divided into two groups, based on the wall structure of the preserved calcareous skeletons. In one group, which probably only contains fragments of the cyclostome bryozoans, there are almost always two clearly separated layers in the wall. One layer extends throughout the zoarium, while the other layer is limited to the individual zooecia. These layers probably correspond to the primary and secondary layers, respectively, as described by Tavener-Smith and Williams (1972). The layer which extends throughout the zoarium is relatively light coloured in the ordinary light and possesses either a laminated or granular structure (pl. 1, figs. 3, 4). The other type of layer is somewhat darker and has always laminated structure (pl. 1, figs. 3, 4). In the other group of bryozoan fragments, which probably all originate from the cheilostome bryozoans, layers, as described above, are hardly ever related in a particular way to either the zoarium or to the zooecia. In ordinary light these fragments are relatively light coloured and appear structureless (pl. 3, fig. 5), while under crossed nicols they show wavy extinction.

The bryozoans make up to maximum 21 % grain bulk in the examined samples. But as a significant component of the skeletal material they occur only in the lower part of the Danian limestone (pl. 4 and pl. 3, fig. 5). The fragments of the bryozoans originated from colonies of various growth forms. Fragments from erect branching colonies or encrusting colonies were most commonly encountered, while the fragments of unilaminar plates are more rare.

In a textural context the bryozoan fragments in the Danian limestone can be characterized as predominantly prolate sedimentary particles. Due to the varied morphology of the bryozoan colonies it is generally not possible to determine the sizes of the fragments in random sections.

Foraminifera. The content of foraminifera ranges from 1 % to 14 % grain bulk of the examined samples. However, as a significant component of the skeletal material they are present only in the Maastrichtian limestone and in the lowermost and middle parts of the Danian limestone (pl. 4 and pl. 3, fig. 7). The largest part of the foraminifera are planktic (pl. 1, fig. 6).

Sponge spicules. The content of sponge spicules ranges from 0 % to 7 % of the examined samples. As a significant constituent of the skeletal material they are present only in the Maastrichtian limestone, while in the lower part of the Danian limestone they only occur in subordinate amounts (pl. 1, figs. 5, 6; pl. 3, fig. 8 and pl. 4).

Serpulids. Fragments of calcareous tubes, which are straight or slightly curved, make up more than 1 % grain bulk only in the uppermost part of the Danian limestone (pl. 4). The tubes have round cross sections and their outer diameters measure a few milimetres. In thin section the tubes appear to consist of two layers: an outer layer of a light brown colour with a prismatic structure (pl. 1, fig. 7 and pl. 2, fig. 1) and an inner layer of a dark brown colour (pl. 1, fig. 7). Minor differences in colour suggest that both layers have concentric structures in transverse sections. In oblique and longitudinal sections of the tubes in peel prints and very thin sections it was established that the inner layer consists of two layers: a thin structureless layer and a thicker layer displaying cone-in-cone structures. The points of the cones are orientated in the growth direction of the tubes (pl. 1, fig. 8).

The microstructures in these calcareous tubes are not comparable to the microstructures observed in the shells of the Tertiary serpulid worms, scaphopods and vermetid gastropods, as described by Smidt (1951) and by Horowitz and Potter (1971). On the other hand, an investigation of the serpulid *Ditrupa schlotheimi,* Rosenkrantz (1920, pp. 25–27), in a specimen of Danian limestone from Terkelskov north of København, has shown that the microstructure in *Ditrupa schlotheimi* is identical with that of the above described calcareous tubes.

2. *Matrix*

The term matrix is here used to designate materials, which consist of *crystals* less than 0.020 mm in size, and to which the term skeletal material, as used in the previous section, could not be applied. The matrix is subdivided into micrite and microspar. Micrite is used for the matrix in which the crystals are smaller than 0.005 mm, and microspar designates the matrix in which the crystals are larger than 0.005 mm; for the definitions of micrite and microspar see also Folk (1962, 1965 and 1974) and Barthurst (1971).

In the samples studied the matrix constitutes 19 % to 75 % grain bulk. Micrite was found to vary from 17 % to 71 % and microspar from 1 % to 31 % (pl. 4). With the exception of the matrix in the sample 030 from the uppermost part of the Danian limestone, it is tentatively assumed that the matrix in the other samples consist predominantly of *particles* smaller than 0.020 mm, thus corresponding to the "lime matrix" of Larsen (1961, p. 7), the "mud" of Dunham (1962, p. 113) and the "lime mud matrix" of Folk (1962, p. 76, fig. 4).

In the sample 030 the micrite component of the matrix in an ordinary thin section appears to be larger aggregates and smaller well defined particles (pl. 3, figs. 1, 2). However, very thin sections and peel prints of this limestone show that the micrite aggregates are made up of well defined but irregular and strongly pitted particles, which are all larger than 0.020 mm (pl. 2, figs. 1, 2). These often contain partially preserved skeletal material, or resemble morphologically that material. Another characteristic of these particles is that due to a certain amount of insoluble components their shape remains almost unchanged when thin sections of this limestone are treated with hydrochloric acid. In the case of all the other particles only small isolated grains of insoluble material are preserved after the etching process.

All other particles in the sample 030 consist of well preserved skeletal material without micritized parts or the micrite envelopes of Bathurst (1966).

They are thus different from the micrite particles for which an intraclastic origin could be suggested, i.e. reworked particles of lightly consolidated sediments exposed within the sedimentary basin (Folk, 1962, pp. 63–64). The occurrence of reworked foraminifera of Maastrichtian age only in the uppermost part of the Danian limestone in the København area, see Bang (1976), supports this interpretation of the origin of the micrite component in the sample 030.

3. Spar

The term spar is here applied to crystals which lack inclusions and are larger than 0.020 mm; see also Folk (1962) and Bathurst (1971).

The content of spar in the samples studied varies between 1 % and 27 % grain bulk. Based on the measurements of the largest diameters of the spar crystals, most of these crystals in the Danian limestone are between 0.020 and 0.063 mm. Only in the upper part of the limestone the spar crystals larger than 0.063 mm are more commonly encountered (pl. 4). The largest portion of the spar component occurs in the form of subhedral and anhedral crystals having equigranular fabric or as syntaxial calcite rims around echinoderm grains. Euhedral crystals are seldom observed and nearly always in intraparticle pore spaces, and not as polycrystalline fringes on the surfaces of the particles.

The information concerning the spar crystals, which came to light in the course of the present investigation, can only in a limited way clarify the problems concerning their formation.

In the samples 126 to 041, where the anhedral and subhedral crystals are more or less evenly distributed in the limestone, due to the high content of matrix, it was not possible to ascertain whether they formed either as cement or as neomorphic spar. In the intraparticle pore spaces of these samples euhedral crystals with length/width ratios close to 1 often occur.

In the sample 030 the main part of the spar crystals are syntaxial on echinoderm fragments, which make up 25 % of the sample. As the spar crystals in this sample are interstitial with sorted and abraded particles which are in depositional contact with each other, it is thought that these crystals are spar cement, i.e. precipitated in the interparticle spaces. Furthermore it is thought that the precipitation of the spar cement was completed once after a general compaction of the deposit took place, because of pressure-solution contacts between many of the particles.

As shown by Evamy and Shearman (1965, 1969) the growth history of syntaxial cement on echinoderm grains can sometimes be revealed by staining because of changes in the amount of Fe^{2+} in the calcite. Staining as proposed by Dickson (1965) was done on thin sections, but no higher concentrations of Fe^{2+} in the interparticle spar cement were proven. Only in a few cases it was proved that the space filling cement in intraparticle pores were precipitated in at least two stages. An early generation of Fe^{2+}-free euhedral crystals with slightly curved faces and with length/width ratios greater than 2 was followed by Fe^{2+}-rich spar cement filling the rest of the pores (pl. 2, fig. 7).

In other intraparticle pores an early generation of euhedral crystals having the same shape as the above mentioned Fe^{2+}-free crystals, was buried in glauconite filling the rest of the pore spaces. A similar case of marine cement was described by Hennig (1899) who studied Danian limestone from the Limhamn area in southern Sweden.

The petrographic data thus show that the spar crystals occur both as marine cement and as spar cement precipitated in a diagenetic environment in which the content of Fe^{2+} in the pore solution was higher than that of sea water. However, it appears that only a subordinate amount of the spar originated in these diagenetic environments. As suggested by Folk (1974) the equigranular, anhedral and subhedral spar crystals, which make up the biggest part of the spar in the Danian limestone, formed in a diagnetic realm in which the content of Mg-ions was low, i.e. either in the subsurface mixing zone or in the meteoric phreatic zone of Folk (1974).

4. Dolomite

Identification and determination of the relative contents of dolomite was done by means of peel prints, which clearly show the difference in the solubility between dolomite and calcite.

It was established that dolomite occurs as a subordinate component in nearly all samples (pl. 4). The crystals of dolomite, between 0.005 and 0.100 mm large, can be either anhedral, subhedral and euhedral (pl. 2, fig. 8). The anhedral and subhedral crystals are relatively evenly distributed in the limestone, while the euhedral crystals, which are more rare, are either evenly distributed in the silicified or clayey parts, or are found to be concentrated within or around the fissures filled with sparry calcite.

The variations in the relative contents of the dolomite and the Mg-ions show the same general pattern throughout the Danian limestone (pl. 4). A closer agreement between the contents of these two components can not be expected, because in the determination of the relative contents the evenly distributed crystals will always tend to be better represented than the crystals occurring in clusters, and also because the Mg-ions form part of dolomite as well as calcite. Also, these ions can possibly be adsorbed by clay minerals.

The weak dolomitization of the Danian limestone has probably taken place in at least two different stages. The evenly distributed crystals may have been formed during an early diagenetic stabilization phase of the high-magnesian calcite, during which the Mg-ions were expelled and redistributed in the form of replacement dolomite, see Folk (1974). Since these early formed crystals were most likely euhedral, the subhedral and anhedral crystals would have been formed during a later dedolomitization, which did not affect the silicified and the clayey parts of the limestone. A subsequent dolomitization can only be related to the filling with sparry calcite of fissures formed at a time when the limestone was already lithified to a certain degree. This lastly formed dolomite crystals are euhedral.

Bulk texture

The concepts "mud-supported" and "grain-supported" were introduced by Dunham (1962) in his classification of the carbonate rocks, whose depositional textures were preserved. According to that author, carbonate rocks in which the grains "float" in a mud matrix are designated, as mud-supported, while those in which the grains form a self supporting network, as grain-supported. The shape of the grains is considered to determine the tightness of such a net work.

Cain (1968) adopted Dunham's concepts and made some quantitative estimates which showed that limestones, in which the grains are predominantly made up of irregular fragments of echinoderms, are most likely grain-supported when the content of grains is larger than 40 % per volume.

Nielsen (1974) estimated that in limestones consisting predominantly of oblate and often branched bryozoan fragments there could only exist a self supporting net work if the particles larger than 0.063 mm make up from 25 % to 33 % grain bulk, but if the particle content was larger than 33 %, oblate and often branched particles will probably always form a self supporting net work. The above estimates agree well with the results presented by Thomsen (1976).

These same concepts and data were applied also in the present study in order to evaluate the "bulk texture" of samples (pl. 4). This semiquantitative characteristic is here designated as bulk texture because 1) it was not established whether the Danian limestone possesses its original depositional texture and 2) because the Danian limestone with a high bryozoan content nearly always contains, within a few centimetres of the rock, self supporting net works of both grains and mud matrix.

The division of the Danian limestone on the basis of the petrography

On the basis of the relative contents of the skeletal material, matrix and the spar component the limestone in the samples 126 to 041 was classified as a biomicrite and the limestone in the sample 030 as a biosparite. The following characteristics may be used to further subdivide these limestones: the biomicrite can be subdivided according to its content of the skeletal material and bulk texture, and the biosparite, as proposed by Folk (1962), according to its content of skeletal material, grain size distribution, sorting and rounding of the grains.

As the present study shows, the limestone sequence in the København area can comprise a biomicrite of Maastrichtian age (samples 126 and 125), overlain by ca. 83 m thick biomicrite (samples 123 to 041) and ca. 8 m thick biosparite (sample 030) of Danian ages.

The Maastrichtian biomicrite contain a certain amount of sponge spicules and foraminifera (pl. 3, fig. 8) as well as bryozoans and foraminifera (pl. 4).

The Danian biomicrite is characterized from bottom upwards by foraminifera (pl. 3, fig. 7), bryozoans (pl. 3, figs. 5, 6), foraminifera and echinoderms (pl. 3, fig. 3). In the samples 108 to 066 the amounts of foraminifera, bryozoans, and echinoderms are approximately the same. Therefore the biomicrite within this part of the section has a transitional character between the underlying bryozoan biomicrite and the overlying echinoderm biomicrite (pl. 3, fig. 4 and pl. 4).

The Danian biosparite (sample 030) has a high content of echinoderms and of intraclasts, see the discussion on the matrix, p. 10. This sample in its lower part consists of a fine grained layer and in its upper part of a coarse grained layer (pl. 3, figs. 1, 2). By means of measurements of the longest diameters of 100 random particles in every layer the geometric mean diameters were calculated to be 0.13 mm in the lower layer and 0.40 mm in the upper layer. The degree of sorting as expressed by the logarithmic standard deviation is 0.7 phi in the fine grained layer and 1.9 phi in the coarse grained layer. Therefore the fine grained layer can be characterised as relatively well "sorted" and the coarse grained layer as unsorted. In both layers there is a considerable amount of well rounded particles.

In the course of the present investigation it was found that several samples contained particles with different types of microborings (pl. 2, figs. 3, 4, 5). A qualitative determination of where in the Danian limestone sequence these microborings appeared was undertaken. This was done on the basis of a study of thin sections from 60 evenly spaced samples (pl. 4).

The qualitative determination of microborings in a limestone sequence is by the present writer considered to furnish an important information in addition to the previously described petrographic characteristics of limestones, as proposed by Folk (1962) and Dunham (1962).

The quantitative data on the composition of the Danian biomicrite below and above the marked lithological horizon at −50.3 m in the core Copenhagen TUBA 13 are listed in table 1. This marked horizon separates the underlying bryozoan limestone unit form the overlying København Limestone, see Stenestad (1976). In both of these limestone units the average contents of the skeletal material, micrite and the insoluble residues are the same, but the content of bryozoans, foraminifera and sponge spicules are the highest in the bryozoan limestone unit, while the content of echinoderms is the highest in the København Limestone.

Organic processes determinative for the formation of the particles

The particles larger than 0.020 mm consist almost exclusively of skeletal material. The exceptions to this are intraclasts and pellets. The pellets, which are round to oval particles of micrite (pl. 2, fig. 6), make up only minor amounts of the samples examined, see the relative content of pellets (pl. 4).

The preserved skeletal material consists either of entire skeletons, intact skeletal elements, or fragments of these. Entire skeletons of many foraminifera are preserved, while sponge remains are most common disintegrated skeletal elements. Echinoderm grains nearly always occur as fragments of single plates.

Fragmentation of skeletons can be evaluated on the basis of some textural characteristics, which Ginsburg (1957) ascribed to early diagenetic organic processes. Reduction of particle size, aggregation of particles, erosion of particles, and structures formed by organisms are results of these organic processes, which can be studied in the course of an ordinary petrographic investigation.

The particle-size reduction, due to detritus feeders, will result in an almost continuous size spectrum of non-rounded particles. In the samples studied here fragments of some of the largest skeletons and skeletal elements, which are bryozoan colonies and the single plates of echinoderms, have such a spectrum ranging from sand to silt size.

The aggregation of particles can take place after passage of particles through the digestive tract of detritus feeding animals, when the individual particles are bound together by organic substances. The pellets, which are recorded in pl. 4, having uniform sizes and shapes, may have been formed in this way.

Erosion due to organisms was observed in several samples, in which most particles were partially perforated by microborings (pl. 4). The activity of boring microorganisms, which may be conducive to abrasion and formation of new particles, is a process not yet fully understood.

The structures formed by organisms comprise many types. These structures are most commonly characterized in a deposit by the absence of laminations. In the present study the X-ray radiographies, in which the method described by Thiede and Larsen (1971) was employed, showed that none of the samples were distincly laminated. However, diffuse and disturbed laminations, as well as burrows were frequently observed.

In recent carbonate sediments the formation of the carbonate mud was described in several instances by, among other authors, Mattews (1966) and Bathurst (1967). Thus Mattews (1966), arrived at the conclusion that a recent calcilutite from British Honduras was of both allochtonous and autochtonous origin. This interpretation was based on both the petrographical data and mineralogical composition, and on the content of trace elements.

Theoretically, in the Danian limestone both autochtonous and allochtonous origin of the matrix are also possible. The part of the matrix which was originally a carbonate mud could have been formed partly through the just described processes, and partly supplied from intra- and extrabasinal areas, where Maastrichtian and Danian deposits were exposed.

Discussion

The data presented in this paper indicate, that the Danian limestone in the København area comprises two texturally different accumulations, namely a biomicrite and a biosparite, and that microborings occur at four different levels of the Danian limestone sequence. An evaluation of the energies and the depths of the environments where this limestone sequence accumulated is based on these results.

Most biomicrites are deposited in low-energy environments and most biosparites in high-energy environments, see Folk (1962). In the opinion of the present writer, a possible exception to this in the case of the Danian limestone, are the bryozoan biomicrites which are grain-supported and grain-mud-supported. An interpretation of the current intensity prevailing during the accumulation of such deposits should be based on whether the grains forming the self supporting net work were of autochtonous or allochtonous origin and on how easily the mud could have been reworked from the self supporting net work.

Radiographies of the Danian bryozoan biomicrite show that the self supporting net work consists of a few centimetres long branching bryozoan fragments. According to Thomsen (1976) an autochtonous origin for this network is most likely even if most of the bryozoan fragments are lying parallel to the bedding plane. The existence of a centimetres thick cover of bryozoan colonies on the depositional surface could mean, see Ginsburg and Lowenstam (1958) and Larsen (1961), that the reworking of accumulated mud was more influenced by the current intensity in the bryozoan cover than by the prevailing current intensity above this cover. Thus a moderate current intensity can not be excluded, but based on the present data no definite conclusion as to the intensity of the current may be reached.

In biosparitic deposits Folk (1962) interpreted the textural spectrum (unsorted, sorted, rounded and textural inversion) as evidence for increasing current and wave intensity in a high-energy environment. In the uppermost part of the Danian biosparite two layers, each a few centimetres thick, were observed. Both layers have rounded and microbored particles but only the lower layer was found to be sorted. The upper layer could be, therefore, tentatively interpreted as an example of a textural inversion. The lack of sorting could, however, be also due to either bioturbation or infiltration by smaller particles among larger sorted particles. Another explanation could be that if the microborings are found in a deposit, the grains were abraded before sorting was completed.

In recent shallow water carbonate sediments algal borings are abundant to depths from 20 to 40 m, see Swinchatt (1969), Hughes Clarke and Keij (1973), Edwards and Perkins (1974) and others. However, microborings produced by other endolithic microorganisms are found from depths of a few metres to 450 m, see Edwards and Perkins (1974).

An interpretation of the relative depth, based on the occurrence of microborings in the Danian limestone, has been proposed by R. G. Bromley (in Asgaard, 1968), who found sponge borings and probable algal borings in the Danian limestone at Fakse on the island of Sjælland.

Apart from the Fakse occurrence, glauconitized grains, described in details by Rørdam (1897, pp. 81–85) and Hennig (1899, pp. 34–35) from the Danian limestone at København and at Limhamn, has by the present writer been interpreted as glauconitized echinoderm fragments with microborings.

In this study microborings were qualitatively recorded at four different levels: one in the lower part of the bryozoan biomicrite, one just above the bryozoan biomicrite, one in the basal part of the København Limestone and, finally, one in the uppermost part of the København Limestone.

Since it is not ascertained which types of microorganisms produced these borings, they can not be definitely considered as depth-indicators. However, the four mentioned levels coincide with marked changes in lithology and petrography in the København area. And three of these levels can also be correlated on the basis of lithostratigraphy with the conglomeratic deposits in the entire Øresund area described by Rosenkrantz (1937) and Berthelsen (1962). This suggests that the microborings in the Danian limestone may also be used as depth-indicators.

Summary and conclusions

The present petrographic study of the core Copenhagen TUBA 13 is based on an investigation of 22 samples representing limestones of Maastrichtian age, bryozoan limestone and the København Limestone which are of Danian age.

On the basis of quantitative and qualitative data the Danian limestone is divided into ca. 83 m thick biomicrite overlain by ca. 8 m thick biosparite.

The marked lithological horizon at −50.3 m which separates the bryozoan limestone from the København Limestone occurs within a part of the biomicrite, which has a transitional character between the underlying bryozoan biomicrite and the overlying echinoderm biomicrite.

On basis of this petrographic study the biomicritic Danian limestone is interpreted as a deposit accumulated in a low-energy environment. However, it is possible that this interpretation ought to be modified for those parts of the biomicrite where the bulk textures are grain-supported and grain-mud-supported. On the other hand the biosparite is interpreted as having been accumulated under high current and wave intensity.

The microborings which occur at four different levels in the Danian limestone coincide with marked changes in the lithology and petrography. Further study remains to be done before it can be establishea whether these microborings originate from algae, in which case they are depth indicators, or some other endolithic microorganisms.

Acknowledgements

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Dansk sammendrag

Petrografisk undersøgelse af danienkalk fra Øst-Danmark. (Kerneboringen København TUBA 13)

Hensigten med denne undersøgelse har været at give en petrografisk beskrivelse af danienkalken i kerneboringen København TUBA 13. Af de ialt 22 undersøgte prøver, stammer de 2 fra den allerøverste del af maastrichtienkalken og de resterende 20 fra den 92 m mægtige danienkalk lagserie. Danienkalken er i denne boring overlejret af selandienaflejringer.

Indholdet af karbonatkomponenterne er bestemt kvantitativt ved undersøgelser af tyndslib og peel-præparater. De vigtigste bestanddele i kalken er »skeletal material«, »matrix« og »spar«, se (pl. 4). Skeletal materialet er domineret af fragmenter af echinodermer, bryozoer og planktiske foraminiferer, medens svampespikler og serpulider kun findes som en underordnet men karakteristisk bestandel af skeletal materialet i henholdsvis den nederste og den allerøverste del af danienkalken. Dolomit forekommer som en underordnet bestandel i næsten hele danienkalk lagserien.

Ved karakteriseringen af de enkelte prøver er den af Folk (1962) og Dunham (1962) foreslåede terminologi anvendt. Denne generelle klassifikation er dog udvidet med resultaterne af en kvalitativ registrering af i hvilke niveauer, der findes mikroboregange.

Danienkalk lagserien i Københavnsområdet, som den fremtræder gennem de undersøgte prøver, omfatter en »biomicrite« med en mægtighed på ca. 83 m overlejret af en »biosparite« med en mægtighed på ca. 8 m. Den biomicritiske danienkalk har i den nederste del et højt indhold af bryozoer og i den øverste del et højt indhold af echinodermer, hvorimod den mellemste del af biomicriten har karakter af en overgangsbjergart mellem disse to kalkstenstyper. Den biosparitiske danienkalk domineres af echinodermer og »intraclast« partikler.

Den markante lithologiske horisont, som adskiller bryozokalk enheden fra kalksandskalk enheden (= København Kalken), findes i den del af den biomicritiske danienkalk, der har karakter af en overgangsbjergart.

På baggrund af den foreliggende petrografiske undersøgelse tolkes den biomicritiske danienkalk som en aflejring, der er akkumuleret i et lav-energi miljø. Det er dog sandsynligt at denne tolkning kan modificeres for de afsnit af biomicriten, hvor de større partikler danner et selvbærende netværk. Den biosparitiske danienkalk er sandsynligvis en høj-energi aflejring.

Mikroboregange er foreløbig fundet i følgende fire niveauer, der alle falder sammen med markante ændringer i danienkalkens lithologi eller petrografiske sammensætning; 1) i den nederste del af bryozo biomicriten, 2) umiddelbart over bryozo biomicriten, 3) i den nederste del af København Kalken og endelig 4) i den øverste del af København Kalken.

Fortsatte petrografiske undersøgelser er dog nødvendige før det kan afgøres om de fundne mikroboregange stammer fra alger, i hvilket tilfælde de er dybde-indikatorer, eller fra andre mikroorganismer.

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Table 1. Per cent grain bulk of the constitutents in the biomicritic Danian limestone. The 95 % confidence intervals are given for the mean.

Copenhagen Core TUBA 13						
Metres below sea level	20–50 m			50–103 m		
Lithostratigraphy	The København Limestone			The bryozoan limestone unit		
Constituents	N	Range	$\bar{x}$	N	Range	$\bar{x}$
Skeletal, sand + silt	7	31–50 %	38.6 ± 6.2	12	25–43 %	38.4 ± 3.4
Skeletal, sand	7	10–27 %	20.7 ± 6.0	12	11–39 %	25.8 ± 4.8
Skeletal, silt	7	8–31 %	17.9 ± 7.5	12	2–21 %	12.6 ± 3.8
Matrix, micrite	7	26–60 %	43.1 ± 11.9	12	22–61 %	43.8 ± 6.8
Matrix, microspar	7	1–14 %	8.6 ± 4.7	12	1–30 %	11.6 ± 5.3
Spar, 20–63 μ	7	1–13 %	5.5 ± 7.0	12	1–11 %	4.6 ± 2.3
Spar, > 63 μ	7	0– 4 %	1.5 ± 1.2	12	0– 4 %	0.5 ± 0.7
Insoluble residue	6a	1– 8 % wt.	3.6 ± 3.6	10a	1–12 % wt.	3.7 ± 2.4
Echinoderms	7	2–23 %	11.2 ± 7.5	12	2– 7 %	4.0 ± 1.1
Bryozoans	7	0– 1 %	0.3 ± 0.4	12	0–21 %	8.9 ± 5.1
Foraminifera	7	1–10 %	3.6 ± 2.8	12	1–14 %	6.0 ± 2.5
Sponge spicules	7	0 %	–	12	0– 7 %	0.8 ± 1.2
Skeletal, indetermined	7	17–35 %	23.4 ± 5.3	12	8–29 %	18.7 ± 4.0

a) Silicified samples excluded.

Plates

Plate 1

Fig. 1. Transverse section of an echinoderm plate. The open meshwork structure is seen because of infilling with micrite. The lumen is shown clearly while syntaxial calcite veils the outer shape. Thin section. Sample 105.

Fig. 2. Fragment of an echinoderm with many inclusions. Some inclusions are rods associated with spheres, which could be casts of microborings. Thin section. Sample 030.

Fig. 3. Transverse section of a cyclostome bryozoan. Two layers with laminar structure are seen in the zoarium. Peel. Sample 079.

Fig. 4. Transverse section of a cyclostome bryozoan. Two layers with laminar structure are seen in the zoarium. Sample 111.

Fig. 5. Transverse, oblique and longitudinal sections of siliceous sponge spicules. Thin section, × nicols. Sample 114.

Fig. 6. Oblique section of calcite cement cast of a sponge spicule. Several tests and fragments of planktic foraminifera are seen in the micritic matrix surrounding the cast. Thin section. Sample 125.

Fig. 7. Slightly oblique section of a serpulide tube. *Ditrupa schlotheimi* exhibiting a dark inner layer and a prismatic outer layer. See also pl. 1, fig. 8 and pl. 2, fig. 1. Thin section. Sample 030.

Fig. 8. Detail of Fig. 7 showing the dark inner layer with a thin structureless layer followed by a layer with cone-in-cone structure. In the prismatic layer dark inclusion outline a probable relict structure. Thin section. Sample 030.

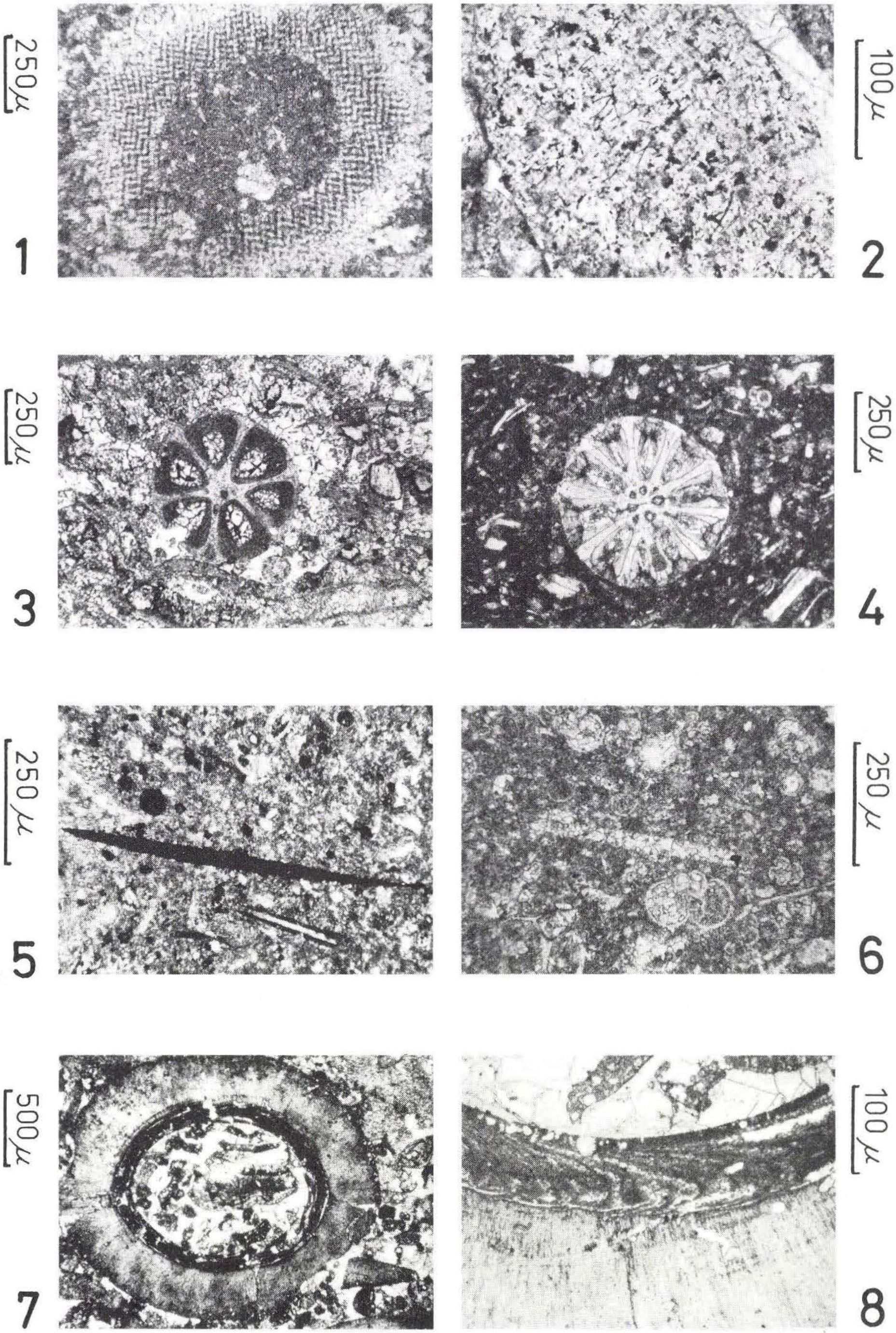
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Plate 2

Fig. 1. Perforated micrite particle surrounded by calcite spar. Lower right: outer prismatic layer of a serpulide tube. Peel. Sample 030.

Fig. 2. Detail of pl. 1, fig. 7. Skeletal fragments and strongly perforated darker intraclasts in a sparry calcite cement. Thin section. Sample 030.

Fig. 3. Microborings in a serpulide fragment. Thin section. Sample 030.

Fig. 4. Echinoderm fragment with glauconite in the original pores and in microborings. Thin section. Sample 120.

Fig. 5. Detail of an echinoderm fragment with glauconite in microborings. Thin section. Sample 030.

Fig. 6. Pellets probably fecal pellets, in a matrix of micrite and microspar. Thin section. Sample 042.

Fig. 7. Detail of vesicular tissue in a pycnodontid mollusk. Two generations of sparry calcite cement are revealed by staining with an acidified solution of potassium ferricyanide. The colourless calcite is iron-free and the dark calcite is iron-rich. Very thin section. Sample 030.

Fig. 8. Euhedral, subhedral and anhedral dolomite crystals. Peel. Sample 105.

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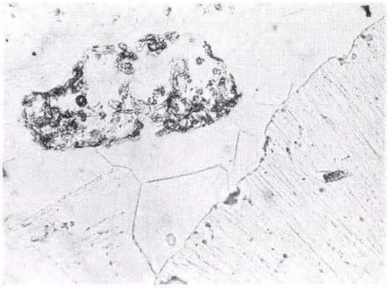
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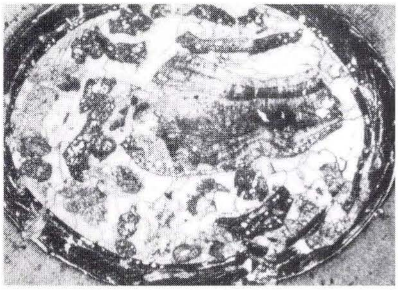
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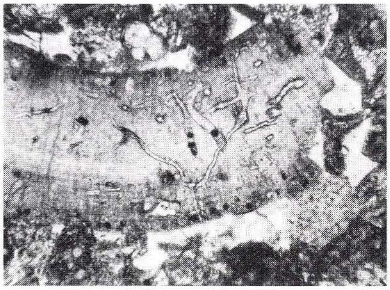
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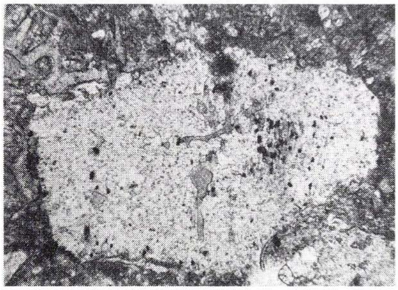
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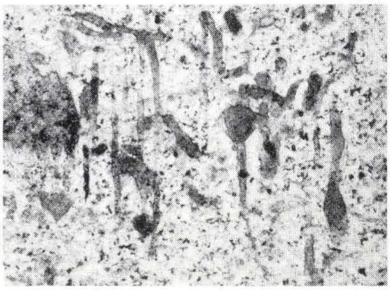
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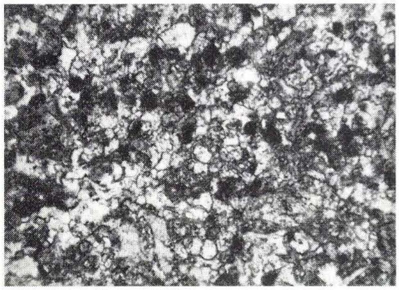
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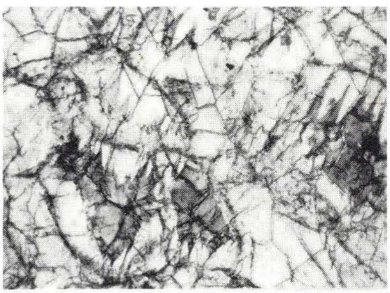
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Plate 3

Fig. 1. Biosparite with fragments of echinoderms, bryozoans, mollusks and serpulids and with intraclasts. The biosparite is unsorted and consists of some rounded particles and particles with microborings. Danian limestone. Thin section. Upper part of sample 030.

Fig. 2. Biosparite with skeletal fragments and intraclasts. The biosparite is sorted and consists of some rounded particles and particles with microborings. Danian limestone. Thin section. Lower part of sample 030.

Fig. 3. Echinoderm biomicrite with mud-supported bulk texture. Danian limestone. Thin section. Sample 047.

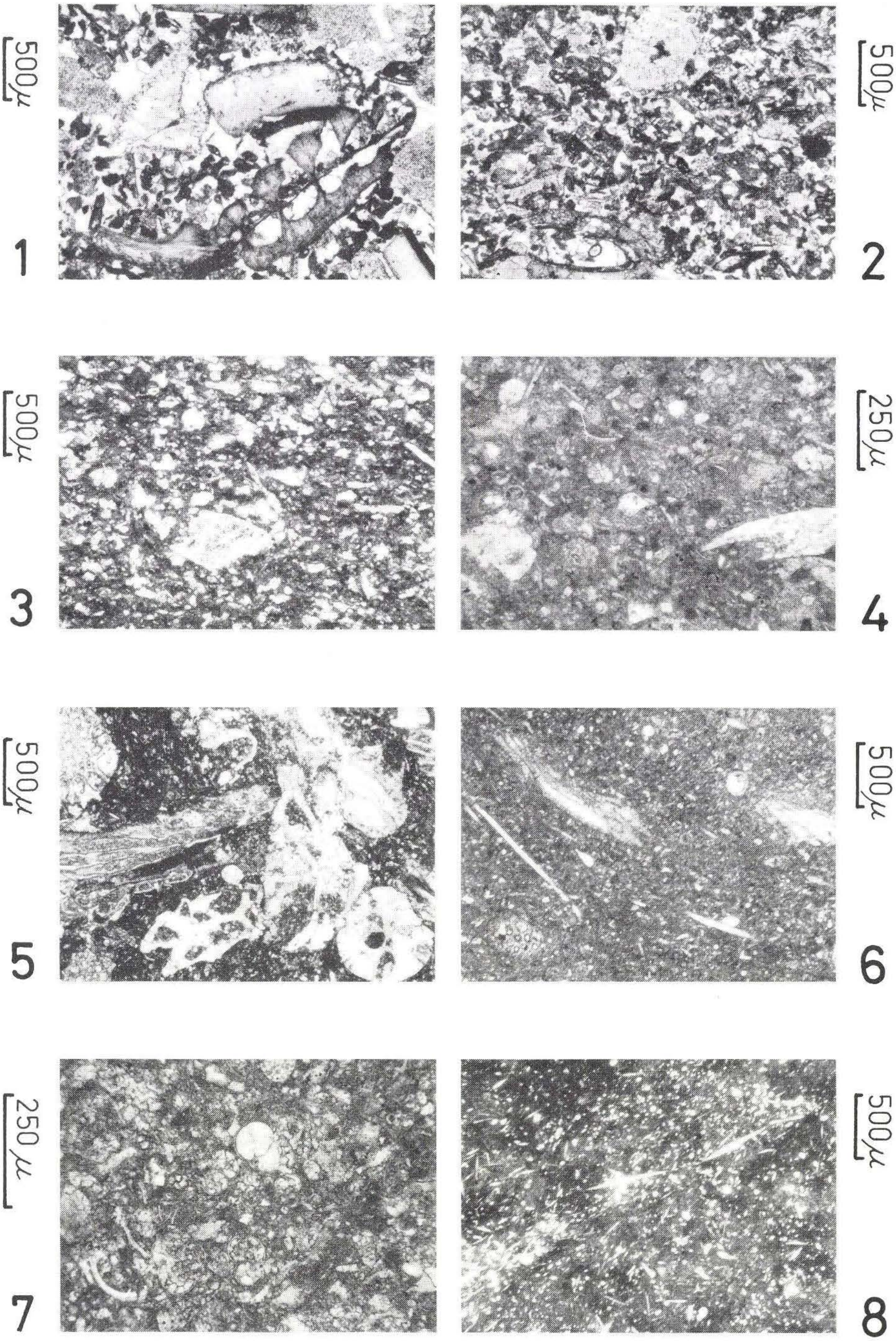
Fig. 4. Biomicrite with mud-supported bulk texture. Several particles show microborings, which are not seen on the photo. Danian limestone. Thin section. Sample 078.

Fig. 5. Bryozoan biomicrite with grain-mud-supported bulk texture. At left: cyclostome bryozoans with laminar layers. At right: cheilostome bryozoans with structureless skeletons. Danian limestone. Thin section. Sample 111.

Fig. 6. Bryozoan-sponge biomicrite with grain-supported bulk texture. Danian limestone. Thin section. Sample 114.

Fig 7. Foraminifera biomicrite with mud-supported bulk texture. Danian limestone. Thin section. Sample 123.

Fig. 8. Sponge-forminifera biomicrite with mud-supported bulk texture. Maastrichtian limestone. Thin section. Sample 126.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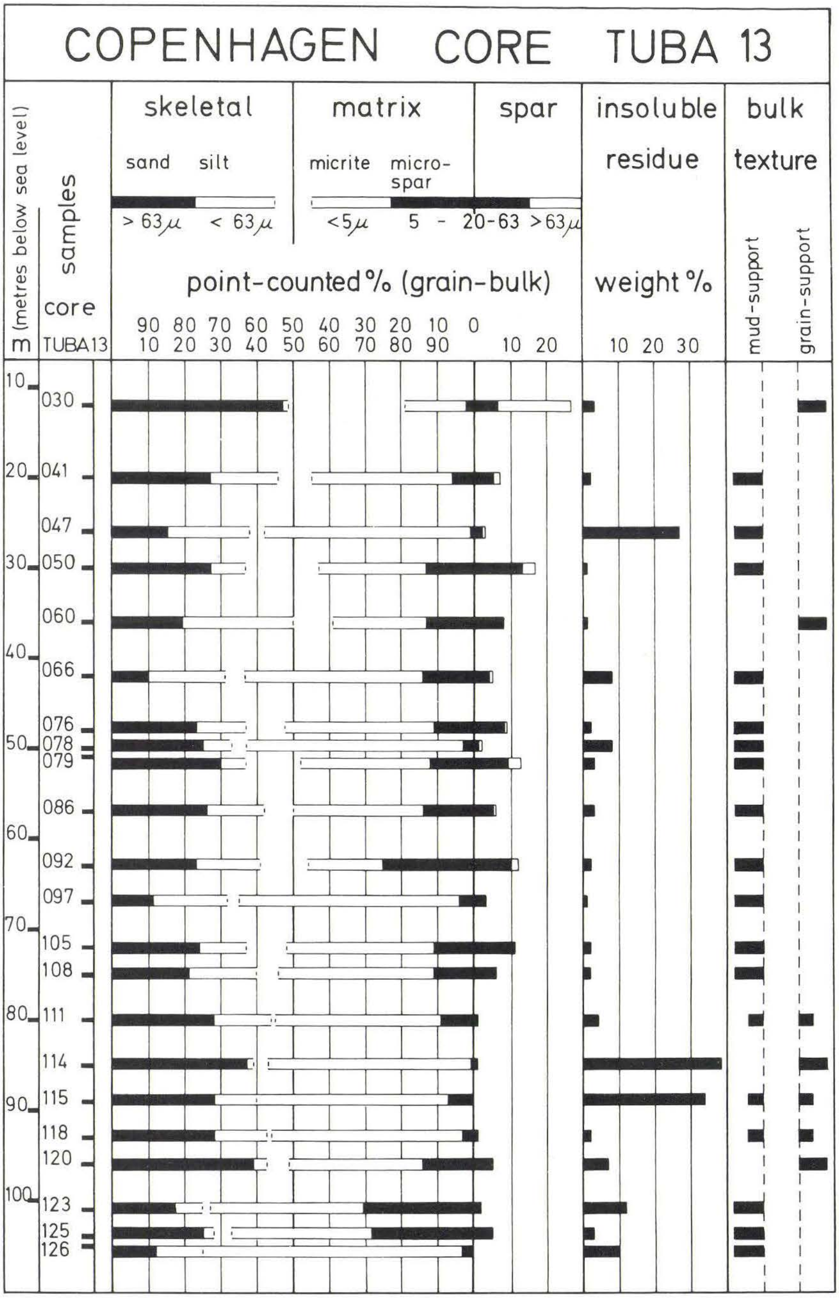
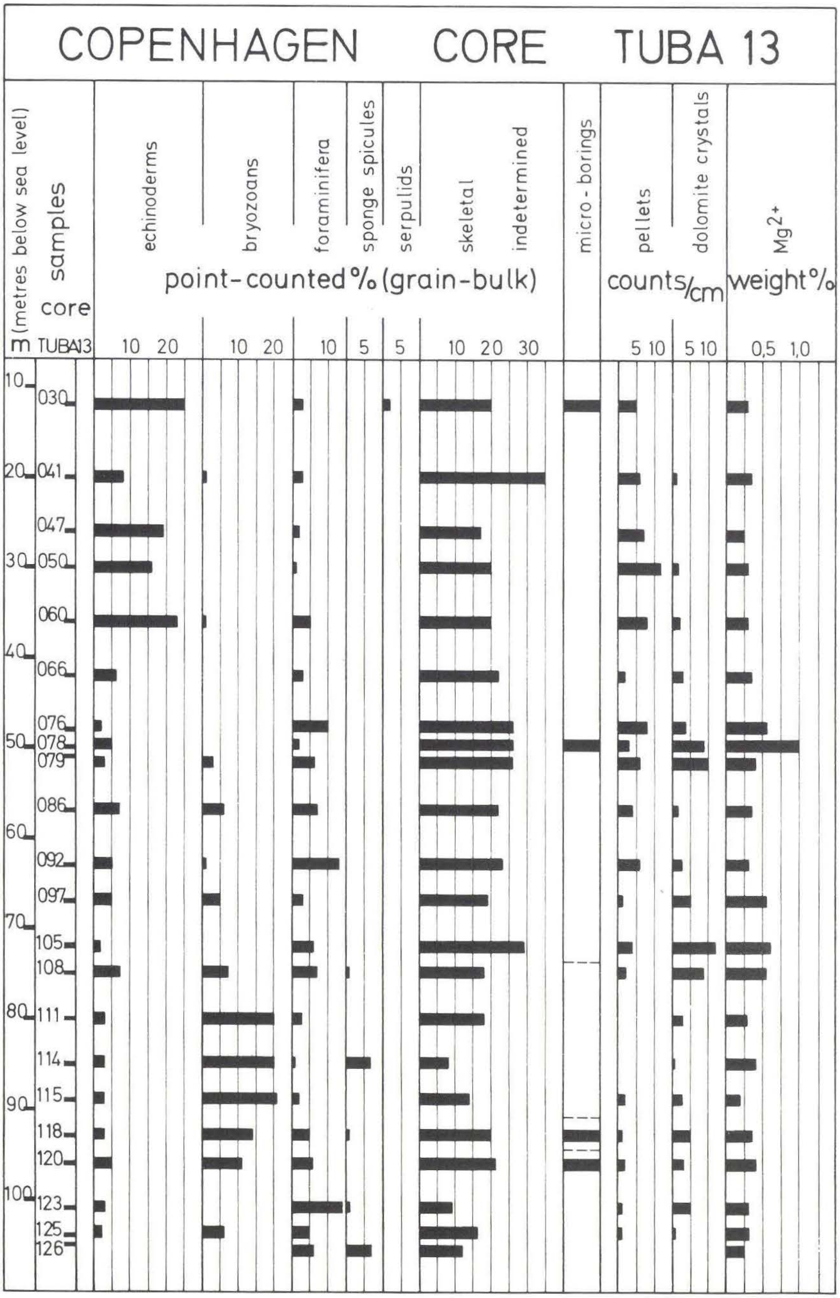


Petrographic data from some Maastrichtian and Danian limestones in the boring Copenhagen Core TUBA 13. Maastrichtian limestone: sample 126 – 125. Danian



limestone: the bryozoan limestone unit, sample 123 – 079, and the København Limestone, sample 078 – 030. The magnification used for identification was ×160.

ANDELSBOGTRYKKERIET
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