The middle Danian Faxe Formation – new lithostratigraphic unit and a rare taphonomic window into the Danian of Denmark

BODIL WESENBERG LAURIDSEN, MORTEN BJERAGER & FINN SURLYK

Lauridsen, B.W., Bjerager, M. & Surlyk, F. 2012. The middle Danian Faxe Formation – new lithostratigraphic unit and a rare taphonomic window into the Danian of Denmark. © 2012 by Bulletin of the Geological Society of Denmark, Vol. 60, pp. 47–60. ISSN 0011–6297 (www.2dgf.dk/publikationer/bulletin). https://doi.org/10.37570/bgsd-2012-60-04

The new middle Danian Faxe Formation is defined on the basis of the succession exposed in the large Faxe quarry in eastern Denmark. The formation is defined as a distinct mappable lithostratigraphic unit of interfingering coral and bryozoan limestone passing laterally into bryozoan limestones of the Stevns Klint Formation. The Baunekule facies is recognized in the upper part of the coral mound complex of the Faxe Formation, where it forms isolated lensoidal bodies in the flanks of some of the coral mounds. It is characterised by a high diversity invertebrate fauna with both calcite and originally aragonite-shelled benthic invertebrates set in weakly consolidated coral-dominated floatstone to rudstone. The diagenesis of the Baunekule facies is of special significance because a high proportion of the originally aragonite-shelled fauna is preserved by recrystallization to calcite during early burial diagenesis. More than 80% of the species from the Baunekule facies are unknown from other parts of the Faxe Formation. The carbonate mud matrix is only slightly consolidated and the invertebrate fossils are accordingly easy to prepare in contrast to the fossils from the lithified parts of the Faxe Formation, which are commonly only preserved as moulds or casts. The facies therefore presents an exceptional taphonomic window into a cold-water coral mound fauna, giving an unusually complete picture of the diversity and density of the shelly invertebrate fauna.

Keywords: Faxe Formation, Baunekule facies, Danian, Denmark, coral limestone, fossil invertebrates, taphonomy.

Bodil Wesenberg Lauridsen [Bodill@geo.ku.dk; bwl@geus.dk], Finn Surlyk [Finns@geo.ku.dk], Department of Geography and Geology, University of Copenhagen, Øster Voldgade 10, DK-1350 Copenhagen K, Denmark. Morten Bjerager [mbj@geus.dk], Geological Survey of Denmark and Greenland, Øster Voldgade 10, DK-1350 Copenhagen K, Denmark.

Received 7 February 2012
Accepted in revised form
10 September 2012
Published online
2 October 2012

A new kind of bryozoan biogenic mounds developed in the Danish Basin in the early Danian shortly after the mass extinction at the Cretaceous/Paleogene (K/T or K/PG) boundary (Thomsen 1995; Surlyk 1997; Surlyk *et al.* 2006; Bjerager & Surlyk 2007a, b; Nielsen *et al.* 2008). In the middle Danian a low diversity azooxanthellate scleractinian coral fauna started to form extensive cold-water coral mound complexes intercalated with bryozoan mounds (Cheetham 1971; Floris 1980; Bernecker and Weidlich 1990, 2005; Willumsen 1995; Bjerager *et al.* 2010). The coral mounds started to grow in relatively deep water below the photic zone over the easternmost part of the Ringkøbing-Fyn High only 2 myr after the mass extinction at the K/T boundary (Fig. 1).

The basal Danian Fiskeler Member and the overlying Cerithium Limestone Member of the Rødvig Formation are followed by bryozoan limestone of the Stevns Klint Formation, the København Limestone Formation, and the Selandian Lellinge Greensand Formation and its correlatives (Fig. 2; Surlyk *et al.* 2006). The cold-water coral mound complex exposed in the Faxe quarry in eastern Denmark is a distinct rock unit which is not included in the Stevns Klint Formation and is covered by the new Faxe Formation defined here (Fig. 2).

Other middle Danian cold-water coral mounds occur at Limhamn in southern Sweden (Brotzen 1959; Cheetham 1971; Holland and Gabrielson 1979). Danian coral limestones are known from boreholes in southern Sjælland and Sweden and are recognized in seismic sections and in cores in the Øresund region (Ødum 1928; Rosenkrantz 1937; Jakobsen *et al.* 1997; Bjerager *et al.* 2010). Framebuilding corals from West

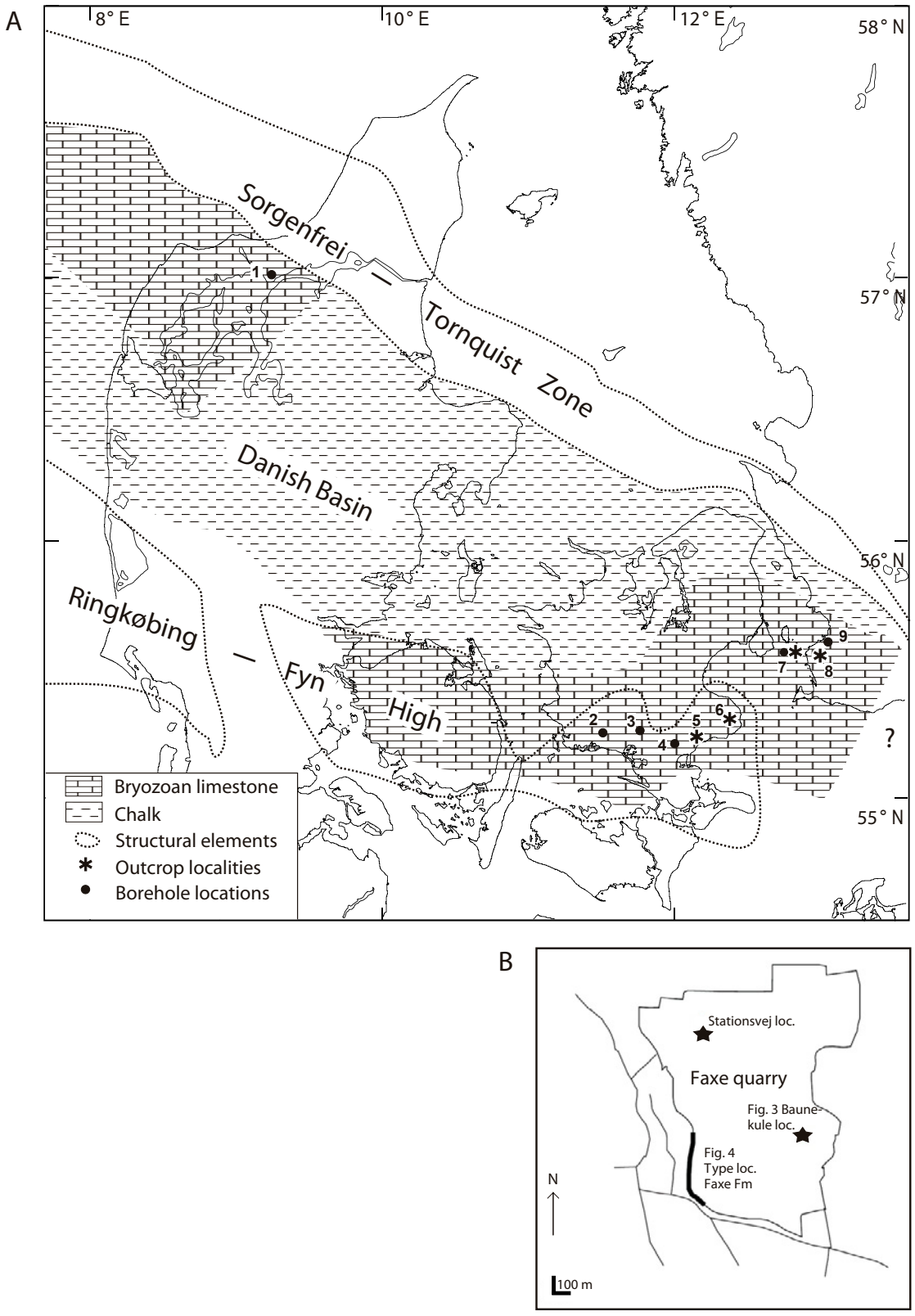

Fig. 1. **A**, Map of the Danish Basin with the main structural elements and distribution of middle Danian bryozoan limestone and chalk (coccolith zone 5 of Thomsen 1995). Locations of selected outcrops and boreholes where middle Danian coral limestone has been encountered: 1, Aggersborggaard; 2, Spjellerup; 3, Herlufsholm; 4, Everdrup; 5, Faxe quarry; 6, Stevns Klint; 7, Flinterenden-Trindelrenden, Øresund (both outcrop and boring); 8, Limhamn quarry; 9, Malmø. **B**, Map of Faxe quarry with the type section of the Faxe Formation and the position of the Baunekule facies indicated. Modified from Bjerager *et al.* (2010).

Greenland are of Danian age, but the dating is uncertain and based on bivalves (Floris 1972). They mainly occur in low monospecific thickets in tuff with only a very limited distribution, and without evidence of calcareous algae. The by far most extensive Danian mound complex is thus the one found in Faxe.

The lithological characteristics are key factors when defining a formation and according to articles 24e and 30f of the North American Stratigraphic Code (ACSN, 2005) a series of organic reefs and carbonate mounds can be distinguished formally as lithostratigraphic units if they are distinct from their surroundings and have a clear stratigraphic position. In that case the fossil content is a diagnostic lithologic property. This approach is followed here. The new Faxe Formation represents a mound complex with a faunal composition of mainly framebuilding corals markedly different from the Stevns Klint Formation which is predominantly composed of mound-forming bryozoans. The Baunekule facies defined here differs from the rest of the Faxe Formation with respect to its palaeontological composition and special diagenesis.

The aim of this study is to define the Faxe Formation as a new lithostratigraphic unit which passes laterally into the bryozoan limestone of the Stevns Klint Formation, to describe a special Baunekule facies, and to highlight the important taphonomic characteristics of this facies.

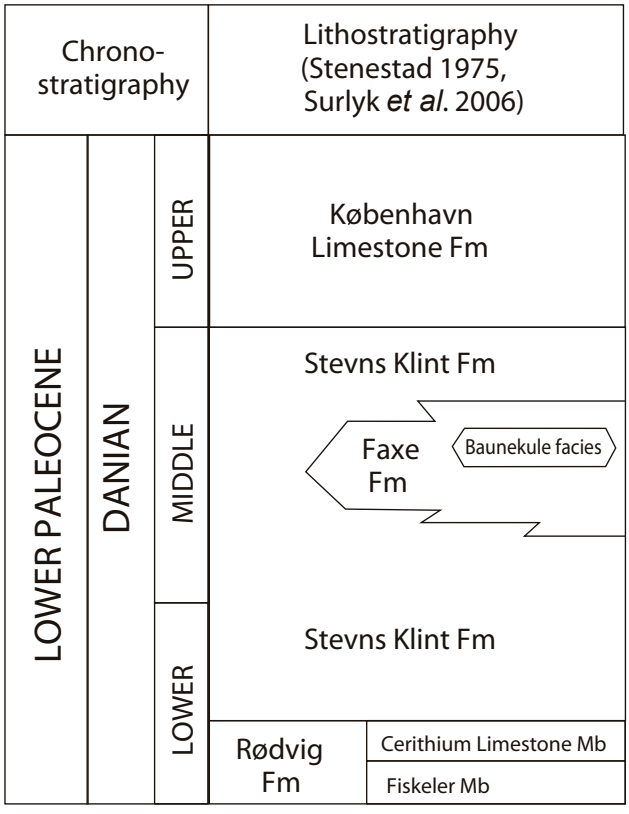

Fig. 2. Stratigraphic scheme of the Danian in the Danish Basin showing the position of the new Faxe Formation and Baunekule facies.

Faxe quarry

The middle Danian limestone exposed in the Faxe quarry represents an extraordinary preservation of a 63 Ma old cold-water coral mound complex (Fig. 1). Coral mounds occur intercalated with smaller bryozoan mounds and are exposed in mainly N–S and E–W oriented profiles. Bryozoan mounds dominate the stratigraphically lower parts and are overlain by interfingering coral and bryozoan mounds. The coral limestone is topped by an extensive hardground with pronounced topographic relief. Coarse-grained bryozoan grainstone rests locally directly on the hardground and fills fissures in the coral limestone (Willumsen 1995). The youngest preserved Danian deposits exposed in the northern end of the quarry are large-scale cross-bedded, flint-free and moderately sorted bryozoan skeletal packstone and grainstone.

The corals from Faxe are termed cold-water corals because they belong to the group of azooxanthellate corals which in modern settings live in cold and commonly deep waters. Their optimal environmental conditions in modern settings are sites with upwelling of cold waters, constant or periodic flow of water, hard substrate, and high zoo- and phytoplankton production in the surface waters. Cold-water corals are therefore commonly concentrated on ridges or rocky outcrops where currents are accelerated (Roberts *et al*. 2006). Modern cold-water coral mounds are long-lived structures where growth is balanced by (bio)erosion to form local topographic highs that alter the hydrodynamic and sedimentary regimes, trap sediment, and provide structural habitats for many other species (Roberts *et al*. 2009). Accordingly, cold-water coral mounds are topographic seafloor structures that have formed over long geological time spans through successive periods of individual mound development, deposition and (bio)erosion. The mound complexes typically contain stratified successions of mound deposits separated by non-mound deposits and erosion surfaces (Roberts *et al*. 2009).

The Faxe quarry exposes a large mound complex that includes individual coral mound bodies. The cold-water corals of the formation lived in a carbonate sedimentary regime devoid of hermatypic corals and algae, and non-skeletal chlorozoan grains are absent. The mound complex is dominated by the framebuilding scleractinian coral species *Dendrophyllia candelabrum* (Hennig 1899) with common *Faksephyllia faxoensis* (Lyell 1837) and a minor content of *Oculina becki* (Nielsen

1922). Modern *Dendrophyllia* and *Oculina* live in cold to cool and commonly deep oceanic waters (Freiwald *et al*. 2004). The modern cold-water corals are generally found in water depths of 50–1000 m at high latitudes and at depths down to 4000 m beneath warm water masses at low latitudes (Roberts *et al*. 2006). Species of *Dendrophyllia* are known to form mounds in the Mediterranean today (Zibrowius 1980) and modern *Oculina* mounds occur offshore Florida where they are believed to form the only extant deepwater *Oculina* mounds (Reed 2002). *Faksephyllia* is only known from the middle Danian of northern Europe (Floris 1980; Bernecker & Weidlich 1990, 2005) and the Danian of West Greenland (Floris 1972). The genus *Dendrophyllia* has been reported from the Upper Cretaceous (Baron-Szabo 2008). However, *D. candelabrum* was not mound-forming before the middle Danian. Other Late Cretaceous scleractinian framebuilding corals are rare and the Danian cold-water coral mound complex at Faxe is possibly the oldest and best developed mound complex of its kind.

A high diversity invertebrate fauna is associated with the coral mound complex of the Faxe Formation. The degree of preservation is extremely variable. In rare cases the aragonite-shelled fossils were, however, recrystallized to calcite during very early burial. Early in the 19th century J.P.J. Ravn found a specific facies which was later informally referred to as 'næsekalk' (nose limestone) because the main outcrop looked like Ravn's nose (Fig. 3). It is here termed the Baunekule facies and contains abundant solitary scleractinian corals and octocorals of the genus *Moltkia*. Framebuilding corals are rare with *Oculina becki* being the most prominent. In addition, the facies contains a high diversity and extremely well preserved fauna.

Most of the older studies are taxonomic descriptions of the rich fauna (Table 1), whereas only a few studies have dealt with the stratigraphy, sedimentology and palaeoecology of the coral mound complex in Faxe (Rosenkrantz 1937; Asgaard 1968; Floris 1972, 1980; Jørgensen 1988; Bernecker and Weidlich 1990, 2005; Willumsen 1995).

Table 1. List of publications dealing with the Faxe fauna; 10 out of the 55 publications are based solely on the fossils from the Baunekule facies. The full references are given in the reference list.

Class	Baunekule facies	Other facies in the Faxe Formation
Porifera		Ravn 1899; Nielsen 1929; Rasmussen 1973; Clausen 1982
Coelenterata	Nielsen 1919	Steenstrup 1847; Nielsen 1913b, 1917, 1922, 1925a; Voigt 1958; Bernecker & Weidlich 2006
Annwelida	Nielsen 1931	
Arthropoda		Darwin 1851; Nielsen 1912; Jakobsen 2003; Jakobsen & Feldmann 2004; Collins & Jakobsen 1994; Jakobsen & Collins 1997
Mollusca, Bivalvia	Ravn 1902a, 1933	Lundgren 1867
Mollusca, Gastropoda	Ravn 1902b, 1933; Schilder, 1928; Schnetler *et al.* 2001; Schnetler & Petit 2006	Lundgren 1867
Mollusca, Polyplacophora	Sigwart *et al.* 2007	
Bryozoa		Pergens & Meunier 1886; Levinsen 1925; Voigt 1923; Berthelsen 1962; Cheetham 1971
Brachiopoda	Nielsen 1911	Lundgren 1867; Posselt 1894; Nielsen 1909, 1914, 1921, 1928; Asgård; 1968, 1970
Echinodermata, Crinoidea and Asteroidea		Hennig 1899; Ravn 1904; Nielsen 1913a, 1943; Rasmussen 1950, 1961, 1972, 1973; Donovan & Jakobsen 2004; Wisshak *et al.* 2009
Echinodermata, Echinoidea		Nielsen 1925b; Ravn 1927, 1928; Brotzen 1959; Gravesen 1993

Fig. 3. View from the SE of the Faxe quarry showing the earliest recorded outcrop of the Baunekule facies, in the literature termed 'Ravns Næse'. The position of the outcrop is marked with an arrow. A horse is encircled for scale. The original picture is from Milthers (1908, his plate 31). Reproduced with permission from GEUS.

Lithostratigraphy

Faxe Formation

New formation

Name. After the type locality, the Faxe quarry, eastern Denmark.

History. The coral limestone of the Faxe Formation has been known for centuries due to the extensive quarrying. In old literature the limestone is referred to as "Faxe Kalk" (Faxe limestone) by Forchhammer (1825), Desor (1847), Johnstrup (1864), Fischer-Benzon (1866), Lundgren (1867) and Milthers (1908). The coral limestone complex is here formally described as a new formation with a prominent occurrence in the Faxe area. Lower to middle Danian bryozoan limestone exposed in the Limhamn quarry in southern Sweden was named the Limhamn Member of the Höllviken Formation in a geological map description (Sivhed *et al*. 1999). The member contains small coral mounds which are here referred to the Faxe Formation together with the interfingering bryozoan limestone. The type locality of the Faxe Formation is a Danish GeoSite and is publicly accessible. More information can be found at www.geosites.dk.

Faxe is the name of the adjacent town and the word Faxe (earlier also spelled Fakse or Faxae) means the mane of a horse. Quarrying has been ongoing since mediaeval times but there are no historical accounts on when the quarry started working. However, in many of the mediaeval churches and other buildings and constructions in the Faxe area, the hard coral limestone has been used as a building stone for the last 600 to 700 years (Gravesen 2001).

Type section. The type section is the protected N–S oriented quarry wall below Geomuseum Faxe in the SW part of the quarry. It is easily accessible and shows the main part of the formation (Figs 1 and 4).

Reference sections. The E–W oriented profile in the southern quarry wall shows the lower boundary of the formation and the initial stages of individual coral mound development. Additional reference sections are exposed in the NW part of the quarry (Fig. 1).

Thickness. Boreholes from the central part of the quarry demonstrate a total thickness of up to 45 m (Floris 1980), but only 25 m are exposed below the Quaternary erosion surface at the type section. Laterally the thickness decreases to a few metres over 3–5 km and the formation passes into the bryozoan limestone of the Stevns Klint Formation of Surlyk *et al*. (2006).

Lithology and palaeontology. The Faxe Formation consists of a number of different coral limestone facies and intercalated bryozoan limestone. The dominant biogenic mound-building facies with essentially in-place fossils include mainly coral rudstone to floatstone and bafflestone (Fig. 5). Associated facies comprise a wide range of fine to coarse grainstone, packstone, and wackestone. A distinct facies in the upper part of the formation composed of a slightly consolidated coral limestone with an unusually well preserved high-diversity invertebrate fauna is termed the Baunekule facies. The intercalated bryozoan limestone facies consists of rudstone, floatstone, packstone, and wackestone.

The degree of diagenesis varies throughout the formation from extensively diagenetically altered to almost unaffected coral limestone. Early diagenesis

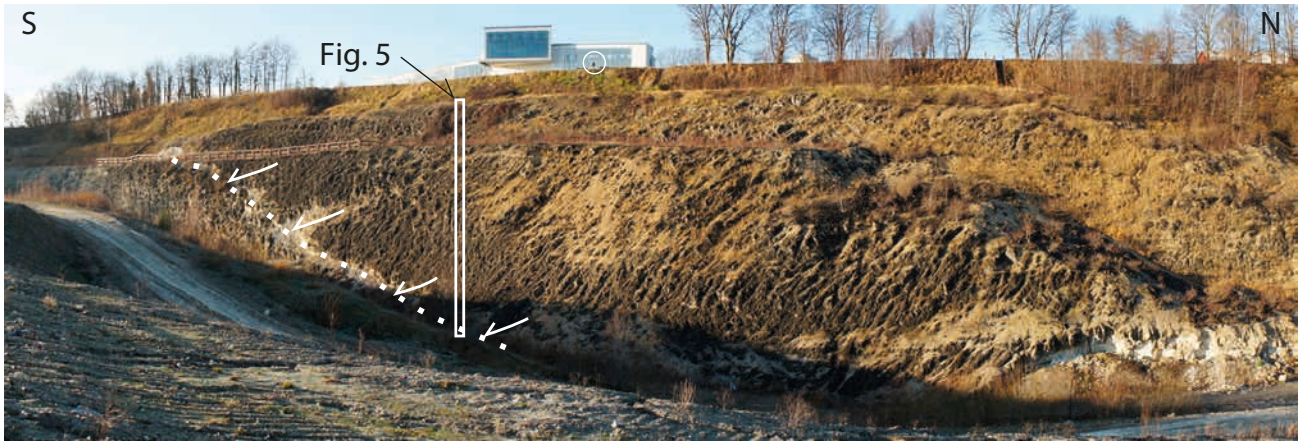

Fig. 4. Type section of the Faxe Formation in the western part of the Faxe quarry. The diachronous boundary (dotted line) between the bryozoan limestone to the left and the overlying coral limestone of the Faxe Formation is indicated. Arrows show the progressive downlap surfaces towards the south. Person is encircled for scale.

was characterised by dissolution of aragonite skeletons and associated calcite deposition and precipitation of matrix cement, cement rims, and interparticle and intraparticle replacement cements (Bernecker & Weidlich 1990; Willumsen 1995; Bjerager *et al.* 2010). Later diagenesis involved recrystallization of shells and hardening of the limestones. Diagenetically precipitated layers of flint nodules are common in the bryozoan limestones but absent from the coral limestone. In a few places meteoric quartz cement occurs in voids in the coral limestone.

The fauna of the coral limestone is dominated by the mound-forming corals *Dendrophyllia candelabrum*, *Faksephyllia faxoensis* and less common occurrences of *Oculina becki*. In addition, a rich benthic invertebrate fauna is associated with the mounds (Fig. 6). The preservation varies markedly due to large variations in diagenesis, resulting in dissolution or only rarely in recrystallization to calcite of aragonitic skeletons of corals, gastropods, bivalves, nautiloid cephalopods and annelids. These fossil groups are therefore mainly preserved either as moulds or casts. *D. candelabrum* and *F. faxoensis* are occasionally preserved in life position, whereas *O. becki* is only found as colony fragments. All corals had a bushy growth form and provided excellent habitats and feeding grounds for a large and diverse benthic invertebrate fauna. Attached brachiopods, bivalves, serpulids and moulds of decapods and gastropods are common.

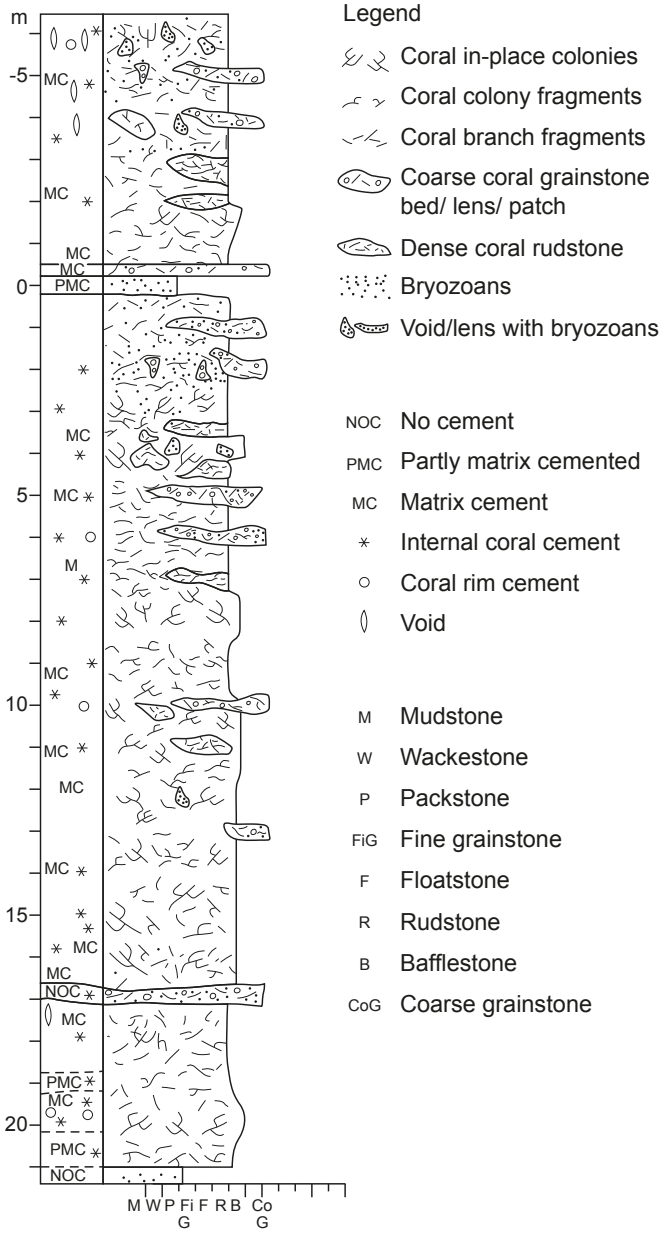

Fig. 5. Sedimentological log through the Faxe Formation at the type locality (Fig. 4). Left column shows diagenetic features and right column shows carbonate facies. The material collected at the type locality for this sedimentological log was difficult to access due to the steepness of the outcrop. At level 0 was a narrow path and material was collected below and above that plateau by rock climbing.

Boundaries. The lower boundary of the formation is situated at about 25 m above present day sea level in the western part of the quarry. However, elsewhere in the quarry the altitude ranges from -10 to +30 m above present day sea level. At the type section it is marked by the boundary between the bryozoan and coral limestone (Figures 4 and 5). In some areas the lower boundary shows a gradual transition from bryozoan-dominated to coral-dominated limestone. The upper boundary is placed at an erosional hardground overlain by bryozoan packstone and grainstone. This boundary is at present poorly exposed in the quarry, but is known from a profiles excavated in the northern part of the quarry present in the early 1990s and 2000s (Fig. 7).

Distribution. The formation is exposed in the Faxe area of Denmark and at Limhamn near Malmø in southern Sweden both in the eastern part of the Danish Basin (Fig. 1). It is recorded in boreholes and seismic profiles in Øresund offshore Malmø and along the northern margin of the Ringkøbing–Fyn High. The formation is contemporaneous with the middle Danian part of the Stevns Klint Formation and passes laterally into this formation in the Faxe area.

Chronostratigraphy. Middle Danian coccolith zones NP3 of Martini (1971), D5–6 of Perch-Nielsen (1979), 5 and lower part of 6 of Thomsen (1995) and NNTp3–NNTp4a of Varol (1998) (E. Sheldon and N. Thibault, personal communications 2011).

Baunekule facies

The Baunekule facies is known from the east central part of the Faxe quarry from four closely located sections at the old Baunekule quarry (Ravn 1903; Milthers 1908; Nielsen 1919; A. Rosenkrantz unpublished notes from the 1930s) and from the north-western part of the quarry (Fig. 7). It is considered to represent a stratigraphic level of isolated, unconsolidated units with unusually abundant and well preserved fossils.

Fig. 6. Fossils from the Faxe Formation in different modes of preservation. **A**, The scleractinian coral *Dendrophyllia candelabrum* in life position, covered with calcite crystals. Note the budding angle of 90º. There is no associated fauna between the branches. **B**, Moulds of *D. candelabrum* in life position. The moulds of the septae are easily recognised. Two small *Moltkia* (*Mo*) octocorals and external moulds of the bivalve *Barbatia* sp. (*Ba*) and the crab *Dromiopsis* sp. (*Dr*) are encircled. **C**, Only the casts of *D. candelabrum* are left and the associated fauna is dissolved or difficult to recognize. **D**, The scleractinian coral *Faksephyllia faxensis* partly recrystallized to calcite. Note the septae and the budding angle of 20° – 30° of the branches. **E**, The scleractinian coral *Oculina becki* showing a regular budding of branches with a constant spacing in two opposite rows. **F**, Mould of the decapod species *Dromiopsis rugosa (Dr).* **G**, Moulds of the bivalve *Protocardia vogeli*. **H**, The calcitic bivalve *Chlamys hennigi* (*Ch*) is well hidden between the branches of *D. candelabrum*. **I**, Casts of the boring *Entobia* formed by clionid sponges. Picture I is from Damholt and Rasmussen (2005) and is reproduced with permission from Østsjællands Museum.

The variations in the faunal content of the individual occurrences are minor. The facies is named after the position of the first outcrop of the facies close to an old small quarry, Baunekule, which today is part of the large Faxe quarry.

The facies and the well preserved fossils were first described by Ravn (1903 p. 86), and the locality and the name 'næsekalk' were discussed by Nielsen (1919, p. 5). The photograph of the section (Fig. 3) was also published by Nielsen (1919, fig. 1). The old profile described by Ravn has now disappeared due to quarrying, probably sometime during the 1930s or 1940s (Fig. 7). Stratigraphic logs of the old sections are not known. However, the Baunekule facies has later been recorded in Faxe in the 1970s from a locality in the east-central part of the quarry just below that part of the road Stationsvej which is now quarried away. The Stationsvej section was recorded by Sten Lennart Jakobsen and Søren Bo Andersen and later exposed again at more or less the same location in the early 1990s. Material from this outcrop was sampled by Mads Willumsen and Alice Rasmussen (Figures 7, 8) close to profile M of Bernecker and Weidlich (1990). The thickness of the facies has not been recorded, but at the Stationsvej locality the lens was about 1 m thick and 7 m long (Fig. 8).

The facies consists of isolated lensoidal bodies in the flanks of the coral mounds, of weakly consolidated coral rudstone to floatstone, with a well preserved, high diversity calcitic and recrystallized, formerly aragonitic fauna. The facies was relatively matrix-poor in the lower part with upward increasing matrix

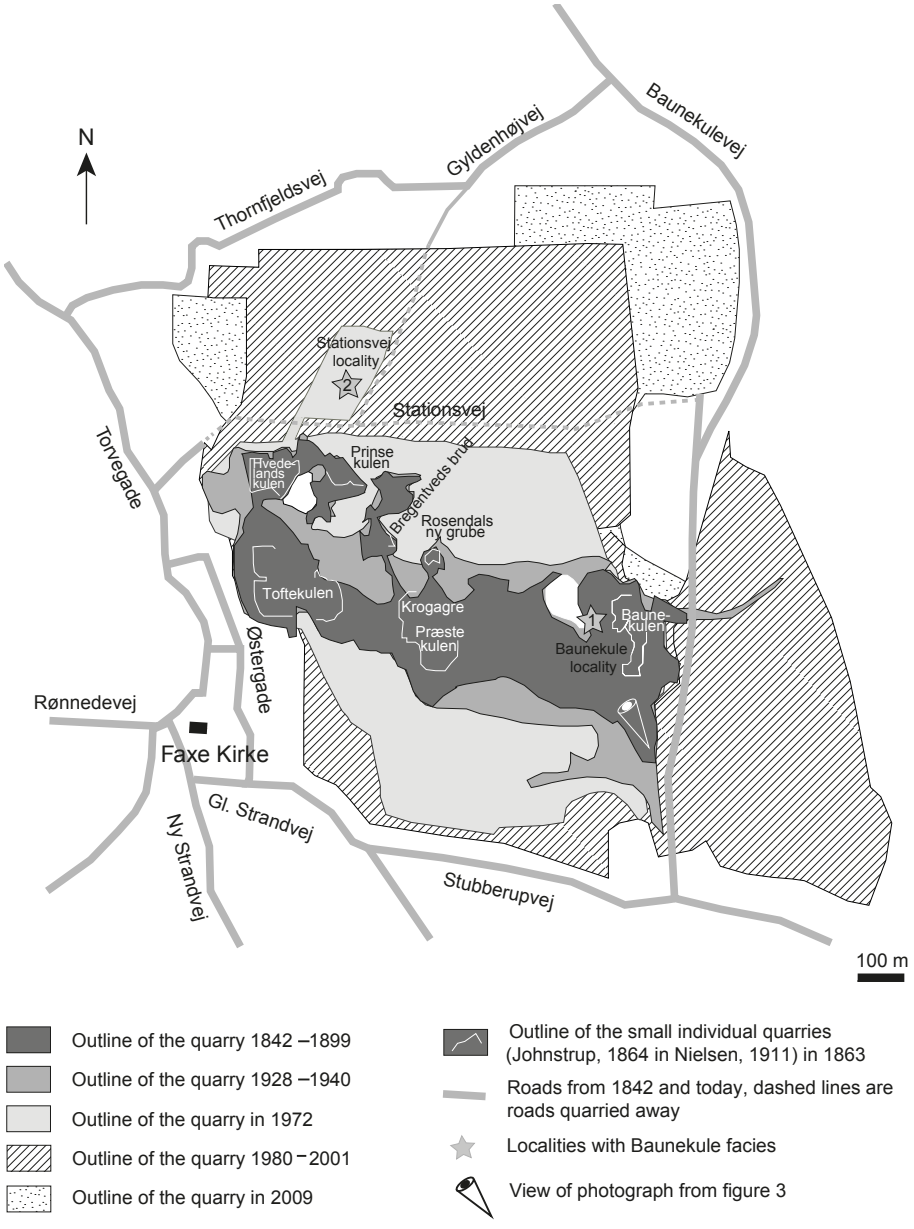

Fig. 7. Map showing the historical development of the quarry and positions of the Baunekule locality (asterisk 1) and the Stationsvej locality (asterisk 2) where the Baunekule facies previously cropped out. The quarry has been active since mediaeval times. In the first many hundred years quarrying took place in small individual pits with different owners and names and the outlines of the pits are marked with white lines. Their positions are from Nielsen (1911).

content. In addition it showed an upwards gradually increasing cementation of the limestone with increasing dissolution of aragonite-shelled fossils. Flint nodules are absent.

The diagenesis of the facies is of special importance as early burial diagenesis resulted in preservation of many of the aragonitic faunal elements by recrystallization to calcite prior to the precipitation of high Mg-calcite cement (Fig. 9). The carbonate mud matrix is only slightly consolidated and the macro- and microfossils are accordingly easy to prepare out in contrast to the fossils from the lithified part of the Faxe Formation. More than 25 000 invertebrate fossils have been collected at the Stationsvej locality, representing at least 300 species. The 12 most common species are shown in Fig. 10. Approximately 60% of the identified species were originally aragonite-shelled, 18% were originally calcitic, 15% were originally a mixture of aragonite and calcite, and the remaining 7% had either phosphatic or unknown shell material. At present no systematic information is available on the dominance of aragonite- versus calcite-shelled species living on modern cold-water coral mounds (André Freiwald, personal communication 2011).

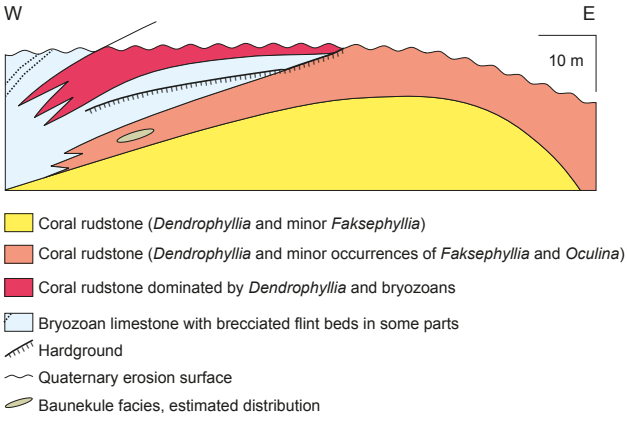

Fig. 8. Sketch of the 1970–1990 Stationsvej locality with the occurrence of the Baunekule facies and section M of Bernecker and Weidlich (1990) and Willumsen (1995). The section was approximately 20 m high, subvertical with an almost E–W orientation. Toward the west it is terminated by a fairly wide, glacially faulted crush zone, containing bryozoan limestone and deformed flint bands. The eastern boundary is placed in a more or less homogeneous coral limestone with no internal structures (modified from Willumsen 1995). Glacial tectonics has exaggerated the flank dips of the mounded structure.

The fossils found in the facies represent a wide range of modes of life and trophic levels. The corals are dominated by species of the octocoral *Moltkia* and by scleractinian solitary coral species of *Parasmilia*. Originally aragonitic stylasterine hydrocorals are also rather common in spite of their very low fossilisation potential. Framebuilding corals are rare and at the Baunekule locality the most common species is *Oculina becki*. Most of the colonial corals are fragmented and no corals have been found in life positions. The originally aragonitic corals have many delicate structures preserved and the associated originally aragonite-shelled fauna provides a rare taphonomic window into the past ecosystem. This is exemplified by the high abundance of millimetre-sized gastropods representing up to about 200 different species. In other parts of the Faxe Formation the small gastropods are only found as rare moulds or casts that are almost impossible to identify to species or even to genus level.

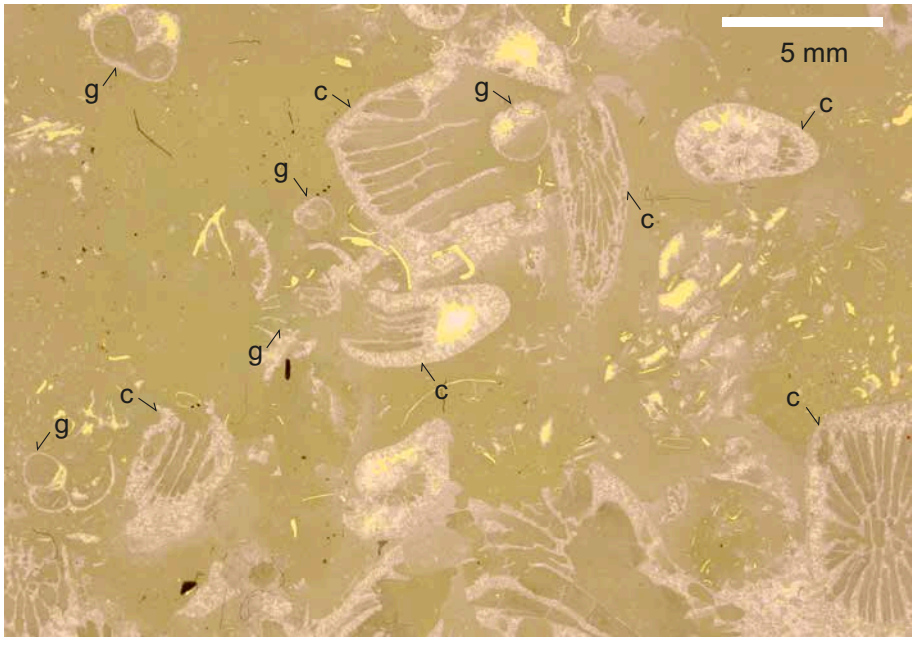

Fig. 9. Thin section of Baunekule facies from the Stationsvej locality. The original aragonite shells of corals (c) and gastropods (g) are recrystallized into calcite.

Infaunal bivalves are also common. Fragile specimens of Aristotle's lantern from regular echinoids and jaw pieces from nereid polychaetes show that the fauna is autochthonous.

The Baunekule facies at the Stationsvej locality and the adjacent hard coral limestone show similar nannofossil ages. The diversity of nannofossils is very low; *Sullivania danica* is very common and *Coccolithus pelagicus* and a few poorly preserved *Praeprinsius tenuiculus* are present, suggesting that the facies belongs to the middle Danian (N. Thibault, personal communication 2011).

Conclusion

The Baunekule facies is important as it preserves an exceptional and high-diversity, originally aragonite-shelled fauna of the middle Danian cold-water coral mound complex of the new Faxe Formation. More than 80% of the species from the mound complex are only known from these relatively thin and isolated lensoidal units that flank the individual mounds in the upper part of the complex. The well preserved invertebrate fauna recorded from the facies shows a very high diversity of more than 300 species in a lim-

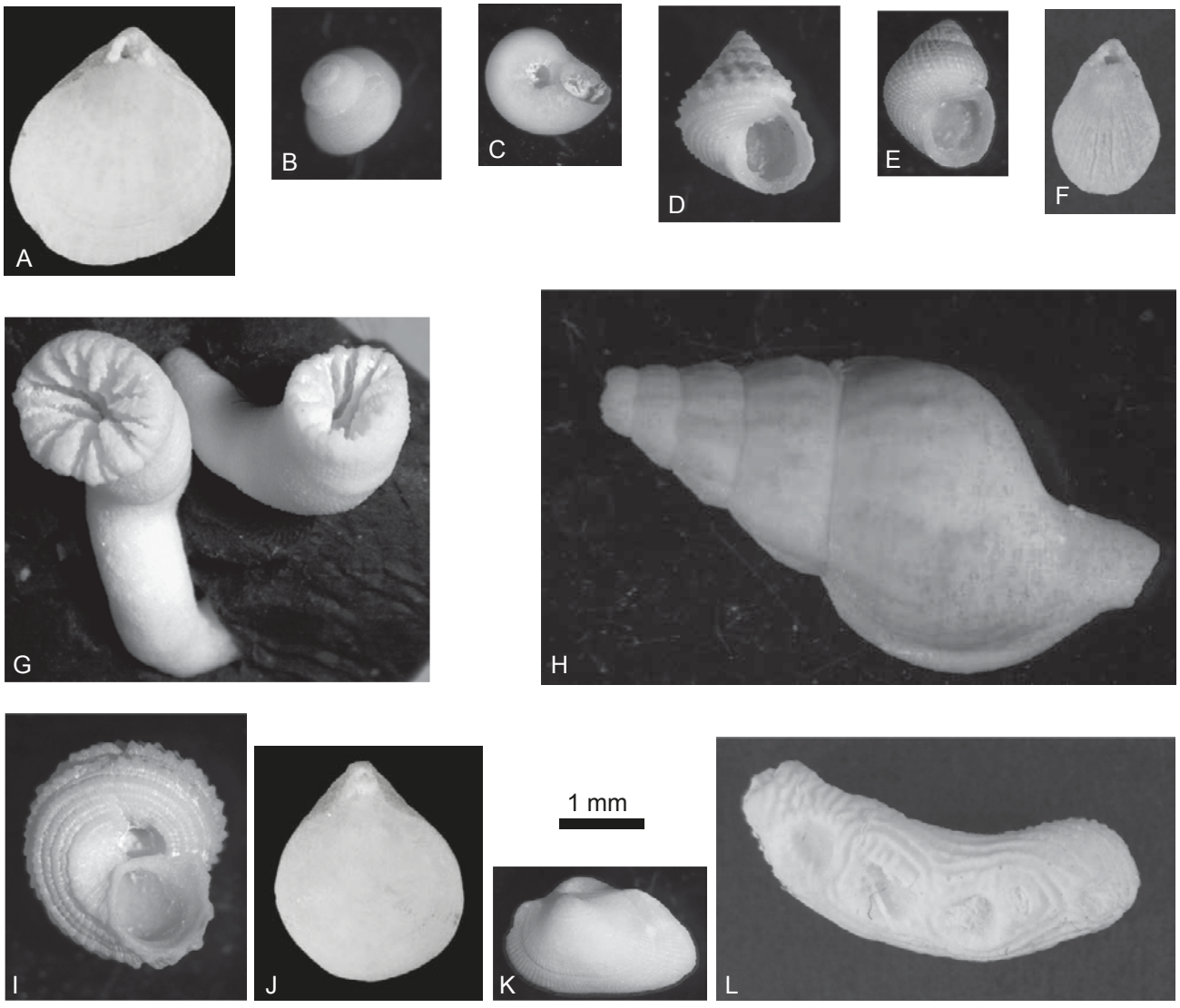

Fig. 10. The 12 most common species from the Baunekule facies. The species highlighted in bold below were originally aragonitic. Note the excellent preservation of the gastropods and corals. **A**, The brachiopod "*Rhynchonella*" *flustracea*. **B**, the gastropod ***Monodonta carinata***. **C**, the gastropod ***Collonia pusilla***. **D**, the gastropod ***Monodonta faxensis***. **E**, the gastropod ***Monodonta fenestra***. **F**, the brachiopod *Terebratulina chrysalis*. **G**, the coral ***Parasmilia elongata***. **H**, the gastropod ***Buccinofusus parvus***. **I**, the gastropod ***Delphinula depressa***. **J**, the brachiopod "*Rhynchonella*" *faxensis*. **K**, the bivalve ***Meiocardia faxensis***. **L**, the coral *Moltkia isis*.

ited stratigraphic interval. This is attributed to special diagenetic conditions which resulted in preservation by recrystallization of the originally aragonite-shelled fauna without cementation of the surrounding matrix. In contrast, other parts of the coral mound complex of the Faxe Formation show a relatively low diversity of the associated fauna.

Dansk sammendrag

En ny mellem Danien litostratigrafisk enhed, Faxe Formationen, er opstillet, og en særlig facies, Baunekule facies, i formationen er beskrevet. Den nye Faxe Formation er en markant enhed, der er nem at kortlægge og repræsenterer et velbevaret kompleks af fossile koldtvandskoralbanker og -bryozobanker. Formationen går lateralt over i mellem Danien bryozokalk tilhørende Stevns Klint Formationen. Faxe Formationen består hovedsaglig af hærdnet koralkalksten af primært scleractine rammebyggende koraller med matriks af karbonatmuddersten samt af mindre dominerende forekomster af ukonsolideret koralkalk primært bestående af oktokoraller. Baunekule facies er i den ældre litteratur benævnt 'næsekalk'. Den findes i den øvre del af Faxe Formationen, hvor den forekommer som isolerede linseformede legemer i koralbankernes flanker. Baunekule facies består af svagt konsolideret koraldomineret floatstone til rudstone og er kendetegnet af en artsrig fauna med velbevarede kalcitskallede og oprindelig aragonitskallede bentiske invertebrater. Denne facies har gennemgået en markant anderledes diagenetisk historie end de øvrige dele af Faxe Formationen. Mere end 80% af faunaen i Baunekule facies er ikke kendt fra andre dele af Faxe Formationen. Denne facies repræsenter derfor et enestående tafonomisk vindue til en stor gruppe af aragonitskallede invertebrater, der levede på det fossile bankekompleks.

Acknowledgements

This study forms part of a Geocenter Denmark project. Support from the Carlsberg Foundation is gratefully acknowledged. BWL thanks the Science International Stipends from the University of Copenhagen for financing a six month visit as a guest researcher studying modern cold-water corals at Senckenberg am Meer, Wilhelmshaven. André Freiwald is thanked for sharing his great knowledge of the modern cold-water coral mounds. Alice, Henning and Leif Rasmussen are thanked for access to their large collection of fossils from the Baunekule facies and for numerous discussions on the fossils from Faxe. Sample material and information from the Stationsvej locality has kindly been provided by Sten L. Jakobsen, Søren B. Andersen and Mads Willumsen. Nicolas Thibault and Emma Sheldon are thanked for nannofossil dating. Faxe Kalk A/S is thanked for access to the quarry. We are grateful to journal reviewers Jon Ineson and Peter Scholle for their constructive comments.

References

ACSN (American Commission on Stratigraphic Nomenclature) 2005: North American stratigraphic code. AAPG Bulletin 89, 1547–1591.

Asgaard, U. 1968: Brachiopod palaeoecology in middle Danian limestones at Fakse, Denmark. Lethaia 1, 103–121.

Asgaard, U. 1970: The syntypes of *Carneithyris incisa* (Buch, 1835). Bulletin of the Geological Society of Denmark 19, 361–367.

Baron-Szabo, R.C. 2008: Corals of the K/T-boundary: Scleractinian corals of the suborders Dendrophylliina, Carophylliina, Fungiina, Microsolenina, and stylinina. Zootaxa 1952, 244 pp.

Bernecker, M. & Weidlich, O. 1990: The Danian (Paleocene) coral limestone of Fakse, Denmark; a model for ancient aphotic, azooxanthellate coral mounds. Facies 22, 103–138.

Bernecker, M. & Weidlich, O. 2005: Azooxanthellate corals in the Late Maastrichtian – Early Paleocene of the Danish basin: bryozoan and coral mounds in a boreal shelf setting. In: Freiwald, A. & Roberts, J.M. (eds): Cold-Water Corals and Ecosystems. Springer-Verlag, Berlin and Heidelberg, 3–25.

Bernecker, M. & Weidlich, O. 2006: Paleocene bryozoan and coral mounds of Fakse, Denmark: Habitat preferences of isidid octocorals. Courier Forschungsinstitut Senckenberg 257, 7–20.

Berthelsen, O. 1962: Cheilostome Bryozoa in the Danian deposits of East Denmark. Danmarks Geologiske Undersøgelse II. Række 82, 290 pp.

Bjerager, M. & Surlyk, F. 2007a: Benthic palaeoecology of Danian deep-shelf bryozoan mounds in the Danish Basin. Palaeogeography, Palaeoclimatology, Palaeoecology 250, 184–215.

Bjerager, M. & Surlyk, F. 2007b: Danian cool-water bryozoan mounds at Stevns Klint, Denmark – a new class of non-cemented skeletal mounds. Journal of Sedimentary Research 77, 634–660.

Bjerager, M., Surlyk, F., Lykke-Andersen, H., Thibault, N. & Stemmerik, L. 2010: Danian cool-water coral reefs in southern Scandinavia localised over seafloor highs. Marine and Petroleum Geology 27, 455–466.

Brotzen, F. 1959: On *Tylocidaris* species (Echinoidea) and the stratigraphy of the Danian of Sweden. Sveriges Geologiska Undersökning Serie C 571, Årsbok 54, 1–81.

Cheetham, A.H. 1971: Functional morphology and biofacies distribution of cheilostome Bryozoa in the Danian Stage (Paleocene) of southern Scandinavia. Smithsonian Contributions to Paleobiology 6, 52 pp.

Clausen, C.K. 1982: *Wienbergia*, new genus for *Barroisia faxensis* (Porifera: Demospongea) from the Middle Danien of Denmark. Bulletin of the Geological Society of Denmark 30, 111–115.

Collins, J.S.H. & Jakobsen, S.L. 1994: A synopsis of the biostratigraphic distribution of the crab genera (Crustacea, Decapoda) of the Danian (Palaeocene) of Denmark and Sweden. Bulletin of the Mizunami Fossil Museum 21, 35–46.

Damholt, T. & Rasmussen, A. 2005: Fossiler fra Faxe Kalkbrud. Østsjællands Museum, 44 pp.

Darwin, C. 1851: A Monograph on the Fossil Lepadidae, or, Pedunculated Cirripedes of Great Britain. London. The Palaeontographical Society, 88 pp.

Desor, E. 1847: Sur le terrain Danien, nouvel étage de la craie. Bulletin de la Societé geologique de la France, Série 2, 4, 179–182.

Donovan, S.K. & Jakobsen, S.L. 2004: An unusual crinoid–barnacle association in the type area of the Danian (Paleocene, Denmark). Lethaia 37, 407–415.

Fischer-Benzon, R. von 1866: Ueber das relative Alter des Faxekalkes und über die in demselben vorkommenden Anomuren und Brachyuren. Kiel Schwers'sche Buchhandlung, 30 pp.

Floris, S. 1972: Scleractinian corals from the Upper Cretaceous and Lower Tertiary of Nûgssuaq, West Greenland. Bulletin Grønlands Geologiske Undersøgelse 100, 1–132.

Floris, S. 1980: The coral banks of the Danian of Denmark. Acta Palaeontologica Polonica 25, 531–540.

Forchhammer, J.G. 1825: Om de geognostiske Forhold i en Deel af Sielland og Naboeöerne. Det Kongelige Danske Videnskabernes Selskab, Physiske og Mathematiske Skrifter II. Deel, 248–280.

Freiwald, A., Fosså, J.H., Grehan, A., Koslow, T. & Roberts, J.M. 2004: Cold-water Coral Reefs. UNEP-World Conservation Monitoring Centre, Cambridge, UK, 86 pp.

Gravesen, P. 1993: Early Danian species of the echinoid genus *Tylocidaris* (Cidaridae, Psychocidarinae) from eastern Denmark. Contributions to Tertiary and Quaternary Geology 30, 41–73.

Gravesen, P. 2001: Den geologiske udforskning af Fakse Kalkbrud fra midten af 1700-tallet til nu. Geologisk Tidsskrift 2001, 2, 1–40.

Hennig, A. 1899: Studier öfver den baltiska Yngre kritans bildningshistoria. Geologiska Föreningens i Stockholm Förhandlingar 21, 19–82 and 133–188.

Holland, B. & Gabrielson, J. 1979: Guide to Limhamn quarry. In: Birkelund, T. & Bromley, R.G. (eds): Cretaceous–Tertiary Boundary Events, Symposium. 1. The Maastrichtian and Danian of Denmark, 142–151. University of Copenhagen.

Jakobsen, P.R., Wilken, U.G. & Lund, N.S. 1997: Feltrapport over dykkergeologisk undersøgelse af udgravninger i Øresund. Danmarks og Grønlands Geologiske Undersøgelse Rapport 150, 1–55.

Jakobsen, S.L. 2003: A new preparatory approach of decapods and thoracian crustaceans from the middle Danian at Fakse, Denmark. Contributions to Zoology 70, 141–145.

Jakobsen, S.L. & Collins, J.S.H. 1997: New middle Danian species of anomuran and brachyuran crabs from Fakse, Denmark. Bulletin of the Geological Society of Denmark 44, 89–100.

Jakobsen, S.L. & Feldmann, R.M. 2004: Epibionts on *Dromiopsis rugosa* (Decapoda: Brachyura) from the late middle Danian limestones at Fakse Quarry Denmark: Novel preparation techniques yield amazing results. Journal of Paleontology 78, 953–960.

Johnstrup, F. 1864: Faxekalkens Dannelse og senere undergaaede Forandringer. Det Kongelige Danske Videnskabernes Selskabs Skrifter 5. Række, Naturvidenskabelig og Mathematisk Afdeling 7, 1–46.

Jørgensen, N.O. 1988: Dolomite and dedolomitization in Danian bryozoan limestone from Fakse, Denmark. Bulletin of the Geological Society of Denmark 37, 63–74.

Levinsen, G.M.R. 1925: Undersøgelser over Bryozoerne i den danske Kridtformation. Det Kongelige Danske Videnskabernes Selskabs Skrifter 8. Række, Naturvidenskabelig og Mathematisk Afdeling 7, 3, 281–445.

Lundgren, B. 1867: Palaeontologiska iakttagelser öfver Faxekalken på Limhamn. Lunds Universitets Årsskrift 1867, 1–31.

Lyell, C. 1837: On the Cretaceous and Tertiary Strata of the Danish Islands of Seeland and Moen. Transactions of the Geological Society of London 6, 243–257.

Martini, E. 1971: Standard Tertiary and Quaternary calcareous nannoplankton zonation. In: Farinacci, A. (ed.): Proceedings 2nd International Conference Planktonic Microfossils, Roma, 739–785.

Milthers, V. 1908: Kortbladene Faxe og Stevns Klint. Beskrivelse til geologiske Kort over Danmark. Danmarks Geologiske Undersøgelse 1. Række 11, 1–291.

Nielsen, K.B. 1909: Brachiopoderne i Danmarks Kridtaflejringer. Det Kongelige Danske Videnskabernes Selskabs Skrifter 6. Række, Naturvidenskabelig og Mathematisk Afdeling 4, 127–178.

Nielsen, K.B. 1911: Brachiopoderne i Faxe. Meddelelser fra Dansk Geologisk Forening 3, 599–618.

Nielsen, K.B. 1912: Cirripederne i Danmarks Danien aflejringer. Meddelelser fra Dansk Geologisk Forening 4, 19–42.

Nielsen, K.B. 1913a: Crinoiderne i Danmarks Kridtaflejringer. Reitzel, København. 113 pp.

Nielsen, K.B. 1913b: *Moltkia isis*, Steenstrup, og andre Octocorallia fra Danmarks Kridttidsaflejringer. Særtryk af Kap. XVIII i Mindeskrift for Iapetus Steenstrup, 1–19.

Nielsen, K.B. 1914: Some remarks on the brachiopods of the chalk in Denmark. Meddelelser fra Dansk Geologisk Forening 4, 287–296.

Nielsen, K.B. 1917: *Heliopora incrustans* nov. sp. with a survey of the Octocorallia in the deposits of the Danian in Denmark. Meddelelser fra Dansk Geologisk Forening 5, 8, 1–13.

Nielsen, K.B. 1919: En Hydrocoralfauna fra Faxe. Meddelelser fra Dansk Geologisk Forening 5, 16, 5–63.

Nielsen, K.B. 1921: Nogle Bemærkninger om de store Terebratler i Danmarks Kridt- og Danienaflejringer. Meddelelser fra Dansk Geologisk Forening 6, 3, 1–18.

Nielsen, K.B. 1922: Zoantharia from Senone and Paleocene Deposits in Denmark and Skaane. Det Kongelige Danske Videnskabernes Selskabs Skrifter 8. Række, Naturvidenskabelig og Mathematisk Afdeling 3, 199–233.

Nielsen, K.B. 1925a: Nogle nye Octocoraller fra Danienet. Meddelelser fra Dansk Geologisk Forening 6, 28, 1–6.

Nielsen, K.B. 1925b: Nogle Echinidrester fra Danmarks Senon og Danien. Meddelelser fra Dansk Geologisk Forening 6, 29, 1–10.

Nielsen, K.B. 1928: *Argiope*-Arterne i Danmarks senone, daniske og paleocæne Aflejringer. Meddelelser fra Dansk Geologisk Forening 7, 215–226.

Nielsen, K.B. 1929: Kalksvampe i Danmarks Senonium og Danium. Meddelelser fra Dansk Geologisk Forening 7, 323–342.

Nielsen, K.B. 1931: Serpulidae from the Senonian and Danian deposits of Denmark. Meddelelser fra Dansk Geologisk Forening 8, 71–113.

Nielsen, K.B. 1943: The Asteroids of the Senonian and Danian deposits of Denmark. Det Kongelige Danske Videnskabernes Selskab, Biologiske Skrifter 2, 68 pp.

Nielsen, L., Brockdorff, A.S. von, Bjerager, M. & Surlyk, F. 2008: Reconstructing three dimensional architecture and development of Danian bryozoan mounds at Limhamn, southwest Sweden, using ground penetrating radar. Sedimentology 56, 695–708.

Perch-Nielsen, K. 1979: Calcareous nannofossil zonation at the Cretaceous–Tertiary boundary in Denmark. In: Birkelund, T. & Bromley, R.G. (eds): Cretaceous–Tertiary Boundary Events. Symposium. 1. The Maastrichtian and Danian of Denmark, 115–135. University of Copenhagen.

Pergens, É. & Meunier, A. 1886: La Faune des Bryozoaires Garumniens de Faxe. Annales de la Société Royale Malacologique de Belgique, 187–242.

Posselt, H.J. 1894: Brachiopoderne i den danske Kridtformation. Danmarks Geologiske Undersøgelse II Række 4, 59 pp.

Rasmussen, H.W. 1950: Cretaceous Asteroidea and Ophiuroidea with special reference to the species found in Denmark. Danmarks Geologiske Undersøgelse II. Række 77, 134 pp.

Rasmussen, H.W. 1961: A monograph on the Cretaceous Crinoidea. Det Kongelige Danske Videnskabernes Selskab, Biologiske Skrifter 12, 1, 428 pp.

Rasmussen, H.W. 1972: Lower Tertiary Crinoidea, Asteroidea and Ophiuroidea from Northern Europe and Greenland. Det Kongelige Danske Videnskabernes Selskab, Biologiske Skrifter 19, 7, 83 pp.

Rasmussen, H.W. 1973: En lyssky hulefauna fra Fakse som vidnesbyrd om koralkalkens dannelse i lyszonen. Dansk Geologisk Forening Årsskrift 1972, 87–91.

Ravn, J.P.J. 1899: Et par danske Kridtspongier. Meddelelser fra Dansk Geologisk Forening 1, 23–30.

Ravn, J.P.J. 1902a: Molluskerne i Danmarks Kridtaflejringer. I Lamellibranchiater. Det Kongelige Danske Videnskabernes Selskabs Skrifter 6. Række, Naturvidenskabelig og Mathematisk Afdeling 11, 2 , 1–70.

Ravn, J.P.J. 1902b: Molluskerne i Danmarks Kridtaflejringer. II Scaphopoder, Gastropoder og Cephalopoder. Det Kongelige Danske Videnskabernes Selskabs Skrifter 6. Række, Naturvidenskabelig og Mathematisk Afdeling 11, 4 , 5–66.

Ravn, J.P.J. 1903: Molluskerne i Danmarks Kridtaflejringer. III Stratigrafiske Undersøgelser. Det Kongelige danske Videnskabernes Selskabs Skrifter 6. Række, Naturvidenskabelig og Mathematisk Afdeling 11, 6, 335–446.

Ravn, J.P.J. 1904: Bemærkninger om lagserien i Stevns Klint samt om *Cyathidium holopus* STEENSTRUP. Geologiska Föreningens i Stockholm Förhandlingar 26, 347–354.

Ravn, J.P.J. 1927: De Irregulære Echinider i Danmarks Kridtaflejringer. Det Kongelige Danske Videnskabernes Selskabs Skrifter 8. Række, Naturvidenskabelig og Mathematisk Afdeling 11, 4, 307–355.

Ravn, J.P.J. 1928: De Regulære Echinider i Danmarks Kridtaflejringer. Det Kongelige Danske Videnskabernes Selskabs Skrifter 9. Række, Naturvidenskabelig og Mathematisk Afdeling 9, 1, 1–63.

Ravn, J.P.J. 1933: Études sur les Pélécypodes et Gastropodes du Calcaire de Faxe. Det Kongelige Danske Videnskabernes Selskabs Skrifter 9. Række, Naturvidenskabelig og Mathematisk Afdeling 9, 2, 1–74.

Reed, J.K. 2002: Deep-water *Oculina* coral reefs of Florida: biology, impacts and management. Hydrobiologica 471, 43–55.

Roberts, J.M., Wheeler, A.J. & Freiwald, A. 2006: Reefs of the deep: the biology and geology of cold-water coral ecosystems. Science 312, 543–547.

Roberts, J.M., Wheeler, A., Freiwald, A. & Cairns, S.D. 2009: Cold-water Corals: The Biology and Geology of Deep-sea Coral Habitats. Cambridge University Press, 334 pp.

Rosenkrantz, A. 1937: Bemærkninger om det østsjællandske Daniens stratigrafi og tektonik. Meddelelser fra Dansk Geologisk Forening 9, 199–212.

Schilder, F.A. 1928: Die Cypraeacea des Daniums von Dänemark und Schonen. Danmarks Geologiske Undersøgelse IV. Række, 2, 1–29.

Schnetler, K.I. & Petit, R.E. 2006: Revision of the gastropod family Cancellariidae from the Danian (Early Paleocene) of Fakse, Denmark. Cainozoic Research 4, 97–108.

Schnetler, K.I., Lozouet, P. & Pacaud, J.-M. 2001: Revision of the gastropod family Scissurellidae from the Middle Danian (Paleocene) of Denmark. Bulletin of the Geological Society of Denmark 48, 79–90.

Sigwart, J. D., Andersen, S.B. & Schnetler, K.I. 2007: First record of a chiton from the Palaeocene of Denmark (Polyplacophora: Leptochitonidae) and its phylogenetic affinities. Journal of Systematic Palaeontology 5, 123–132.

Sivhed, U., Wikman, H. & Erlström, M. 1999: Beskrivning til berggrundskarta 1C Trelleborg NV och SO samt 2C Malmö SV, SO, NV och NO. Sveriges Geologiska Undersökning Serie Af 191, 192, 193, 194, 196, 198, 143.

Steenstrup, J. 1847: Über Korallen in der Faxöer Kreide, Moltkia und Cyathidium. Amtlicher Bericht über die 24. Versammlung deutscher Naturforscher und Ärzte in Kiel im September 1846. Akademische Buchhandlung, Kiel, pp. 148–150.

Surlyk, F. 1997: A cool-water carbonate ramp with bryozoan mounds; Late Cretaceous – Danian of the Danish Basin. In: James, N. P., Clarke, J. A. D. (eds): Cool-water Carbonates. Special Publication – SEPM (Society for Sedimentary Geology) 56, 293–307. Tulsa, OK, USA.

Surlyk, F., Damholt, T. & Bjerager, M. 2006: Stevns Klint, Denmark: Uppermost Maastrichtian chalk, Cretaceous–Tertiary boundary, and lower Danian bryozoan mound complex. Bulletin of the Geological Society of Denmark 54, 1–48.

Thomsen, E. 1995: Kalk og kridt i den danske undergrund. In: Nielsen, O.B. (ed.): Århus Geokompendier 1, 31–67.

Varol, O. 1998: Palaeogene. In: Bown, P.R. (ed.): Calcareous Nannofossil Biostratigraphy. British Micropalaeontological Society Series. Chapman & Hall/Kluwer Academic, Cambridge, 200–224.

Voigt, E. 1923: Über einige neue und wenig bekannte Bryozoen der Gattung *Floridina* aus dem Danien von Faxe. Meddelelser fra Dansk Geologisk Forening 6, 20, 1–9.

Voigt, E. 1958: Untersuchungen an Oktokorallen aus der oberen Kreide. Mitteilungen aus dem Geologischen Staatsinstitut in Hamburg 27, 5–49.

Willumsen, M. 1995: Early lithification in Danian azooxanthellate scleractinian lithoherms, Faxe Quarry, Denmark. Beiträge zur Paläontologie 20, 123–131.

Wisshak, M., Neumann, C., Jakobsen, J. & Freiwald, A. 2009: The 'living-fossil community' of the cyrtocrinoid *Cyathidium foresti* and the deep-sea oyster *Neopycnodonte zibrowii* (Azores Archipelago). Palaeontology, Palaeoclimatology, Palaeoecology 271, 77–83.

Zibrowius, H. 1980: Les scleractiniaires de la Mediterranee et de l'Atlantique nord-oriental. Mémoires de l'Institut Océanographique, Monaco 11, 284 pp.

Ødum, H. 1928: Vort sydligste Danium. Meddelelser fra Dansk Geologisk Forening 7, 201–214.