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Stratigraphy of the Upper Jurassic to lowermost Cretaceous in the Rødryggen-1 and Brorson Halvø-1 boreholes, Wollaston Forland, North-East Greenland

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Abstract

Two shallow cores drilled in northern Wollaston Forland, North-East Greenland, provide a combined section covering the upper Kimmeridgian (Upper Jurassic) – Barremian (Lower Cretaceous) and comprising the Bernbjerg, Lindemans Bugt, Palnatokes Bjerg and Stratumbjerg Formations. A new lithostratigraphic unit, the Storsletten Member, is defined within the Lindemans Bugt Formation. The black mudstone-dominated intervals are dated primarily by dinoflagellate cysts and ammonites, whereas the calcareous mudstones of the Palnatokes Bjerg Formation – sandwiched between the black mudstones – are dated by calcareous nannofossils. The stratigraphy demonstrates an almost complete succession in the Rødryggen-1 core, representing a deeper position in the basin, where the hiatus at the latest Jurassic rift climax predicted in previous models for the eastern Wollaston Forland Basin is absent. In contrast, the Brorson Halvø-1 core represents a position closer to a block crest where unconformities developed. In combination, the cores provide a key biostratigraphic reference section for the Jurassic–Cretaceous boundary interval in the Arctic.

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Abbreviations:

AOM: amorphous organic matter
API: American Petroleum Institute
FO: first occurrence
GEUS: Geological Survey of Denmark and Greenland
GR: gamma ray
GSSP: global boundary stratotype section and point
TD: total depth
aff.: affinis
spp.: species plural
sp. juv.: species juvenile
undiff.: undifferentiated

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1. Introduction

The Rødryggen-1 and Brorson Halvø-1 cores were drilled in northern Wollaston Forland, North-East Greenland (Figs 1, 2). They are the second and third cores in an onshore drilling programme designed to characterise the Upper Jurassic source-rock succession in North-East Greenland (Bojesen-Koefoed *et al.* 2014). The programme started with the drilling of the Blokelv-1 core in central Jameson Land (Fig. 1; Ineson & Bojesen-Koefoed 2018).

The Rødryggen-1 borehole is located on the western side of Rødryggen (meaning 'red ridge') at the eastern margin of Storsletten, Wollaston Forland. Previous studies in the area have suggested that the Rødryggen ridge consists of Upper Jurassic dark mudstones, separated with a major hiatus from overlying Ryazanian–Hauterivian (Lower Cretaceous) light grey or yellowish and red mudstones and is capped by dark, mid-Cretaceous mudstones (Surlyk 1978; Alsen 2006; Pauly *et al*. 2013; Bjerager *et al.* 2020; Surlyk *et al*. 2021). Coring was initiated in the Valanginian and terminated in upper Kimmeridgian strata at 234 m depth.

The Brorson Halvø-1 drill site at the south-western flank of Bern Plateau is situated approximately 10 km to the NE from the Rødryggen-1 drill site, across the Sumpdalen lowland that separates the Rødryggen ridge from the Brorson Halvø peninsula (Fig. 2). Coring was initiated stratigraphically somewhat higher, in Barremian dark mudstones, and reached 225 m depth, also in Kimmeridgian strata.

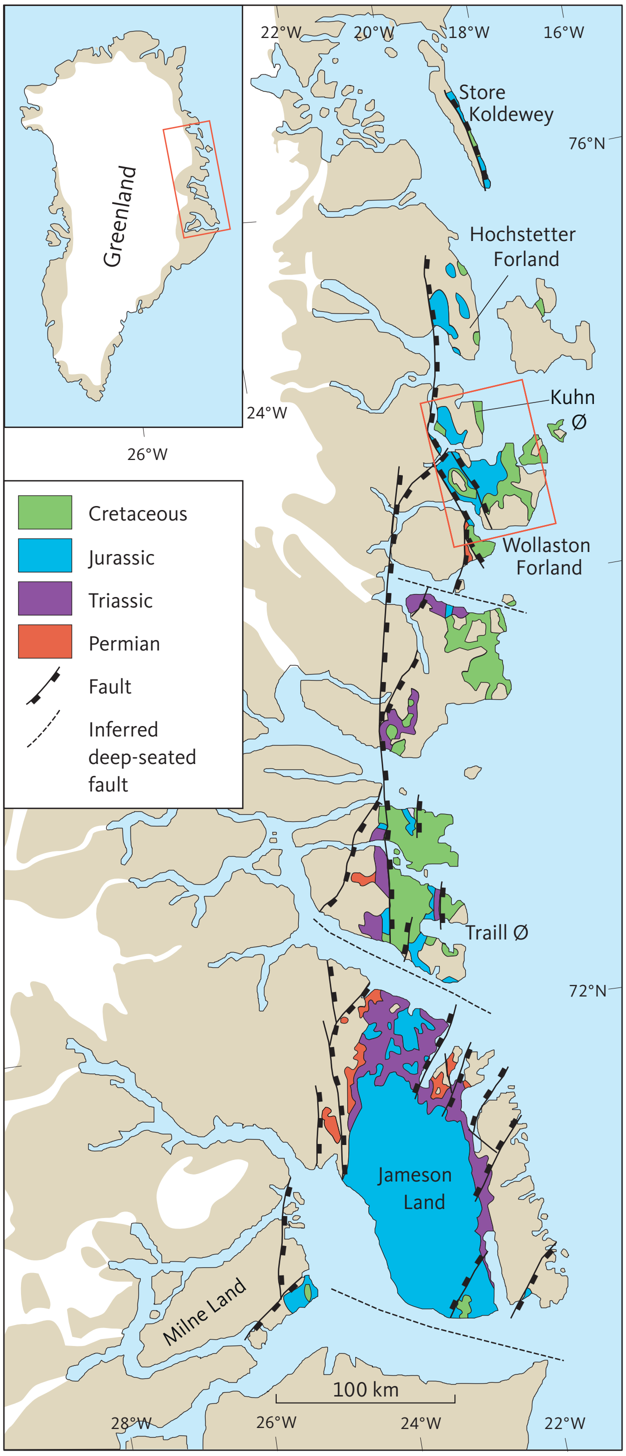

Fig. 1 Simplified geological map showing the distribution of Permian–Cretaceous sedimentary rocks in North-East Greenland. Position of study area in Fig. 2 indicated with a **red box**. Reproduced from Bojesen-Koefoed *et al.* (2023a, this volume, fig. 1).

The Blokelv-1 core in Jameson Land documents black mudstone deposition during the Oxfordian–Kimmeridgian (Alsen & Piasecki 2018; Bjerager *et al*. 2018). The two cores in Wollaston Forland document the longevity and termination of the Late Jurassic black mudstone deposition in North-East Greenland. The Blokelv-1 core reflects a sag basin setting, whereas the Wollaston Forland area is characterised by block faulting and rotation and half-graben formation (Surlyk 1978, 2003). The two cores drilled in Wollaston Forland document different depositional histories at different structural positions within the half-graben complex. Hence, the Brorson Halvø-1 well is located near the elevated hanging wall crest of the Permpas Block (Fig. 2; Surlyk 1978), whereas the Rødryggen-1 well is located near the basin centre of the same block.

The aim of this study is to document in detail the lithostratigraphy and biostratigraphy of the composite cores section. This study not only adds significantly to the knowledge on the complexity of the Upper Jurassic stratigraphy in the area, but also presents new data of regional significance on the biostratigraphy of the Jurassic–Cretaceous boundary interval in the Arctic. The targeted core interval, the Upper Jurassic dark mudstone succession, consists of two lithostratigraphic units: (1) the Kimmeridgian – lower Volgian Bernbjerg Formation and (2) a middle Volgian – lower Ryazanian new unit, which is here established as a new member – the Storsletten Member – within the Lindemans Bugt Formation.

2. Previous stratigraphic studies of the Upper Jurassic and Lower Cretaceous in Wollaston Forland

Upper Jurassic – Lower Cretaceous strata in Wollaston Forland were mapped during the Lauge Koch–led mapping campaigns in the 1940s (Vischer 1943; Maync 1947). The Jurassic–Cretaceous boundary interval was further investigated by Donovan (1964) in the northern Wollaston Forland, eastern Kuhn Ø and Lindeman Fjord areas (Fig. 2). The Jurassic – lowermost Cretaceous lithostratigraphy was formally established by Surlyk (1977, 1978) and recently revised and updated (Surlyk *et al.* 2021), whereas a Cretaceous lithostratigraphy was established by Bjerager *et al.* (2020). The Late Jurassic ammonite faunal succession in western Wollaston Forland was described by Sykes & Surlyk (1976), whereas the ammonite and *Buchia* bivalve zonation in the thick rift-climax succession at the Jurassic–Cretaceous boundary was established by Surlyk (1978) and Surlyk & Zakharov (1982). Nøhr-Hansen (1993) presented a dinoflagellate cyst biostratigraphic subdivision of the Barremian–Albian in North-East Greenland, partly based on sampled sections in Wollaston Forland. The zonation was recently extended and revised by Nøhr-Hansen *et al*. (2020). Macrofossils and the biostratigraphy of the Palnatokes Bjerg Formation from localities in central Wollaston Forland were described by Alsen & Rawson (2005), Harper *et al.* (2005), Alsen (2006) and Alsen & Mutterlose (2009), followed by calcareous nannofossil and isotope stratigraphic studies by Pauly *et al.* (2012a) and Möller *et al.* (2015).

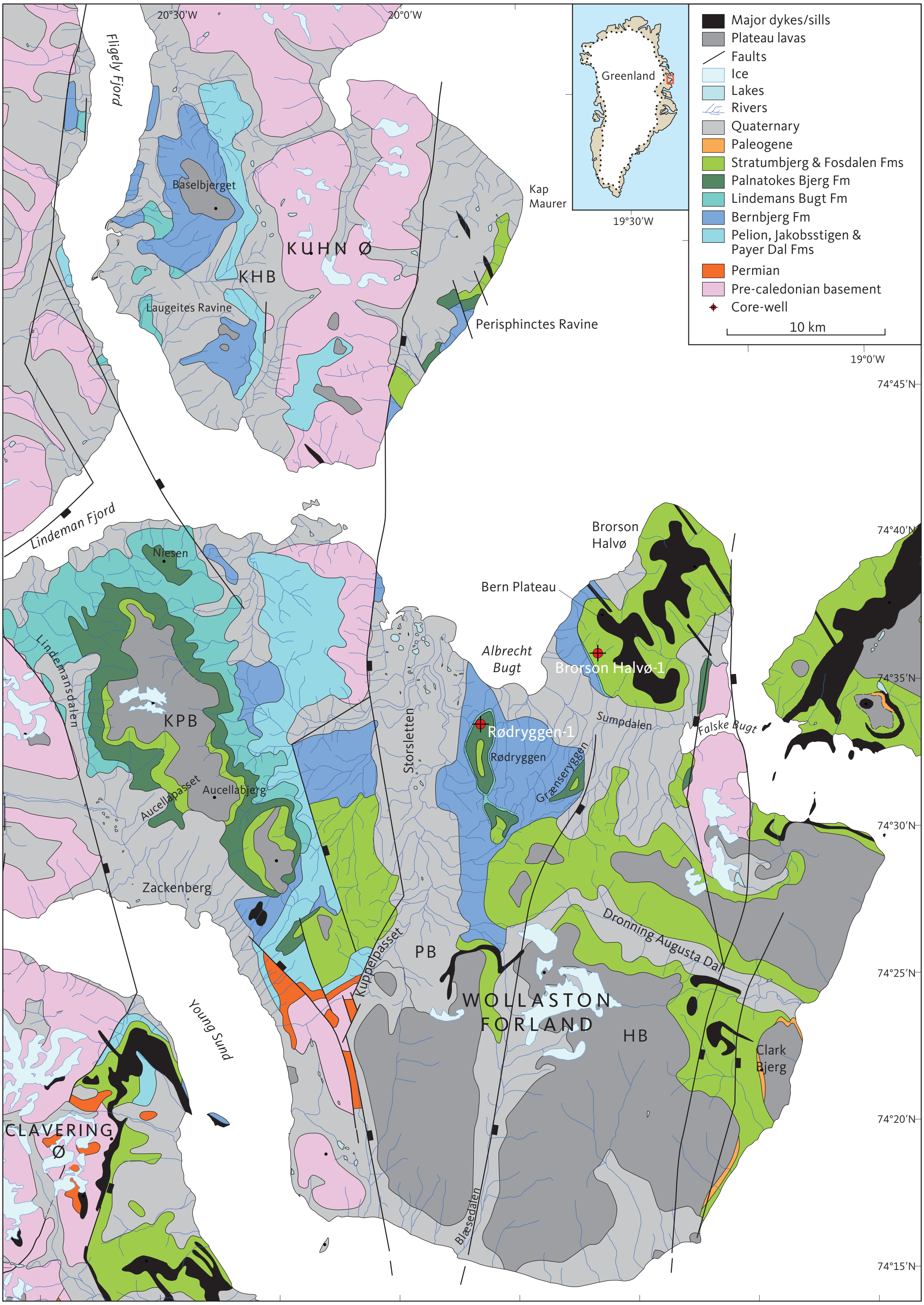

Fig. 2 Geological map of the study area. **KHB**: Kuhn Ø Block. **KPB**: Kuppel Block. **PB**: Permpas Block. **HB**: Hühnerbjerg Block. Modified from Bojesen-Koefoed *et al.* (2023a, this volume, fig. 1).

3. Geological framework and lithostratigraphy

The Upper Jurassic – lowermost Cretaceous in the East Greenland Rift Basin was deposited in a series of sub-basins between Jameson Land in the south at *c.* 70.5°N to Store Koldewey at *c.* 76.5°N in the north (Fig. 1; Surlyk 2003). The southernmost sub-basin in the Jameson Land area acted as an extensive, gently tilted platform subsiding asymmetrically with greatest subsidence to the west. North of Jameson Land, especially in the Wollaston Forland – Kuhn Ø area, basins are characterised by block faulting and tilting, initiated in the Middle Jurassic and culminating in the latest Jurassic (Volgian), with segmentation into narrower, strongly tilted fault blocks (Surlyk 1978). Middle–Late Jurassic deposition records an overall transgression and backstepping of the depositional system (Surlyk 1977, 1978). The Middle Jurassic sandstone-dominated succession is thus overlain by Upper Jurassic offshore mudstones with a diachronous boundary, younging towards the north. The upper Oxfordian – lower Volgian comprises a 500–600 m thick black mudstone succession in the study area. Highest sea level and maximum transgression was in the Kimmeridgian, but greatest water depths were likely reached during the Volgian rift climax, in the deepest parts of westerly tilted half-grabens (Surlyk 2003). Thick successions of very coarse, deep marine, clastic material were deposited in half-graben basins along the western, major fault scarp but rapidly passed into finer clastic deposition towards the east away from the scarp (Surlyk 1978). The more easterly situated half-graben segments are almost all covered by younger successions. The Late Jurassic stratigraphy and deposition of those segments are thus poorly understood but are addressed by Hovikoski *et al.* (2023a, this volume) and in the present study based on the new core data obtained from the Rødryggen-1 and Brorson Halvø-1 cores. Rifting waned in the earliest Cretaceous (Ryazanian–Hauterivian) when half-graben sediment prisms were draped by relatively finer-grained sediments (Surlyk 2003). The following early to mid-Cretaceous (Barremian – early Albian) period was characterised by tectonic quiescence, thermal subsidence and deposition of a relatively thick succession of dark, marine siltstones and mudstones.

Both boreholes were initiated in the Lower Cretaceous and reach down into the Upper Jurassic. Together they penetrate three major lithostratigraphic units, the Vardekløft, Wollaston Forland and Brorson Halvø Groups (Figs 3, 4). Both cores exhibit the Bernbjerg, Lindemans Bugt and Palnatokes Bjerg Formations. The Bernbjerg Formation represents the upper part of the Upper Jurassic (Oxfordian – lower Volgian) tectonostratigraphic unit, reflecting increased rifting and marine flooding (J2.4 in Surlyk 2003). The Lindemans Bugt and Palnatokes Bjerg Formations of the Wollaston Forland Group represent the culmination of rifting and tilting of fault blocks (J2.5) and the end of rifting and regional drowning (J2.6), respectively. In Rødryggen-1, coring began within the Albrechts Bugt Member, the lower member of the Palnatokes Bjerg Formation. The Brorson Halvø-1 core was initiated stratigraphically higher and contains the Rødryggen Member, the upper member of the Palnatokes Bjerg Formation and the overlying Stratumbjerg Formation. The Stratumbjerg Formation is the lower part of an upper Hauterivian – mid-Albian (Cretaceous) tectonostratigraphic unit defined by Bjerager *et al.* (2020).

3.1 Bernbjerg Formation (Vardekløft Group)

The upper Oxfordian – lower Volgian Bernbjerg Formation is a widespread depositional unit in North-East Greenland cropping out on Store Koldewey in the north to Traill Ø in the south (Surlyk *et al.* 2021 and references therein). Its type and reference sections are located in Wollaston Forland and south-western Kuhn Ø (Surlyk 1977), where the formation reaches a maximum thickness of 500–600 m (Surlyk 1977; Surlyk & Clemmensen 1983; Alsgaard *et al*. 2003). The Bernbjerg Formation sharply overlies either the Payer Dal Formation or the Jakobsstigen Formation (Surlyk *et al.* 2021). Neither the Rødryggen nor the Brorson Halvø cores reached the lower boundary of the Bernbjerg Formation. The nature of the upper contact to the Wollaston Forland Group depends on location within a tilted fault block; in the downfaulted part of a fault block, the boundary is conformable, whereas the contact is an angular unconformity on the elevated fault block crests (Surlyk 1977, 1978, 1991). Lithologically, the formation is characterised mainly by dark grey to black mudstone and interlaminated sandstone and mudstone. Sandstone beds, 5–50 cm thick, may locally show current and wave-ripple cross-stratification (Surlyk 1977). Surlyk (2003) referred the lowermost heterolithic unit to the Ugpik Ravine Member. The cores described here from the Rødryggen-1 and Brorson Halvø-1 boreholes reveal only the mud-dominated upper part of the Bernbjerg Formation.

3.2 Lindemans Bugt Formation (Wollaston Forland Group)

Prior to this study, middle Volgian – lower Ryazanian deposits were not known to crop out in the tilted Permpas Block, and the Palnatokes Bjerg Formation was considered to rest directly on the Bernbjerg Formation. The outcropping Bernbjerg Formation forms a badland area east of the Rødryggen ridge (Figs 2, 5) towards the Grænseryggen ridge. To the north, the Bernbjerg Formation is poorly exposed in the foot of the south-western slopes of the Bern Plateau (Fig. 6) separated from the badland exposures in the Rødryggen–Grænseryggen

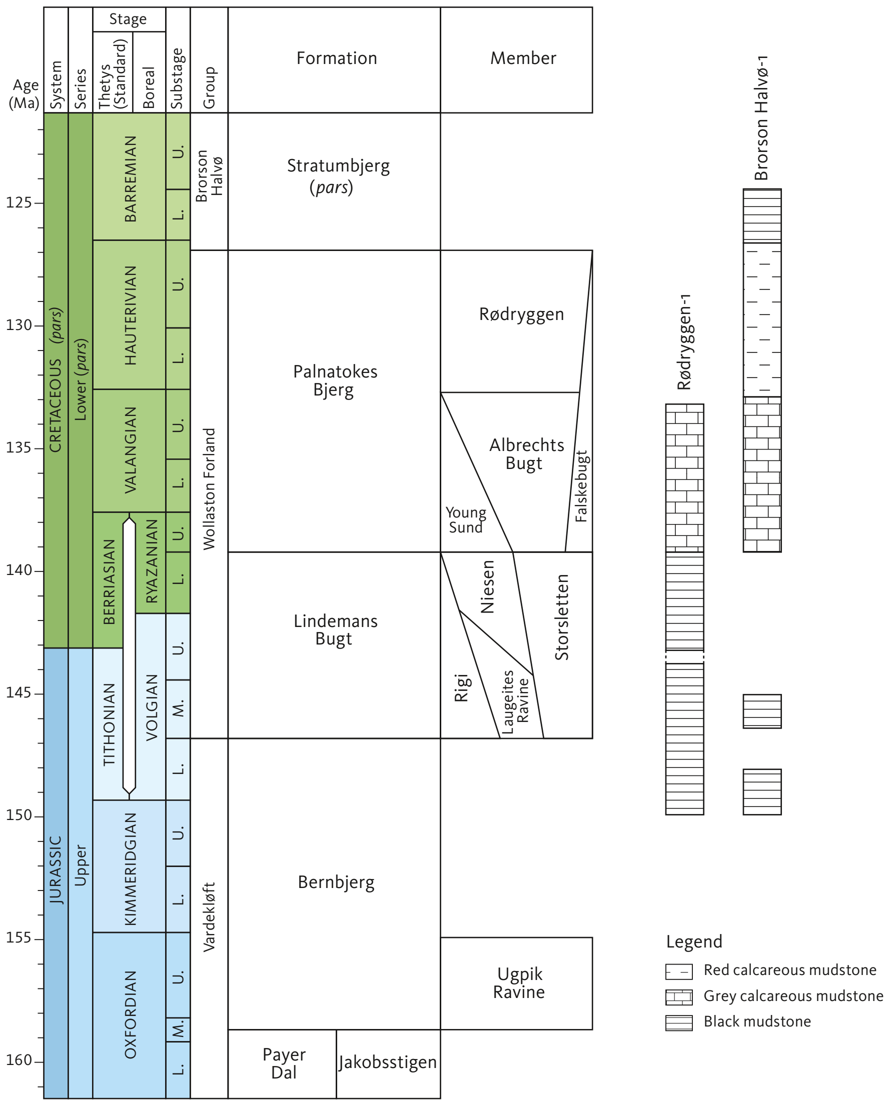

Fig. 3 Oxfordian–Barremian lithostratigraphy for Wollaston Forland. **L.**: lower. **M.**: middle. **U.**: upper.

area by the Sumpdalen valley (Fig. 2). Vischer (1943) and Maync (1947) reported Kimmeridgian black shales with ammonites, some referred to *Amoeboceras*, others unidentified, from south of Albrechts Bugt and south and north of Sumpdalen. The upper part of the Bernbjerg Formation was thus considered removed by 'pre-Valanginian' erosion, i.e. pre-Palnatokes Bjerg Formation, during the rift culmination at the Jurassic–Cretaceous transition (Surlyk 1977, 1978). Maync (1947) reported the Kimmeridgian to be directly overlain by 'Aptian' strata in places, i.e. the Stratumbjerg Formation. The poorly exposed mudstones below the Albrechts Bugt Member at the foot of the Rødryggen ridge (and at Brorson Halvø) were thus also considered Upper Jurassic Bernbjerg Formation, in older terminology the so-called Black Series (e.g. Maync 1947; Koch & Haller 1971; Surlyk 1978). However, the palynostratigraphic ages obtained in the present work from these exposed strata demonstrate the presence of middle Volgian – lower Ryazanian mudstones in this area, as confirmed by the borehole data. The equivalent and comparable deposits in terms of age and lithology to the west are the fine-grained Laugeites Ravine and, particularly, Niesen Members of the Lindemans Bugt Formation. Those units are, however, confined to the westernmost tilted Kuppel and Kuhn Ø Blocks (Surlyk 1978) and are related to distal parts of fan deltas. We therefore consider the middle Volgian – lower Ryazanian mudstones in the cored sections on the Permpas Block as separate, detached from those other members, and thus group them into a new member, the Storsletten Member (Fig. 3), as defined formally here (Section 3.1.2.1). The unit is probably distributed throughout the Permpas Block, which was blocked from receiving the coarse-grained sediments that dominated deposition along the main fault to the west, since it was separated by the elevated block crest of the Kuppel Block and the Kuhn Block. Other tilted block basins separated from the westernmost blocks are also likely to have been dominated by mud deposition during the middle Volgian – early Ryazanian.

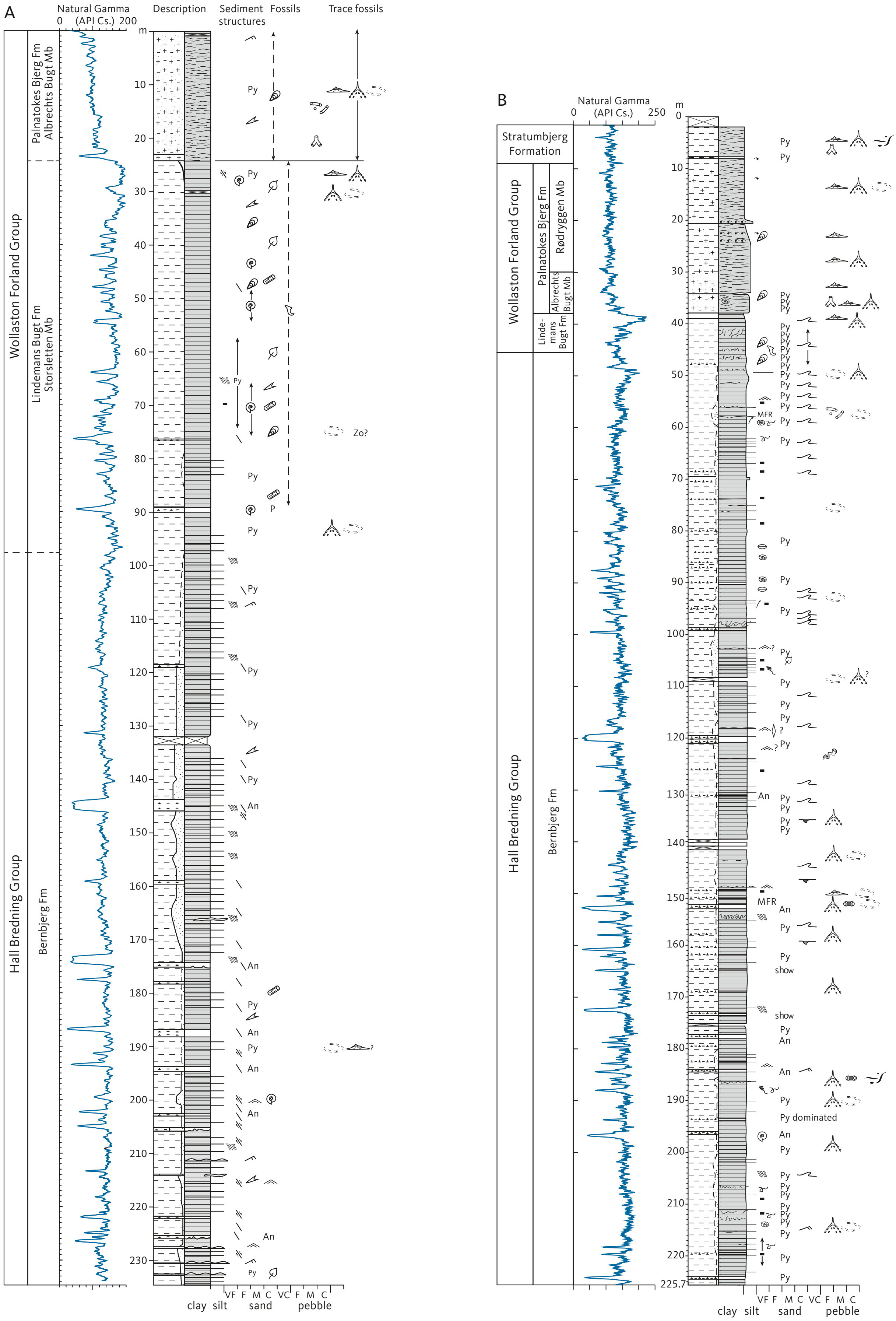

Fig. 4 Sedimentological logs of (**A**) the Rødryggen-1 core, (**B**) the Brorson Halvø-1 core and (**C**) legend to both logs. **API Cs.**: American Petroleum Institute units. **VF**: very fine. **F**: fine. **M**: medium. **C**: coarse. **VC**: very coarse.

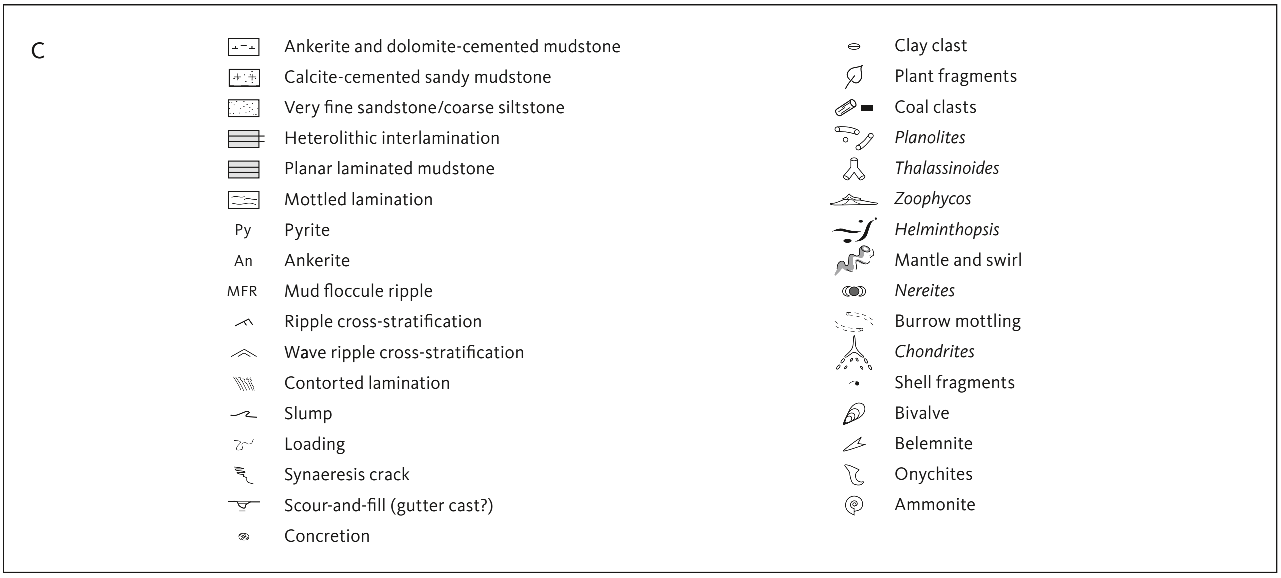

Fig. 4 (Continued) Sedimentological logs of (**A**) the Rødryggen-1 core, (**B**) the Brorson Halvø-1 core and (**C**) legend to both logs. **API Cs.**: American Petroleum Institute units. **VF**: very fine. **F**: fine. **M**: medium. **C**: coarse. **VC**: very coarse.

3.2.1 Storsletten Member

new member

History. The member was not known when the Lindemans Bugt Formation was erected (Surlyk 1978). The formation encompasses mudstones deposited on the Permpas Block during the tectonostratigraphic phase J2.5 in Surlyk (2003).

Type section. The Rødryggen-1 core between 97 and 24.4 m depth (Fig. 4A). Position: N 74°32.561′, W 19°50.924′ (Figs 2, 5).

Reference section. The Brorson Halvø-1 core between 45.5 and 37.5 m depth (Fig. 4B). Position: N 74°35.227′, W 19°34.327′ (Figs 2, 6).

Thickness. The thickness of the member varies depending on the position on the tilted fault block. The unit is thickest where it is most complete, in the deeper, western part of the half-graben basin. It is 72.5 m thick in the Rødryggen-1 core (Fig. 4A). Due to major hiatuses, it is only 8 m thick in the Brorson Halvø-1 core (Fig. 4B).

Lithology. Dark grey to black, laminated to structureless mudstone, commonly rich in pyrite and marine fossils. Slump folding is common locally (Brorson Halvø-1 core); for lithological and diagenesis data, see Hovikoski *et al.* (2023a, this volume) and Olivarius *et al*. (2023, this volume), respectively. The member differs from the other coeval members by its higher content of organic carbon and the oxygen-restricted nature of its deposits (Bojesen-Koefoed *et al*. 2023b, this volume).

Fossils. Ammonites, buchiid bivalves, common fragments of inoceramids and palynomorphs.

Depositional environment. Deep oxygen-restricted basin and slope, below storm wave base. The oxygen-restricted character is demonstrated by inorganic and organic geochemistry as well as the scarcity of bioturbation (Bojesen-Koefoed *et al*. 2023b, this volume; Olivarius *et al*. 2023, this volume; Hovikoski *et al.* 2023b).

Boundaries. The boundary between the Bernbjerg Formation and the Lindemans Bugt Formation is lithologically transitional in the type section and occurs between 125 and 76 m (Fig. 4A). The formation boundary in the type section is placed at 97 m, where the gamma-ray values increase to *c.* 200 API (American Petroleum Institute units) for the first time (Bojesen-Koefoed *et al*. 2023b, this volume). The formation change is also recognisable as gradational facies change from mudstone showing silt-clay interlamination to laminated clayey mudstone, increasing pyrite and fossil content and locally increasing slump-folding. Moreover, the formation change is well-expressed in a variety of source-rock characteristics such as increasing Hydrogen Index, S2 and C_{30} desmethyl sterane values, reflecting increasing marine organic matter content (Bojesen-Koefoed *et al*. 2023b, this volume). The upper boundary towards the Albrechts Bugt Member of the Palnatokes Bjerg Formation is gradational in the Rødryggen-1 core, whereas in the Brorson Halvø-1 core, the boundary is erosional and represents a hiatus (Fig. 4). The gradation occurs within 1 m in the type section,

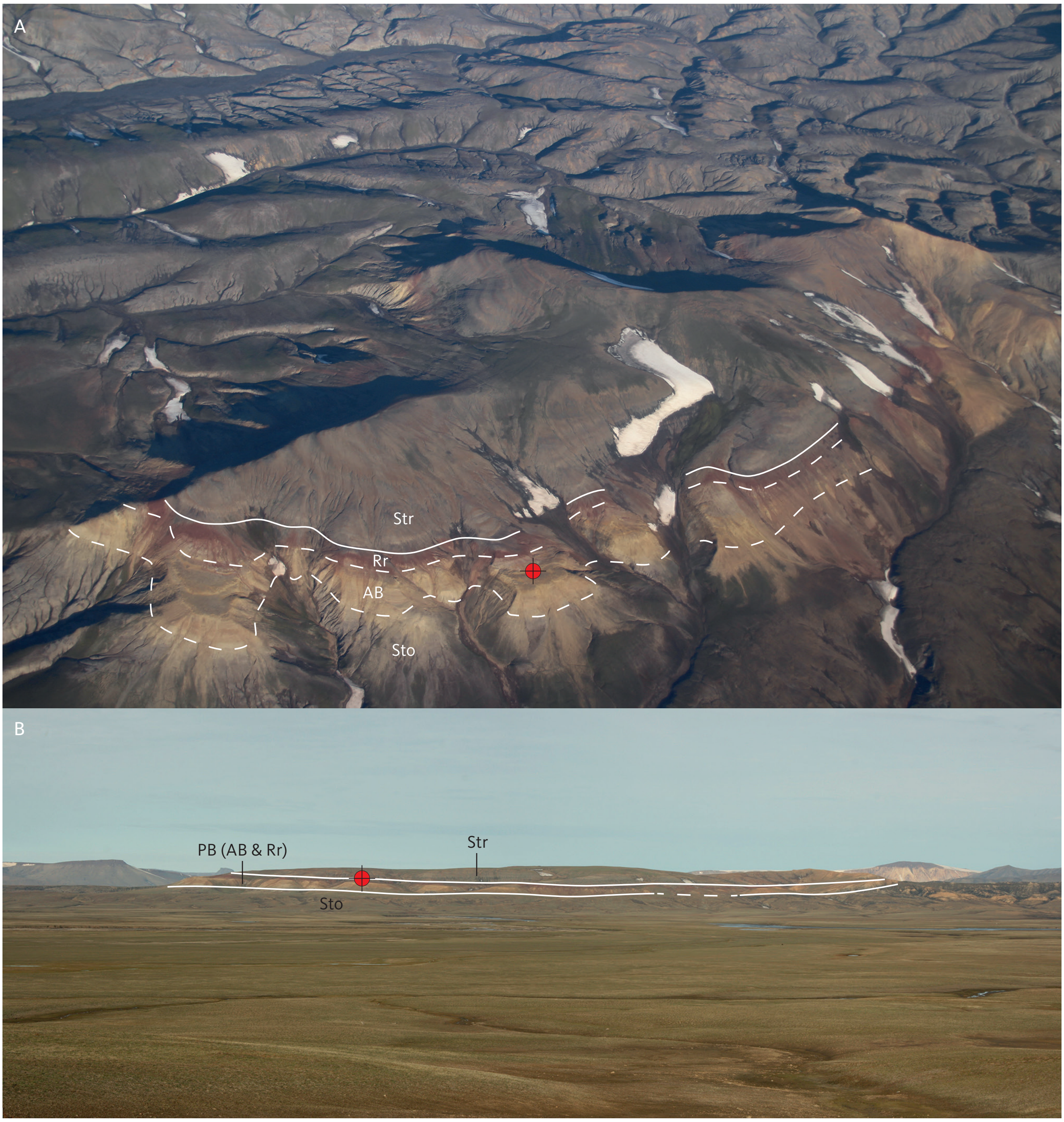

Fig. 5 Views of the Rødryggen-1 drill site. (**A**) Oblique aerial view, towards the south-east of the Rødryggen ridge showing the outcropping units and the position of the Rødryggen-1 drill site (**red dot**) situated on a plateau within the yellowish weathering Albrechts Bugt Member. The badlands area in the background is the Upper Jurassic Bernbjerg Formation. (**B**) View across the Storsletten plain towards the east and the Rødryggen ridge. **AB**: Albrechts Bugt Member. **PB**: Palnatokes Bjerg Formation. **Rr**: Rødryggen Member. **Sto**: Storsletten Member. **Str**: Stratumbjerg Formation.

25.5–24.4 m (Fig. 4A). The boundary is readily recognisable by an abrupt decrease in gamma-ray values, increasing matrix carbonate content, a change in matrix colour from black to light grey, increasing bioturbation intensity and a change in fossil content with nannofossils, foraminifera and *Buchia* shells becoming abundant.

Distribution. Recorded only in the Rødryggen-1 and Brorson Halv-1 core wells and in restricted exposures close to the well sites.

Chronostratigraphy. Middle Volgian *Dorsoplanites primus* ammonite chronozone – lower Ryazanian upper *Gochteodinia villosa villosa* dinoflagellate cyst zone.

3.3 Palnatokes Bjerg Formation (Wollaston Forland Group)

The upper syn-rift to early post-rift succession is represented by the Palnatokes Bjerg Formation. It contains the Albrechts Bugt Member, overlain by the

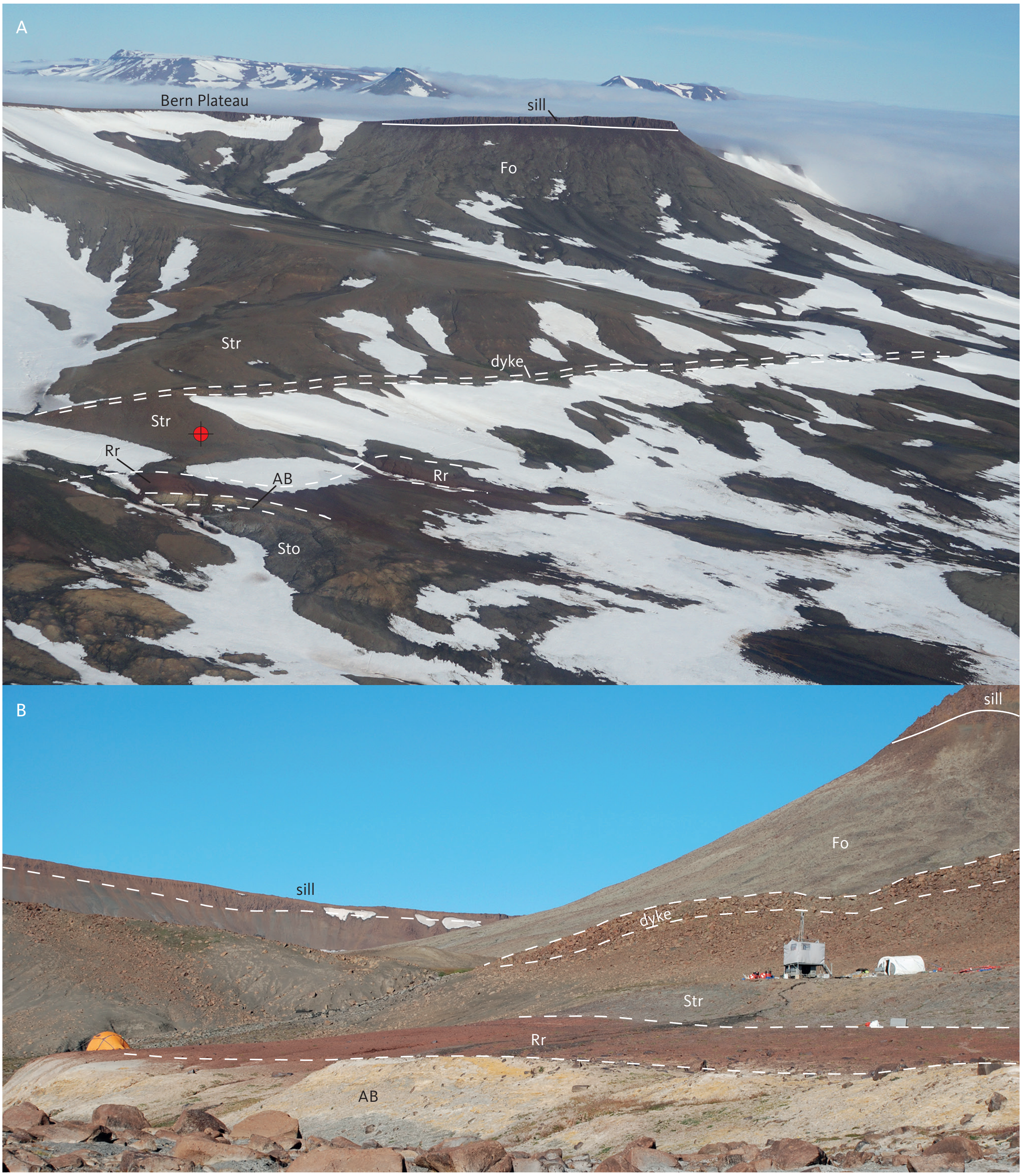

Fig. 6 Views of the Brorson Halvø-1 drill site. (**A**) Oblique aerial view of the Brorson Halvø-1 drill site (**red dot**) at the foot of the southern slope of Bern Plateau, SW Brorson Halvø. (**B**) Geology around the drill site. Pale, yellowish weathering of the Albrechts Bugt Member is seen sharply overlain by the Rødryggen Member (both Palnatokes Bjerg Formation), overlain by the Stratumbjerg Formation. A roughly SE–NW-oriented doleritic dyke intersects the Stratumbjerg Formation and a doleritic sill caps the Bern Plateau (sill; upper right). The drill site was situated on a small plateau in the lower part of the Stratumbjerg Formation (grey tent on platform). Photo: A. Ryge. **AB**: Albrechts Bugt Member. **Fo**: Fosdalen Formation. **Rr**: Rødryggen Member. **Sto**: Storsletten Member. **Str**: Stratumbjerg Formation.

Rødryggen Member. The Young Sund and Falske Bugt Members are coarse-grained units that developed in western and eastern parts of the basin, respectively, and were not encountered in the wells drilled in the Permpas Block.

3.3.1 Albrechts Bugt Member

The Albrechts Bugt Member consists of calcareous sandy, light grey to yellowish mudstone with abundant calcareous concretions (Surlyk 1978; Surlyk *et al*. 2021). At outcrop, the member weathers in conspicuous bright, yellow colours that contrast strongly with the essentially grey colour of the fresh and unweathered rock. The deposits are typically highly bioturbated and rich in *Buchia* bivalves, belemnites and ammonites (see also Alsen 2006).

The lithological contact between the Lindemans Bugt Formation and Albrechts Bugt Member of the Palnatokes Bjerg Formation is gradational in the Rødryggen-1 core and sharp in the Brorson Halvø-1 core. The boundary is readily recognisable by an abrupt decrease in gamma-ray (GR) values, increasing matrix carbonate and sand content, decreasing clay content, a change in matrix colour from black to light grey, increasing bioturbation intensity and a change in fossil content, with nannofossils, foraminifera and *Buchia* shells becoming abundant. The boundary is placed at 24.4 m in the Rødryggen-1 core and at 37.5 m in the Brorson Halvø-1 core (Fig. 4). The thickness of the unit is laterally variable; it reaches a maximum thickness of *c.* 300 m at Mt. Niesen (Wollaston Forland), where it interfingers with the fine-grained facies of the Young Sund Member. Towards the east, on the Permpas Block, the member rapidly pinches out to *c.* 30 m (Surlyk 1978). The upper boundary is transitional when overlain by the red mudstones of the Rødryggen Member.

3.3.2 Rødryggen Member (only in the Brorson Halvø-1 core)

The Rødryggen Member consists of red, massive or laminated hematitic mudstones with intercalated fine sandy yellow mudstones (Surlyk 1978; Surlyk *et al*. 2021). The contact between the Albrechts Bugt and Rødryggen Members is transitional and interlayered within a 70 cm interval in the Brorson Halvø-1 core. The change is visible as a gradational change in colour from light grey to red; the boundary is placed at 30.0 m where the matrix turns permanently red (Fig. 4B). Moreover, the Rødryggen Member differs from the Albrechts Bugt Member in microfossil and macrofossil content with foraminifers and inoceramid shell becoming more common.

3.4 Stratumbjerg Formation (Brorson Halvø Group; only in Brorson Halvø-1 core)

The Stratumbjerg Formation marks a return to deposition of dark, fine-grained sediments in an oxygen-restricted environment below storm wave base during the tectonically quiescent phase after the Volgian rift climax and Ryazanian–Valanginian late rift phases. The unit is widely distributed throughout North-East Greenland, from Traill Ø in the south to Store Koldewey in the north (Bjerager *et al*. 2020). The boundary to the underlying Rødryggen Member is gradational within an 80 cm interval in the Brorson Halvø-1 core. The boundary is placed at 8.7 m (top of transition), where the bioturbated grey mudstones no longer interfinger with reddish mudstones (Fig. 4B).

4. Biostratigraphic methods and approach

The Rødryggen-1 borehole is 234.5 m deep, and the Brorson Halvø-1 borehole is 225.7 m deep. Both boreholes were fully cored, with recoveries of 99%. The core diameter in both cores is 42 mm. Each core is essentially treated as one sample and assigned codes with the prefix 'GEUS'. The Rødryggen-1 well is designated as GEUS 517001, and the Brorson Halvø-1 is designated as GEUS 517003. Sub-numbers were assigned to the extracted material, which was sampled for a suite of core analysis, including biostratigraphy, geochemistry, rock properties and provenance (see also Bojesen-Koefoed *et al.* 2023b, this volume; Olivarius *et al*. 2023, this volume). For simplicity, in this study, we only refer to the levels or borehole depths (below surface) for the respective subsamples, for example in range charts, tables and figure captions.

4.1 Macrofossils

Before the cores were subject to slabbing and sampling for the standard analytical programme, they were examined for macrofossils. Examination for macrofossils was particularly directed to where the core had naturally split along bedding planes, commonly along planes with fossils, so that all ends of the individual core pieces were inspected. Most of the fossils are fragmented. Identification also suffers from the relatively small diameter of the core such that only small portions of a fossil were usually available for study, and thus fewer diagnostic characters are available in these cases.

4.2 Palynomorphs and calcareous nannofossils

Mudstones for palynostratigraphic analysis were initially sampled at an even spacing throughout the core. Upon initial biostratigraphic screening, additional material was subsequently sampled in selected intervals, for example, across lithostratigraphic or chronostratigraphic boundaries such as the Jurassic–Cretaceous boundary interval, to obtain higher biostratigraphic subdivision and precision. The calcareous mudstone intervals of the Palnatokes Bjerg Formation were sampled specifically for calcareous nannofossil stratigraphy. Each sample for palynomorphs and nannofossil analysis comprised a split/slabbed, 4 to 6 cm thick core interval. The well depth of a mudstone sample is the medium point of the thickness of the sample.

The palynological preparation methods of the crushed sample material include processing with HCl, HF, oxidation with HNO_3 and heavy-liquid separation. Samples from the Bernbjerg and Lindemans Bugt Formations contain abundant marine and terrestrial organic matter, which required repeated oxidation and ultrasonic treatment to release identifiable dinoflagellate cysts, with slides produced after each repeated preparation step. When a state of sufficient oxidation was reached, the organic residue was sieved with a 21 µm filter. The coarser fraction was swirled and eventually mounted on glass slides using a glycerine jelly medium.

The dinoflagellate cyst content was analysed using a normal light microscope. All dinoflagellate cysts in one slide from each sample were counted to perform a semiquantitative analysis. This approach applies to dark mudstone intervals, whereas the diversity and abundance in the very low organic, calcareous mudstones of the Palnatokes Bjerg Formation do not allow for comparison with data from the dark mudstone units. In addition to dinoflagellate cysts, acritarchs and phrasinophycean and freshwater algae were also counted. The palynological taxonomy follows the Lentin and Williams Index of Fossil Dinoflagellates, 2004 Edition (Fensome & Williams 2004), unless otherwise indicated by author references.

Nannofossil slides were prepared using the simple smear slide technique of Bown & Young (1998). Where samples appeared to be barren with respect to calcareous nannofossils, three length traverses of the smear slide were examined. Where a particular species of nannofossil dominated the slide, one length traverse was counted, and then two further lengths were checked for rare forms. Biostratigraphic ranges of nannofossils are adapted from Burnett (1998), Bown *et al*. (1998) and Pauly *et al*. (2012a).

4.3 Stratigraphic nomenclature and methodology

The Tithonian and Berriasian are the standard stages for the uppermost Jurassic and lowermost Cretaceous, respectively, as defined in the Tethyan Realm. Due to pronounced faunal provincialism around the system boundary and the recognition of faunally clearly separated Tethyan and Boreal Realms, a parallel stage nomenclature has evolved for the Boreal area. Until improved correlation between Boreal and Tethyan areas is obtained, a Boreal subdivision and stage nomenclature are commonly adopted in Greenland, including in this study. This study also follows the stratigraphic concept commonly applied for Middle–Upper Jurassic stratigraphic studies in East Greenland, which considers ammonite zones as chronozones, representing rock units that are also identifiable by means of fossil groups other than ammonites. The East Greenland Upper Jurassic ammonite zonation is thus closely integrated with the dinoflagellate cyst record (see also discussion in Alsen & Piasecki 2018 and references therein).

4.4 Rødryggen-1 core

The Rødryggen-1 core was initially sampled at 37 levels for palynostratigraphy and nannofossil stratigraphy with a standard *c.* 10 m spacing, but with somewhat denser sampling in the lowermost and uppermost parts of the core. Subsequent sampling at critical levels resulted in a total of 63 sampled levels being analysed for palynostratigraphy. The dark mudstones of the Bernbjerg, Lindemans Bugt and Stratumbjerg Formations were primarily dated with palynostratigraphy aided by ammonite stratigraphy. The pale, calcareous mudstones of the Albrechts Bugt Member (Palnatokes Bjerg Formation) were dated by a combination of palynostratigraphy and calcareous nannofossil stratigraphy.

Ammonites occur only in two intervals, between 225 and 197 m, and in a *c.* 65 m thick interval between 90 and 26 m (Fig. 4A). The few ammonites in the lower interval are of little biostratigraphic value (Table 1), so age-significant ammonites are essentially restricted to the Storsletten Member of the Lindemans Bugt Formation. No ammonites were found in the interval between 90 and roughly 200 m. The latter interval is characterised by finely laminated dark mudstones, which theoretically have a good preservation potential for fossils. Ammonites are thus probably present. However, the interval is intensely fractured hampering both the preservation and detection of fossils.

Ten samples from the Rødryggen-1 core were examined for nannofossil content. Seven mudstone samples from the Bernbjerg and Lindemans Bugt Formations were almost barren with respect to calcareous nannofossils. Thus, only the three samples from the calcareous mudstones of the Albrechts Bugt Member (Palnatokes Bjerg Formation) yielded relatively good nannofossil recovery.

4.5 Brorson Halvø-1 core

The Brorson Halvø-1 core was sampled for palynostratigraphy and nannofossil stratigraphy with default sample spacing of *c.* 10–15 m, a slightly less dense sampling strategy than used for the Rødryggen-1 core. Subsequent closer sampling was undertaken in lithostratigraphic and chronostratigraphic boundary intervals to obtain higher precision, for example, to ascertain the stratigraphic significance of hiatuses.

Well-preserved ammonites are absent in the core and the integration of ammonite and palynostratigraphy, which was of great benefit in the analysis of the Rødryggen-1 core, could not be undertaken. The biostratigraphy of the core receives only minor support from the

Table 1 Summary of macrofossils recorded in the Rødryggen-1 core.

Depth	GEUS 517001 and sub-sample number	MGUH no.[a]	Figure no. (this study)	Description / taxononomy	Faunal horizon *sensu* Callomon & Birkelund (1982)	Ammonite stratigraphy
27.73 m	–401	34200	10.S	*Hectoroceras* sp.		*H. kochi* Zone
35.80 m	–402			bivalve		*P. maynci* Zone
37.49 m	–438	34199	10.R	cf. *Praetollia maynci* Spath		*P. maynci* Zone
40.22 m	–437			*Buchia* bivalve		*S.* (*Sw.*) *primitivus* Zone
43.18 m	not sampled			Ammonite indet.		*S.* (*Sw.*) *primitivus* Zone
43.21 m	–403	34198	10.Q	*Subcraspedites* (*Swinnertonia*) sp. juv.		*S.* (*Sw.*) *primitivus* Zone
45.37 m	–404	34197	10.P	*S.* (*Swinnertonia*) cf. *subundulatus* Swinnerton		*S.* (*Sw.*) *primitivus* Zone
45.73 m	–405			bivalve		(*P. exoticus* Zone)
47.20 m	–406	34196	10.O	aptychus		(*P. exoticus* Zone)
47.52 m	–407			bivalve		(*P. exoticus* Zone)
47.94 m	–436			?*Praechetaites* sp.		(*P. exoticus* Zone)
48.09 m	–435			*Buchia* bivalve		(*P. exoticus* Zone)
48.37 m	–408	34195	10.N	Ammonite indet.		(*P. exoticus* Zone)
48.54 m	–427	34194	10.M	cf. *Praechetaites exoticus* (Shulgina)		(*P. exoticus* Zone)
48.82 m	–434	34193	10.L	cf. *Praechetaites exoticus* (Shulgina)		(*P. exoticus* Zone)
49.94 m	–433			ammonite; indeterminate juvenile		(*P. exoticus* Zone)
50.14 m	–432			cf. *Praechetaites exoticus* (Shulgina)		(*P. exoticus* Zone)
51.55 m	–409	34192	10.K	*Laugeites* cf. *planus* Mesezhnikov	M 47	*L. groenlandicus* Zone
52.30 m	–431			ammonite fragment; indeterminate		*L. groenlandicus* Zone
52.50 m	–430			*L.* cf. *biplicatus*	M 47	*L. groenlandicus* Zone
52.82 m	–410	34191	10.J	*Laugeites* cf. *intermedium* Donovan		*L. groenlandicus* Zone
53.27 m	–429			ammonite aptychi		*L. groenlandicus* Zone
53.67 m	–411	34190	10.I	*Laugeites* cf. *biplicatus* Mesezhnikov	M 47	*L. groenlandicus* Zone
54.53 m	–412			?*Laugeites* sp.		*L. groenlandicus* Zone
55.25 m	–413			Ammonite indet.		*E. pseudapertum* Zone
55.98 m	–414	34189	10.H	*Epipalliceras* cf. *pseudapertum* Spath	M 42	*E. pseudapertum* Zone
62.43 m	–415	34188	15.B	micro-onychites		*D. gracilis* Zone
66.54 m	–416			belemnite		*D. gracilis* Zone
66.84 m	–417			Ammonite indet.		*D. gracilis* Zone
70.06 m	–418	34187	10.G	*Dorsoplanites jamesoni* Spath	M 40?	*D. gracilis* Zone
74.03 m	–419	34186	10.F	*Pavlovia* cf. *corona* Callomon & Birkelund	M 37	*D. liostracus* Zone
74.20 m	–420	34185	10.E	*Dorsoplanites* aff. *liostracus*	M 37	*D. liostracus* Zone
75.43 m	–421	34184	10.D	*Pavlovia* cf. *variocostata* Callo-mon & Birkelund	M 35	*P. communis* Zone
89.26 m	–422	34183	15.A	mega-onychites		*D. primus* Zone
89.30 m	–423	34182	10.C	*Dorsoplanites primus* Callomon & Birkelund	M 31	*D. primus* Zone
90.85 m	–424	34181	10.B	*Dorsoplanites* sp.		*D. primus* Zone
199.42 m	–425			Ammonite indet.		?
227.72 m	–426	34180	10.A	*Amoeboceras*? sp.		?

[a]The specimens are stored in the Palaeontology Type Collection at the Natural History Museum of Denmark and each labelled with an MGUH number – Museum Geologica Universitas Hafniensis.

macrofossils collected in exposures near the drill site, where Alsen (2006) recorded the ammonite fauna in the Albrechts Bugt and Rødryggen Members.

A total of 41 samples were analysed for palynomorphs: 19 in the Bernbjerg Formation, 7 in the Lindemans Bugt Formation (Storsletten Member), 12 in the Palnatokes Bjerg Formation and 3 in the Stratumbjerg Formation. From the upper part of the Brorson Halvø-1 core (40.27 to 6.16 m), analysis of calcareous nannoplankton was applied in 19 samples. The lowest sample represents dark mudstone of the Lindemans Bugt Formation and is barren, as are equivalent black mudstone samples from the Rødryggen-1 core. In the remaining samples, the preservation of the calcareous nannoplankton varies from good to moderate. Most samples of the Albrechts Bugt Member yield well-preserved calcareous nannoplankton. The calcareous nannoplankton in the Rødryggen Member shows good to moderate preservation and overgrowth by iron oxide minerals. Surprisingly, the organic-rich grey mudstones of the Stratumbjerg Formation also yielded well-preserved calcareous nannoplankton assemblages.

5. Biostratigraphy of the Rødryggen-1 core

The biostratigraphic subdivision of the Rødryggen-1 core is described from total depth (TD) at 234.40 m upwards. The location of bulk-rock samples for palynostratigraphy is seen in the charts illustrating the distribution and ranges of dinoflagellate cyst taxa, palyno events and calcareous nannofossil taxa (Figs 7, 8). The recorded ammonite levels are listed in Table 1 and illustrated in a stratigraphic distribution chart (Fig. 9). Selected ammonites and dinoflagellate cysts are illustrated in Figs 10–13.

5.1 *Aulacostephanus eudoxus* Chronozone (234.40 m (TD) – 220.51 m)

Fossils. The recognition of the zone is based on its dinoflagellate cyst record. One poorly preserved ammonite is a possible *Amoeboceras* (227.72 m; Fig. 10A; Table 1). The base of the zone is arbitrarily placed at the base of the core (at TD). The dinoflagellate cyst assemblage is relatively diverse, and cysts are abundant. The zone is dominated by *Perisseiasphaeridium pannosum*, *Paragonyaulacysta capillosa* and *Cribroperidinium* spp., whereas *Epiplosphaera reticulospinosa* and *Paragonyaulacysta borealis* are common taxa at discrete levels within the zone.

Biostratigraphy. Abundant *P. pannosum* is reported to range from ammonite faunal horizon M 20, at the base of the *Aulacostephanus eudoxus* Zone, to a level between faunal horizons M 22 and M 23 near the top of the *A. eudoxus* Zone in Milne Land (Fig. 14; Piasecki 1996). *P. pannosum* was used as a key taxon of the *A. eudoxus* Zone in the Blokelv-1 core in Jameson Land (Alsen & Piasecki 2018) and the Brorson Halvø-1 core (herein). *Rhycodiniopsis cladophora* has its uppermost occurrence at M 21 in Milne Land (Piasecki 1996). *P. borealis* is common in these assemblages and is present from 234.41 m, but it is known to range much deeper, to the *P. baylei* Zone level in Milne Land (Piasecki 1996). *Dingodinium minutum*, *Gonyaulacysta jurassica*, *Taeniophora iunctispina* and possibly *Nannoceratopsis pellucida* occur scattered and are rare in this chronozone, either as last occurrences or reworked from strata below.

Age. Kimmeridgian, Late Jurassic.

Organic matter. Amorphous kerogen (often termed AOM) together with a large proportion of terrestrial organic material from higher land plants, especially degraded black grains of woody material, dominate the interval. The presence of dinoflagellate cysts indicates a marine environment, and the dominance of AOM is suggestive of oxygen-deficient bottom conditions.

5.2 *Aulacostephanus autissiodorensis* Chronozone (220.51–150.25 m)

Fossils. The recognition of this chronozone is based on its dinoflagellate cyst record. It contains only one indeterminable ammonite (199.42 m; Table 1). The base of the zone is recognised as the level with the lowest occurrence of abundant *Oligosphaeridium patulum* (220.51 m). The composition of the dinoflagellate cyst assemblage changes from 220.51 m to be characterised by abundant *Oligosphaeridium patulum*, *Cribroperidinium* spp. and *Cyclonephelium distinctum*. *Paragonyaulacysta capillosa* is common but less frequent upwards. The assemblage is characterised by low diversity and low abundance, probably due to the high content of organic material.

Biostratigraphy. Abundant *O. patulum* appears in the basal *A. autissiodorensis* Chronozone between ammonite faunal horizons M 22 and M 23 in Milne Land (Fig. 14; Piasecki 1996; Alsen & Piasecki 2018). *Cribroperidinium complexum* has its highest occurrence at the boundary of the *A. autissiodorensis* and *P. elegans* Chronozones (BioStrat 2018).

Age. Kimmeridgian, Late Jurassic.

Organic matter. The interval is characterised by abundant amorphous kerogen together with a large proportion of terrestrial organic material from higher land plants, especially brown to black woody material. The

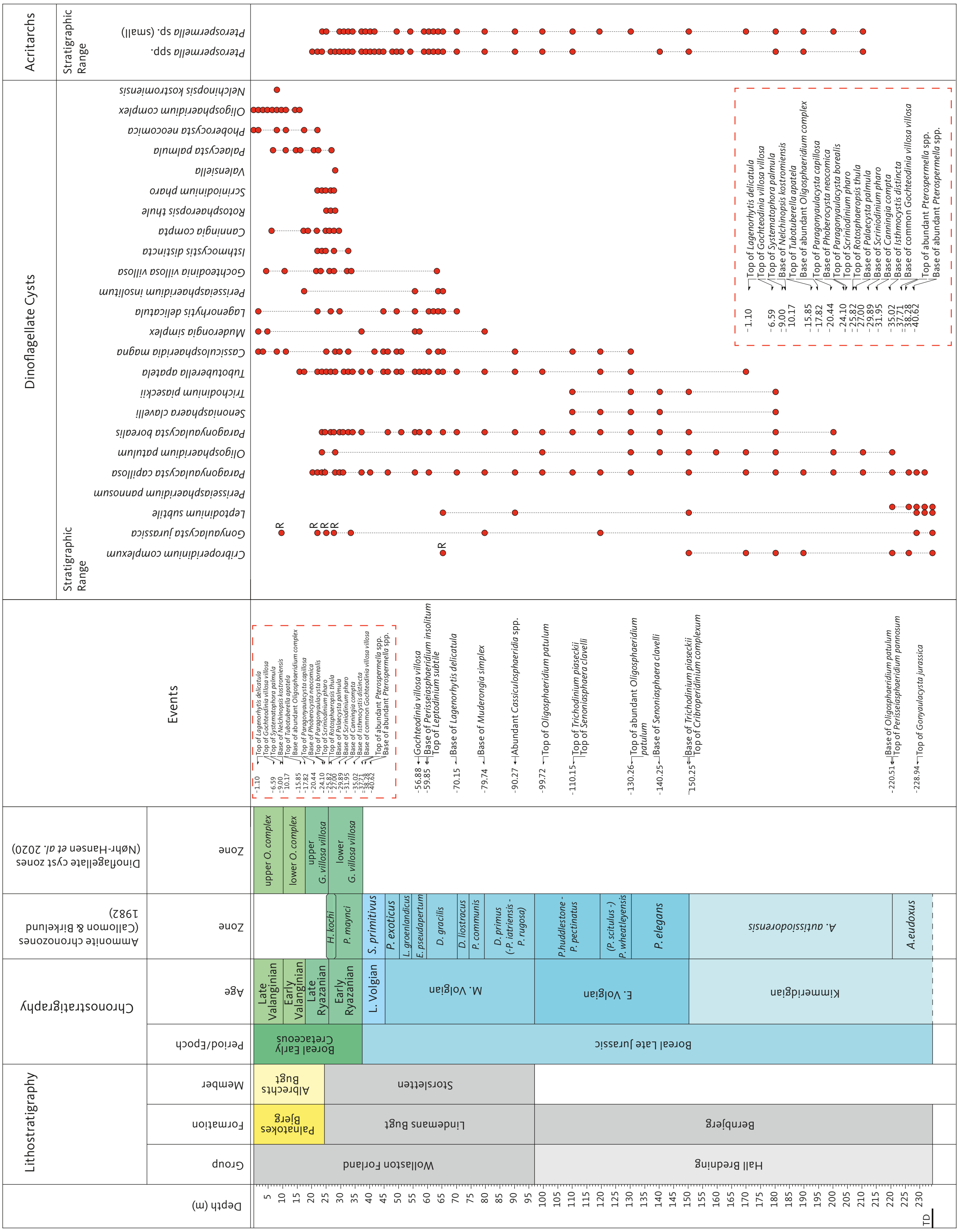

Fig. 7 The ranges of key dinoflagellate cyst taxa in the Rødryggen-1 core. The dinoflagellate cyst species are stratigraphically arranged according to the succession of their lowest occurrences. A range chart showing all taxa recorded in the core is available in Supplementary Data File 1.

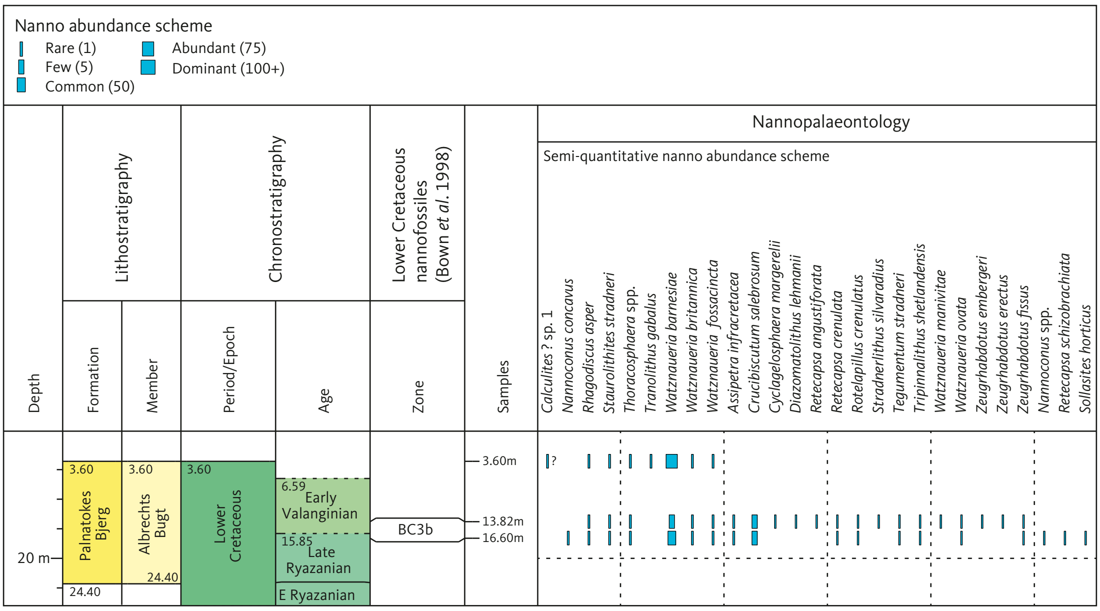

Fig. 8 The distribution of calcareous nannofossils in the Rødryggen-1 core.

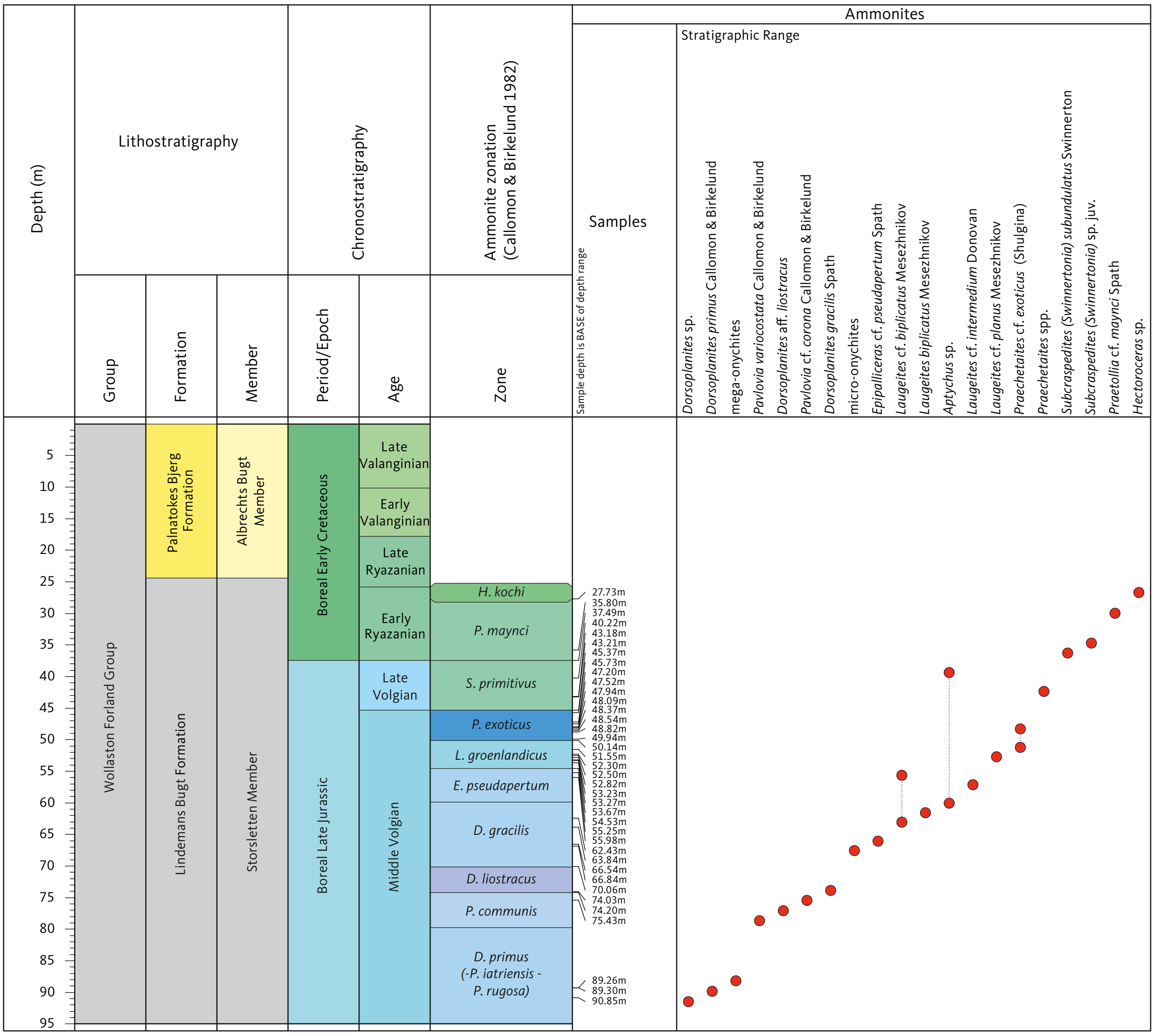

Fig. 9 The ranges of ammonite taxa recorded in the Rødryggen-1 core.

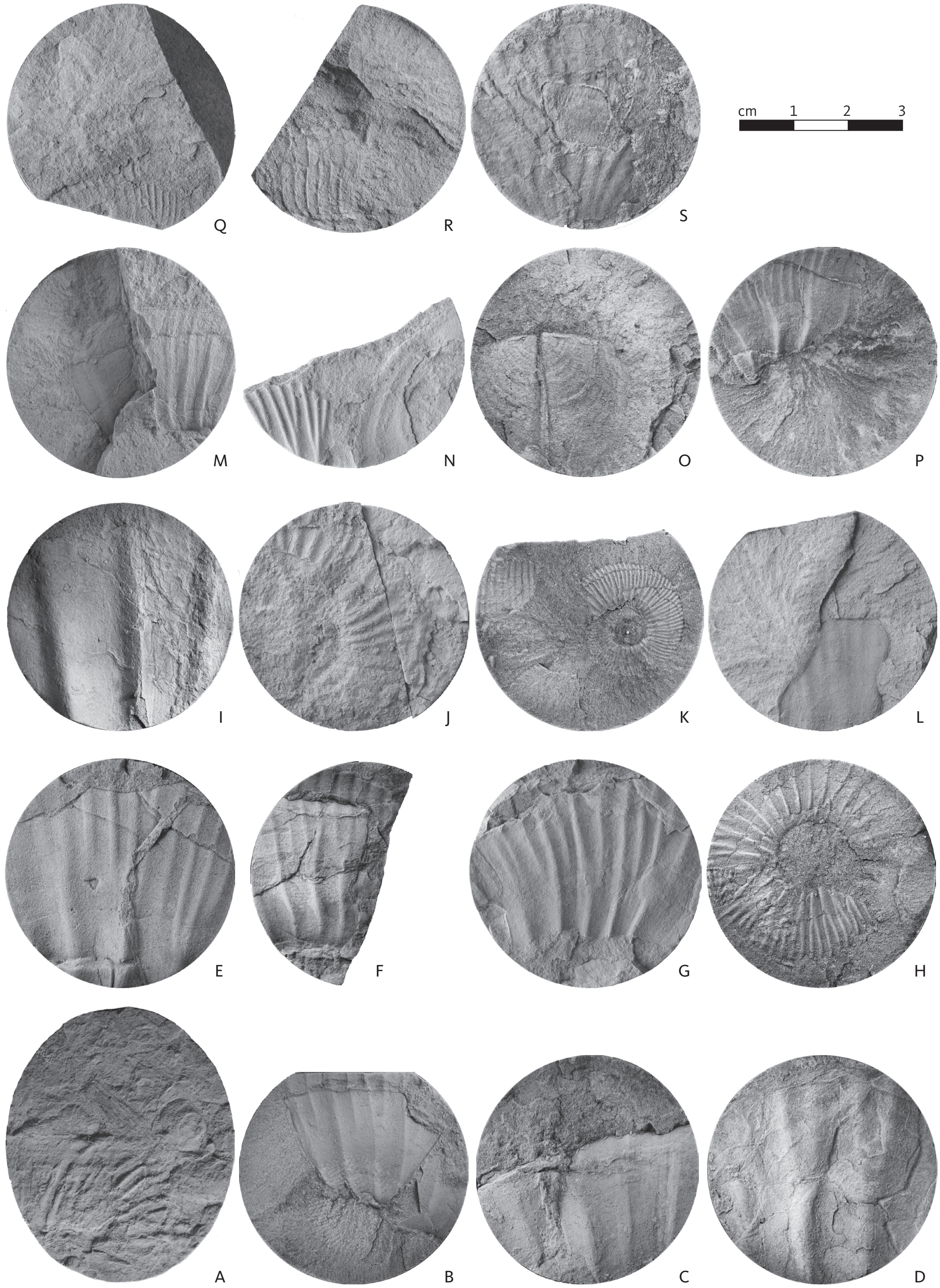

Fig. 10 Selected ammonites recorded in the Rødryggen-1 core. **A**: *Amoeboceras*? sp., level 227.72 m, MGUH 34180. **B**: *Dorsoplanites* sp., level 90.85 m, MGUH 34181. **C**: *Dorsoplanites primus*, level 89.30 m, MGUH 34182. **D**: *Pavlovia cf. variocostata*, level 75.43 m, MGUH 34184. **E**: *Dorsoplanites* aff. *liostracus*, level 74.20 m, MGUH 34185. **F**: *Pavlovia* cf. *corona,* level 74.03 m, MGUH 34186. **G**: *Dorsoplanites jamesoni*, level 70.06 m, MGUH 34187. **H**: *Epipallasiceras* cf. *pseudapertum,* level 55.98 m, MGUH 34189. **I**: *Laugeites* cf. *biplicatus*, level 53.67 m, MGUH 34190. **J**: *Laugeites* cf. *intermedium*, level 52.82 m, MGUH 34191. **K**: *Laugeites* cf. *planus*, level 51.55 m, MGUH 34192. **L**: cf. *Praechetaites exoticus*, level 48.82 m, MGUH 34193. **M**: cf. *Praechetaites exoticus*, level 48.54 m, MGUH 34194. **N**: Ammonoidea indet., level 48.37 m, MGUH 34195. **O**: aptychus, level 47.20 m, MGUH 34196. **P**: *S.* (*Swinnertonia*) cf. *subundulatus*, level 45.37 m, MGUH 34197. **Q**: *Subcraspedites* (*Swinnertonia*) sp. Juv., level. 43.21 m, MGUH 34198. **R**: cf. *Praetollia maynci* Spath, level 37.49 m, MGUH 34199. **S**: *Hectoroceras* sp., level 27.73 m, MGUH 34200. The specimens are stored in the Palaeontology Type Collection at the Natural History Museum of Denmark and each labelled with an MGUH number – Museum Geologica Universitas Hafniensis.

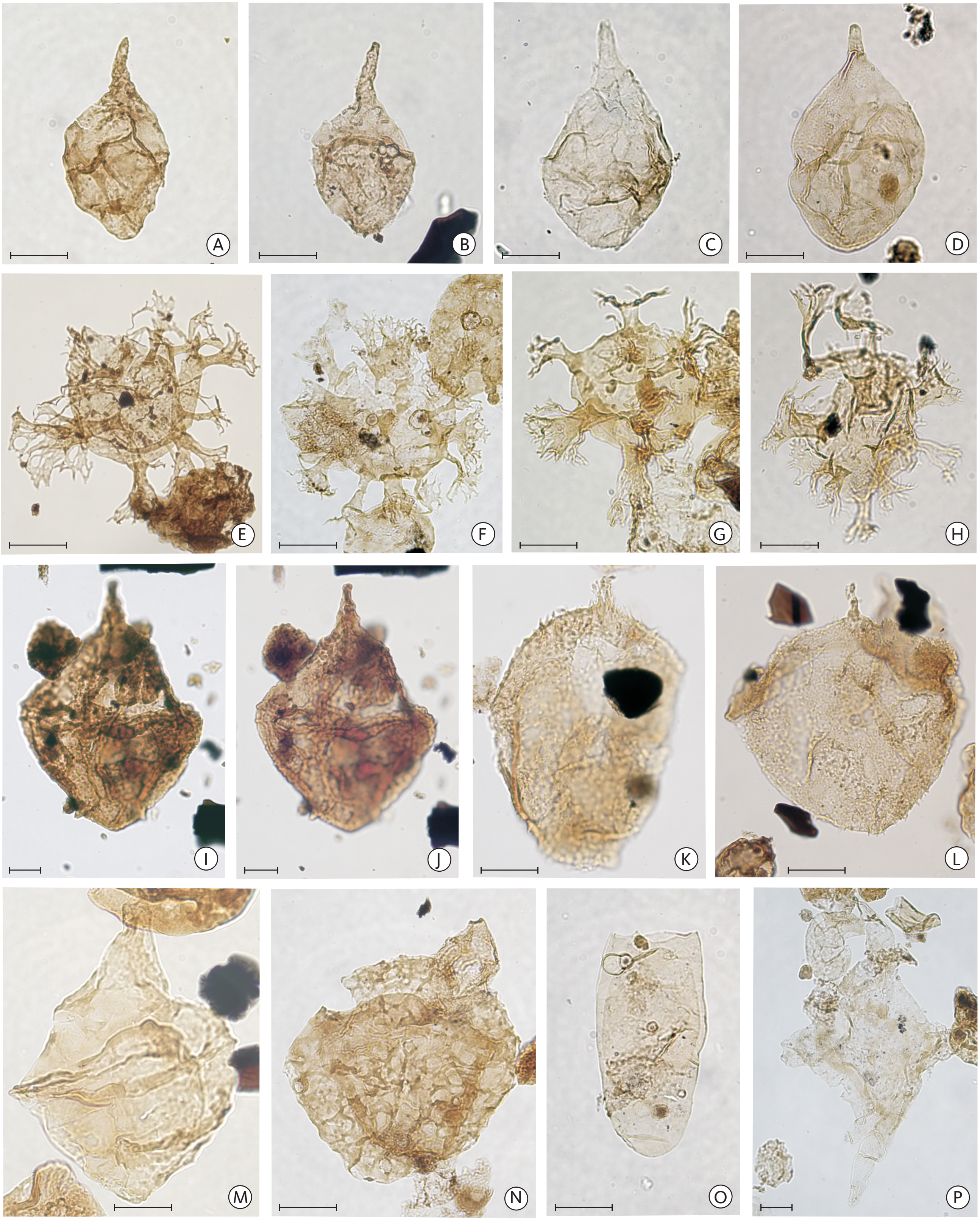

Fig. 11 Selected biostratigraphically significant dinoflagellate cysts and acritarchs from the Rødryggen-1 core. Scale bars: 25 µm. **A** and **B**: *Paragonyaulacysta capillosa*, sample 234.4 m, slide 2. **C** and **D**: *Paragonyaulacysta borealis*, sample 140.25 m, slide 6, and 136.26 m, slide 5. **E** and **F**: *Perisseiasphaeridium pannosum*, sample 226.22 m, slide 4. **G** and **H**: *Oligosphaeridium patulum*, sample 130.26 m, slide 6. **I** and **J**: *Cribroperidinium complexum*, low and high focus on the same specimen, sample 234.5 m, slide 5. **K** and **L**: *Trichodinium piaseckii*, sample 136.26 m, slide 6. **M**: *Senoniasphaera clavellii*, sample 90.27 m, slide 5. **N**: *Cassiculosphaeridium magna*, sample 90.27 m, slide 5. **O**: *Wallodinium krutzschii*, sample 110.15 m, slide 4. **P**: *Muderongia simplex*, sample 76.74 m, slide 4.

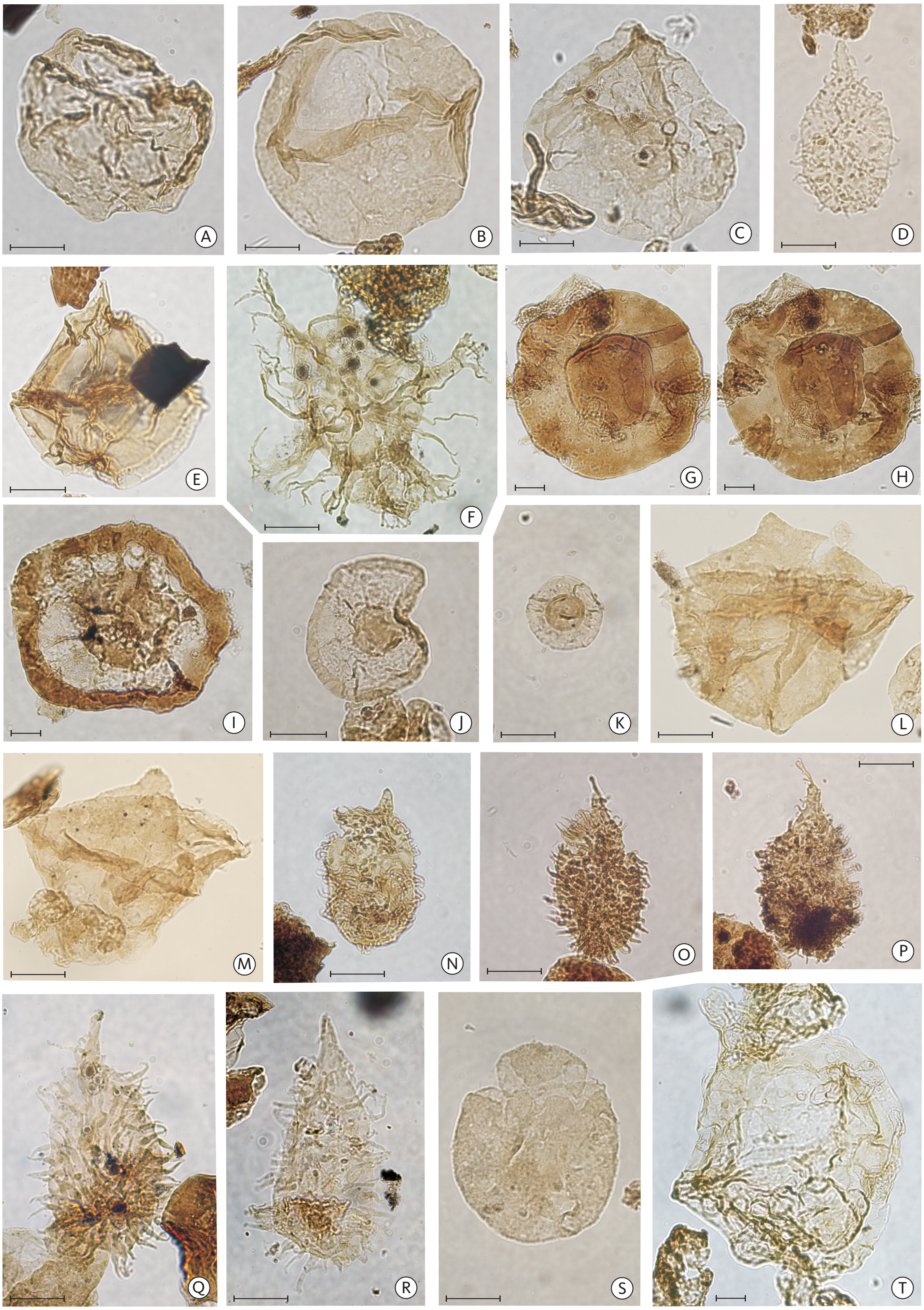

Fig. 12 Selected biostratigraphically significant dinoflagellate cysts and acritarchs from the Rødryggen-1 core. Scale bars: 25 µm. **A**, **B** and **C**: *Lagenorhytis delicatula*, showing variable morphology, sample 54.31 m, slide 7. **D**: *Gochteodinia villosa* subsp. *villosa*, sample 56.88 m, slide 4 and 5. **E**: *Leptodinium subtile*, sample 90.27 m, slide 5. **F**: *Perisseiasphaeridium insolitum*, sample 59.85 m, slide 4. **G**, **H** and **I**: large *Pterospermella* spp., sample 40.62 m, slide 5, and sample 35.2 m, slide 7. **J** and **K**: small *Pterospermella* spp., sample 43.43 m, slide 5 and sample 35.2, slide 7. **L** and **M**: *Isthmocystis distincta*, sample 35.02 m, slide 3. **N**, **O**, **P**, **Q** and **R**: morphological variations of *Gochteodinia villosa* subsp. *villosa*, (N–Q) sample 37.71 m, slide 7, and (R) sample 35.02 m, slide 4. **S**: *Circulodinium compta*, sample 31.95 m, slide 4. **T**: *Scriniodinium pharo*, sample 24.1 m, slide 3.

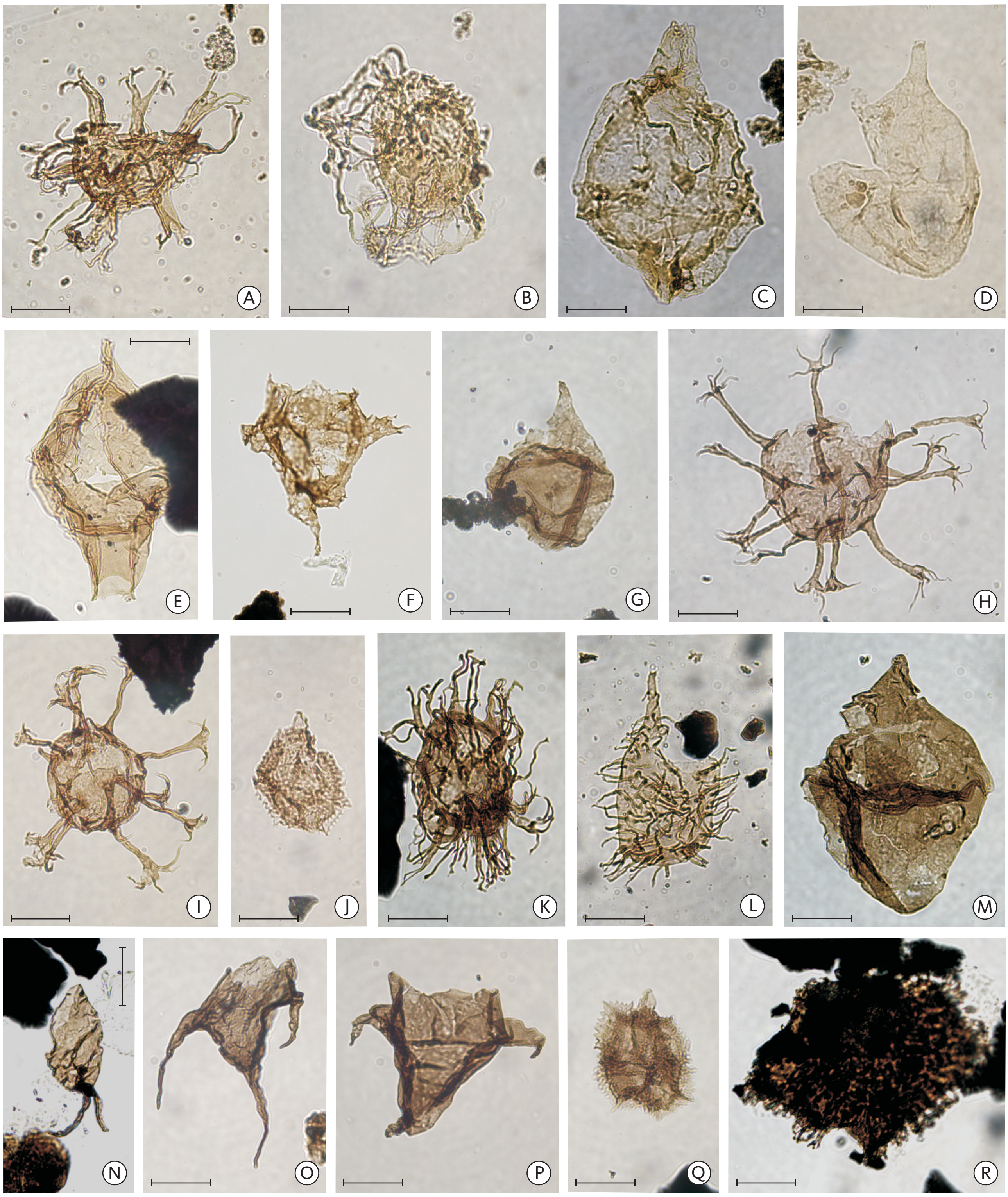

Fig. 13 Selected biostratigraphically significant dinoflagellate cysts and acritarchs from the Rødryggen-1 (A–M) and the Brorson Halvø-1 (N–R) cores. Scale bars: 25 µm. **A**: *Palaecysta palmula*, sample 24.1 m, slide 2. **B**: *Rotosphaeropsis thule*, sample 27.0 m, slide 7. **C**: *Scriniodinium pharo*, sample 27.1 m, slide 3. **D**: *Paragonyaulacysta borealis*, sample 35.2 m, slide 4. **E**: *Tubotuberella apatela*, sample 25.0 m, slide 9. **F**: *Phoberocysta neocomica*, sample 13.2 m, slide 2. **G**: *Paragonyaulacysta capillosa*, sample 21.38 m, slide 2. **H**: *Oligosphaeridium complex*, sample 10.17 m, slide 2. **I**: *Oligosphaeridium complex*, sample 17.82 m, slide 2. **J**: *Nelchinopsis kostromiensis*, sample 10.17 m, slide 2. **K**: *Palaecysta palmula*, sample 9.00 m, slide 2. **L**: *Gochteodinia villosa* subsp. *villosa*, sample 24.1 m, slide 3. **M**: *Lagenorhytis delicatula*, sample 2.78 m, slide 4. **N**: *Batioladinium longicornutum*, sample 3.37 m, slide 3. **O**: *Muderongia tetracantha*, sample 9.18 m, slide 3. **P**: *Muderongia staurota*, sample 9.18 m, slide 3. **Q**: *Nelchinopsis kostromiensis*, sample 6.16 m, slide 3. **R**: *Pseudoceratium anaphrissum*, sample 3.37 m, slide 3.

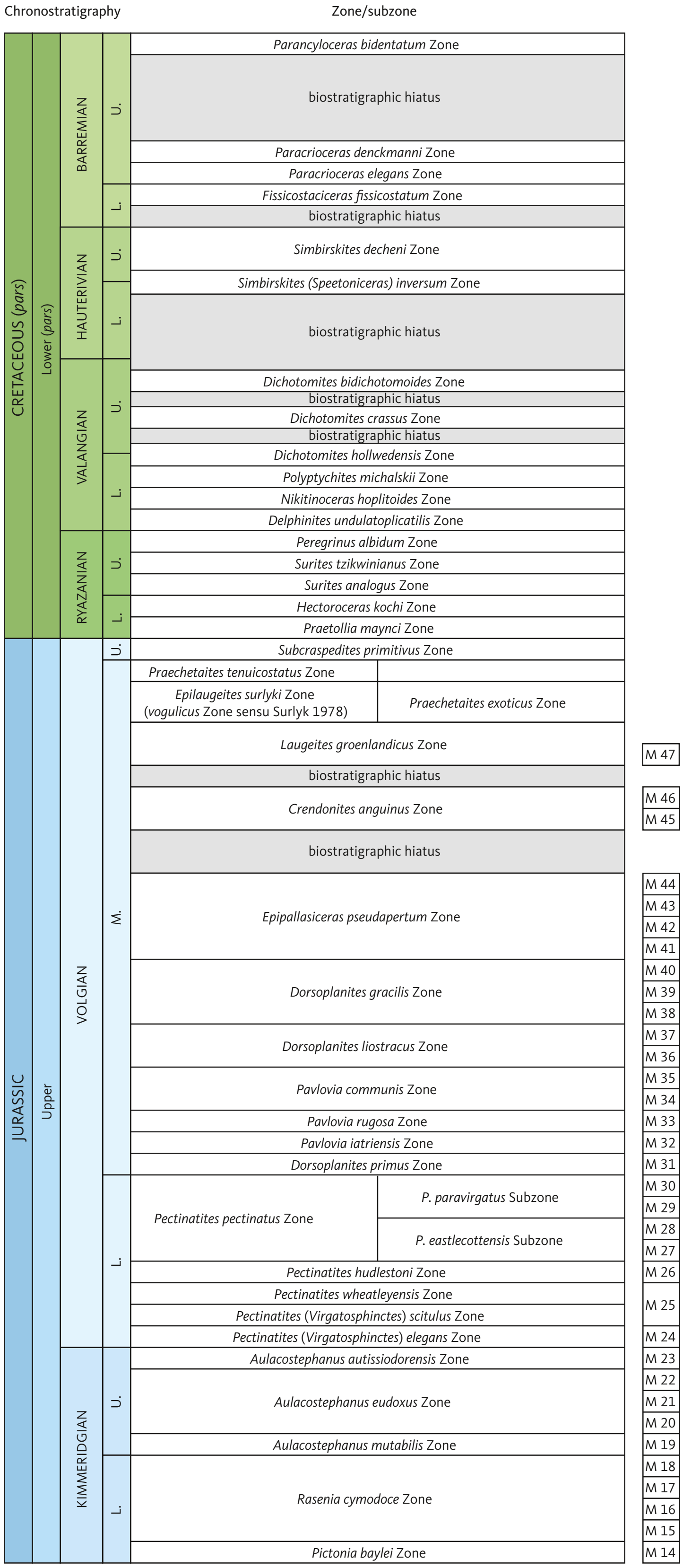

Fig. 14 Kimmeridgian – Barremian ammonite zonation for North-East Greenland. M 14 to M 47 are faunal horizons recorded in Milne Land by Callomon & Birkelund (1982). **L.**: lower. **M.**: middle. **U.**: upper.

presence of dinoflagellate cysts indicates a marine environment, and the dominance of AOM is suggestive of oxygen-deficient bottom conditions.

5.3 *Pectinatites elegans* Chronozone (150.25–130.26 m)

Fossils. The recognition of this chronozone is based on its dinoflagellate cyst record. The dinoflagellate cyst assemblage is characterised by abundant *Oligosphaeridium patulum*, *Cribroperidinium* spp., *Sirmiodinium grossii* and *C. distinctum*. *Paragonyaulacysta capillosa* is common but less frequent upwards. The assemblage is mostly of low diversity and low abundance, probably due to the abundance of organic material.

Biostratigraphy. The base of the zone is recognised as the level with the last occurrence of *Cribroperidinium complexum* and the first occurrence of *Trichodinium piaseckii*.

Age. Early Volgian, Late Jurassic

Organic matter. The interval is characterised by abundant amorphous kerogen together with a large proportion of terrestrial organic material from higher land plants, especially brown to black woody material. The presence of dinoflagellate cysts indicates a marine environment, and the dominance of AOM is suggestive of oxygen-deficient bottom conditions.

5.4 (*Pectinatites scitulus* –) *Pectinatites wheatleyensis* Chronozones undiff. (130.26–119.70 m)

Fossils. The recognition of the interval is based on its dinoflagellate cyst record. The base is placed above the last occurrence of abundant *Oligosphaeridium patulum*. The dinoflagellate cyst assemblage is characterised by *Cribroperidinium* spp. and *Sirmiodinium grossii*. *Apteodinium* spp., *Cassiculosphaeridium magna*, *Paragonyaulacysta capillosa* and *P. borealis* are locally common. The assemblage is recorded as moderately diverse and abundant.

Biostratigraphy. The *P. scitulus* ammonite Zone has never been proven by ammonites in Greenland but is included in the zonal scheme due to the general resemblance of the ammonite successions in Greenland and England (Fig. 14; Birkelund *et al.* 1984). Hence, we refer to it with caution, as indicated by the brackets. The top of abundant *O. patulum* occurs in ammonite faunal horizon M 25 (Piasecki 1996). This succession therefore correlates with the (*P. scitulus* –) *P. wheatleyensis* Chronozones.

Age. Early Volgian, Late Jurassic.

Organic matter. The interval is characterised by abundant amorphous kerogen together with a large proportion of terrestrial organic material from higher land plants, especially brown to black woody material. The presence of dinoflagellate cysts indicates a marine environment, and the dominance of AOM is suggestive of oxygen-deficient bottom conditions.

5.5 *Pectinatites huddlestoni* – *Pectinatites pectinatus* Chronozones undiff. (119.70–97.00 m)

Fossils. The recognition of the interval is based on its dinoflagellate cyst record. *Trichodinium piaseckii* and *Senoniasphaera clavellii* have the highest occurrence in 110.15 m, and the last occurrence of *O. patulum* is at 99.72 m near the top of the interval. The assemblage is characterised by *Oligosphaeridium patulum*, *Paragonyaulacysta capillosa*, *P. borealis* and *Sirmiodinium grossii*. The assemblage is considered moderately diverse and abundant. Within this interval, *Pterospermella* spp. acritarchs have their first appearance and become common and abundant from this interval and upwards until their highest occurrence at 21.38 m.

Biostratigraphy. The last occurrences of *Trichodinium piaseckii* and *Senoniasphaera clavellii* are recorded between ammonite fauna horizons M 25 and M 29, *P. wheatleyensis* and *P. pectinatus* Chronozones in Milne Land (Fig. 14; Piasecki 1996). This is in accordance with the type occurrences of the zonal index species in the North Sea region, UK (Bailey *et al.* 1997). The last consistent occurrence of *O. patulum* in Milne Land is a few metres above fauna M 25, *P. wheatleyensis* Zone.

Age. Early Volgian, Late Jurassic.

Organic matter. Abundant amorphous kerogen together with terrestrial organic material from higher land plants, especially sporomorphs and brown to black woody material, characterises the interval. The black woody material becomes more lath-shaped upwards in the succession. The presence of dinoflagellate cysts indicates a marine environment, and the dominance of AOM is suggestive of oxygen-deficient bottom conditions.

5.6 *Dorsoplanites primus* Chronozone (and *Pavlovia iatriensis* and *Pavlovia rugosa* Chronozones; 97.00–79.74 m)

Fossils. The recognition of this zone(s) is based on its content of dinoflagellate cysts and ammonites. The base is placed below the lowest occurrence of *Dorsoplanites* ammonites (Table 1) at the lithostratigraphic boundary between the Bernbjerg and Lindemans Bugt Formations (97 m). The interval marks the first appearance of ammonites after

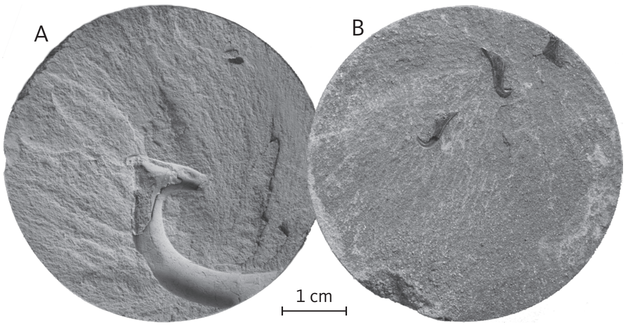

Fig. 15 Onychites in Rødryggen-1 core. **A**: mega-onychites, level 89.26 m, MGUH 34183. **B**: micro-onychites, level 62.43 m, MGUH 34188.

an interval barren of ammonites between 199.42 m and 90.85 m. A crushed, medium-sized ammonite fragment at 90.85 m, showing subdued ribbing with straight primaries and intercalated secondaries beginning on mid-flank and a gently sloping umbilical wall, is assigned to *Dorsoplanites* sp. (Fig. 10B; Table 1). A small fragment of a large specimen found at 89.30 m has straight, blunt distant ribs that bifurcate very high. The specimen is crushed but identified as the zonal index species *D. primus* by Callomon & Birkelund (1982; Fig. 10C; Table 1). In addition, mega-onychites – arm hooks of belemnites – are encountered (Fig. 15A; Table 1).

The palynomorph assemblage from one sample contains abundant dinoflagellate cysts: *Cassiculosphaeridium magna* and *Leptodinium subtile* and common *Cribroperidinium* spp., *Paragonyaulacysta borealis*, *Sirmiodinium grossii*, *Tubotuberella apatela*, as well as the acritarch *Pterospermella* spp. The dinoflagellate cyst assemblage is relatively diverse and abundant, but chorate dinoflagellate cysts are essentially absent.

Biostratigraphy. *Dorsoplanites primus* indicates the faunal horizon M 31 in Milne Land. The general appearance of the genus *Dorsoplanites* in the East Greenland ammonite succession is recorded in the *D. primus* Zone and ranges up to M 42 in the upper middle Volgian *Crendonites anguinus* Zone (Fig. 14; Callomon & Birkelund 1982). The first occurrence of *Dorsoplanites* encountered here agrees well with the presence of the *D. primus* Zone. Mega-onychites are generally considered indicative of Upper Jurassic deposits, Kimmeridgian–Volgian strata, in the Arctic part of the Boreal Realm (Hammer *et al*. 2013). The lack of age-diagnostic fossils in the upper part of this interval leaves room for the presence of the *P. iatriensis* and *P. rugosa* Zones, which are thus indicated with caution. The dinoflagellate cysts *Cassiculasphaeridium* spp. have their maximum abundance in this interval. BioStrat (2018) reports a maximum occurrence of *Cassiculasphaeridium* spp. in the middle of the Subboreal *P. pallasioides* ammonite Chronozone, which probably corresponds to the Boreal *D. primus* – *P. iatriensis* ammonite Chronozones (Callomon & Birkelund 1982).

Age. Earliest middle Volgian, Late Jurassic.

Organic matter. Abundant amorphous kerogen together with terrestrial organic material from higher land plants, especially sporomorphs and brown to black woody material, characterises the interval. Lath-shaped, black woody material is common. The presence of dinoflagellate cysts indicates a marine environment, and the dominance of AOM is suggestive of oxygen-deficient bottom conditions.

5.7 *Pavlovia communis* Chronozone (79.74–74.20 m)

Fossils. The recognition of the zone is based on its content of dinoflagellate cysts and ammonites. The base is placed at the lowest appearance of *Muderongia simplex*. One ammonite is recorded in the interval (75.43 m; Table 1). The visible section of the ammonite shows coarse, biplicate rursiradiate ribbing from a large form, resembling various species within the genus *Pavlovia.* It appears closest to *P. variocostata* Callomon & Birkelund, characterised by a modification to subdued, irregular widely spaced and extremely coarse biplicate ribs in adult stage*.* Considering the restricted visible part, the present specimen is cautiously referred to as *P.* cf. *variocostata* (Fig. 10D).

The dinoflagellate cyst assemblage, based on one sample (79.74 m), contains *Apteodinium* spp., *Cribroperidinium* spp., *Muderongia simplex*, *Sirmiodinium grossii*, *Paragonyaulacysta borealis* and *P. capillosa*. The diversity of the assemblage is relatively high, whereas the abundance is low. Chorate cysts are almost absent.

Biostratigraphy. In North-West Europe, the lowest appearance of common *Muderongia simplex* spp. is well established in the *P. rotunda* (ammonite) Zone (e.g. Riding & Thomas 1992; Riding *et al*. 2000). The *P. rotunda* Zone is correlated with the *P. communis* Zone (M 34 to M 35) in East Greenland (Fig. 14; Birkelund *et al.* 1984). The first appearance of *Muderongia simplex* is thus here considered to indicate the *P. communis* Zone. This agrees well with the presence of the ammonite *P.* cf. *variocostata*, recorded *c.* 4 m higher in the core. The ammonite indicates the M 35 faunal horizon, which lies in the upper part of the *P. communis* Zone (Fig. 14; Callomon & Birkelund 1982). The appearance of *Muderongia simplex* in Milne Land occurs somewhat higher, in the faunal horizon M 46, in the *C. anguinus* ammonite zone (Piasecki 1996) corresponding to its highest common occurrence in North-West Europe (Riding *et al*. 2000).

Age. Middle Volgian, Late Jurassic.

Organic matter. Abundant amorphous kerogen together with terrestrial organic material from higher land plants, mainly spores and pollen and brown to black woody material, characterises the interval. Lath-shaped, black woody material is common. The presence of dinoflagellate cysts indicates a marine environment, and the dominance of AOM is suggestive of oxygen-deficient bottom conditions.

5.8 *Dorsoplanites liostracus* Chronozone (74.20–70.15 m)

Fossils. The base of this zone is placed at the occurrence of an ammonite specimen. No samples were analysed for dinoflagellate cysts within this interval. Two ammonite specimens were found at closely spaced levels (Table 1). The lower ammonite, a large form, shows dense, subdued ribbing, with blunt primaries that divide almost in a fasciculate manner into 3–4 secondaries and intercalatories. The subdued ribbing somewhat resembles, but does not exactly match, that of *Dorsoplanites liostracus* Callomon & Birkelund. The present specimen is thus tentatively referred to *Dorsoplanites* aff. *liostracus* (Fig. 10E). The higher specimen is a crushed fragment with slightly flexuous, relatively strong, blunt primary ribs and weak intercalating secondaries (Fig. 10F). This ribbing style resembles that of the much larger *Pavlovia corona* Callomon & Birkelund (1982, pl. 3, fig. 1). The present specimen is thus referred to *P.* cf. *corona*.

Biostratigraphy. Both *P.* aff. *liostracus* and *P.* cf. *corona* indicate the faunal horizon M37 in the upper part of the *D. liostracus* Zone (Fig. 14; Callomon & Birkelund 1982).
Age. Middle middle Volgian, Late Jurassic.
Organic matter. No palynological samples.

5.9 *Dorsoplanites gracilis* Chronozone (70.15–59.85 m)

Fossils. The base of this interval is placed at the lowest occurrence of the dinoflagellate cyst *Lagenorhytis delicatula*. The interval contains both ammonites and dinoflagellate cysts. A few centimetres above the base of the zone, an ammonite fragment from an apparently evolute form shows ornamentation with relatively distant ribs (Fig. 10G). Primaries are blunt, gently prorsiradiate and forward concave. Secondaries mostly intercalate and develop at mid-flank. Considering the presence of *P.* cf. *corona* in the underlying zone and *E.* cf. *pseudapertum* in the overlying zone, the closest resembling ammonite forms are likely to be found in the *Dorsoplanites gracilis* group in the faunal horizons M 37 to M 42 and are assigned to the *D. liostracus* – *E. pseudapertum* Zones, middle Volgian East Greenland (Spath 1936; Callomon & Birkelund 1982). The ribbing pattern of the present specimen resembles the 'indistinct' pattern of *Dorsoplanites jamesoni* Spath (1936, pl. 29, fig. 3). Additional fossils include a crushed indeterminate ammonite, a poorly preserved recrystallised belemnite rostrum and small onychites (Fig. 15B; Table 1). The dinoflagellate cyst assemblage is relatively diverse and moderately abundant. It is dominated by *Lagenorhytis delicatula*, the acritarch *Pterospermella* spp. and *Cribroperidinium* spp. Chorate cysts are absent.

Biostratigraphy. The exact assignment of the species *Dorsoplanites jamesoni* to a faunal horizon remains, but it probably belongs to the upper part of the *D. gracilis* Zone and possibly the M 40 faunal horizon (Fig. 14; Birkelund *et al.* 1984).

The first appearance of *Lagenorhytis delicatula* is just below the occurrence of the ammonite *Dorsoplanites jamesoni* at 70.06 m. *L. delicatula* is generally assigned a Lower Cretaceous range (Costa & Davey 1992) and is also present here in Ryazanian strata higher in the core. Hence, its first appearance in the middle Volgian *D. gracilis* Zone and consistent presence into the overlying Ryazanian are surprising, and its first occurrence in the middle Volgian potentially represents an excellent local marker event.

Age. Middle middle Volgian, Late Jurassic.

Organic matter. The interval is characterised by abundant amorphous kerogen, together with limited terrestrial organic material, mainly as spores and pollen, black woody material and carbonised, rounded grains. The presence of dinoflagellate cysts indicates a marine environment, and the dominance of AOM is suggestive of oxygen-deficient bottom conditions.

5.10 *Epipallasiceras pseudapertum* Chronozone (59.85–54.53 m)

Fossils. The base of this zone is placed at the uppermost occurrence of *Leptodinium subtile*. The interval contains both ammonites and dinoflagellate cysts. A small ammonite with well-preserved, relatively distant ribbing has strong, straight, prorsiradiate primaries that divide rather high up on the flank into two secondaries (Fig. 10H). It resembles *Epipallasiceras pseudapertum* Spath (1936; pl. 9, fig. 4) and is cautiously referred to *E.* cf. *pseudapertum.* A level less than one metre higher contains another, but poorly preserved and indeterminate, ammonite (Table 1).

The dinoflagellate cyst assemblage, based on three samples, is abundant and diverse. It is dominated by *Cribroperidinium* spp. with common *Lagenorhytis delicatula* and *Apteodinium daveyi* in the lower part. Rare, small and poorly preserved *Gochteodinia villosa villosa* and *Gochteodinia* spp. occur at 56.88 m but are not recorded in any samples above until 37.71 m, in the *Subcraspedites primitivus* Zone (upper Volgian). Chorate and cavate cysts are rare in the lower sample and slightly more common in the upper sample.

Biostratigraphy. The ammonite indicates the M-42 faunal horizon and is the index of the middle Volgian *E. pseudapertum* Zone (Fig. 14). This is in good biostratigraphic accordance with the record of the uppermost occurrence of the dinoflagellate cyst *L. subtile*, which is a well-known marker from North-West Europe, where it has its highest occurrence in the *P. albani* Zone (Riding & Thomas 1992). The upper *P. albani* Zone is correlated with the *E. pseudapertum* Zone in the East Greenland ammonite zonation (Birkelund *et al.* 1984). The first appearances of *Perisseiasphaeridium insolitum* and *Apteodinium daveyi* at 59.85 m are slightly earlier than the recorded first occurrence of both species in the *Galbanites okusensis* – *G. kerberus* ammonite zones in England (Davey 1982). The dinoflagellate cyst assemblage (59.85–55.88 m) is dominated by *Cribroperidinium* spp. but becomes poorer upwards.

Age. Middle middle Volgian, Late Jurassic.

Organic matter. This interval records a significant change to a low content of organic matter in general, especially of terrestrial woody material; this shift appears in the lower *E. pseudapertum* Chronozone and continues upwards to the *Subcraspedites primitivus* Chronozone in the upper Volgian. This is combined with low abundance and diversity of the dinoflagellate cysts assemblage. A fully marine environment is indicated by the fossil record.

5.11 *Laugeites groenlandicus* Chronozone (54.53–50.14 m)

Fossils. The zone is recognised by its ammonite assemblage, whereas the dinoflagellate cyst assemblage is impoverished and poorly preserved. Acritarchs are present but have little stratigraphic value. The base of the zone is placed at the lowest occurrence of a possible *Laugeites* ammonite (54.53 m), a few centimetres below a fragment of an apparently very large *Laugeites* (Table 1). The latter is characterised by straight, strong and distant primary ribs, which begin sharp but appear to become blunt and flatten on or towards the (mid?-)flank (Fig. 10I). It resembles *Laugeites biplicatus* Mesezhnikov figured by Repin *et al.* (2006), although that specimen is somewhat different from the holotype established by Mesezhnikov (in Zakharov & Mesezhnikov 1974). Considering its fragmented nature, the specimen from the core is cautiously referred to *L.* cf. *biplicatus.* Further levels with ammonites include *L.* cf. *intermedius* Donovan, another *L.* cf. *biplicatus* and *L.* cf. *planus* Mesezhnikov (in Zakharov & Mesezhnikov 1974; Table 1). The former closely resembles the specimen figured by Donovan (1964, pl. 1, fig. 5) from Laugeites Ravine, Kuhn Ø (Fig. 10J). The second is a fragment with distant, low, blunt ribs, which resembles the ornamentation on the mid-flank in the outer whorls of *Laugeites biplicatus* as seen in, for example, Repin *et al*. (2006, pl. 47, fig. 2) and Rogov (2010, pl. 4, fig. 6). The latter is a complete, small juvenile (?) specimen with relatively high whorl sides and narrow umbilicus, very dense and delicate ribbing with more than 31 primaries per whorl that divide or bifurcate almost immediately or low on the flank into dense and fine secondaries (Fig. 10K). Ribbing is slightly concave. By comparison with material figured by Donovan (1964) and Surlyk *et al*. (1973), the specimen is referred to the genus *Laugeites*, which is characterised as being smaller, more compressed and more delicately ribbed than its predecessor *Dorsoplanites* (see discussion in description of *Dorsoplanites intermissus* in Callomon & Birkelund 1982, appendix, p. 368). *L. parvus* Donovan and other Greenland *Laugeites* closely resemble the specimen but have more forward-leaning ribs, whereas the ribbing on the present specimen is almost radiate. The closest resemblance of our specimen is with *Laugeites planus* Mesezhnikov (in Zakharov & Mesezhnikov 1974) from subarctic Urals, Russia. In addition, the interval contains indeterminate, crushed ammonite fragments and aptychi (Table 1).

The dinoflagellate cyst assemblage (samples from 54.31–50.53 m) is poor in the lower part of the zone with common *Apteodinium*, *Cribroperidinium* and *Lagenorhytis*. The acritarchs *Cymatiosphaera*, *Veryhachium*, *Pterospermella*, *Leiosphaeridia* and the prasinophyte algae *Tasmanites* occur scattered amongst the dinoflagellate cysts and become common in the upper part of the zone where dinoflagellate cysts disappear.

Biostratigraphy. In North-East Greenland, the genus *Laugeites* is restricted to the M 47 faunal horizon in the *Laugeites groenlandicus* Zone (Fig. 14; Spath 1936; Donovan 1964; Surlyk 1978; Callomon & Birkelund 1982). The present records of *L.* cf. *planus* and *L.* cf. *biplicatus* are new for Greenland, where *L. groenlandicus* (Spath 1936), *L. parvus* Donovan (1964) and *L. intermedius* Donovan (1964) had been recorded previously. *L. biplicatus* indicates the *Epivirgatites nikitini* Zone in Russia, which is correlative to the upper part of the *Laugeites groenlandicus* Zone and the overlying *Epilaugeites vogulicus* Zone *sensu* Surlyk (1978), i.e. M 47 and higher levels (Rogov 2010, 2020). In the Rødryggen-1 core, *L.* cf. *biplicatus* occurs below *L.* cf. *planus*, which indicates the *Laugeites groenlandicus* Zone and M 47 faunal horizon; this delimits the occurrence of *L.* cf. *biplicatus* in the core to the

L. groenlandicus Zone. Note that Kelly *et al.* (2015) and Rogov (2020), based on observations of the ammonite faunal succession in Perisphinctes Ravine, eastern Kuhn Ø (Fig. 2), added another faunal horizon, the *L. lambecki* horizon, above the M 47 *Laugeites groenlandicus* horizon, to the *L. groenlandicus* Zone. However, Callomon & Birkelund (1982) argued that the *Laugeites* fauna recorded in the northern Wollaston Forland and Kuhn Ø areas by Donovan (1964) and Surlyk (1978) represents the higher part of the *L. groenlandicus* Zone. It seems more justified to introduce a *L. parvus* horizon, based on Donovan's and Surlyk's documentation of the fauna, above the M 47 horizon, rather than an *L. lambecki* horizon and zone.

The absence of *Crendonites anguinus* Zone fossils is not necessarily attributed to a hiatus, given that there are no sedimentological or depositional signs of erosion. The zone is thus considered not proven in the core, either due to the low sample density or due to low sedimentation rates.

Age. Late middle Volgian.

Organic matter. The interval contains very little organic matter with few or no dinoflagellate cysts. Despite the dominance of acritarchs and terrestrial organic material, the presence of ammonites testifies to continued fully marine conditions.

5.12 *Praechetaites exoticus* Chronozone (50.14–45.37 m)

Fossils. The zone is recognised by its ammonite assemblage, whereas the dinoflagellate cyst assemblage is poor and poorly preserved. Acritarchs are present but have little stratigraphic value. The interval is relatively rich in macrofossils containing several ammonites, various bivalves, including *Buchia*, and ammonite aptychi. The base is placed at 50.14 m, at the occurrence of a crushed ammonite fragment with relatively distant, low, sharp, primary ribs that divide into three closely spaced low, sharp, secondary ribs (Table 1). The ornamentation is close to that in inner–middle whorls of *Praechetaites exoticus* (Shulgina) as illustrated in, for example, Shulgina (1967, pl. 1, fig. 1b). An ammonite occurring *c.* 1.5 m higher is a fragment, probably from mid-flank, with very faint ribbing of distant primaries that are very low, almost smooth, developing into faint secondaries and intercalatories (Fig. 10L) similar to ornamentation in the mid-flank of *Praechetaites exoticus* (Shulgina; e.g. Shulgina 1967, pl. 4, fig. 1; Rogov 2010, pl. 6, fig. 5). A few centimetres higher in the core, another ammonite fragment has low, wide, relatively sharp crested ribs that appear to develop into faint sheaves of very fine lirae-like secondaries (Fig. 10M), resembling the ornamentation observed in *Praechetaites exoticus* (Shulgina; e.g. Shulgina 1967, pl. 4, fig. 1). Considering their preservation, the fragments are with some caution referred to *Praechetaites* cf. *exoticus* (Shulgina). Two additional ammonites are indeterminate fragments, one of them possibly also belonging to the genus *Praechetaites* (Fig. 10N; Table 1).

The dinoflagellate cyst assemblage varies from barren to poor. Reworked specimens become more common, with specimens of *Wanaea* and *Nannoceratopsis*. Acritarchs are present in all samples, for example, *Fromea*, *Pterospermella* and *Leiosphaeridia*.

Biostratigraphy. *P. exoticus* is the index species of the Northern Siberian *P. exoticus* Zone. Its presence in Greenland closely above the *L. groenlandicus* Zone does not leave much room for the *Epilaugeites vogulicus* Zone that supposedly overlies the *Laugeites groenlandicus* Zone (Fig. 14; Surlyk 1978). It could thus be that the *P. exoticus* and *E. vogulicus* Zones may be time-equivalent correlatives. However, since representatives of the two zones were so far not found together, it remains uncertain whether *P. exoticus* occurs in the *E. vogulicus* Zone in Greenland and thus would link the Russian and Greenland zones, or whether the *P. exoticus* Zone may represent a level in between the *L. greenlandicus* Zone and the *E. vogulicus* Zone. Rogov (2010, 2020) correlated the *P. exoticus* Zone to both the *E. vogulicus* Zone and the *P. tenuicostatus* Zone or beds in Greenland. Rogov & Zakharov (2011) noted that the specimens of *E. vogulicus* from Greenland (Surlyk *et al*. 1973; Surlyk 1978) differ from 'true' *E. vogulicus* in Siberia (Ilovaisky 1917; Mikhailov 1966; Zakharov & Mesezhnikov 1974). Accordingly, the Greenland records were referred to a new species, *E. surlyki* Rogov (2020), which thus also becomes index for the *E. surlyki* Zone in Greenland.

Age. Latest middle Volgian. It should be noted, however, that there is disagreement amongst Russian ammonite stratigraphers about whether the *P. exoticus* Zone should be attributed to the uppermost middle or the lowermost upper Volgian (Meledina *et al*. 2010; Rogov & Zakharov 2011). The unit was originally introduced as a subzone in the lowest part of the *Craspedites okensis* Zone (upper Volgian), whereas the ammonite succession in the Jurassic–Cretaceous boundary key section at Nordvik suggests that the *P. exoticus* Zone should be referred to the uppermost middle Volgian (e.g. Zakharov & Rogov 2006, 2008; Rogov & Zakharov 2009, 2011; Rogov 2020).

Organic matter. The interval has a very low organic content. Marine palynomorphs are rare or absent, although acritarchs are present. They contain a limited component of terrestrial organic material, mostly sporomorphs and unstructured organic material. Woody material is mostly carbonised and degraded to small angular fragments. Although the palynomorphs provide a predominantly terrestrial signal, ammonites are present indicating a fully marine environment.

5.13 *Subcraspedites primitivus* Chronozone (45.37–37.49 m) and lowermost *Gochteodinia villosa villosa* Zone (NEG Cr 1; 37.71–37.49 m)

Fossils. The interval is recognised from its ammonite and dinoflagellate cyst content. The base of the *S. primitivus* Zone is located at the occurrence of an ammonite fragment showing strong, distant, bullate primaries that divide into somewhat weak secondaries (Fig. 10P; Table 1). These sets of secondaries are intercalated with weak ribs that start at a level equal to the furcation level of the primaries, resulting in an appearance of distant primaries and dense secondaries and intercalatories. The bullate primaries are forward-leaning, whereas the rear secondary in the rib sets is relatively rectiradiate on the mid-flank before leaning forward towards the ventral shoulder. This gives a sinuous appearance of the ornamentation. The closest resemblance is found outside Greenland in the taxon *Subcraspedites* (*Swinnertonia*) *subundulatus*, known from England (Casey 1973). It has similar distant primaries and dense secondaries with a sinuous appearance. The limited material only allows cautious reference to *S.* (*S.*) cf. *subundulatus.* Another fragment of a small ammonite, a couple of metres higher in the core, shows dense, fine, delicate parallel ribbing (Fig. 10Q; Table 1). Its reference to *Subcraspedites* (*Swinnertonia*) sp. juv. rests both on the other specimen described from the zone and on comparison with the similarly finely ribbed juvenile *Subcraspedites* (*Swinnertonia*) sp. juv. from England (Casey 1973, pl. 4). In addition, the interval contained another ammonite fragment, poorly preserved and not sampled, and a *Buchia* bivalve.

Dinoflagellate cysts are rare or absent. Relatively common taxa are *Apteodinium daveyi*, *Cribroperidinium* spp., *Cassiculosphaeridium magnum* and *Sirmiodnium grossii*. Other species are present but very rare in one or two samples, whereas acritarchs, especially *Pterospermella* spp., are common to abundant in a thin interval (40.62–38.28 m). Stratigraphically significant species are generally missing, but the appearance of *Gochteodinia villosa villosa* in the *S. primitivus* Chronozone indicates the lower boundary of the *G. villosa villosa* Zone (NEG Cr 1; Nøhr-Hansen *et al*. 2020) and is followed by consistent *G. villosa villosa* in higher strata. This event is stratigraphically slightly higher (one ammonite zone) than the reported first appearances in the Subboreal region (*Paracraspedites oppressus* Zone; e.g. Woollam & Riding 1983), but, in contrast, the odd occurrence of rare *G. villosa villosa* mentioned above in the *E. pseudapertum* Chronozone (59.85–54.53 m) is much lower. From the Russian Platform, Riding *et al.* (1999) report the first appearance of rare *G. villosa* in the *Kachpurites fulgens* ammonite Zone, which they correlate with the *Subcraspedites preplicomphalus* Ammonite Zone of North-West Europe (Rogov 2020).

Presumed reworked dinoflagellate cysts are present, for example, *Ambonosphaera staffinensis*, *Gonyaulacysta jurassica*, *Endoscrinium galeritum*, *Nannoceratopsis* sp., *Pareodinia halosa* and *Taeniaesporites iunctispina*, mostly derived from Oxfordian–Kimmeridgian strata.

Biostratigraphy. *Subcraspedites* (*Swinnertonia*) *subundulatus* occurs in the upper Volgian *Subcraspedites* (*Swinnertonia*) *primitivus* Zone in England (Casey 1973, pl. 4, fig. 1). That zone is now adopted in the East Greenland zonation (Fig. 14). The upper Volgian is poorly represented by ammonites in Greenland, and the Upper Jurassic key section in Milne Land has a hiatus between the middle Volgian *Epilaugeites surlyki* Zone and the lower Valanginian (Callomon & Birkelund 1982). A more complete Volgian succession appears to occur in the Wollaston Forland area. In addition to the *S. primitivus* Zone recorded here in the Rødryggen-1 core, Rogov (2010, 2020) recognised *Supracraspedites sowerbyi* in the faunal succession, presumably in the CASP collection from Perisphinctes Ravine, eastern Kuhn Ø (Fig. 2; Kelly *et al*. 2015). The specimens were assigned to 'Beds with *S. sowerbyi*'. The species as such indicates the *S. preplicompalus* Zone in England, where it overlies the *S. primitivus* Zone (Casey 1973). Rogov (2010, 2020) also identified beds with *Chetaites chetae* overlying *Subcraspedites sowerbyi*. The upper Volgian may thus possibly be subdivided into *S. primitivus* – *S. preplicomphalus* – *C. chetae* zones. The *Gochteodinia villosa villosa* Zone (*Nøhr-Hansen et al.* 2020) is revised. The lower boundary is now defined by the first occurrence of common presence *G. villosa villosa.* It was previously defined by the first occurrence of the taxon, but random records of *G. villosa villosa* stratigraphically lower than the *G. villosa villosa* Zone in the East Greenland successions makes the former definition inaccurate.

Age. Late Volgian.

Organic matter. The organic content is low, and terrestrial woody material is rare. The diversity and abundance of marine plankton is low in this zone and becomes significantly reduced up through the zone; the lowest content is recorded in the uppermost sample (38.28 m).

5.14 *Praetollia maynci* Chronozone and lower *Gochteodinia villosa villosa* Zone (NEG Cr 1; 37.49–27.73 m)

Fossils. The interval is recognised from its ammonite and dinoflagellate cyst content. The base of the zone is placed at the occurrence of an ammonite fragment (37.49 m) with delicate, low, sharp, slightly sinuous ribs (Fig. 10R; Table 1). Its ornamentation resembles *Praetollia maynci* Spath as illustrated in, for example, Spath (1952) and Surlyk (1978, pl. 5, fig. 1). A *Buchia* bivalve was also recorded in this interval.

Four samples with abundant and diverse dinoflagellate cysts assemblages are placed in this ammonite chronozone. *Sirmiodinium grossi* and *Cribroperidinium* spp. dominate the assemblage together with common *Cassiculosphaeridium magnum*, *Gochteodinia villosa villosa* and *Paragonyaulacysta borealis*. The acritarch *Pterospermella* spp. is common. *Istmocystis distincta* appears for the first time at 35.02 m, and *Canningia compta*, *Scriniodinium pharo* and *Palaecysta palmula* have their first appearances higher in the zone.

Biostratigraphy. *P. maynci* is the index species of the *P. maynci* Zone (Fig. 14). The base of the Ryazanian is the base of the Cretaceous in a Boreal sense. However, a formally chosen base of the Cretaceous, in terms of the global boundary stratotype section and point (GSSP) of the Berriasian stage in the Tethyan Realm, is yet to be defined. It has recently been proposed to take the base of the *Calpionella alpina* calpionellid Zone as the boundary, which would most probably correlate to the Russian *Taimyroceras taimyrensis* and *C. nodiger* zones and the English *S. lamplughi* Zone in the Boreal upper Volgian stage (Gale *et al*. 2020; Wimbledon *et al*. 2020).

Age. Earliest Ryazanian, Early Cretaceous.

Organic matter. The organic content is low, and terrestrial woody material is rare. In contrast, the dinoflagellate cyst assemblage is rich and diverse, in contrast to the poor assemblages in the underlying *S. primitivus* Chronozone, and indicates fully marine conditions.

5.15 *Hectoroceras kochi* Chronozone and lower *Gochteodinia villosa villosa* Zone (NEG Cr 1; 27.73–25.82 m)

Fossils. The interval is recognised from its ammonite and dinoflagellate cyst content. An ammonite with ribs that radiate from a very narrow umbilicus indicates pronounced involuteness (Fig. 10S; Table 1). Primaries divide into two secondaries and bend forward from the level of furcation. This ornamentation and the narrow umbilicus characterise the genus *Hectoroceras*, and the specimen is referred to *Hectoroceras* sp.

Regarding the dinoflagellate cysts (one sample), *Palaecysta palmula* dominates the unit. The acritarch *Pterospermella* spp. is common. The assemblage is relatively diverse and abundant.

Biostratigraphy. Species of the ammonite genus *Hectoroceras* are only recorded in the *Hectoroceras kochi* Zone (Fig. 14; Wright *et al.* 1996). The base of the zone is placed at the ammonite in the core at 27.73 m. The top of the zone is based at the last occurrence of *Rotosphaeropsis thule* (*G. villosa* Zone, top of DSK1 Subzone; Poulsen & Riding 2003). *Palaecysta palmula* appears in the top of the *H. kochi* Zone of the North-West European Subboreal ammonite zonation (Riding & Thomas 1992). In the Rødryggen-1 core, *P. palmula* appears just above the ammonite. The *P. maynci* and *H. kochi* ammonite zones correlate with the lower *G. villosa villosa* Zone (Nøhr-Hansen *et al*. 2020).

The *Hectoroceras kochi* Zone is the highest ammonite zone identified and is correlated with the dinoflagellate cyst stratigraphy in this core. Alsen (2006) identified ammonites and ammonite zones in the Albrechts Bugt Member in sections near the Rødryggen-1 core. Due to solifluction in the outcrop sections, precise correlation with the core is not possible. Correlation of the dinoflagellate cyst stratigraphy with local ammonite stratigraphy in the upper Ryazanian to Valanginian is therefore beyond the scope of this study. The Ryazanian fauna is strictly Boreal, whereas the Valanginian fauna comprises Tethyan, Subboreal and Boreal elements (Alsen 2006).

Age. Latest early Ryazanian, Early Cretaceous.

Organic matter. The organic content is low. Degraded organic material dominates, terrestrial material is represented by sporomorphs and woody material is very rare. The fossil record testifies to a fully marine environment.

5.16 Upper *Gochteodinia villosa villosa* Zone (NEG Cr 1; 25.82–17.82 m)

Fossils. The interval is recognised based on its content of dinoflagellate cysts from the last occurrence of *R. thule* at 25.82 m to the first appearance of *Oligosphaeridium complex* at 17.82 m. The last occurrences of *Paragonyaulacysta borealis* and *P. capillosa* are in this interval. *Epiplosphaera* spp., *Heterosphaeridium*? spp., *Sirmiodinium grossii*, *Palaecysta palmula* and *Systematophora daveyi* dominate this unit locally. The assemblage is relatively diverse and abundant in the lower part but becomes poorer in the upper part. This change is associated with a significant depositional shift from black shale to calcareous mudstone, probably reflecting a shift to more oxygen-rich bottom conditions.

Biostratigraphy. R. thule has its last occurrence in the *H. kochi* Zone of the Subboreal ammonite zonation in North-West Europe (Riding & Thomas 1992; BioStrat 2018). *O. complex* appears for the first time at the Ryazanian–Valanginian boundary in North-West Europe (Riding & Thomas 1992) and in the *Peregrinoceras albidum* Zone, uppermost Ryazanian, on Store Koldewey, North-East Greenland (Nøhr-Hansen *et al.* 2020).

Age. Late Ryazanian, Early Cretaceous.

Organic matter. The organic content is very low and totally dominated by black, rounded grains, probably reflecting strongly oxidising bottom conditions. The presence of marine plankton, however, is indicative of a fully marine environment.

5.17 Lower *Oligosphaeridium complex* Zone (NEG Cr 2; 17.82–10.17 m)

Fossils. The interval is recognised based on its content of dinoflagellate cysts in the succession from the first appearance of *Oligosphaeridium complex* (15.85 m) to the first occurrence of *Nelchinopsis kostromiensis*. *Oligosphaeridium complex*, *Oligosphaeridium* spp. and *Epiplosphaera* spp. dominate the assemblage. The assemblage is relatively diverse and abundant in the lower part but becomes poorer upwards.

The interval is also represented by two samples analysed for calcareous nannofossils (at 16.6 and 13.82 m). The low diversity assemblage in the lower sample is dominated by *Watznaueria barnesiae*. *Watznaueria fossacincta* and *Crucibiscutum salebrosum* are also common. In addition, *Watznaueria britannica*, *Watznaueria ovata*, *Retecapsa schizobrachiata*, *Retecapsa crenulata*, *Rotelapillus crenulatus*, *Sollasites horticus*, *Staurolithites stradneri*, *Assipetra infracretacea*, *Tegumentum stradneri*, *Rhagodiscus asper*, *Zeugrhabdotus fissus* and *Nannoconus concavus* are present. The upper sample has an assemblage dominated by *Crucibiscutum salebrosum* and *Watznaueria barnesiae*. Also present are *Assipetra infracretacea*, *Diazomatolithus lehmanii*, *Retecapsa crenulate*, *Rhagodiscus asper*, *Watznaueria fossacincta*, *Watznaueria britannica*, *Watznaueria manivitiae*, *Retecapsa angustiforata*, *Zeugrhabdotus embergeri*, *Cyclagelosphaera margerelii*, *Staurolithites stradneri*, *Stradnerlithus silvaradius*, *Tegumentum stradneri*, *Zeugrhabdotus erectus*, *Tripinnilithus shetlandensis*, *Zeugrhabdotus fissus* and *Thoracosphaera* spp.

Biostratigraphy. O. complex appears for the first time at the Ryazanian–Valanginian boundary in north-western Europe (Riding & Thomas 1992), and in the top Ryazanian of North-East Greenland, *Peregrinoceras albidum* Zone (Stefan Piasecki unpublished data). The highest occurrence of *Gochteodinia villosa villosa* and *Palaecysta palmula* is in the lower Valanginian (Davey 1982; Riding & Thomas 1992). Poulsen & Riding (2003) correlate the last occurrence of *G. villosa villosa* with the top of the *P. albidum* Zone in North-West Europe, but this taxon is present into the lower Valanginian in the Rødryggen-1 core. The highest occurrence of *Palaecysta palmula* is at the top of the *Paratollia* Zone, upper lower Valanginian, in North-West Europe (Costa & Davey 1992) and at the top of the 'EKZ6 zone' in BioStrat (2018; mid-lower Valanginian). *Nelchinopsis kostromiensis* is first recorded at 10.17 m, corresponding to the last occurrence of *P. palmula* (Costa & Davey 1992). However, in North-East Greenland, *N. kostromiensis* occurs for the first time in the upper Valanginian (Nøhr-Hansen *et al.* 2020). The calcareous nannofossil stratigraphy agrees fairly well with the palynostratigraphy. It indicates late Ryazanian to early Valanginian ages from high abundances of *C. salesbrosum* and *Watznaueria* spp. co-occuring with *S. horticus* in the upper Ryazanian to lower Valanginian of the North Sea area (Jeremiah 2001) and offshore mid-Norway (Mutterlose & Kessels 2000). *R. crenulata* has its first occurrence in the upper upper Ryazanian (Jakubowski 1987). The presence of *Nannoconus concavus* and *Tripinnilithus shetlandensis* in the absence of *Micrantholithus speetonensis* indicates the lower Valanginian nannofossil subzone BC3b (Bown *et al.* 1998). Pauly *et al.* (2012a) documented the first occurence (FO) of *Crucibiscutum* spp., *Rhagodiscus asper* and *Watznaueria* spp. in the upper Ryazanian of North-East Greenland.

Age. Early Valanginian, Early Cretaceous.

Organic matter. The organic content is very low. The presence of marine plankton, albeit scarce, indicates marine conditions. The organic terrestrial material is heavily oxidised into carbonised, angular to rounded black grains.

5.18 Upper *Oligosphaeridium complex* zone (NEG Cr 2; 10.17–1.10 m)

Fossils. The interval is recognised based on its content of dinoflagellate cysts. The base is placed at the first occurrence of *Nelchinopsis kostromiensis* (10.17 m), followed by the last occurrences of *Palaecysta palmula* (9.00 m) and *G. villosa villosa* (6.59 m), and the highest record of *Lagenorhytis delicatula* (1.10 m). The top of the zone is not recorded.

The dinoflagellate cyst assemblage is very poor, and the presence or absence of several species may reflect random occurrences. However, *Oligosphaeridium complex* dominates the assemblage, and *Cassiculosphaeridium magnum*, *Circulodinium distinctum*, *Epiplosphaera* spp. and *Downiesphaeridium tribuliferum* are common locally. The dinoflagellate cysts are fairly well preserved but constitute a very small fraction of the organic matter.

The interval also contains one sample analysed for its calcareous nannofossil content. The nannofossil assemblage has a low diversity dominated by *Watznaueria barnesiae*. Also present are *Watznaueria fossacincta*, *Calculites*? sp.1, *Tranolithus gabalus*, *Staurolithites stradneri*, *Rhagodiscus asper*, *Watznaueria britannica* and *Thoracosphaera* spp. *C. salesbrosum* is absent.

Biostratigraphy. The occurrence of *Nelchinopsis kostromiensis* indicates a late Valanginian age based on reports from the Arctic (Davies 1983; Nøhr-Hansen *et al.* 2020; Ingrams *et al.* 2021) in contrast to North-West Europe where it appears in lower Valanginian strata (e.g. Heilmann-Clausen

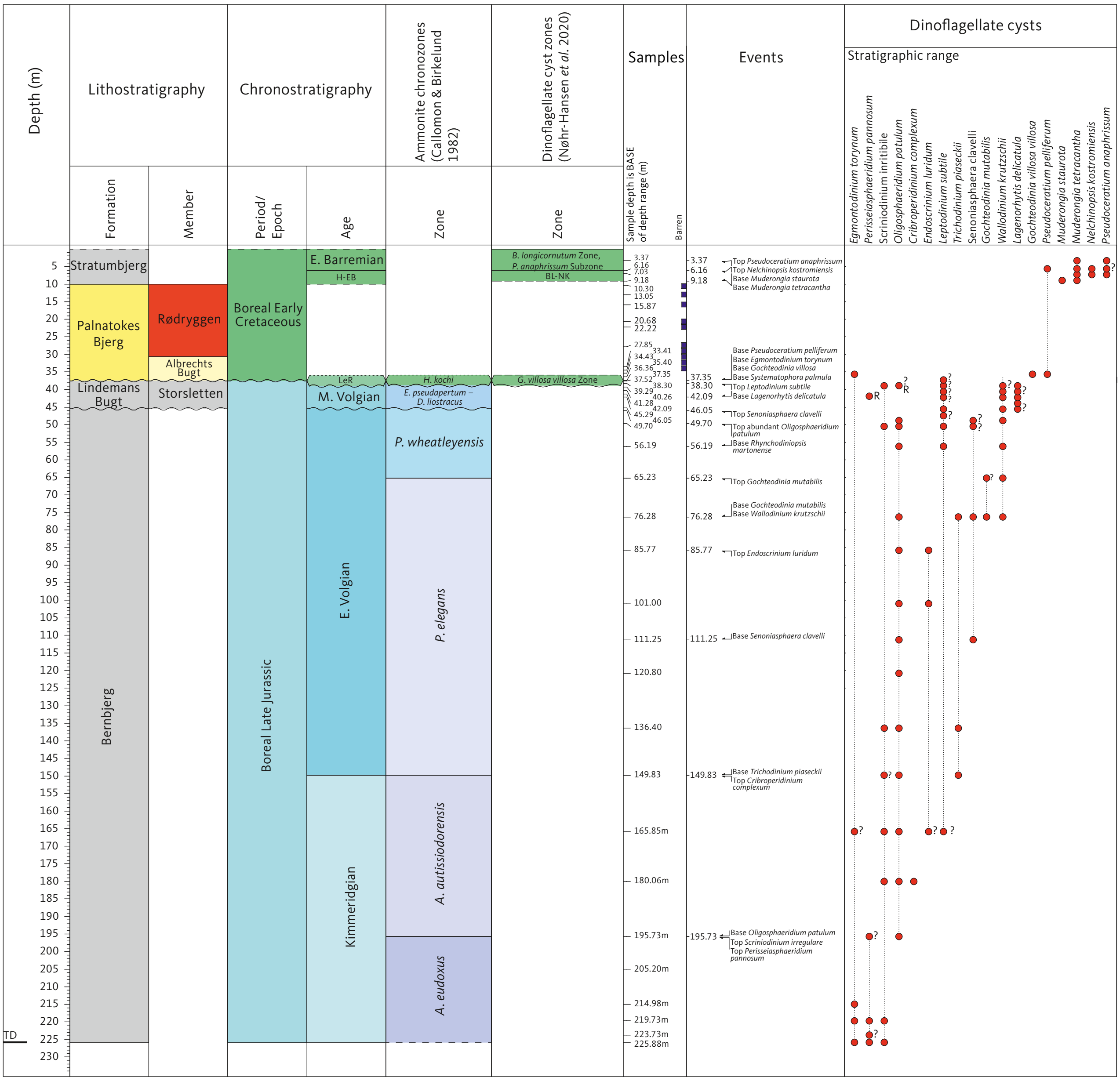

Fig. 16 The ranges of key dinoflagellate cyst taxa in the Brorson Halvø-1 core. The dinoflagellate species are arranged according to the succession of their lowest occurrences. Question mark (**?**): uncertainty in taxonomic identification. **R**: reworked or redeposited. A range chart showing all taxa recorded in the core is available in Supplementary Data File 2. **H-EB**: Hauterivian – Early Barremian. **LeR**: Latest early Ryazanian. **BL-NK**: *B. longicornutum* Zone – *N. kostromiensis* Subzone. **E.**: early. **M.**: middle.

& Birkelund 1987; Costa & Davey 1992; BioStrat 2018). The last occurrences of *Gochteodinia villosa villosa* and *P. palmula* and the continuous presence of *Lagenorhytis delicatula* in the uppermost core sample may suggest upper Valanginian strata as recorded in North-West Europe (Davey 1982; Riding & Thomas 1992).

The calcareous nannofossils *T. gabalus*, *R. asper* and *Watznaueria* spp. range from the upper Ryazanian in the North Sea (Jakubowski 1987; Jeremiah 2001), North-East Greenland (Pauly *et al.* 2012a) and off mid-Norway in the northern North Atlantic (Mutterlose & Kessels 2000). *Calculites*? sp.1 was described in Bown *et al.* (1998) as ranging from the Early Hauterivian? to the Early? Barremian, albeit in Tunisia and Bulgaria. Of note is the absence of *C. salesbrosum*. In North-East Greenland, this species has its last appearance datum in the late Hauterivian (Pauly *et al.* 2012a) and a little later in the North Sea (Jakubowski 1987). However, the absence of this species is probably an artefact of preservation, since the age suggested by its apparent absence is too young compared with the palynostratigraphy of the interval, as well as the ammonite stratigraphy obtained in an outcrop study of the Albrechts Bugt Member at the drill site (Alsen 2006).

Age. Late Valanginian, Early Cretaceous.

Organic matter. The interval is characterised by a low organic content with little marine plankton and no

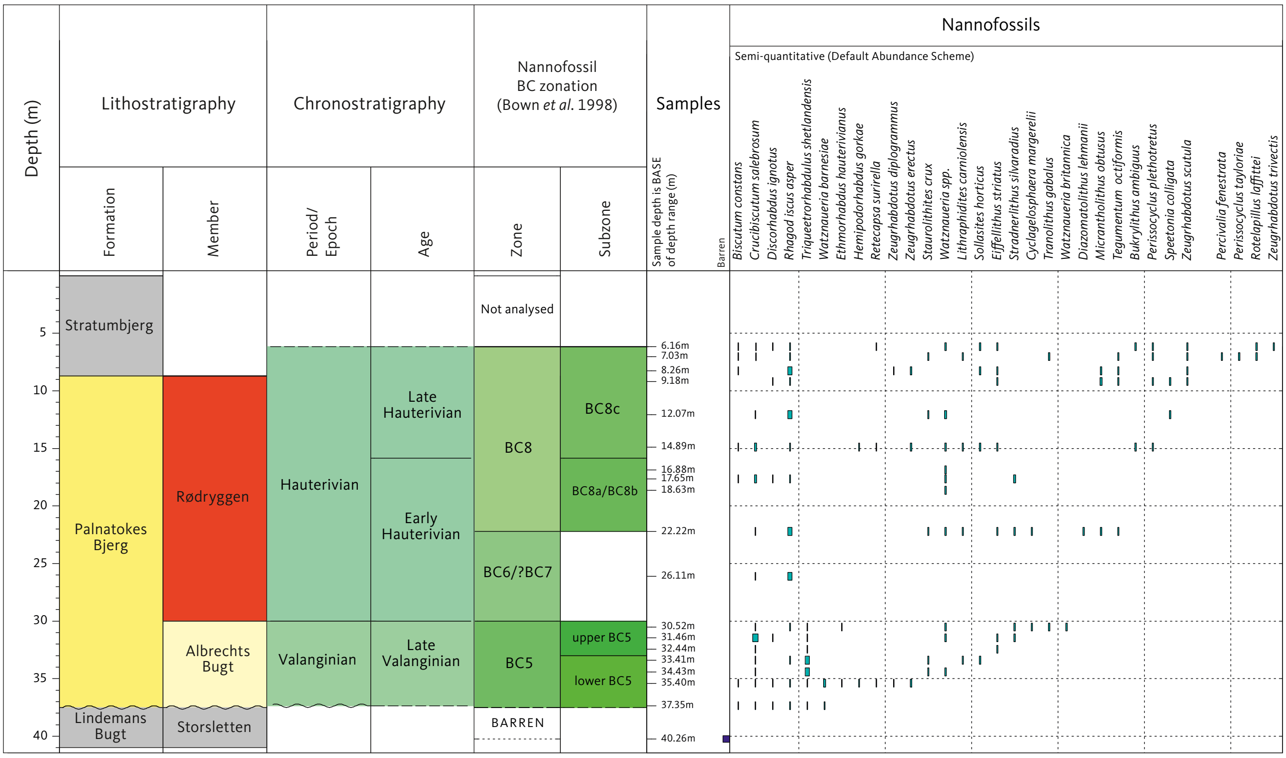

Fig. 17 The distribution of calcareous nannofossils in the Brorson Halvø-1 core.

recognisable terrestrial organic material. Marine conditions are indicated by the macrofauna and calcareous flora.

6. Biostratigraphy of the Brorson Halvø-1 core

The biostratigraphic subdivision of the Brorson Halvø-1 core is described from TD at 225.7 m upwards. The location of bulk-rock samples is seen in the charts, illustrating the distributions and ranges of dinoflagellate cyst and calcareous nannofossil taxa (Figs 16, 17). Selected dinoflagellate cysts are figured in Fig. 13.

6.1 *Aulacostephanus eudoxus* Chronozone (225.7 m (TD) – 195.73 m)

Fossils. The recognition of the zone is based on the dinoflagellate cyst record. The base of the zone is placed at the base of the core (at TD 225.7 m). The dinoflagellate cyst assemblage is generally poor, and dinoflagellate cysts are not common; *Gonyaulacysta jurassica*, *G. dualis*, *Sirmiodinium grossii* and *Scriniodinium irregulare* are locally common. *Perisseiasphaeridium pannosum* is rare to common, but not as abundant as normally recorded in East Greenland.

Biostratigraphy. *P. pannosum* occurs in the lowermost analysed sample at 225.88 m and is common at the top, at 195.73 m, where it coincides with the appearance of common to abundant *Oligosphaeridium patulum*. This indicates an interval corresponding to the ammonite horizons M 20 – M 22, *A. eudoxus* Zone (Piasecki 1996). No other recorded dinoflagellate cysts indicate correlation to zones below the *A. eudoxus* Chronozone, and the succession correlates, therefore, with the *A. eudoxus* Chronozone. The dinoflagellate cysts *Atopodinium haromense*, *Dingodinium minutum*, *Nannoceratopsis pellucida*, *Paragonyaulacysta capillosa* and *Taeniophora iunctispina* occur scattered throughout this zone.

Age. Kimmeridgian, Late Jurassic.

Organic matter. Amorphous kerogene dominates together with terrestrial, organic material from higher land plants, especially sporomorphs and black woody material. The woody material is physically degraded to rounded and angular grains in the lower levels of the succession; the grains become lath-shaped and larger upwards. The presence of dinoflagellate cysts indicates a marine environment, and the dominance of AOM is suggestive of oxygen-deficient bottom conditions.

Remarks. The interpreted late Kimmeridgian age at the base of the well agrees with the find of an ammonite in a measured outcrop section, *c.* 200 m below the Albrechts Bugt Member, Palnatokes Bjerg Formation (M. Bjerager, pers. comm. 2022). The ammonite is identified as *Amoeboceras subkitchini* from the upper lower Kimmeridgian *Rasenia cymodoce* Zone (Figs 14, 18).

6.2 *Aulacostephanus autissiodorensis* Chronozone (195.73–149.83 m)

Fossils. The recognition of the zone is based on its dinoflagellate cyst record. The base of the zone is placed at the first appearance of common to abundant *Oligosphaeridium patulum* (195.73 m) and its top at the first appearance of *Trichodinium piaseckii* coincident with the last occurrence of *Cribroperidinium complexum* (149.83 m).

The dinoflagellate cyst assemblage is generally poor but is characterised by common to abundant *Oligosphaeridium patulum* and *Paragonyaulacysta capillosa*. *Atopodinium* spp., *Circulodinium* spp., *Pareodinia* spp. and *Sirmiodinium grossii* are common locally. The assemblage is mostly of low diversity and low abundance, probably due to the abundance of organic matter in the samples.

Biostratigraphy. Common to abundant *O. patulum* appears between ammonite horizons M 22 – M 23 in Milne Land near the boundary between the *A. eudoxus* and *A. autissiodorensis* Zones (Piasecki 1996; Alsen & Piasecki 2018). *T. piaseckii* appears below ammonite fauna horizon M 25, *P. wheatleyensis* Zone (Piasecki 1996). The succession is, therefore, correlated with the *A. autissiodorensis* and *P. elegans* Zones.

Age. Kimmeridgian, Late Jurassic.

Organic matter. The interval contains amorphous kerogen together with abundant terrestrial organic material from higher land plants, especially sporomorphs and black, lath-shaped woody material. The presence of dinoflagellate cysts indicates a marine environment, and the dominance of AOM is suggestive of oxygen-deficient bottom conditions.

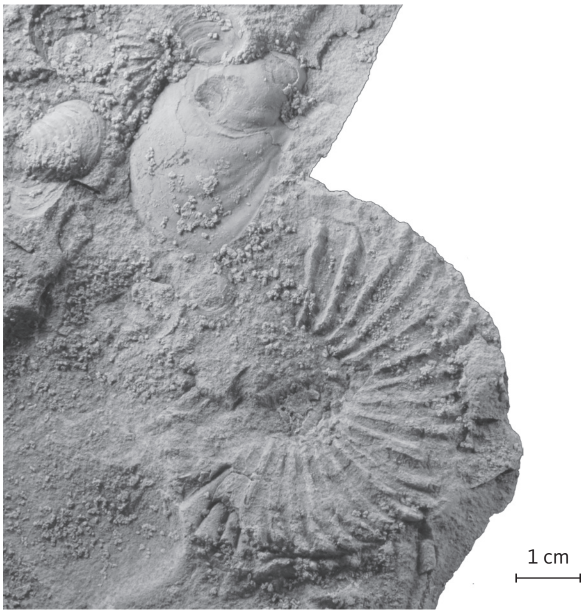

Fig. 18 *Amoeboceras subkitchini* (MGUH 34201 from GEUS 469823) ammonite from upper lower Kimmeridgian *Rasenia cymodoce* Zone. Collected stratigraphically *c.* 200 m below the Albrecht Bugt Member (Palnatokes Bjerg Fm) in an outcrop section measured along a small ravine from the Brorson Halvø-1 drill site and towards the west. The specimen is housed in the Palaeontology Type Collection at the Natural History Museum of Denmark and labelled with an MGUH number – Museum Geologica Universitas Hafniensis.

6.3 *Pectinatites elegans* Chronozone (149.83–65.23 m)

Fossils. The zone is based on the dinoflagellate cyst record. The base of the zone is recognised at the first occurrence of *Trichodinium piaseckii* coincident with the last occurrence of *Cribroperidinium complexum*.

The dinoflagellate cyst assemblage is dominated by *Cribroperidinium* spp., *Circulodinium* spp., *Oligosphaeridium patulum*, *Pareodinia* sp., *Paragonyaulacysta borealis* and *P. capillosa* in the lower part of the zone. *Cassiculosphaeridium magnum*, *Gochteodinia mutabilis*, *Oligosphaeridium patulum*, *Paragonyaulacysta capillosa*, *Sirmiodinium grossii*, *Tenua hystrix*, *Tubotuberella* spp. and the acritarch *Wallodinium krutschi* are more common in the upper part of the zone. The assemblage is relatively diverse and abundant.

Biostratigraphy. The first occurrence of *T. piaseckii* is coincident with the last occurrence of *C. complexum* in this core and in the Rødryggen-1 core, where it correlates with the lower boundary of the *P. elegans* Zone. The first occurrence of *T. piaseckii* is followed successively by the first occurrences of *Senoniasphaera clavellii* and *Gochteodinia mutabilis* and the last occurrence of common *O. patulum*. All these events are located below ammonite horizon M 25, Wheatleyensis Zone, in Milne Land (Piasecki 1996) suggesting correlation with the *P. elegans* Zone. These events coincide in the relatively condensed succession in Milne Land, whereas they occur in succession in both Rødryggen-1 and Brorson Halvø-1 cores.

Age. Early Volgian, Late Jurassic.

Organic matter. Abundant amorphous kerogen dominates together with abundant terrestrial organic material from higher land plants, especially sporomorphs and brown and black woody material. The presence of dinoflagellate cysts indicates a marine environment, and the dominance of AOM is suggestive of oxygen-deficient bottom conditions.

6.4 *Pectinatites wheatleyensis* Chronozone (65.23–45.5 m)

Fossils. The zone is based on the dinoflagellate cyst record. The base of this zone is placed at the last occurrence of common *Gochteodinia mutabilis*. The top of the zone is bounded by an unconformity marking a significant hiatus.

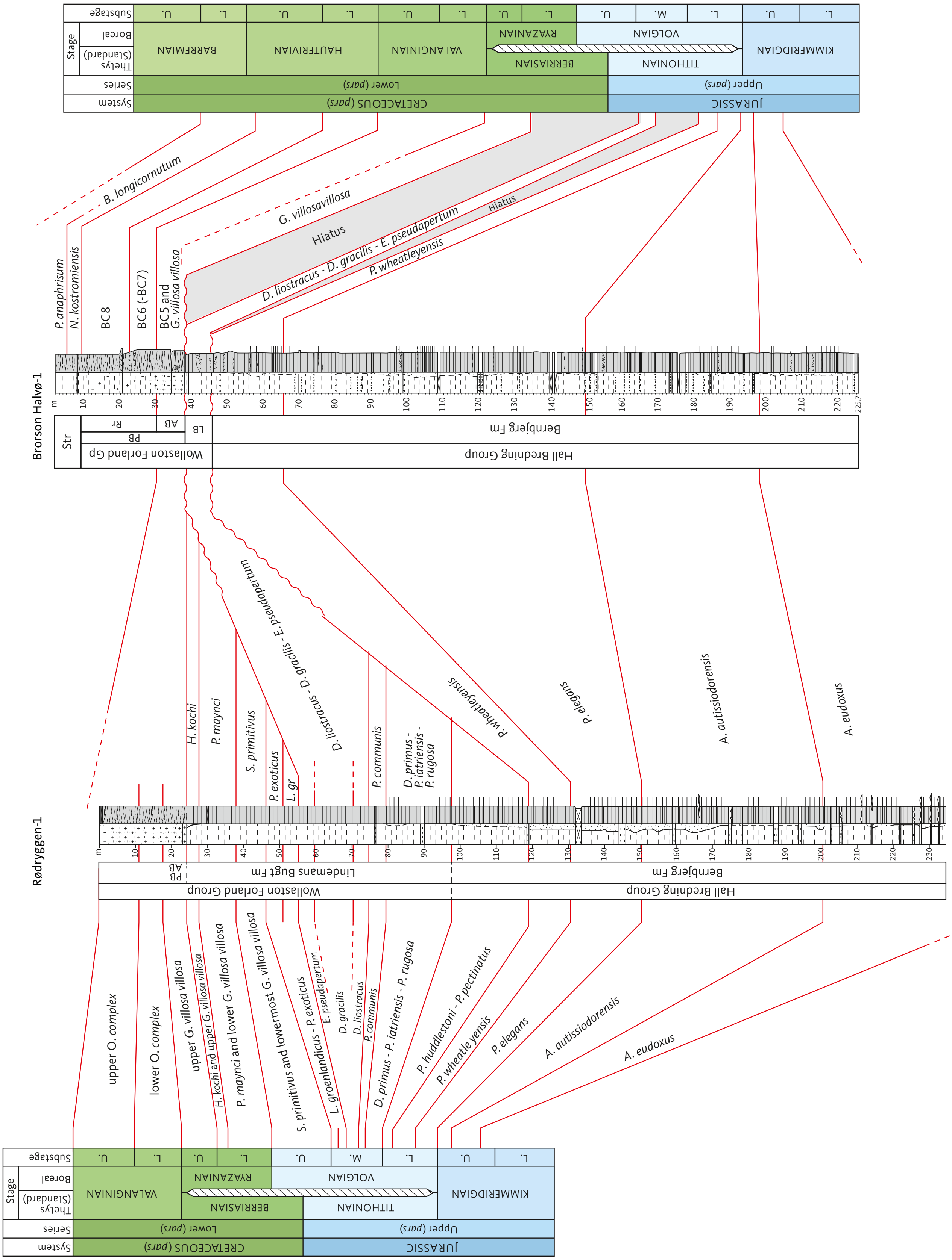

Fig. 19 The correlation between the Rødryggen-1 and Brorson Halvø-1 boreholes; the datum is the base of the Palnatokes Bjerg Formation. Note the complete stratigraphy in the Rødryggen-1 well compared to the significant hiatuses within the Volgian–Ryazanian in the Brorson Halvø-1 core. The zones that are present in the Rødryggen-1 well and absent in the Brorson Halvø-1 well are here shown schematically to onlap the unconformity. Although it could be argued that these zones were also represented in the Brorson Halvø-1 area and subsequently removed by erosion of the crest during tilting of the fault block, the lack of redeposited palynomorphs of these ages in the Rødryggen-1 core favours an onlap model. **AB**: Albrechts Bugt Mb. **LB**: Lindemans Bugt Formation. **PB**: Palnatokes Bjerg Fm. **Rr**: Rødryggen Member. **Str**: Stratumbjerg Formation. See Fig. 4 for legend and grain size.

Biostratigraphy. Common *G. mutabilis* characterises the dinoflagellate cyst assemblage in the uppermost *P. elegans* Zone in Milne Land and ammonite faunal horizon M 25, and *P. wheatleyensis* Zone correlates with the top of this interval (Piasecki 1996). The last occurrences of abundant *O. patulum* and *S. clavellii* occur in the upper part of the interval, followed by a change in composition of the dinoflagellate cyst assemblage in overlying strata.

Age. Early Volgian, Late Jurassic.

Organic matter. Abundant amorphous kerogen together with dinoflagellate cysts dominates; terrestrial plant material is less significant, occurring mainly as sporomorphs but also some black woody material. The presence of dinoflagellate cysts indicates a marine environment, and the dominance of AOM is suggestive of oxygen-deficient bottom conditions.

6.5 Unconformity (45.5 m)

The occurrence of the *D. liostracus* – *E. pseudapertum* Zones immediately overlying the *P. wheatleyensis* Zone defines a significant stratigraphic break. The unconformity corresponds to the *P. huddlestoni* – *P. communis* Zones, spanning the upper lower Volgian to lower middle Volgian. Biostratigraphically, the unconformity is located between 42.09 and 46.05 m and placed at the lithostratigraphic boundary at 45.5 m.

6.6 *Dorsoplanites liostracus* – *Epipallasiceras pseudapertum* Chronozones undiff. (45.5–37.50 m)

Fossils. The zone is based on the dinoflagellate cyst record and correlated with the succession in the Rødryggen-1 core from the first appearance of *Lagenorhytis delicatula* (42.09 m) to the top of *Leptodinium subtile* (38.30 m). *Cribroperidinium* spp. dominates the assemblage, and *Rhynchodiniopsis* spp. is common. The lower boundary, however, is placed at the inferred unconformity at the lithostratigraphic boundary at 45.5 m. The assemblage is relatively diverse and abundant.

Biostratigraphy. The unusual appearance of *Lagenorhytis delicatula* as stratigraphically low as the middle Volgian strata is recorded in the Rødryggen-1 core (this study). In contrast, the last occurrence of *Leptodinium subtile* is a well-known stratigraphic marker in North-West Europe, where it has its highest occurrence in the *Progalbanites albani* (ammonite) Zone (Riding & Thomas 1992). The upper *P. albani* Zone is correlated with the *E. pseudapertum* Zone in the East Greenland ammonite zonation (Birkelund *et al.* 1984). The top occurrence of *L. subtile* just below the ammonite *Epipalliceras pseudapertum* in the Rødryggen-1 core (this study) supports this correlation. Characteristic Boreal, uppermost Jurassic species, e.g. *Paragonyaulacysta borealis*, *P. capillosa* and the acritarch *Wallodinium krutzschii*, that are common in the lower core interval disappear in this zone and are absent throughout the rest of the overlying uppermost Jurassic interval.

Age. Middle Volgian, Late Jurassic.

Organic matter. The interval contains abundant amorphous kerogen with little terrestrial plant material, mainly sporomorphs and a limited content of dinoflagellate cysts. The presence of dinoflagellate cysts indicates a marine environment, and the dominance of AOM is suggestive of oxygen-deficient bottom conditions.

6.7 Unconformity (37.50 m)

The *G. villosa villosa* dinoflagellate cyst Zone, here equivalent to the *H. kochi* ammonite Chronozone, directly overlies the *P. liostracus* – *E. pseudapertum* Zones. It marks a major stratigraphic break with a hiatus corresponding to the *C. anguinus* – *P. maynci* Zones interval, spanning the middle middle Volgian to the lower Ryazanian (Fig. 14).

6.8 *Gochteodinia villosa villosa* Zone (NEG Cr 1) and Calcareous Nannofossil Zone BC5 (37.35–30.52 m)

Fossils. The palynozone is recognised only in one sample at 37.35 m. The assemblage is poor, low density, but due to hardly any other organic matter in this sample, the whole assemblage is recovered in one slide. The assemblage is characterised by a high diversity, especially compared to the organic-rich samples analysed from deeper levels in the core. The interval is barren of dinoflagellate cysts in the upper part (36.36–30.52 m).

The calcareous nannofossil zone BC5 has its base at 37.35 m, 15 cm above the base of the calcareous Albrecht Bugt Member (Fig. 17). The upper boundary is placed at 30.52 m, where the assemblage is characterised by very low diversity without age-diagnostic nannofossils. The assemblage of BC5 consists of common to abundant *Crucibiscutum salebrosum*, *Watznaueria* spp., few *Biscutum constans*, *Rhagodiscus asper*, *Triquerhabdulus shetlandensis*, *Staurolitithes* crux, *Zeugrhabdotus* spp., *Cretarhabdus* spp. and *Discorhabdus* spp. (Fig. 17).

Biostratigraphy. The combined presence of dinoflagellate cysts *Rotosphaeropsis thule* and *Palaecysta palmula* indicates a Lower Cretaceous, mid-Ryazanian assemblage. *R. thule* has its range top in uppermost lower Ryazanian, *H. kochi* Zone in the Rødryggen-1 core. *P. palmula* is reported to appear in the top of the *H. kochi* Zone, uppermost lower Ryazanian in North-West Europe (Riding & Thomas 1992) and in the Rødryggen-1 core (this study), where it appears just above an *H. kochi* ammonite. The absence of abundant *Oligosphaeridium complex* supports the Ryazanian age, since its first appearance is in the lowermost Valanginian as reported both in North-West Europe (Riding & Thomas 1992) and in the Rødryggen-1 well (this study) as well as in the *P. albidum* ammonite Zone, uppermost Ryazanian on Store Koldewey, northern East Greenland (Nøhr-Hansen *et al.* 2020). The *G. villosa villosa* Zone thus correlates with the *H. kochi* (ammonite) Zone.

The calcareous nannofossil assemblage suggests the presence of the calcareous nannofossil zone BC5 of Bown *et al.* (1998). Common *T. shetlandensis* and the high abundance of *C. salebrosum* in the lower four samples and the co-occurrence of *Eiffellithus striatus* with *T. shetlandensis* in the upper three samples further suggest subdivision of the interval and the identification of the lower and upper BC5-zonal intervals, respectively (Fig. 17).

Age. Latest early Ryazanian – Valanginian. The dinoflagellate cysts indicate the base of the interval to be latest early Ryazanian. The calcareous nannofossil assemblages, on the other hand, indicate a late Valanginian age that is somewhat younger than the palynostratigraphic age derived from the basal sample of the interval. Previous studies of the ammonite assemblage collected from outcrops of the Albrechts Bugt Member at the drill site suggested a late Ryazanian – late early Valanginian age (Alsen 2006). A late Valanginian age based on the BC5 zone also significantly differs from the BC1 zone and late Ryazanian age of the base of the Albrechts Bugt Member in the Wollaston Forland area (Pauly *et al.* 2012a). A slight revision of stratigraphic ranges of Ryazanian–Valanginian calcareous nannofossil zones in the Boreal scheme was based on Sr-isotope and C-isotope stratigraphy (Möller *et al.* 2015). The offset in ages obtained from dinoflagellate cysts and calcareous nannofossils observed is, however, far beyond the smaller adjustments recorded by Möller *et al.* (2015).

Organic matter. A very little organic content comprising rounded to angular, carbonised grains with some dinoflagellate cysts and hardly any terrestrial plant material. This abrupt change in the nature of the organic fraction in the Brorson Halvø-1 core reflects a significant hiatus, whereas a corresponding rapid environmental change in the Rødryggen-1 well takes place over approximately 1 m of transitional beds in the Upper Ryazanian (this study).

6.9 Calcareous nannofossil Zones BC6–BC7? (30.52–22.22 m)

Fossils. This interval is characterised by the lack of age-diagnostic calcareous nannofossils hampering a precise age assessment. The interval is barren of dinoflagellate cysts. The absence of the calcareous nannofossils *T. shetlandensis*, *Eprolithus antiquus* and *Tegumentum octiformis* indicates the possible presence of the zones BC6–BC7, and the interval is tentatively assigned to BC6–BC7? (Fig. 17).

Age. The BC6 and BC7 zones are considered early Hauterivian in age (Bown *et al*. 1998).

Organic matter. The interval has a very low organic content of angular to rounded carbonised grains.

6.10 Calcareous nannofossil Zone BC8 (22.22–9.18 m)

Fossils. The assemblage contains common to abundant *Watznaueria* spp., *R. asper, B. constans*, *Zeugrhabdotus* spp. as well as few *D. ignotus*, *Eiffellithus striatus*, *Perissocyclus* spp. and rare *Sollasites horticus*, *C. salebrosum*, *Bukrylithus ambiguus* and *pentaliths*; all are characteristic of the higher Rødryggen Member. The interval is barren of dinoflagellate cysts.

Biostratigraphy. The assemblage suggests the presence of the BC8 Zone. *E. striatus*, *T. octiformis*, a few *Stradnerlithus silvaradius* and rare *C. salebrosum* in the lower part indicate the presence of the BC8a–b Subzone; *Perissocyclus plethotretus* and *Z. scutula* in the upper part indicate the overlying BC8c Subzone (Fig. 17).

Age. Late early Hauterivian – early late Hauterivian. In contrast to the conflicting ages obtained for the underlying Albrechts Bugt Member (interval 37.50–30.52 m), the calcareous nannofossil age indicated for this interval, the upper part of the Rødryggen Member, agrees well with the previously recorded age of the Rødryggen Member (Alsen 2006; Alsen & Mutterlose 2009; Pauly *et al*. 2012a).

Organic matter. The interval has a very low organic content of angular to rounded carbonised grains.

6.11 *Batioladinium longicornutum* Zone (I), *N. kostromiensis* palyno Subzone (I1) and calcareous nannofossil Zone BC9 (9.18–6.16 m)

Fossils. The base of the zone is placed at the first occurrence of the palynomorphs *Nelchinopsis kostromiensis*, *Muderongia staurota* and *M. tetracantha*. The index fossil of the subzone is thus present, whereas the index of the

Batioladinium longicornutum longicornutum Zone was absent. The dinoflagellate cyst assemblage is characterised by *Oligosphaeridium asterigerum*, *Oligosphaeridium complex*, *Circulodinium distinctum*, *Clesistosphaeridium aciculare*, *Muderongia staurota* and *M. tetracantha*. *Oligosphaeridium asterigerum* and *Circulodinium distinctum* dominate the assemblage (Supplementary Data File 2). The assemblage is relatively poor in the lower part but becomes diverse and abundant upwards.

The calcareous nannofossil assemblage is characterised by common to abundant *Watznaueria* spp., *R. asper*, *B. constans* and *Zeugrhabdotus* spp. It contains few *D. ignotus*, *Eiffellithus striatus* and *Perissocyclus* spp., and rare *Sollasites horticus*, *C. salebrosum*, *Bukrylithus ambiguus* and *pentaliths*.

Biostratigraphy. *Muderongia staurota* and *M. tetracantha* have their first occurrences in the upper Hauterivian *S. gottschei* ammonite Zone according to Costa & Davey (1992) and Duxbury (2001). The highest occurrence of *Nelchinopsis kostromiensis* is in the upper Hauterivian? – lower Barremian *Nelchinopsis kostromiensis* Subzone (I1) in Nøhr-Hansen (1993) and Nøhr-Hansen *et al*. (2020).

The presence of the calcareous nannofossils *E. striatus*, *P. plethotretus*, *P. tayloriae*, *T. octiformis*, *S. colligata* and *Z. scutula* combined with the absence of *C. salebrosum*, *S. silvaradius*, *Tegulalithus septentrionalis* and *Clepsilithus maculosus* suggest the BC9 Zone (Fig. 17).

Age. Late Hauterivian to early Barremian based on palynostratigraphy. Calcareous nannofossils indicate a late Hauterivian age.

Organic matter. The interval is characterised by a very low organic content that is dominated by black angular to rounded carbonised grains with few dinoflagellate cysts; the latter testify to a marine depositional environment.

Remarks. It is noteworthy that this interval, which is in the lower part of the Stratumbjerg Formation, yields calcareous nannofossils despite a return to black mudstone deposition. Calcareous nannofossils are thus not restricted to the marls of the underlying Albrechts Bugt and Rødryggen Members. Despite a sharp boundary between the Palnatokes Bjerg Formation and the Stratumbjerg Formation observed in the field (Figs 5, 6), there appears to be a gradual transition between the two units in terms of palaeoecology and calcareous nannoplankton production.

6.12 *Batioladinium longicornutum* Zone (I), *P. anaphrissum* Subzone (I2) (6.16–0 m)

Fossils. The subzone is based on the dinoflagellate cyst record in one sample (Fig. 16; Supplementary Data File 2). The base of the subzone is recognised at the last occurrence of *Nelchinopsis kostromiensis*. The subzone ranges to the last occurrences of *Pseudoceratium anaphrissum*. *Oligosphaeridium asterigerum*, *Oligosphaeridium complex*, *Circulodinium distinctum, Clesistosphaeridium aciculare* and *Muderongia tetracantha* dominate the assemblage.

Biostratigraphy. The highest occurrence of *Nelchinopsis kostromiensis* is in upper Hauterivian? to lower Barremian, *Nelchinopsis kostromiensis* Subzone (I1) in Nøhr-Hansen (1993). The highest occurrences of *Batioladinium longicornutum* and *Hystrichodinium aborispinum* are in the upper Barremian, whereas the highest occurrence of *Pseudoceratium anaphrissum* is in the upper part of the lower Barremian *Pseudoceratium anaphrissum* Subzone (I2) in Nøhr-Hansen (1993) and Nøhr-Hansen *et al*. (2020).

Age. Early Barremian, Early Cretaceous.

Organic matter. The interval has a very low organic content dominated by black, angular, carbonised grains with few dinoflagellate cysts, the latter of which indicate a marine depositional environment.

7. Discussion

7.1 The Jurassic–Cretaceous boundary in (North-East) Greenland

The Jurassic system is characterised by a highly detailed subdivision by means of ammonite zones, which form the standard biostratigraphic and chronostratigraphic framework. Ammonite provincialism in some intervals hampers direct correlation to the standard ammonite zonation (established in North-West Europe), and secondary standards are then established locally. Difficulties in ammonite correlation are particularly pronounced around the Jurassic–Cretaceous boundary leading to separate chronostratigraphic divisions even at the Stage level in separate faunal provinces. The ammonite zonation for most of the Upper Jurassic in East Greenland is mainly based on the ammonite successions in Milne Land and Jameson Land (Callomon & Birkelund 1982; Birkelund *et al*. 1984; Birkelund & Callomon 1985). The Oxfordian ammonite zonation used in East Greenland belongs to the Boreal and Subboreal faunal provinces (Sykes & Callomon 1979; Birkelund *et al.* 1984; Zeiss 2003). Less provincialism during the Kimmeridgian allows the ammonite succession in Greenland to be referred to the standard ammonite zonation of North-West Europe (Birkelund & Callomon 1985; Zeiss 2003). Provincialism increased progressively during the latest Jurassic. The lower Volgian ammonite zonation in Greenland is adopted from England, whereas a separate Boreal zonation was established for the middle Volgian in Greenland, allowing only few correlation levels to the Subboreal zonation of England (Callomon & Birkelund 1982; Zeiss 2003).

The Milne Land area is characterised by a gap in the sedimentary succession between the middle Volgian and the lowermost Cretaceous, whereas the upper Volgian in southern Jameson Land is documented by scattered biostratigraphic data. Further to the north, a more complete Jurassic–Cretaceous boundary succession exists in the Wollaston Forland – Kuhn Ø area. The thick, coarse-grained succession represents synrift deposition and contains only sporadic levels with ammonites. The ammonite succession was documented by Maync (1949), Donovan (1964) and Surlyk (1978) providing a zonation that covers the middle Volgian to Ryazanian. Only one zone (*Praechaetaites tenuicostatus* Zone) has been assigned to the upper Volgian; this has since been referred to the uppermost middle Volgian (Rogov 2020). However, the presence of *Subcraspedites* (*Swinnertonia*) from Kuhn Ø (Casey 1973) and a record of this genus in the present study indicate the presence of the Subboreal *Subcraspedites primitivus* Zone in Greenland, providing a correlation of the base upper Volgian from Greenland to North-West Europe.

The ammonite zonation of the Upper Jurassic to Lower Cretaceous interval of relevance to the present study is shown in Fig. 14. Note the usage of Boreal Stage names and the position of the Boreal Upper Jurassic – Lower Cretaceous boundary at the Volgian–Ryazanian boundary. The Jurassic–Cretaceous boundary in the standard chronostratigraphy established in the Tethyan Realm is placed at the Tithonian–Berriasian boundary. That level probably corresponds to the middle–upper Volgian boundary, implying that the uppermost Boreal Jurassic is to be considered lowermost Cretaceous in an international sense.

The definition of the base of the Cretaceous System in terms of a GSSP still remains unresolved. It is agreed that the GSSP should be located in the Tethyan Realm, but it remains to be determined what proxies (e.g. calpionelid microfossils and magnetostratigraphy) are most appropriate for defining the boundary. Once formal recognition is achieved, correlation with the Boreal and Arctic regions can be undertaken. The sedimentary cores recovered at Rødryggen-1 and Brorson Halvø-1 may thus become important reference sections for the Jurassic–Cretaceous boundary in the Boreal Realm as they record a succession across the boundary. In this regard, Rødryggen-1 is particularly significant with its biostratigraphically nearly unbroken section (Fig. 19).

7.2 Basin evolution

Deposition of the Palnatokes Bjerg Formation marked an abrupt end to the Late Jurassic dysoxic-anoxic–euxinic basin environment and black, organic-rich mudstone deposition (the Bernbjerg Formation and the Storsletten Member of the Lindemans Bugt Formation). The Palnatokes Bjerg Formation was deposited in the final, waning phase of rifting, during which the tilted and rotated Jurassic fault blocks possibly underwent a last phase of faulting, which led to an even finer subdivision of the blocks. The differences in lithology and thickness observed in the Albrechts Bugt and Rødryggen Members reflect strong local control on deposition. For example, the Albrechts Bugt Member at the Rødryggen-1 and Brorson Halvø-1 well sites at Stratumbjerg and at Perisphinctes Ravine (Kuhn Ø) is characterised by highly condensed, relatively carbonate-rich mudstones that were deposited on local submarine highs (Surlyk 1978; Alsen 2006). The carbonate content is mainly derived from calcareous nannofossils (Pauly *et al.* 2012a). The member is markedly thicker, less condensed and carbonate poor at, for example, Kuhnpasset and Niesen (Surlyk 1978), reflecting greater accommodation space and higher sedimentation rates in deeper parts of the basin. This probably reflects a change from half-graben basins on a rotated, westerly-tilted block during the Middle Jurassic to Volgian to greater fragmentation in the late Ryazanian to Hauterivian, when deposition occurred in smaller horst and graben systems.

The light grey and red sediments of the condensed Albrechts Bugt and Rødryggen Members, deposited on submarine highs, reflect well-oxygenated conditions related to a period of cold climate (Alsen 2006). Oceanographic changes driven by deep-water formation in the northern proto-North Atlantic or in the Boreal Arctic Sea resulted in a palaeo-Gulf Stream that allowed for the immigration of several Tethyan faunal and floral elements to eastern Greenland (Ager 1971; Alsen 2006; Pauly *et al.* 2012b). Time-equivalent units, which are compositionally similar to the calcareous Albrechts Bugt and Rødryggen Members, occur scattered in the northern North Atlantic and the Arctic, for example, on Andøya, on the Norwegian shelf, in the Barents Sea and at Svalbard (Kong Karls Øya). These units show that oceanic currents ventilated the sea water throughout the Greenland–Norwegian rift basin and the Arctic Sea during the late Ryazanian–Valanginian–Hauterivian. The Palnatokes Bjerg Formation is overlain by the Stratumbjerg Formation, which marks the return to grey, dark mudstone deposition. Deposition of the Stratumbjerg Formation reflects the rising sea level during post-rift thermal subsidence. In most places, the base of the formation is in the Barremian (Bjerager *et al.* 2020), but at some localities, including the Brorson Halvø-1 core, the transition from the red mudstones of the Rødryggen Member to the grey mudstones of the Stratumbjerg Formation occurs in the upper Hauterivian (Bjerager *et al.* 2020; Nøhr-Hansen *et al.* 2020).

8. Conclusions

The Rødryggen-1 core (234.4 m thick) is assigned to the Bernbjerg Formation (234.4 (TD) – 97 m), the Lindemans Bugt Formation (97–24.40 m) and the Palnatokes Bjerg Formation (24.40–0 m). The Lindemans Bugt Formation is represented by a new member, the Storsletten Member, which records deposition of dark mudstones on the Permpas Block. This region is detached from the coarse-grained depositional system of the western fault blocks fringing the main rift-basin bounding fault. The age of the cored succession is determined from integrated ammonite, palynofossil and calcareous nannofossil stratigraphy and ranges from the upper Kimmeridgian *A. eudoxus* ammonite Zone to the upper Valanginian *O. complex* dinoflagellate cyst Zone. There are essentially no biostratigraphic gaps in the succession.

The Brorson Halvø-1 core (225.70 m thick) is assigned to the Bernbjerg Formation (225.7 (TD) – 45.5 m), the Lindemans Bugt Formation (Storsletten Member; 45.5–37.5 m), the Palnatokes Bjerg Formation, including the Albrechts Bugt (37.5–30 m) and Rødryggen Members (30–8.7 m), and the Stratumbjerg Formation (8.7–0 m). The age of the cored succession is determined from integrated ammonite, palynofossil and calcareous nannofossil stratigraphy and ranges from the late Kimmeridgian *A. eudoxus* ammonite Zone to the lower Barremian *B. longicornutum* dinoflagellate cyst Zone or *P. anaphrisum* Subzone. The succession is characterised by two major biostratigraphic gaps representing unconformities in the succession that bound the Storsletten Member. They reflect rotation of the Permpas Block and uplift of the block crest during the middle Volgian rift climax, which resulted in repeated non-deposition in contrast to the deeper basin setting of Rødryggen-1.

Both cores, but in particular, the stratigraphically complete Rødryggen-1 core, provide key stratigraphic reference sections for the Jurassic–Cretaceous boundary interval in Greenland, with wider implications in the Arctic and North Atlantic regions.

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Author contributions

PAL: Concept. Writing – original draft (lead), ammonites and stratigraphy, lithostratigraphy, discussion, editing
SPI: Concept. Writing – original draft (second lead), palynostratigraphy Jurassic interval
HNH: Writing – palynostratigraphy Cretaceous interval
ES: Writing – calcareous nannofossil stratigraphy Rødryggen-1 core
SPA: Writing – calcareous nannofossil stratigraphy Brorson-1 core
JH: Writing – lithostratigraphy

Competing interests

The authors declare no competing interests.

Additional files

Two figures are available as supplementary files at *https://doi.org/10.22008/FK2/KTPO5R*. Supplementary Data File 1: A full range chart for palynomorphs in the Rødryggen-1 core is provided to supplement Fig. 7. Supplementary Data File 2: A full range chart for palynomorphs in the Brorson Halvø-1 core is provided to supplement Fig. 16.

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