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A Cretaceous dinoflagellate cyst zonation for NE Greenland

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Original Article

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Abstract

A palynostratigraphic zonation is for the first time established for the entire Cretaceous succession in NE Greenland from Traill Ø in the south to Store Koldewey in the north (72–76.5° N). The zonation is based on samples from three cores and more than 100 outcrop sections. The zonation is calibrated to an updated ammonite zonation from the area and to palynozonations from the northern North Sea, Norwegian Sea and Barents Sea areas. The palynozonation is primarily based on dinoflagellate cyst and accessory pollen. The Cretaceous succession is divided into 15 palynozones: seven Lower Cretaceous zones and eight Upper Cretaceous zones. The two lowermost zones are new. The following five (Lower Cretaceous) zones have already been described. Two of the Upper Cretaceous zones are new. The zones have been subdivided into 20 subzones, 11 of which have been described previously and one of which has been revised/redefined. Nine subzones (Upper Cretaceous) are new. More than 100 stratigraphical events representing more than 70 stratigraphic levels have been recognized and presented in an event-stratigraphic scheme.

1. Introduction

Mesozoic sediments in East Greenland have been studied for almost 150 years. A detailed historical review of the expeditions in the area between 1870 and 1956 was given by Donovan (1957) and updated by Surlyk (1978*a*). Cretaceous biostratigraphy and the dating of the Cretaceous successions in East and NE Greenland (Fig. 1) were sparse until the 1990s, especially compared with the studies of the Jurassic strata in the same area. During the historic exploration of East and NE Greenland (e.g. Surlyk, 1978*a*), Cretaceous biostratigraphy of the sedimentary basins remained fragmentary and variably developed, partly because the majority of the succession is badly exposed and commonly severely intruded and covered by Palaeogene basalts providing poor recovery of fossils from the sedimentary successions. The most comprehensive biostratigraphy has been recorded in lowermost Cretaceous strata with relatively good exposures, for example in the Wollaston Forland – Kuhn Ø region (e.g. Surlyk, 1978*a*; 'Ø' is Danish for island). The ammonite succession was documented by Maync (1949) and Donovan (1964); Surlyk (1978*a*) provided a middle Volgian (*c.* middle Tithonian) – Lower Cretaceous ammonite zonation and an Upper Jurassic – Lower Cretaceous *Buchia* zonation was introduced by Surlyk & Zakharov (1982). The correlation to the Tithonian–Berriasian stages is based on Wimbledon (2017). In contrast, mid-Cretaceous biostratigraphic data were sparse and Upper Cretaceous data were almost missing, despite the large efforts invested in fieldwork over many years (e.g. Ravn, 1911; Koch, 1929*a*, *b*, 1935; Frebold, 1932*a*, *b*, 1934, 1935; Frebold & Noe-Nyegaard, 1938; Maync, 1949; Donovan, 1949, 1953, 1954, 1955, 1957, 1961, 1964, 1972*a*, *b*).

Nøhr-Hansen (1993, 1994) introduced dinoflagellate cysts (dinocysts) as a stratigraphic tool in the Cretaceous successions of East and NE Greenland. Based on a comprehensive study of the Lower Cretaceous dinocyst flora, a detailed zonation of the upper Hauterivian? – Lower Cenomanian? was established. Thirty-seven sections and three shallow cores without macrofossils were dated on the basis of dinocysts throughout NE Greenland.

In more recent times, Alsen (2006) monographed an upper Ryazanian (*c.* upper Berriasian) – Hauterivian ammonite fauna in the Wollaston Forland region and later applied Upper Jurassic – Lower Cretaceous ammonite stratigraphy on the Rødryggen-1 core (Bojesen-Koefoed *et al.* 2014). Alsen & Mutterlose (2009) demonstrated the stratigraphic potential of Lower Cretaceous belemnites in this region. Recently, dinocysts (Nøhr-Hansen *et al.* 2018), foraminifers and nannofossils have been applied for stratigraphy on restricted intervals where calcareous tests are preserved (Pauly *et al.* 2012*a*, *b*; Rødryggen-1 core, Bojesen-Koefoed *et al.* 2014), Brorson Halvø-1 core (Bojesen-Koefoed *et al.* 2014), Store Koldewey study (Piasecki *et al.* 2012) and the Nanok-1 core (Bojesen-Koefoed *et al.* 2014).

During the petroleum geological studies in East and NE Greenland (2008–2011), Cretaceous biostratigraphic data have been collected from the whole region between Traill

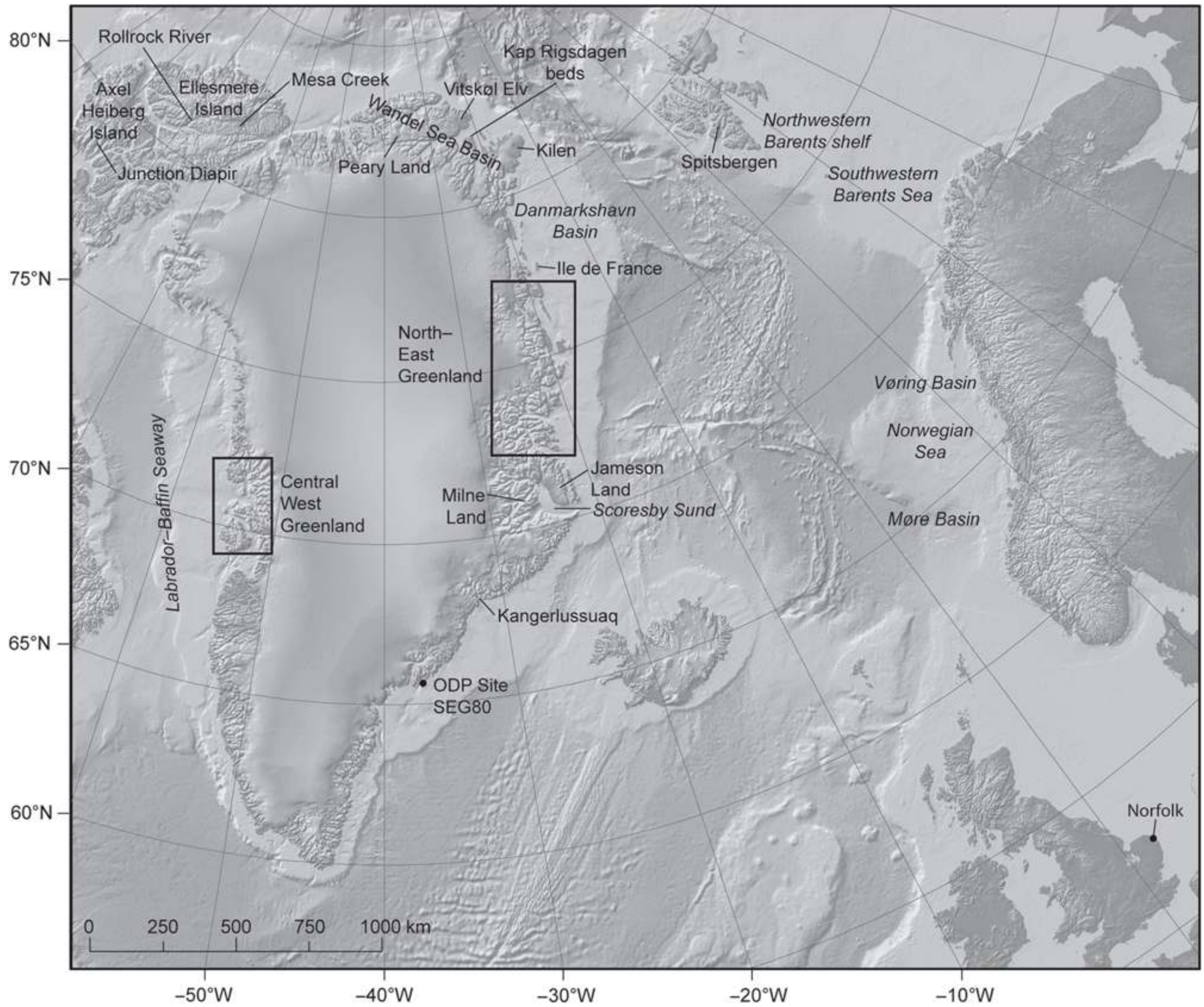

Fig. 1. Location map of Greenland and surrounding areas.

Ø (72° N) in the south to Store Koldewey (latitude, 76–76.5° N) in the north (Figs 2–5). It incorporates previous work in the area but has been centred around a resent intensive programme of fieldwork, including drilling of cored wells (Bojesen-Koefoed *et al.* 2014). In order to develop a better understanding of the onshore geology, the goal was to identify basin evolutionary trends and describe depositional systems that would be valuable in interpreting existing and future datasets offshore NE Greenland, particularly in the Danmarkshavn Basin (Fig. 1) at the northern limit of the onshore project. Palynomorphs, primarily dinocyst, recorded from more than 100 sections throughout the region, dated the sequence as late Tithonian – late Campanian or ?Early Maastrichtian. The dinocyst zonation of Nøhr-Hansen (1993) is expanded stratigraphically to now include the upper Tithonian – Valanginian strata in addition to the Cenomanian – Campanian or ?Lower Maastrichtian strata. Extensive collection of macrofossils has improved the calibration of dinocyst zonation with ammonite stratigraphy and higher precision has been achieved. The improved biostratigraphy has been used extensively to date the units of a revised and updated Cretaceous lithostratigraphy. This comprehensive revision is nearing completion (Geological Survey of Denmark and Greenland) but is presently unpublished; the lithostratigraphic framework utilized here (Fig. 6) is therefore provisional and hence informal. The informal units are in lower case in the text and in Figure 6.

North of the studied area, from Germania Land north of Store Koldewey, macrofossils from loose boulders of Aptian age have been reported by Ravn (1911) and Rosenkrantz (1934, p. 24), but no outcrops have been recorded. Reworked dinocysts of early Aptian and late Albian ages have been recorded as reworked in Pliocene deposits at Ile de France (Fig. 1; unpublished data). Ammonites of late Volgian (*c.* late Tithonian) – early Valanginian and Early–middle Albian ages have been reported by Birkelund & Håkansson (1983) and Alsen (2018) from the Wandel Sea Basin in North Greenland (Fig. 1). Dinocysts from the same area indicate ages of middle Oxfordian – early Valanginian (Håkansson *et al.* 1981). Dinocysts of Early Albian age have also been recorded from the area by Århus (1991). Recently, Piasecki *et al.* (2018) described *in situ* Barremian and reworked Upper Cretaceous dinocyst assemblages from the Wandel Sea Basin (81° N), and Pedersen *et al.* (2018) described middle Albian – late Coniacian dinocysts, inoceramid and ammonite assemblages

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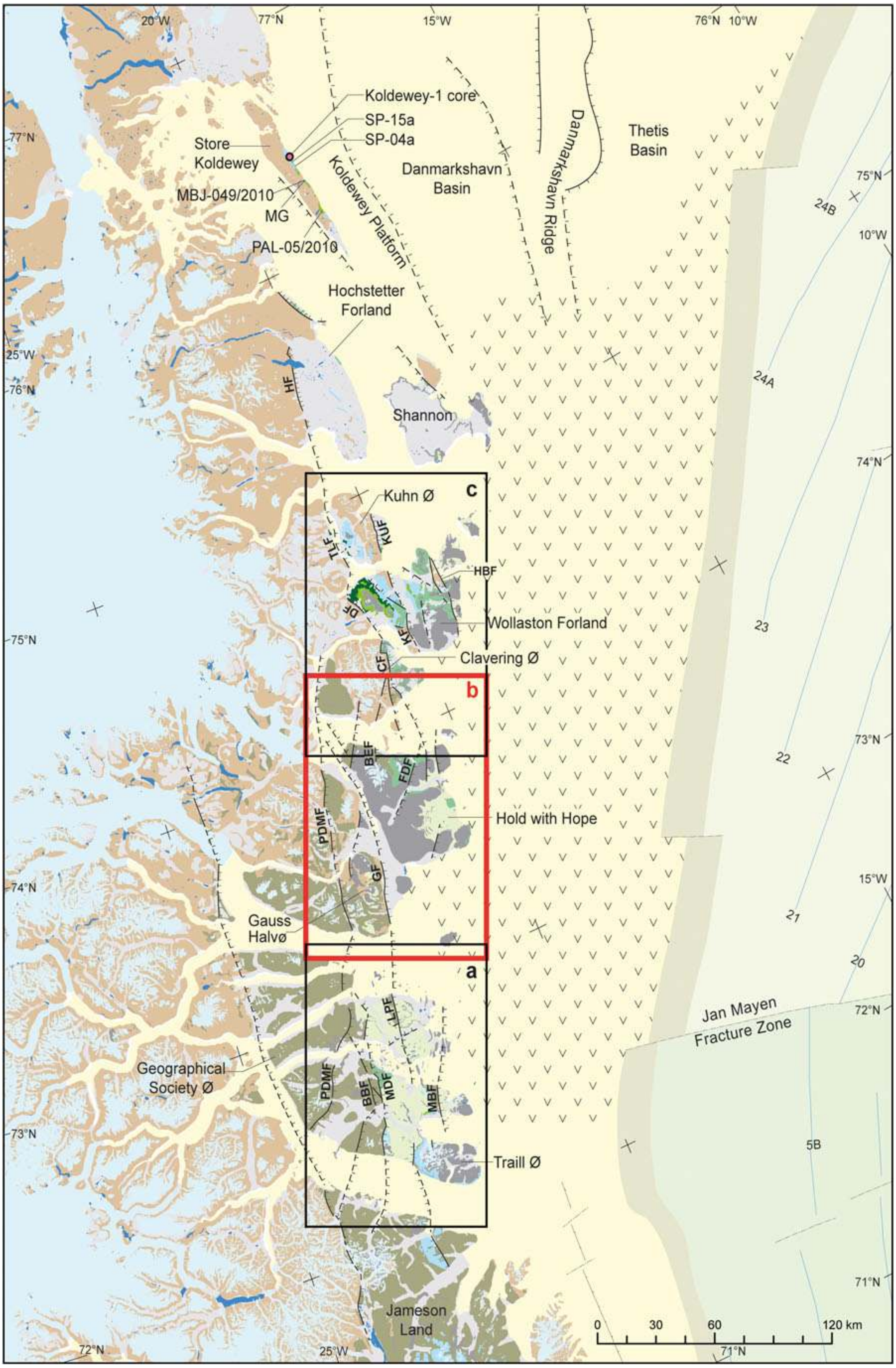

Fig. 2. Geological map of NE Greenland showing study area stretching from Traill Ø to Store Koldewey. Insert maps: a, Traill Ø and Geographical Society Ø (Fig. 3); b, Gauss Halvø and Hold with Hope (Fig. 4); and c, Clavering Ø and Wollaston Forland (Fig. 5). BBF – Bordbjerg Fault; BEF – Blå Elv Fault; CF – Clavering Fault; DF – Dombjerg Fault; GF – Gisecki Fault; HBF – Hühnerbjerg Fault; HF – Hochstetter Fault; FDF – Fosdalen Fault; KUF – Kuhn Fault; LPF – Laplace Bjerg Fault; MDF – Månedal Fault; MG – Midter Gneisnæs; MBF – Mols Bjerge Fault; PDMF – Post-Devonian Main Fault; TLF – Thomsen Land Fault.

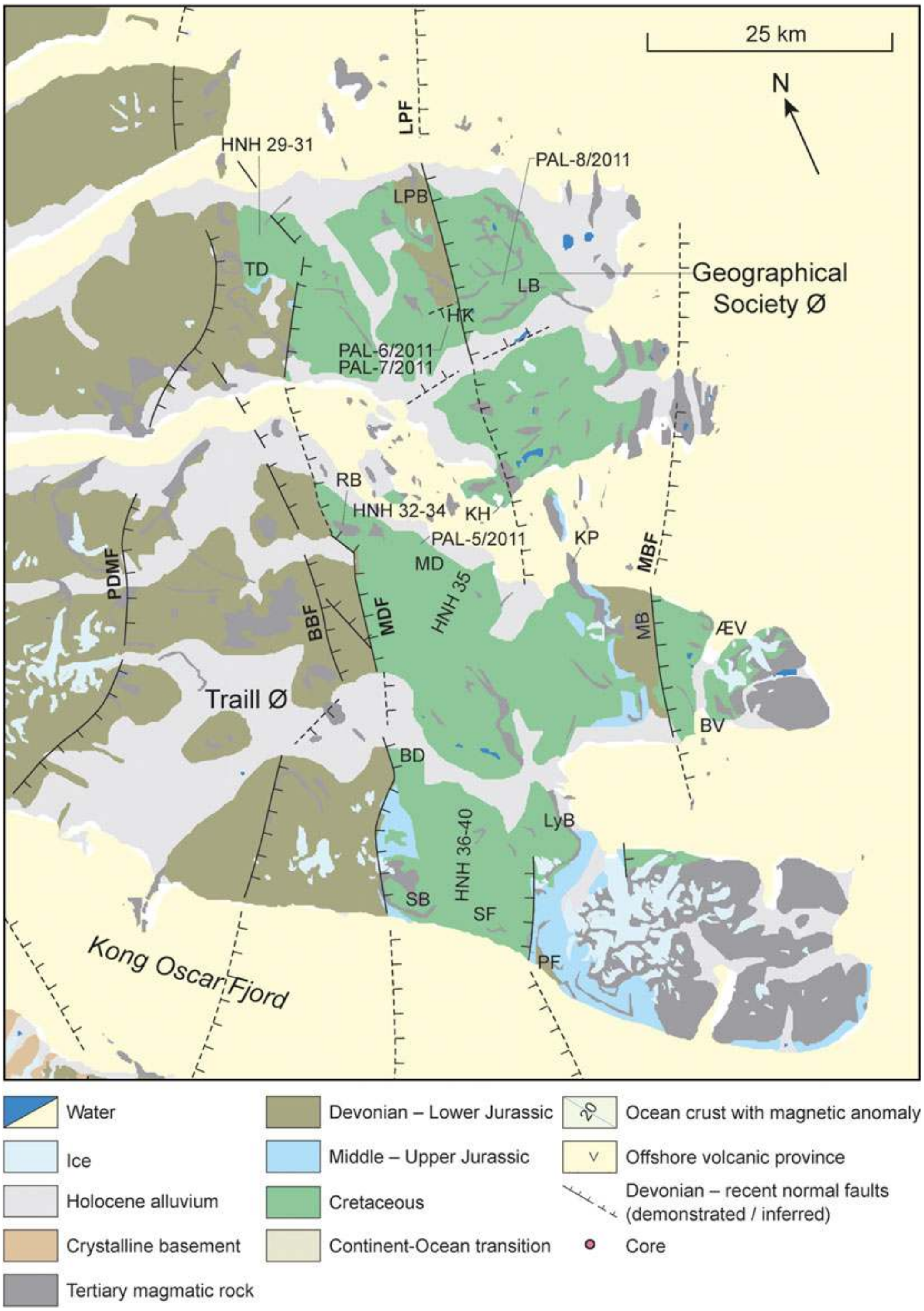

Fig. 3. Geological map of the Traill Ø and Geographical Society Ø. Faults: BBF – Bordbjerg Fault; LPF – Laplace Bjerg Fault; MDF – Månedal Fault; MBF – Mols Bjerge Fault; PDMF – Post-Devonian Main Fault. Localities: BD – Bjørnedal; BV – Beitrup Vig; HNH 29-40 (localities of Nøhr-Hansen; 1993); LB – Leitch Bjerg; LPB – Laplace Bjerg; LyB – Lycett Bjerg; HK – Hundeklemmen; KH – Kap Hovgaard; KP – Kap Pallander; MB – Mols Bjerge; PF – Prospekt Fjeld; RB – Rold Bjerge; SB – Svinhuvuds Bjerge; SF – Sorte Fjelde; TD – Tværdal; ÆV – Æbletoft Vig.

from Kilen (Fig. 1; 81° N). From southern Jameson Land (Fig. 1), south of the studied area, the youngest Lower Cretaceous formation described is the Berriasian – lower Valanginian Hesteelv Formation (Surlyk *et al.* 1973; Fig. 1). According to C. Marcussen (pers. comm. 1991), seismic data from Scoresby Sund (Fig. 1), south of Jameson Land, indicate that the Jameson Land basin continues to the south beneath the lower Cenozoic basalts on the southern shore of the fjord. The Lower Cretaceous successions possibly attain a total thickness here of up to 500 m. On Milne Land (Fig. 1; 70° N), dinocysts indicating

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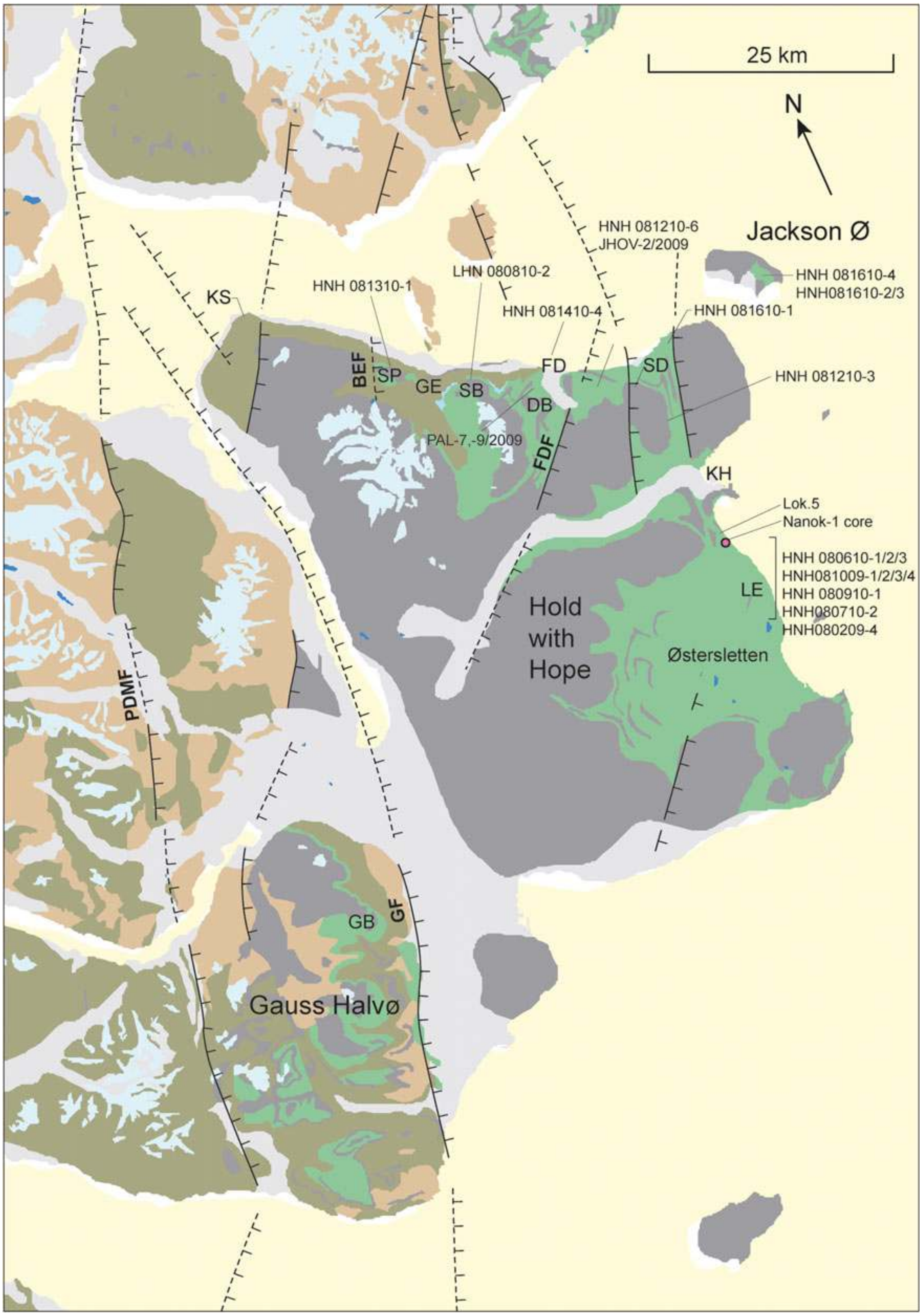

Fig. 4. Geological map of Hold with Hope and Gauss Halvø. Faults: BEF – Blå Elv Fault; GF – Gisecke Fault; FDF – Fosdalen Fault; PDMF – Post-Devonian Main Fault. Localities: DB – Diener Bjerg; FD – Fosdalen; GB – Gisecke Bjerge; GE – Gulelv; KH – Knudshoved; LE – Lygnaelv; KS – Kap Stosch; SB – Steensby Bjerg; SD – Snerta Dal; SP – Stensiö Plateau.

middle Volgian (*c*. middle Tithonian) – late Ryazanian (*c*. late Berriasian – early Valanginian) ages have been reported by Piasecki (1979). Cretaceous dinocysts of Albian–Maastrichtian ages have been recorded by Nøhr-Hansen (2012) further south in the Kangerdlugssuaq area (Fig. 1; 68° N), and dinocysts of Albian age have been reported from reworked sandstones obtained offshore Tasiilaq at Ocean Drilling Program (ODP) Site SEG80 during the transect EG65 (Fig. 1; Thy *et al*. 2007).

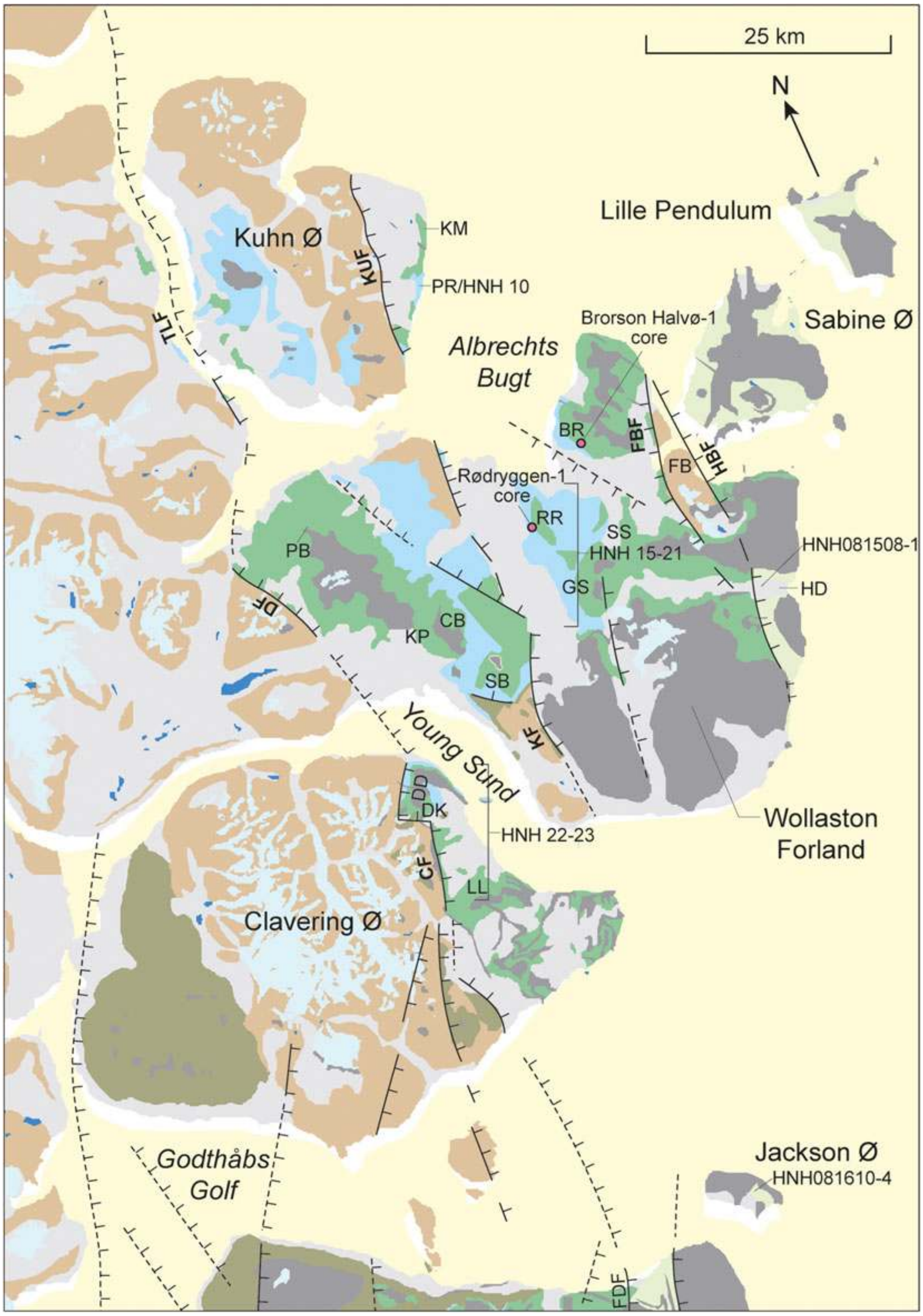

Fig. 5. Geological map of the Clavering Ø to Kuhn Ø area. Faults: CF – Clavering Fault; DF – Dombjerg Fault; FBF – Falkebjerg Fault; HBF – Hühnerbjerg Fault; KF – Kuppel Fault; KUF – Kuhn Fault; TLF – Thomsen Land Fault. Localities: BR – Brorson Halvø; CB – Cardioceras Bjerg; DD – Dolomit Dal; DK – Djævlekløften; FB – Falkebjerg; GS – Gyldenspids; HD – Haredal; HNH 15–23 (localities of Nøhr-Hansen, 1993); KM – Kap Mauer; KP – Kuhn Passet; LL – Langelinie PB – Palnatokes Bjerg; PR – Perisphinctes Ravine; RR – Rødryggen; SB – Stratumbjerg; SS – Stor Sletten.

2. Geological setting

The NE Greenland margin and the conjugate margin on the Norwegian continental shelf were formed by periodic rifting since the late Palaeozoic Era (Surlyk, 1990). Extensional collapse and basin formation were initiated during the Devonian Period, following the culmination of the Caledonian Orogeny in Silurian and Devonian times as Laurentia (represented by Greenland and North America) collided with Baltica and Avalonia (Higgins & Leslie, 2008). A number of large, mostly

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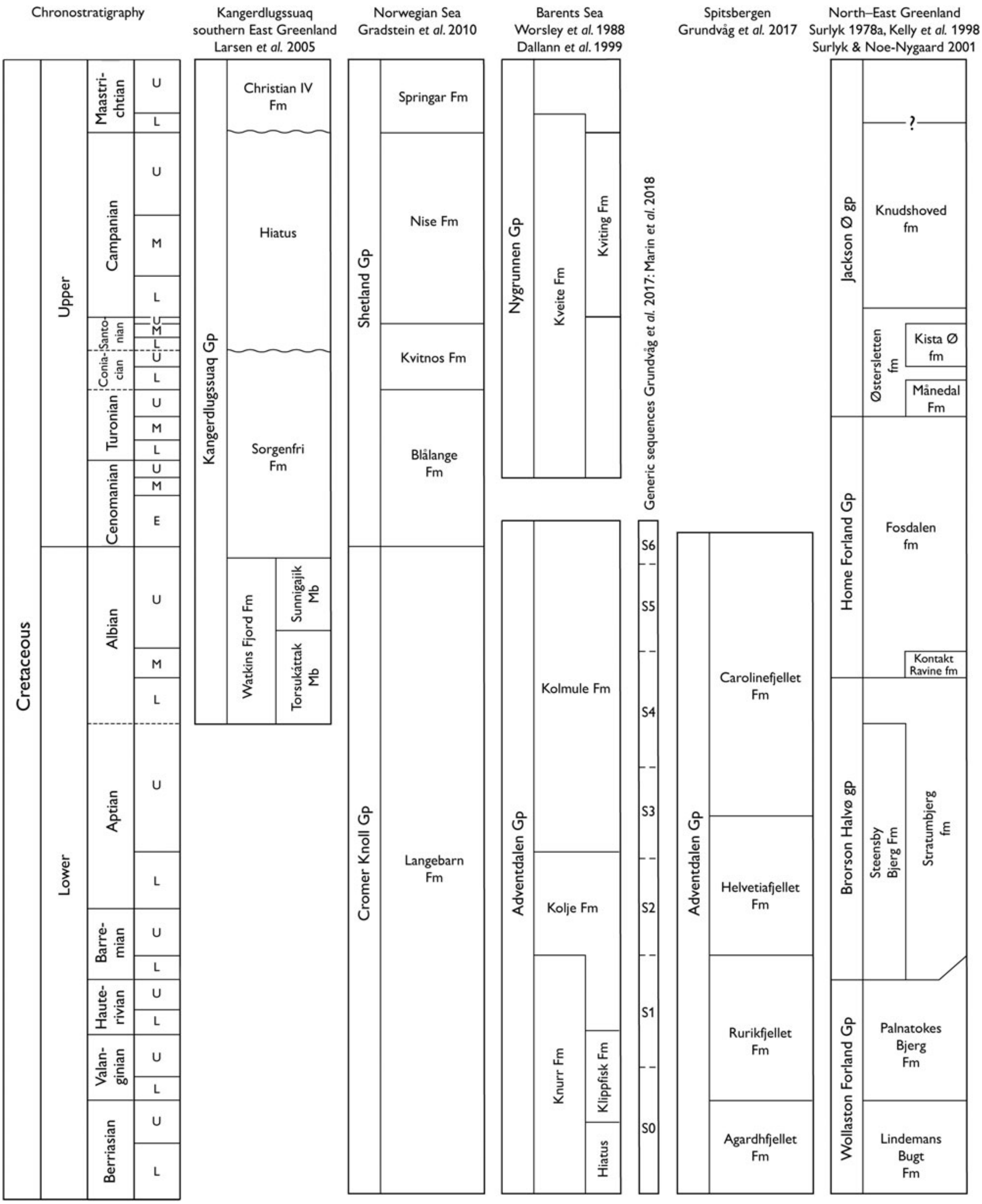

Fig. 6. Regional lithostratigraphic correlation scheme. The lithostratigraphic framework utilized here for NE Greenland is provisional and hence informal, being based on a comprehensive revision nearing completion (Geological Survey of Denmark and Greenland, unpublished data). Informal units in lower case.

N–S- to NNE–SSW-trending, normal faults confine the post-Caledonian sedimentary basins in the area, broadly mimicking the Caledonian structural grain of the region (Fig. 2). Devonian and Carboniferous rifting resulted in the formation of deep basins filled by more than 8 km of non-marine deposits (Larsen et al. 2008). Subsequent rift episodes affected the area during Permian, Early–middle Triassic and Middle Jurassic – earliest Cretaceous times (Surlyk *et al.* 1981; Surlyk, 1990;

Stemmerik *et al.* 1993). Further North Atlantic extension during Late Cretaceous and Early Palaeogene times ultimately led to continental separation during the Early Eocene Epoch and Atlantic seafloor spreading to present. The pre-Eocene extensional basins of NE Greenland, onshore and offshore, are thus complemented by the offshore record of the conjugate Norwegian margin. This is particularly relevant to the Cretaceous period, when the NE Greenland margin represented the proximal portion of a symmetrical marine trough. The axial deep-water part of the rift basin is represented by the Vøring and Møre basins and the terraced Norwegian margin, mirroring that of NE Greenland (Fig. 1).

The North Atlantic region experienced two major rift episodes during late Mesozoic – early Cenozoic times. Rifting related to widespread broadly E–W-aligned extension in the North Atlantic region, accompanying Central Atlantic spreading, began during late Bajocian times in NE Greenland (Doré *et al.* 1999). Middle–Late Jurassic extension in East Greenland resulted in broad, fault-controlled depocentres, propagating northwards from Jameson Land with time (Surlyk, 2003); this phase of regional basin subsidence and expansion was accompanied by a eustatic sea-level rise and resulted in the accumulation of the world-renowned Kimmeridgian source rocks from the North Sea through the Greenland–Norway rift to the Barents Sea (Bojesen-Koefoed *et al.* 2018). During latest Jurassic – earliest Cretaceous times, extension culminated in the development of a rugged rift topography due to marked rotation of narrow fault blocks (10–25 km across) along broadly N–S-aligned faults (Vischer, 1943; Surlyk, 1978*a*, 2003). This event and the resulting unconformity is an important feature throughout the North Atlantic rift and a key seismic marker on the Norwegian shelf (e.g. Tsikalas *et al.* 2005) and in the Danmarkshavn Basin (Hamann *et al.* 2005; Fig. 1). The second phase of rifting during Late Cretaceous – Early Palaeogene times heralded the eventual break-up and onset of sea-floor spreading at the Paleocene–Eocene boundary. The onset of rifting in the Campanian is typically linked to the initiation of sea-floor spreading in the Labrador Sea (Fig. 1), and is associated with a shift in the extension direction in the North Atlantic region from N–S to NE–SW (Doré *et al.* 1999). In NE Greenland, this rift phase is poorly documented in the sedimentary record due to uplift and exhumation linked to the rift event. Much of the Cretaceous sedimentary record of onshore NE Greenland, from the Hauterivian–Barremian to the lowermost Campanian – ?Lower Maastrichtian strata, thus occupies the timespan between these two regional North Atlantic rift phases and can be broadly considered as 'post-rift', deposited during a time of relative tectonic quiescence (Færseth & Lien, 2002; Lien, 2005).

3. Material and methods

The studied material includes samples from the Nanok-1 (517004, Fig. 4), Rødryggen-1 (517001, Fig. 5) and Store Koldewey-1 (517002, Fig. 2) cores and numerous outcrop sections, as well as a restudy of several of the old samples originally described by Nøhr-Hansen (1993). The palynological zonation established below is based on the study of more than 1000 samples representing more than 100 sections throughout the area (Figs 2–5). The new established Upper Cretaceous zones follow the roman numerals system established for the Lower Cretaceous zones by Nøhr-Hansen (1993), whereas the two lowermost Cretaceous zones are named NEG Cr 1 and NEG Cr 2 (NE Greenland Cretaceous 1 and 2). The *Heterosphaeridium difficile*, *Aquilapollenites* and *Cerodinium diebelii* intervals identified in West Greenland were originally not intended to be formal biostratigraphic zones (Nøhr-Hansen, 1996); they therefore do not preoccupy the names for the new *Heterosphaeridium difficile* (IX), *Aquilapollenites* (XII) or *Cerodinium diebelii* (XIII) zones. The majority of the sections are named with the initial of the collector (all Geological Survey of Denmark and Greenland (GEUS) employees), often followed by section number, for example SP-15a (Stefan Piasecki section 15a, Fig. 2); with initial, section number and year, for example MBJ-049/2010 (Morten Bjerager, section 49, 2010, Fig. 2), JHOV -2/2009 (Jussi Hovikoski section 2, 2009, Fig. 4) and PAL-8/2011 (Peter Alsen, section 8, 2011, Fig. 4); or with initial, month, date, year of collection and section number, for example HNH 081610-4 (Henrik Nøhr-Hansen 16th of August 2010 section 4, Fig. 4) or LHN 080810-1 (Lars Henrik Nielsen 8th of August 2010 section 1, Fig. 4). The sections named HNH followed by a number (e.g. HNH 29–31; Fig. 3) refers to the sections described by Nøhr-Hansen (1993).

The palynology samples were processed by a methodology including treatment with hydrogen chloride (HCl), hydrogen fluoride (HF), oxidation with nitric acid (HNO_3) and heavy liquid separation. At each preparation step, a slide was inspected to follow the process closely. Finally, the organic residue was sieved on a 21 µm, occasionally on 30 µm, filter (to concentrate palynomorphs in samples, poor in dinocysts), swirled and was finally mounted on glass slides using a glycerine jelly medium. The dinocyst content was analysed using a normal light microscope.

Approximately 100 identifiable dinocysts per sample were counted to perform a relative abundance analysis. Prasinophycean and freshwater algae and acritarchs in the slide were also counted in addition to the main dinocyst tally. Additional dinocyst species occurring outside the 100 counted specimens in the first slide or in other slides were recorded as present. The taxonomy used here follows that of Williams *et al.* (2017).

The stratigraphic results are illustrated in a stratigraphic event chart (Fig. 7a–d; timescale (Ma) from Ogg *et al.* 2016). Since all analysed material is from cores or outcrops, caving is not an issue. Reworked dinocyst taxa are recorded. The spore and pollen flora is not recorded systematically, but reworked and selected stratigraphic marker mio- and macrospores are recorded.

4. Stratigraphic methods

Based on the oldest or first occurrence (FO) and youngest or last occurrence (LO) of stratigraphically important dinocyst species (events), the studied succession has been calibrated to ammonite zones of the local Boreal ammonite zonation (Surlyk, 1973, 1977, 1978*a*, *b*; Callomon & Birkelund, 1982; Birkelund *et al.* 1984; Birkelund & Callomon, 1985; Kelly & Whitham, 1999; Alsen, 2006). Adjusted or new calibrations of dinocyst events calibrated by the local ammonite stratigraphy have been established in this work. The ammonite biozonation correlates with ammonite chronozones and the succession is dated on the basis of these chronostratigraphic units. Ammonite zonations vary with geographically separate faunal provinces and these diverging zonations are not precisely correlated at many stratigraphic levels; however, stratigraphic schemes generally ignore this fact. Calibrating dinocyst events with ammonite zones in different faunal provinces, and then comparing these ammonite zones

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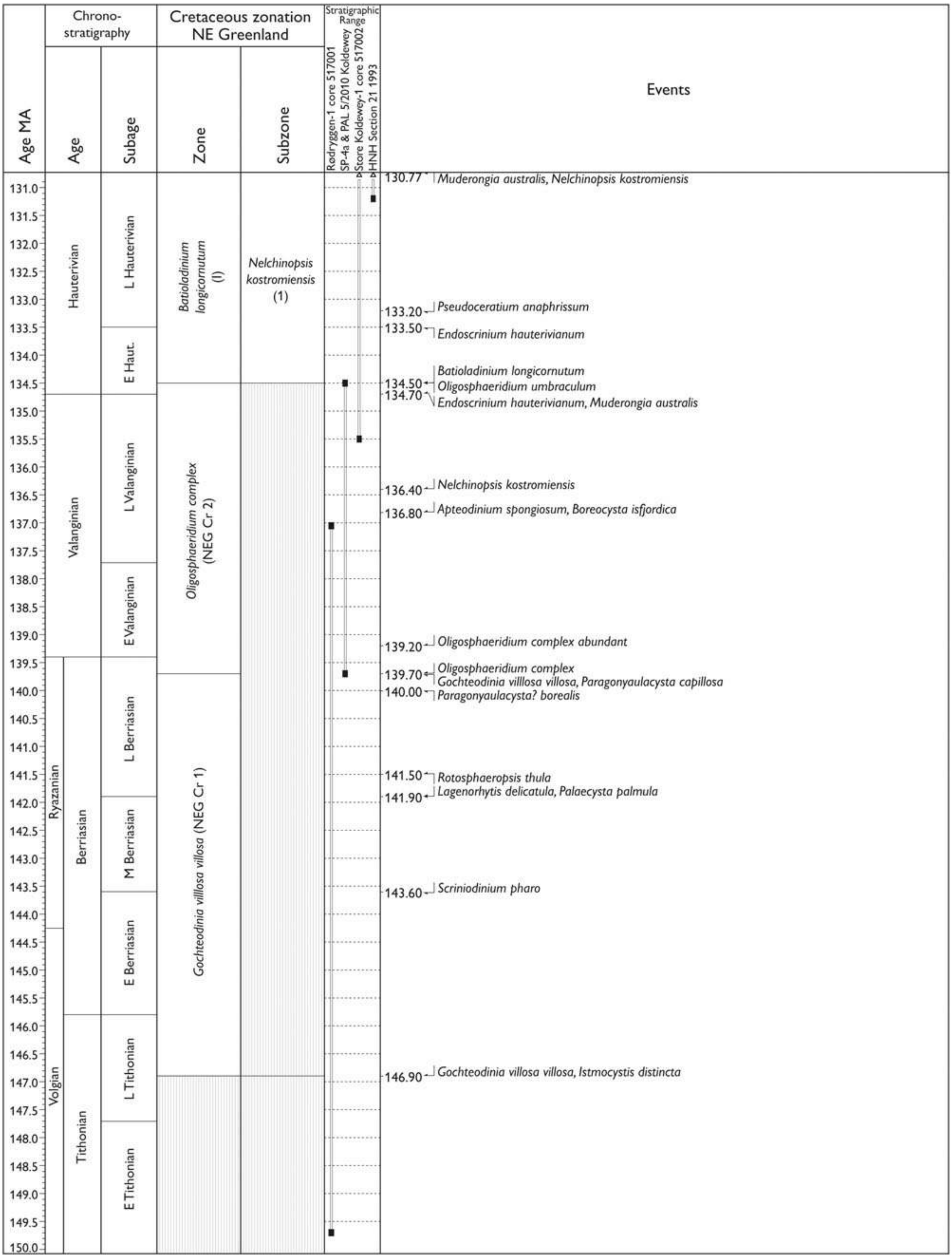

Fig. 7. (a–d) Palynostratigraphic zonation and event stratigraphy (primarily based on dinocysts) for the upper Tithonian – Lower Maastrichtian stages in NE Greenland based on the study of three cores and more than 100 sections, of which 29 are selected as reference sections representing the studied Cretaceous succession. Timescale (Ma) from Ogg *et al.* (2016).

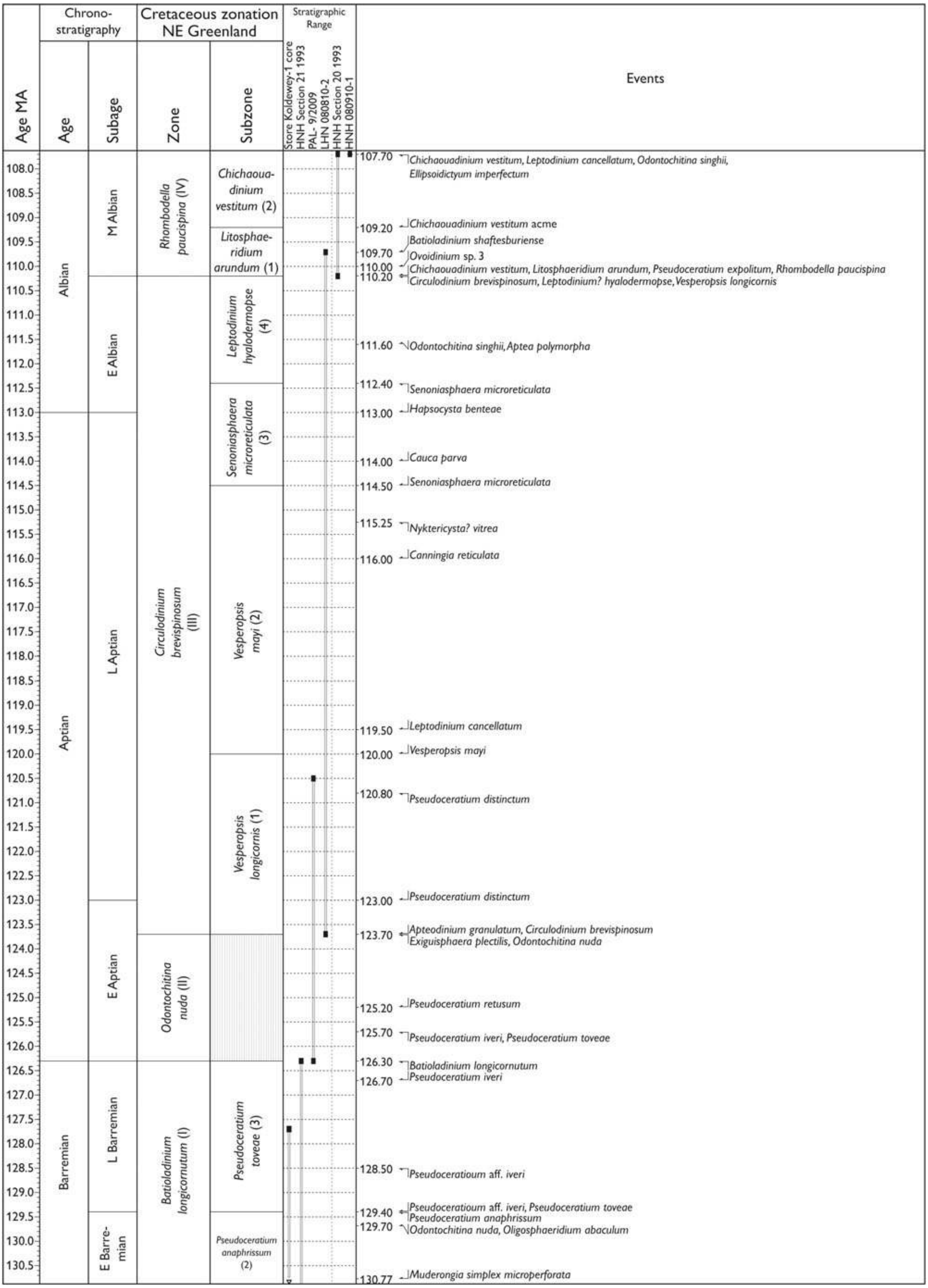

Fig. 7. (Continued).

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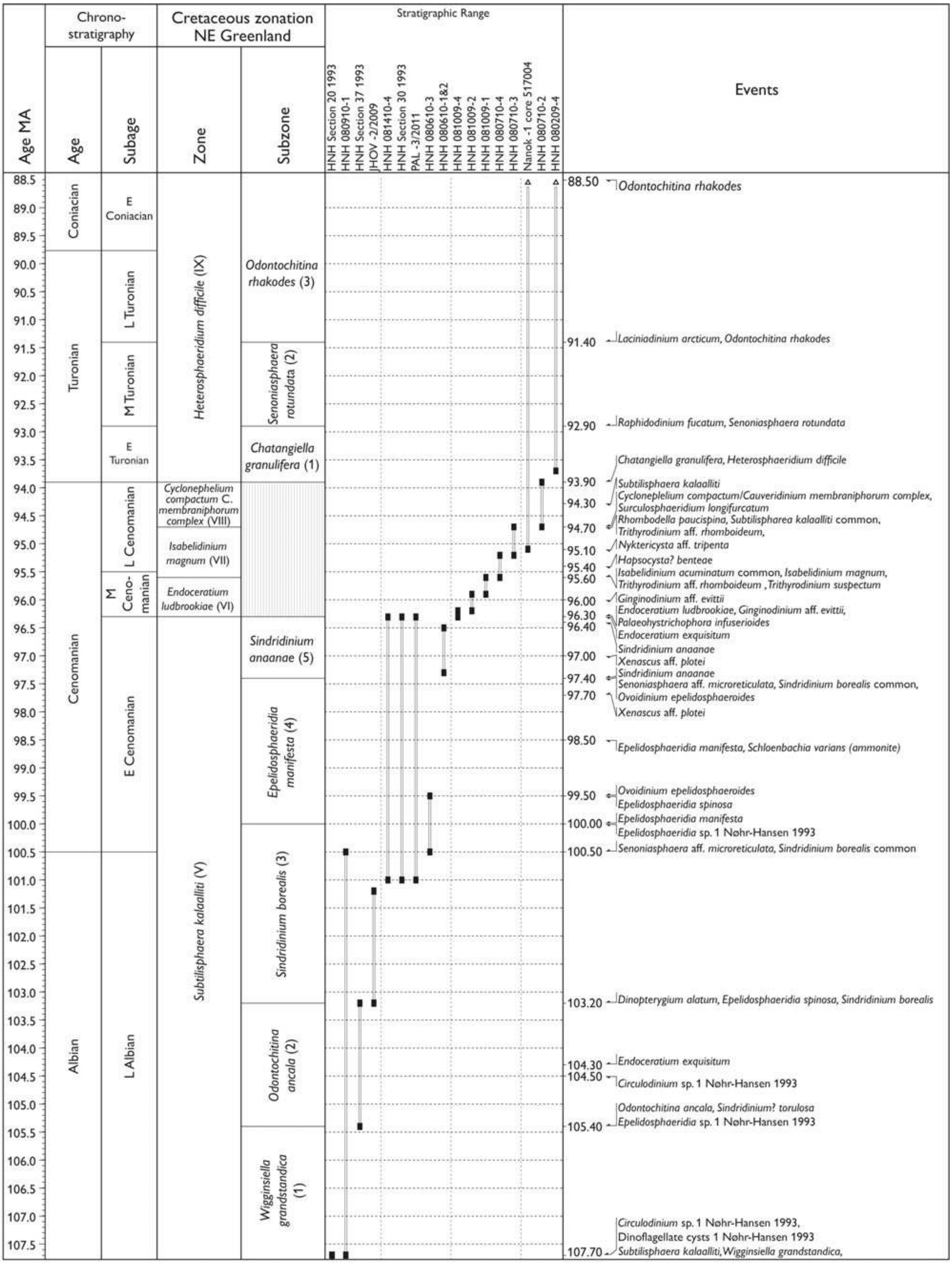

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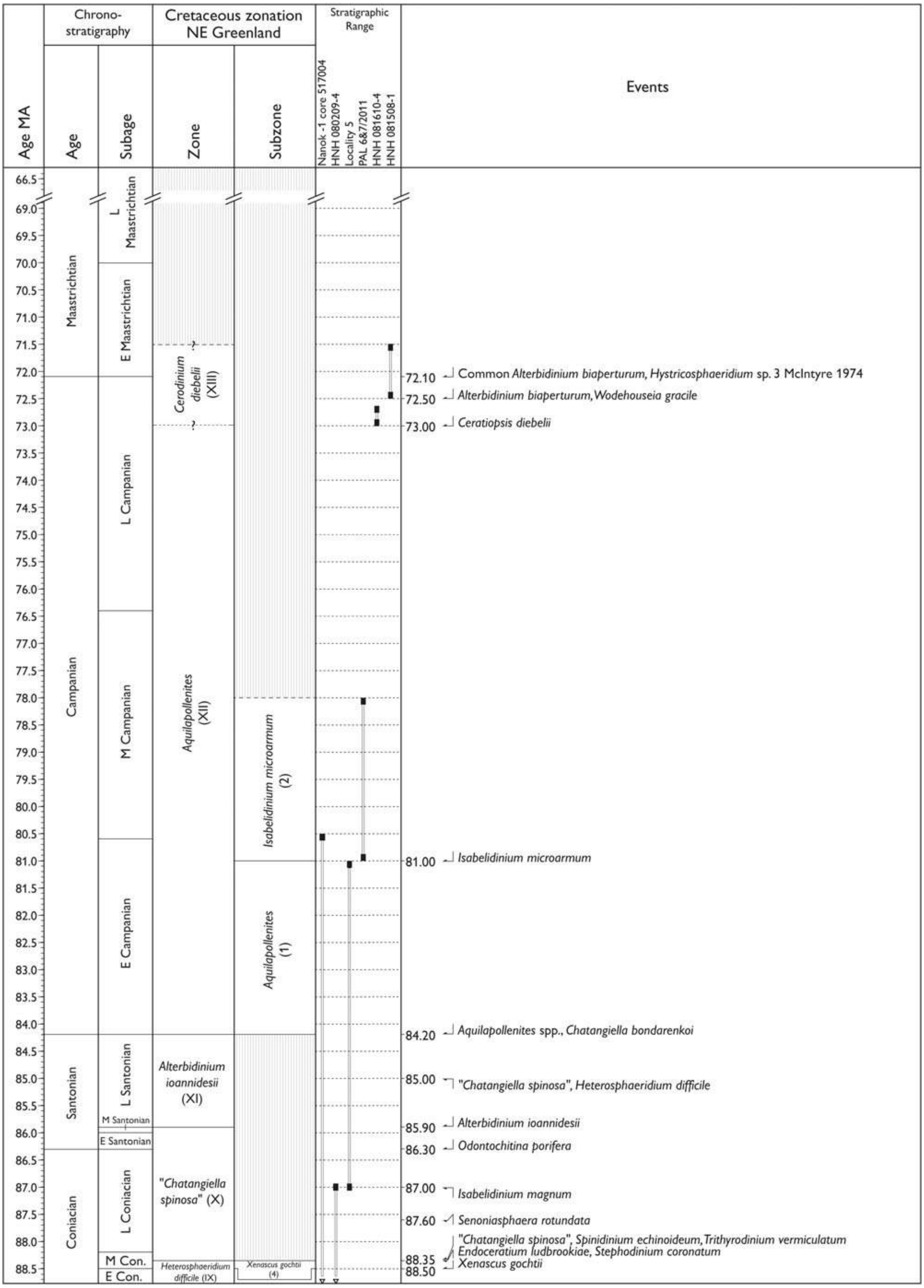

Fig. 7. (Continued).

across biogeographic boundaries to obtain a relevant age, is hazardous; however, this is the only possibility in some cases. The lowermost Cretaceous flora varies significantly in composition, diversity and abundance from sub-Boreal to Boreal and Arctic regions (e.g. Brideaux & Fisher, 1976; Brideaux, 1977; Lebedeva & Nikitenko, 1999; Riding *et al.* 1999; Smelror & Dypvik, 2005); consequently, the age of stratigraphic events may also vary. Examples are documented in this work based on the common ammonite and dinocyst stratigraphy presented here.

5. Ammonite zonation

Since the biostratigraphic review of Donovan (1957), the most important contribution to Cretaceous ammonite stratigraphy in NE Greenland has been on the Jurassic–Cretaceous boundary beds in Wollaston Forland and Kuhn Ø (Donovan, 1964; Surlyk, 1973, 1978*a*), the lower Aptian beds from Hold with Hope (Kelly & Whitham, 1999) and the upper Berriasian – Hauterivian strata in Wollaston Forland (Alsen & Rawson, 2005; Alsen, 2006). Recent sampling has added data from levels and intervals previously not known to contain ammonites. The Berriasian (*c.* uppermost Volgian) –Hauterivian zones are mainly documented from the Lindemans Bugt Formation and Palnatokes Bjerg Formation in the Wollaston Forland area (Surlyk, 1978*a*; Alsen, 2006; Fig. 6). The Hauterivian zone was only referred to as *Simbirskites* beds by Alsen (2006) based on the first but poorly preserved finds of *Simbirskites*, but further collection now allow the identification of the *Simbirskites* (*Speetoniceras*) *inversum* Zone and the *Simbirskites decheni* Zone (Fig. 8). The former documents that the deposition of the Rødryggen Member of the Palnatokes Bjerg Formation extended into the upper Hauterivian Stage is also reflected by the recently established belemnite and calcareous nannofossil stratigraphies (Alsen & Mutterlose, 2009; Pauly *et al.* 2012*a*). Finds of crioceratid heteromorphs at Store Koldewey and Stratumbjerg, Wollaston Forland (Figs 2, 5) are the first ammonite evidence of the Barremian Stage. The assemblage has close affinity with assemblages described from northern Germany (Kakabadze & Hoedemaeker, 2010). The identified taxa indicate the presence of three zones that are adopted from the lower–upper Barremian boundary interval in northern Germany. However, sampling conditions did not allow a clear separation of the zones in Greenland. The zones are accordingly indicated as undifferentiated as *Fissicostaticeras fissicostatus* – *Paracrioceras elegans* – *Paracrioceras denckmanni* zones (Fig. 8). Rare material from Store Koldewey has shown the presence of the uppermost Barremian *Paranclyloceras bidentatum* Zone (Fig. 8), also adopted from NW Europe. *Deshayesites* in Greenland marks the base of the Aptian Stage. Occurrences are recorded from Kuhn Ø (Bøgvad & Rosenkrantz, 1934), Hochstetter Forland (Surlyk, 1978*b*) and Hold with Hope (Kelly & Whitham, 1999). *Deshayesites* are now also recorded from Store Koldewey. Lower Aptian *Deshayesitid* zonation is partly adopted from the lowermost Aptian strata of NW Europe. It is overlain by strata with ammonites of the genus *Tropaeum* that allows the adoption of the *Tropaeum bowerbanki* Zone from NW Europe (Fig. 8). The remaining Cretaceous succession (Albian–Campanian) only contains rare and scattered ammonites (Donovan, 1957). The Albian *Hoplites dentatus* Zone is identified by the index species. The Cenomanian in places contains a rich *Schloenbachia* fauna, especially in Tværdal, Geographical Society Ø, where its marks the base of the Cenomanian Stage. Rare *Schloenbachia* occur in Lygnaelv, Hold with Hope, followed by a thick interval without ammonites. A few reports have been made on Turonian ammonites (Spath, 1946; Donovan, 1953, 1954) that have not been confirmed by new material. Revisits to the Scaphitid-bearing succession in the eastern Geographical Society Ø, yielded well-preserved *Hoploscaphites ikorfatensis*, in addition to the reports of *Hoploscaphites greenlandicus* providing rare ammonite dated levels of middle and late Campanian, respectively. In summary, the Cretaceous ammonite succession and zonation remains incomplete and subject to improvements. In the present study, its main purpose is to provide calibration points between the Cretaceous succession in NW Europe (commonly well-dated by ammonites) and the locally established palyno-stratigraphy in NE Greenland.

6. Palynostratigraphic zonation

The Cretaceous succession is divided into 15 biozones and intervals and 20 subzones, and more than 100 stratigraphic events representing more than 70 stratigraphic levels have been recognized (Fig. 7a–d). Dinocysts and pollen markers are illustrated in Figures 9–15.

6.a. Zone: Gochteodinia villosa villosa (NEG Cr 1) new

Age: latest Tithonian – latest Berriasian, latest Jurassic – Early Cretaceous.

Definition: From the FO of *Gochteodinia villosa villosa* to the FO of *Oligosphaeridium complex*.

Comments: Gochteodinia villosa villosa appears in the *Praechetaites tenuicostatum* – *Praetollia maynci* ammonite zones in the Rødryggen-1 core (517001) Wollaston Forland (Fig. 5) near the Jurassic–Cretaceous boundary and in Perisphinctes Ravine, Kuhn Ø, section HNH 10 (Nøhr-Hansen, 1993). The nominate species *G. villosa villosa* has a stratigraphic range in NE Greenland, spanning the entire zone. The range of the *G. villosa villosa* Zone is from near the Jurassic–Cretaceous boundary to the uppermost Berriasian (*c.* uppermost Ryazanian) in NE Greenland. The autonym subspecies *G. villosa villosa* is applied here to distinguish this zone from earlier *G. villosa* zones and to focus on the range of this subspecies in contrast to the ranges of other present or future subspecies. *Gochteodinia villosa* refers to the species in the following discussion.

Woollam & Riding (1983) defines the *G. villosa* Zone (Gv) in England based on Davey's (1979) "*Pareodinia dasyforma*" Zone. The definition of the zone is based on species that are not common in East Greenland (e.g. *Ctenidodinium panneum* (now *Dichadogonyaulax? pannea*) and *C. culmula* (now *D? cumula*)). However, the zone nearly coincides with the range of *G. villosa*. The FO of *G. villosa* is in the basal *Paracraspedites oppressum* ammonite Zone (uppermost Tithonian) to the *Peregrinus albidum* ammonite Zone (uppermost Berriasian), that is, a range very similar to that recorded in East Greenland. The range of *G. villosa* may extend into basal Valanginian (e.g. Costa & Davey, 1992), but may be reworked into higher strata.

On the Russian Platform, Riding *et al.* (1999) report the first appearance of rare *G. villosa* in the *Kachpurites fulgens* ammonite Zone (correlative to the *Subcraspedites primitivus* ammonite Zone of NW Europe) and then again very near the Tithonian–Berriasian (Jurassic–Cretaceous) boundary. Riding *et al.* (1999) suggest a *G. villosa* Zone (RPJ17) defined from the FO of G. *villosa* to the FO of *Batioladinium* spp. in the basal upper

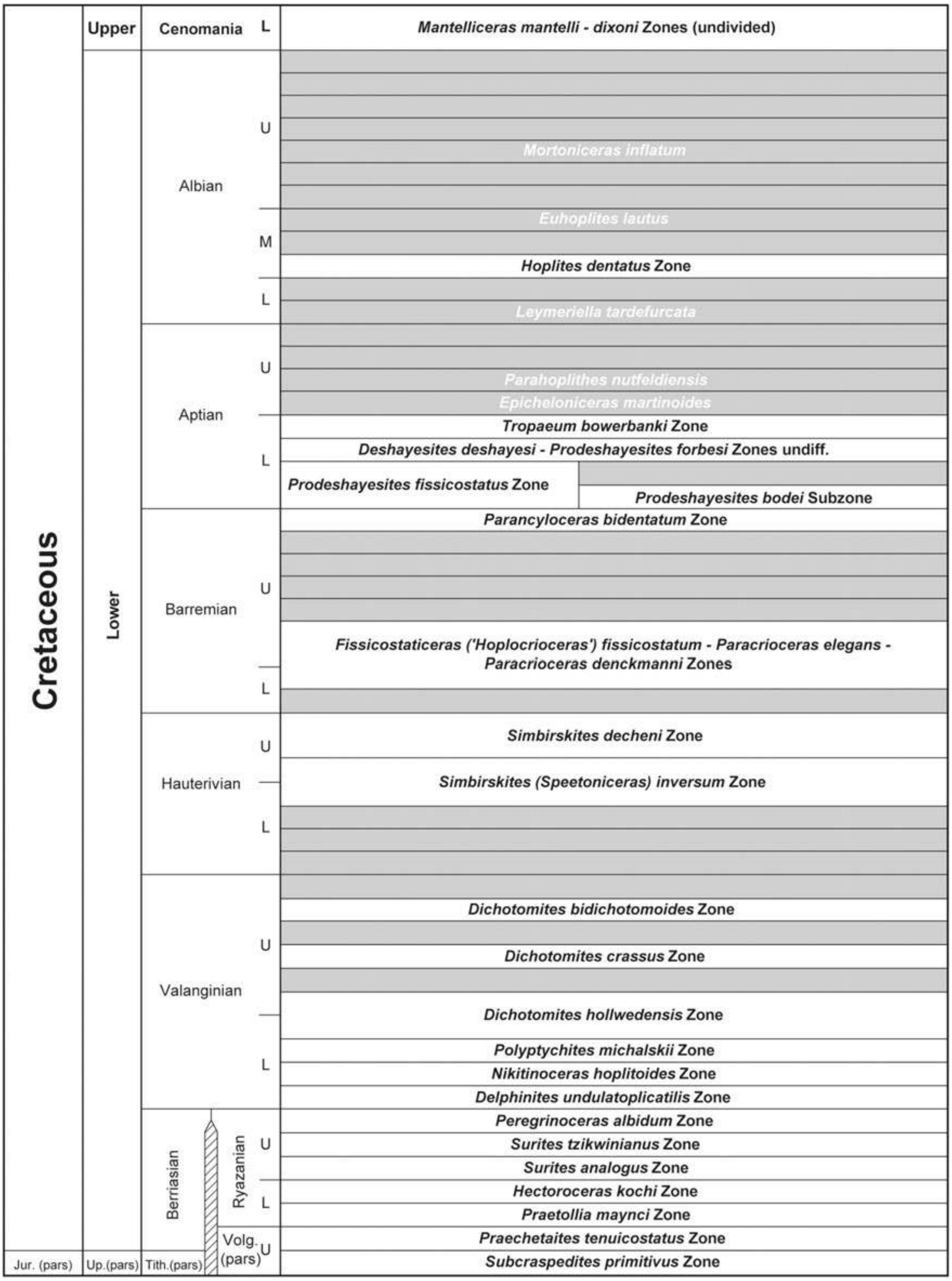

Fig. 8. Cretaceous ammonite zonation of NE Greenland. Lower Cretaceous after Surlyk (1978*a*, Ryazanian approximately equivalent to Berriasian), Kelly & Whitham (1999, lower Aptian), Alsen (2006, Ryazanian – Hauterivian) and this work. Zones shaded in grey indicate intervals that are not present or not yet proven in NE Greenland. Zones younger than Early Cenomanian have not been observed in NE Greenland. Zones shaded in grey and with indices in white are zones referred to in correlation with the palynological zonations for the central North Sea area of Duxbury (2001) and Davey (2001). The indices are adopted from the (NW European) Boreal ammonite zonation (Gradstein *et al.* 2004) since most of the zones in NE Greenland have close affinity to that area. The two upper Volgian zones are approximately equivalent to the upper Tithonian zone (Wimbledon, 2017).

Ryazanian (*c.* upper Berriasian; *Rjazanensis-Spasskensis* ammonite Zone). The *G. villosa villosa* Zone does not correlate well with dinoflagellate zones in the corresponding successions on Svalbard, the Janusfjellet Formation, because *G. villosa villosa* is not recorded below the basal Valanginian, probably due to an impoverished Boreal dinocyst flora in the pre-Valanginian strata (Århus, 1988). Consequently, the local FO of *G. villosa villosa* coincides with the FO of *Oligosphaeridium complex* (Århus, 1988).

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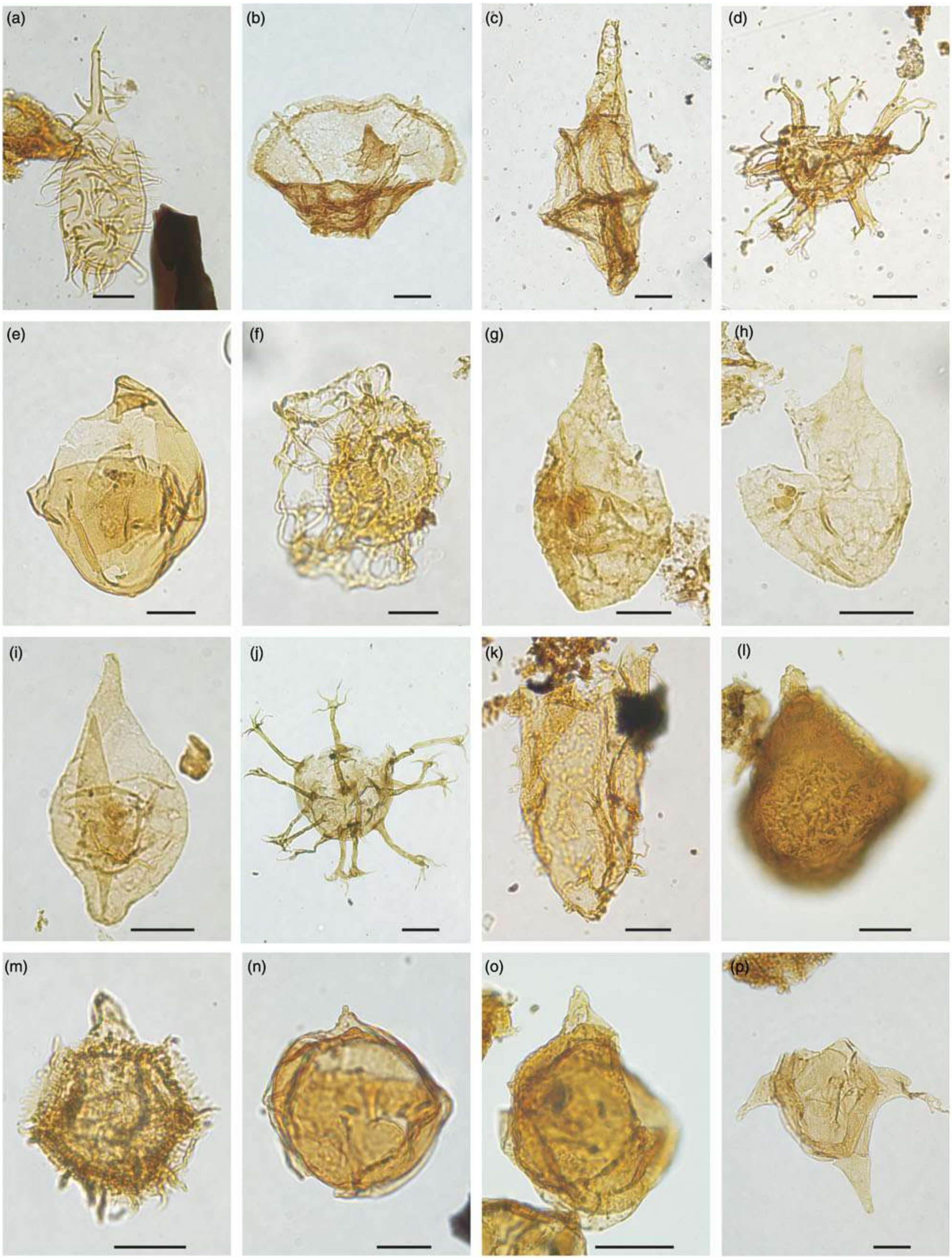

Fig. 9. Dinocysts marker of latest Jurassic – Early Cretaceous age (late Tithonian, Berriasian, Valanginian and earliest Hauterivian). Picture reference number, locality, slide number and England Finder co-ordinates are listed for the specimens illustrated. Scale bars all 20 µm. (a) *Gochteodinia villosa* subsp. *villosa*, 2324, Store Koldewey-1 core, 517002-86-7, Q37/1. (b) *Isthmocystis distincta*, 2332, Perisphinctes Ravine, Kuhn Ø, HNH 87-3, 342088-4, O27. (c) *Scriniodinium pharo*, 2329, Rødryggen-1 core, 517001-3-3, F35-4. (d) *Palaecysta palmula* subsp. *palmula*, 2328, Rødryggen-1 core, 517001-3-2, J20/1. (e) *Lagenorhytis delicatula*, 2307, SP-4a Store Koldewey, 523201, D23/3. (f) *Rotosphaeropsis thule*, 2288, Rødryggen-1 core, 517001-7-7, X29/2. (g) *Paragonyaulacysta? borealis*, 2286, Rødryggen-1 core, 517001-5-10, W27/1. (h) *Paragonyaulacysta? borealis*, 2287, Rødryggen-1 core, 517001-304-4, M18/3. (i) *Paragonyaulacysta capillosa*, 2298, Hvidekløft Store Koldewey, 517649-3, J60-4. (j) *Oligosphaeridium complex*, 2331, Rødryggen-1 core, 517001-330-2, W14/2. (k) *Boreocysta isfjordica*, 1411, PAL-5/2010 Store Koldewey, 495984-4, R29/3. (l) *Apteodinium spongiosum*, 2403, PAL-5/2010 Store Koldewey, 495988-5, W35/1. (m) *Nelchinopsis kostromiensis*, 2326, Store Koldewey-1 core, 517002-137-5, X70/3. (n) *Endoscrinium hauterivianum*, 1117, Store Koldewey-1 core, 517002-139-5, B39. (o) *Endoscrinium hauterivianum*, 1116, Store Koldewey-1 core, 517002-138-5, B60/3. (p) *Muderongia australis*, 2319, Store Koldewey-1 core, 517002-82-3, W27/4.

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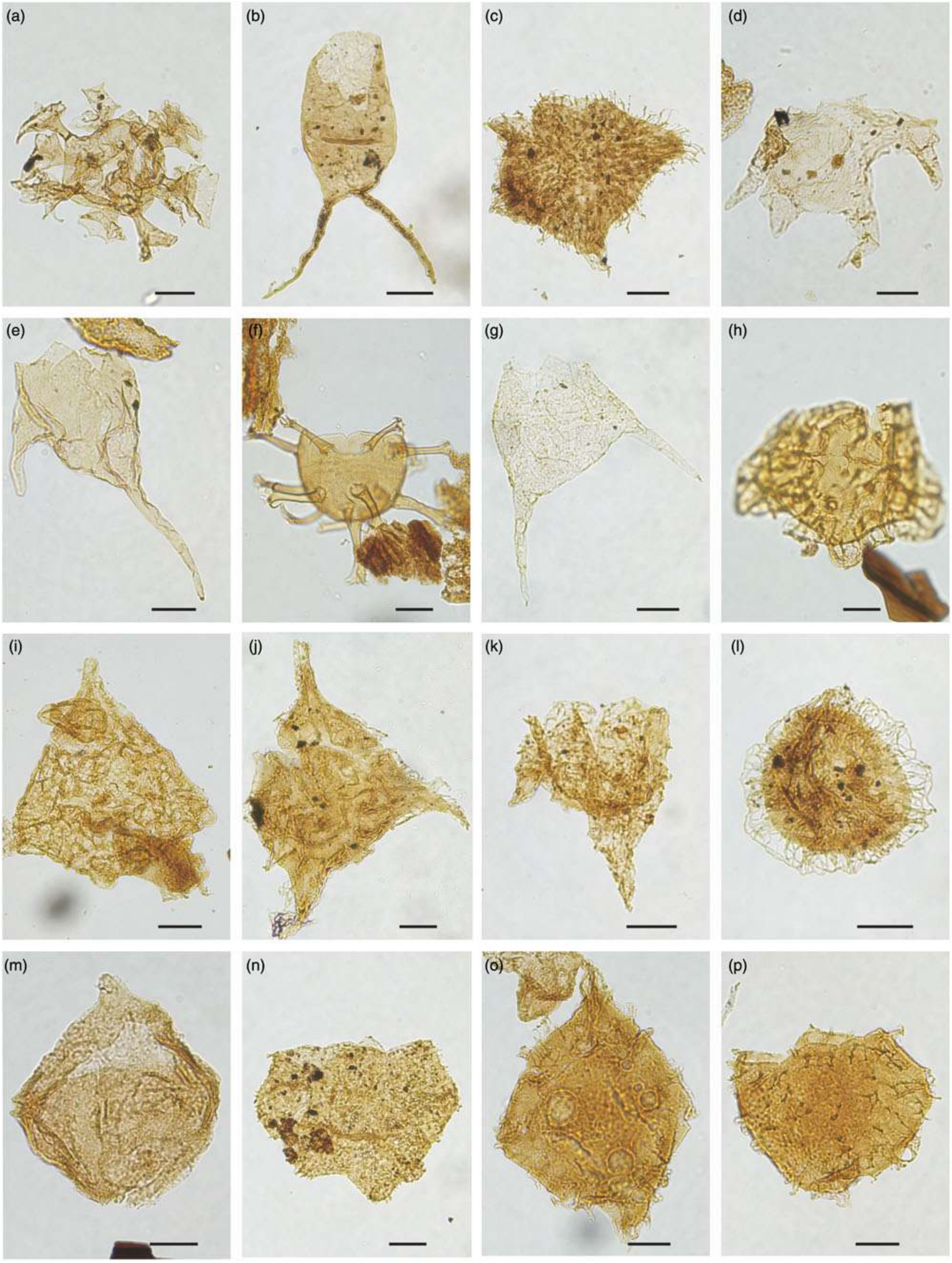

Fig. 10. Dinocysts marker of Early Cretaceous age (earliest Hauterivian, Barremian and Aptian). Picture reference number, locality, slide number and England Finder co-ordinates are listed for the specimens illustrated. Scale bars all 20 µm. (a) *Oligosphaeridium umbraculum*, 1111, Store Koldewey-1 core, 517002-82-4, N42-3. (b) *Batioladinium longicornutum*, 2334, HNH section 21 1993, 342239-4, M41/2. (c) *Pseudoceratium anaphrissum*, 2335, HNH section 16 1993, 351512-4, J40-3. (d) *Muderongia simplex* subsp. *microperforata*, 2316, Store Koldewey-1 core, 517002-79-6, P46. (e) *Odontochitina nuda*, 2317, Store Koldewey-1 core, 517002-79-6, X42. (f) *Oligosphaeridium abaculum*, 1096, Store Koldewey-1 core, 517002-75-5, V47/3. (g) *Pseudoceratium toveae*, 2336, HNH section 17 1993, 342161-5, Q49/2. (h) *Pseudoceratium* aff. *iveri*, 1098, Store Koldewey-1 core, 517002-75-3, A27/3. (i) *Pseudoceratium* aff. *iveri*, 1080, Store Koldewey-1 core, 517002-76-3, K52/2. (j) *Pseudoceratium iveri*, 2337, HNH section 17 1993, 342161-5, K46/2. (k) *Pseudoceratium retusum*, 2338, HNH section 7 1993, 342087-10, H31-2. (l) *Exiguisphaera plectilis*, 2339, HNH section 7 1993, 342087-4, Y39-2. (m) *Apteodinium granulatum*, 2310, PAL 9-2009, 518672-4, X39/4. (n) *Circulodinium brevispinosum*, 2340, HNH section 34 1993, 324556-4, E45/3. (o) *Pseudoceratium distinctum*, 2311, PAL 9-2009, 518674-4, T45. (p) *Pseudoceratium distinctum*, 2313, PAL 9-2009, 518674-4, H50/3.

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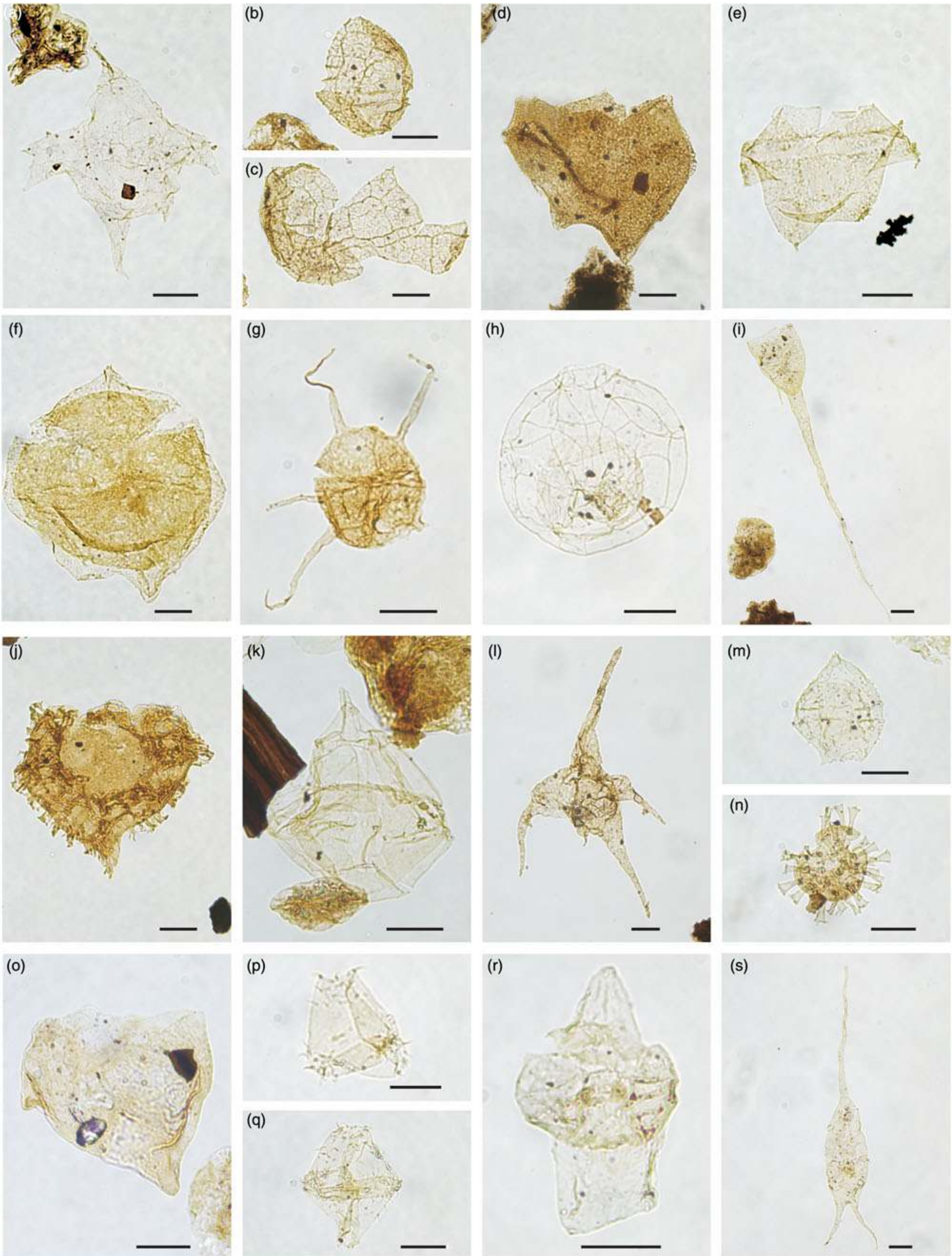

Fig. 11. Dinocysts marker of Early Cretaceous age (late Aptian – middle Albian). Picture reference number, locality, slide number and England Finder co-ordinates are listed for the specimens illustrated. Scale bars all 20 µm. (a) *Vesperopsis mayi*, 2341, HNH section 13 1993, 351587-4, Q35/1. (b) *Leptodinium cancellatum*, 2342, HNH section 12 1993, 351589-4, N34/4. (c) *Leptodinium cancellatum*, 2343, HNH section 20 1993, 342176-4, P50/4. (d) *Canningia reticulata*, 2344, HNH section 37 1993, 351592-4, F26/4. (e) *Nyktericysta? vitrea*, 2345, HNH section 17 1993, 342169-4, J53/4. (f) *Senoniasphaera microreticulata*, 2346, HNH section 17 1993, 342172-4, Q26/2. (g) *Cauca parva*, 2347, HNH section 30 1993, 342620-7, U20/3. (h) *Hapsocysta? benteae*, 2348, HNH section 30 1993, 342619-3, Q30/4. (i) *Odontochitina singhii*, 2349, HNH section 20 1993, 342183-4, N34/1. (j) *Aptea polymorpha*, 2351, HNH section 20 1993, 342191-5, U30/2. (k) *Leptodinium? hyalodermopse*, 2353, HNH section 17 1993, 342167-4, R23/2. (l) *Vesperopsis longicornis*, 2354, HNH section 34 1993, 342556-4, E33/3. (m) *Chichaouadinium vestitum*, 2355, HNH section 20 1993, 342202-4, T23/3. (n) *Litosphaeridium arundum*, 2356, HNH section 23 1993, 351670-4, F34/3. (o) *Pseudoceratium expolitum*, 2357, HNH section 20 1993, 342194-4, R25-1. (p) *Rhombodella paucispina*, 2358, HNH section 30 1993, 342615-3, S31/4. (q) *Rhombodella paucispina*, 2359, HNH section 30 1993, 342615-3, Q36/3. (r) *Ovoidinium* sp. 3 HNH 1993, 2360, HNH section 21 1993, 342240-7, D46/3. (s) *Batioladinium shaftesburiense*, 2361, HNH section 26 1993,351630-4, D43/3.

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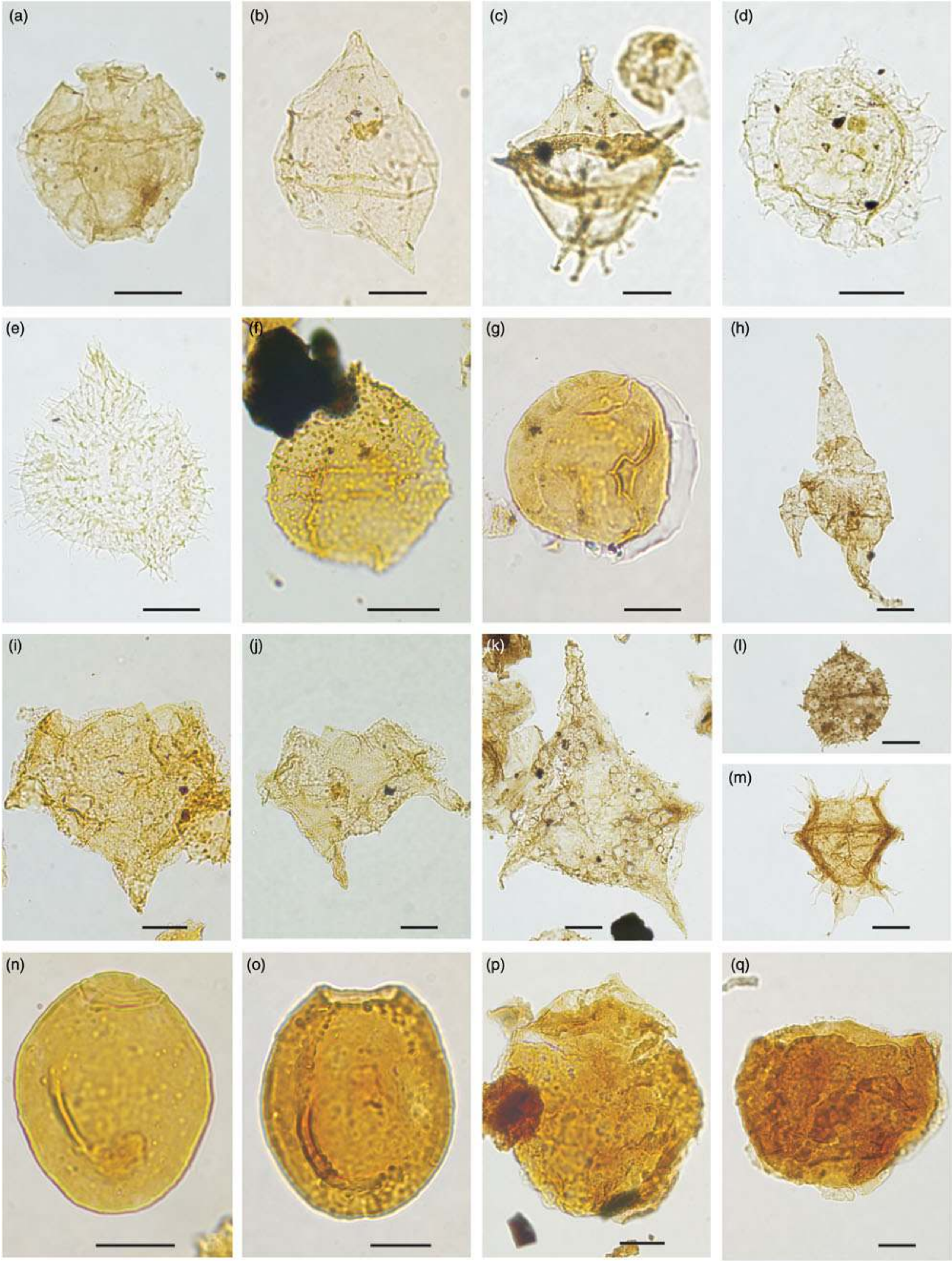

Fig. 12. Dinocysts marker of Early–Late Cretaceous age (middle Albian – earliest Cenomnian). Picture reference number, locality, slide number and England Finder co-ordinates are listed for the specimens illustrated. Scale bars all 20 μm. (a) *Ellipsoidictyum imperfectum*, 2363, HNH section 21 1993, 342240-4, W20/1. (b) *Subtilisphaera kalaallitii*, 1484, HNH section 30 1993, 522066-4, U66/2. (c) *Wigginsiella grandstandica*, 2364, HNH section 29 1993, 324599-4, X24/3. (d) Dino sp. 1 HNH 1993, 2371, HNH section 31 1993, 324623-4, C18/4. (e) *Circulodinium* sp. 1 HNH 1993, 2370, HNH section 30 1993, 324619-3, H53/4. (f) *Epelidosphaeridia* sp. 1 HNH 1993, JHOV 2/2009, 518602-7, R45/1. (g) *Sindridinium*? *torulosa*, 1560, HNH section 30 1993, 324608-8, W21/4. (h) *Odontochitina ancala*, 2367, HNH section 36 1993, 324092-7, K55/2. (i) *Endoceratium exquisitum*, 1221, HNH 081410-4, 487620-3, T17-4. (j) *Endoceratium exquisitum*, 1519, PAL3-2011, 522085-4, X45/3. (k) *Endoceratium exquisitum*, 2382, HNH 081009-4, 475197-3, W39/2. (l) *Epelidosphaeridia spinosa*, 2373, HNH section 39 1993, 335321-4, X34/4. (m) *Dinopterygium alatum*, 2368, HNH section 30 1993, 324613-8, N42/3. (n) *Sindridinium borealis*, 1463, PAL3-2011, 522076-4, U53/1. (o) *Sindridinium borealis*, 1462, PAL3-2011, 522076-4, W53/4. (p) *Senoniasphaera* aff. *microreticulata*, 1218, HNH 081410-4, 487640-3, D42/2. (q) *Senoniasphaera* aff. *microreticulata*, 1203, HNH 081410-4, 487633-3, P46/4.

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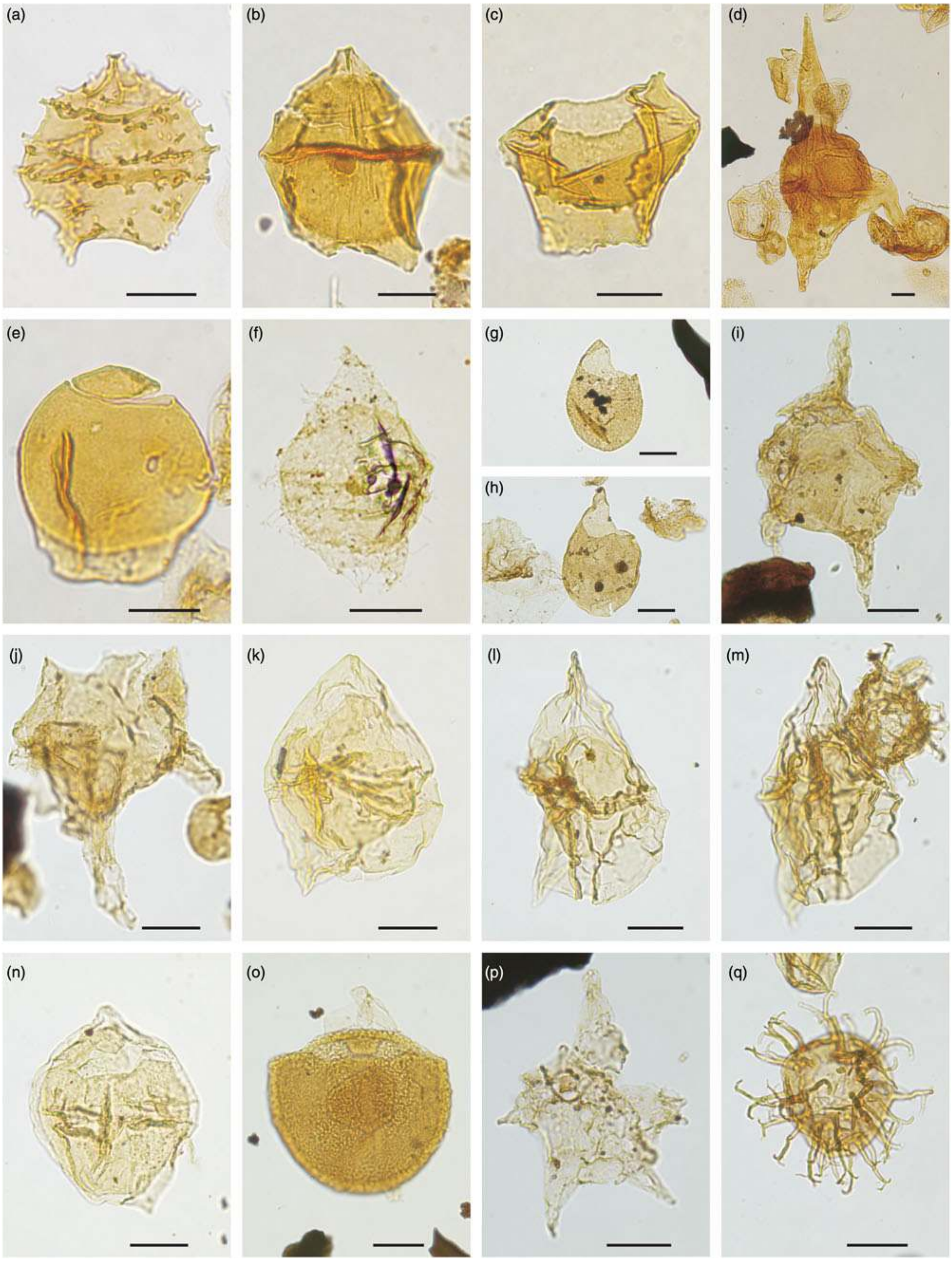

Fig. 13. Dinocysts marker of Late Cretaceous age (earliest Cenomnian – late Cenomanian). Picture reference number, locality, slide number and England Finder co-ordinates are listed for the specimens illustrated. Scale bars all 20 μm. (a) *Epelidosphaeridia manifesta*, 1206, HNH 081410-4, 487643-3, F52/4. (b) *Ovoidinium epelidosphaeroides*, 1507, PAL3-2011, 522082-3, Y27/1. (c) *Ovoidinium epelidosphaeroides*, 1516, PAL3-2011, 522084-5, K33/3. (d) *Xenascus* aff. *plotei*, 1551, HNH 081410-4, 487620-3, B27/4. (e) *Sindridinium anaanae*, 1464, HNH 081410-4, 487631-3, O28/2. (f) *Palaeohystrichophora infusorioides*, 2374, HNH section 30 1993, 324613-8, O51/3. (g) *Ginginodinium* aff. *evittii*, 2376, HNH 081009-1, 475185-2, C27. (h) *Ginginodinium* aff. *evittii*, 2377, HNH 081009-1, 475185-2, W48/2. (i) *Endoceratium ludbrookiae*, 2383, HNH 081009-2, 475190-2, Q41/4. (j) *Endoceratium ludbrookiae*, 2384, HNH 081009-2, 475195-3, G35/3. (k) *Isabelidinium acuminatum*, 0098, Nanok-1 core, 517004-136-5,S20/1. (l) *Isabelidinium magnum*, 2387, HNH 080209-4, 475175-2, Y32. (m) *Isabelidinium magnum*, 2386, HNH 080209-4, 475175-2, O20/2. (n) *Trithyrodinium* aff. *rhomboideum*, 2378, HNH 080710-4, 475435-6, Y23/3. (o) *Trithyrodinium suspectum*, 2380, Knudshoved locality 5, 433504-4, J37/1. (p) *Nyktericysta* aff. *tripenta*, 2381, HNH 081009-2, 475197-2, X36/2. (q) *Surculosphaeridium longifurcatum*, 2390, HNH 080209-4, 475179-2, K22/3.

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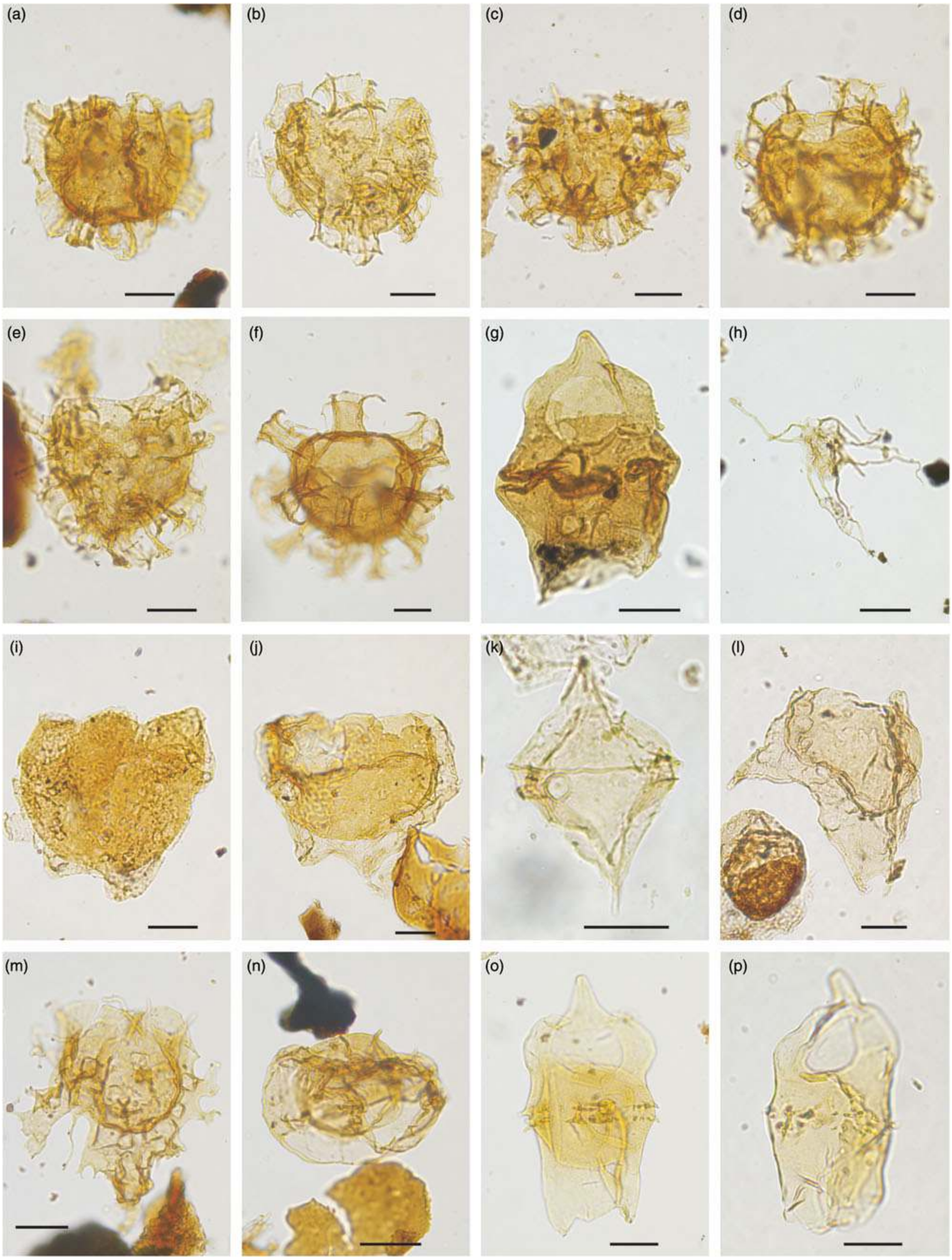

Fig. 14. Dinocysts marker of Late Cretaceous age (late Cenomanian – middle Coniacian). Picture reference number, locality, slide number and England Finder co-ordinates are listed for the specimens illustrated. Scale bars all 20 μm. (a) *Cyclonephelium compactum-Cauveridinium membraniphorum* complex, 118, Nanok-1 core, 517004-116-6, B42/2. (b) *Cyclonephelium compactum-Cauveridinium membraniphorum* complex, 97, Nanok-1 core, 517004-136-5, T48/2. (c) *Cyclonephelium compactum-Cauveridinium membraniphorum*, complex, 110, Nanok-1 core, 517004-117-7, W71/2. (d) *Heterosphaeridium difficile*, 116, Nanok-1 core, 517004-166-6, N58/4. (e) *Heterosphaeridium difficile*, 115, Nanok-1 core, 517004-166-6, G41/1. (f) *Heterosphaeridium difficile*, 125, Nanok-1 core, 517004-316-9, H53/1. (g) *Chatangiella granulifera*, 2379, Nanok-1 core, 517004-110-7, L59/2. (h) *Raphidodinium fucatum*, 2397, Nanok-1 core, 517004-113-3, F23/2. (i) *Senoniasphaera rotundata*, 1705, Nanok-1 core, 517004-101-5, M59/1. (j) *Senoniasphaera rotundata*, 1707, Nanok-1 core, 517004-317-5, B28/4. (k) *Laciniadinium arcticum*, 2300, 470105-2, HNH081508-1, M18/2. (l) *Odontochitina rhakodes*, 1767, Nanok-1 core, 517004-106-, Y63/3. (m) *Xenascus gochtii*, 124, Nanok-1 core, 517004-101-5, Y52/4. (n) *Stephodinium coronatum*, 126, Nanok-1 core, 517004-317-3, W31/4. (o) "*Chatangiella spinosa*", 134, Nanok-1 core, 517004-311-10, M38/2. (p) "*Chatangiella spinosa*", 130, Nanok-1 core, 517004-315-9, B40/1.

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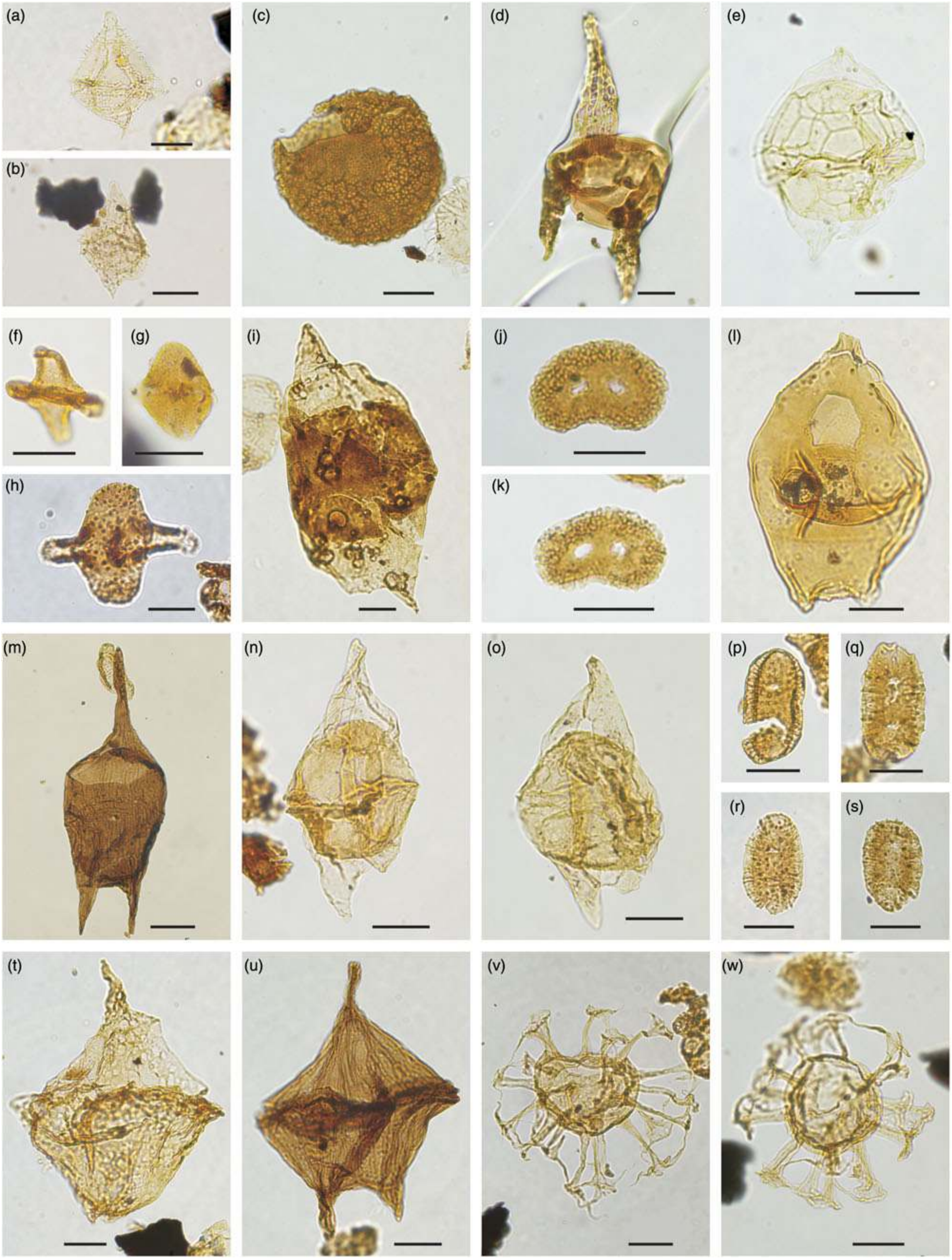

Fig. 15. Dinocysts marker of Late Cretaceous age (late Coniacian – ?Early Maastrichtian). Picture reference number, locality, slide number and England Finder co-ordinates are listed for the specimens illustrated. Scale bars all 20 µm. (a) *Spinidinium echinoideum*, 132, Nanok-1 core, 517004-314-9, T23/4. (b) *Spinidinium echinoideum*, 129, Nanok-1 core, 517004-317-3, F34/2. (c) *Trithyrodinium vermiculatum*, 2394, HNH 080209-4, 475134-2, S44/3. (d) *Odontochitina porifera*, 2391, Knudshoved locality 5, 433898-4, W20/2. (e) *Alterbidinium ioannidesii*, 2395, HNH 080209-3, 475113-8, V36/4. (f) *Aquilapollenites* sp., 136, Nanok-1 core, 517004-81-2, T47/2. (g) *Aquilapollenites* sp., 135, Nanok-1 core, 517004-313-4, G48. (h) *Aquilapollenites* sp., 2270, HNH081508-2, 470107-5, V15/2. (i) *Chatangiella bondarenkoi*, 2296, PAL-6/2011, 529719-6, V21-3. (j) *Azonia fabacea*, 2400, Knudshoved locality 5, 700802-4, V21/1. (k) *Azonia fabacea*, 2401, Knudshoved locality 5, 700802-4, K24/4. (l) *Isabelidinium magnum*, 2297, PAL-6/2011, 529716-4, T30/4. (m) *Cerodinium diebelii*, 2238, HNH081508-2, 470102-5, B17-2. (n) *Alterbidinium biaperturum*, 2241, HNH081508-2, 470102-4, J31/2. (o) *Alterbidinium biaperturum*, 2239, HNH081508-2, 470102-3, N40/3. (p) *Wodehouseia gracile*, 2272, HNH081508-2, 470107-5, Y25/1. (q) *Wodehouseia gracile*, 2243, HNH081508-2, 470102-6, Q18/2. (r) *Wodehouseia gracile*, 2234, HNH081508-2, 470102-1, X14/2. (s) *Wodehouseia gracile*, 2269, HNH081508-2, 470106-2, G42/2. (t) *Spongodinium delitiense*, 2247, HNH081508-2, 470104-3, C30. (u) *Phelodinium kozlowskii*, 2244, HNH081508-2, 470102-6, W20. (v) *Hystrichosphaeridium* sp. 3 McIntyre 1974, 2268, HNH081508-2, 470106-4, X48. (w) *Hystrichosphaeridium* sp. 3 McIntyre 1974, 2266, HNH081508-2, 470106-4, V39/2.

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Similarly, Boreal Volgian–Ryazanian (*c.* upper Berriasian) dinocyst assemblages without *G. villosa villosa* are reported from cores in the Barents Sea (Århus *et al.* 1990).

Gochteodinia villosa occurs in the subboreal regions of NW Europe and the Russian Platform as well as the Boreal East Greenland apparently with similar FOs based on correlation of local ammonite zonations. The last occurrence of *G. villosa* is not well constrained; the upper boundary of the *G. villosa villosa* Zone is therefore selected at the widespread and distinct FO of *O. complex*. The *G. villosa villosa* Zone (NEG Cr 1) is a robust dinocyst biozone of the lowermost Cretaceous deposits in the North Atlantic region. However, *G. villosa villosa* is rare or absent in the high Boreal regions of Canada, North Greenland, the Barents Sea and northern Siberia (Davies, 1983, Århus, 1988; Århus *et al.* 1990; Smelror *et al.* 1998; Pestchevitskaya, 2007*a*, *b*; Nikitenko *et al.* 2008).

Stratigraphic events: *Istmocystis distincta* has FO contemporaneous with *G. villosa villosa*. The FO of *Lagenorhytis delicatula*, *Palaecysta palmula* and *Phoberocysta neocomica* and the LO of *Rotosphaeropsis thule* occur in or above the *Hectoroceras kochi* ammonite Zone (near the lower–upper Berriasian boundary) in the Rødryggen-1 core, Wollaston Forland (Fig. 5). *Gochteodinia villosa villosa, Paragonyaulacysta? borealis* and *P. capillosa* have their stratigraphic LO in the upper part of the *G. villosa villosa* Zone, upper Berriasian in the Rødryggen-1 core, even though they are reported to continue into lower Valanginian successions in Canada, Svalbald, the Barents Sea, Siberia and Arctic Russia (e.g. Davies, 1983; Århus, 1988; Pestchevitskaya, 2007*a*, *b*; Nikitenko *et al.* 2008).

6.b. Zone: *Oligosphaeridium complex* (NEG Cr 2) new

Age: latest Ryazanian (*c.* latest Berriasian) – earliest Hauterivian, Early Cretaceous.

Definition: From the FO of *Oligosphaeridium complex* to the FO of *Batioladinium longicornutum*.

Comments: Oligosphaeridium complex appears (FO) in the *Peregrinus albidum* ammonite Zone, uppermost Berriasian (or lower Valanginian according to Gradstein *et al.* 2012; in SP-04a, SP-15a Koldewey, Fig. 2) and is abundant in the lower Valanginian deposits (e.g. Rødryggen-1 core (517001) Wollaston Forland, Fig. 5; PAL05/2010 , Koldewey, Fig. 2). In NW Europe, Costa & Davey (1992) and Duxbury (2001) suggest that the FO of *Oligosphaeridium complex* occurs in the lowermost Valanginian strata.

Stratigraphic events: The FO of abundant *Oligosphaeridium complex* is followed by the FO of *Apteodinium spongiosum, Boreocysta isfjordica* and *Nelchinopsis kostromiensis* in the lower part of this zone (PAL05/2010 , Koldewey, Fig. 2) and by the FO of *Endoscrinium hauterivianum* and *Muderongia australis* in the uppermost part of the zone (Store Koldewey-1 core (517002), Fig. 2). Duxbury (2001) mentioned that *Endoscrinium hauterivianum* is essentially a lower Hauterivian form that can range into the upper Hauterivian Stage.

6.c. Zone: *Batioladinium longicornutum* (I) of Nøhr-Hansen (1993) redefined

Age: early Hauterivian – latest Barremian.

Definition: From the FO to the LO of *Batioladinium longicornutum*.

Comments: Nøhr-Hansen's (1993) original definition of the lower boundary of the zone is here redefined from the FO of *Muderongia australis* to the slightly younger FO of *Batioladinium longicornutum*, which seems to be a more reliable marker. The zone was subdivided into the three subzones by Nøhr-Hansen (1993): *Nelchinopsis kostromiensis* (1) redefined, *Pseudoceratium anaphrissum* (2) and *Pseudoceratium toveae* (3). Detailed studies of a core and numerous sections from Store Koldewey have enabled a refinement of the dinoflagellate stratigraphy of the *Batioladinium longicornutum* (I) Zone, Nøhr-Hansen (1993).

Correlations: The FO of *B. longicornutum* correlates with the middle part of the lowermost Hauterivian *Endomoceras amblygonium* ammonite Zone according to Davey's (2001; Fig. 8) dinocyst correlation with lower Hauterivian ammonite stratigraphy at Speeton, east England. *B. longicornutum* has its LO in the upper Barremian Stage (Nøhr-Hansen, 1993).

6.d. Subzone: *Nelchinopsis kostromiensis* (1) of Nøhr-Hansen (1993) redefined

Age: early–late Hauterivian.

Definition: From FO of *Batioladinium longicornutum* to the LO of *Nelchinopsis kostromiensis*.

Comments: Nøhr-Hansen's (1993) original definition of the lower boundary of the zone is redefined from the FO of *Muderongia australis* to the slightly younger FO of *Batioladinium longicornutum*, which seems to be a more reliable marker.

Stratigraphic events: The FO of *B. longicornutum* at the base and LO of *Endoscrinium hauterivianum* in the middle part of the subzone. Other stratigraphic markers are the FO of *Pseudoceratium anaphrissum* and the LO of *Apteodinium spongiosum*, *Muderongia australis* and *Stanfordella ordocava* in the upper part of the subzone. The distinct species *Oligosphaeridium umbraculum* has been recorded from the lowermost part of the present subzone.

Correlations: The FO of *B. longicornutum* correlates with the middle part of the lowermost Hauterivian *Endomoceras amblygonium* ammonite Zone according to Davey's (2001) dinocyst correlation with lower Hauterivian ammonite stratigraphy at Speeton, east England. The LO of *Endoscrinium hauterivianum* in the present subzone may correlate with the LO of the species in the lowermost part of the upper Hauterivian LKP16.1 Zone (Duxbury, 2001), which is approximately equivalent to the *Simbirskites* (*Milanowskia*) *speetonensis* ammonite Zone (Fig. 8). Originally *O. umbraculum* was described from the lower Hauterivian Stage (Duxbury, 2001). *Nelchinopsis kostromiensis* and *Phoberocysta neocomica* are common in the *Nelchinopsis kostromiensis* Subzone, which is well-represented in the Store Koldewey-1 core (517002, Fig. 2). Recently, the subzone has been recorded from Genetic Sequence 1 (approximately equivalent to parts of the Knurr and Klippfisk formations) Loppa High, southwestern Barents Sea (Fig. 6) by Marin *et al.* (2018).

6.e. Subzone: *Pseudoceratium anaphrissum* (2) of Nøhr-Hansen (1993)

Age: early Barremian.

Definition: From the LO of *Nelchinopsis kostromiensis* to the LO of *Pseudoceratium anaphrissum*.

Stratigraphic events: Hystrichosphaeridium arborispinum, *Muderongia simplex* subsp. *microperforata*, *Oligosphaeridium asterigerum* and *Pseudoceratium anaphrissum* are often common to abundant within the subzone. *Muderongia simplex* subsp. *microperforata* has FO in the lower part wheras *Oligosphaeridium*

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abaculum, Odontochitina nuda, Pseudoceratium aff. *iveri* and *P. toveae* have FO in the upper part of the subzone.

Correlation: The LO of *Nelchinopsis kostromiensis* correlates with the uppermost Hauterivian *Simbirskites variabilis* ammonite Zone (Gradstein *et al.* 2004). Previously, the *Simbirskites variabilis* Zone was thought to represent the lowermost Barremian Stage (Kemper *et al.* 1981). Recently, the subzone has been recorded from the Rurikfjellet and Helvetiafjellet formations on Spitsbergen and from Genetic Sequence 1 (approximately equivalent to the Knurr Formation) Barents Shelf by Grundvåg *et al.* (2017), and from Genetic Sequence 1 (approximately equivalent to parts of the Knurr and Klippfisk formations) Loppa High, southwestern Barents Sea (Fig. 6) by Marin *et al.* (2018).

6.f. Subzone: Pseudoceratium toveae (3) of Nøhr-Hansen (1993)

Age: late Barremian.

Definition: From the LO of *Pseudoceratium anaphrissum* to the LO of *Batioladinium longicornutum*.

Stratigraphic events: An acme of *Pseudoceratium toveae* occurs in this subzone. The species *Pseudoceratium* aff. *iveri* has its LO within the lower part and *Pseudoceratium iveri* has its FO in the upper part of the subzone. *Pseudoceratium* aff. *iveri* is common in the northern part of Store Koldewey, where it occurs in the major part of the Store Koldewey-1 core (517002, Fig. 2). The middle part of the subzone is well represented on Store Koldewey, for example at PAL-6/2010 (Fig. 2), between Ravn Pynt and Trækpasset where it can be calibrated with ammonites of the *Fissicostaticeras fissicostaum* – *Paracrioceras denckmanni* zones (Fig. 8) and in the Midter Gneisnæs area (MBJ-049, 053/2010, Fig. 2), where it is further characterized by the presence of brackish to marginal marine dinocysts (*Vesperopsis longicornis* and *Hurlandsia rugara*), the zygospore *Tetrangulare conspicuum* and the colonial algae *Scenedesmus*.

Correlations: Pseudoceratium aff. *iveri* has previously been recorded as ?*Pseudoceratium anaphrissum* in the lower part of the *Pseudoceratium toveae* (3) Subzone at Rødryggen and Stratumbjerg, Wollaston Forland (sections 16, 21, Nøhr-Hansen, 1993, Fig. 5).

The species *P. iveri* was previously recorded only from the upper part of the *Pseudoceratium toveae* (3) Subzone e.g. at Stratum Bjerg, Wollaston Forland (section 21, Nøhr-Hansen, 1993; Fig. 5) and from the Diener Bjerg area (PAL-9/2009, Fig. 4), northern Hold with Hope (Nøhr-Hansen, 1993). In the present study the species is also recorded from the lowermost part of the overlying *Odontochitina nuda* (II) Zone (previously the *Pseudoceratium nudum* Zone of Nøhr-Hansen, 1993) from the Stensiö Plateau Member of the Steensby Bjerg Formation (Figs 6, 7) at Stensiö Plateau (HNH 081310-1, Fig. 4), northern part of Hold with Hope. The record of the ammonite *Prodeshayesites* sp. by Kelly & Whitham (1999) at Stensiö Plateau dates the Stensiö Plateau Member as earliest Aptian *Prodeshayesites fissicostatus* Zone, and confirms that *P. iveri* range into the lowermost part of the lower Aptian *Odontochitina nuda* (II) Zone. The zone has previously been recorded from the south Sabine section, Melville Island, Arctic Canada (Nøhr-Hansen & McIntyre, 1998). The subzone has recently been recorded from the Kap Rigsdagen beds, Valdemar Gluckstad Land in North Greenland (Fig. 1) by Piasecki *et al.* (2018) and from the upper part of the Genetic Sequence 1 (approximately equivalent to the middle part of the Kolje Formation) from Loppa High, southwestern Barents Sea by Marin *et al.* (2018; Fig. 6), and from the lower part of the Genetic Sequence 2 (approximately equivalent to the upper part of the Kolje Formation) from Barents Shelf and the north-central Barents Sea by Grundvåg *et al.* (2017) and Kairanov *et al.* (2018), respectively.

6.g. Zone: Odontochitina nuda (II) (previously Pseudoceratium nudum Zone of Nøhr-Hansen, 1993)

Age: early Aptian.

Definition: From the LO of *Batioladinium longicornutum* to the LO of *Odontochitina nuda*.

Comments: Dinocysts characterizing the *Odontochitina nuda* (II) Zone from the Midter Gneisnæs area, Store Koldewey (MBJ-049, –53/2010, Fig. 2) have been recorded from a concretion with the ammonite *Deshayesites* (*Prodeshayesites*) cf. *bodei*, suggesting the *Prodeshayesites bodei* Subzone of the *Prodeshayesites fissicostatus* ammonite Zone is of earliest Aptian age (Fig. 8).

Stratigraphic events: Pseudoceratium aff. *iveri* and *Pseudoceratium toveae* both have their LO in the lower part, the FO of *Pseudoceratium retusum* is in the middle part and the LO of *Odontochitina nuda* and *Exiguisphaera plectilis* are in the top of the zone. *Subtilisphaera perlucida* and *Vesperopsis longicornis* are common within the zone and *Protoellipsodinium clavulus* is present.

Correlations: The presence of *Protoellipsodinium clavulus* seems to be a good lower Aptian marker in NE Greenland. It occurs in the Gulelv Member of the Steensby Formation at Diener Bjerg and in the laterally equivalent Rødelv Member of the Stratumbjerg Bjerg Formation (Fig. 6) at Steensby Bjerg (East) in the northern part of Hold with Hope. Previously, it was recorded only from the lower part of the *Odontochitina nuda* (II) Zone at Aucellabjerget, Wollaston Forland (Nøhr-Hansen, 1993; section 17, Fig. 5). The zone has previously been recorded from the Mesa Creek section, Ellesmere Island, Arctic Canada (Nøhr-Hansen & McIntyre, 1998; Fig. 1). Recently, the zone has been recorded from the Carolinefjellet Formation (Fig. 6), Spitsbergen by Grundvåg *et al.* (2017), and questionably from Genetic Sequence 2 (approximately equivalent to the upper Kolje Formation – lower Kolmule Formation) on the Barents Shelf by Grundvåg *et al.* (2017), southwestern Barents Sea by Marin *et al.* (2017), the Loppa High, southwestern Barents Sea by Marin *et al.* (2018) and possibly from Genetic Sequence 3 (approximately equivalent to the lower Kolmule Formation) north central Barents Sea by Kairanov *et al.* (2018).

6.h. Zone: Circulodinium brevispinosum (III) of Nøhr-Hansen (1993)

Age: early Aptian to Early Albian.

Definition: From the LO of *Odontochitina nuda* to the LO of *Circulodinium brevispinosum*.

Comments: The zone was subdivided into four subzones by Nøhr-Hansen (1993): *Vesperopsis longicornis* (1), *Vesperopsis mayi* (2), *Senoniasphaera microreticulata* (3) and *Leptodinium? hyalodermopse* (4). Detailed studies of two sections through the Rødelv Member from Diener Bjerg (PAL-9/2009 , Fig. 4) and Steensby Bjerg (East) (LHN 080810-2, Fig. 4) in the northern part of Hold with Hope have refined the dinoflagellate stratigraphy of the *Circulodinium brevispinosum* (III) Zone (see below).

Correlations. The zone has previously been recorded from the Mesa Creek section and the Rollrock River section, Ellesmere Island and the Junction Diapir section, Axel Heiberg Island, Arctic Canada (Nøhr-Hansen & McIntyre, 1998; Fig. 1).

Recently, the zone has been recorded from the genetic sequences 2–3/?4 (approximately equivalent to the Kolmule Formation; Fig. 6) Loppa High, southwestern Barents Sea by Marin *et al.* (2018).

6.i. Subzone: *Vesperopsis longicornis* (1) of Nøhr-Hansen 1993

Age: late early – early late Aptian. This revised age assignment differs slightly from the late early Aptian age of Nøhr-Hansen (1993).

Definition: From the LO of *Odontochitina nuda* to the FO *Vesperopsis mayi*.

Stratigraphic events: FO of *Circulodinium brevispinosum* and *Apteodinium granulatum* at the base of the zone, common *Apteodinium granulatum* in the middle part and FO and LO of *Pseudoceratium distinctum* in the middle and upper part, respectively. *Vesperopsis longicornis* is common to abundant throughout the subzone.

Correlations: The common occurrence of *Apteodinium granulatum* and the FO of *P. distinctum* (Rødelv Member sample 518674 from Diener Bjerg, PAL-9/2009, Fig. 4) in the middle part of the zone may correlate with the dinocyst zones LKP27.2 or LKP28 of Duxbury (2001), which he tentatively correlates with the upper part of the *Tropaeum bowerbanki* ammonite Zone (uppermost lower Aptian) and the lowermost *Epicheloniceras martinoides* ammonite Zone (lower upper Aptian; Fig. 8), respectively. A *Tropaeum bowerbanki* Zone ammonite has also been recorded from the *V. longicornis* Subzone in the Rødelv Member at Diener Bjerg (section PAL-7/2009). The LO of *P. distinctum* in the middle part of the subzone correlates with dinocyst LKP30 Zone of Duxbury (2001), tentatively correlated with the *Parahoplites nutfieldensis* ammonite Zone (middle upper Aptian; Fig. 8). The subzone has recently been recorded from Genetic Sequence 2 (approximately equivalent to the lower Kolmule Formation) on the Barents Shelf and from the southwestern Barents Sea by Grundvåg *et al.* (2017) and Marin *et al.* (2017), respectively.

6.j. Subzone: *Vesperopsis mayi* (2) of Nøhr-Hansen (1993)

Age: late Aptian. The age is revised and differs slightly from the latest early Aptian – late Aptian? age of Nøhr-Hansen (1993), a consequence of the redating of the older *Vesperopsis longicornis* (1) Subzone.

Definition: From the FO of *Vesperopsis mayi* to the FO of *Senoniasphaera microreticulata*.

Stratigraphic events: FO of *Vesperopsis mayi* at the base and FO of *Leptodinium cancellatum* in the lower part of the subzone, whereas the FO of *Canningia reticulata* and the LO of *Nyktericysta? vitrea* occur in the upper part.

Correlations: Duxbury (2001) reported the FO of consistent *L. cancellatum* from his LKP32.2 Subzone, tentatively correlated with the middle part of the *Leymeriella tardefurcata* ammonite Zone (of earliest Albian age; Fig. 8), but mentions that the species can occur sporadically in his older, late Aptian LKP31 Zone. The study of 22 samples from the Vitskøl Elv section, Peary Land (Fig. 2) date the lower part of the section to possibly early–late Aptian, based on the presence of *Vesperopsis mayi* and *Circulodinium brevispinosum* indicating the presence of the *Vesperopsis mayi* Subzone (unpublished data). Recently, the subzone has been recorded from the middle part of Genetic Sequence 2 (approximately equivalent to the Kolmule Formation) in the southwestern Barents Sea by Marin *et al.* (2017).

6.k. Subzone: *Senoniasphaera microreticulata* (3) of Nøhr-Hansen (1993)

Age: late Aptian – Early Albian.

Definition: From the FO to the LO of *Senoniasphaera microreticulata*.

Stratigraphic events: FO of *Cauca parva* is in the lower part of the subzone, whereas the FO of *Hapsocysta? benteae* occurs in the upper part of the subzone.

Correlations: The study of 22 samples from the Vitskøl Elv section, Peary Land (Fig. 2) dates the upper part as late Aptian – Early Albian based on the FO of *Senoniasphaera microreticulata* indicating the presence of the *Senoniasphaera microreticulata* Subzone (unpublished data).

6.l. Subzone: *Leptodinium? hyalodermopse* (4) of Nøhr-Hansen (1993)

Age: Early Albian.

Definition: From the LO of *Senoniasphaera microreticulata* to the LO of *Circulodinium brevispinosum*.

Stratigraphic events: FO of *Aptea polymorpha* and *Odontochitina singhii* occur in the middle part of the subzone, whereas the LO of *Circulodinium brevispinosum*, *Leptodinium hyalodermopse* and *Vesperopsis longicornis* occur at the top of the subzone.

Correlations: Duxbury (2001) recorded the FO of *Odontochitina singhii* from the base of his Lower Albian dinocyst LKP33 Subzone, tentatively correlated with the upper part of the *Leymeriella tardefurcata* ammonite Zone (of Early Albian age; Fig. 8).

6.m. Zone: *Rhombodella paucispina* (IV) of Nøhr-Hansen (1993)

Age: middle Albian.

Definition: From the LO of *Circulodinium brevispinosum* to the FO of *Subtilisphaera kalaallitii*.

Comments: The zone was subdivided into the two subzones by Nøhr-Hansen (1993): *Litosphaeridium arundum* (1) and *Chichaouadinium vestitum* (2). Studies of a section through the Rødelv Member from east Steensby Bjerg (LHN 080810-2, Fig. 4), northern part of Hold with Hope, have refined the dinocyst stratigraphy of the lower part of the *Rhombodella paucispina* (IV) Zone.

Correlations: The zone has previously been recorded from the Mesa Creek section, Ellesmere Island and the Junction Diapir section, Axel Heiberg Island, Arctic Canada (Nøhr-Hansen & McIntyre, 1998; Fig. 1). The *Rhombodella paucispina* (IV) Zone has been recorded from the Albian succession in Kangerlussuaq southern, East Greenland (Nøhr-Hansen, 2012; Fig. 1). The zone has recently been recorded from the lower part of Genetic Sequence 4 (approximately equivalent to the Kolmule Formation) from the Loppa High, southwestern Barents Sea by Marin *et al.* (2018).

6.n. Subzone: *Litosphaeridium arundum* (1) of Nøhr-Hansen (1993)

Age: middle Albian.

Definition: From the LO of *Circulodinium brevispinosum* to the FO of common specimens of *Chichaouadinium vestitum*.

Stratigraphic events: FO of *Chichaouadinium vestitum*, *Litosphaeridium arundum*, *Pseudoceratium expolitum* and *Rhombodella paucispina* at the base of the subzone followed by

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the FO of *Batioladinium shaftesburiense* in the middle part; *Ovoidinium* sp. 3 Nøhr-Hansen (1993) is also present.

Correlations: The presence of the informal species *Ovoidinium* sp. 3 Nøhr-Hansen (1993) seems to be a useful lower middle Albian marker in NE Greenland. It occurs in Rødelv Member at eastern Steensby Bjerg in the northern part of Hold with Hope, and was originally recorded from the lower part of the *Litosphaeridium arundum* (1) Subzone at Stratumbjerg, Wollaston Forland and at Kontaktravine, Clavering Ø (Nøhr-Hansen, 1993; section 21, 22, Fig. 5). Duxbury (2001) recorded the FO of *L. arundum* from the base of his Lower Albian dinocyst subzone LKP33 Subzone.

6.o. Subzone: *Chichaouadinium vestitum* (2) of Nøhr-Hansen (1993)

Age: middle Albian.

Definition: From the FO of the acme of *Chichaouadinium vestitum* to the FO of *Subtilisphaera kalaallitii*.

Stratigraphic events: LO of *Aptea polymorpha*, *Chichaouadinium vestitum*, *Ellipsoidictyum imperfectum*, *Leptodinium cancellatum* and *Odontochitina singhii* occurs at the top of the subzone.

Correlations: Duxbury (2001) recorded an increase in abundance of *E. imperfectum* in the top of his dinocyst LKP34 Subzone upper middle Albian tentatively correlated with the *Euhoplites lautus* ammonite Zone and the LO of *O. singhii* in the dinocyst LKP35.1 Subzone , lowermost upper Albian, *Mortoniceras inflatum* ammonite Zone (Fig. 8). The subzone has recently been recorded from the upper part of Carolinefjellet Formation on Spitsbergen by Grundvåg *et al.* (2017) and from the older part of the Kangoq Ryg Member, Galadriel Fjeld Formation at Kilen, eastern North Greenland (Hovikoski *et al.* 2018; Pedersen *et al.* 2018; Fig. 1).

6.p. Zone: *Subtilisphaera kalaallitii* (V) of Nøhr-Hansen (1993) redefined

Age: late Albian – middle Cenomanian.

Definition: From the FO of *Subtilisphaera kalaallitii* to the FO of *Endoceratium ludbrookiae*.

Comments: Originally the top of the zone was defined at the LO of *Epelidosphaeridia spinosa* (Nøhr-Hansen, 1993); in the present study this is changed to the slightly higher FO of *Endoceratium ludbrookiae*, which seems to be a more reliable marker.

The original zone was subdivided into four subzones by Nøhr-Hansen (1993): *Wigginsiella grandstandica* (1), *Odontochitina ancala* (2), *Ovoidinium* sp. 1 (3) and *Epelidosphaeridia spinosa* (4). The redefined *Subtilisphaera kalaallitii* Zone is subdivided into the following five subzones: *Wigginsiella grandstandica* (1), *Odontochitina ancala* (2), *Sindridinium borealis* (3) new, *Epelidosphaeridia manifesta* (4) new and *Sindridinium anaanae* (5) new.

Correlations: The zone has previously been recorded from the Junction Diapir section, Axel Heiberg Island, Arctic Canada (Nøhr-Hansen & McIntyre, 1998; Fig. 1). Recently, the *Subtilisphaera kalaallitii* (V) Zone Nøhr-Hansen (1993) was recorded from the Albian–Cenomanian Sorgenfri Formation in Kangerlussuaq, southern East Greenland (Nøhr-Hansen, 2012; Fig. 6). The middle part of the *Subtilisphaera kalaallitii* Zone was reported from the Kolmule Formation in the southwestern Barents Sea and from the Langebarn Formation in the Norwegian Sea (Fig. 6) by Radmacher *et al.* (2014) and by Radmacher *et al.* (2015), respectively. Recently, the lower part of the subzone has been questionably recorded from Genetic Sequence 4 (approximately equivalent to the Kolmule Formation) from the Loppa High, southwestern Barents Sea by Marin *et al.* (2018).

6.q. Subzone: *Wigginsiella grandstandica* (1) of Nøhr-Hansen (1993)

Age: early late Albian.

Definition: From the FO of *Wigginsiella grandstandica* to the FO of *Odontochitina ancala*.

Stratigraphic events: FO of *Subtilisphaera kalaallitii*, *Wigginsiella grandstandica* and *Circulodinium* sp. 1 Nøhr-Hansen (1993) at the base of the subzone. *Subtilisphaera kalaallitii* and *Rhombodella paucispina* are common to dominant within the present subzone. The informal species Dinoflagellate cyst 1 Nøhr-Hansen (1993) is present in a narrow interval within the lower part of the present subzone, and seems to be a good lowermost upper Albian marker in NE Greenland.

Correlations: Dinoflagellate cyst 1 Nøhr-Hansen (1993) was originally recorded from the lower part of the *Wigginsiella grandstandica* (1) Subzone at Tværdal, Geographical Society Ø (Nøhr-Hansen, 1993; section 30, p. 162, Fig. 3). It also occurs together with *W. grandstandica* in the lower part of Fosdalen formation (Fig. 6) at Diener Bjerg, northern Hold with Hope (PAL-9/2009, Fig. 4) and in a more than 500 m thick, E-dipping succession in the river valley (HNH 080910-1, Fig. 4) of western Lygnaelv, southern Hold with Hope. Recently, the subzone has been recorded from the older part of the Kangoq Ryg Member, Galadriel Fjeld Formation at Kilen, eastern North Greenland (Hovikoski *et al.* 2018; Pedersen *et al.* 2018; Fig. 1).

6.r. Subzone: *Odontochitina ancala* (2) of Nøhr-Hansen (1993)

Age: middle–late Albian.

Definition: From the FO of *Odontochitina ancala* to the FO of *Sindridinium borealis*.

Comments: The *Odontochitina ancala* (2) Subzone is represented by a more than 200-m-thick succession at Svinhufvud Bjerge (section 37, Nøhr-Hansen, 1993; Fig. 3) on Traill Ø and less than 82-m-thick in Tværdal, Geographical Society Ø (section 30, Nøhr-Hansen, 1993; Fig. 3). Nøhr-Hansen (1993, section 28; Fig. 4) dated two samples to middle–late Albian at the eastern mouth of Lygnaelv, southern Hold with Hope. The succession was referred to the *Odontochitina ancala* (2) Subzone Nøhr-Hansen (1993) despite the lack of the zonal index species. Analyses of samples from this locality (HNH 080610-1&2, Fig. 4) confirmed the presence of *Odontochitina ancala*, together with the Lower Cenomanian zonal marker *Sindridinium anaanae*.

The Early Cenomanian age correlates with a latest Albian – Cenomanian age based on the recovery of *Inoceramus dunveganensis* McLean and the annelid *Ditrupa* almost at the same site (CASP Loc. W. 3141; Kelly *et al.* 1998). The ammonite *Schloenbachia ventiosa* Stieler of probable Early Cenomanian age occurs further inland at Lygnaelv (Kelly *et al.* 1998; CASP Loc. K.7359). Kelly *et al.* (1998) therefore regarded the *Odontochitina ancala* (2) Subzone of Nøhr-Hansen (1993) as Cenomanian. However, palynological studies of two successions from this locality refer these successions to the new *Epelidosphaeridia manifesta* (4) Subzone of Early–middle Cenomanian age (see below).

Stratigraphic events: The FO of *Epelidosphaeridia* sp. 1 Nøhr-Hansen (1993), *Odontochitina ancala* and *Sindridinium? torulosa* at the base of the subzone and LO of *Circulodinium*

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sp. 1 Nøhr-Hansen (1993) in the lower part of the subzone. The FO of *Endoceratium exquisitum* in the middle of the subzone seems to be a good stratigraphic marker; the species was wrongly reported and illustrated as *Endoceratium dettmanniae* by Nøhr-Hansen *et al.* (2018, pl. 9, figs 1–6). *Circulodinium* sp. 1 Nøhr-Hansen (1993), *Subtilisphaera kalaallitii* and *Rhombodella paucispina* are common to dominant in this subzone.

Correlations: The *Odontochitina ancala* (2) Subzone was recently recorded from thin (less than 10 cm) mudstone layers within an approximately 5-m-thick sandy section and the approximately 40-m-thick overlying mudstone section situated at the northern part of Snertadal, Hold with Hope (HNH081210-6, Fig. 4). The section contains a low-diversity assemblage, including the brackish water form *Nyktericysta dictyophora* (former *Quantouendinium dictyophorum* according to Fensome *et al.* 2016) previously recorded from the *Odontochitina ancala* Subzone at Svinhufvud Bjerge, Traill Ø (section 36, 37, Nøhr-Hansen, 1993; Figs 2, 3) as *Vesperosis* aff. *V. fragilis*. Recently, the subzone has been recorded from the younger part of the Kangoq Ryg Member, Galadriel Fjeld Formation at Kilen, eastern North Greenland (Hovikoski *et al.* 2018; Pedersen *et al.* 2018).

6.s. Subzone: *Sindridinium borealis* (3) new

Age: latest Albian – Early Cenomanian.

Definition: From the FO of *Sindridinium borealis* to the FO of *Epelidosphaeridia manifesta*.

Comments: The *Sindridinium borealis* (3) Subzone corresponds to the lower part of the former *Ovoidinium*? sp. 1 Subzone of Nøhr-Hansen (1993). Two morphologically almost similar forms of *Ovoidinium* sp. 1 Nøhr-Hansen (1993) (non-cavate and hypocavate forms) were earlier assumed to occur together; however, Nøhr-Hansen *et al.* (2018) recorded that *S. borealis* (the non-cavate form) has no or little overlap with the younger *Sindidinium anaanae* (the hypocavate form). The base of the up to 130-m-thick *Sindridinium borealis* (3) Subzone is recognized in four sections on Hold with Hope (Snertadal, JHOV-2/2009, east of Fosdalen HNH081410-4 and western Lygnaelv HNH 080910-1, HNH080610-3, Fig. 4) and from the Tværdal section, Geographical Society Ø (section 30 of Nøhr-Hansen 1993; PAL-3/2011, Nøhr-Hansen *et al.* 2018).

Stratigraphic events: FO of *Epelidosphaeridia spinosa*, *Dinopoterygium alatum* and *Sindridinium borealis* at the base of the subzone. LO of *Epelidosphaeridia* sp. 1 Nøhr-Hansen (1993), FO of *Senoniasphaera* aff. *microreticulata* and FO of common *S. borealis* in the upper part of the subzone. *Subtilisphaera kalaallitii* and *Rhombodella paucispina* are common to dominant within the present subzone. The brackish to marginal marine indicator, the acritarch *Limbicysta*, is recorded from the upper part of the subzone at Lygnaelv, HNH080610-3.

Correlations: The *Ovoidinium* sp. 1 (3) Subzone Nøhr-Hansen (1993) was recorded from the Albian Sorgenfri Formation in Kangerlussuaq, southern East Greenland (Nøhr-Hansen, 2012; Figs 1, 6). An acme of *S. borealis* was reported from the Komule Formation in the southwestern Barents Sea (Radmacher *et al.* 2014; Figs 1, 6). *Sindridinium borealis* also occurs in the Lower Cenomanian at Norfolk, onshore eastern England and in the Lower Cenomanian Kolmule Formation in Troms and Hammerfest basins, Barents Sea (Nøhr-Hansen *et al.* 2018; Fig. 1).

6.t. Subzone: *Epelidosphaeridia manifesta* (4) new

Age: Early Cenomanian.

Definition: From the FO *Epelidosphaeridia manifesta* to the FO of *Sindridinium anaanae*.

Comments: The *Epelidosphaeridia manifesta* (4) Subzone correlates with the middle part of the *Ovoidinium*? sp. 1 Subzone of Nøhr-Hansen (1993). The subzone is represented by more than 100 m at Tværdal, Geographical Society Ø (section 30, Nøhr-Hansen, 1993; Fig. 3). Resampling and restudy of the approximately 415-m-thick succession in Tværdal on Geographical Society Ø (section 30 of Nøhr-Hansen, 1993; Pal-3/2011, Fig. 4) have yielded a rich assemblage of the ammonite *Schloenbachia varians* from 349 m, that is, a level in the upper part of the *Epelidosphaeridia manifesta* (4) Subzone indicating an earliest Cenomanian age (*Mantelliceras mantelli – M. dixoni* ammonite zones (undivided), Fig. 8; Nøhr-Hansen *et al.* 2018).

The subzone is also recorded from a more than 200-m-thick succession (HNH 081410-4, Fig. 4) in the hanging wall east of the Fosdalen Fault, east of Fosdalen, northern Hold with Hope.

The *Epelidosphaeridia manifesta* (4) Subzone has also been recorded in the uppermost part of an E-dipping succession along Lygnaelv (HNH 080610-3, Fig. 4), southern Hold with Hope. Here the ammonite *Schloenbachia* sp. is collected very close to Kelly *et al.*'s (1998) inland locality at Lygnaelv (CASP Loc. K.7359), where they found the ammonite *Schloenbachia ventiosa* that was probably of Early Cenomanian age. These records of *Schloenbachia* ammonites within the *Epelidosphaeridia manifesta* (4) Subzone both at Lygnaelv and in Tværdal provide an important palynostratigraphic means of placing the Albian–Cenomanian boundary in NE Greenland, and confirm that the boundary is in the *Sindridinium borealis* (3) Subzone and not in the underlying *Odontochitina ancala* (2) Subzone of Nøhr-Hansen (1993) as suggested by Kelly *et al.* (1998).

Stratigraphic events: FO of *Epelidosphaeridia manifesta* and *Ovoidinium epelidosphaeroides* in the lower part of the subzone, both species are previously observed from the Lower Cenomanian Kolmule Formation in Troms and Hammerfest basins, Barents Sea (Nøhr-Hansen *et al.* 2018). The LO of *E. manifesta* occur in the middle of the subzone, whereas the FO of *Xenascus* aff. *plotei* and the LO of *O. epelidosphaeroides*, *Senoniasphaera* aff. *microreticulata* and common *Sindridinium borealis* occur in the uppermost part of the Subzone. *Sindridinium borealis*, *Subtilisphaera kalaallitii* and *Rhombodella paucispina* are common to dominant within the present subzone. The brackish to marginal marine indicator, the acritarch *Limbicysta* and the zygospore *Tetrangulare conspicuum* are recorded from the subzone east of Fosdalen (HNH081410-4) and the Tværdal sections (section 30 of Nøhr-Hansen 1993 and GEUS, PAL-3/2011).

6.u. Subzone: *Sindridinium anaanae* (5) new

Age: Early – ?middle Cenomanian.

Definition: From the FO of *Sindridinium anaanae* to the FO of *Endoceratium ludbrookiae*.

Comments: The *Sindridinium anaanae* (5) Subzone correlates with the upper part of the *Ovoidinium*? sp. 1 Subzone of Nøhr-Hansen (1993). The subzone is represented by a total thickness of more than 190 m in three sections at the hanging wall east of the Fosdalen fault, east of Fosdalen, northern Hold with Hope

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(HNH 081410-4, Fig. 4, sections 24 and 25 of Nøhr-Hansen, 1993), overlying the older *Epelidosphaeridia manifesta* (4) Subzone, whereas the upper boundary has still to be recorded in a continuous exposed section.

Stratigraphic events: FO of *Sindridinium anaanae* and the LO of *Xenascus* aff. *plotei* at the lower part, whereas *Rhombodella paucispina* and *Subtilisphaera kalaallitii* are common to dominant within the present subzone. The brackish water to marginal marine indicator, the acritarch *Limbicysta*, is recorded from the lower part of the subzone at Fosdalen.

Correlations: Sindridinium anaanae are previously observed from the Lower Cenomanian Kolmule Formation in Troms and Hammerfest basins, Barents Sea (Nøhr-Hansen *et al.* 2018).

6.v. Zone: *Endoceratium ludbrookiae* (VI) new

Age: middle Cenomanian (*pars*)

Definition: From the FO of *Endoceratium ludbrookiae* to the FO of *Isabelidinium magnum*.

Comments: The *Endoceratium ludbrookiae* (VI) Zone has been recorded from three small sections: one 3-m- and two 25-m-thick successions south of Knudshoved at the east coast of Hold with Hope (HNH 081009-4, HNH 081009-2 and HNH 081009-1; Fig. 4). The incoming of *E. ludbrookiae* has not been observed in a continuous exposed section; in the Knudshoved sections the species occurs from the base of the exposures.

Stratigraphic events: FO of *Endoceratium ludbrookiae*, *Ginginodinium* aff. *evittii* and *Palaeohystrichophora infusorioides* together with the LO (or reworked specimens) of *Endoceratium exquisitum* at the base of the zone. *Dorocysta litotes*, *Hapsocysta? benteae* and *Rhombodella paucispina* are present and *Subtilisphaera kalaalliti* is abundant within this new zone.

Correlations: Endoceratium ludbrookiae has an upper Albian – upper Cenomanian range according to Helby *et al.* (1987) and a middle Lower – end upper Cenomanian range according to BioStrat (2018). The presence of *G.* aff. *evittii* may indicate an age not younger than Early Cenomanian according to Singh (1983); however, the absence of *Epelidosphaeridia spinosa* and *Isabelidinium magnum* may suggest a middle Cenomanian age. Based on the FO of *Palaeohystrichophora infusorioides*, this new *E. ludbrookiae* Zone may correlate with the lower part of the Cenomanian *Palaeohystrichophora infusorioides – P. palaeoinfusa* Interval Zone established from the intra-Early to intra-late Cenomanian part of the Kveite Formation from the southwestern Barents Sea by Radmacher *et al.* (2014; Figs 1, 6) and later reported from the Langebarn and Blålange formations from the Norwegian Sea by Radmacher *et al.* (2015; Figs 1, 6). Recently, the FO of *Endoceratium ludbrookiae* has been recorded from the younger part of the Kangoq Ryg Member, Galadriel Fjeld Formation at Kilen, eastern North Greenland (Fig. 1), suggesting the presence of the subzone (Hovikoski *et al.* 2018; Pedersen *et al.* 2018).

6.w. Zone: *Isabelidinium magnum* (VII) new

Age: ?middle–late Cenomanian.

Definition: From the FO of *Isabelidinium magnum* to the FO of *Cyclonephelium compactum – Cauveridinium membraniphorum* complex.

Comments: The *Isabelidinium magnum* (VII) Zone is recorded from two 15-m-thick successions (HNH080710-3 and HNH080710-4; Fig. 4) south of Knudshoved, and in the lowermost 5 m of the Nanok-1 core (517004) at the east coast of Hold with Hope.

Stratigraphic events: FO of *Isabelidinium magnum*, *Isabelidinium acuminatum*, *Isabelidinium* spp., *Trithyrodinium* aff. *rhomboideum* and *Trithyrodinium suspectum* at the base of the zone. LO of *Hapsocysta? benteae* is in the lower part and LO of *Rhombodella paucispina* and *T.* aff. *rhomboideum* are in the uppermost part of the zone. *Subtilisphaera kalaalliti* is abundant in the lower part and common in the upper part of the zone. *Palaeohystrichophora infusorioides* is common in the middle part of the zone and *Isabelidinium* spp. is common throughout the new zone.

Correlations: The FO of *I. magnum* suggests a late Cenomanian age (Costa & Davey, 1992) and the FO of *T. suspectum* suggests a middle–late Cenomanian age (Costa & Davey, 1992; Williams *et al.* 2004). *Trithyrodinium rhomboideum* is described from the middle Cenomanian Stage of Alberta, Canada (Singh, 1983). The FO of *Isabellidinium magnum* and *Trithyrodinium suspectum* have recently been recorded from the older part of the Sølverbæk Formation at Kilen, eastern North Greenland (Fig. 1), suggesting the presence of the subzone (Hovikoski *et al.* 2018; Pedersen *et al.* 2018).

6.x. Zone: *Cyclonephelium compactum – Cauveridinium membraniphorum* complex (VIII) new

Age: latest Cenomanian.

Definition: From the FO of *Cyclonephelium compactum – Cauveridinium membraniphorum* complex to the FO of *Heterosphaeridium difficile*.

Comments: The new *Cyclonephelium compactum – Cauveridinium membraniphorum* complex (VIII) Zone has been recorded from a 22-m-thick succession (HNH080710-2, Fig. 4) south of Knudshoved and represented by 37 m in the Nanok-1 core (517004) at the east coast of Hold with Hope. *Cauveridinium membraniphorum* was originally described as *Cyclonephelium membraniphorum* by Cookson & Eisenack (1962, p. 495), and the *Cyclonephelium compactum – Cauveridinium membraniphorum* complex was reported as the *Cyclonephelium compactum – C. membraniphorum* complex until Fauconnier & Masure (2004, p. 97) transferred the species *Cyclonephelium membraniphorum* into the genus *Cauveridinium*.

Stratigraphic events: The FO of *Cyclonephelium compactum – Cauveridinium membraniphorum* complex and *Surculosphaeridium longifurcatum* at the base of of the zone. *Chlamydophorella nyei*, *Isabelidinium* spp., *Palaeohystrichophora infusorioides* and *Spiniferites* spp. are common throughout the zone and *S. longifurcatum* are common in the upper part of the new zone. The last consistent occurrence of *Subtilisphaera kalaalliti* occurs in the middle part of the zone.

Correlations: The first common occurrence of *C. compactum – C. membraniphorum* complex is reported in upper Cenomanian onshore UK (Marshall & Batten, 1988; Dodsworth, 2000; Pearce *et al.* 2009). Recently, *Cauveridinium membraniphorum* was recorded from an upper Cenomanian succession in Kangerlussuaq, southern East Greenland (Nøhr-Hansen, 2012; Fig. 1). Based on the FO of *C. compactum – C. membraniphorum* complex and *S. longifurcatum*, the base of the present new zone may correlate with the middle part of the Cenomanian *P. infusorioides – P. palaeoinfusa* Interval Zone established from the intra-Early to intra-late Cenomanian part of the Kveite Formation from the southwestern Barents Sea by Radmacher *et al.* (2014; Figs 1, 6) and later reported from the Langebarn and Blålange formations from the Norwegian Sea by

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Radmacher *et al.* (2015; Figs 1, 6). *Subtilisphaera kalaalliti* becomes extinct in the uppermost part of their *Palaeohystrichophora infusorioides* – *P. palaeoinfusa* Interval Zone from the Norwegian Sea according to Radmacher *et al.* (2015). The last consistent occurrence of *S. kalaalliti* within the new *C. compactum* – *C. membraniphorum* complex Zone may indicate that its upper boundary is slightly younger than the *Palaeohystrichophora infusorioides* and *P. palaeoinfusa* Interval Zone of Radmacher *et al.* (2014). Recently, the FO of *Cauveridinium membraniphorum* has been recorded from the older part of the Sølverbæk Formation at Kilen, eastern North Greenland, suggesting the presence of the subzone (Hovikoski *et al.* 2018; Pedersen *et al.* 2018; Fig. 1).

6.y. Zone: *Heterosphaeridium difficile* (IX) new

Age: Early Turonian – ?middle Coniacian.

Definition: From the FO of *Heterosphaeridium difficile* to the FO of the undefined species informally named "*Chatangiella spinosa*" in industrial reports.

Comments: The *Heterosphaeridium difficile* (IX) Zone has been recorded from a 27-m-thick succession (HNH080209-4) and represented by 28 m in Fosdalen formation in the Nanok-1 core (517004) south of Knudshoved at the east coast of Hold with Hope (Fig. 4). The zone is subdivided into four new subzones: *Chatangiella granulifera* (1), *Senoniasphaera rotundata* (2), *Odontochitina rhakodes* (3) and *Xenascus gochtii* (4). The *Heterosphaeridium difficile* (IX) Zone differs from the informal *Heterosphaeridium difficile* interval of Coniacian – Early Santonian age described by Nøhr-Hansen (1996) from West Greenland, which was defined from the LO of *Arvalidinium scheii* to the LO of *Heterosphaeridium difficile*.

Correlations: Parts of the informal *Heterosphaeridium difficile* interval of Nøhr-Hansen (1996) were recently recorded from the Turonian–Coniacian succession in the Sorgenfri Formation at Kangerlussuaq, southern East Greenland (Nøhr-Hansen, 2012; Figs 1, 6) and from the Turonian – ?intra-early Coniacian part of the Kveite Formation in the southwestern Barents Sea (Radmacher *et al.* 2014) and from the Turonian – ?intra-early Coniacian part of the Blålange and Kvitnos formations in the Norwegian Sea (Radmacher *et al.* 2015; Figs 1, 6). Recently, the FO of *Heterosphaeridium difficile* has been recorded from the older part of the Sølverbæk Formation at Kilen, eastern North Greenland, suggesting the presence of the subzone (Hovikoski *et al.* 2018; Pedersen *et al.* 2018; Fig. 1).

6.z. Subzone: *Chatangiella granulifera* (1) new

Age: Early Turonian.

Definition: From the FO of *Chatangiella granulifera* to the FO of *Senoniasphaera rotundata*.

Comments: The *Chatangiella granulifera* (1) Subzone has been recorded from a 4-m-thick Fosdalen formation succession (HNH080209-4) south of Knudshoved and is represented by 6 m in the Nanok-1 core (517004) at the east coast of Hold with Hope (Fig. 4).

Stratigraphic events: The FO of *Chatangiella granulifera* and *Heterosphaeridium difficile* at the base of the subzone.

Correlations: Both *C. granulifera* and *H. difficile* have their FO at the base of the Turonian Stage according to Costa & Davey (1992). Pearce *et al.* (2003), Williams *et al.* (2004) and BioStrat (2018) suggest an age not older than Early Turonian for the FO of *H. difficile*. Dodsworth (2000) recorded the FO of rare *H. difficile* from the Lower Turonian bed 95, 1.2 m above the global boundary stratotype section and point (GSSP) at the type section at Pueblo, Colorado, USA. Eldrett *et al.* (2015) recently dated the FO of *H. difficile* to middle Turonian (92.28 ma) from Texas, USA, based on astronomical calibration. An Early Turonian age for the FO of *H. difficile* is tentatively used in the present paper. Bell & Sellnes (1997) suggested an Early–middle Cenomanian FO age for *H. difficile* based on its co-occurrence with members of the *Endoceratium dettmanniae* – *E. ludbrookiae* plexus, offshore Norway. However, *E. ludbrookiae* has in the present study been recorded in assemblages together with *H. difficile* and the Turonian – middle Coniacian marker species *Odontochitina rhakodes* and *Xenascus gochtii* from Nanok-1 core (517004) at the east coast of Hold with Hope, and together with *H. difficile* and *O. rhakodes* from the middle – upper part of the Sølverbæk Formation at Kilen, eastern North Greenland (Hovikoski *et al.* 2018; Pedersen *et al.* 2018; Fig. 1), suggesting either reworking or a Coniacian LO for *E. ludbrookiae*. Olde *et al.* (2015) mention (based on Bell & Sellnes, 1997; Bloch *et al.* 1999) the FO of *H. difficile* in the Cenomanian Stage in the high northern latitudes, suggests that *H. difficile* is a cold-water-tolerant species that migrated southwards with the predominant Late Cretaceous cooling; however, Lenniger *et al.* (2014, unpublished data) recorded its FO in the Lower Turonian Stage from Axel Heiberg Island, Artic Canada and from the Baffin Bay area.

6.aa. Subzone: *Senoniasphaera rotundata* (2) new

Age: middle Turonian.

Definition: From the FO of *Senoniasphaera rotundata* to the FO of *Odontochitina rhakodes*.

Comments: The *Senoniasphaera rotundata* (2) Subzone has been recorded from a 6-m-thick Fosdalen formation succession (HNH080209-4) south of Knudshoved, and is represented by 3 m in the Nanok-1 core (517004) at the east coast of Hold with Hope (Fig. 4).

Stratigraphic events: The FO of *Senoniasphaera rotundata* and *Raphidodinium fucatum* at the base of the subzone. *Surculosphaeridium longifurcatum* are common in the subzone.

Correlations: Senoniasphaera rotundata has a FO in the ?upper Turonian – lower Coniacian stages according to Costa & Davey (1992). However, an FO in the middle Turonian Stage and a first common occurrence in the uppermost Turonian Stage was reported by Pearce *et al.* (2003). The FO of *R. fucatum* in the middle Turonian Stage is described by Costa & Davey (1992) and was also recorded from the North Sea area, Norwegian Sea and West Greenland by Radmacher *et al.* (2015), Pedersen & Nøhr-Hansen (2014) and Nøhr-Hansen *et al.* (2016), respectively; an upper Coniacian FO was reported by Nøhr-Hansen (2012) from the Sorgenfri Formation at Kangerlussuaq, southern East Greenland.

6.ab. Subzone: *Odontochitina rhakodes* (3) new

Age: ?middle Turonian – ?early Coniacian. The suggested age is tentative, based on the ages of the subzones below and above.

Definition: From the FO of *Odontochitina rhakodes* to the FO of *Xenascus gochtii*.

Comments: The *Odontochitina rhakodes* (3) Subzone has been recorded from a 12-m-thick Fosdalen formation succession (HNH080209-4) south of Knudshoved, and represented by 4 m in the Nanok-1 core (517004) at the east coast of Hold with Hope (Fig. 4).

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Stratigraphic events: FO of *Laciniadinium arcticum* and *Odontochitina rhakodes* at the base of the subzone and LO of *O. rhakodes* at the top of the subzone. *Palaeohystrichophora infusorioides* and *Spiniferites* spp. and *Surculosphaeridium longifurcatum* are common in the subzone.

Correlations: A Lower Turonian LO for *O. rhakodes* was reported by Fensome *et al.* (2008). The FO of *Laciniadinium arcticum* was reported as most likely in the lower Coniacian Stage from West Greenland by Nøhr-Hansen (1996), whereas a Turonian FO was reported from Europe by Stover *et al.* (1996). Recently, the FO of *Odontochitina rhakodes* has been recorded from the Sølverbæk Formation at Kilen eastern North Greenland, suggesting the presence of the subzone (Hovikoski *et al.* 2018; Pedersen *et al.* 2018; Fig. 1).

6.ac. Subzone: *Xenascus gochtii* (4) new

Age: ?early–middle Coniacian.

Definition: From the FO of *Xenascus gochtii* to the FO of "*Chatangiella spinosa*" (undescribed species, informally named so in industrial reports).

Comments: The *Xenascus gochtii* (4) Subzone has been recorded from a 0.65-m-thick succession (HNH080209-4) from the uppermost part of Fosdalen formation underlying the Nanok Member (Kelly *et al.* 1998) south of Knudshoved and from the uppermost 14 m of Fosdalen formation, in the Nanok-1 core (517004) at the east coast of Hold with Hope (Fig. 4). Kelly *et al.* (1998) mentioned that the records of inoceramids (e.g. *Inoceramus lamarcki*) near the top of the Fosdalen Member (referred to as Fosdalen formation here; Fig. 6) near Knudshoved indicate a late Turonian – possible Coniacian age.

Stratigraphic events: FO of *Xenascus gochtii* at the base of the subzone and LO of *Stephodinium coronatum* at its top. *Palaeohystrichophora infusorioides* is common to abundant in this subzone.

Correlations: An ?early–middle Coniacian age is suggested for the new *Xenascus gochtii* (4) Subzone based on the FO of *X. gochtii* that indicates an age not older than middle Coniacian (Prince *et al.* 2008). The LO of *S. coronatum* indicates an age not younger than latest Turonian according to Costa & Davey (1992), whereas the middle Coniacian LO published by Williams *et al.* (2004) is most likely based on misidentification (M. Pearce, pers. comm. 2019). In the present study, *S. coronatum* has been recorded in assemblages together with *H. difficile* and the Turonian – middle Coniacian marker species *Odontochitina rhakodes* and *Xenascus gochtii* from Nanok-1 core (517004) at the east coast of Hold with Hope. Recently, *S. coronatum* has been recorded together with *H. difficile* and *X. gochtii* from southern East Greenland (Nøhr-Hansen, 2012), and together with *H. difficile* and *O. rhakodes* from the middle to upper part of the Sølverbæk Formation at Kilen, eastern North Greenland (Hovikoski *et al.* 2018; Pedersen *et al.* 2018; Fig. 1). These records may suggest either reworking or a Coniacian LO for *S. coronatum*. Based on the LO of *S. coronatum*, the top of the subzone may correlate with the top of the Turonian – ?intra-early Coniacian *Heterosphaeridium difficile* Interval Zone recorded from the Kveite Formation in the southwestern Barents Sea (Radmacher *et al.* 2014) and from the top of the Turonian – ?intra-early Coniacian part of the Blålange and Kvitnos formations in the Norwegian Sea (Radmacher *et al.* 2015; Figs 1, 6). Recently, the FO of *Xenascus gochtii* has been recorded from the upper part of Sølverbæk Formation at Kilen, eastern North Greenland, suggesting the presence of the subzone (Hovikoski *et al.* 2018; Pedersen *et al.* 2018; Fig. 1).

6.ad. Zone: "*Chatangiella spinosa*" (X) new

Age: middle Coniacian – middle Santonian.

Definition: From the FO of "*Chatangiella spinosa*" (informal name for an undefined species used in biostratigraphic reports within petroleum exploration drilling) to the FO of *Alterbidinium ioannidesii*.

Comments: The "*Chatangiella spinosa*" (X) Zone has been recorded from the lowermost 14.5 m of the Østersletten formation (including the Nanok Member, which forms the basal 2.5 m of the formation; Fig. 6) in the exposed section (HNH080209-4) south of Knudshoved, and from the lower 6 m of the Østersletten formation in the Nanok-1 core (517004, Fig. 4).

Stratigraphic events: FO of "*Chatangiella spinosa*", *Spinidinium echinoideum* and *Trithyrodinium vermiculatum* at the base of this zone. LO of *Senoniasphaera rotundata* in the lower part and LO of *Isabelidinium magnum* and FO of *Odontochitina porifera* in the middle part of the zone. *Palaeohystrichophora infusorioides* and *S. echinoideum* are common in the subzone.

Correlations: The informal "*C. spinosa*" is assumed to have a middle Coniacian – middle Santonian range in the Norwegian Sea according to BioStrat (2018). *Trithyrodinium vermiculatum* was recorded from the middle Coniacian strata by Schiøler (1992). The FO of *O. porifera* may support a Santonian age. *O. porifera* has a Lower Santonian – lower Campanian range in Australia according to Helby *et al.* (1987), whereas Fensome *et al.* (2008) and Fensome *et al.* (2016) recorded an LO of *O. porifera* in the upper Santonian deposits in the Scotian Margin and Labrador Sea, respectively. The zone may correlate with the lower part of the ?intra-early Coniacian – late Santonian *Dinopterygium alatum* Interval Zone in the Kveite Formation in the southwestern Barents Sea (Radmacher *et al.* 2014). Radmacher *et al.* (2015) reported abundant occurrence of *T. vermiculatum*, and abundant occurences of "*C. spinosa*" at the base of the *D. alatum* Interval Zone from the Kvitnos and Nise Formations from the Norwegian Sea (Figs 1, 6).

6.ae. Zone: *Alterbidinium ioannidesii* (XI) new

Age: late Santonian.

Definition: From the FO of *Alterbidinium ioannidesii* to the FO of *Aquilapollenites* spp.

Comments: The *Alterbidinium ioannidesii* (XI) Zone is recorded from the 26-m-thick succession representing the middle and upper part of the Østersletten formation at locality 5 south of Knudshoved and represented by 32 m in the Nanok-1 core (517004) at the east coast of Hold with Hope (Fig. 4), from a 20-m-thick succession at northeastern Hold with Hope (HNH081610-1, Fig. 4), from an approximately 100-m-thick succession on southern Jackson Ø (HNH081610-2, 3, Fig. 4) and from the upper 23 m of the 80-m-thick Kista Ø formation type section (Pal-5/2011, Figs 3, 6) eastern Månedal, Trail Ø.

Stratigraphic events: FO of *Alterbidinium ioannidesii* at the base of this zone and LO of "*Chatangiella spinosa*" and *Heterosphaeridium difficile* in the middle part of this zone.

Correlations: *A. ioannidesii* has a stratigraphical range from the ?upper Santonian – middle–lower Campanian strata in the Norwegian Sea (Pearce, 2010). "*Chatangiella spinosa*" has a top Early Santonian LO according to BioStrat (2018), whereas other consultants mention a middle Santonian LO. The LO of

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H. difficile indicates an age no younger than late Santonian. *Heterosphaeridium difficile* is often very abundant in Coniacian – Lower Santonian deposits in the North Sea, but isolated specimens are recorded from the upper Santonian onshore England (Prince *et al.* 1999).

6.af. Zone: *Aquilapollenites* (XII) new

Age: early–late Campanian.

Definition: From the FO of the pollen genus *Aquilapollenites* to the FO *Cerodinium diebelii*.

Comments: The lower part of the zone is subdivided into two new subzones: *Aquilapollenites* (1) and *Isabelidinium microarmum* (2). The *Aquilapollenites* Zone (XII) differs from the lower–middle Campanian informal *Aquilapollenites* interval of Nøhr-Hansen (1996) by defining the upper boundary at the FO of *Cerodinium diebelii* instead at the LO of *Isabelidinium microarmum*. The upper boundary of the *Aquilapollenites* Zone has not been recognized in a continuous exposed succession in NE Greenland.

The *Aquilapollenites* Zone has been recorded from a 12-m-thick succession (locality 5) representing the uppermost 5 m of the Østersletten formation and the lowermost 7 m of the Knudshoved formation (Fig. 6) south of Knudshoved (east coast of Hold with Hope, Fig. 4); it is represented by 37 m in the nearby Nanok-1 core (517004) and from three sections at Geographical Society Ø, namely, a 65-m- and 20-m-thick succession at Hundeklemmen (PAL-6/2011, PAL-7/2011, Fig. 3) and a 45-m-thick succession west of Leitch Bjerg (PAL-8/2011, Fig. 3).

6.ag. Subzone: *Aquilapollenites* (1) new

Age: early Campanian.

Definition: From the FO of the pollen genus *Aquilapollenites* to the FO *Isabelidinium microarmum*.

Comments: The lower part of the *Aquilapollenites* Subzone has been recorded from a 12-m-thick succession (locality 5) representing the uppermost 5 m of the Østersletten formation and the lowermost 7 m of the Knudshoved formation south at Knudshoved, represented by 37 m in the Nanok-1 core (517004) at the east coast of Hold with Hope (Fig. 4). The *Aquilapollenites* Subzone (1) differs from the lower–middle Campanian informal *Aquilapollenites* interval of Nøhr-Hansen (1996) by defining the upper boundary at the FO of *Isabelidinium microarmum* instead of at the LO of *I. microarmum*.

Stratigraphic events: FO of the pollen genera *Aquilapollenites* spp. and *Chatangiella bondarenkoi*. The presence of *Alterbidinium ioannidesii*, *Odontochitina operculata* and *Trithyrodinium suspectum* throughout the Knudshoved formation at locality 5 (Fig. 4) and the presence of *Fromea nicosia* in the middle part of the formation suggest an age not younger than early Campanian. The diverse assemblages from the lower part of the Knudshoved formation contain common *Chatangiella* spp., *Palaeohystrichophora infusorioides*, *Palaeoperidinium pyrophorum*, *Spiniferites* spp. and *Trithyrodinium suspectum*.

Correlations: *Aquilapollenites* has its first occurrence in the lower Campanian Stage (Nøhr-Hansen, 1996). The presence of the pollen *Azonia fabacea* in the lower part of the zone may support an early Campanian age. The species is representative of the lower Campanian deposits in Yukon, Canada (Nichols & Sweet, 1993). *Chatangiella bondarenkoi* occurs in the middle Campanian Stage in West Greenland (Nøhr-Hansen, 1996), but in the Santonian–Campanian stages of the Canadian Arctic (Lentin & Vozzhennikova, 1990). *C. bondarenkoi* is typical of the lower Campanian Stage in the Barents Sea (Radmacher *et al.* 2014). The present subzone may correlate with the early Campanian *Palaeoglenodinium cretaceum* Interval Zone from the Kveite Formation from the Barents Sea (Radmacher *et al.* 2014), and from the early Campanian Nise Formation from the Norwegians Sea (Radmacher *et al.* 2015; Figs 1, 6). Based on the presence of radially ribbed sphenoceramid bivalves and the absence of the pollen genus *Aquilapollenites*, the former Knudshoved Member (referred to as Knudshoved formation here) was considered as late Santonian in age by Kelly *et al.* (1998). The present study suggests an early Campanian age for the lower studied part of the Knudshoved formation at Knudshoved.

6.ah. Subzone *Isabelidinium microarmum* (2) new

Age: early–middle Campanian.

Definition: From the FO to the LO of *Isabelidinium microarmum*.

Comments: The lower part of the *Isabelidinium microarmum* Subzone is recorded in the uppermost part of the Knudshoved formation in the Nanok-1 core (517004) at the east coast of Hold with Hope (Fig. 4) and in three sections at Geographical Society Ø, namely, a 65-m- and a 20-m-thick succession at Hundeklemmen (PAL-6/2011, PAL-7/2011, Fig. 3) and a 45-m-thick succession west of Leitch Bjerg (PAL-8/2011, Fig. 3). The outgoing of *I. microarmum* has not been observed in a continuous exposed section; the species occurs at the top of the studied exposures in NE Greenland.

Stratigraphic events: FO and LO of *Isabelidinium microarmum*, presence of *Alterbidinium ioannidesii*.

Correlations: The presence of *Alterbidinium ioannidesii* throughout the Knudshoved formation at Geographical Society Ø suggests an age not younger than early Campanian according to Pearce (2010), who recorded a range up to the middle–lower Campanian in the Norwegian Sea and a range from the lower part of the echinoid *Offaster pillula* Zone (low lower Campanian) to the lower part of the belemnite *Gonioteutus quadrata* Zone (middle lower Campanian) at Norfolk, United Kingdom (Fig. 1). The present record of *A. ioannidesii* below and above the ammonite *Scaphites ikorfatensis* in the Hundeklemmen section, Geographical Society Ø (PAL-7/2011, Fig. 3) may indicate an extention of the range of *A. ioannidesii* into the upper middle Campanian *Bostrychoceras polyplocum* ammonite Zone (according to Kaplan *et al.* 2005, p. 152). The FO of *I. microarmum* at the base of the zone (uppermost part of the Nanok-1 core: 517004, at Knudshoved), and the presence of the species in all the three sections at Geographical Society Ø, may suggest that these sections are younger than the type locality of the Knudshoved formation (locality 5). *Isabelidinium microarmum* was described from the lower Campanian – Maastrichtian in northwestern Canada by McIntyre (1975), and recorded from the lower–middle Campanian Stage in West Greenland (Nøhr-Hansen, 1996) and from the lower Campanian Stage in northern Siberia (Lebedeva, 2006). In a palynological zonation scheme of the northern North Sea and Norwegian Sea, BioStrat (2018) shows a lower middle Campanian LO for *A. ioannidesii* and *I. microarmum*. The new subzone may correlate with the intra-Campanian *Hystrichosphaeridium dowlingii* – *Heterosphaeridium* spp. Interval Zone from Nise Formation in the Norwegian Sea (Radmacher *et al.* 2015; Figs 1, 6).

6.ai. Zone: Cerodinium diebelii (XIII) new

Age: ?late Campanian – Early Maastrichtian.

Definition: From the FO of *Cerodinium diebelii* to the FO of the pollen *Wodehouseia spinata*.

Comments: The *Cerodinium diebelii* Zone has been recorded from a 25-m-thick succession on the south side of Haredal, Wollaston Forland (HNH081508-4, Fig. 3), and the lowermost part of the zone may be represented in an 80-m-thick succession east of Jacksontoppen, Jackson Ø (HNH081610-4, Fig. 4). The presence of *C. diebelii* has not been observed in a continuous exposed section, and the species occurs from the base of the exposures in NE Greenland. The FO of the pollen *Wodehouseia spinata* has not been observed in the studied section.

Stratigraphic events: FO of *Cerodinium diebelii* in the Jackson Ø section. All palynomorphs from this 80-m-thick succession are thermally overmature (thermal alteration index, TAI 3+ to 4−). *C. diebelii*, *Hystrichosphaeridium tubiferum* and *Odontochitina operculata* and the pollen *Aquilapollenites* spp. are present and *Palaeperidinium pyrophorum* is common, whereas the pollen genus *Wodehouseia* was not recorded in the very poorly preserved material.

The FO of *Alterbidinium biaperturum*, *C. diebelii* and *Wodehouseia gracile* are recorded from the base of the Haredal section followed by the FO of *Hystrichosphaeridium* sp. 3 McIntyre (1974). *Phelodinium kozlowskii* and *Spongodinium delitiense* are present throughout and *A. biaperturum* is common in the upper part of the Haredal section.

Correlations: McIntyre (1974, 1975) recorded an Early Maastrichtian FO age for *C. diebelii* in the Northwest Territories of Canada and a late Campanian – Early Maastrichtian age for *W. gracile*, his *Hystrichosphaeridium* sp. 3 and *Deflandrea biapertura* (now *Alterbidinium biaperturum*, according to Fensome *et al.* 2016). BioStrat (2018) recorded the FO of *Hystrichosphaeridium* sp. 3 McIntyre (1974) and the first commom occurrences of *A. biaperturum* and *C. diebelii* from the Early Maastrichtian Age in the northern North Sea and in the Norwegian Sea. A late Campanian FO for *W. gracile* is recorded in southern Alberta, Canada (Braman, 2018). The *Cerodinium diebelii* Zone (XII) differs slightly from the Early Maastrichtian informal *Cerodinium diebelii* interval of Nøhr-Hansen (1996) by its content of *Wodehousia* species, and the questionable extension into the latest Campanian Age. The informal *C. diebelii* interval of Nøhr-Hansen (1996) was also reported by Radmacher *et al.* (2014) from the Lower Maastrichtian part of the Kveite Formation in the Barents Sea. The present zone partly correlates with the interpreted Lower Maastrichtian *Cerodinium diebelii* interval recorded from southern East Greenland (Nøhr-Hansen, 2012). The Haredal section has previously been referred to an early to middle Campanian age based on the presence of the dinocysts *Alterbidinium ioannidesii* (one specimen only) and *C. diebelii* (Nøhr-Hansen *et al.* 2011). Re-examinations of the palynological material from Haredal revealed the presence of the pollen *Wodehouseia gracile* in all six studied samples, whereas the presence of one specimen of the Santonian – middle Campanian marker species *A. ioannidesii* in the uppermost sample is considered as reworked.

Discussion of the late Campanian and/or Early Maastrichtian age: Schiøler & Wilson (2001) recorded the FO of *C. diebelii*, followed by a younger LO of the genus *Odontochitina*, within the uppermost Campanian in the Campanian–Maastrichtian stratotype at Tercis les Bains, France. The absence of the pollen genus *Wodehouseia* and the co-occurrence of *C. diebelii* and *O. operculata* may suggest a late Campanian age for the Jackson Ø section. Likewise, the FO *A. biaperturum* and *W. gracile* in the lower part of the Haredal may also indicate a late Campanian age, whereas the common occurrence of *A. biaperturum* and the FO of *Hystrichosphaeridium* sp. 3 McIntyre (1974) (=*Rigaudella apenninica* according to M. Pearce, pers. comm. 2019) may advocate for an Early Maastrichtian age for the upper part of the Haredal section.

7. Upper Maastrichtian

Records of late Maastrichtian palynomorphs in NE Greenland have been restricted to reworked material deposited in Palaeogene successions from Langsiden, Hold with Hope and Haredal, Wollaston Forland (Nøhr-Hansen *et al.* 2011; Fig. 5). The late Maastrichtian pollen marker species *Wodehouseia spinata* has not been observed *in situ* in NE Greenland, but is reported from upper Maastrichtian successions in southern East Greenland (Nøhr-Hansen, 2012) and in central West Greenland (Nøhr-Hansen, 1996; Pedersen & Nøhr-Hansen, 2014).

8. Conclusion

The palynostratigraphic zonation presented here is the first to cover the entire Cretaceous succession in East and NE Greenland. The zonation is correlated with other areas from where stratigraphic data are available.

The biostratigraphy is primarily based on dinocysts, which are present in all sections with marine deposits except when the sediments are severely thermally affected (e.g. by intrusions or subsidence).

The Cretaceous succession is divided into 15 palynozones. Six zones are subdivided into 20 subzones. More than 100 palynostratigraphic events representing more than 70 stratigraphic levels are recorded. The average age of zones is approximately 5 ma. Two new zones are erected in the lowermost Cretaceous succession, and the stratigraphy for the remaining Lower Cretaceous is based on the zonation by Nøhr-Hansen (1993) in an updated and revised version. Eight Upper Cretaceous palynozones are all new. Several of these Upper Cretaceous stratigraphic units are also recognized in the Kangerlussuaq area, SW Greenland by Nøhr-Hansen (2012). The Upper Cretaceous zonation partly correlates with the informal intervals identified from central West Greenland (Nøhr-Hansen, 1996) and with the zonations from the Barents and Norwegian seas (Radmacher *et al.* 2014, 2015).

Dinocyst stratigraphy is the principal means of biostratigraphic dating of the Cretaceous deposits in NE Greenland. Cretaceous ammonite stratigraphy is incomplete in the area due to the occurrence of barren intervals. When ammonites are present, they are used for calibration of the palynostratigraphic units.

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