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RESEARCH ARTICLE

The *Scriniodinium crystallinum* dinoflagellate cyst zone in the Middle–Upper Oxfordian, Upper Jurassic, Ilimananngip Nunaa (Milne Land), East Greenland

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Abstract

The biostratigraphy of the Jurassic in East Greenland is historically based on macroscopic fossils. Stratigraphy based on palynomorphs (spores, pollen and dinoflagellate cysts) has progressed more slowly and sporadically. The *Scriniodinium crystallinum* dinoflagellate cyst Zone is identified in middle – upper Oxfordian strata of Ilimananngip Nunaa (Milne Land), central East Greenland. The lower boundary is defined by the last occurrence of *Trichodinium scarburghense* in the *Cardioceras tenuiserratum* ammonite Zone. The upper boundary is defined by the last occurrence of *S. crystallinum* in the uppermost *Amoeboceras rosenkrantzi* ammonite Zone. However, the subzonal division of the *S. crystallinum* Zone recorded in North-West Europe is not identified in Greenland. Eighteen characteristic dinoflagellate cyst events are considered stratigraphically significant and useful in East Greenland. Fifteen of these events provide an informal, detailed stratigraphical subdivision of the *S. crystallinum* Zone into 10 subunits. Identification of the zone is an addition to the previously defined upper Bathonian – middle Oxfordian zonation, where the uppermost palynostratigraphical event was recorded to be the last occurrence of *T. scarburghense*. With this study, the correlation of dinoflagellate cyst and ammonite stratigraphy in the lower and middle Oxfordian is slightly modified. The *S. crystallinum* Zone documented here, in combination with the zonation used for the stratigraphy of the Blokelv-1, Rødryggen-1 and Brorson Halvø-1 cores of the Upper Jurassic to Lower Cretaceous, completes the dinoflagellate cyst stratigraphy of the marine Jurassic in East Greenland. Together with previous studies of spores and pollen in less marine units, the first complete palynological Jurassic stratigraphy is thus established for the Jurassic succession in East Greenland.

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1 Introduction

Jurassic biostratigraphy is historically based mainly on macroscopic fossils, especially on ammonites but with significant contributions from other fossil groups. The Jurassic ammonite stratigraphy became the standard stratigraphical zonation, and the ammonite zones were applied as chronozones (e.g. Callomon 1984, 1993). Integration and correlation of microscopic fossil stratigraphy with ammonite stratigraphy developed and accelerated in the 1950s–1960s, following increasing demand of stratigraphical frameworks from expanding, worldwide industrial drilling programs primarily for offshore energy exploration. Studies of dinoflagellate cysts and their stratigraphical occurrences were established relatively early for the Jurassic in Europe but with somewhat slower progress in the northern Atlantic region. On Jameson Land, East Greenland (Fig. 1), Jurassic sedimentary samples for dinoflagellate cyst stratigraphy were collected systematically from beds with ammonites by Tove Birkelund in the 1970s and made accessible to students and industry palynologists.

On Ilimananngip Nunaa (Milne Land) in 1977, samples for palynological studies were collected mainly by this author, with contributions from members of the field team: T. Birkelund, John H. Callomon (ammonites), Claus Heinberg and Franz Fürsich (molluscs) and Lars Stemmerik (sedimentology). Successions at 52 localities were sedimentologically logged, collected for fossils and sampled for palynology, coordinated by three field teams. The studied localities were numbered 1–52 (Piasecki 1980, fig. 1; Birkelund & Callomon 1985, fig. 1).

Locality 39 east of Visdal on Milne Land (Fig. 1C) was measured in 1977, and a series of samples were marked by Birkelund & Callomon (1985, figs 1 and 3) and collected (Piasecki 1980, fig. 34). The succession belongs to the Kosmocerasdal, Aldinger Elv and Bays Elv Members of the Kap Leslie Formation (Fig. 2). Five faunal horizons of ammonites were identified and referred to the Milne Land ammonite faunal horizons M 12, M 13 and M 14 (Fig. 3; Callomon & Birkelund 1980; Birkelund & Callomon 1985). These faunas represent the Boreal faunal province (*Amoeboceras regulare* and *Amoeboceras rosenkrantzi* ammonite zones) and the Sub-Boreal province (*Pictonia baylei* ammonite Zone) of the upper Oxfordian to the lowermost Kimmeridgian (Fig. 3). Such a complete ammonite zonation has not been documented in any other exposure on Milne Land or Jameson Land, though faunal horizons M 13 and M 14 were tentatively identified in the fine-grained Hareelv Formation on Jameson Land (Callomon & Birkelund 1980, fig. 3).

Faunal horizons are not recorded in the lower part of the succession at locality 39 of Kosmocerasdal Member (Fig. 2). Comparison with other exposures in eastern Milne Land indicates that this part of Kosmocerasdal Member presumably correlates with the upper Oxfordian, uppermost *Amoeboceras glosense* – *Amoeboceras serratum* ammonite zones. Faunal horizon M 11, *A. serratum* ammonite Zone, is only recognised in coarse-grained, sandstone exposures of Aldinger Elv Member (Fürsich & Heinberg 1983), where no samples were collected for dinoflagellate cysts.

Locality 39 displays a condensed and continuous upper Oxfordian succession, well dated by ammonites, and is probably the only complete section in central East Greenland. The sediment is mostly fine-grained sandstone with concretions and little potential for palynological content. Nevertheless, dinoflagellate cyst assemblages have been recovered from all samples.

For this study, palynological sample materials from ammonite bearing beds and horizons were collected for direct comparison of palynology and ammonite stratigraphy in the Oxfordian from a composite section from Kosmocerasdal (locality 2), Nordøstelv (locality 3), 'Ilovaiskii' Dal (locality 4) and 'Hystrix' Dal (locality 5) – all below Aldinger Elv Member in the north-eastern exposures of Jurassic sediments on Milne Land (Figs 1 and 4). This composite succession is integrated with that of locality 39 and extends the Jurassic succession in East Greenland downwards into the existing dinoflagellate cyst stratigraphy of Smelror (1988).

2 Material and methods

All material was originally sampled in the field campaign of 1977 from the Kap Leslie Formation at localities 2–6 and 39 (locations in Fig. 1). The Kap Leslie Formation is dominated by conglomerates, sand and muddy sandstone. Only the Gråkløft Member of the Kap Leslie Formation comprises laminated dark mudstones (Figs 2 and 4).

The stratigraphical range chart presented here (Fig. 5) is a combination of two successions. The lower part is from localities 2–5 (shown at reduced scale in Fig. 5 and true scale in Fig. 4). The upper part is from locality 39 (illustrated at true scale in Fig. 5). The Bays Elv Member above the Aldinger Elv Member in Cardioceraskløft (locality 6) has no confidently identified ammonite faunal horizons but correlates with the upper succession of locality 39 (Fig. 4; Piasecki 1980; Birkelund & Callomon 1985). Stratigraphical events from the Cardioceraskløft succession (Fig. 4) are compared here with data from locality 39, to support the new palynological zone for the upper Oxfordian but are not included in the range chart in Fig. 5.

The ammonites were generally recovered in carbonate cemented sandstone beds or calcareous concretions and were subsequently referred to ammonite faunal horizons, M 1–M 15, by Callomon & Birkelund (1980; e.g. M 2 is the second faunal horizon on Milne Land). The faunal horizons are referred to ammonite zones (Fig. 3).

The ammonite stratigraphy applied here follows the East Greenland tradition (e.g. Sykes & Surlyk 1976; Callomon 1993) of combined Boreal and Sub-Boreal zonation (Fig. 3) and likewise the concept of considering ammonite zones as chronozones. Here, however, ammonite zones are consequently referred to as biozones. The basis of an ammonite zone is indicated at the lowermost occurrence of the index species in a faunal horizon, and the top of the zone is defined by the appearance of the next index species. Compared to earlier interpretations, the *Cardioceras densiplicatum* and *Cardioceras tenuiserratum* ammonite zones are consequently reduced slightly in thickness and sample density, whereas the thickness of *A. glosense* ammonite Zone is expanded.

The sample material was processed by standard methods. The crushed samples were prepared with acid (HCl, HF and HNO_3) to remove carbonate and silica (clay, silt and sand) from the samples. Organic matter is resistant to the acid, and the remains contained abundant terrestrial organic material, especially brown and black woody material. The separation method developed by Hansen & Gudmundsson (1979) was applied to the organic residue and successfully removed most of the abundant woody material and improved the recovery of identifiable dinoflagellate cysts significantly. The remaining organic residue was mounted in glycerine-gelatine on preparation glasses for visual analysis using a standard light microscope. Although the slides were prepared in the 1970s, most are

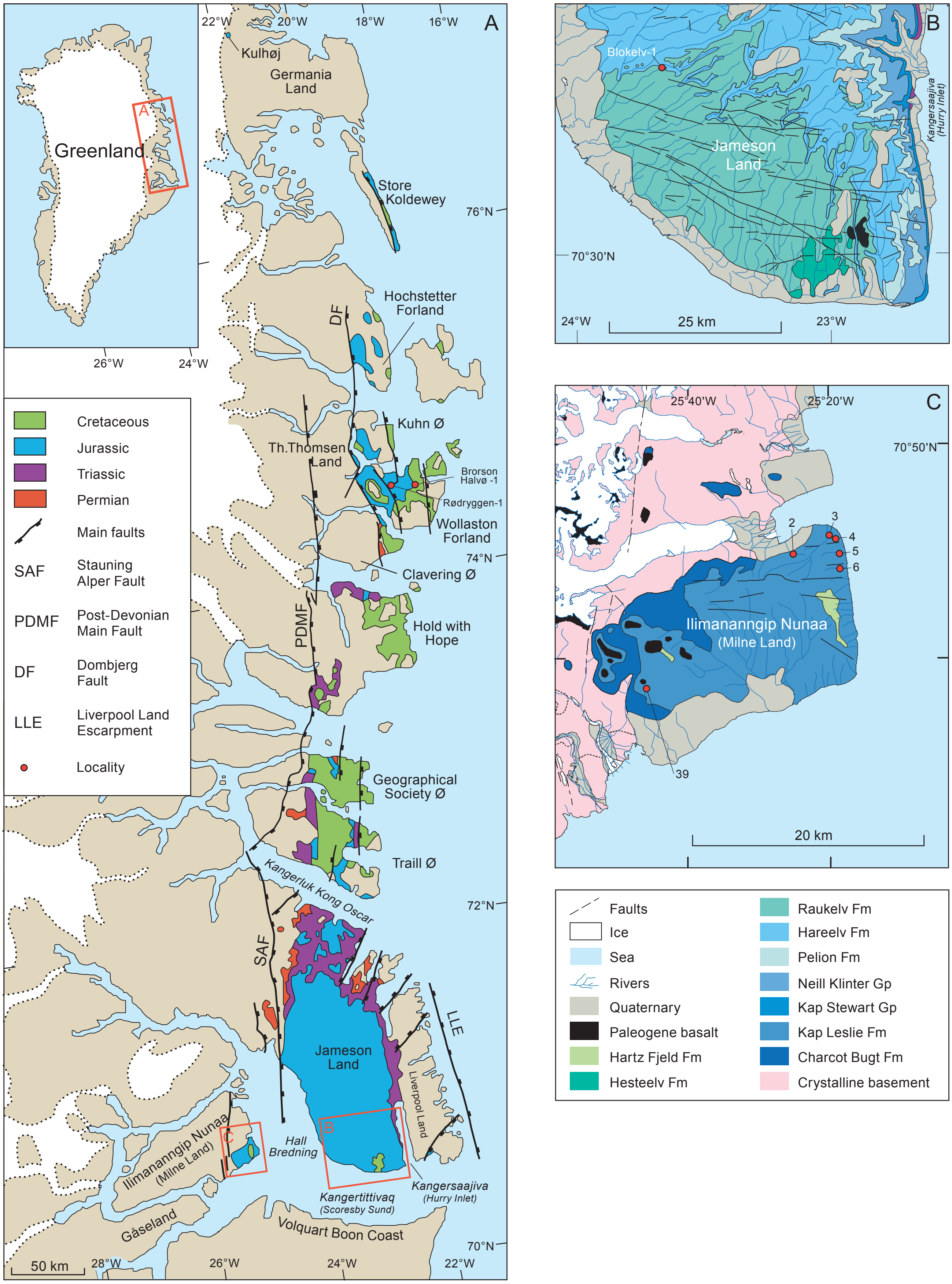

Fig. 1 Map of the study area. **A**: Geological map of East Greenland (modified from Surlyk *et al.* 2021) with locations of the Rødryggen-1 and Brorson Halvø-1 drilling sites. Inset: maps of localities analysed in this study. **B**: Jameson Land with Blokelv-1 core and **C**: Ilimananngip Nunaa (Milne Land) with localities M 2, 3, 4, 5, 6 and 39 (locality numbers *sensu* Birkelund *et al.* 1984).

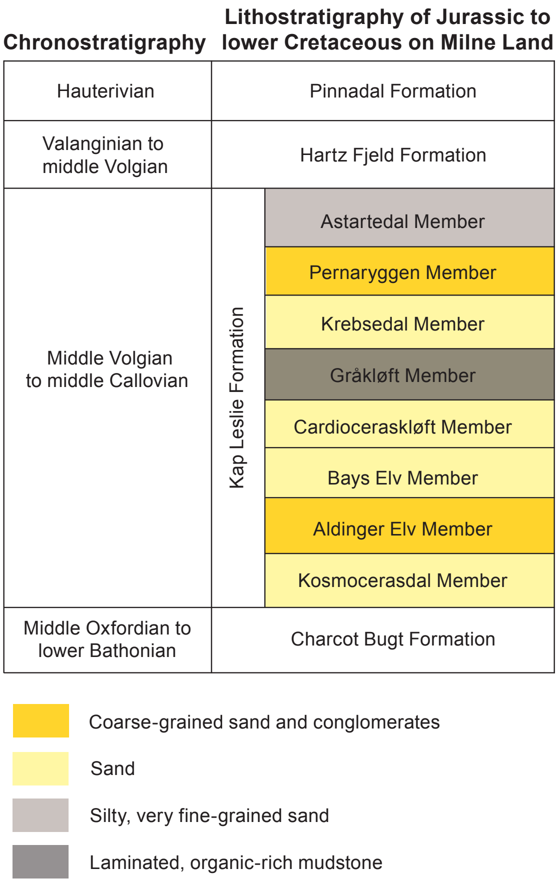

Fig. 2 Lithostratigraphical scheme of Jurassic to Lower Cretaceous sediments on Milne Land based on Callomon & Birkelund (1980), Birkelund & Callomon (1985), Birkelund *et al.* (1984) and Surlyk *et al*. (2021).

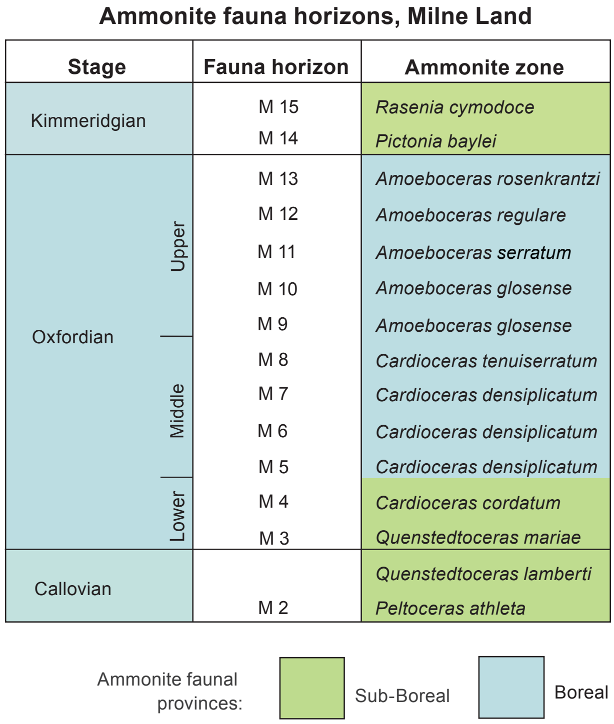

Fig. 3 Ammonite faunal horizons on Milne Land correlated with ammonite zones (Callomon & Birkelund 1980; Birkelund & Callomon 1985). Shading indicates the faunal province affiliations.

still perfectly preserved, and only a few had to be restored for the present study. The dinoflagellate cyst taxonomy follows Fensome *et al*. (2019) and Riding *et al*. (2022) with respect to the former *Gonyaulacysta jurassica* group.

2.1 History of dinoflagellate cyst stratigraphy in East Greenland

Overall, the Middle – Upper Jurassic, Boreal or Sub-Boreal ammonite stratigraphy in East Greenland is well documented on Milne Land (Callomon & Birkelund 1980; Birkelund *et al*. 1984; Birkelund & Callomon 1985), Jameson Land (Surlyk *et al*. 1973; Callomon *et al.* 2015) and in North-East Greenland (Sykes & Surlyk 1976). The studies mentioned in the following focus on Middle – Upper Jurassic dinoflagellate cysts from central East Greenland. The number of studies is limited, and only a few cover the middle – upper Oxfordian interval.

Samples collected from central Jameson Land by R.C. Whatley and D.C. Brown in 1964 were prepared in the laboratory of University of Nottingham, UK, but were subject to a fire in the laboratory. Only parts of two preparations survived and were analysed by W.A.S. Sarjeant (1972). But the value of these data suffers from uncertainties of their stratigraphical derivation. The age of the two samples was considered Bathonian to Callovian of the Vardekløft Formation, now Vardekløft Group (Surlyk *et al.* 2021). The samples were collected near the locality Langryggen in central Jameson Land, probably from within the lowermost Olympen Formation (Athene and Hades Members) to Fossilbjerget Formation interval (see Larsen & Surlyk 2003; Surlyk *et al.* 2021). The uppermost sample comprises *Endoscrinium luridum*, *Trichodinium scarburghense* and *Wanaea digitata* and several other species that are in accordance with a latest Callovian – earliest Oxfordian age of the *Quenstedtoceras lamberti – Quenstedtoceras mariae* ammonite zones. The age of the dinoflagellate cyst assemblage of the lower sample (*c*. 75 m lower in the section) is imprecise. The presence of *Gonyaulacysta eisenackii*, *Rhynchodiniopsis* (*Gonyaulacysta*) *cladophora* and *Pareodinia prolongata* as well as a more marine assemblage may indicate that the sample is from the uppermost Fossilbjerget Formation of Callovian age (see Surlyk *et al.* 2021).

A new acritarch genus (later referred to dinoflagellate cysts) *Mendicodinium* (*Thuledinium*) *groenlandicum* was described by Pocock & Sarjeant (1972) based on type material from Sarjeant's upper sample. The species is abundant in this sample, and it is known to have peak abundance in the *Q. lamberti* ammonite Zone (e.g. Smelror 1988), indicating that the sample is from this ammonite zone, and consequently that both of Sarjeant's samples are of Callovian age.

A geographically and stratigraphically wide suite of 27 Jurassic samples collected by T. Birkelund on Jameson

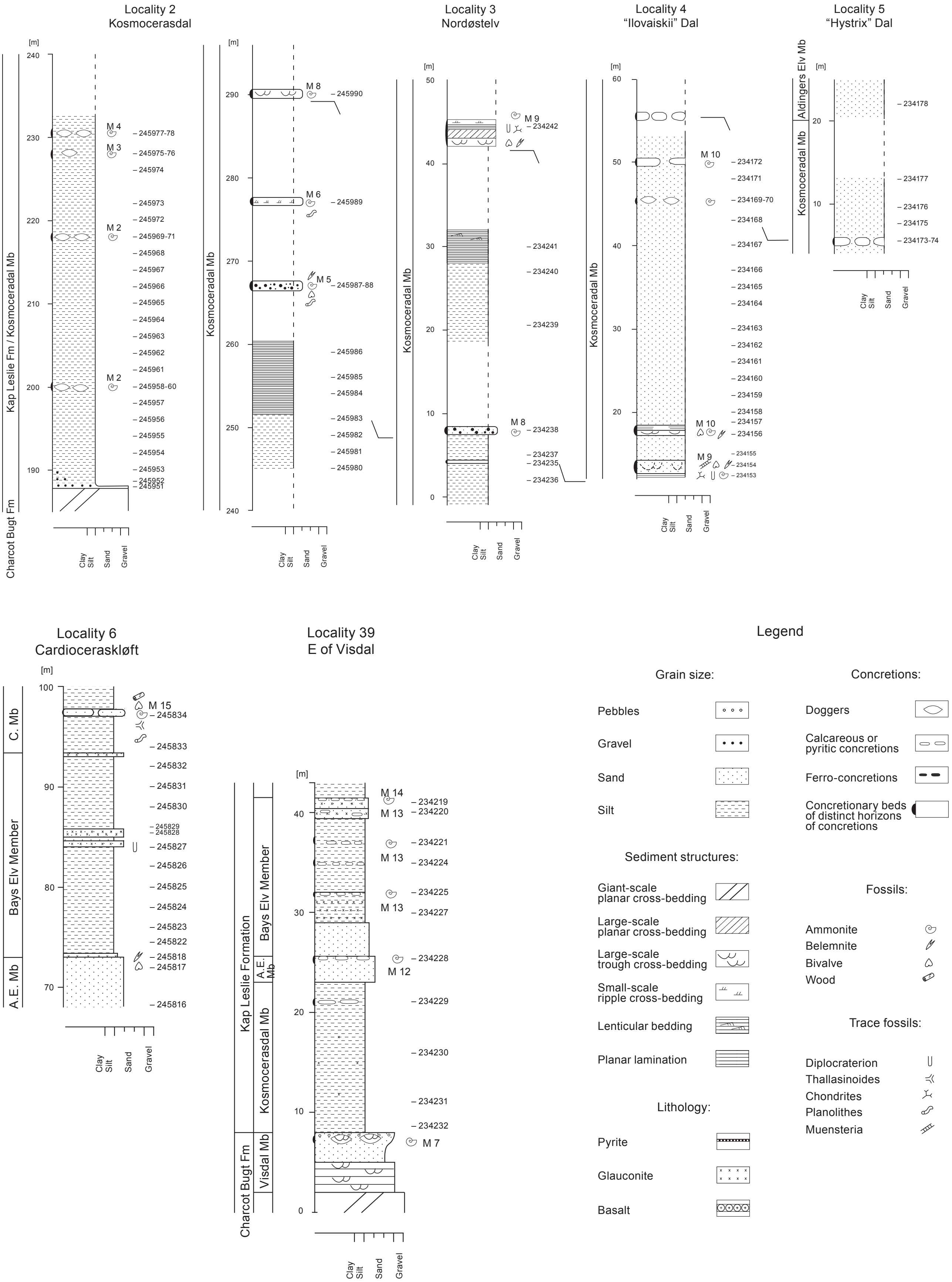

Fig. 4 Measured and sampled sedimentary successions from Milne Land with ammonite faunal horizons (e.g. M 14) and palynological samples (e.g. GGU245951) modified from Piasecki (1980). The locality numbers are from Piasecki (1980, fig.3) and Birkelund & Callomon (1985, fig. 2). The sedimentary succession from localities 2–5 shows the complete Kosmocerasdal Member, Kap Leslie Formation. Sedimentary logs from locality 6, Cardioceraskløft, and locality 39, east of Visdal, are correlated by the upper boundary of Aldinger Elv Member and the basis of Bays Elv Member.

Land were published by Fensome (1979). This comprehensive, taxonomic and excellent pioneering work in East Greenland included four samples presumed to be of upper Oxfordian – lower Kimmeridgian from southern and middle Jameson Land. These samples could be expected to overlap stratigraphically with the material from middle – upper Oxfordian to lowermost Kimmeridgian of the present study. However, the proposed age of three of these samples was not based on correlation with ammonite zonation but on their presumed lithostratigraphical affiliation to the Hareelv Formation. The presence of *Wanaea fimbriata*, *W. digitata*, *Rigaudella aemula* and *T. scarburghense* in these samples (Fensome 1979) suggests an earliest Oxfordian age. These samples are therefore stratigraphically comparable with the lower Olympen Formation, especially the dark shales of the Hades Member (see Larsen & Surlyk 2003; Surlyk *et al*. 2021). Two of the samples were collected close to Sarjeant's locality in central Jameson Land. The fourth sample was referred to the '?*decipia* ammonite zone, lower Kimmeridgian, but this zone is classed as upper Oxfordian in the stratigraphical scheme (Fensome 1979, Table 1 after Surlyk *et al.* 1973). The sample is assigned to the middle – upper Oxfordian based on the dinoflagellate cyst content, and the species are also common in the assemblages of the present study. Distinction of lower Oxfordian black shales of the Olympen Formation from the upper Oxfordian Hareelv Formation is problematic in the south to mid-Jameson Land Basin, where the shales are deposited successively. The two dark shale units cannot be distinguished lithologically from each other but only by biostratigraphy (Finn Surlyk, pers. comm. 2023).

Piasecki (1980) analysed dinoflagellate cysts from Callovian to Middle Volgian on Milne Land. The correlation of dinoflagellate cyst stratigraphy with ammonite zones is revised slightly herein for a few of these samples (Fig. 4). The results have been published in various reports and used for analysis of sections and core-drillings during fieldwork in East to North Greenland from 1982 to 2012 (e.g. the core-drillings Blokelv-1, Rødryggen-1 and Brorson Halvø-1; Alsen & Piasecki 2018; Bjerager *et al*. 2018; Alsen *et al.* 2023).

Poulsen (1985) analysed a high-resolution series of samples for dinoflagellate cysts across the boundary of the Fossilbjerget – Hareelv Formations at Ugleelv. The samples were collected by S. Piasecki, and scattered samples from the overlying Hareelv Formation were sampled by T. Birkelund and C. Heinberg in Ugleelv, Jameson Land. One ammonite faunal horizon M 9, *Amoeboceras ilovaiskii* Subzone, lower *A. glosense* ammonite Zone is correlated with the dinoflagellate cyst stratigraphy (faunal horizon J 49 on Jameson Land, Callomon 1993). As mentioned earlier, the lower black shales assigned to the Hareelv Formation should have been classified as the Olympen Formation (see also Callomon 1993, fig. 2).

Upper Bathonian to middle Oxfordian dinoflagellate cyst assemblages from Fossilbjerget and Olympen localities on Jameson Land and from Kosmocerasdal on Milne Land were reported by Smelror (1988) based on samples collected by T. Birkelund, J.H. Callomon and S. Piasecki. The samples were correlated with ammonite stratigraphy, and a dinoflagellate cyst zonation was established up to the middle Oxfordian, *C. densiplicatum* ammonite Zone at the last appearance of the dinoflagellate cyst *T. scarburghense*.

Gen. *et sp*. *Nidarocysta jubilaea* was described by Monteil (1966) from upper Oxfordian – lower Kimmeridgian core material in Norway and East Greenland. The East Greenland sample material is from Sjællandselv-3 core 303116 in Jameson Land (Bjerager *et al*. 2018).

In a study of stacked sandstone bodies from the Bathonian to uppermost Oxfordian on Milne Land and Jameson Land, Larsen *et al*. (2003) applied integrated ammonite and dinoflagellate cyst stratigraphy, the uppermost part of which overlaps with the present study.

Kelly *et al*. (2015) applied Jurassic biostratigraphy from North-West Europe to East Greenland without much documentation.

Alsen & Piasecki (2018) reported integrated ammonite and dinoflagellate cyst from the Jurassic Blokelv-1 core on Jameson Land dated to the Hareelv Formation. Relatively few stratigraphical events of dinoflagellate cysts were assigned to the upper Oxfordian – lowermost Kimmeridgian interval. Meanwhile, Alsen *et al.* (2023) reported integrated ammonite and dinoflagellate cyst stratigraphy in the Upper Jurassic – Lower Cretaceous cores of the Rødryggen-1 and Brorson Halvø-1 wells drilled in Wollaston Forland (locations in Fig. 1). However, these wells did not reach the Oxfordian – lowermost Kimmeridgian.

2.2 Biozonation

Palynological analysis of the middle to upper Oxfordian sedimentary succession on Milne Land, East Greenland, shows a relatively poor and low diversity dinoflagellate cyst assemblage (Fig. 5). However, the assemblage can be referred to the *G. jurassica* – *S. crystallinum* Zone (Gj/Sc) of North-West Europe (Woollam & Riding 1983; amended by Riding & Thomas 1988, 1992). The zone is defined from the last occurrence of *T. scarburghense* (formerly *Acanthaulax senta*) to the last occurrence of *S. crystallinum* and is correlated with the base of *C. tenuiserratum* ammonite Zone to the *P. baylei* ammonite Zone, middle Oxfordian to lowermost Kimmeridgian in North-West Europe.

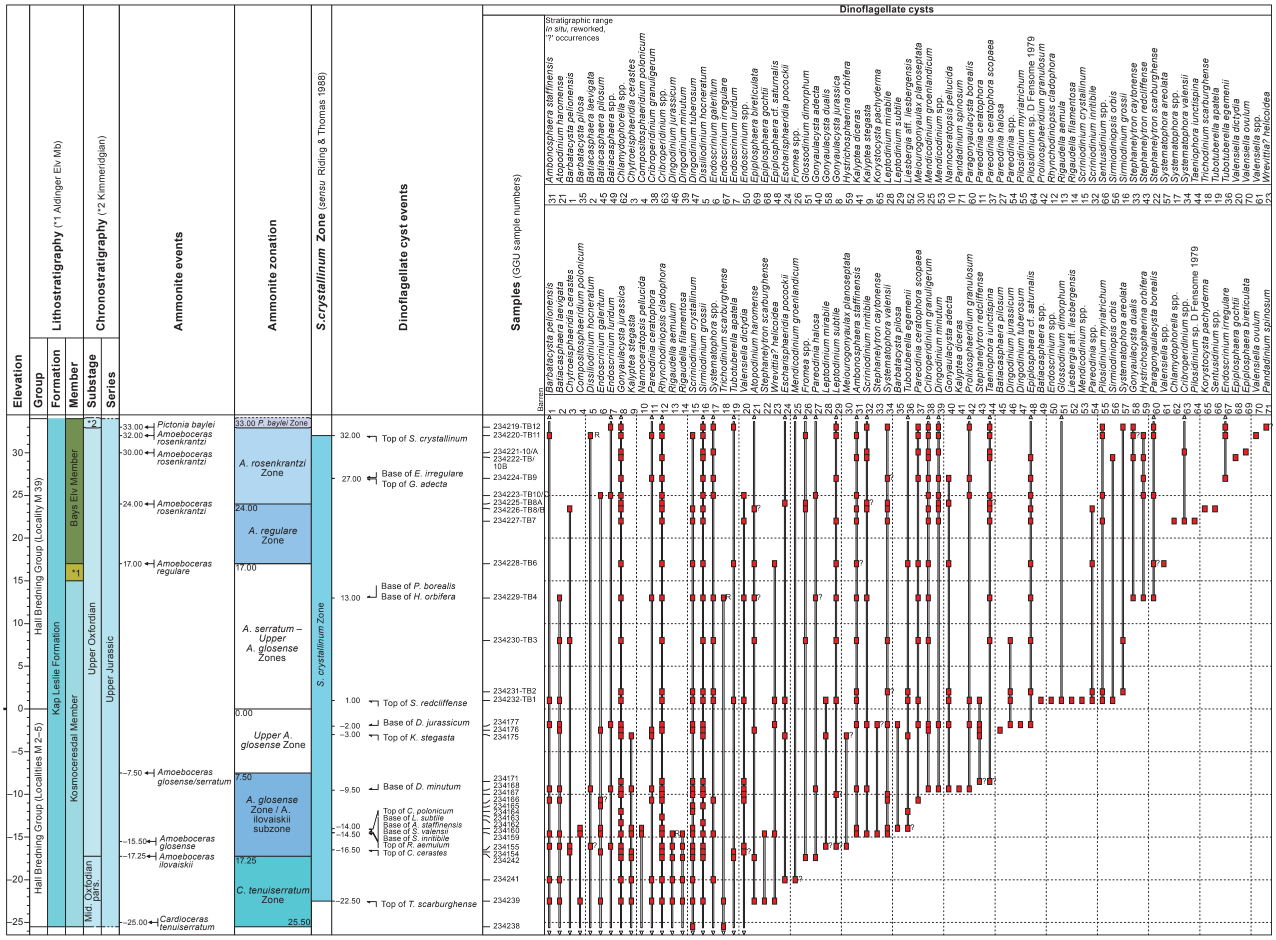

Fig. 5 Dinoflagellate cyst range-chart based on data from a composite succession of Kosmocerasdal Member to Bays Elv Member, Kap Leslie Formation. The range-chart is combined from successions at localities 2–5 and 39. To fit to the page, the composite succession of Kosmocerasdal Member is reduced 4 times in thickness and arranged from 0 to –25 m. The succession from locality 39 is shown to scale and spans 34 m from the basis of Kosmocerasdal Member to the top of Bays Elv Member. Abbreviations: **Mid.**: middle. ***1**: Aldinger Elv Mb. ***2**: Kimmeridgian. Dinoflagellate cyst names in Figs 5–7.

In East Greenland, the last occurrence of *T. scarburghense* is also recorded in the lower *C. tenuiserratum* ammonite Zone in Kosmoceras Dal, Milne Land, locality 2 (Piasecki 1980). The last occurrence of *S. crystallinum* is recorded in the top of *A. rosenkrantzi* ammonite Zone, locality 39, East of Visdal (Figs 2–4). The *S. crystallinum* Zone extends the zonation of Smelror (1988) to the base of the Kimmeridgian.

The zone name was simplified to *S. crystallinum* Zone (Riding & Thomas 1988), and both lower and upper boundaries were subsequently redefined based on other recorded events. The position of the last occurrence of *S. crystallinum* varies slightly in later reports (Riding & Thomas 1988, 1992, 1997) from *A. rosenkrantzi* ammonite Zone to *P. baylei* ammonite Zone followed by rare scattered, higher stratigraphic occurrences. The last occurrence of *S. crystallinum* in the *P. baylei* ammonite Zone is maintained by Poulsen & Riding (2003).

Woollam & Riding (1983) divided the zone into three subzones. The lower subzone 'a' is defined from the last occurrence of *T. scharburghense* to the last occurrence of *Compositosphaeridium polonicum* and is well recognised in East Greenland (Fig. 5). The two stratigraphically higher subzones 'b' and 'c' are not recognised within East Greenland stratigraphy. Poulsen & Riding (2003) applied five subzones, named DSJ23–27, to the *S. crystallinum* Zone, including part of the upper *T. scarburghense* Zone (where DSJ refers to dinoflagellate cysts, Sub-Boreal zonation and Jurassic). The five subzones are not readily recognised in East Greenland partly due to the absence or rarity of the most indicative species. Also, the uppermost subzone DSJ27 is not recognised in East Greenland due to the absence of *S. crystallinum* in the lowermost Kimmeridgian, *P. baylei* ammonite Zone (Figs 5 and 6). The dinoflagellate cyst assemblage in the *P. baylei* ammonite Zone is thus referred to the *E. luridum* Zone (Woollam & Riding 1983; Nøhr-Hansen 1986) although the nominate dinoflagellate cyst itself is not abundant in East Greenland (Fig. 6). In contrast, the middle Oxfordian to lowermost Kimmeridgian dinoflagellate cyst zone interval, named JZ32–JZ38 in the North Atlantic (where JZ refers to Jurassic Zone, *sensu* Bailey 2023), is based on

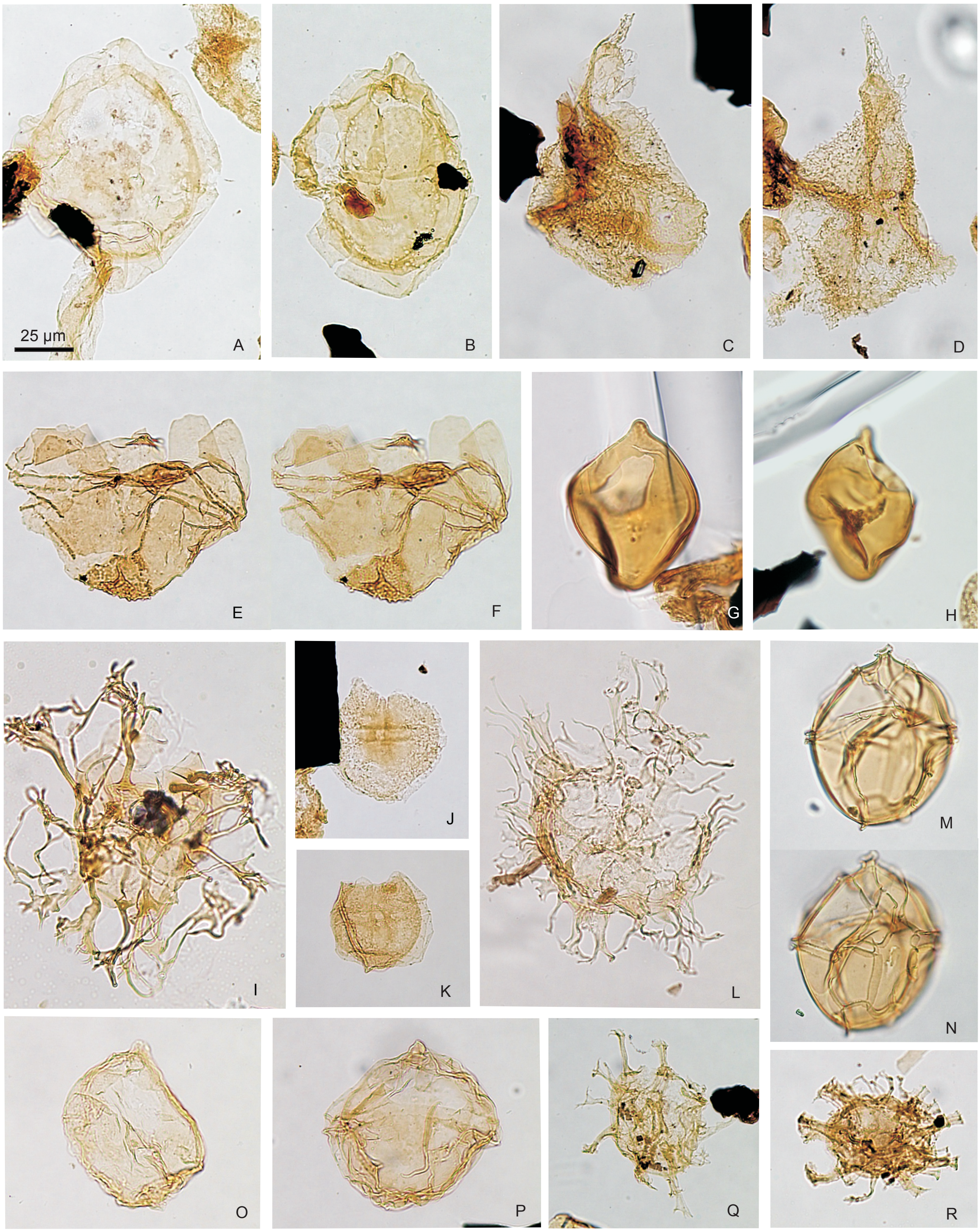

Fig. 6 Stratigraphically significant dinoflagellate cysts from the middle to upper Oxfordian *S. crystallinum* Zone in Milne Land, from locality 39, east of Visdal, and localities 2 (Kosmoceras Dal), 3 (Nordøstelv) and 4 ('Hystrix' Dal), eastern Milne Land (locations in Fig. 1). The illustrated specimens are referred to locality numbers, GGU sample number, slide number and England Finder coordinates. The illustrated specimens are marked with a red circle on the original slides. Magnification is x400 as indicated by a 25 µm scalebar in panel **A** that applies to all figures. **A**: *Scriniodinium crystallinum*, locality 39, sample GGU234229, slide 7, E.F. U35/2. **B**: *Scriniodinium crystallinum*, locality 39, sample GGU234229, slide 7, E.F. P25/2. **C**: *Trichodinium scarburghense*, locality 2, sample GGU234235, slide 4, E.F. K29/4. **D**: *Trichodinium scarburghense*, locality 2, sample GGU234235, slide 4, T34/3. **E**, **F**: *Atopodinium haromense*, high and low focus, locality 3,

Figure 6 continued on next page

Figure 6 continued

sample GGU234242, slide 8, P49/2. **G**: *Chytroeisphaeridia cerastes*, locality 2, sample GGU234155, slide 7, E.F. J26. **H**: *Chytroeisphaeridia cerastes*, locality 2, sample GGU234155, slide 7, E.F. K52/3. **I**: *Rigaudella aemula*, locality 2, sample GGU234240, slide 6, E.F. H51. **J**: *Ambonosphaera staffinensis*, locality 39, sample GGU234227, slide 7, E.F. O26. **K**: *Ambonosphaera staffinensis*, locality 39, sample GGU234223, slide 7, E.F. U53/2. **L**: *Systematophora valensii*, locality 39, sample GGU234230, slide 3, E.F. U48/1. **M**, **N**: *Leptodinium subtile*, high and low focus, locality 39, sample GGU234219, slide 3, P53/2. **O**: *Scriniodinium inritibile*, locality 39, sample GGU 234230, slide 7, E.F. R51. **P**: *Scriniodinium inritibile*, locality 39, sample GGU234220, slide 7, E.F. N28/1. **Q**: *Compositosphaeridium polonicum*, locality 4, sample GGU234159, slide 8, E.F. K36/3. **R**: *Compositosphaeridium polonicum*, locality 2, sample GGU234239, slide 4, E.F. H46/m4.

events with good correlation to events in the *S. crystallinum* Zone in East Greenland. Some events are based on informally identified species that are not identified in East Greenland.

The Jurassic dinoflagellate cyst stratigraphy of the circum Arctic region (Bujak *et al.* 2022) adopted the stratigraphy for lower Oxfordian of East Greenland of Smelror (1988) and reported no data for the middle and upper Oxfordian. To preserve a clear and practical definition of the *S. crystallinum* Zone in East Greenland, the older definition of the zonal boundaries (Woollam & Riding 1983) is maintained here. This also provides a simple extension of the preceeding dinoflagellate biostratigraphy of Smelror (1988; Fig. 6).

Dinoflagellate cyst events of the *S. crystallinum* Zone were recognised in two other Milne Land localities in the northern Visdal region (Larsen *et al.* 2003, their fig. 1, localities 5, 8 and 12) but were not discussed further in that study. The *S. crystallinum* Zone is also recognisable in the Blokelv-1 core on Jameson Land based on the last occurrence of *T. scarburghense* to the last occurrence of *S. crystallinum* (Alsen & Piasecki 2018, fig. 8). The upper part of the zone is also identified in the eastern slope of Tværdal, Geographical Society Ø, in a sandy succession, which is now correlated with the *A. regulare – A. rosenkrantzi* ammonite zones (Surlyk *et al.* 2023). The *S. crystallinum* Zone is commonly recognised in the Oxfordian in both published (Piasecki *et al.* 2004; Piasecki & Stemmerik 2004) and unpublished materials from the Hold with Hope and Wollaston Forland regions but becomes uncertain in more northerly successions from Store Koldewey to Peary Land, North Greenland (S. Piasecki, unpublished data).

Smelror (2021) analysed palynological material from three boreholes in the Ramså Basin, Andøya, Norway. Part of the upper Bonteigen Member, Ramså Formation, is referred to the *P. baylei* Chronozone, lowermost Kimmeridgian, based on dinoflagellate cysts. No Oxfordian succession is recorded below this. Several dinoflagellate cyst species in the three lowermost sedimentary samples range from the upper Oxfordian into the lowermost Kimmeridgian in East Greenland. However, correlated with data in the present paper, the presence of *Dingodinium minutum* supports Smelror's stratigraphical interpretation of these strata as lowermost Kimmeridgian, as this species occurs no higher than the *P. baylei* ammonite Zone in East Greenland.

3 Results

The dinoflagellate cyst assemblage is relatively poor or limited in all samples from the succession at localities 2–5 and 39 (Fig. 4). This is partly due to low organic content in the sandy lithology, but, in general, reflects the low abundance and diversity in most of the mid- to upper Oxfordian interval in East Greenland. A typical succession commonly contains at least some samples with a few common species. In decreasing abundance, these are *G. jurassica*, *R. cladophora*, *Sirmiodinium grossii*, *Systematophora* spp., *Taeniophora iunctispina* and *Cribroperidinium* spp.

Ten stratigraphical units based on dinoflagellate cyst events within the *S. crystallinum* Zone on Milne Land are identified in the dinoflagellate cyst range chart (Fig. 5). Here, the focus is on describing correlative events instead of defining subzones that become less useful north and south of the Jameson Land Basin. Specimens mentioned in the following are illustrated in Figs 6 and 7.

The lowest occurrence of the index species of the *S. crystallinum* Zone (Fig. 6A–B) occurs far below the zone itself. It is recorded in the *Peltoceras athleta* ammonite Zone, upper Callovian, in Kosmocerasdal (locality 2, Piasecki 1980) as well as in the *P. athleta* ammonite zone in North-West Europe (Riding & Thomas 1992).

The highest occurrence of *T. scarburghense* (Figs 5 and 6C–D) defines the lower boundary of the *S. crystallinum* Zone in the lower *C. tenuiserratum* ammonite Zone, in Kosmocerasdal (locality 2, Piasecki 1980). The lowest occurrences of *Glossodinium dimorphum* and *Scriniodinium inritibile* were implemented by Poulsen & Riding (2003) into the definition of the basal boundary of the *S. crystallinum* Zone as lower than the highest occurrence of *T. scarburghense* in North-West Europe. However, *G. dimorphum* is very rare, and like *S. inritibile*, it appears in the *A. glosense* ammonite Zone in East Greenland. *Atopodinium haromense* (Fig. 6E–F) with vague morphological characteristics occurs rarely in the lowermost *S. crystallinum*

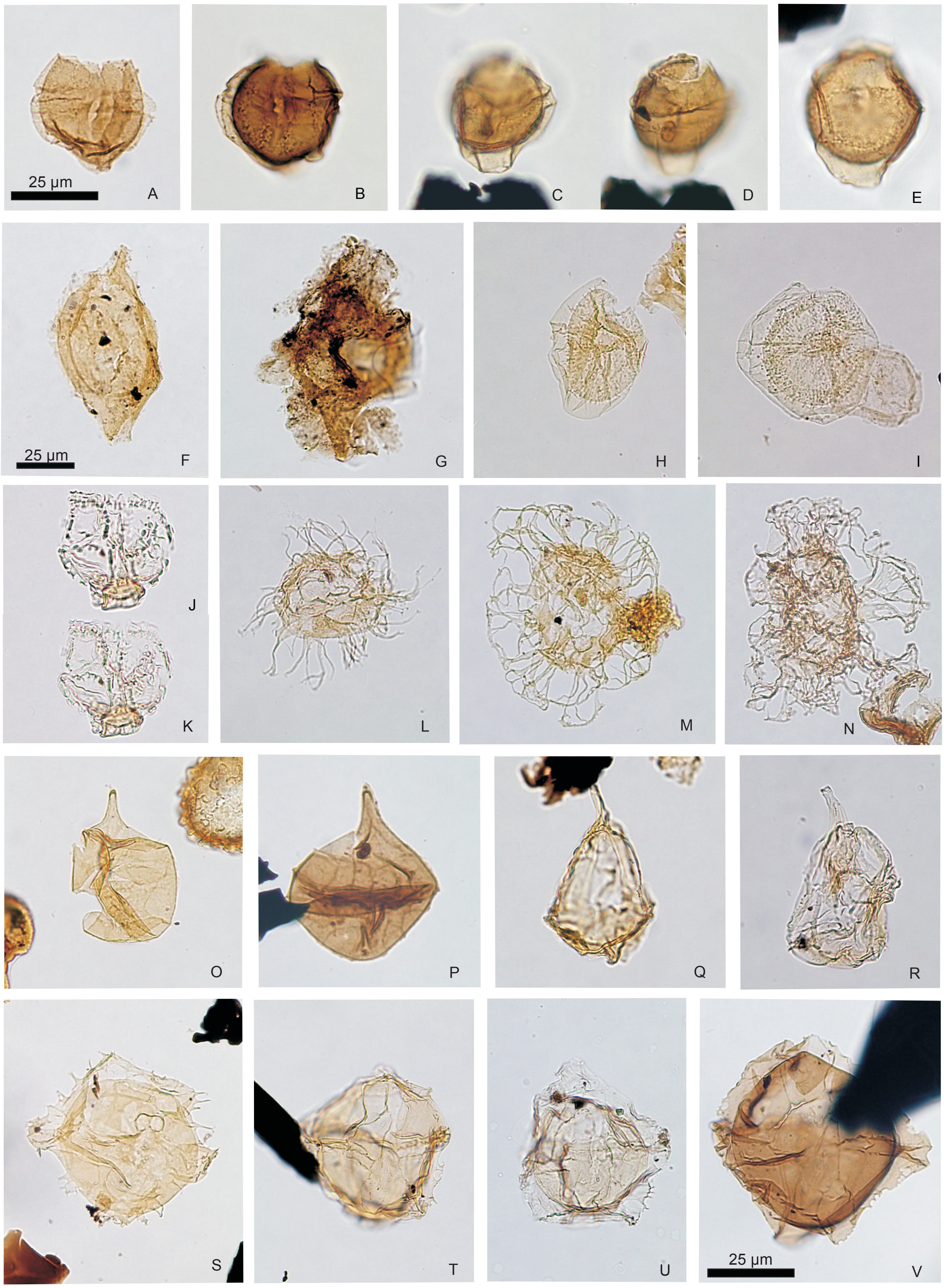

Fig. 7 Stratigraphically significant dinoflagellate cysts from the middle to upper Oxfordian in Milne Land from locality 39, Kosmoceras Dal, east of Visdal, and localities 2 and 6, Cardioceraskløft, in eastern Milne Land (locations in Fig. 1). The illustrated specimens are referred to locality numbers, GGU

Figure 7 continued on next page

Figure 7 continued

sample numbers, slide number and England Finder coordinates. The illustrated specimens are marked with a red circle on the original slide. **A**: *Dingodinium minutum*, locality 6, sample GGU245827, slide 8, E.F. G32/2. Magnified x600. **B**: *Dingodinium minutum*, locality 6, sample GGU245828, slide 8, E.F. S53/3. Magnified x600. Scale in A. **C**, **D**: *Dingodinium minutum*, high and low focus, locality 6, sample GGU245830, slide 9, E.F. J47. Magnified x600. Scale in A. **E**: *Dingodinium minutum*, locality 6, sample GGU245830, slide 9, E.F. H29. Magnified x600. Scale in A. **F**: *Kalyptea stegasta*, locality 2, sample GGU234159, slide 8, E.F. T27/4. Magnified x400. **G**: *Kalyptea stegasta*, locality 2, sample GGU234239, slide 4, E.F. G34. Magnified x400. Scale in F. **H**: *Dingodinium jurassicum*, locality 39, sample GGU234231, slide 9, U37/2. Magnified x400. Scale in F. **I**: *Dingodinium tuberosum*, locality 39, sample GGU234231, slide 6, G23/3. Magnified x400. Scale in F. **J**, **K**: *Stephanelytron redcliffense*, high and low focus, locality 39, sample GGU234232, slide 3, E.F. M27/1. Magnified x400. Scale in F. **L**: *Systematophora areolata*, locality 39, sample GGU234230, slide 3, E.F. V37/1. Magnified x400. Scale in F. **M**: *Hystrichosphaerina orbifera*, locality 39, sample GGU234221, slide 3, E.F. O49/2. Magnified x400. Scale in F. **N**: *Hystrichosphaerina orbifera*, locality 39, sample GGU234220, slide 3, E.F. N45/2. Magnified x400. Scale in F. **O**: *Paragonyaulacysta borealis*, locality 39, sample GGU234223, slide 6, E.F. O39/3. Magnified x400. Scale in F. **P**: *Paragonyaulacysta borealis*, locality 6, sample GGU245827, slide 8, E.F. R32/3-S32/1. Magnified x400. Scale in F. **Q**: *Gonyaulacysta adecta*, locality 39, sample GGU234228, slide 10, E.F. J48/2. Magnified x400. Scale in F. **R**: *Gonyaulacysta adecta*, locality 39, sample GGU234232, slide 3, E.F. P23. Magnified x400. Scale in F. **S**: *Endoscrinium irregulare*, locality 39, sample GGU234224, slide 7, E.F. T28/3–4. Magnified x400. Scale in F. **T**: *Endoscrinium irregulare*, locality 39, sample GGU234220, slide 7, E.F. S48. Magnified x400. Scale in F. **U**: *Endoscrinium irregulare*, locality 39, sample GGU234220, slide 6, E.F. N45.4. Magnified x400. Scale in F. **V**: *Endoscrinium irregulare*, locality 6, sample GGU245827, slide 8, E.F. W35. Magnified x600.

Zone but becomes more morphologically characteristic upwards. Smelror (1988) refers the Oxfordian *Atopodinium* species with no *Atopodinium prostatum* characters to morphological variation of an *A. prostatum*-complex, whereas Riding & Thomas (1997) record *A. haromense* from the basal middle Oxfordian and upwards.

Chytroeisphaeridia cerastes (Fig. 6G–H) occurs with certainty up to the lower *A. glosense* ammonite Zone and the *A. ilovaiskii* Subzone. Morphologically similar specimens occur higher in the succession but both their small size and uncertain archaeopyle type suggest another classification for those specimens.

Rigaudella aemula (Fig. 6I) commonly occurs up to the lower *A. glosense* ammonite Zone and *A. ilovaiskii* Subzone. *Leptodinium subtile* (Fig. 6M–N) and *Leptodinium mirabile* appear contemporaneously in this horizon, but only *L. subtile* occurs regularly in higher strata. *Ambonosphaera staffinensis* (Fig. 6J–K), *S. inritibile* (Fig. 6O–P) and *Systematophora valensii* (Fig. 6L) appear from this horizon and continue above the *S. crystallinum* Zone.

Compositosphaeridium polonicum (Fig. 6Q–R) occurs consistently but not commonly, with a highest occurrence in the lower *A. glosense* ammonite Zone and *A. ilovaiskii* Subzone.

The lowermost occurrence of *D. minutum* (Fig. 7A–E) appears in *A. glosense* ammonite Zone and *A. ilovaiskii* Subzone. Specimens of *D. minutum* may represent morphological variants of *A. staffinensis* (Fig. 6J–K) since specimens occur with apparent transitional morphology. However, *D. minutum* has a prominent tabulation, an antapical keel with a vertical antapical plate on the ventral side and a prominent flagellar scar in the mid-sulcal area. *D. minutum* was previously informally recorded as *A*. '*utera*' by Piasecki (1980).

Kalyptea stegasta (Fig. 7F–G) is common and has a clear uppermost occurrence in the upper *A. glosense* ammonite Zone. It is recorded higher neither in the *S. crystallinum* Zone nor above, but it is recorded to the top of the lower Volgian in North-West Europe (Riding & Thomas 1992).

Dingodinium jurassicum (Fig. 7H) is present in the uppermost sample from the *A. glosense* ammonite Zone of Kosmocerasdal Member and the three lowermost samples of locality 39 in the upper *A. glosense/A. serratum* ammonite Zone. The short range of this species apparently forms a stratigraphically narrow and locally useful occurrence. A few instances of *Dingodinium tuberosum* (Fig. 7I) are also recorded in the lowermost level with *D. jurassicum*. This deviates from North-West Europe, where the first occurrences of *D. jurassicum* and *D. tuberosum* are recorded at stratigraphically different levels: lower and higher, respectively (e.g. Riding & Thomas 1992; Poulsen 1996). The sculpture of the endophragm and the overall shape and morphology of *D. jurassicum* are quite different from *D. tuberosum* (Fig. 7H–I).

Hystrichosphaerina orbifera (Fig. 7L) appears in the upper *A. glosense/A. serratum* ammonite zones. Chorate cysts are rare in most samples and mostly too crushed or degraded for reliable identification. In comparison, the characteristic process complexes of *H. orbifera* make it an identifiable species. *Paragonyaulacysta borealis* (Fig. 7O–P) also appears in this sample. In East Greenland, *P. borealis* is obviously tabulated but with vague parasutures. Hence, specimens are mostly identified on the basis of overall size, shape, surface sculpture of the autophragm and the apicular structure in comparison with more distinct tabulated specimens in North-East and North Greenland.

Gonyaulacysta adecta (Fig. 7Q–R) occurs highest in the *A. rosenkrantzi* ammonite Zone. *G. adecta* is basically a *G. jurassica* but lacking a hypocoel. All morphological structure on *G. jurassica* varies radically possibly in response to environmental or climatic conditions. *Endoscrinium irregulare* (Fig. 7S–V) appears in the same sample level. *E. irregulare* is not considered stratigraphically significant, but it has a significant morphology and a clear first occurrence in the *A. rosenkrantzi* ammonite Zone.

Scriniodinium crystallinum (Fig. 6A–B) has its highest occurrence in the top of the *A. rosenkrantzi* ammonite

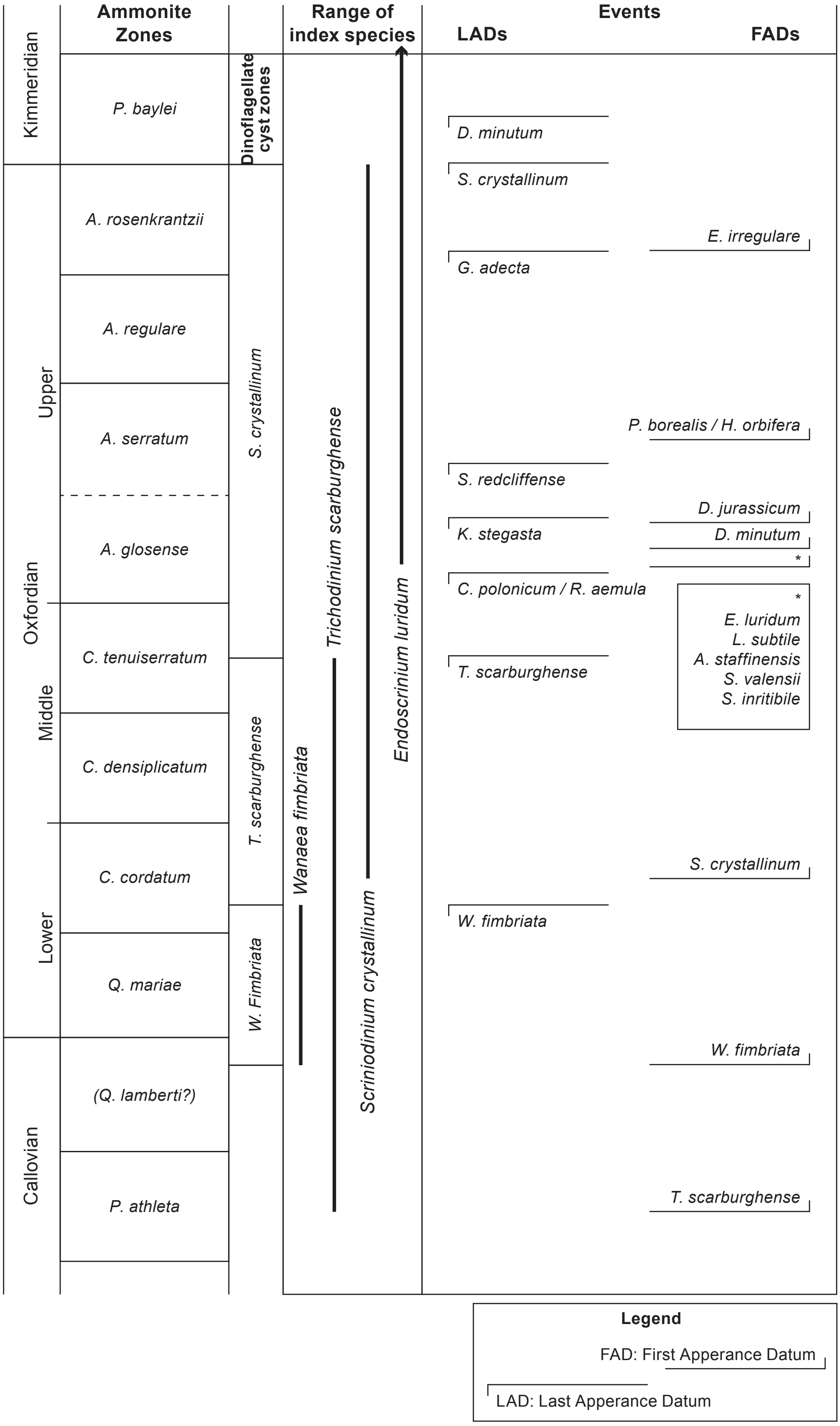

Fig. 8 Schematic correlation of the Oxfordian ammonite zones, dinoflagellate cyst zones and events on Milne Land, East Greenland.

Zone at locality 39. Rare specimens have been recorded much higher in the succession at other localities, but they are considered to have been reworked or are possibly misinterpretations.

Dingodinium minutum (Fig. 7A–E) occurs highest into the *P. baylei* ammonite Zone, lowermost Kimmeridgian. This is higher than the *S. crystallinum* Zone and the lowermost *E. luridum* Zone.

4 Discussion

The *S. crystallinum* Zone appears to be a useful identifier of middle to upper Oxfordian strata in East Greenland based on palynological analyses (Fig. 8). Seventeen dinoflagellate cyst events characterise the lower and upper boundaries and subdivide the zone into 10 units. The dinoflagellate cyst zone correlates with five succeeding ammonite zones, from lowermost to uppermost: the *C. tenuiserratum*, *A. glosense*, *A. serratum*, *A. regulare* and *A. rosenkrantzi* zones. The stratigraphical positions of both base and top of the *S. crystallinum* Zone in the study area deviate slightly from the corresponding zone in North-West Europe, but this may reflect the limited amount or spacing of samples studied in East Greenland. Barski (2018) shows that common *S. crystallinum* reaches into the lower *P. Baylei* ammonite Zone on the Isle of Skye, Scotland. However, other dinoflagellate cyst studies in North-West Europe show different stratigraphical ranges to East Greenland, such as *Perisseiasphaeridium pannosum* and *Senoniasphaera jurassica*. Most of the events in North-West Europe applied for stratigraphical subdivision of zones into subzones do not appear at the same stratigraphical levels in East Greenland.

The lowermost appearance of *T. scarburghense* is between two faunal horizons of M 2 in Kosmocerasdal and is referred to the *P. athleta* ammonite Zone (Fig. 4). The lower boundary of the *W. fimbriata* Zone (Smelror 1988) was defined by the first occurrence of *W. fimbriata* below faunal horizon M 3, *Q. mariae* ammonite Zone. The assumed *Q. lamberti* ammonite Zone beneath faunal horizon M 3 is not recorded in the Kosmocerasdal succession (locality 2), but the lower boundary of the *W. fimbriata* Zone is still hypothetically referred to this ammonite zone marked by (?) in Fig. 8.

The lower boundary of the *T. scarburghense* Zone (Smelror 1988) was defined by the highest occurrence of *W. fimbriata*, now referred to the lower *Cardioceras cordatum* ammonite Zone (Fig. 8).

The lower boundary of the *S. crystallinum* Zone in East Greenland coincides with the highest occurrence of *T. scarburghense* Zone (Smelror 1988) defined by the highest occurrence of *T. scarburghense* in the *C. tenuiserratum* ammonite Zone (Fig. 8). The upper zonal boundary is in the uppermost *A. rosenkrantzi* ammonite Zone and not the *P. baylei* ammonite Zone as in North-West Europe.

Some recorded species may have a slightly problematic taxonomic affinity due to vaguely expressed morphological characters or bad preservation. *Paragonyaulacysta borealis* has very discrete tabulation on Milne Land, but it is recorded consistently from Jameson Land towards the north along East and North-East Greenland to North Greenland (Håkansson *et al*. 1981). *A. staffinensis* and *D. minutum* appear to have transitional morphologies, and the distinction between the two may be uncertain in some cases. Some *C. cerastes*-shaped specimens have been excluded here due to their small size and incomplete archaeopyles, and many *Systematophora*-like specimens cannot be identified to species level due to fragmentation, folding or bad preservation. *Epiplosphaera saturnalis* is not typically recorded here, but the reduced surface sculptural elements on *E.* cf. *saturnalis* are similar to the elements of the holotype (Brideaux & Fisher 1976; plate 6, figs 1–7 and plate 7, fig. 10). Comparable specimens have been recorded from Milne Land to North Greenland as *Lanterna saturnalis* (Håkansson *et al.* 1981).

5 Conclusions

In this study, the history of Oxfordian dinoflagellate cyst stratigraphy in East Greenland is summarised and updated. The dinoflagellate cysts stratigraphy of the marine deposited, Middle to Upper Jurassic succession is documented and correlated with ammonite stratigraphy.

It is found that the *S. crystallinum* Zone from North-West Europe is applicable in East Greenland in its original definition. However, the later associated stratigraphical markers for both the lower and upper boundary are not directly applicable in East Greenland. The subdivision of five subzones in North-West Europe is mostly based on species that are rare or absent in the East Greenland, including the first and last subzones (DJS23 and -27), which are not included in the *S. crystallinum* Zone in East Greenland.

Fifteen events are suggested to subdivide the *S. crystallinum* zone into 10 units by characteristic and common species in East Greenland. The zonal boundaries and the stratigraphic events are directly integrated with the ammonite stratigraphy.

The *S. crystallinum* Zone is applicable in the Jurassic sedimentary basins of East and North-East Greenland and may be applicable in parts of the North Atlantic region.

With this contribution to the Jurassic biostratigraphy in East Greenland and together with the Upper Jurassic biostratigraphy of two previously drilled cores Rødryggen-1 and Brorson Halvø-1, the whole Jurassic succession in East Greenland has now been palynologically analysed based on spores and pollen or dinoflagellate cysts.

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The author declares no competing interests.

Author contributions

SP: Conceptualisation; Investigation; Visualisation; Writing – original draft; Writing – review and editing.

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