

Palynostratigraphy and palaeoenvironment of the Middle Jurassic Sortehat Formation (Neill Klintner Group), Jameson Land, East Greenland

Eva B. Koppelhus and Carina F. Hansen

The grey–black mudstones of the Sortehat Formation form part of the Middle Jurassic fill of the Jameson Land Basin in East Greenland. The formation is exposed in the southernmost part of the north–south-trending, Mesozoic rift system in East Greenland that was part of the epeiric sea-way between East Greenland and Norway. Sedimentological observations of the Sortehat Formation indicate deposition in an offshore marine setting that was typically low energy and periodically oxygen-deficient but was influenced by storm currents on occasion. Detailed palynological studies of the Sortehat Formation have resulted in the definition of three palynological assemblage zones recognised at four localities, namely Enhjørningen Dal and Pelion (north Jameson Land), the type section at Sortehat (central Jameson Land) and Albuen at Neill Klintner along Hurry Inlet (south-east Jameson Land). In stratigraphic order, these zones are termed the *Botryococcus* Assemblage Zone, the *Nannoceratopsis gracilis*–*Nannoceratopsis senex* Assemblage Zone, and the *Sentusidinium pelionense* Assemblage Zone. They are recognised on the basis of the identification of approximately 110 species of palynomorphs, including 45 species of spores, 30 of pollen, 22 of dinoflagellate cysts, 10 acritarch species, two species of algae, and some fungal spores. An Aalenian – ?Early Bajocian age is suggested for the Sortehat Formation on the basis of the palynoflora.

Interpretation of the palynomorph assemblages suggests that the formation accumulated in a shallow, brackish marine environment. A significant terrestrial input, including the freshwater green alga *Botryococcus*, is recorded in the lower part of the formation and interpreted as an allochthonous accumulation in an offshore marine environment related to transgression of a low-lying coastal plain. A marked shift in the palynomorph assemblage seen by diversification of marine microplankton above the base of the formation, indicates an increase in the marine signal probably related to the onset of highstand conditions following the marine transgression.

Keywords: East Greenland, Jameson Land Basin, Middle Jurassic, Aalenian – ?Early Bajocian, palynostratigraphy, sedimentology, palaeoenvironment, transgressive–highstand mudstones, allochthonous *Botryococcus* assemblage

E.B.K., *Geological Survey of Denmark and Greenland, Geocenter Copenhagen, Øster Voldgade 10, DK-1350 Copenhagen K, Denmark.* Present address: *Royal Tyrrell Museum of Palaeontology, Box 7500, Drumbeller TOJ 0Y0, Alberta, Canada.* E-mail: *evakoppelhus@hotmail.com*

C.F.H., *Geological Institute, University of Copenhagen, Geocenter Copenhagen, Øster Voldgade 10, DK-1350 Copenhagen K, Denmark.* Present address: *Skovbøgn 4, DK-3460 Birkerød, Denmark.*

The Middle Jurassic Sortehat Formation of the East Greenland rift basin is a distinctive and laterally persistent mudstone-dominated succession sandwiched

between the sandstone-dominated Ostreaelv Formation beneath and the sandstones of the Pelion Formation above (Figs 1, 2). The stratigraphic terminology adapted

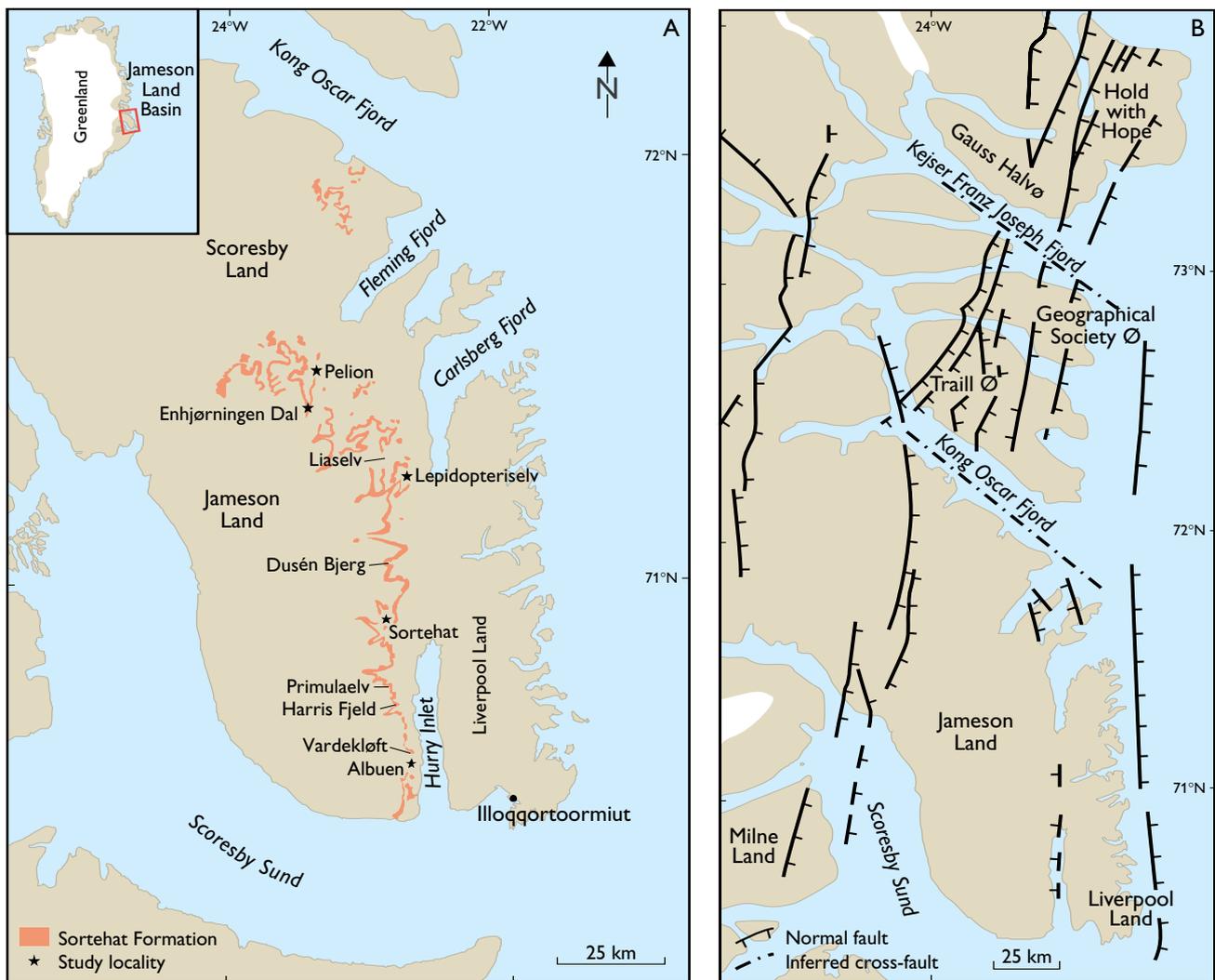


Fig. 1. **A:** Map showing the outcrop of the Sortehat Formation in the Jameson Land Basin; the outcrop pattern is aligned roughly north–south, parallel to the basin axis. **B:** Structural outline of the southern part of the East Greenland rift basin. The Jameson Land Basin was bounded by faults to the east, west and north, and by the Liverpool Land high towards the east. The nature of the southern boundary is unknown. The structural setting suggests an elongate semi-enclosed basin during deposition of the Sortehat Formation. Modified from Engkilde & Surlyk (1993).

in this paper follows the revised scheme of Dam & Surlyk (1998). Although the biostratigraphy and sequence stratigraphy of the sandy formations have been the subject of considerable study in recent years (Engkilde & Surlyk 1993; Engkilde 1994; Dam & Surlyk 1995; Engkilde & Surlyk 2003, this volume; Koppelhus & Dam 2003, this volume), the precise age, the nature of the boundaries and the depositional history of the Sortehat Formation remain poorly understood. The aim of this paper, therefore, is to present the results of a detailed palynological study of these strata that was undertaken in close co-operation with a sedimentological and sequence stratigraphic study (Hansen 1999). In partic-

ular, this paper focuses on establishing the age of the Sortehat Formation, elucidation of the stratigraphic significance of the formation boundaries and contributing to an understanding of the depositional history of the Sortehat Formation.

Regional setting and stratigraphy

The Middle Jurassic Sortehat Formation is exposed in the Jameson Land Basin in the southernmost part of the north–south-trending, failed-rift system in East Greenland (Fig. 1). Rifting was initiated in the late Palaeozoic, and

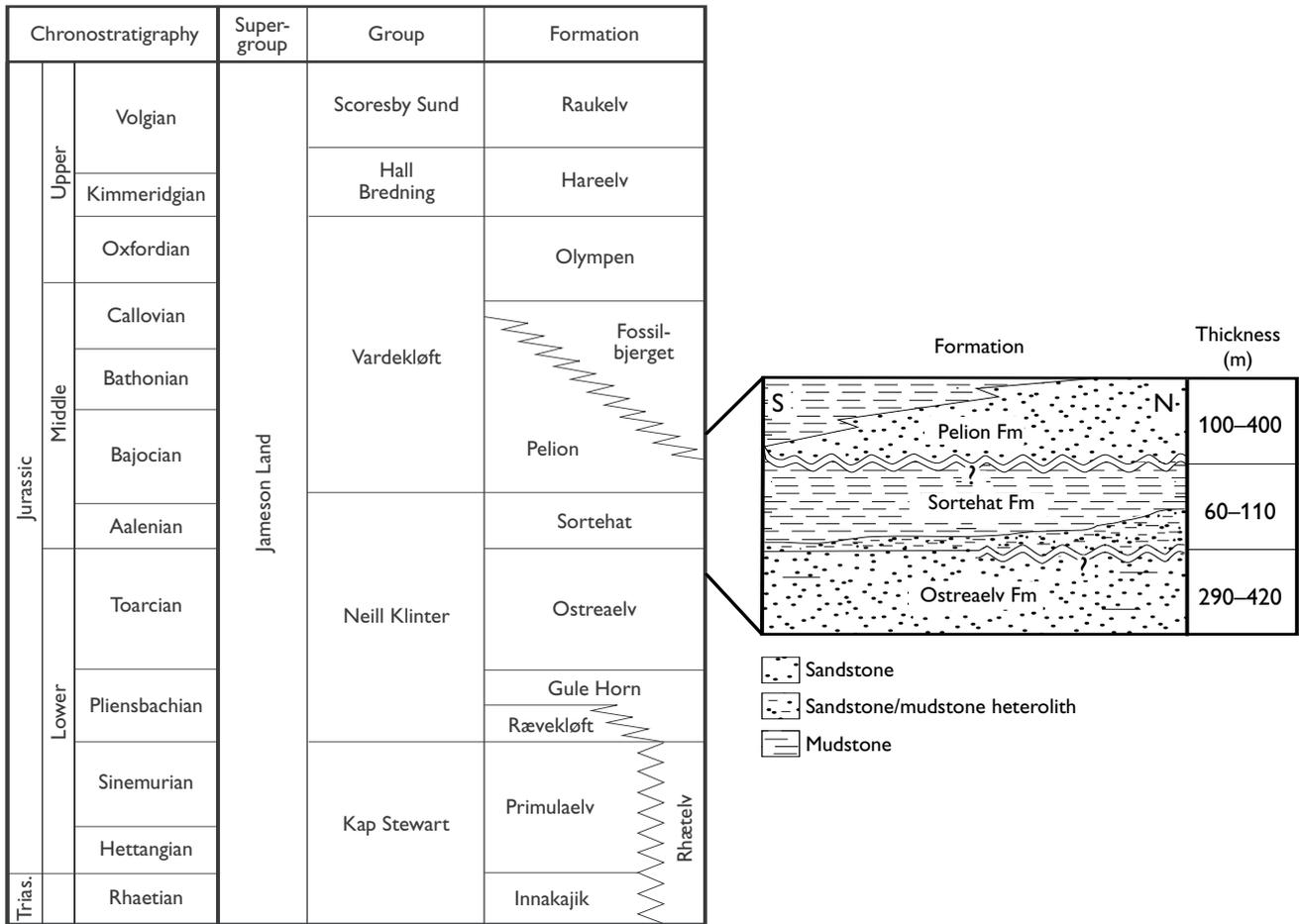


Fig. 2. Lithostratigraphy of the Jurassic of Jameson Land, East Greenland showing the stratigraphic position of the Sortehat Formation in the uppermost Neill Klintner Group. Modified from Surlyk (2003, this volume, fig. 5). The boundary between the Ostreaelv Formation and the Sortehat Formation is sharp and erosive in the northern proximal part of the basin and truncates shoreface deposits (indicated by the **wavy** line). At southern localities, the offshore mudstones of the Sortehat Formation gradually overlie transgressive lower shoreface to offshore deposits. The Sortehat Formation thins towards the south. The heterolithic unit in the lowermost part of the formation also thins towards the south. The upper boundary of the Sortehat Formation is erosional (**wavy** line) and may record a minor hiatus.

from Late Permian through Mesozoic times the basin was characterised by relatively uniform thermal subsidence interrupted by periods of faulting (Surlyk *et al.* 1981; Surlyk 1990a). The basin was bounded to the west by a major, approximately north–south-trending fault zone and to the east by faults and the elongated NNE–SSW-trending Liverpool Land high (Fig. 1; Surlyk *et al.* 1981; Surlyk 1990a). To the north, the basin was bounded by a number of NW–SE-trending cross-faults in Kong Oscar Fjord. The southern boundary is unknown but the basin probably extended further south under the present-day Scoresby Sund. The original extent of the Sortehat Formation is not known in detail, but during Middle Jurassic time it probably covered the present

land area of Jameson Land and Scoresby Land (Fig. 1). It was deposited in an elongate, semi-enclosed seaway, connected in the south with the epeiric Jurassic seaway between Greenland and Norway (Surlyk *et al.* 1981).

The Sortehat Formation, as adopted here, was originally erected as the lower member (the Sortehat Member) of the Vardekløft Formation (Surlyk *et al.* 1973). It was raised to the status of formation by Surlyk (1990b, fig. 3); formal definition of the Sortehat Formation as the uppermost formation of the Neill Klintner Group was undertaken by Dam & Surlyk (1998). The type locality of the Sortehat Formation at Sortehat (Fig. 1A) is identical to that of the former Sortehat Member (Surlyk *et al.* 1973).

The Sortehat Formation overlies the sandstone-dominated Ostreaelv Formation (Figs 2, 3) which records deposition within a shallow wave, storm and tidally influenced marine embayment (Dam & Surlyk 1995, 1998). The boundary with the overlying black mudstones of the Sortehat Formation is distinct at all localities but changes from a sharp ravinement surface in northern localities to a gradational drowning surface in southern localities (Figs 3, 4; Hansen 1999). The Sortehat Formation is 60–100 m thick and is overlain by the sandy, marine Pelion Formation (Fig. 2); the boundary is sharp throughout the basin.

Sedimentologically, the boundary between the Ostreaelv and Sortehat Formations represents a landwards shift in facies and a rise in relative sea level. The contact is interpreted as a transgressive erosional surface (Surlyk 1990a, b; Hansen & Surlyk 1994, Hansen 1999) and marks a basinwide flooding event within an overall transgressive period. The upper boundary of the Sortehat Formation represents a seawards shift in facies related to a fall in sea level and is interpreted as a marine erosional surface formed during forced regression (Surlyk 1990a, b; Engkilde & Surlyk 1993).

Facies and depositional setting

The Sortehat Formation consists of dark grey to black mudstones with subordinate heterolithic levels (Figs 3, 4). The formation thins southwards away from the northern basin margin, from 100 m at Enhjørningen Dal to 60 m at Albuen (Fig. 4). A discrete, heterolithic unit of interbedded mudstones, sandstones and siltstones, 20 m thick, occurs at the base of the formation at the northern locality of Enhjørningen Dal; this unit thins to 8 m at the type locality of the Sortehat Formation and ultimately wedges out towards the south (Figs 3, 4).

Mudstone facies

The mudstones of the Sortehat Formation are darker and more fissile in the lowermost part of the formation and generally become lighter upwards, changing from black at the base to dark grey at the top. The dark grey mudstones, which dominate the formation, commonly appear structureless but locally show bioturbated fabrics, including subhorizontal traces such as *Curvolithus* isp. and *Planolites*-like burrows and, near the top of the formation, some vertical traces referred to *Diplocraterion* isp. The black mudstones, in contrast, show a well-

developed coarse parallel lamination formed by an alternation of thin sand/siltstone layers and mudstone layers. The mudstones contain plant debris and calcareous concretions are present locally. Macrofossils include belemnites and ostreid bivalves.

Both mudstone facies are broadly interpreted as having been deposited from suspension below wave base in an offshore environment. The lack of bioturbation in the black mudstone facies suggests that the sea floor was periodically inhospitable, probably due to poor oxygenation.

Sandstone facies

The interbedded sandstone layers from the heterolithic levels are very fine- to medium-grained; they locally show well-developed wave ripples but more commonly appear as lenses and streaks of sandstone, 2–15 mm thick, reflecting incipient ripple development (Fig. 3C; cf. the ‘incipient lenses’ of de Raaf *et al.* 1977). Laterally persistent sandstone layers, 5–30 cm thick, are present locally and show hummocky cross-stratification (Fig. 3C). The trace fossils *Ophiomorpha nodosa* and *Pelecypodichnus amygdaloides* occur in some of the sandstone layers.

The basal heterolithic unit records deposition in the upper offshore – offshore transition zone, influenced by storm sand deposition on a muddy shelf. The persistent hummocky cross-stratified sand sheets represent higher energy storm events above storm wave base. The bioturbation associated with the sandstones indicates well-aerated bottom-water conditions, at least on occasion.

Depositional setting

The preliminary interpretation is that the black to dark grey mudstones that dominate the formation were deposited from suspension. In combination with the thin storm sand layers, the mudstones indicate deposition in an offshore environment, probably a muddy, shallow epeiric sea. The basal thick heterolithic unit at Enhjørningen Dal and Sortehat records northwards shoreface retreat prior to final drowning of the entire basin. A detailed sedimentological and sequence stratigraphic analysis of the Sortehat Formation was presented by Hansen (1999).

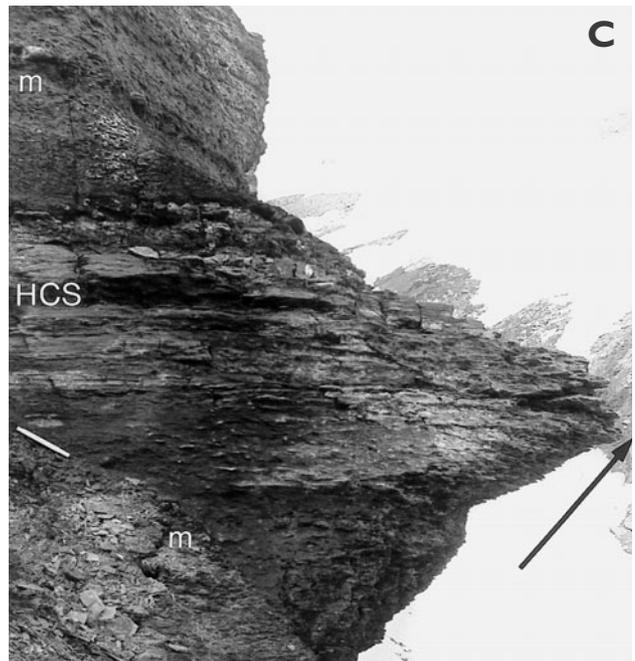
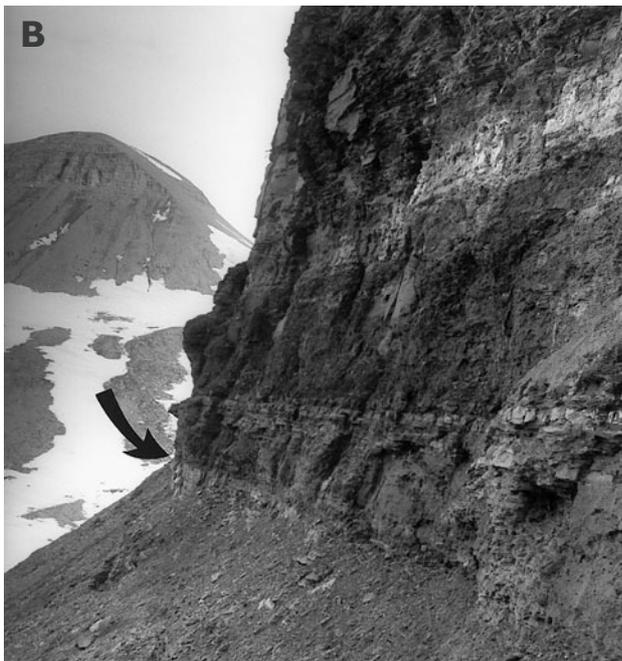


Fig. 3. **A:** The Sortehat Formation at the southernmost locality, Albuén, Neill Klinter. The Sortehat Formation consists mainly of dark grey to black mudstones deposited in an offshore environment. The boundary with the underlying fully marine sandy Ostreaelv Formation (**arrow**) is a particularly distinctive facies boundary within the Mesozoic succession of the East Greenland rift basin and represents a marine flooding event. The profile shown is c. 80 m thick. **B:** The lower, heterolithic unit of the Sortehat Formation at the northern locality of Enhjørningen Dal (basal boundary marked by **arrow**; c. 15 m of the Sortehat Formation illustrated). **C:** In contrast to the shaly appearance at the southern locality of Albuén (see Fig. 3A), this 20 m thick heterolithic unit at Enhjørningen Dal consists of stacked coarsening-upwards units (**arrow**); the example illustrated here passes up from mudstone (**m**) to hummocky cross-stratified sandstone (**HCS**). These stacked units probably record repeated slowing of transgression and shoreline progradation at the northern basin margin. Measuring rule (centre left) is 20 cm long.

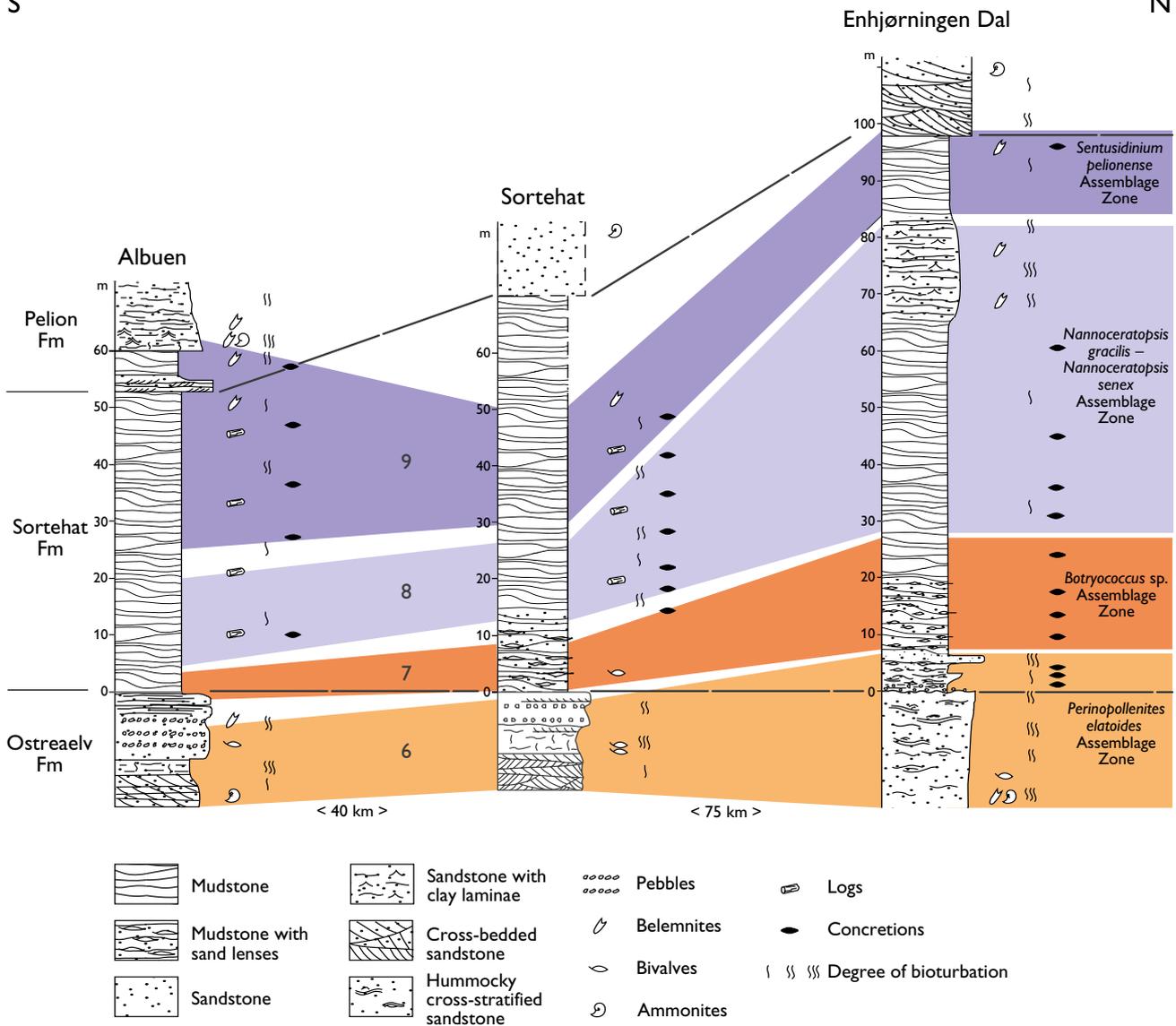


Fig. 4. Correlation between the three localities Albuen, Sortehat and Enhjørningen Dal showing the palynological zonation (Assemblage Zones 6–9). The upper part of the Sortehat Formation and the overlying Pelion Formation at the type locality (Sortehat) have been removed by recent erosion. The base and top of the Sortehat Formation are indicated by the **dotted** line.

Previous work

The age of the Sortehat Formation is not well known. Belemnites have been collected from the formation but to date have not been systematically identified. According to Dam & Surlyk (1998), belemnites from the upper levels of the underlying Ostreaelv Formation were collected by Rosenkrantz (1934) and studied by Doyle (1991); the belemnite *'Parabrachybelus' subaduncatus* from this level probably has a range restricted to the latest Toarcian Levesquei Zone (Doyle 1991). The ammonite *Cranocephalites borealis* has been found in

the basal beds of the Pelion Formation, overlying the Sortehat Formation, indicating an age not younger than early Late Boreal Bajocian for these beds (Surlyk *et al.* 1973; Callomon 1993).

The dark shales of the Sortehat Formation have been subjected to three palynological studies and a geochemical study (Fensome 1979; Lund & Pedersen 1985; Krabbe *et al.* 1994; Underhill & Partington 1994) although none of these studies were based on a comprehensive, closely-spaced sampling programme. Three samples from the Sortehat Formation were analysed for dinoflagellate cysts by Fensome (1979). One sample (144112)

was from the type section at Sortehat, and two (144229 and 144231) were from a locality north of Dusén Bjerg. Sample 144112 yielded a sparse assemblage of well-preserved palynomorphs, including *Nannoceratopsis gracilis*. Sample 144229 yielded a dinoflagellate cyst assemblage dominated by *N. gracilis*. The assemblage in sample 144231 was dominated by the acritarch *Verybanchium sortehatense*. Fensome (1979) concluded that the palynomorph assemblages determined from the three samples from the Sortehat Formation did not allow for accurate dating. It is worth noting that the dinoflagellate cyst *Sentusidinium pelionense* was not found in any of the three samples from the Sortehat Formation, but was common in one sample (144111) from the overlying Pelion Formation.

Lund & Pedersen (1985) presented the results of a palynological study concerning the Neill Klinte and Vardekløft Groups and the lower part of the Hareelv Formation. Four samples (142832–35) are from the Sortehat Formation. These samples yielded abundant *Sentusidinium pelionense* but *Nannoceratopsis gracilis* was not found, whereas the pollen *Perinopollenites elatoides* was abundant. Sample 142833 had the lowest number of marine cysts, whereas *Botryococcus* was common in 142832 and 142835. On the basis of these data, Lund & Pedersen (1985) suggested a Middle–Late Bajocian age for the Sortehat Formation.

The Neill Klinte and Vardekløft Groups were also studied palynologically by Underhill & Partington (1994). The material on which their study was based was sampled at Liaselv (their section 1), Vardekløft (section 2), and Harris Fjeld/Primulaelv at Neill Klinte, the western slope of Hurry Inlet (section 3; Fig. 1). Twenty samples from the Sortehat Formation were analysed from their sections 1 and 2 (7 samples from section 1, 13 samples from section 2; their fig. 10). An Aalenian–Bajocian age was proposed for the Sortehat Formation. On the basis of these data, Underhill & Partington (1994) suggested that the Aalenian–Bajocian record was essentially complete, without apparent biostratigraphic or sedimentological evidence of the ‘mid-Cimmerian event’ known from the North Sea area. Underhill & Partington (1994) concluded that the boundary between the Sortehat Formation and the underlying Ostreaelv Formation does not represent an important unconformity. This is confirmed by recent work (Koppelhus & Dam 2003, this volume) on the uppermost part of the Ostreaelv Formation which has been referred to the Late Toarcian – early Aalenian on the basis of the palynological assemblages.

The organic geochemistry and the palynofacies of the Sortehat Formation were discussed by Krabbe *et al.* (1994). Based on the palynofacies study, the succession was divided into three facies: (1) *Botryococcus*-dominated, (2) spore/pollen and brown/blackwood and (3) blackwood-dominated, few spore/pollen. These results, together with the geochemical data, suggest an increase in the salinity of the depositional environment with time (Krabbe *et al.* 1994).

Materials and methods

This study is primarily based on material collected by the authors in the 1993 and 1994 field seasons. The Sortehat Formation was investigated along a north–south-trending profile through the Jameson Land Basin, parallel to the basin axis. Sections were sampled and studied at four localities: Albuen (Neill Klinte along Hurry Inlet) and Sortehat (the type locality of the formation) in the south and Enhjørningen Dal and Pelion in the northern part of Jameson Land (Fig. 1; Appendix 1). The boundary between the Ostreaelv and the Sortehat Formations is a well-defined stratigraphic surface and was used as a datum for the sections measured at outcrop; the structural dip of the succession is negligible. The outcrop sections were measured by Jacob staff in metres relative to this surface. Altimeter readings for the datum surface are listed in Appendix 1; sample locations are thus referred to height above sea level, being the sum of the datum altitude (measured by altimeter) and the measured section thickness above the datum. Samples taken from core from the borehole at the type locality of the Sortehat Formation are related to an arbitrary datum (base of cored section) within the upper Ostreaelv Formation (Appendix 1).

Approximately 300 samples were processed at the palynological laboratory of the former Geological Survey of Greenland using standard techniques (Nøhr-Hansen 1993). The palynomorphs were studied using a transmitted light microscope. For each sample, 200 specimens were counted, and all species were registered in the range chart program SIS. The palynomorphs illustrated in Plates 1–6 are from the borehole at the type locality of the Sortehat Formation and from a section at Lepidopteriselv; the latter has not been used in the correlation between the three other localities. All the palynomorph taxa recorded in the samples are listed in Appendix 2 with author attributions and dates, and the slides are stored in the collections of the Geological Survey of Denmark and Greenland.

Palynological zones: definition

The data presented here form part of a broader study encompassing the entire Neill Klintner Group. Nine palynological assemblage zones (1–9) have been recognised in the group; assemblage zones 1–6 from the Rævekløft, Gulehorn and Ostreaelv Formations are presented in a companion paper (Koppelhus & Dam 2003, this volume). The three assemblage zones of the Sortehat Formation, based on the occurrence of miospores, dinoflagellate cysts and freshwater algae, are named from below: (7) the *Botryococcus* Assemblage Zone, (8) the *Nannoceratopsis gracilis* – *Nannoceratopsis senex* Assemblage Zone and (9) the *Sentusidinium pelionense* Assemblage Zone. Assemblage Zone 7 is also recognised in the upper levels of the Ostreaelv Formation and is described briefly in Koppelhus & Dam (2003, this volume), but is defined herein.

Assemblage Zone 7: *Botryococcus*

new assemblage zone

<i>Occurrence.</i>	Albuen	438.5–443.5 m
	Enhjørningen Dal	425.35–445 m
	Pelion	550–567 m
	Sortehat (core)	27.82–36.36 m

In the cored section from Sortehat, this assemblage occurs in the lower levels of the Sortehat Formation, the base being immediately above the lower boundary of the formation (Figs 4, 5). At Albuen, the assemblage is represented in the uppermost few metres of the Ostreaelv Formation and extends up into the Sortehat Formation (Figs 4, 6; Fig. 6 faces page 794). At Enhjørningen Dal, Assemblage Zone 7 is restricted to the lower Sortehat Formation although here the base is some 6 m above the lower boundary of the Sortehat Formation (Figs 4, 7; Fig. 7 faces page 795). Assemblage Zone 7 occurs within the lower levels of sequence SQ7 of Dam & Surlyk (1995, 1998).

Reference section. Sortehat (core), 27.82 m (sample 303143-73) – 36.36 m (sample 303143-62; Figs 4, 5).

Additional sections. Albuen, 438.5 m (sample 397452) – 443.5 m (sample 397468; Figs 4, 6). Enhjørningen Dal, 425.35 m (sample 398341) – 445 m (sample 398417; Figs 4, 7).

Base. The base of the assemblage is placed at the first sample in which *Botryococcus* spp. overwhelmingly dominates the assemblage and the dinoflagellate cysts *Nannoceratopsis gracilis* and *Nannoceratopsis senex* and dinoflagellate cysts in general become rare. In the Albuen section (Fig. 6), this event coincides with the first co-occurrence of *Callialasporites dampieri* (pollen) and *Mendicodinium groenlandicum* (dinoflagellate cyst) although in other sections (e.g. Sortehat, Enhjørningen Dal; Figs 5, 7) these species first occur together some metres below the *Botryococcus* spp. influx.

Top. The upper boundary is defined by the uppermost sample showing the *Botryococcus*-dominated assemblage. Above this level, *Botryococcus* spp. are scarce and *Nannoceratopsis gracilis* and *N. senex* become abundant once more.

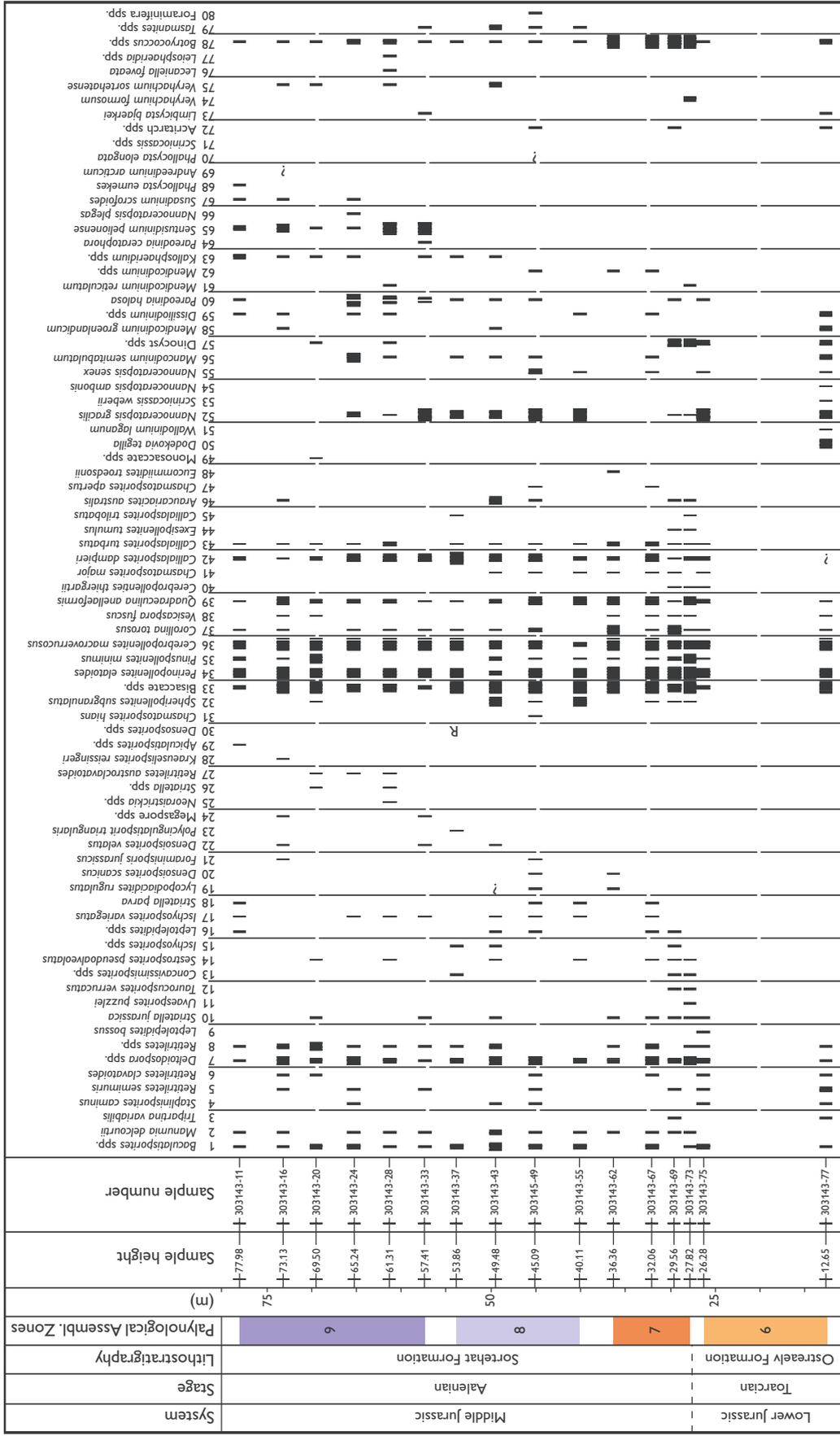
Characteristics. The assemblage is characterised by the overwhelming dominance of the freshwater alga *Botryococcus* spp. and the scarcity of dinoflagellates. Pollen species such as *Perinopollenites elatoides*, *Cerebropollenites macroverrucosus* and bisaccate pollen are also abundant.

Suggested age. Aalenian (see discussion below).

Palaeoenvironment. The palynomorph assemblage indicates a brackish marine environment. The abundant *Botryococcus* and the common spores and pollen reflect a significant allochthonous terrestrial input related to transgression (see later discussion).

Remarks. The *Botryococcus* Assemblage is, as the name indicates, dominated by *Botryococcus* spp. (Plate 4, fig. 4), but spores and pollen also play an important role. The spore flora is diverse, but there are only few specimens of each species, whereas pollen species are less diverse but occur abundantly, such as *Perinopollenites elatoides* (Plate 2, fig. 5), bisaccate pollen, *Cerebropollenites macroverrucosus* (Plate 3, fig. 3) and *Corollina torosus* (Plate 3, fig. 2). Some of the less abundant pollen are stratigraphically significant, such as *Quadraeculina anellaeformis* (Plate 3, fig. 5) and *Callialasporites dampieri* (Plate 2, fig. 1). Acritarchs and dinoflagellate cysts occur only rarely. Among the latter are *Dissilodinium* sp. (Plate 6, fig. 4), *Mendicodinium* sp., *Pareodinia balosa* (Plate 4, fig. 6), *Mancodinium semitabulatum* (Plate 6, fig. 1) and a few specimens of *Nannoceratopsis senex* (Plate 5, fig. 2) and *N. gracilis* (Plate 5, fig. 1).

Sortehat



- Alphabetical species list**
- 72 Acrtarch spp.
 - 69 Andredinium arctium
 - 29 Apicalisporites spp.
 - 46 Arucariacites australis
 - 1 Baculatisporites spp.
 - 3 Baryococcus spp.
 - 3 Biscaccate spp.
 - 78 Boryococcus spp.
 - 42 Callialisporites dampieri
 - 45 Callialisporites trilobatus
 - 43 Callialisporites turbatus
 - 36 Cerebropollenites macroverrucosus
 - 40 Cerebropollenites thiergartii
 - 47 Chasmatosporites apertus
 - 31 Chasmatosporites hians
 - 30 Chasmatosporites spp.
 - 29 Apicalisporites spp.
 - 28 Kraeuselisporites reisingeri
 - 27 Retritiles austroclavataoides
 - 26 Sratella spp.
 - 25 Neorastickia spp.
 - 24 Megaspore spp.
 - 23 Polycingulatisporit triangulatis
 - 22 Densosporites velatus
 - 21 Forminisporites jurassicus
 - 20 Densosporites scanicus
 - 19 Lycopodioidites rugulatus
 - 18 Sratella parva
 - 17 Ischyosporites variegatus
 - 16 Leptolepidites bossus
 - 9 Leptolepidites bossus
 - 8 Retritiles spp.
 - 7 Deltoispora spp.
 - 6 Retritiles clavataoides
 - 5 Retritiles semimuris
 - 4 Staphlisporites caninus
 - 3 Tripartina variabilis
 - 2 Mannumii delcourti
 - 1 Baculatisporites spp.
 - 1 Baclatisporites spp.
 - 11 Uvesporites puzzei
 - 12 Tauracosporites verrucatus
 - 13 Concastissimisporites spp.
 - 14 Sastrosporites pseudoovaleolatus
 - 15 Ischyosporites spp.
 - 16 Leptolepidites bossus
 - 17 Ischyosporites variegatus
 - 18 Sratella parva
 - 19 Lycopodioidites rugulatus
 - 20 Densosporites scanicus
 - 21 Forminisporites jurassicus
 - 22 Densosporites velatus
 - 23 Polycingulatisporit triangulatis
 - 24 Megaspore spp.
 - 25 Neorastickia spp.
 - 26 Sratella spp.
 - 27 Retritiles austroclavataoides
 - 28 Kraeuselisporites reisingeri
 - 29 Apicalisporites spp.
 - 30 Chasmatosporites spp.
 - 31 Chasmatosporites hians
 - 32 Spheripollenites subgranulatus
 - 33 Biscaccate spp.
 - 34 Fernoipollenites elatoides
 - 35 Finsipollenites minimus
 - 36 Cerebropollenites macroverrucosus
 - 37 Corollina torosus
 - 38 Vestispore fuscus
 - 39 Quadraeculina anellaiformis
 - 40 Cerebropollenites thiergartii
 - 41 Chasmatosporites major
 - 42 Callialisporites dampieri
 - 43 Callialisporites turbatus
 - 44 Exesipollenites tumulus
 - 45 Callialisporites trilobatus
 - 46 Arucariacites australis
 - 47 Chasmatosporites apertus
 - 48 Eucommidiites treosonii
 - 49 Monosaccate spp.
 - 50 Dodekovia tegilla
 - 51 Valodiinium lagnum
 - 52 Nannoceratopsis gracilis
 - 53 Scrimiocassis weberii
 - 54 Nannoceratopsis ambonis
 - 55 Nannoceratopsis senex
 - 56 Mankodinium semitubulatum
 - 57 Dinocyst spp.
 - 58 Mendicodinium greolandicum
 - 59 Dissiliodinium spp.
 - 60 Pareodinia halosa
 - 61 Mendicodinium reticulatum
 - 62 Mendicodinium spp.
 - 63 Kalliosphaeridium spp.
 - 64 Pareodinia ceratophora
 - 65 Sentsusidium pelionense
 - 66 Nannoceratopsis plegas
 - 67 Susadinium scrofaoides
 - 68 Phallocyta eumekes
 - 69 Andredinium arctium
 - 70 Phallocyta elongata
 - 71 Scrimiocassis spp.
 - 72 Acrtarch spp.
 - 73 Limbicysta bjaerkei
 - 74 Verhyachium formosum
 - 75 Verhyachium sortehatense
 - 76 Lecanella foveata
 - 77 Leiosphaeridia spp.
 - 78 Boryococcus spp.
 - 79 Tasmanites spp.
 - 12 Tauracosporites verrucatus
 - 3 Tripartina variabilis
 - 11 Uvesporites puzzei
 - 74 Verhyachium formosum
 - 75 Verhyachium sortehatense
 - 38 Vesicospora fuscus
 - 51 Wallodiinium lagnum
 - 5 Retritiles semimuris
 - 8 Retritiles spp.
 - 71 Scrimiocassis weberii
 - 53 Scrimiocassis weberii
 - 65 Sentsusidium pelionense
 - 14 Sastrosporites pseudoovaleolatus
 - 32 Spheripollenites subgranulatus
 - 4 Staphlisporites caninus
 - 10 Sratella jurassica
 - 18 Sratella parva
 - 26 Sratella spp.
 - 6 Retritiles clavataoides
 - 67 Susadinium scrofaoides
 - 55 Nannoceratopsis senex
 - 25 Neorastickia spp.
 - 64 Pareodinia ceratophora
 - 60 Pareodinia halosa
 - 34 Perinopollenites elatoides
 - 70 Phallocyta eumekes
 - 35 Pinusipollenites minimus
 - 23 Polycingulatisporit triangularis
 - 39 Quadraeculina anellaiformis
 - 54 Nannoceratopsis ambonis
 - 52 Nannoceratopsis gracilis
 - 6 Retritiles clavataoides

Fig. 5. Chart showing the distribution of palynomorphs from the cored borehole at Sortehat, the type locality of the Sortehat Formation.

Assemblage Zone 8: *Nannoceratopsis gracilis* – *Nannoceratopsis senex*

new assemblage zone

<i>Occurrence.</i>	Albuen	444.5–460 m
	Enhjørningen Dal	446–500 m
	Pelion	573–577 m
	Sortehat (core)	40.11–53.86 m

Assemblage Zone 8 occurs within the Sortehat Formation; it thus falls within sequence SQ7 of Dam & Surlyk (1995, 1998).

Reference section. Sortehat (core), 40.11 m (sample 303143-55) – 53.86 m (sample 303143-37; Figs 4, 5).

Additional sections. Albuen, 444.5 m (sample 397469) – 460 m (sample 397474; Figs 4, 6). Enhjørningen Dal, 446 m (sample 395625) – 500 m (sample 398442; Figs 4, 7).

Base. The lower boundary is placed at the first sample in which *Botryococcus* spp. is rare and *Nannoceratopsis gracilis* and *N. senex* are abundant.

Top. This is defined by the last sample showing the characteristic assemblage (see below), above which level *Nannoceratopsis gracilis* becomes less common and *Sentusidinium pelionense* is the most common dinoflagellate cyst.

Characteristics. *Botryococcus* spp. is rare in this assemblage whereas *Nannoceratopsis gracilis* is abundant and there is a general increase in diversity and abundance of dinoflagellate cysts relative to the underlying zone.

Suggested age. Aalenian (see discussion below).

Palaeoenvironment. The palynological data indicate a brackish marine environment.

Remarks. Dinoflagellate cysts are abundant, whereas *Botryococcus* spp. becomes rare at 40.11 m in the type section at Sortehat (Fig. 5). There are a few acritarchs, such as *Verybachiium sortehatense* (Plate 4, fig. 2), and some of the same spores and pollen as observed in the *Botryococcus* Assemblage Zone (Plates 1, 2).

Assemblage Zone 9: *Sentusidinium pelionense*

new assemblage zone

<i>Occurrence.</i>	Albuen	465–502 m
	Enhjørningen Dal	502–516.75 m
	Sortehat (core)	57.41–77.98 m

Assemblage Zone 9 occurs in the upper Sortehat Formation in the Sortehat section; note that the sampled interval in this section is restricted to the Sortehat Formation (Figs 4, 5). At Albuen and Enhjørningen Dal, the assemblage extends through the upper Sortehat Formation and persists up into the overlying Pelion Formation (Figs 4, 6, 7). Assemblage Zone 9 is thus characteristic of the upper levels of sequence SQ7 of Dam & Surlyk (1995, 1998), and at Albuen and Enhjørningen Dal spans the sequence boundary at the base of the Pelion Formation and extends into sequence P1 of Engkilde & Surlyk (2003, this volume).

Reference section. Sortehat (core), 57.41 m (sample 303143-33) – 77.98 m (sample 303143-11; Figs 4, 5).

Additional sections. Albuen, 465 m (sample 397475) – 502 m (sample 397498; Figs 4, 6). Enhjørningen Dal, 502 m (sample 395679) – 516.75 m (sample 398448; Figs 4, 7).

Base. The base of the zone is placed at the sample in which *Sentusidinium pelionense* is the most common dinoflagellate cyst; *Nannoceratopsis gracilis* and *N. senex* are absent or rare.

Top. The upper boundary of the assemblage zone is not defined here. The *Sentusidinium pelionense* Assemblage Zone extends from the upper part of the Sortehat Formation into the lowermost beds of the Pelion Formation. The full extent of the zone within the Pelion Formation is not known. It is likely, however, that the top of the zone occurs within the lower levels of the Pelion Formation (S. Piasecki, personal communication 1997).

Characteristics. *Sentusidinium pelionense* is abundant. In some of the investigated sections, *S. pelionense* is accompanied by *Nannoceratopsis gracilis* in samples at the boundary between the two palynomorph assemblage zones. In other sections, they do not overlap, i.e. *N. gracilis* is replaced by *S. pelionense* up-section.

Suggested age. Aalenian – ?Early Bajocian (see discussion below).

Palaeoenvironment. The palynological data indicate that most of the organic material came from a brackish marine source.

Remarks. The assemblage contains fewer spores and pollen than the underlying assemblage zone. The most abundant dinoflagellate cysts are *Sentusidinium pelionense* (Plate 6, fig. 5) and *Pareodinia balosa* (Plate 4, fig. 6) although a few specimens of *Phallocysta eumekes* were recorded. The acritarch *Limbicysta bjaerkei* was also found.

Palynological results

Sortehat

At the type locality, the Sortehat Formation is a minimum of 50 m thick; the top of the formation is not seen due to recent erosion. Seventy samples were collected and seventeen of these are shown on the distribution chart (Fig. 5).

The palynological assemblages from the entire section fall into three distinct assemblages. There is a distinct change from the *Perinopollenites elatoides* Zone (Assemblage Zone 6, described by Koppelhus & Dam 2003, this volume) in the underlying Ostreaelv Formation to the *Botryococcus* Assemblage Zone (Assemblage Zone 7), which is overwhelmingly dominated by the freshwater alga *Botryococcus*. This change is first observed at 27.82 m (sample 303143-73) just above the lithological boundary between the Sortehat and Ostreaelv Formations at 27.6 m. The *Perinopollenites elatoides* Zone is characterised by the first appearance of *Staplinisporites caminus*, *Sestrosporites pseudoalveolatus*, *Phallocysta eumekes* and *Wallodinium laganum*; *Callialasporites dampieri* makes its first appearance near the top of the zone. The data from the three Ostreaelv Formation samples from the Sortehat section do not show exactly the same pattern although *S. caminus* and *C. dampieri* have their first appearance in the uppermost sample from the Ostreaelv Formation and the dinoflagellate cyst *W. laganum* is very common in sample 303143-80 at 6.64 m (not shown on Fig. 5), approximately 20 m below the boundary between the Ostreaelv and Sortehat Formations.

In sample 303143-73 at 27.82 m, 0.22 m above the base of the Sortehat Formation, the freshwater alga

Botryococcus appears and the acme extends for approximately 9 m before *Botryococcus* disappears and the dinoflagellate cyst *Nannoceratopsis gracilis* begins to dominate the assemblage. In three samples (303143-75, 303143-73 and 303143-69) an unidentified dinocyst (*Dinocyst* sp.) is common to abundant; this dinoflagellate cyst is similar to one described as *Dinoflagellate* sp. indet. 2 from Callovian deposits from Spitsbergen where it is said to occur in profusion in some assemblages (Bjærke 1980). This species was also common in the lowermost sample from the Pelion locality (Fig. 8).

N. gracilis continues to be the dominant dinoflagellate for 14 m to 53.86 m (sample 303143-37) above which there is an acme of *Sentusidinium pelionense* together with abundant *Pareodinia balosa*.

Albuen

The Sortehat Formation at Albuen covers about 60 m and 41 samples have been investigated from this interval (Fig. 6). The boundary between the Ostreaelv and Sortehat Formations is at 440 m, but the palynomorph assemblages change between sample 405449 at 434 m and sample 397452 at 438.6 m, several metres below the top of the Ostreaelv Formation, where *Botryococcus* becomes common, dinoflagellate cysts become rare (*Mendicodinium groenlandicum*, *Nannoceratopsis gracilis* and *Nannoceratopsis senex* are present but rare), and pollen are more common than spores. At 443.5 m in sample 397468, 3.5 m above the base of the Sortehat Formation, *Botryococcus* is abundant for the last time; above this level *N. gracilis* and *N. senex* become abundant and are accompanied by *Sentusidinium pelionense*. *S. pelionense* is only common in one sample (397471), and *Pareodinia balosa* is common in two other samples, 397475 and 347477. This assemblage changes between 460 m and 465 m, above which level *S. pelionense* is the only common dinoflagellate; this species disappears above 496 m, within the lower levels of the Pelion Formation. The overall dinoflagellate cyst diversity decreases from the upper part of the *Nannoceratopsis gracilis* – *Nannoceratopsis senex* Assemblage Zone through the *Sentusidinium pelionense* Assemblage Zone in the upper part of the Sortehat Formation. A few dinoflagellate cysts have been found in most of the samples, and pollen are more common than spores. The samples that span the boundary between the Sortehat Formation and the overlying Pelion Formation yielded an impoverished palynomorph assemblage without any age-diagnostic species.

Enhjørningen Dal

Enhjørningen Dal is a composite section spanning the top of the Ostreaelv Formation, the entire Sortehat Formation and the lowermost part of the Pelion Formation (Fig. 7). The boundary between the Ostreaelv and Sortehat Formations is at 418 m; the first change in the palynomorph assemblages is observed in sample 398341 at 425.35 m. This lower interval (belonging to the uppermost part of the Ostreaelv Formation and the lowermost part of the Sortehat Formation) is completely dominated by the dinoflagellate species *Nannoceratopsis gracilis* and *Nannoceratopsis senex*, and by the pollen *Perinopollenites elatoides*. This interval is accordingly referred to the *Perinopollenites elatoides* Assemblage Zone (Assemblage Zone 6; Koppelhus & Dam 2003, this volume) which is of Late Toarcian – early Aalenian age. At 425.35 m (sample 398341), *Botryococcus* appears in abundance and persists in large numbers up to sample 398417 at 445 m. From sample 395625 at 446 m to sample 398442 at 500 m, the palynomorph assemblage contains few *Botryococcus*; *N. gracilis* and *N. senex* are very common in the lower part of this interval. In the upper part of the section, however, from sample 395657 at 476 m to the uppermost sample (398448) at 516.75 m, *N. gracilis* and *N. senex* are absent whereas other dinoflagellates are present but rare (e.g. *Mancodinium semitabulatum*, *Pballocysta eumekes*, *Susadinium scrofoides*, *Parvocysta barbata*, *Dissilodinium* sp. and *Mendicodinium* sp.). *Sentusidinium pelionense* is abundant in samples 395679 and 395671, *Pareodinia halosa* is common in sample 395671 and *Kallosphaeridium* sp. is abundant in the uppermost sample (398448). Among the pollen at this level, bisaccates and *Cerebropollenites macroverrucosus* are especially abundant. Trilete spores seem to decrease in diversity and density compared to the lower part of the section.

Pelion

Ten samples were investigated from the Pelion locality (Fig. 8). They cover the lowermost 27 m of the Sortehat Formation, which is approximately 110 m thick at this locality. Generally, the palynomorph assemblages are rich but the preservation is poor. The assemblage from the lowermost 17 m of the formation (sample 339702 at 550 m to sample 339709 at 567 m) is dominated by *Botryococcus*. In sample 339709, *Botryococcus* has its last abundant appearance. In this interval, dinofla-

gellate cysts are present and locally common (*Nannoceratopsis gracilis*, *Mendicodinium groenlandicum* and *Mendicodinium* sp.). The two uppermost samples (sample 339710 at 573 m and sample 339711 at 577 m) yielded an assemblage rich in dinoflagellate cysts including *Nannoceratopsis gracilis*, *Nannoceratopsis tricerias*, *Nannoceratopsis plegas*, *Nannoceratopsis triangulata* and *Mancodinium semitabulatus* and some acritarchs. Spores and pollen are common to abundant throughout the 27 m section.

Discussion

The palynological study reported here has implications both for the age and regional correlation of the Sortehat Formation and for the environmental understanding of the formation, in association with the detailed sedimentological and sequence stratigraphic study (Hansen 1999).

Age and correlation

On the basis of macrofauna in the underlying and overlying formations (see previous discussion), the age of the Sortehat Formation is constrained between the latest Toarcian and the mid-Bajocian; previous palynological work has indicated an Aalenian–Bajocian (Underhill & Partington 1994) or a Middle–Late Bajocian age (Lund & Pedersen 1985). With a view to a more well-founded understanding of the stratigraphy of the Sortehat Formation, the results of this study are compared with published palynological data from the North Atlantic region. Although palynological assemblages from the Toarcian–Bajocian interval have been widely reported from this region, few of the sections have been independently dated using ammonites and the Aalenian assemblages, in particular, are commonly dominated by terrestrial material.

The Aalenian stage is named after Aalen in Germany, where the lowest part of the ‘Braunjura’ crops out at the northern edge of the Swabian Alps. Although no palynological papers have been published on material from the type locality, a dinoflagellate cyst assemblage has been described from two cores from Hausen in south-western Germany, 40 km from the type locality, and the lithological units have been correlated with the ammonite zonation from the Eastern Swabian Alb (Feist-Burkhardt 1990). The palynological assemblages are rich in spores and pollen, and only 5–20% of the total

palynomorph content is microplankton. In the Sortehat Formation, where the assemblages are also rich in spores and pollen, microplankton form 25–40% of the total palynomorph content. In the material from south-western Germany, twelve of the eighteen dinoflagellate cysts recognised have also been identified in the material from the Sortehat Formation. However, none of the four stratigraphically significant species for the Aalenian/Bajocian boundary from Hausen, *Carpathodinium* sp., *Dissilodinium giganteum*, *Dissilodinium* sp. A, and *Durotrigia daveyi*, have with certainty been found in the material from the Sortehat Formation.

The closest succession to Jameson Land with known palynological data of Aalenian age is the Stø Formation (Unit C) from the Møre Basin, offshore mid-Norway (Smelror *et al.* 1994). Ammonites have not been found to confirm the age, but a few foraminifera of little stratigraphic value have been used, together with the presence of the dinoflagellate cyst *Phallocysta eumekes*, which is restricted to the latest Early Toarcian – Aalenian in Europe (Riding & Thomas 1992). Spores, pollen and dinoflagellate cysts from Unit C are similar to those from the *Botryococcus* and *Nannoceratopsis gracilis* – *Nannoceratopsis senex* Assemblage Zones of the Sortehat Formation. Two thin levels with *Botryococcus* have been observed in the Stø Formation although not as rich in abundance as in the Sortehat Formation (Smelror *et al.* 1994). Moreover, the abrupt shift seen in the Sortehat Formation from an assemblage dominated by *Botryococcus* to one dominated by the dinoflagellate cysts *Nannoceratopsis gracilis*, *Nannoceratopsis senex* and *Pareodinia halosa* is not recognised in the Møre Basin. It should be noted, however that the *Botryococcus* Assemblage Zone of the Sortehat Formation is not stratigraphically significant but reflects only the palaeo-environmental conditions within the Jameson Land Basin at the time of deposition (see discussion below).

Aalenian palynomorph assemblages have also been identified from Arctic Canada and south-east Canada (Johnson & Hills 1973; Davies 1983; Bujak & Williams 1977), Barents Sea (Hammerfest Basin, Nordkap Basin, and Franz Josef Land; Smelror & Below 1992; Smelror 1994), north-west Scotland, north Yorkshire and Gloucestershire in England (Riding 1983, 1984a, b, 1987; Riding *et al.* 1991; Riding & Thomas 1992), Sweden (Guy-Ohlson 1994; Guy-Ohlson & Norling 1994), the Danish Subbasin (Dybkjær 1991; Seidenkrantz *et al.* 1993; Poulsen 1994), Øresund and the Baltic Sea (Koppelhus & Nielsen 1994; Koppelhus & Batten 1996), and north-west and south-west Germany (Prauss 1989).

The first dinoflagellate cyst zonation of the Jurassic of the Canadian Arctic was made by Johnson & Hills (1973). Their *Nannoceratopsis gracilis* Range Zone covers the Toarcian–Bajocian. They recorded the ammonite *Leioceras opalinum*, but the only dinoflagellate cyst in common with the East Greenland material is *Nannoceratopsis gracilis*. Bujak & Williams (1977) erected the *Nannoceratopsis gracilis* Zone for the Pliensbachian–Aalenian and the *Mancodinium semitabulatum* Zone for the Bajocian, from successions offshore south-eastern Canada. Several species are common to the assemblages from the Sortehat Formation and from the Canadian Arctic but the age has not been confirmed by any marine micro- or macrofauna. Davies (1983) established eight zones covering the Upper Pliensbachian – Callovian, also from the Canadian Arctic, of which the *Dapcodinium coalitum* – *Phallocysta eumekes* Zone, of Late Toarcian – Early Bajocian age, contains species in common with the Sortehat Formation assemblages. Davies (1983) stated that the macrofauna possibly indicates a Toarcian – Early Bajocian age.

In the Barents Sea area, seven dinoflagellate cyst zones have been recognised in the Toarcian – Lower Oxfordian (Smelror & Below 1992). One of them, the *Dodekovia bulla* – *Nannoceratopsis senex* Concurrent Range-Zone, has a number of species (*Nannoceratopsis gracilis*, *Nannoceratopsis senex*, *Nannoceratopsis tricerias*, *Scriniocassis weberi*, *Susadinium scrofoides*, *Pareodinia halosa* and *Phallocysta eumekes*) in common with the assemblages from the Sortehat Formation. The presence of the earliest Aalenian Opalinum Zone on Svalbard has been confirmed on the basis of ammonites.

In the United Kingdom, the Aalenian palynomorph assemblages are divided into Sub-biozone c (Opalinum Zone) and Sub-biozone d (Murchisonae and Concavum Zones) of the *Nannoceratopsis gracilis* Zone (Riding & Thomas 1992; the DSJ10 and DSJ11 Zones of Poulsen & Riding 2003, this volume). These zones are based on the FAD (first appearance datum) and the LAD (last appearance datum) of specific dinoflagellate cyst species. Of the stratigraphically significant species appearing in these zones, *Susadinium scrofoides*, *Wallodinium laganum* and other species of the genus *Parvocysta* have also been found in the material from the Sortehat Formation. Other common but stratigraphically less restricted species are *Nannoceratopsis gracilis*, *Nannoceratopsis senex*, *Mancodinium semitabulatum* and *Scriniocassis weberi*. The palynological zonation in the UK area has been related to the standard ammonite-based zones (Riding & Thomas 1992).

In Skåne, southern Sweden, the upper part of the Rya Formation and the lower part of the Vilhelmsfält Formation contain palynomorph assemblages dominated by terrestrial material deposited in a freshwater environment, although thin marine and brackish levels occur. Palynological zone III is suggested to be of Aalenian age (Guy-Ohlson & Norling 1994), and shows similarities to the palynomorph assemblages from the three zones of the Sortehat Formation. No ammonites have been found in the Middle Jurassic of southern Sweden but a foraminifera zonation has been established.

In the Danish Basin, rocks of Toarcian and early Aalenian age have been identified based on the occurrence of species of the genus *Parvocysta* (Poulsen 1994). A miospore and dinoflagellate cyst zonation was erected for the Lower and Middle Jurassic of the Danish Basin (Dybkjær 1991). The *Perinopollenites elatoides* miospore zone of Dybkjær (1991) covers sediments of Aalenian – Early Bajocian age, whereas the equivalent dinoflagellate cyst zone includes *Nannoceratopsis gracilis* and comprises sediments of Late Pliensbachian – Bajocian age. Similar palynomorph assemblages have been reported from the Øresund area (Koppelhus & Batten 1996). A miospore zonation was recommended for the Lower–Middle Jurassic of Bornholm in the Baltic area, where the *Callialasporites–Perinopollenites* Zone from the Bagå Formation has many species in common with the Sortehat Formation (Batten *et al.* 1994; Koppelhus & Nielsen 1994). Dinoflagellate cysts (*Nannoceratopsis gracilis*) have only been found in the lowermost part of this zone. The *Callialasporites–Perinopollenites* Zone is defined by the first appearance of *Callialasporites* and the dominance of *Perinopollenites elatoides*. Unfortunately, confirmatory ammonite or microfossil data is lacking in the Danish area to support the proposed Aalenian–Bathonian age, which is based entirely on comparison to other palynological studies in Europe. In the *Sentusidinium pelionense* Assemblage Zone of the Sortehat Formation, spores and pollen are abundant, and dinoflagellate cysts are locally present. The dinoflagellate cyst *Sentusidinium pelionense* has also been found in the Jydegård Formation on Bornholm in the Baltic Sea (Piasecki 1984; Noe-Nygaard *et al.* 1987). However, with the exception of the presence of *S. pelionense*, the *Sentusidinium pelionense* Assemblage Zone of the Sortehat Formation is more closely comparable to assemblages from the Norwegian and UK areas than to those of the Danish Basin and Bornholm.

Palynomorph assemblages from the Pliensbachian–Callovian of north-west Germany were described by Prauss (1989). The palynomorph assemblage from the

Nannoceratopsis plegas Zone of Aalenian age, has a number of species in common with the three zones from the Sortehat Formation, such as *Nannoceratopsis gracilis*, *Mancodinium semitabulatum*, *Pareodinia balosa*, *Dodekovia tegillata*, *Scrinioicassis weberi*, *Phallocysta eumekes* and *Kallospharidium* sp. Unfortunately the suggested Aalenian age is not confirmed by ammonites.

To conclude this review, the Sortehat Formation palynomorph assemblages clearly show close similarities to assemblages of inferred Aalenian age in the North Atlantic region. Few of these studies, however, include independent ammonite data with which to accurately constrain the age of the strata. A notable exception, upon which the age assignment of the Sortehat Formation depends, is the work of Riding (1982), Woollam & Riding (1983) and Riding & Thomas (1992) from the Jurassic of the UK. According to the zonation presented by these workers, the stratigraphically important palynomorphs recorded from the Sortehat Formation are *Mancodinium semitabulatum*, *Nannoceratopsis ambonis*, *Phallocysta eumekes* and *Nannoceratopsis plegas*. *M. semitabulatum*, which was recorded throughout the Sortehat Formation, has a range of Late Pliensbachian – Early Bajocian (Woollam & Riding 1983; Riding & Thomas 1992). *N. ambonis*, which occurs in the lower half of the formation, was initially thought to range from the Aalenian to the Early Bajocian (Riding 1982; Woollam & Riding 1983) but its range has subsequently been extended to Late Pliensbachian – Early Bajocian (Riding & Thomas 1992). *P. eumekes*, which occurs throughout the Sortehat Formation, has a restricted range of Late Toarcian – Aalenian in Europe (Riding & Thomas 1992). However, the species was first described from Bathonian strata in Arctic Canada where it has a range of Toarcian–Bathonian (Dörhöfer & Davies 1980) and is generally considered a more long-ranging species in Boreal regions (Riding 1984c). *N. plegas* is rare in the Sortehat Formation although its presence in the lower levels of the formation indicates an early Aalenian age for this part of the succession (Riding & Thomas 1992).

In association, therefore, these palynomorphs indicate an Aalenian – ?Early Bajocian age for the Sortehat Formation. This study thus confirms the age determination of Underhill & Partington (1994), although it is clear from the above review that more detailed studies of both the miospore and the dinoflagellate cyst stratigraphies of the early Middle Jurassic are urgently needed to further resolve the stratigraphy of the Sortehat Formation.

A notable conclusion of this study is that there is no evidence, on palynological grounds, for a significant hiatus at, or near, the lower boundary of the Sortehat Formation (see also Koppelhus & Dam 2003, this volume), nor within the Sortehat Formation itself. These observations are particularly pertinent to regional studies of Middle Jurassic uplift in the North Atlantic region (see Underhill & Partington 1994). The stratigraphic significance of the upper boundary of the Sortehat Formation is less well-constrained palynologically, although there is no direct evidence from this study of a major stratigraphic break at this surface.

Environmental implications of the palynological data

The three palynomorph assemblage zones of the Sortehat Formation can be recognised and correlated throughout the Jameson Land Basin (Fig. 4). Regionally, the *Botryococcus* Assemblage Zone ranges in thickness from 9–17 m and spans the uppermost part of the Ostreaelv Formation and the lower part of the Sortehat Formation. The zone starts several metres below the boundary between the Ostreaelv and Sortehat Formations in the southernmost locality at Albuen, whereas the appearance of the zone coincides with the boundary at the Sortehat type locality. Farther north, at Enhjørningen Dal, this change in the palynomorph assemblage does not occur until 7 m above the formation boundary (Figs 4, 7). At the northernmost locality of Pelion, the change takes place 5 m above the boundary.

The green alga *Botryococcus* is a freshwater form (Guy-Ohlson 1992) with no stratigraphic value as it ranges from the Carboniferous to the present (Tyson 1995; Batten & Grenfell 1996). However, the abundance of *Botryococcus* in the organic material from the lowermost Sortehat Formation in Jameson Land is notable. Sedimentologically, the depositional shift from the Ostreaelv Formation to the Sortehat Formation marks a basinwide flooding event within an overall transgressive period. As the abundance of *Botryococcus* is restricted to the section around the flooding surface (base of Sortehat Formation) and extends up to the maximum flooding surface, it seems to be linked to the flooding event (Hansen 1999). The question is whether the abundance of *Botryococcus* reflects *in situ* deposition under freshwater conditions that prevailed throughout the basin or if it represents an allochthonous accumulation of algae transported out to sea from inland freshwater environments. The continuous occurrence

of dinocysts throughout the Sortehat Formation, albeit in reduced numbers in the *Botryococcus* Assemblage Zone, suggests a persistent marine influence. Indeed, the reduced number of marine dinoflagellate cysts in this zone may be in part an artefact related to the counting procedure such that the abundance of *Botryococcus* and terrestrial sporomorphs tends to dilute the marine dinoflagellate cysts. Given the co-occurrence of the freshwater alga *Botryococcus* and the marine dinoflagellate cysts, the abundance of *Botryococcus* is here interpreted as an allochthonous accumulation. Seawards transport of material from inland areas suggests either a major freshwater input from rivers or inundation and erosion of coastal areas with seawards transport of land-derived material during transgression. During marine flooding, the initial rise of base-level causes expansion of lakes on low-lying areas within the coastal plain (Wells & Coleman 1987; Dominguez & Wanless 1991; Surlyk *et al.* 1995). As transgression proceeds, physical communication with the open sea is established, resulting in the possibility for a large influx of freshwater algae into the marine system.

Such an allochthonous origin related to transgression is consistent with the fact that the top of the *Botryococcus* Assemblage Zone coincides with the maximum flooding surface and the end of the transgressive period (Hansen 1999). A similar influx of *Botryococcus*, related to a flooding event, has been described from the Middle Jurassic Brent Group of the North Sea by Williams (1992), who interpreted this as an allochthonous accumulation resulting from the flushing of a freshwater environment into a marine environment.

The diversification of the dinoflagellate cysts in the basal part of the *Nannoceratopsis gracilis* – *Nannoceratopsis senex* Assemblage Zone is suggestive of a general increase in marine influence. This may be related to an increase in salinity during sea-level highstand following the transgression, as it is generally suggested that an increased diversity of dinoflagellate cysts points to more open marine conditions (Gorin & Steffen 1991; Leckie *et al.* 1992).

Upwards within the *Nannoceratopsis gracilis* – *Nannoceratopsis senex* Assemblage Zone and through the *Sentusidinium pelionense* Assemblage Zone, especially at Albuen and partly at Enhjørningen Dal, there is a marked decrease in the diversity of dinoflagellate cyst species, although the assemblage still shows marine influence. A decrease in diversity indicates more stressed and unfavourable environmental conditions, often with unstable salinities (Gorin & Steffen 1991; Leckie *et al.* 1992; Tyson 1995).

Although the strength of the marine signal partly increases up-section, the dinoflagellate cysts are characterised by forms tolerant of reduced salinities (e.g. *Nannoceratopsis gracilis*, *Nannoceratopsis senex* and *Sentusidinium pelionense*; Piasecki 1986; Prauss & Riegel 1989; Krabbe *et al.* 1994). The palynological data therefore indicate a marine environment, yet restricted in terms of salinity such that brackish conditions prevailed during deposition of the Sortehat Formation.

Conclusions

The age of the Sortehat Formation is Aalenian to ?Early Bajocian. This age assignment is based on comparison of the three palynomorph assemblage zones (the *Botryococcus* Assemblage Zone, the *Nannoceratopsis gracilis* – *Nannoceratopsis senex* Assemblage Zone and the *Sentusidinium pelionense* Assemblage Zone) with palynomorph assemblages in the North Atlantic region that have been recorded either from sections dated directly by ammonites or from sections that can be reliably correlated to successions with good ammonite control.

No major changes have been detected in the miospore and microplankton assemblages across the lower boundary of the Sortehat Formation. This confirms the suggestion by Underhill & Partington (1994) that the boundary between the Ostreaelv Formation and the Sortehat Formation does not represent a biostratigraphically significant hiatus surface.

The change in depositional environment from the sandy, shallow marine deposits of the Ostreaelv Formation to the mudstones of the Sortehat Formation records a marine drowning event. This sharp lithological boundary is broadly coincident with an influx of *Botryococcus* (the *Botryococcus* Assemblage Zone). The abundant occurrence of the freshwater green alga *Botryococcus* together with marine dinoflagellate cysts is suggested to represent an allochthonous accumulation of *Botryococcus* in a marine environment caused by seawards transport of material from an inland freshwater environment during the marine transgression.

In general, there is an increase in the marine signal passing up-section from the *Botryococcus* Assemblage Zone, as testified by the diversification of marine microplankton in the *Nannoceratopsis gracilis* – *Nannoceratopsis senex* Assemblage Zone associated with a decrease in the proportion of spores and the disappearance of *Botryococcus*. In the uppermost part of the Sortehat Formation (the upper part of the *Sentusidinium pelionense* Assemblage Zone), the palynomorph assem-

blages become poor in diversity and richness, suggesting more stressed conditions, but dinoflagellate cysts continue into the sandy Pelion Formation.

Acknowledgements

This study was supported by a grant from the Danish Energy Research Programme (EFP-93, projects 1313/93-0010, -0017) to the Geological Survey of Greenland. We are grateful to David J. Batten, Karen Dybkjær, Jon R. Ineson, Henrik Nøhr-Hansen, Stefan Piasecki and Finn Surlyk for discussion and critical reading of the manuscript and to Henrik Nøhr-Hansen in particular for patient assistance with the distribution charts.

References

- Batten, D.J. & Grenfell, H.R. 1996: *Botryococcus*. In: Jansonius, J. & McGregor, D.C. (eds): Palynology: principles and applications. American Association of Stratigraphic Palynologists Foundation **1**, 205–214.
- Batten, D.J., Koppelhus, E.B. & Nielsen, L.H. 1994: Uppermost Triassic to Middle Jurassic palynofacies and *palynomiscellanea* in the Danish Basin and Fennoscandian Border Zone. *Cahiers de Micropaléontologie* **9**, 21–45.
- Bjærke, T. 1980: Mesozoic palynology of Svalbard IV. Toarcian dinoflagellates from Spitsbergen. *Palynology* **4**, 57–77.
- Bujak, J.P. & Williams, G.L. 1977: Jurassic palynostratigraphy of offshore Eastern Canada. In: Swain, F.M. (ed.): Stratigraphic micropaleontology of Atlantic Basin and borderlands, 321–339. Amsterdam: Elsevier.
- Callomon, J.H. 1993: The ammonite succession in the Middle Jurassic of East Greenland. *Bulletin of the Geological Society of Denmark* **40**, 83–113.
- Dam, G. & Surlyk, F. 1995: Sequence stratigraphic correlation of Lower Jurassic shallow marine and paralic successions across the Greenland–Norway seaway. In: Steel, R.J. *et al.* (eds): Sequence stratigraphy on the Northwest European margin. Norwegian Petroleum Society (NPF) Special Publication **5**, 483–509.
- Dam, G. & Surlyk, F. 1998: Stratigraphy of the Neill Klintner Group; a Lower – lower Middle Jurassic tidal embayment succession, Jameson Land, East Greenland. *Geology of Greenland Survey Bulletin* **175**, 80 pp.
- Davies, E.H. 1983: The dinoflagellate Opper-zonation of the Jurassic – Lower Cretaceous sequence in the Sverdrup Basin, Arctic Canada. *Geological Survey of Canada Bulletin* **359**, 60 pp.
- de Raaf, J.F.M., Boersma, J.R. & van Gelder, A. 1977: Wave-generated structures and sequences from a shallow marine succession, Lower Carboniferous, County Cork, Ireland. *Sedimentology* **24**, 451–483.
- Dominguez, J.M.L. & Wanless, H.R. 1991: Facies architecture of a falling sea-level strandplain, Doce River coast, Brazil. In: Swift, D.J. *et al.* (eds): Shelf sand and sandstone bodies. International

- Association of Sedimentologists Special Publication **14**, 259–281.
- Dörhöfer, G. & Davies, E.H. 1980: Evolution of archeopyle and tabulation in rhaetogonyaulacinean dinoflagellate cysts. Life Sciences Miscellaneous Publications 1979, 91 pp. Toronto: Royal Ontario Museum.
- Doyle, P. 1991: Belemnites from the Lower Jurassic of East Greenland and their biostratigraphical and biogeographical significance. Bulletin of the Geological Society of Denmark **39**, 123–141.
- Dybkjær, K. 1991: Palynological zonation and palynofacies investigation of the Fjerritslev Formation (Lower Jurassic – basal Middle Jurassic) in the Danish Subbasin. Danmarks Geologiske Undersøgelse Serie A **30**, 150 pp.
- Engkilde, M. 1994: The Middle Jurassic Vardekloft Formation, East Greenland: depositional environments and sequence stratigraphy of shallow marine sandstones deposited in a low-gradient epeiric seaway, 207 pp. Unpublished Ph.D. thesis, University of Copenhagen, Denmark.
- Engkilde, M. & Surlyk, F. 1993: The Middle Jurassic Vardekloft Formation of East Greenland – analogue for reservoir units of the Norwegian shelf and the northern North Sea. In: Parker, J.R. (ed.): Petroleum geology of Northwest Europe: proceedings of the 4th conference, 533–542. London: Geological Society.
- Engkilde, M. & Surlyk, F. 2003: Shallow marine syn-rift sedimentation: Middle Jurassic Pelion Formation, Jameson Land, East Greenland. In: Ineson, J.R. & Surlyk, F. (eds): The Jurassic of Denmark and Greenland. Geological Survey of Denmark and Greenland Bulletin **1**, 813–863 (this volume).
- Feist-Burkhardt, S. 1990: Dinoflagellate cyst assemblages of the Hausen coreholes (Aalenian to early Bajocian), south-west Germany. Bulletin des Centres de Recherches Exploration-Production Elf-Aquitaine **14**, 611–633.
- Fensome, R.A. 1979: Dinoflagellate cysts and acritarchs from the Middle and Upper Jurassic of Jameson Land, East Greenland. Bulletin Grønlands Geologiske Undersøgelse **132**, 98 pp.
- Gorin, G.E. & Steffen, D. 1991: Organic facies as a tool for recording eustatic variations in marine fine-grained carbonates – example of the Berriasian stratotype at Berrias (Ardèche, SE France). Palaeogeography, Palaeoclimatology, Palaeoecology **85**, 303–320.
- Guy-Ohlson, D. 1992: *Botryococcus* as an aid in interpretation of palaeoenvironment and depositional processes. Review of Palaeobotany and Palynology **71**, 1–15.
- Guy-Ohlson, D. 1994: Palaeoenvironmental interpretation of Aalenian and Bajocian transition sediments in Sweden. Miscellanea del Servizio Geologico Nazionale **5**, 297–304.
- Guy-Ohlson, D. & Norling, E. 1994: Jurassic sequences in Sweden. Geobios **17**, 275–286.
- Hansen, C.F. 1999: Sedimentology, sequence stratigraphy and geochemistry of the Sortehat Formation, Jameson Land, East Greenland **1–3**, 167 pp. Unpublished Ph.D. thesis, University of Copenhagen, Denmark.
- Hansen, C.F. & Surlyk, F. 1994: A major marine flooding surface associated with change from fully to restricted marine conditions in an intracratonic rift basin (Lower/Middle Jurassic Sortehat Formation, East Greenland). In: Johnson, S.D. (ed.): High resolution sequence stratigraphy: innovations and applications, Liverpool University, UK, 28–30 March, 1994. Abstracts, 379–381.
- Johnson, C.D. & Hills, L.V. 1973: Microplankton zones of the Savik Formation (Jurassic), Axel Heiberg and Ellesmere Islands, District of Franklin. Bulletin of Canadian Petroleum Geology **21**, 178–218.
- Koppelhus, E.B. & Batten, D.J. 1996: Applications of a palynomorph zonation to a series of short borehole sections, Lower to Middle Jurassic, Øresund, Denmark. In: Jansonius, J. & McGregor, D.C. (eds): Palynology: principles and applications. American Association of Stratigraphic Palynologists Foundation **2**, 779–793.
- Koppelhus, E.B. & Dam, G. 2003: Palynostratigraphy and palaeoenvironments of the Rævekløft, Gule Horn and Ostreelv Formations (Lower–Middle Jurassic), Neill Klint Group, Jameson Land, East Greenland. In: Ineson, J.R. & Surlyk, F. (eds): The Jurassic of Denmark and Greenland. Geological Survey of Denmark and Greenland Bulletin **1**, 723–775 (this volume).
- Koppelhus, E.B. & Nielsen L.H. 1994: Palynostratigraphy and palaeoenvironments of the Lower to Middle Jurassic Bagå Formation of Bornholm, Denmark. Palynology **18**, 139–194.
- Krabbe, H., Christiansen, F.G., Dam, G., Piasecki, S. & Stemmerik, L. 1994: Organic geochemistry of the Lower Jurassic Sortehat Formation, Jameson Land, East Greenland. Rapport Grønlands Geologiske Undersøgelse **164**, 5–18.
- Leckie, D.A., Chaitanya, S., Bloch, J., Wilson, M. & Wall, J. 1992: An anoxic event at the Albian–Cenomanian boundary: the Fish Scale Marker Bed, northern Alberta, Canada. Palaeogeography, Palaeoclimatology, Palaeoecology **92**, 139–166.
- Lund, J.J. & Pedersen, K.R. 1985: Palynology of the marine Jurassic formations in the Vardekloft ravine, Jameson Land, East Greenland. Bulletin of the Geological Society of Denmark **33**, 371–400.
- Noe-Nygaard, N., Surlyk, F. & Piasecki, S. 1987: Bivalve mass mortality caused by toxic dinoflagellate blooms in a Berriasian–Valanginian lagoon, Bornholm, Denmark. Palaios **2**, 263–273.
- Nøhr-Hansen, H. 1993: Dinoflagellate cyst stratigraphy of the Barremian to Albian, Lower Cretaceous, North-East Greenland. Bulletin Grønlands Geologiske Undersøgelse **166**, 171 pp.
- Piasecki, S. 1984: Dinoflagellate cyst stratigraphy of the Lower Cretaceous Jydegård Formation, Bornholm, Denmark. Bulletin of the Geological Society of Denmark **32**, 145–161.
- Piasecki, S. 1986: Palynological analysis of the organic debris in the Lower Cretaceous Jydegård Formation, Bornholm, Denmark. Grana **25**, 119–129.
- Poulsen, N.E. 1994: Dinoflagellate cyst biostratigraphy of Rhaetian–Ryazanian (uppermost Triassic – lowermost Cretaceous) deposits from the Danish Subbasin. Geobios **17**, 409–414.
- Poulsen, N.E. & Riding, J.B. 2003: The Jurassic dinoflagellate cyst zonation of Subboreal Northwest Europe. In: Ineson, J.R. & Surlyk, F. (eds): The Jurassic of Denmark and Greenland. Geological Survey of Denmark and Greenland Bulletin **1**, 115–144 (this volume).
- Prauss, M. 1989: Dinozysten-Stratigraphie und Palynofazies im Oberen Lias und Dogger von NW-Deutschland. Palaeontographica B **214**, 124 pp.
- Prauss, M. & Riegel, W. 1989: Evidence from phytoplankton associations for causes of black shale formation in epicontinental seas. Neues Jahrbuch für Geologie und Paläontologie Monatshefte **1989/11**, 671–682.

- Riding, J.B. 1982: Jurassic dinocysts from the Warboys Borehole, Cambridgeshire, England. *Journal of Micropalaeontology* **1**, 13–18.
- Riding, J.B. 1983: The palynology of the Aalenian (Middle Jurassic) sediments of Jackdaw Quarry, Gloucestershire, England. *The Mercian Geologist* **9**, 111–120.
- Riding, J.B. 1984a: Observations on the Jurassic dinoflagellate cyst *Nannoceratopsis ambonis* Drugg, 1978. *Journal of Micropalaeontology* **3**, 75–79.
- Riding, J.B. 1984b: A palynological investigation of Toarcian to Aalenian strata from the Blea Wyke area, Ravenscar, North Yorkshire. *Proceedings of the Yorkshire Geological Society* **45**, 109–122.
- Riding, J.B. 1984c: Dinoflagellate cyst range-top biostratigraphy of the uppermost Triassic to lowermost Cretaceous of north-west Europe. *Palynology* **8**, 195–210.
- Riding, J.B. 1987: Dinoflagellate cyst stratigraphy of the Nettleton Bottom Borehole (Jurassic: Hettangian to Kimmeridgian), Lincolnshire, England. *Proceedings of the Yorkshire Geological Society* **46**, 231–266.
- Riding, J.B. & Thomas, J.E. 1992: Dinoflagellate cysts of the Jurassic system. In: Powell, A.J. (ed.): *A stratigraphic index of dinoflagellate cysts*, 7–97. British Micropalaeontological Society Publication Series. London: Chapman & Hall.
- Riding, J.B., Walton, W. & Shaw, D. 1991: Toarcian to Bathonian (Jurassic) palynology of the Inner Hebrides, Northwest Scotland. *Palynology* **15**, 115–179.
- Rosenkrantz, A. 1934: The Lower Jurassic rocks of East Greenland. Part I. *Meddelelser om Grønland* **110**(1), 150 pp.
- Seidenkrantz, M.-S., Koppelhus, E.B. & Ravn-Sørensen, H. 1993: Biostratigraphy and palaeoenvironmental analysis of a Lower to Middle Jurassic succession on Anholt, Denmark. *Journal of Micropalaeontology* **12**, 201–218.
- Smelror, M. 1994: Jurassic stratigraphy of the western Barents Sea region: a review. *Geobios* **17**, 441–451.
- Smelror, M. & Below, R. 1992: Dinoflagellate biostratigraphy of the Toarcian to Lower Oxfordian (Jurassic) of the Barents Sea region. *Norwegian Petroleum Society (NPF) Special Publication* **2**, 495–513.
- Smelror, M., Jacobsen, T., Rise, L., Skarbø, O., Verdenius, J.G. & Vigran, J.O. 1994: Jurassic to Cretaceous stratigraphy of shallow cores on the Møre Basin margin, mid-Norway. *Norsk Geologisk Tidsskrift* **74**, 89–107.
- Surlyk, F. 1990a: Timing, style and sedimentary evolution of Late Palaeozoic – Mesozoic extensional basins of East Greenland. In: Hardman, R.F.P. & Brooks, J. (eds): *Tectonic events responsible for Britain's oil and gas reserves*. Geological Society Special Publication (London) **55**, 107–125.
- Surlyk, F. 1990b: A Jurassic sea-level curve for East Greenland. *Palaeogeography, Palaeoclimatology, Palaeoecology* **78**, 71–85.
- Surlyk, F. 2003: The Jurassic of East Greenland: a sedimentary record of thermal subsidence, onset and culmination of rifting. In: Ineson, J.R. & Surlyk, F. (eds): *The Jurassic of Denmark and Greenland*. Geological Survey of Denmark and Greenland Bulletin **1**, 659–722 (this volume).
- Surlyk, F., Callomon, J.H., Bromley, R.G. & Birkelund, T. 1973: Stratigraphy of the Jurassic – Lower Cretaceous sediments of Jameson Land and Scoresby Land, East Greenland. *Bulletin Grønlands Geologiske Undersøgelse* **105**, 76 pp.
- Surlyk, F., Clemmensen, L.B. & Larsen, H.C. 1981: Post-Paleozoic evolution of the East Greenland continental margin. In: Kerr, J.W., Ferguson, A.J. & Machan, L.C. (eds): *Geology of the North Atlantic borderlands*. Canadian Society of Petroleum Geologists Memoir **7**, 611–645.
- Surlyk, F., Arndorff, L., Hamann, N.-E., Hamberg, L., Johannessen, P.N., Koppelhus, E.B., Nielsen, L.H., Noe-Nygaard, N., Pedersen, G.K. & Petersen, H.I. 1995: High-resolution sequence stratigraphy of a Hettangian–Sinemurian paralic succession, Bornholm, Denmark. *Sedimentology* **42**, 323–354.
- Tyson, R.V. 1995: *Sedimentary organic matter. Organic facies and palynofacies*, 615 pp. London: Chapman & Hall.
- Underhill, J.R. & Partington, M.A. 1994: Use of genetic sequence stratigraphy in defining and determining a regional tectonic control on the “mid-Cimmerian unconformity” – implications for North Sea basin development and the global sea-level chart. In: Weimer, P. & Posamentier, H.W. (eds): *Siliciclastic sequence stratigraphy. Recent developments and applications*. American Association of Petroleum Geologists Memoir **58**, 449–484.
- Wells, J.T. & Coleman, J.M. 1987: Wetland loss and the subdelta life cycle. *Estuarine, Coastal and Shelf Science* **25**, 111–125.
- Williams, G. 1992: Palynology as a palaeoenvironmental indicator in the Brent Group, northern North Sea. In: Morton, A.C. *et al.* (eds): *Geology of the Brent Group*. Geological Society Special Publication (London) **61**, 203–212.
- Woollam, R. & Riding, J.B. 1983: *Dinoflagellate cyst zonation of the English Jurassic*. Institute of Geological Sciences Report **83/2**, 42 pp. London: Her Majesty's Stationery Office.

Appendix 1: Locality information and Geological Survey of Greenland (GGU) numbers of samples used in this study

Albuen

Location. 70°34'10"N, 22°38'54"W.

Section datum. The boundary between the Ostreaelv and the Sortehat Formations is the datum for the measured section and is located 440 m above sea level.

Sample numbers. GGU 397452–397498, 398501, 398507, 398509, 398513.

Sortehat borehole

Location. 70°53'50"N, 22°49'56"W.

Section datum. For the drill-core, an arbitrary datum was defined 80 m below the top of the borehole. The boundary between the Ostreaelv and the Sortehat Formations occurs 27.6 m above this datum.

Sample numbers. GGU 303143-11–303143-80.

Lepidopteriselv

Location. 71°15'12"N, 22°37'04"W.

Section datum. The boundary between the Ostreaelv and the Sortehat Formations, which forms the datum for the section, lies at c. 810 m above sea level.

Sample numbers. GGU 398151–398199.

Enhjørningen Dal

Two sections were measured in Enhjørningen Dal; Figure 7 is a composite of these sections. The boundary between the Ostreaelv and the Sortehat Formations, at 418 m above sea level, is the datum for the composite section.

West Enhjørningen Dal

Location. 71°26'53"N, 23°25'41"W; the northernmost of two small ravines.

Sample numbers. GGU 398203–398299, 398308–398372.

East Enhjørningen Dal

Location. 71°26'14"N, 23°21'52"W; the northernmost of two small ravines.

Sample numbers. GGU 395616–395668, 398417–398448.

Pelion

Location. 71°28'N, 23°19'W.

Sample numbers. GGU 339702–339711. These samples were collected by Lars Stemmerik in 1990.

Appendix 2: List of all recorded palynomorph taxa

Miospores:

- Alisporites robustus* Nilsson 1958
Apiculatisporites spp.
Araucariacites australis Cookson 1947
Baculatisporites comaumensis (Cookson) Potonié 1956
 (Plate 1, fig. 3)
B. spp.
 Bisaccates indeterminate
Callialasporites dampieri (Balme) Dev 1961 (Plate 2, fig. 1)
C. microvelatus Schulz 1966 (Plate 2, fig. 3)
C. minus (Tralau) Guy 1971
C. segmentatus (Balme) Dev 1961
C. trilobatus (Balme) Dev 1961
C. turbatus (Balme) Schulz 1967 (Plate 2, fig. 2)
C. spp.
Calamospora tener (Leschik) Mädlar 1964
Camarozonasporites spp.
Cerebropollenites macroverrucosus (Thiergart) Schulz 1967
 (Plate 3, fig. 3)
C. thiergartii Schulz 1967
Chasmatosporites apertus Nilsson 1958
C. hians Nilsson 1958 (Plate 2, fig. 4)
C. major Nilsson 1958 (Plate 2, fig. 6)
Chomotriletes minor (Kedves) Pocock 1970 (Plate 4, fig. 1)
Cibotiumspora jurienensis (Balme) Filatoff 1975
Conbaculatisporites mesozoicus Klaus 1960
C. spp.
Concavissimisporites spp.
Corollina torosus (Reissinger) Cornet & Traverse 1975
 (Plate 3, fig. 2)
C. spp.
Deltoidospora minor (Couper) Pocock 1970
D. spp.
D. toralis (Leschik) Lund 1977
Densoisporites scanicus Tralau 1968
D. velatus Weyland & Krieger 1953
Densosporites spp.
Eucommiidites troedsonii Erdtman 1948
Exesipollenites tumulus Balme 1957 (Plate 3, fig. 1)
Foraminisporis jurassicus Schulz 1967
 Fungal spores
Iraqispora labrata Singh 1964
Ischyosporites crateris Balme 1957
I. spp. (Plate 1, fig. 6)
I. variegatus (Couper) Schulz 1967
Kekryphalospora distincta Fenton & Riding 1987
Kraeuselisporites reissingeri (Harris) Morbey 1975
Leptolepidites bossus (Couper) Schulz 1967
L. major Couper 1958
L. spp.
Limboisporites lundbladii Nilsson 1958
Lycopodiacidites rugulatus (Couper) Schulz 1967
Manumia delcourtii (Pocock) Dybkjær 1991 (Plate 1, fig. 8)
 Megaspore fragments
 Monosaccate pollen
Monosulcites spp.
Murospora spp.
Neoraistrickia gristhorpensis (Couper) Tralau 1967
N. taylorii Playford & Dettmann 1965
N. spp.
Perinopollenites elatoides Couper 1958 (Plate 2, fig. 5)
Pinuspollenites minimus (Couper) Kemp 1970 (Plate 3, fig. 6)
Polycingulatisporites circulus Simoncsics & Kedves 1961
Polycingulatisporites triangularis (Bolkhovitina) Playford & Dettmann 1965
Quadraeculina anellaeformis Malyavkina 1949 (Plate 3, fig. 5)
Retitrites austroclavatidites (Cookson) Döring *et al.* 1963
 (Plate 1, fig. 1)
R. clavatoides (Couper) Döring *et al.* 1963 (Plate 1, fig. 2)
R. semimuris (Danzé-Corsin & Laveine) McKellar 1974
R. spp.
Ricciisporites tuberculatus Lundblad 1954
Rogalskaisporites cicatricosus (Rogalska) Danzé-Corsin & Laveine 1963
Sestrosporites pseudoalveolatus (Couper) Dettmann 1963
Spheripollenites psilatus Couper 1958
S. spp. (Plate 3, fig. 4)
S. subgranulatus Couper 1958
Staplinisporites caminus (Balme) Pocock 1970 (Plate 1, fig. 5)
S. spp.
Stereisporites stereoides (Potonié & Venitz) H.D. Pflug in: Thomson & Pflug 1953
Striatella jurassica Mädlar 1964b (Plate 1, fig. 4)
S. parva (Li & Shang) Filatoff & Price 1988
S. seebergensis Mädlar 1964b
S. spp.
 Striate spp.
Taeniasporites rhaeticus Schulz 1967
T. spp.
Taurocusporites verrucatus Schulz 1967
T. spp.
Tigrisporites spp.
Todisporites major Couper 1958
T. minor Couper 1958
Triancoraesporites spp.
 Trilete spp.
Tripartina variabilis Malyavkina 1949 (Plate 1, fig. 7)

Uvaesporites puzzlei Guy 1971

U. spp.

Vesicaspora fuscus (Pautsch) Morbey 1975

Vitreisporites pallidus (Reissinger) Nilsson 1958

Zebraesporites laevigatus (Schulz) Schulz 1967

Phytoplankton:

Acritarch spp.

Andreedinium arcticum Below 1987

Beaumontella caminuspina (Wall) Below 1987

Botryococcus spp. (Plate 4, fig. 4)

Chytroesphaeridia chytroeoides (Sarjeant) Downie & Sarjeant 1965

Cymatiosphaera spp.

Dinocyst spp.

Dissilodinium spp. (Plate 6, figs 2, 4)

Dodekovia tegillata Prauss 1989

Foraminiferal linings (Plate 4, fig. 3)

Fungal spp.

Kallosphaeridium spp.

Lecaniella foveata Singh 1971

Leiosphaeridia spp.

Limbicysta bjaerkei (Smelror) MacRae *et al.* 1996

Mancodinium semitabulatum Morgenroth 1970 (Plate 6, fig. 1)

M. spp.

Mendicodinium groenlandicum (Pocock & Sarjeant) Davey 1979 (Plate 6, fig. 3)

M. reticulatum Morgenroth 1970

M. spp.

Miscellaneous

Nannoceratopsis ambonis Drugg 1978 (Plate 5, fig. 3)

N. gracilis Alberti emend. van Helden 1977 (Plate 5, fig. 1)

N. plegas Drugg 1978 (Plate 5, fig. 4)

N. ridingii Poulsen 1992

N. senex van Helden 1977 (Plate 5, fig. 2)

N. spp.

N. triangulata Prauss 1987

N. tricerias Drugg 1978

Pareodinia ceratophora Deflandre 1947

P. halosa (Filatoff) Prauss 1989 (Plate 4, fig. 6)

P. spp.

Parvocysta barbata Bjærke 1980

P. spp.

Phallocysta eumekes Dörhöfer & Davies 1980

P. thomasi Smelror 1991

P. spp.

Pterospermella spp

Scrinocassis weberi Gocht 1964

S. spp.

Sentusidinium pelionense Fensome 1979 (Plate 6, figs 5, 6)

S. spp.

Susadinium scrofoides (Dörhöfer & Davies) Below 1987

Tasmanites spp.

Valensiella ovulum (Deflandre) Eisenack 1963

Verybanchium collectum Wall 1965

V. formosum Stockmans & Williere 1960

V. sortehatense Fensome 1979 (Plate 4, fig. 2)

V. spp.

Walloodinium laganum Feist-Burkhardt & Monteil 1994 (Plate 4, fig. 5)

Plates 1–6

Plate 1

Figs 1–4 and 6–8 are from the Lepidopteriselv section, fig. 5 is from the borehole at Sortehat, the type locality of the Sortehat Formation. Scale bar is 10 microns. For each of the illustrated specimens, the EFR (England Finder Reference) is given.

Fig. 1. *Retitriletes austroclavatidites*.

Sample 398181, slide 3, EFR E36.

Fig. 2. *Retitriletes clavatoides*.

Sample 398181, slide 3, EFR F50.

Fig. 3. *Baculatisporites comaumensis*.

Sample 398158, slide 4, EFR S26.

Fig. 4. *Striatella jurassica*.

Sample 398158, slide 5, EFR K271.

Fig. 5. *Staplinisporites caminus*.

Sample 303143-26, slide 3, EFR J51.

Fig. 6. *Ischyosporites* sp.

Sample 398189, slide 4, EFR M40.

Fig. 7. *Tripartina variabilis*.

Sample 398189, slide 4, EFR R43.

Fig. 8. *Manumia delcourtii*.

Sample 398192, slide 4, EFR W383.

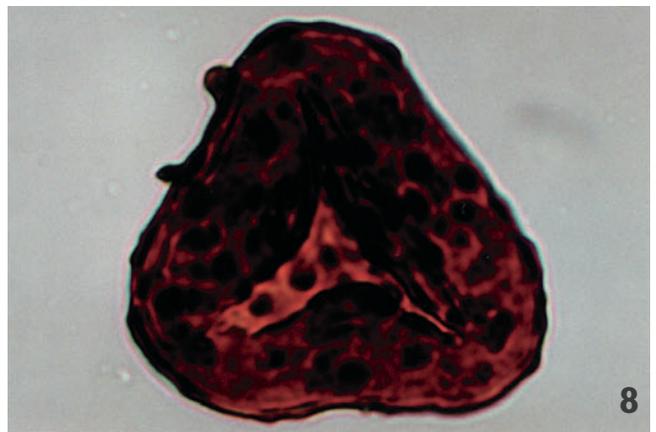
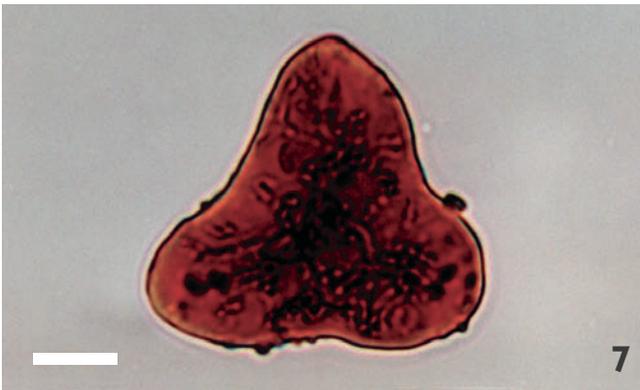
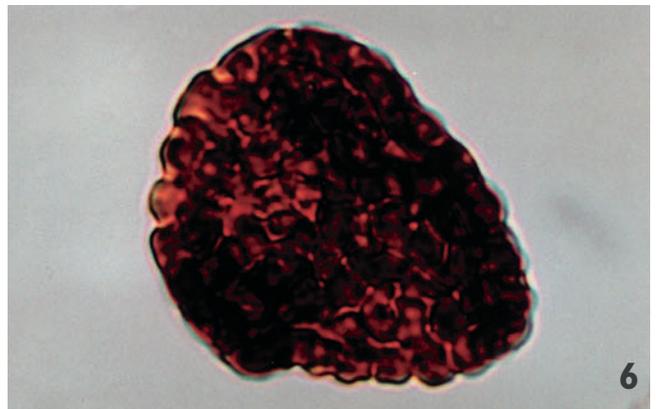
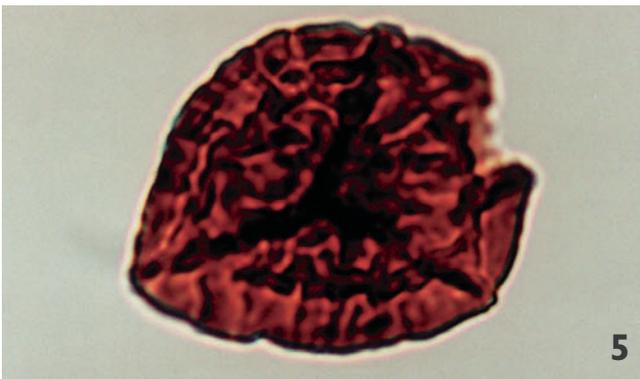
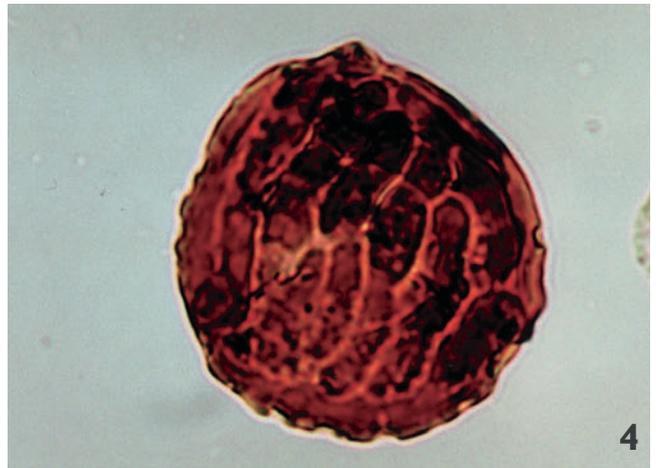
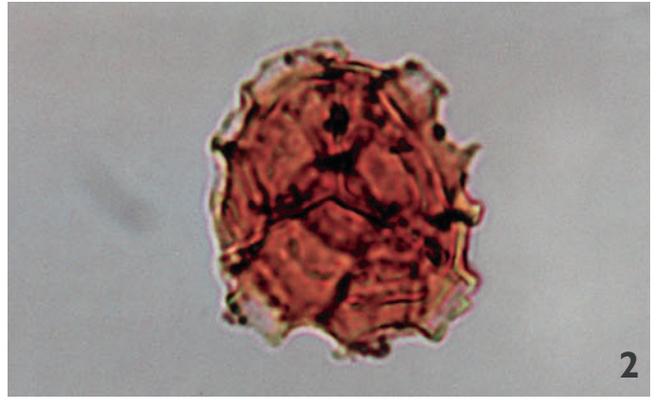
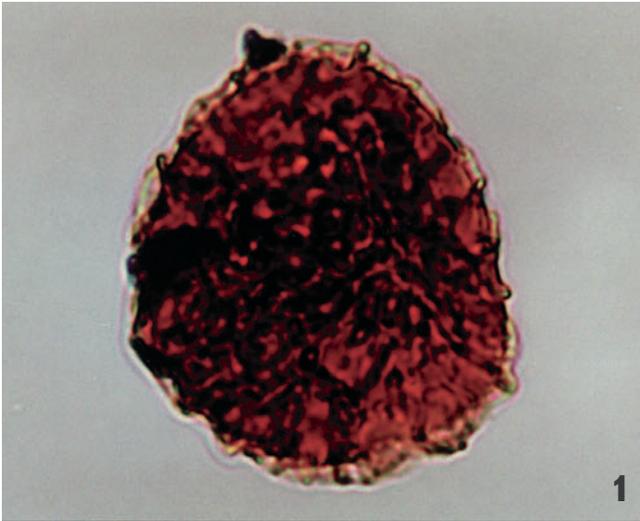


Plate 2

Figs 1 and 4–6 are from the borehole at Sortehat, figs 2 and 3 are from the Lepidopterisely section. Scale bar is 10 microns.

Fig. 1. *Callialasporites dampieri*.
Sample 303143-46, slide 3, EFR F222.

Fig. 2. *Callialasporites turbatus*.
Sample 398158, slide 4, EFR P25.

Fig. 3. *Callialasporites microvelatus*.
Sample 398158, slide 4, EFR H382.

Fig. 4. *Chasmatosporites hians*.
Sample 303143-46, slide 3, EFR L42.

Fig. 5. *Perinopollenites elatoides*.
Sample 303143-13, slide 3, EFR N25.

Fig. 6. *Chasmatosporites major*.
Sample 303143-46, slide 3, EFR K43.

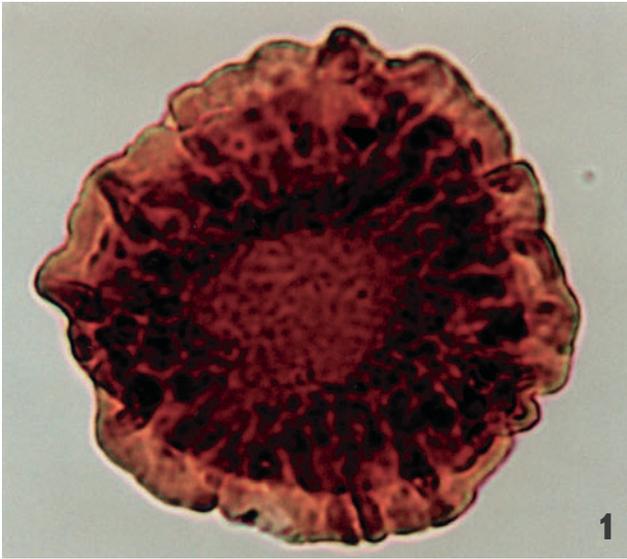


Plate 3

Figs 1, 2, 5 and 6 are from the Lepidopteriselv section, figs 3 and 4 are from the borehole at Sortehat. Scale bar is 10 microns.

Fig. 1. *Exesipollenites tumulus*.

Sample 398181, slide 3, EFR J362.

Fig. 2. *Corollina torosus*.

Sample 398158, slide 5, EFR M33.

Fig. 3. *Cerebropollenites macroverrucosus*.

Sample 303143-40, slide 3, EFR F24.

Fig. 4. *Spheripollenites* sp.

Sample 303143-46, slide 3, EFR W20.

Fig. 5. *Quadraeculina anellaeformis*.

Sample 398158, slide 4, EFR S384.

Fig. 6. *Pinuspollenites minimus*.

Sample 398158, slide 5, EFR D522.

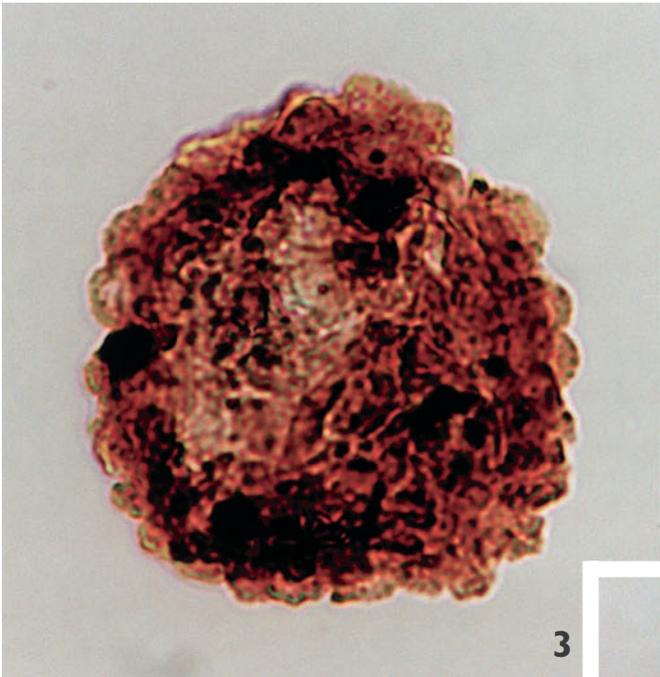


Plate 4

Figs 1, 2 and 6 are from the borehole at Sortehat, figs 3–5 are from the Lepidopteriselv section. Scale bar is 10 microns.

Fig. 1. *Chomotriletes minor*.

Sample 303143-46, slide 3, EFR K46.

Fig. 2. *Verybachium sortehatense*.

Sample 303143-46, slide 3, EFR H22.

Fig. 3. Foraminiferal inner lining.

Sample 398158, slide 4, EFR H31.

Fig. 4. *Botryococcus* sp.

Sample 398189, slide 4, EFR E492.

Fig. 5. *Wallostinium laganum*.

Sample 398194, slide 4, EFR Z39.

Fig. 6. *Pareodinia halosa*.

Sample 303143-26, slide 3, EFR M51.

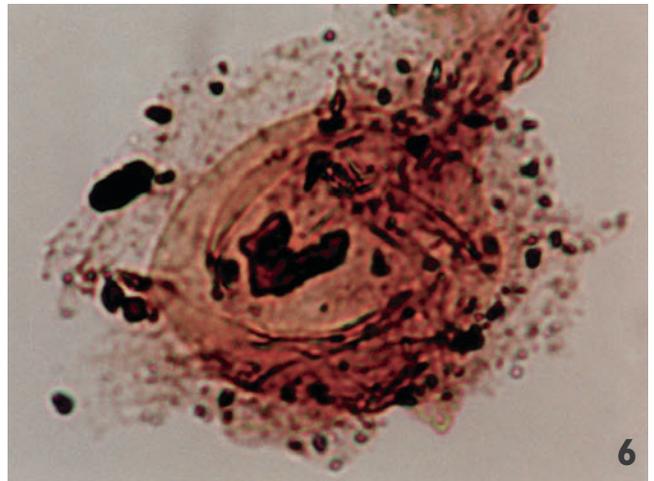
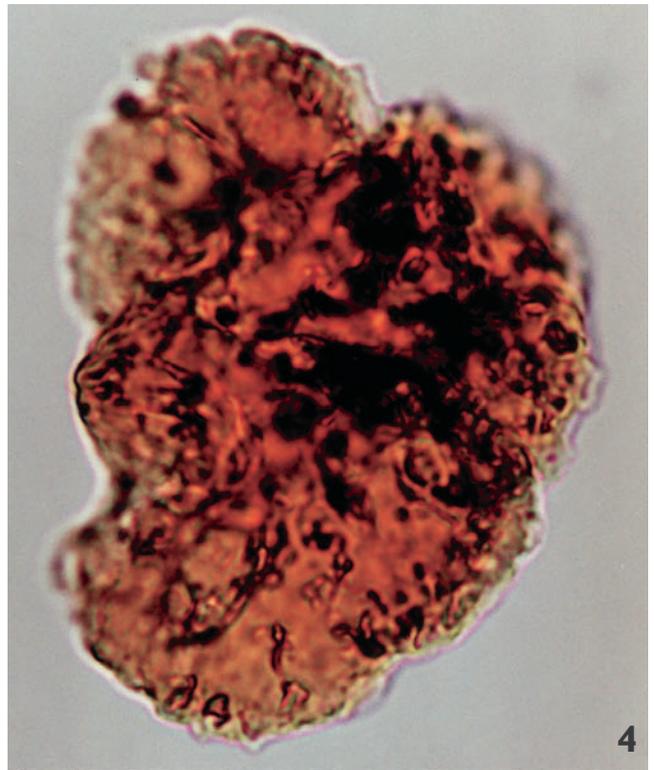
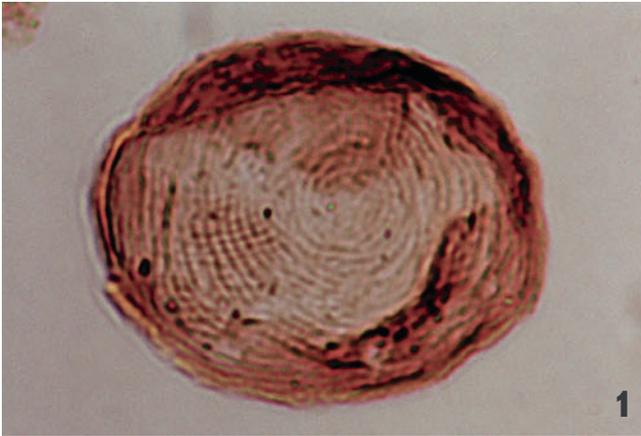


Plate 5

Fig. 1 is from the Lepidopteriselv section, figs 2–4 are from the borehole at Sortehat. Scale bar is 10 microns.

Fig. 1. *Nannoceratopsis gracilis*.

Sample 398158, slide 4, EFR H54.

Fig. 2. *Nannoceratopsis senex*.

Sample 303143-40, slide 3, EFR S363.

Fig. 3. *Nannoceratopsis ambonis*.

Sample 303143-46, slide 3, EFR J40.

Fig. 4. *Nannoceratopsis plegas*.

Sample 303143-40, slide 3, EFR M482.

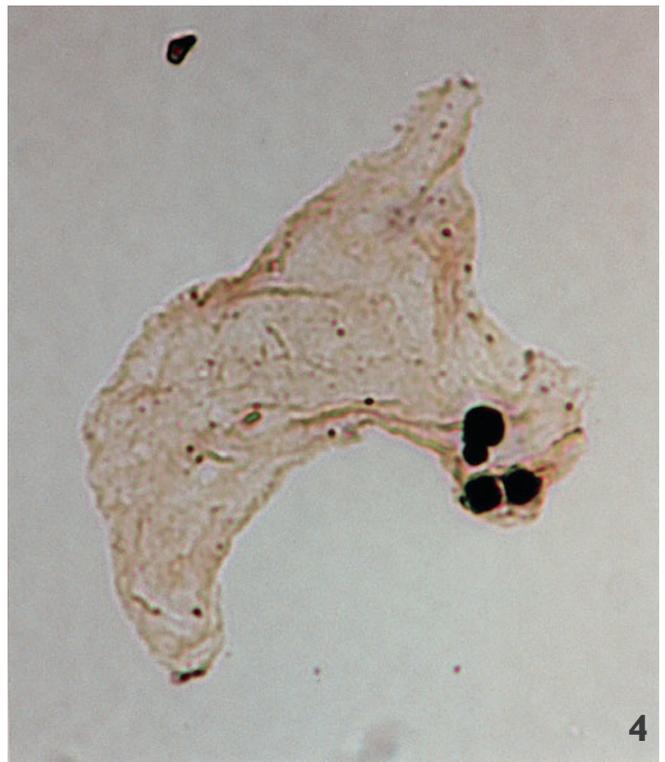


Plate 6

Figs 1, 2 and 4–6 are from the borehole at Sortehat, fig. 3 is from the Lepidopteris selv section. Scale bar is 10 microns.

Fig. 1. *Mancodinium semitabulatum*.

Sample 303143-46, slide 3, EFR S264.

Fig. 2. *Dissilodinium* sp.

Sample 303143-30, slide 3, EFR K324.

Fig. 3. *Mendicodinium groenlandicum*.

Sample 398158, slide 5, EFR R39.

Fig. 4. *Dissilodinium* sp.

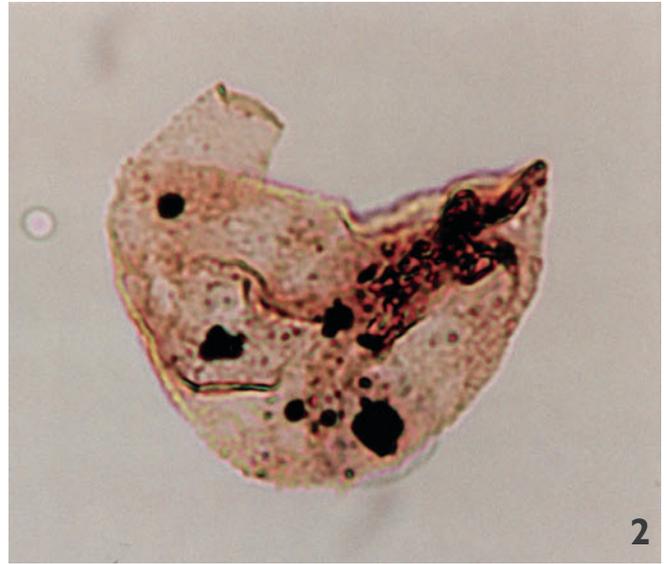
Sample 303143-26, slide 3, EFR C54.

Fig. 5. *Sentusidinium pelionense*.

Sample 303143-20, slide 3, EFR M51.

Fig. 6. *Sentusidinium pelionense*.

Sample 303143-26, slide 3, EFR E53.



Albuen (A)

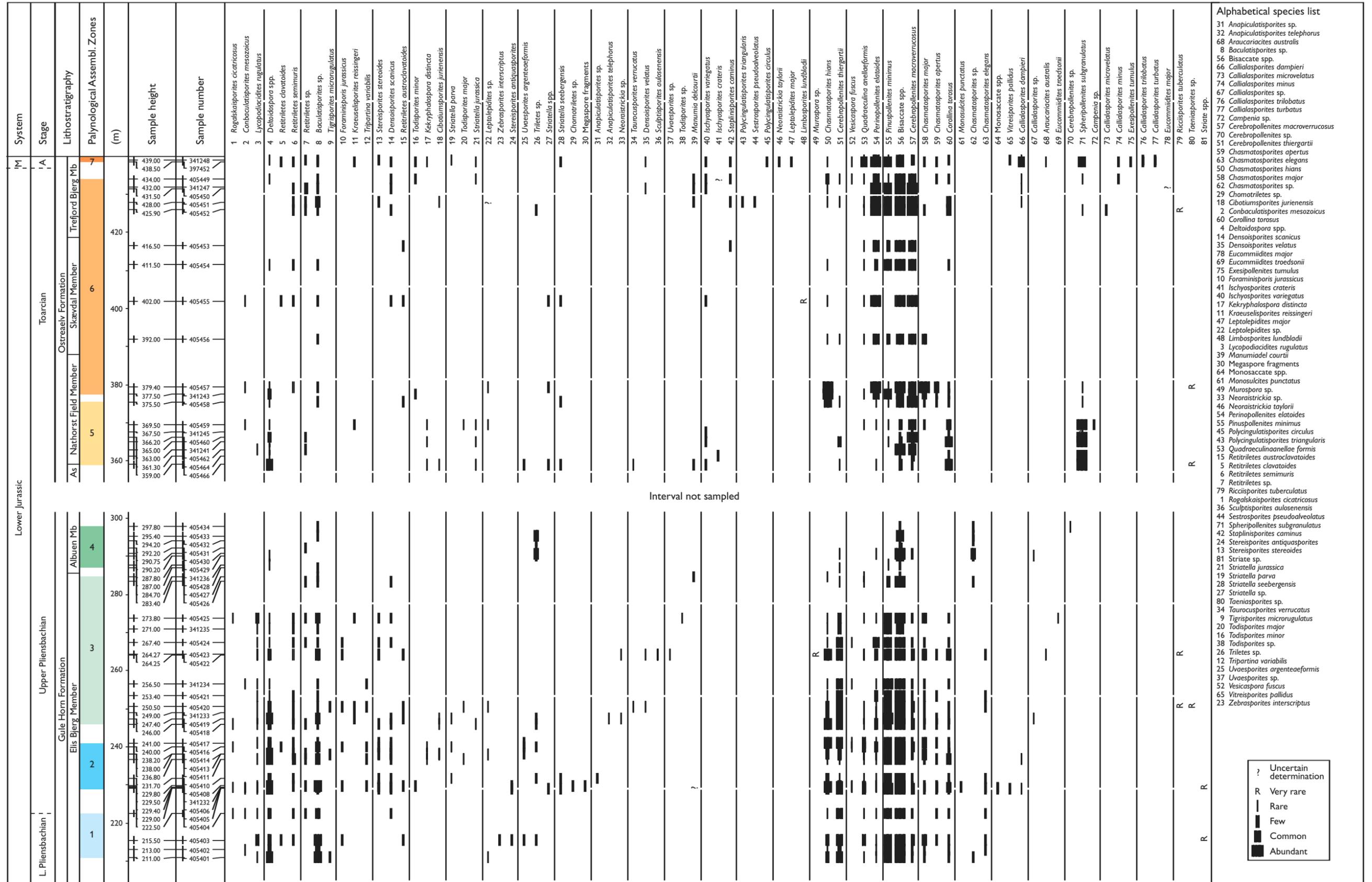


Fig. 4A. Terrestrial palynomorph distribution chart for the Gule Horn and Ostreaelv Formations at Albuen (for location, see Fig. 1). M, Middle Jurassic; A, Aalenian; AS, Astartekloft Member.

Albuen (B)

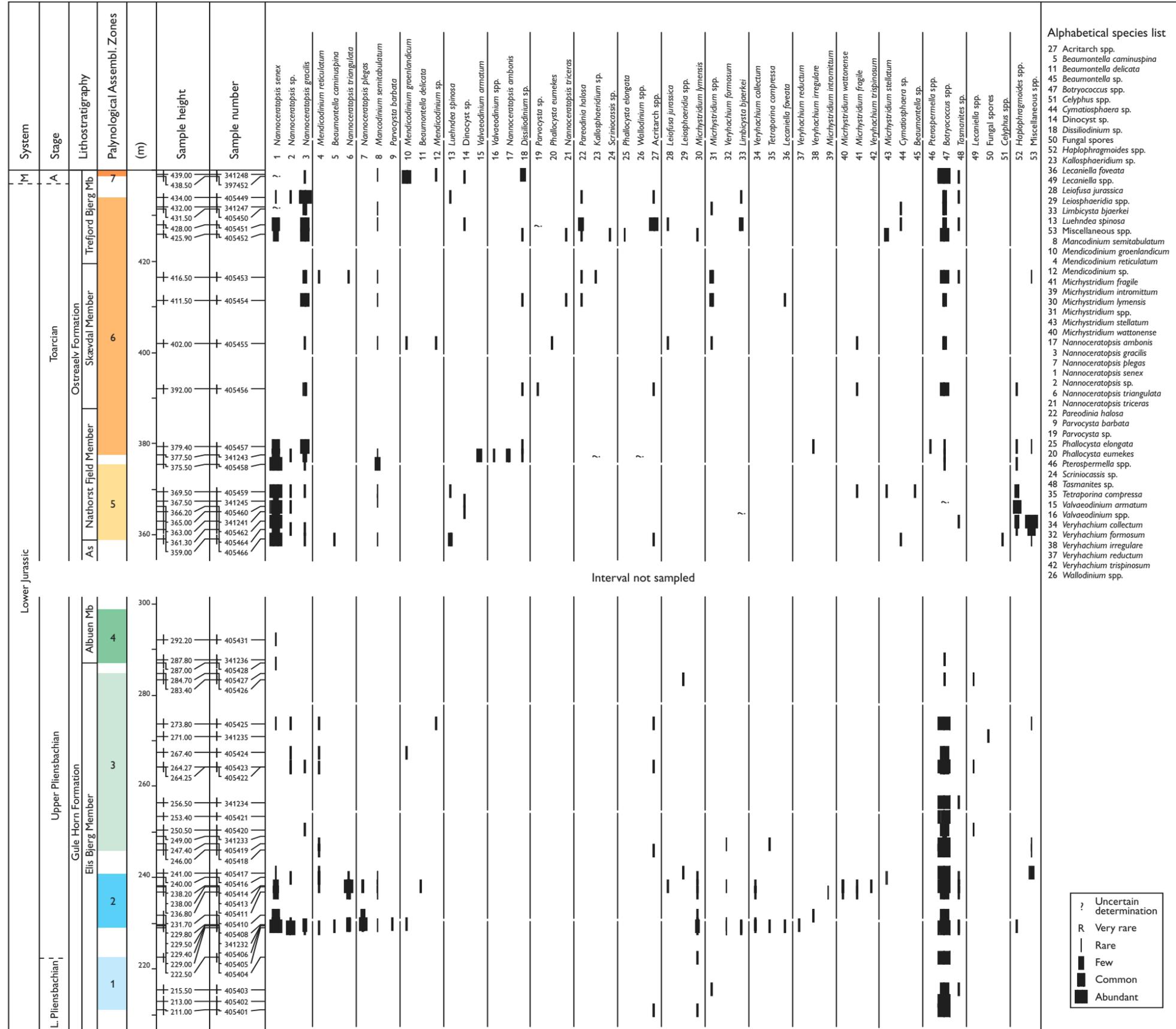


Fig. 4B. Marine palynomorph distribution chart for the Gule Horn and Ostreaelv Formations at Albuen (for location, see Fig. 1). M, Middle Jurassic; A, Aalenian; As, Astartekløft Member.

