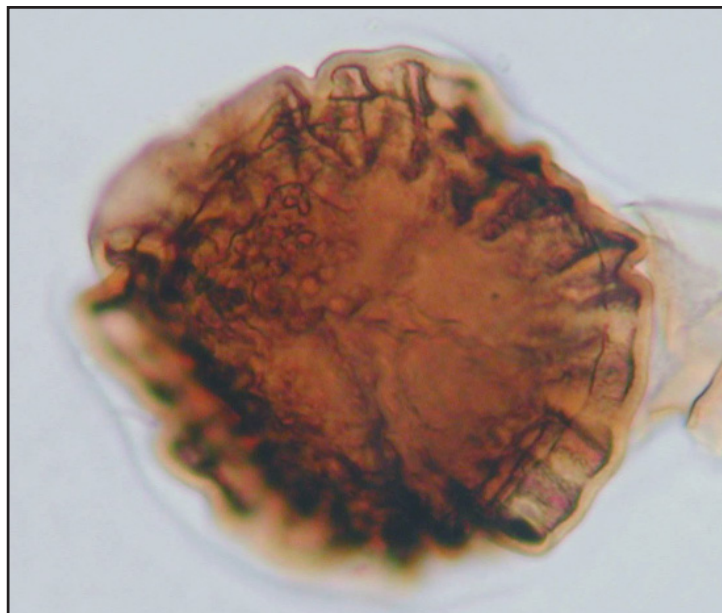


Palyno-stratigraphy and palaeo-climatic analysis of the Lower - Middle Jurassic (Pliensbachian - Bathonian) of the Inner Hebrides, NW Scotland

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Palynostratigraphy and palaeo-climatic analysis of the Lower-Middle Jurassic (Pliensbachian - Bathonian) Inner Hebrides, NW Scotland

Master thesis
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Palynostratigrafisk och paleoklimatisk analys av tidig - mellan jura (pliensbach-bathon) på inre Hebriderna, NV Skottland

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Vid en palynostratigrafisk undersökning av delvis ammonitdaterade sektioner av tidig – mellan jurassisk ålder (pliensbach – bathon), på öarna Skye och Raasay, inre Hebriderna i nordvästra Skottland, har en artrik, men inte alltid välbevarad pollen och spor flora och en mindre divers marin mikroplankton flora påvisats. Det studerade intervallet har indelats i fem biozoner, A - E, baserat på första uppträdandet, vanliga uppträdandet och första vanliga uppträdandet samt den relativa kvantiteten av olika nyckeltaxa av pollen och sporer. Biozon A (pliensbach) är definierad av förekomsten av ett flertal taxa med lång stratigrafisk utbredning tillsammans med sällsynta *Spheripollenites subgranulatus*, medan biozon B (sen toarc – tidig aalen) definieras av en betydande mängd av *S. psilatus*. Biozon C (sen aalen - tidig bajoce) definieras av det första samtida uppträdandet av *Callialasporites dampieri*, *C. turbatus* och *C. minus*, och biozon D (mellan bajoce – tidig bathon) av det första uppträdandet av *Neoraistrickia gristhorpensis*. Den översta zonen, biozon E (mellan/sen bathon) definieras av en signifikant ökning i förekomsten av *Perinopollenites elatoides* och *Araucariacites australis*.

De här upprättade biozonerna korrelerar bra med andra biostratigrafiska zoner och palynologiska resultat i nordvästra Europa, men tidigare spor-pollen zoner saknar ofta andra stratigrafiska dateringar. Denna studie möjliggör därför, för första gången, en noggrann stratigrafisk datering av några viktiga spor-pollen händelser.

Avsättningsmiljön har här tolkats som marin under pliensbach – toarc (tidig jura), kustnära till marin i intervallet aalen – bajoce (mellan jura) och slutligen brackvatten/lagun till terrestrisk i bathonian (mellan jura). Detta är konsekvent med tidigare tolkningar av avsättningsmiljö inom detta intervall i området.

En ekologisk och klimatologisk tolkning baserad på de sannolika källväxternas ekologiska och klimatiska preferenser, har utförts i intervallet toarc – bathon. Resultatet indikerar ett varmt och fuktigt klimat under sen toarcian, följt av en kallare period under tidig aalen, med ett efterföljande varmt och torrt klimat under sen aalen/tidig bajoce. Därefter blir klimatet gradvis svalare och fuktigare under mellan bajoce – mellan/tidig bathon. Detta resultat överensstämmer med andra klimat tolkningar i intervallet.

Nyckelord: palynologi, jura, miospor, paleoklimat, Inre Hebriderna, Skottland.

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Palynostratigraphy and palaeoclimatic analysis of the Lower - Middle Jurassic (Pliensbachian - Bathonian) of the Inner Hebrides, NW Scotland

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A palynostratigraphic investigation of partly ammonite dated, Pliensbachian to Bathonian (Early – Middle Jurassic) strata on the Isles of Skye and Raasay, Inner Hebrides in Northwest Scotland, has recovered a diverse but not always well preserved miospore flora and a less diverse dinoflagellate cysts flora. The studied interval has been subdivided into five biozones, A - E, based on the first occurrence, common occurrence, first common occurrence, and relative abundance of pollen and spore key taxa. Biozone A (Pliensbachian) is defined by the co-occurrence of several long ranging taxa, e.g. *Corollina* spp. and *Cerebropollenites* spp., as well as the presence of rare *Spheripollenites subgranulatus*. Biozone B (late Toarcian-early Aalenian) is defined by abundant presence of *Spheripollenites subgranulatus*. Biozones A and B are separated by a large hiatus. The lower boundary of Biozone C (late Aalenian - early Bajocian) is marked by the first co-occurrence of *Callialasporites dampieri*, *C. turbatus* and *C. minus*. The lower boundary of Biozone D (middle Bajocian - early Bathonian) is defined by the first occurrence of *Neoraistrickia gristhorpensis*, while the uppermost zone, Biozone E (middle/late Bathonian), is marked by a significant increase in the abundance of *Perinopollenites elatoides* and *Araucariacites australis*. The erected biozones correlate well with other biostratigraphic zonations and palynological results from Northwest Europe. Existing spore-pollen zonations from NW Europe often lack independent stratigraphic dating. Hence, the results from this study provide, for the first time, biostratigraphical constraints on some important spore-pollen events during the Early - Middle Jurassic.

The depositional environments are interpreted as marine during the Pliensbachian – Toarcian (Early Jurassic), marine near shore in Aalenian – Bajocian (Middle Jurassic) and brackish/lagoonal to terrestrial in Bathonian (Middle Jurassic). This is consistent with previous interpretations of the depositional environment in the Inner Hebrides Basin during this time interval.

An environmental interpretation based on ecological and climatological preferences of the probable parent plants has also been performed for the Toarcian – Bathonian interval. The results indicate a warm and humid climate in Late Toarcian, followed by a cooling period in Early Aalenian. In the late Aalenian/Early Bajocian the conditions become warm and dry, after which the climate becomes gradually cooler and more humid during the mid Bajocian – middle/late Bathonian. This interpretation correlates well with other climatic interpretations over the interval.

Keywords: palynology, Jurassic, miospore, palaeoclimate, Inner Hebrides, Scotland.

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1 Introduction

1.1 Background

Norsk Hydro (now StatoilHydro) is a leading oil- and energy company that operates mainly on the Norwegian continental shelf. As a part of their work they also conduct geological and biostratigraphical research around the world. To improve the biostratigraphic knowledge of Jurassic deposits in the North Sea and Barents Sea area a sampling program was initiated in the early 1980s. During the summer of 1982 the Stratigraphic Services Limited, a part of Stratigraphic Services International (SSI), carried out sampling on behalf of Norsk Hydro ASA (now StatoilHydro) with the aim to provide a comprehensive set of samples from Mesozoic deposits of Great Britain and the northwest of France (SSI 1982).

The majority of the sampled sections had already been dated by ammonite biostratigraphy. As the spore - pollen zonations of NW Europe to a great extent lack independent stratigraphical dating, this presents an important opportunity to correlate the miospore result with the ammonite zonation.

1.2 Purpose and goal

The purpose of this study is to document the palynological content; i.e. pollen, spores and microalgae, in an interval encompassing Early to Middle Jurassic strata (Pliensbachian—Bathonian) in the Inner Hebrides, Northwest Scotland. The main purpose is to establish a palynostratigraphic biozonation, integrate this with the SubBoreal ammonite biozonation and compare it with other spore, pollen and dinoflagellate floras of similar age in northwest Europe. The second purpose is to, if possible, interpret the depositional environment and climate- and vegetation changes.

The results will become part of the Norwegian StatoilHydro biostratigraphic database for the Jurassic period.

2. Geological setting

2.1 Regional geology

The Jurassic strata in Great Britain form gentle dipping plateaus that have been faulted down among older rocks (Arkell 1933). They are in general not affected by folding, but are locally intensely thermally altered due to the injection of numerous sills and dykes (Arkell 1933). The deposits have been preserved due to protective sheets of basalt and granophyne that were extruded through the sedimentary succession during the Eocene (Arkell 1933).

2.1.1 Paleogeography

In the Early Jurassic a transgressive trend that lasted through the whole period had commenced. By the end of the Early Jurassic a marine seaway was created between the Tethyan and Boreal marine realms for the first time (Doré 1991).

During most of the Early Jurassic (Hettangian, Sinemurian and Pliensbachian), the area which became the Isles of Skye and Raasay formed part of a shallow shelf (Grigerlis & Norling 1999). In the Toarcian the depositional environment became paralic, brackish-lagoonal and tidal in the northern part of the area, i.e. in the Trotternish Peninsula and the north part of Raasay (Grigerlis & Norling 1999). In the early Middle Jurassic, depositions on the Isles of Skye and Raasay took place in intermediate environments (Grigerlis & Norling 1999). The Bajocian and Bathonian successions consist predominantly of continental sediments that were formed in fluvial, deltaic, lacustrine and marshy environments, developed on the border of a denudation area (Grigerlis & Norling 1999).

2.2 The Hebrides basin

The Mesozoic Hebrides basin is tectonically related to the early rifting phases during the evolution of the North Atlantic Ocean (Morton 1989). The basin formed part of the Laurasian Seaway that connected the Boreal ocean in the north with the Tethys sea in the south (Hesselbo & Coe 2000). The basin subsided during the Triassic and Jurassic and its overall geometry is controlled by a series of half-grabens oriented NNE-SSW (Hesselbo & Coe 2000). It is one of the few places where you can find significant onshore Jurassic outcrops, as they are preserved beneath Paleogene volcanics (Morton 1987). Outcrops occur mainly on several islands, for instance Mull, Eigg, Skye and Raasay, and in Morvern, Ardnamurchan, Applecross of the North West Highlands, Scotland (Morton 1987) (fig. 1). The basin is subdivided into the western Sea of the Hebrides Basin and the eastern Inner Hebrides Basin (Hesselbo & Coe 2000). A schematic log of the Inner Hebrides Jurassic geology is illustrated in fig. 2.

2.3 Local geology

The samples were collected from five different localities on the Isles of Skye and Raasay northwest Scotland: Duntulm, Rubha Nam Brathairean, Berreraig Bay, Rigg and Hallaig (fig. 1) (SSI 1982). The latter locality is situated on the southeastern part of the Isle of Raasay whereas the other four are located on the Trotternish Peninsula of the Isle of Skye (www.skye.co.uk) (SSI 1982). The Trotternish Peninsula is located on the northeast of Skye and is the largest and most northerly peninsula on the island (www.skye.co.uk). Rubha Nam Brathairean, Rigg and Berreraig Bay are situated within 10 kilometres of each other on the west side of the peninsula. Duntulm is situated in the northern part of the Trotternish Peninsula (SSI 1982).

On the islands of Skye and Raasay, deposition occurred throughout the Jurassic with the highest depositional rates during the Sinemurian–Pliensbachian and the Bajocian–Bathonian (Hesselbo & Coe 2000).

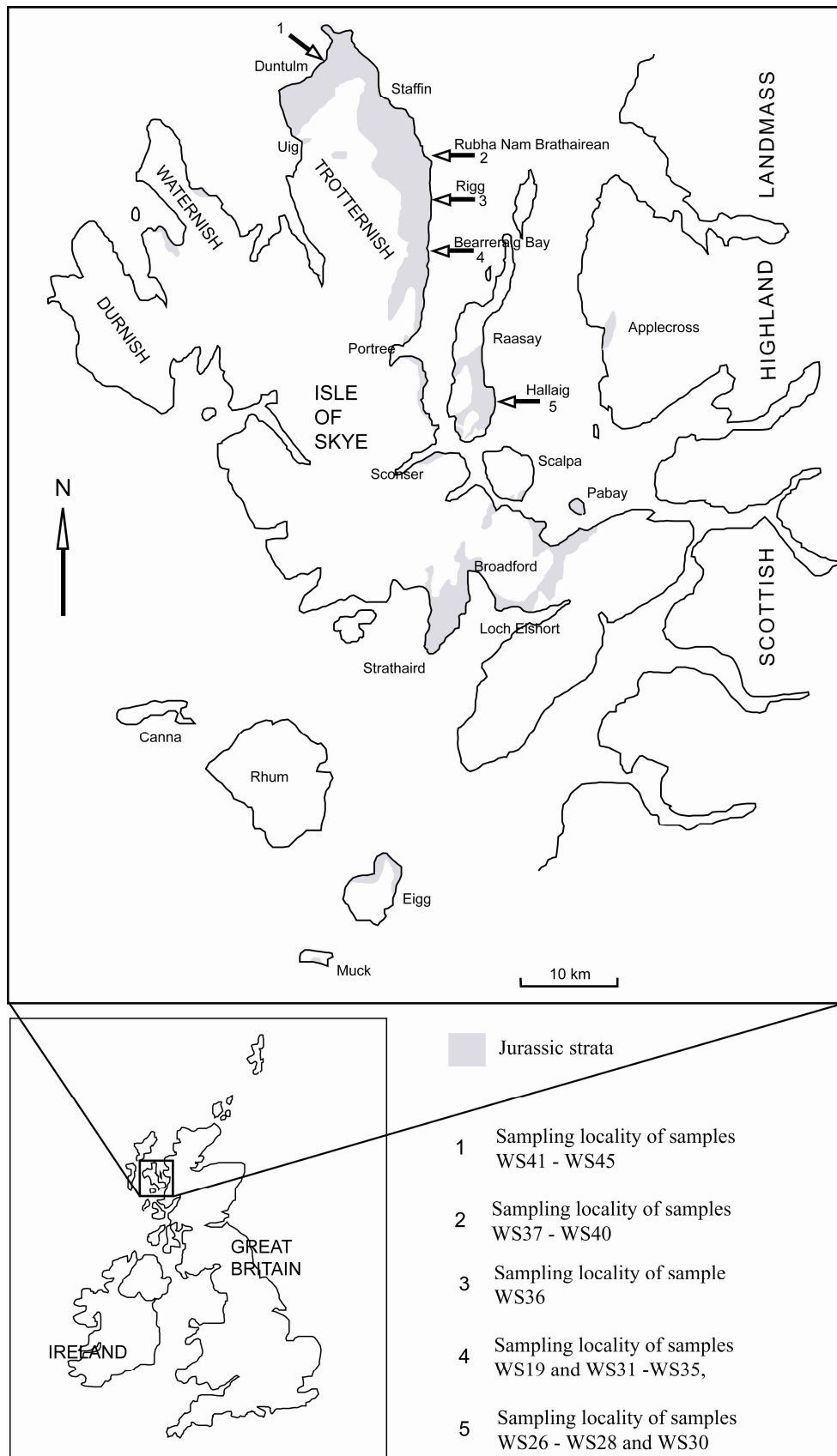


Fig. 1. Map showing the position of the isle of Skye in Great Britain and the distribution of Jurassic strata on the Isles of Skye end Raasay as well as the localities of the collected samples (modified from Morton & Hudson 1995 and http://en.wikipedia.org/wiki/Image:Europe_location_SCO_2.png)

2.3.1 Early Jurassic

The earliest Jurassic deposits (Hettangian–earliest Sinemurian) belongs to the Breakish Formation (formerly Lower Broadford Beds) which consists of mixed carbonate and siliciclastic sediments of shallow water origin (Hesselbo & Coe 2000). Hummocky cross-stratification in the sandstones and keystone vugs in oolitic and peloidal limestones suggest deposition between the storm-wave base and the backshore (Hesselbo & Coe 2000). In the lower Sinemurian, at the base of the Pabay Shale Formation (former Upper Broadford Beds and Pabba Shales), there is a change to deeper water argillaceous facies, establishing the dominantly siliciclastic character of the basin (Hesselbo & Coe 2000). The Pabay Shale Formation consists mostly of silty mudstone (fig. 2) with two sand deposits, the Hallaig Sandstone and the Suisnish Sandstone (Hesselbo & Coe 2000). The abrupt transition to the Scalpa Sandstone Formation in the upper Pliensbachian signals a change to shallow marine environments (Hesselbo & Coe 2000). This sandstone unit is locally capped by chamositic ironstone and consists of a coarsening upward sequence, which was deposited above the wave base (Morton 1987). The beginning of the Toarcian is represented by the Portree Shale Formation, a succession of fine grained organic rich shales (fig. 2) that were deposited during the Early Toarcian oceanic anoxic event, a palaeotemperature maximum and a mass extinction (Hesselbo & Coe 2000). The Raasay Ironstone Formation is a chamosite oolite or shelly chamositic mudstone with ferruginous shale partings (fig. 2). It was deposited approximately at the wave base (Morton 1987). The top of the Lower Jurassic is represented by the Dun Caan Shales Member (Morton 1987), which forms part of the Berreraig Sandstone Formation (Morton 1976) and consists of micaceous shales (fig. 2) deposited below the wave base (Morton 1987).

2.3.2 Middle Jurassic

The Middle Jurassic section consists of two lithostratigraphic units, the Berreraig Sandstone Formation and the Great Estuarine Group (fig. 2) (Hesselbo & Coe 2000). The Berreraig Sandstone Formation is of marine origin and consists of six members, the Dun Caan Shales, Ollach Sandstone, Udairn Shales, Holm Sandstone, Rigg Sandstone and the Garantiana Clay (Morton 1976). The formation was deposited both above and below the wave base (Morton 1987). The entire Berreraig Sandstone Formation can be seen in Berreraig Bay, where the type section is located, and in Prince Charles's Cave (Morton 1965). The Dun Caan Shales Member, which has been described above, is succeeded by the Ollach Sandstone Member (the Lower Sandstone of Morton 1965), which consists of massive yellowish-brownish sandstones with lenticels of calcareous sandstone (fig. 2) (Morton 1965). The Ollach Sandstone Member is overlain by the Udairn Shales Member (the Shaly Sandstone of Mor-

ton 1965), dominated by soft dark grey shaly sandstone with nodules of sandy limestone (fig. 2) (Morton 1965). The Udairn Shales Member is succeeded by the Holm Sandstone Member (the Massive sandstone of Morton 1965), characterized by a soft sandstone, whitish in colour, and with lenticels of calcareous sandstone (fig. 2) (Morton 1965). The Holm Sandstone Member is overlain by the Rigg Sandstone Member (the Upper Sandstone by Morton 1965 and also including the Berreraig Grit), which consists of alternating beds of dark grey shaly sandstones and medium grey sandy limestones (fig. 2) (Morton 1965). The youngest member in the Berreraig Sandstone Formation is the Garantiana Clay Member which consists of fine grained dark grey clay (fig. 2) (Morton 1965). Many of the more coarse grained facies display well developed cross-bedding indicating tidal influence (Hesselbo & Coe 2000).

The Great Estuarine Group is the only part of the Jurassic strata in the Hebrides that is not exclusively marine (Riding 1991). It consists of two main sand deposits, representing small deltas, and intervals of more argillaceous facies representing both marine, brackish and freshwater environments (fig. 2) (Hesselbo & Coe 2000). The Great Estuarine Group is subdivided into seven formations: namely the Cullaidh Shale, Elgol Sandstone, Lealt Shale, Valtos Sandstone, Duntulm, Kilmaluag, and the Skudiburgh formations (Harris & Hudson 1980).

The oldest formation of the Great Estuarine Group is the Cullaidh Shale Formation (previously named Basal Oil Shale). It consists of a black bituminous shale with numerous fish scales, and it is occasionally developed as a true oil shale in the basal 2 meters (fig. 2) (Harris & Hudson 1980). It is overlain by the Elgol Sandstone Formation (previously named White Sandstone) which is a typical coarsening-upward deltaic sequence (fig. 2) (Harris & Hudson 1980). This formation is succeeded by the Lealt Shale Formation (previously named Estheria Shales), which consists of shales with bedding planes covered with *Cyzius* carapaces and interbedded thin oolitic limestones (Harris & Hudson 1980). It was deposited in a brackish-marine lagoonal environment (Andrews 1985). The Lealt Shale Formation is overlain by the Valtos Sandstone Formation (previously named Concretionary Sandstone Series), which was deposited in a tidally influenced shore lagoon complex and consists of a medium-coarse-grained sandstone with calcite concretions (Harris & Hudson 1980). The Valtos Sandstone Formation is overlain by beds mostly composed of oyster shells with a matrix of shale or limestone interbedded with siltstones, limestone and fine sandstones that are assigned to the Duntulm Formation (previously named Lower Ostrea Beds) (Harris & Hudson 1980). The depositional environment is considered to have been marine-brackish lagoonal (Andrews 1985). The Duntulm Formation is succeeded by the Kilmaluag Formation (previously named Ostracod Limestone), which consists of calcareous mud-

stones and nodular marlstones (Harris & Hudson 1980) deposited in a freshwater lagoonal environment (Andrews 1985). The youngest formation of the Great Estuarine Group is the Skudiburgh Formation (previously named Mottled Clay), which consists of red-grey fluvial mottled silty mudstones (Harris & Hudson 1980; Hesselbo & Coe 2000).

3. Previous work

There are only a few published palynological reports of the Inner Hebrides. More attention has been given to the northeast of Scotland in this aspect. There are numerous palynological reports on the Jurassic of Northwest Europe.

Riding (1991) described Toarcian to Bathonian palynofloras from the Inner Hebridean Isles of Skye, Raasay, Eigg and Mugg. His report emphasizes the dinoflagellate cyst stratigraphy, and he conducted an extensive investigation with 200 samples and presented a reference section.

Riding (2005) conducted a palynological investigation of the Middle and Upper Jurassic (Callovian to Kimmeridgian) of the Moray Firth Basin, northeast Scotland. This report shows that the previously established dinoflagellate cyst biozonation can be applied also to the region and time interval of this study.

Dybckjær (1991), Lund (1977), and Koppelhus and Dam (2003) have all produced palynological biozonations for the Jurassic in the Danish Subbasin and Greenland.

4. Material and methods

4.1 Material

Sixty-four samples were collected by SSI from various localities on the Isles of Skye and Raasay, north-western Scotland (WS) during the summer of 1982 (fig. 2). The samples were collected from lithologies suitable for micropalaeontological and palynological studies. Unsuitable lithologies were only included where no alternatives were available (SSI 1982). Twenty Samples, WS26–WS45, representing Pliensbachian to Bathonian, were selected to be analysed in this study (fig. 3). The samples covers approximately a period of twenty million years.

As a large part of western Scotland has been affected by dykes, sills and lava flows, the rocks tend to be hard and the preservation of the microfossils is generally poor (SSI 1982).

4.1.1 Sample description

Samples WS26, WS27 and WS28 represent the late Pliensbachian *Ibex* Zone (SSI 1982). They were collected from Pabay Shale Formation on the Isle of Raasay in Hallaig (SSI 1982). Sample WS29 represents the early Toarcian *Falciferum* Zone (SSI 1982), and it was collected from the Portree Shale Formation on the Isle of Skye, 1 km south of Bearreraig Bay (SSI 1982). Sample WS30 represents the Toarcian *Bifrons*

Zone, from the Raasay Ironstone Formation at Hallaig on the Isle of Raasay (SSI 1982). These five samples above are all from shales (SSI 1982).

Samples WS31 and WS32 represent the Aalenian, *Opalinum-Scissum* and *Murchisonae* zones (SSI 1982). The former (WS31) is a shale sample collected from the Dun Caan Shales Member at Bearreraig Bay on the Isle of Skye, while the latter (WS32) was collected from a sandy shale just below the transition to Ollach Sandstone Member (SSI 1982).

Samples WS33, WS34 and WS35 from the Bearreraig Sandstone Formation at Bearreraig Bay on the Isle of Skye represent the late Aalenian *Concavum* Zone (WS33), the Bajocian, *Discites* (WS34) and *Humphriesianum* zones (WS35) (SSI 1982). The samples were collected from the more silty lithologies of the formation (SSI 1982). Samples WS33 and WS34 are collected from a sandy shale in the Udairn Shale Member, and sample WS35 is from a sandy limestone in the Rigg sandstone Member (SSI 1982). These samples are the last to be dated with ammonite biostratigraphy within this interval.

Sample WS36 is believed to represent the lower Bathonian, and was collected from the upper part of the Cullaidh Shale Formation (sandy shale lithology) of the Great Estuarine Group at Rigg on the Isle of Skye (SSI 1982). Samples WS37, WS38, WS39 and WS40 are also from the lower Bathonian but were collected from the Lealt Shale Formation (probably a clay lithology) at Rubha Nam Brathairean on the Isle of Skye (SSI 1982).

Samples WS41, WS42, WS43, WS44 and WS45 are from the Duntulm Formation at Duntulm on the Isle of Skye (SSI 1982), and are believed to represent the lower/middle Bathonian. Samples WS41, WS42 and WS45 are from a clay lithology, while samples WS43 and WS44 are from a limestone lithology.

4.2 Methods

The samples were processed according to standard palynological methods (Gray 1965; Bars & Williams 1973). From every sample a number of slides were made (SSI 1982). From these 2–5 slides per sample were selected to take part of this study, a total of fifty-three slides.

Qualitative analysis and identification of the palynological contents of the samples were made in a Nikon light microscope. The specimens were identified using primarily Koppelhus & Dam (2003), Riding & Thomas (1992), Batten & Koppelhus (1996), Koppelhus & Batten (1996) and Guy-Ohlson (1986). Quantitative analysis was made in all but four of the samples. The slides with the best preserved palynomorphs were selected for the quantitative analyses to give the best result in the ecology and climate assessment. In the quantitative analysis pollen and spores were counted up to 300 specimens (per sample) where possible. If pollen and spores were scarce, counting proceeded until the total amount of palynomorphs reached approximately 600 specimens. This study em-

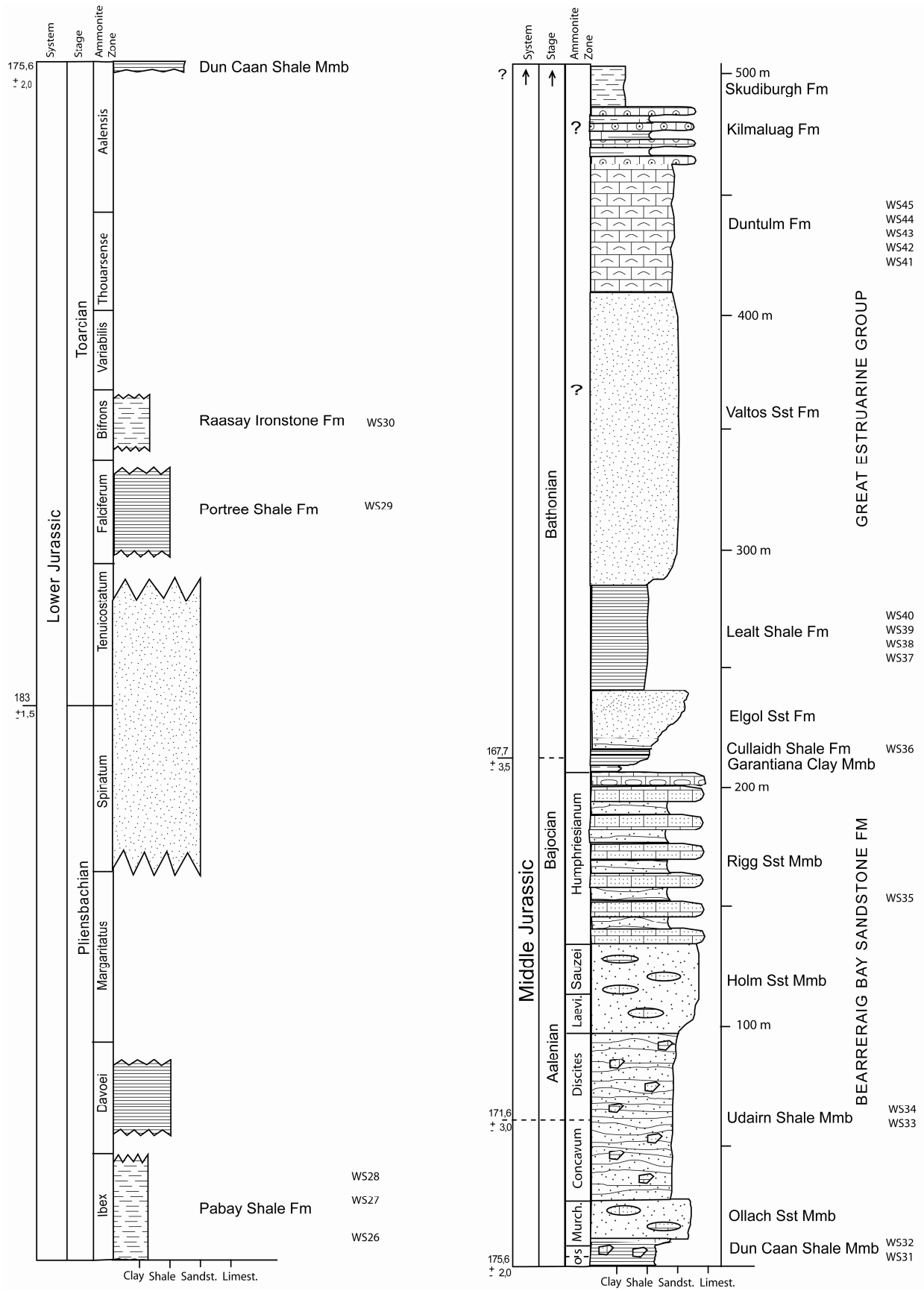














Fig. 2. A schematic log over the geology of the Inner Hebrides, the Isles of Skye and Raasay. The log on the left is not to scale. (Harris & Hudson 1980; Morton 1965; SSI 1982)

LEGEND					
	Shale		Calcareous Grit		Mudstone/Claystone
	Sandstone		Nodular Marlstone		Nodules with Sandy Limestone
	Shaly Sandstone		Oyster shells with matrix		Lenticles with Calcareous Sandstone
	Sandy Limestone		Cross-bedded Sandstone		Calcareous Mudstone

phasizes on pollen and spores, but dinoflagellate cysts have been identified and counted where possible, but no analysis of these, other than age assessment, were made.

Photographs were taken with a Nikon Coolpix 990 camera in a Nikon Optiphot-2 light microscope. The photographs were processed in Adobe Photoshop 7.0.

All the data from the qualitative and quantitative analyses were processed in Microsoft Excel. The amounts of unidentifiable fragments were subtracted before the quantitative calculations were made. However, the amount of unidentifiable fragments can be used as a measure of sample preservation. All figures were created in Adobe Illustrator 9.0 and CS.

As many pollen and spores as possible were divided into ecological assemblages, according to Abbink (1998), and an ecological and climatic assessment was made (see below).

5. Ecological assemblages

Pollen and spores are produced in vast amounts from their parent plants, thousands and sometimes millions in one season. Being dispersed with wind and water they settle within large areas in different environments, not necessarily similar to the environment of the parent plant (Chaloner & Muir 1968; Traverse 2007). There are, however, several factors that influence the relative amount of pollen and spores that settle in one particular location (Chaloner & Muir 1968; Traverse 2007). The amount of spores produced from a single parent plant, the number of parent plants in the source area, the distance between the parent plant and area of deposition, are all significant factors (Chaloner & Muir 1968), as are differences in preservation due to different amount of sporopollenin in the exine (Traverse 2007). The ability to be transported by wind and/or water, their size, weight and morphology, and the mode of transport (wind and/or water) must also be considered (Muller 1959; Traverse 2007). It is, however, generally accepted that the relative changes within a sporomorph assemblage reflect changes in the palaeovegetation and are not severely influenced by the factors mentioned above, especially in near coastal,

coastal and terrestrial environments (Chaloner & Muir 1968; Muller 1959; Traverse 2007). The Neves effect, however, describes how a sporomorph assemblage responds to changes in the distance to the parent communities (Chaloner & Muir 1968). In more marine environment the relative amount of bisaccate grains, the parent plants of which usually grow in upland environments, tend to be high due to their ability to travel far by wind (Muller 1959; Chaloner & Muir 1968; Traverse 2007).

In Quaternary palynology the relationship between sporomorph assemblages and the composition of the plant communities are used to reconstruct past vegetation, environments and climates, and changes therein (Huntley 1990). When attempting to use this relationship to make interpretations concerning pre-Quaternary records the difficulties in identifying sporomorph categories that represent environmentally significant plant categories, become a major problem as the sporomorphs mostly represent extinct plant taxa (Abbink 2001). In the Mesozoic, one can assume that distinctive habitat-bounded communities existed and that they were represented by taxa with comparable ecological preferences (Abbink 2001).

Abbink (1998) introduced the term Sporomorph EcoGroup (SEG) for pollen and spores of land plants that reflect a distinct plant community. Abbink (1998) used Grime's (1979) three plant strategies, depending on the two factors, stress and disturbance, to construct an ecological framework for the palaeocommunities. A competitive strategy has low stress and low disturbance, while a stress tolerant strategy has high stress and low disturbance, and a ruderal strategy has low stress and high disturbance, but an environment with high stress and high disturbance can not support plant life (Grime 1979). Abbink (1998) presented six different SEG:s; Upland SEG, Lowland SEG, River SEG, Pioneer SEG, Coastal SEG and Tidally influenced SEG. In this study the River SEG has been embedded in Lowland SEG and the Pioneer SEG has not been used.

Lowland SEG reflects lowland communities and has a competitive strategy. In this environment there is easy access to nutrients and water and there is no influence from the sea except under extreme cir-

cumstances. The land can occasionally become flooded by water (Abbink 1998).

Upland SEG reflects communities living on higher ground at a distance from the ocean, and they have a stress tolerant strategy. In this environment the possible lack of nutrients and/or water can introduce ecological stress. The land never becomes flooded by water (Abbink 1998).

Coastal SEG reflects communities live close to the ocean. They have a stress tolerant strategy, the environment has a possible ecological stress in the form of influence of salt water and salt sprays. The same circumstances are true for Tidal SEG:s as well, except that the ecological stress would be even higher there (Abbink 1998).

The relative amount of elements from the different SEG:s can depend on other factors than climate. One important factor is the relative sea level and its fluctuations (Abbink 1998). During a transgression the coast is “pushed” further inland and the Lowland SEG is replaced by the Coastal- and Tidal SEG. The Upland SEG is however not affected and hence the Lowland SEG decreases and the Coastal and Tidal SEG:s increase. During a regression the Lowland SEG increases again while the Coastal SEG and Tidal SEG decrease. Thus, the Coastal and Tidal SEG reach a maximum directly after a maximum transgression. As described above, the sea level fluctuations predominantly influence the Coastal SEG and the Tidal SEG, and not the Upland SEG.

6. Results

6.1 Identified palynomorphs

A total number of 144 palynomorph taxa were identified in the studied samples, including 99 taxa of pollen and spores, 34 taxa of dinoflagellate cysts, 7 taxa of acritarchs and algae and 4 taxa of microforaminiferas, fungi and insects. A list of the identified palynomorphs and their ecological/climatological classification can be seen in appendix 1. A total number of 7609 palynomorphs were counted, of these were 4424 pollen or spores. A list of all palynomorphs and their distribution through the interval is presented in Appendix 2. Most of the pollen and spore taxa are long ranging and thus have little stratigraphic value. Some are, however, useful biostratigraphic markers or key taxa (fig. 3). Selected palynomorphs are illustrated in figures 5 and 6.

6.2 Biozonation

Using the first and last occurrences, and quantitative variations of important key taxa of identified pollen and spores, the studied interval can be divided into five biozones (figs. 3 and 6), described below. The percentages mentioned below are calculated from the total amount of pollen and spores excluding fragments. An exception is the percentage of fragments which is calculated from the total amount of pollen and spores, including fragments.

6.2.1 Biozone A (Middle Pliensbachian)

6.2.1.1 Base

The base of the biozone is not defined, but includes the lowermost part of the studied interval. Biozone A is defined by the presence of *Corollina* spp., *Cerebropollenites* spp., and *Retitriletes clavatooides* as well as the absence or very scarce presence of *Spheripollenites subgranulatus*.

6.2.1.2 Top

The top of the biozone is placed just below the first common occurrence, FAO, of *Spheripollenites subgranulatus*.

6.2.1.3 Characteristics

The biozone is dominated by bisaccate grains (62%), e.g. *Alisporites robustus*, *A. radialis* and *Pinuspollenites minimus*. Other characteristic taxa are *Osmundacidites wellmannii* and *Exesipollenites tumulus*, as well as *Deltoidospora minor*, *Perinopollenites elatoides*, *Quadraeculina anellaeformis* and *Chasmatosporites hians*. These species continue to be characteristic throughout the entire studied interval.

There are very few complete dinoflagellate specimens in this zone. The first rare occurrence of *Dissilodinium* spp. (late Pliensbachian – post Portlandian; Koppelhus & Dam 2003), and *Pareodinia aphelia* (? - early Bathonian; Poulsen 1998), as well as one questionable specimen each of *Susadinium* spp. (early Toarcian – Aalenian; Riding & Thomas 1992) and *Mendicodinium groenlandicum* (early Pliensbachian – Portlandian; Riding & Thomas 1992) are registered at the top of the biozone.

6.2.1.4 Samples

The biozone comprises samples WS26 – WS28. As there is a large hiatus between WS28, the last sample in Biozone A, and WS29, the first sample in Biozone B, the precise location of the boundary between Biozone A and Biozone B can not be established herein. It can only be stated that its occurrence between late Ibez Zone and late Falciferum Zone.

The palynomorphs from Biozone A are poorly to very poorly preserved, and only WS28 could be analyzed quantitatively, although the relative amount of fragments in that assemblage is high (50 %).

6.2.1.5 Ammonite zones

The samples in Biozone A have been collected from the Pliensbachian Ibez Zone.

6.2.1.6 Age

The miospore assemblages in Biozone A consist of long-ranging taxa, with the exception of *Monolites couperi* which has previously been reported from Toarcian – Bathonian strata (Guy-Ohlson 1989). *Dissilodinium* spp., *Mendicodinium groenlandicum* and the possible *Susadinium* spp. indicate a late Pliensbachian age.

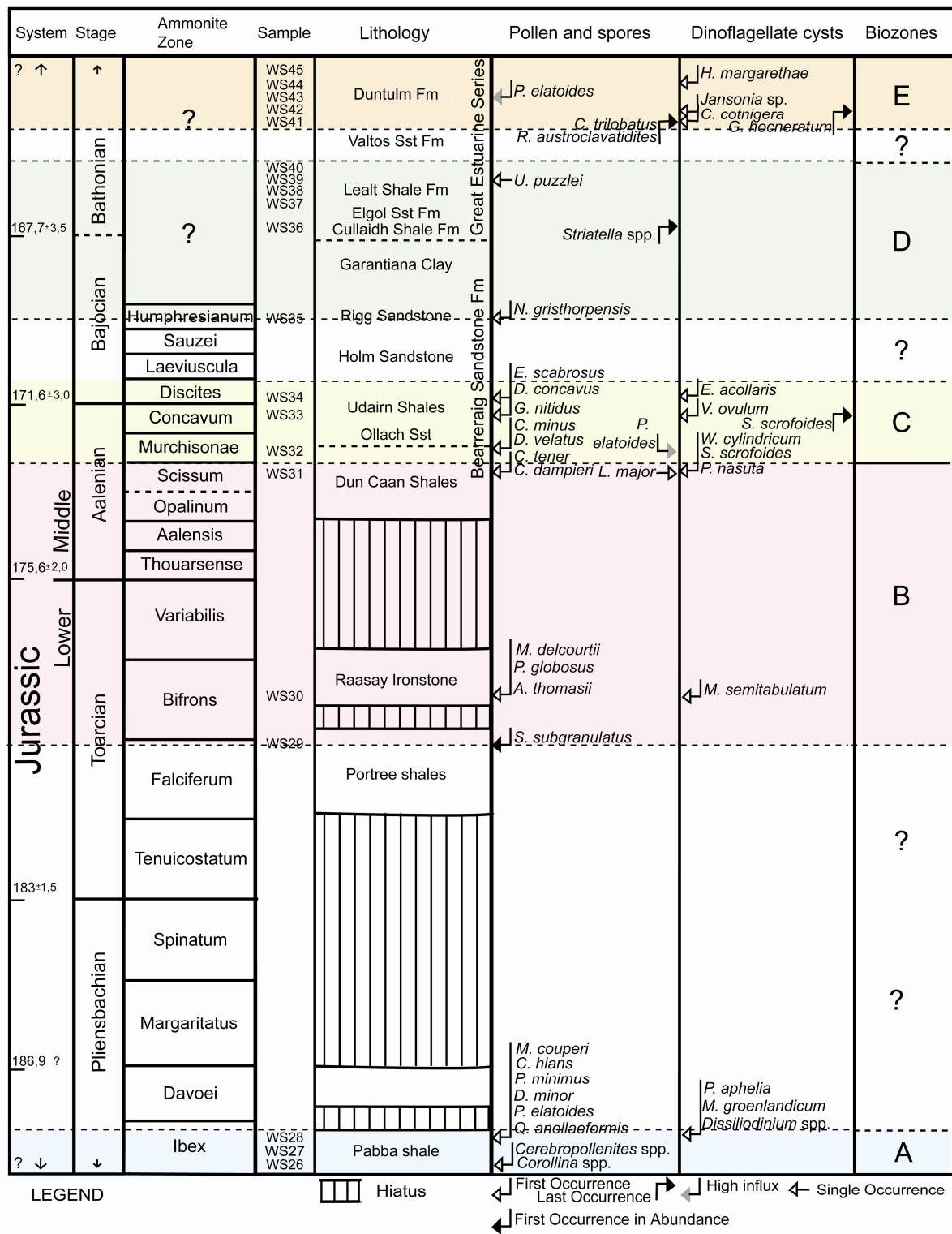


Fig. 3. Biostratigraphic zonation of the studied interval, with sample levels and significant datums for miospores and dinoflagellate cysts, (modified from SSI 1982). The miospore- and dinoflagellate cysts datums are from this study.

6.2.1.7 Remarks

The poor preservation made the qualitative analysis difficult, especially the dinoflagellate cysts, as they were fragmented to a larger degree than the pollen and spores.

6.2.2 Biozone B (middle Toarcian – middle Aalenian)

6.2.2.1 Base

Biozone B is defined by the first common occurrence of *Spheripollenites subgranulatus*.

6.2.2.2 Top

The top of the biozone is below the first co-occurrence of *Callialasporites dampieri*, *C. minus* and *C. turbatus*.

6.2.2.3 Characteristics

Within the zone are the first occurrences, FO, of *Manumia delcourtii* (FO late Pliensbachian; Batten & Koppelhus 1996), and *Leptolepidites* spp. Other characteristic species are: *Perinopollenites elatoides*, *Punctatisporites globosus* which appears for the first time within the studied interval, *Corollina* spp. and *Cerebropollenites* spp. Specimens of *Kekryphalospora distincta* (late Pliensbachian – early Bajocian; Fenton & Riding 1987) were found in two samples from the biozone.

The dinoflagellate taxa in the lower and middle part of the biozone are essentially the same as in Biozone A. However, *Mancodinium semitabulatum* (late Pliensbachian – early Bajocian; Riding & Thomas 1992) has its first occurrence in the middle sample of the biozone, and near the top of the biozone more taxa have their first appearances, for instance the stratigraphically important: *Nannoceratopsis* spp. (late Pliensbachian – Bathonian; Riding & Thomas 1992), *Wallodinium laganum* (late Toarcian; Koppelhus & Dam, 2003), *Sentusidinium pelionense*, *Wallodinium cylindricum* (latest Toarcian – early Bajocian; Riding & Thomas 1992) and *Nannoceratopsis spiculata* (Aalenian – Bajocian; Riding & Thomas, 1992).

6.2.2.4 Samples

The Biozone comprises samples WS29 – WS31. In sample WS29, the preservation is very poor and thus no quantitative analysis could be carried out. The qualitative analysis was also very difficult due to the poor preservation. Material from sample WS30 is somewhat better preserved, while the preservation is fair in the last sample from the zone, WS31. The lower and the middle part of the biozone are dominated by bisaccate grains (43%), but in the upper part of the zone the bisaccate grains comprises only 3% of the assemblage. The average percentage of fragments is 40.

6.2.2.5 Ammonite zones

Biozone B ranges from the upper Falciferum Zone to the upper Scissum Zone, i.e. middle Toarcian to middle Aalenian.

6.2.2.6 Age

The lowermost sample of the zone (WS29) is considered to be of late Pliensbachian – early Toarcian age, mainly based on the suggested age of the samples above and below. In the middle sample of the biozone (WS30) an acme in *Spheripollenites* suggests a Toarcian age (Koppelhus & Dam, 2003; Dybkjær, 1991). In the uppermost sample of Biozone B (WS31) a large number of dinoflagellate cyst taxa have their first occurrence. However, the co-occurrence of *Wallodinium cylindricum*, *Wallodinium laganum* and *Nannoceratopsis spiculata* suggest a latest Toarcian – early Aalenian age.

6.2.2.7 Remarks

As in the biozone below, the preservation of the samples herein is generally poor, especially in the first two samples of the zone. The fact that many taxa have their first occurrence in sample WS31 is probably due to the poor preservation of the preceding samples.

6.2.3 Biozone C (late Aalenian – early Bajocian)

6.2.3.1 Base

The lower boundary of Biozone C is defined by the first co-occurrence of three *Callialasporites* species: *C. dampieri*, *C. minus* and *C. turbatus*.

6.2.3.2 Top

The upper boundary of the biozone is below the first occurrence of *Neoraistrickia gristhorpensis* and a decrease in *Corollina* spp. to <5%.

6.2.3.3 Characteristics

The zone is dominated by *Corollina* spp. with an average occurrence of 20%, and a maximum abundance of 37%. Other characteristic taxa of the biozone are *Spheripollenites psilatus* (11%) and *Perinopollenites elatoides* (9%) and to a lesser degree *Deltoidospora* spp. (5%). Within the zone is the first occurrence of *Cycadopites nitidus*, while *Spheripollenites subgranulatus* is registered for the last time.

The dinoflagellate cyst taxa in this zone do not differ much from the previous biozone. There are a few new occurrences, the more important ones being *Phallocysta eumekes* (early Toarcian – Aalenian; Riding & Thomas, 1992), *Valensiella ovulum* (Aalenian – Portlandian; Riding & Thomas, 1992) *Gongylocladus hocneratum* (early Bajocian – early Bathonian; Riding & Thomas, 1992) and *Energlynia acollaris* (early Bajocian – early Oxfordian; Riding & Thomas, 1992).

6.2.3.4 Samples

The biozone comprises samples WS32–WS34. Samples WS32 and WS34 are fairly well preserved, while sample WS35 is well preserved. All samples have been quantitatively and qualitatively analyzed. The average relative amount fragments is 36%.

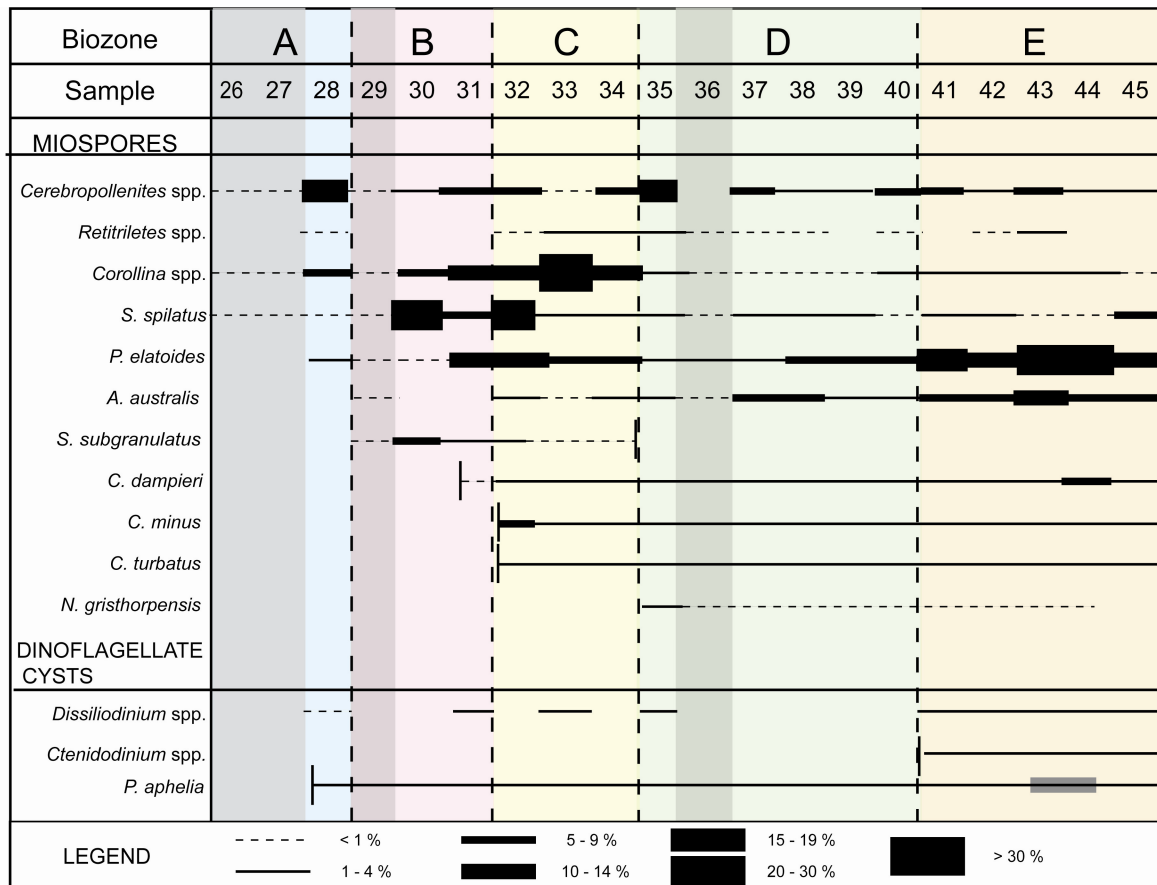


Fig. 4. First- and last occurrences of important key taxa as well as their relative abundance. The shaded samples are very poorly preserved and have not been qualitatively analyzed.

6.2.3.5 Ammonite zones

Biozone C ranges from the top of the Scissum Zone to the top of the Discites Zone, i.e. late Aalenian to early Bajocian.

6.2.3.6 Age

Leptolepidites paverus (middle Aalenian – Bathonian; Guy-Ohlson 1986), *Valensiella ovulum* and *Phallocysta eumekes* suggest an age no older than Aalenian for this biozone. *Gongylocladus hocneratum* and *Energlynia acollaris* in the last sample of the zone suggests an age no younger than early Bajocian.

6.2.4 Biozone D (middle Bajocian – early Bathonian)

6.2.4.1 Base

The lower boundary of the fourth biozone is defined by the first occurrence of *Neoraistrickia gristhorpensis* (Bajocian – Bathonian; Guy-Ohlson 1989).

6.2.4.2 Top

The upper boundary is just below a marked increase in *Perinopollenites elatoides* to over 10%.

6.2.4.3 Characteristics

The biozone is dominated by bisaccate grains (46%), mainly *Alisporites radialis* and *Pinuspollenites minimus*. Other characteristic elements include *Cerebropollenites* spp. (8%), *Callialasporites* spp. (6%) and *Exesipollenites tumulosus* (4%). Within the zone *Ischyosporites* spp. and *Callialasporites trilobatus* appear for the first time, as well as one specimen of *Uvaesporites puzzlei* (Bajocian – Bathonian; Guy-Ohlson 1986). This biozone contains very few dinoflagellate cysts, although some e.g. *Mendicodinium groenlandicum* and *Mancodinium semitabulatum* have been registered.

6.2.4.4 Samples

The zone comprises samples WS35 – WS40. These samples are well preserved except WS36, which has been exposed to contact metamorphism and is very poorly preserved. This sample was not quantitatively analysed, and the qualitative analysis was very difficult. The average relative amount of fragments in the zone is 31%.

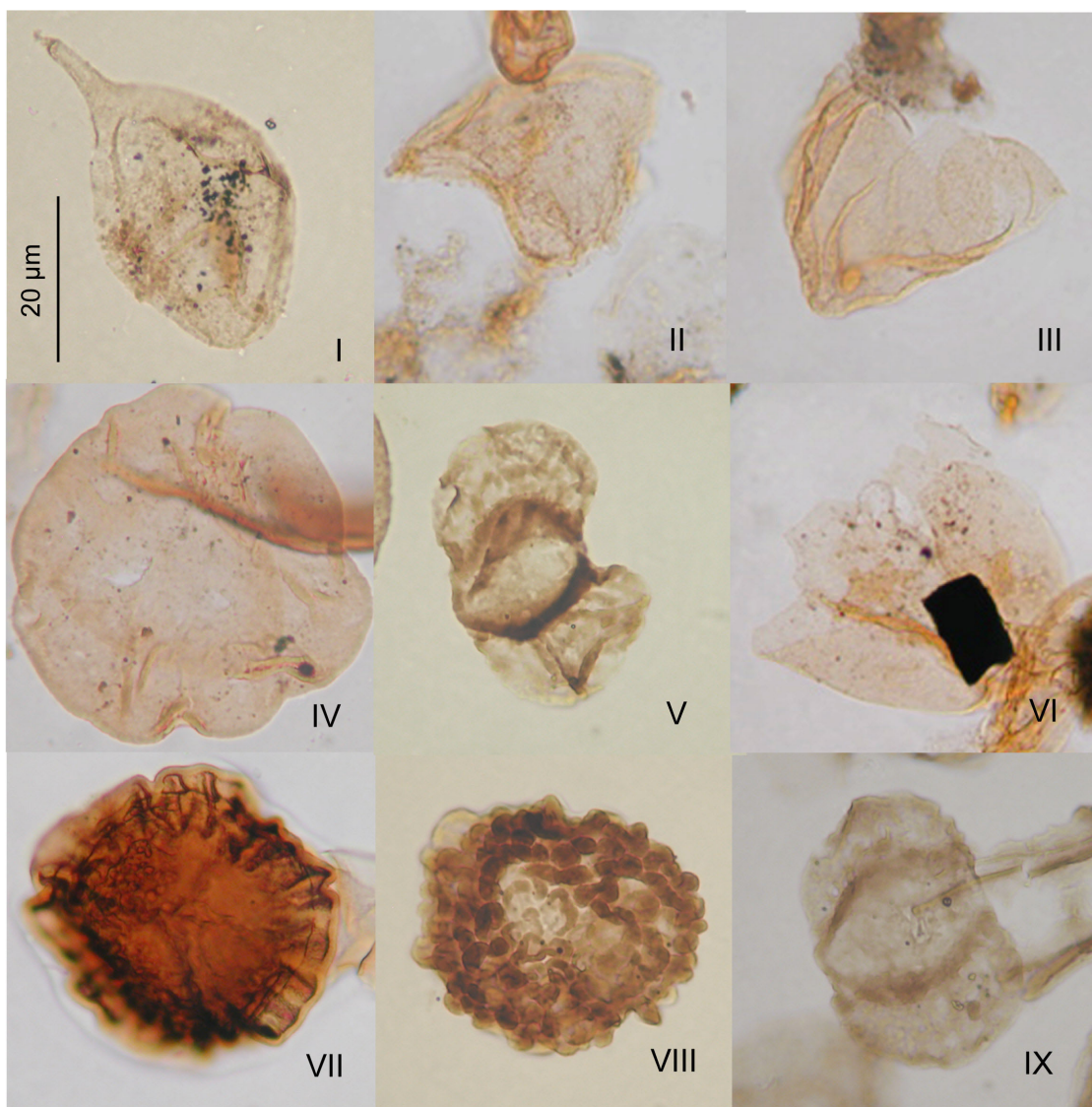


Fig. 5. Photographs of selected taxa, photographed at a magnification of x500. Each specimen identified by sample-, slidenumber and England finder coordinates. I) *Pareodinia aphelia*, WS44:1, K26:2, II) *Nannoceratopsis spiculata*, Stover 1966, WS31:1, R38:3, III) *Sentusidinium pelionse*, Fensome 1979, WS31:1, Q33:3, IV) *Callialasporites turbatus* (Balme) Schultz 1967, WS33:2, O30:3, V) *Alisporites* spp., WS37:1, K31:1 VI) *Dissiliodinium* spp., WS31:1, M29:3, VII) *Callialasporites dampieri*, (Balme) Dev 1961, WS35:1, K38:2, VIII) *Cerebropollenites macroverrucosus*, (Thiergart) Schultz 1967, WS37:1, G30:3, (XI) *Alisporites thomasi* (Couper) Nilsson 1958, WS37:1, N39.

6.2.4.5 Ammonite zones

In this biozone only the first sample has been dated by ammonites, as there are no ammonites available in the Great Estuarine Group. Biozone D ranges from the middle Bajocian Humphriesianum Zone, to the estimated age early Bathonian.

6.2.4.6 Age

Neoraistrickia gristhorpensis and *Uvaesporites puzzlei* suggest an age no older than Bajocian and no younger than Bathonian.

6.2.4.7 Remarks

This zone ranges over the Lealt Shale Formation of the Great Estuarine Group and the samples are considered to be nonmarine. This is consistent with the lack of dinoflagellate cysts.

6.2.5 Biozone E (middle Bathonian?)

6.2.5.1 Base

The lower boundary of this biozone is defined by a marked increase in *Perinopollenites elatoides*, to between 10% and 24%.

6.2.5.2 Top

The biozone covers the top of the studied interval, thus the upper boundary of Biozone E cannot be defined.

6.2.5.3 Characteristics

The zone is otherwise dominated by bisaccate grains (23 %) and *Perinopollenites elatoides* (17 %). Other characteristic taxa are *Callialasporites* spp. (8 %). *Neoraistrickia gristhorpensis* and *Manumia delcourtii* are not registered in the top sample of this zone.

The beginning of the biozone coincides with the first appearance of the stratigraphically important dinoflagellate cysts *Ctenidodinium cornigera* (Bathonian; Riding & Thomas 1992) and *Pareodinia prolongata* (sample WS41 herein; late Bathonian – middle Oxfordian; Riding & Thomas 1992). Within the zone are *Meiourugonyaulax planoseptata* (early Callovian; Riding & Thomas 1992), *Jansonia* spp. (sample WS42 herein; Bathonian; Riding & Thomas 1992), *Pareodinia antennata* (sample WS43 herein) and *Hapsidaulax margarethae* (Sample WS45 herein; middle – late Bathonian; Riding & Thomas 1992) registered for the first time. There is also a large influx of *Pareodinia aphelia* coinciding with the maximum of *Perinopollenites elatoides* and *Araucariacites australis*. *Nannoceratopsis* spp. and *Energlynia acollaris* are also present within the biozone.

6.2.5.4 Samples

The zone comprises samples WS41 – WS45, which are rather well to well preserved. The relative amount of fragments are 42%.

6.2.5.5 Ammonite zones

There are no samples in this biozone which has been dated by ammonites. The suggested age is early/middle Bathonian to middle/late Bathonian.

6.2.5.6 Age

Ctenidodinium cornigera and *Jansonia* spp. indicates that the biozone is no older or no younger than Bathonian, while *Pareodinia prolongata* and *Hapsidaulax margarethae* suggest a middle – late Bathonian age.

6.2.5.7 Remarks

As the preceding biozone is deposited in a nonmarine environment the first occurrences reported from the lower part of this zone are not necessarily true first occurrences but a result of the depositional environment. The occurrence of dinoflagellate cysts and lack of ammonites suggest a marginal marine environment.

6.3 Environment and Climate

The quantitative variations within the different SEG:s, and the inferred ecological and climatological results are presented in figure 7.

6.3.1 Environment

Through the Pliensbachian and the larger part of the Toarcian the sporomorph assemblages are dominated by upland pollen and spores (samples WS26-WS30). These samples are all collected from shales. The samples are poorly to very poorly preserved, but contain fairly large amounts of fragmented dinoflagellate cysts. The depositional environment is interpreted as marine, based on the dinoflagellate cyst content and the lithology. This interpretation is verified by Riding (1991) and Grigelis & Norling (1999). Since the upland communities mostly consist of bisaccate pollen, the domination of this assemblage is interpreted as a result of the depositional environment.

Towards the end of Toarcian, there is a shift to lowland dominance with a peak (34%) in the Opalinum Zone (middle Aalenian). This peak occurs in samples collected from the Dun Can Shales. This is succeeded by a short interval of coastal dominance with a peak (42%) in the Concavum Zone (late Aalenian), in samples collected from Udairn Shale Member. During this time the influx of upland elements diminishes, reaching a minimum in the Scissum Zone (0%). This is immediately succeeded by a peak in coastal elements in the Concavum Zone. The depositional environment is still marine, but it becomes more near shore in the Berreraig Sandstone Formation (Hesselbo & Coe 2000). Closer to shore the environmental and climatic signal becomes stronger (Muller, 1959). The decrease in upland elements is consistent with a more near shore environment.

When the coastal elements decrease there is a brief period with a small increase in the lowland assemblage within the early Bajocian Discites Zone of the Udairn Shale Member. This is succeeded by a period, with a marked peak in late Bajocian, when upland elements once again become dominant. This period starts within the Rigg Sandstone Formation and continues up in the Great Estuarine Group where it ends in the Duntulm Formation. The samples are collected from the shalier parts of the Rigg Sandstone, the Cullaidh Shale Formation, the Lealt Shale Formation and the Duntulm Formation (SSI 1982). Only the first and the last sample in this interval contain substantial amounts of dinoflagellate cysts. The lack of dinoflagellate cysts in the remaining samples investigated herein, is consistent with the lagoonal/brackish environment interpretation of the Great Estuarine Group (Andrews 1987).

During the middle/late Bathonian lowland elements dominate. The samples are collected from the shalier parts of the Duntulm Formation in the Great Estuarine Group. This interval lacks ammonites, but the presence of dinoflagellate cysts indicates marine influenced environment. The depositional environment is interpreted as brackish/lagoonal with a marine influence, this correlates with previous interpretations (Andrews 1985).

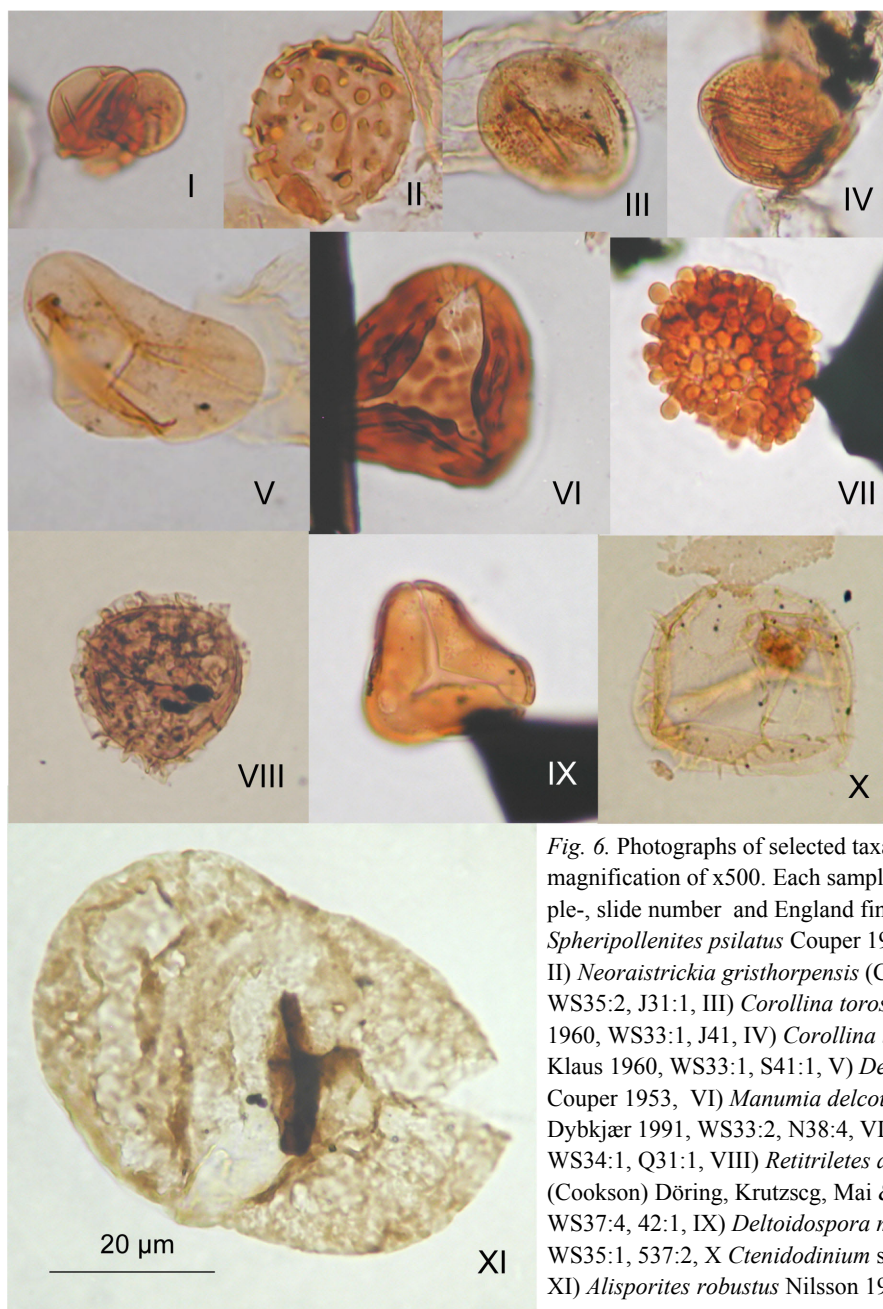


Fig. 6. Photographs of selected taxa, photographed at a magnification of x500. Each sample identified by sample-, slide number and England finder coordinates. I) *Spheripollenites psilatus* Couper 1958, WS35:2, G40:4, II) *Neoraistrickia gristhorpensis* (Couper) Tralau 1968, WS35:2, J31:1, III) *Corollina torosa* (Reissinger) Klaus 1960, WS33:1, J41, IV) *Corollina torosa* (Reissinger) Klaus 1960, WS33:1, S41:1, V) *Deltoidospora australis* Couper 1953, VI) *Manumia delcourtii* (Pocock) Dybkjær 1991, WS33:2, N38:4, VII) *Leptolepidites* spp. WS34:1, Q31:1, VIII) *Retitriletes austroclavatoides* (Cookson) Döring, Krutzsch, Mai & Schultz 1963, WS37:4, 42:1, IX) *Deltoidospora minor* Couper 1953, WS35:1, 537:2, X) *Ctenidodinium* spp. WS43:2, R24:3, XI) *Alisporites robustus* Nilsson 1958, WS37:1, G32.

6.3.2 Climate

Within the coastal and lowland assemblages it is possible to distinguish some climatic indicators. The relative abundances of these are shown in two different graphs, one for coastal and one for lowland. Some coastal elements are characterized either as representing warmer or cooler conditions, i.e. temperature. Warm elements, herein *Corollina* spp., dominate practically all throughout the Pliensbachian, Toarcian, Aalenian and into early Bajocian with a minimum in Scissum Zone (46%), where cooler elements have a very brief peak of dominance. Cooler elements, *Araucariacites australis* and *Callialasporites* spp., dominate the coastal assemblages through the remaining

part of the Bajocian and the Bathonian, with a peak in the early/middle Bathonian (100%). As there is only one element which composes the warm indicator in the coastal environment, the result is completely dependent on the presence or absence of this taxon. The cool indicators, however, comprise *Araucariacites australis* as well as all present *Callialasporites* species, *C. dampieri*, *C. turbatus* and *C. minus*. As *Callialasporites* has its first known occurrence in Late Toarcian (middle Aalenian herein) *Araucariacites australis* is the only cool indicator in coastal environment in pre-late Toarcian strata.

The climatic indicators for lowland environments are more complex as they not only provide indications of temperature but also of humidity.

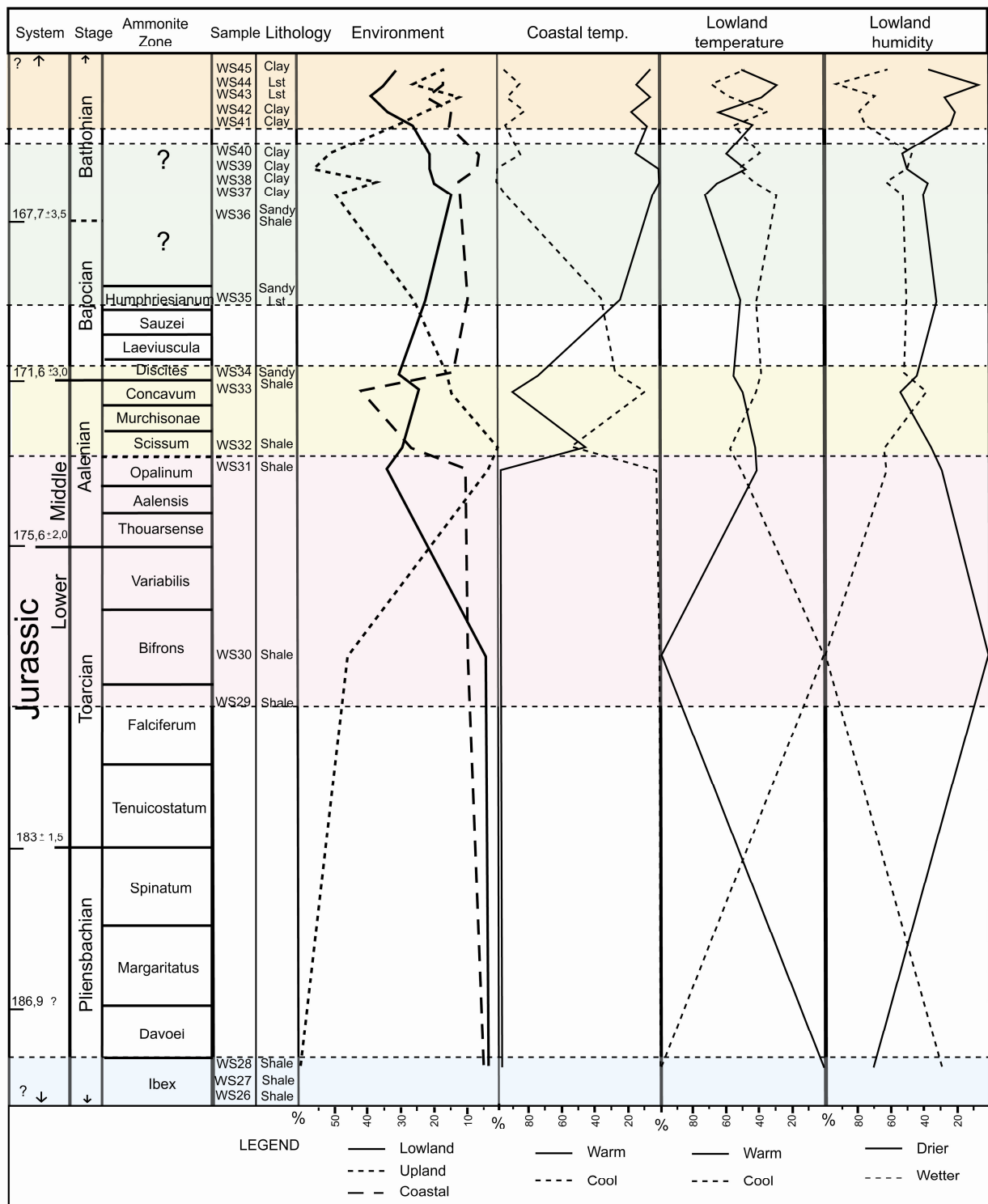


Fig 7. Graphs illustrating the relative amount of pollen and spores assemblages, selected sample levels with lithology and the biozonation from this study.

Graphs showing the relative abundance of lowland elements indicating temperature and humidity are shown in fig 7.

The temperature graph in the lowland environment shows a similar trend as the temperature graph in the coastal environment although less pronounced.

In the Ibex Zone (Pliensbachian) cool elements dominate completely (100%). In the next quantitatively analysed sample from the Bifrons Zone (Toarcian) warm elements dominate totally (100%). In the Scissum Zone (middle Aalenian) cool elements peak (57%) followed by a dominance of warm elements

throughout the Bajocian culminating with a peak (73%) in the early/middle Bathonian. In middle/late Bathonian both the warm and the cool indicators exhibit a zigzag pattern, a warm maximum coincides with a cool minimum and the opposite, and the oscillations in the graphs become more distinct with time. A similar zigzag pattern can be seen in the coastal elements but the pattern is less obvious as the warm and cool graphs are separated from each other. The warm peaks in coastal and the warm peaks in lowland do correlate rather well with each other.

The graph showing humidity in the lowland environment correlates fairly well with the temperature graphs of both coastal and lowland environments. In the Bifrons Zone (middle Toarcian) wetter elements display peaks (100%) coinciding with a warm dominance of both lowland and coastal elements. In the Scissum Zone (middle Aalenian) wetter elements are still dominating, but a peak in cooler elements indicate a cooler climate. A brief peak of drier elements coincides with the strong warm peak in coastal as well as a small more indistinctive warm peak in lowland. Wetter elements dominate through the rest of Bajocian and in the early Bathonian. From early to middle Bathonian a trend towards wetter conditions is indicated, with a marked maximum (93%) at the end of the studied interval.

The combined interpretation of the climate (fig. 8) indicates a warm and humid climate during the late Toarcian, followed by a cool and humid climate during the early Aalenian. In the late Aalenian the climate becomes warm and dry, followed by a cool and more humid trend through the Bajocian and Bathonian.

7. Comparison, correlation and discussion

7.1 Biozonation

The biozonation herein is correlated with other palynological investigations from north-west Europe. Riding (1991) presents results from the Inner Hebrides, Dybkjær (1991) from the Danish Subbasin and Koppellhus and Dam (2003) from Greenland. A comparison between the different biozonations, with the exception of Riding (1991), who did not subdivide his results into biozones, can be seen in figure 8.

7.1.1 Scotland

The results of the identified pollen and spores in this study are very similar to those of Riding (1991), but for the dinoflagellate cysts the result differs somewhat. Riding (1991) did not subdivide his investigated interval into biozones, but a comparison between the biozonation used herein and the data from Riding (1991) is given below.

The Toarcian samples in Riding (1991) are from the same formation as the samples in this study,

the Raasay Ironstone Formation, but not from the same location. Both studies show a palynoflora dominated by bisaccate pollen and consisting mostly of long ranging taxa. Riding (1991) reports no *Spheripollenites subgranulatus*, one of the definitions of Biozone B herein, but his record of *Araucariacites australis* and the absence of *Callialasporites* are consistent with Biozone B herein. In both studies questionable specimens of *Kekryphalospora distincta* were found in the Raasay Ironstone Formation, and in this study an additional specimen was also recovered from the succeeding Dun Can Shale Member. According to Riding (1991) the Toarcian assemblage contains < 5% marine microplankton, with no more than 9 species of dinoflagellate cysts, dominated by *Nannoceratopsis gracilis*. The assemblages assigned to Biozone B in the present study, contain very few marine microplankton taxa below or within the Raasay Ironstone Formation (5%) but display a dramatic increase in the Dun Can Shale Member above (79%). The first occurrence of *Leptodinium* cf. *subtile* was in Riding (1991) lowered to the Laeviuscula Zone (early Bajocian), but in this study, however, a specimen was found even lower, in the Opalinum Zone (middle Aalenian). In this study *Dissilodinium* spp. (late Toarcian - post Portlandian; Koppellhus & Dam 2003) and *Sirmiodiniopsis orbis* (late Bajocian - early Kimmeridgian; Riding & Thomas 1992) are registered already in late Pliensbachian and early Aalenian respectively. The marine microplankton and the dominance of bisaccate pollen, indicate a marine depositional environment, and this is consistent with the shaly lithology.

In the Aalenian (Opalinum Zone) to early Bajocian (Sauzei Zone), corresponding to Biozone C herein, Riding (1991) studied several samples from the Berreraig Sandstone Series. His results show a palynoflora dominated by gymnospermous pollen. The pollen assemblage is dominated by, among others, bisaccate pollen and *Callialasporites*, few at the beginning and more frequent at the end of the period. *Araucariacites australis*, *Cerebropollenites macroverrucosus*, *Corollina* and *Perinopollenites elatoides* are also characteristic components of the palynoflora. Among the spores, long ranging taxa such as *Deltoidospora*, *Retitriletes austroclavatooides*, *Coronatisporites valdensis* and *Osmundacidites wellmannii* occur. Within this interval Riding (1991) also records the first and last occurrence of *Kekryphalospora distincta*. These results compare well with the results of this study. The co-occurrence of *C. dampieri* and *C. turbatus* that Riding (1991) registered in the late Toarcian corresponds to the hiatus between Biozone B and Biozone C in the present study. Riding (1991) did not find *C. minus* in any of his samples, but *C. microvelatus* and *C. segmentatus* were, however, identified.

Among the marine microplankton Riding (1991) registered within this interval (Aalenian - Bajocian), *Nannoceratopsis* spp. is dominating, frequently comprising above 50% of the dinoflagellate cysts. Also present were *Parvocysta* spp., *Walldinium elon-*

gatum and *Susadinium scrofoides*. The oldest occurrence of *Dissiliodinium* spp. was registered in the Discites Zone and as mentioned previously, that of *Leptodinium* cf. *subtile*, in the Laeviuscula Zone. The relative amount of marine microplankton is less than 13.3%.

The first occurrence of *Neoraistrickia gristhorpensis*, the definition of the beginning of Biozone D, is reported in late Bajocian. This is approximately at the same level as in this study. In the middle of Bajocian to early Bathonian, Humphriesianum - ? (equivalent to Biozone D herein) the palynoflora continues to be dominated by gymnospermous pollen, bisaccate pollen and *Callialasporites*. The spores include *Calamospora mesozoica*, *Punctatisporites globosus*, the first occurrence of *Leptolepidites* spp. and *Neoraistrickia gristhorpensis*. At times *Botrycoccus* is abundant. Marine microplanktons were recorded in significant proportions throughout the interval. Significant dinoflagellate cysts in the beginning of the interval are *Caddasphaera halosa*, *Ctenidodinium sellwoodii*, *Nannoceratopsis spiculata* and *Pareodinia ceratophora*. *Acanthaulax crispata*, *Energlynia acollaris* and *Valvaeodinium spinosum*. These are also stratigraphically important, suggesting a late Bajocian - early Bathonian age. At the end of the interval, in the early Bathonian, the diversity of dinoflagellate cysts diminishes and the preservation of these becomes poorer. This is interpreted by Riding (1991) as dinoflagellate cysts from older strata are reworked into this assemblage. The results of Riding (1991) in this interval correlate well with Biozone D herein. Riding's (1991) interpretation of the reworked dinoflagellate cysts corresponds to the interpreted nonmarine environment in the Lealt Shale Formation in this study.

In the middle/late Bathonian well preserved, diverse palynofloras with a dominance of marine microplankton are reported by Riding (1991). The dinocyst taxa *Ctenidodinium sellwoodii*, *Batiacaspheera* spp., *Meiourogoniaulax reticulata*, *Sentusidinium* spp. and *Pareodinia ceratophora* all have high relative abundances. *Ctenidodinium cornigera*, *Ctenidodinium combazii*, *Energlynia acollaris*, *Aldorfia aldorfensis* are also characteristic of the assemblage. *Hapsidaulax margarethae* is one stratigraphically important species. Gymnospermous pollen, bisaccate grains and *Callialasporites*, are more dominant than pteridophyte spores. The last occurrence of *Neoraistrickia gristhorpensis* is near the end of this interval. This corresponds well with Biozone E herein with the high relative abundance of *Pareodinia aphelia*, and the occurrence of *Ctenidodinium*, *Meiourogoniaulax*, *Sentusidinium* and *Hapsidaulax margarethae*. The last occurrence of *Neoraistrickia gristhorpensis* and the dominance of *Callialasporites* and bisaccate grains are also consistent with Biozone E herein.

7.1.2 Danish Basin

The spore-pollen zonation of the Danish Subbasin was erected by Lund (1977), Dybkjær (1991) and Koppelhus & Nielsen (1994). Dybkjær (1991) studied an interval covering the late Rhaetian to early Bajocian and divided this period into biozones. The base of the Sinemurian – Pliensbachian *Cerebropollenites macroverrucosus* Zone is defined by the first occurrence of *Cerebropollenites macroverrucosus* and the top of the zone is immediately below a distinct rise in the abundance of *Spheripollenites*, as well as the first occurrence of *Ischyosporites* and/or *Leptolepidites*.

Cerebropollenites macroverrucosus is in the present study registered throughout the entire studied interval. A distinct increase in *Spheripollenites* is herein reported in the Bifrons Zone (middle Toarcian), sample WS30. The first occurrences of *Leptolepidites* and *Ischyosporites* respectively, are within Opalinum Zone (middle Aalenian), sample WS31 and Scissum Zone (middle Aalenian), sample WS32. The *Cerebropollenites macroverrucosus* zone (Dybkjær 1991) and Biozone A herein correlate well in part, with the exception of the first occurrence of *Ischyosporites* and/or *Leptolepidites*.

The Toarcian *Spheripollenites* – *Leptolepidites* Zone of Dybkjær (1991) has a base defined by an increase in *Spheripollenites*, as well as the first occurrence of *Leptolepidites* and/or *Ischyosporites* (see above). The top of the *Spheripollenites* – *Leptolepidites* zone is immediately below a marked increase in *Perinopollenites elatoides* and a decrease in *Spheripollenites*. Within this zone a maximum of *Spheripollenites* and a maximum of *Corollina* coincide with a minimum of bisaccate pollen in early Toarcian (Dybkjær 1991). The *Spheripollenites* – *Leptolepidites* zone of Dybkjær (1991) and Biozone B herein can be correlated based on several similarities, namely an increase of *Spheripollenites* at the beginning of the zones and the increase in *Perinopollenites elatoides* just above the top boundary of the zone. There are, however, also several differences; the decrease of *Spheripollenites* occurs in this study in the middle sample of Biozone C, Concavum Zone (late Aalenian). The coinciding maxima of *Spheripollenites*, *Corollina* and minimum of bisaccate grains occur in Biozone C herein, in the Murchisonae and Concavum zones (Late Aalenian). The first occurrences of *Ischyosporites* and *Leptolepidites* are in this study not registered until the end of Biozone B.

The Aalenian – early Bajocian *Perinopollenites elatoides* Zone of Dybkjær (1991), has a base defined by an increase in the abundance of *Perinopollenites elatoides*, as well as a decrease of *Corollina torosus* and *Spheripollenites psilatus*. The top of the zone is not defined. The zone is characterized by a dominance of *Perinopollenites elatoides*, as well as a low abundance of *C. torosus* and bisaccate pollen. In the present study there is an increase in *Perinopollenites elatoides*, as well as a decrease in

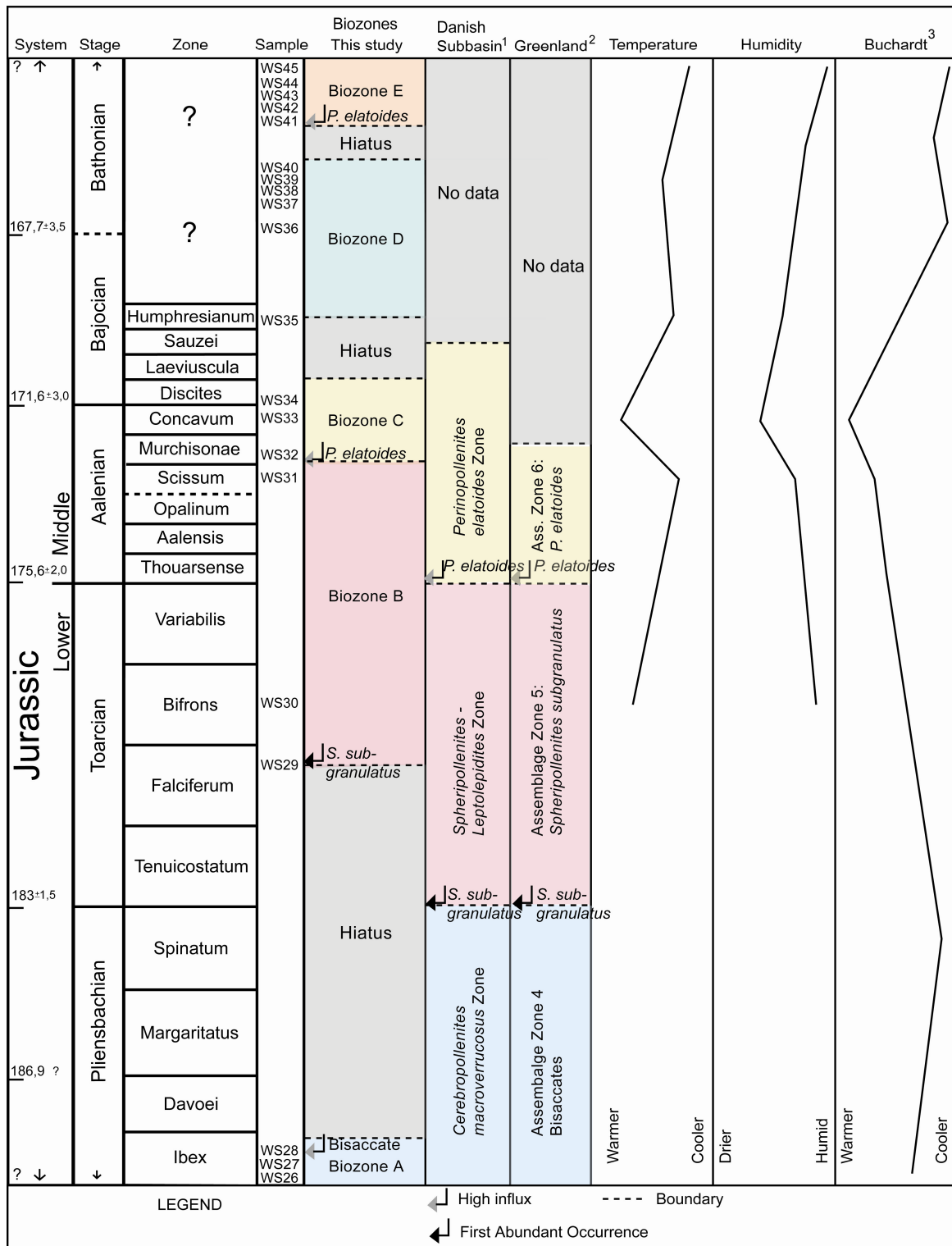


Fig. 8. Correlation between biozonation from this study and 1) Dybkjær (1991) and 2) Koppelhus & Dam (2003). Climate interpretations from this study are also illustrated and correlated with 3) Burchardt (2003).

Spheripollenites psilatus in the beginning of Biozone C, see above, as well as a low abundance of bisaccate pollen. This does, however, coincide with a marked increase in *Corollina*, not a decrease. Consequently the *Perinopollenites elatoides* zone and Biozone C herein can be correlated with the exception of the increase in *Corollina*.

7.1.3 Greenland

Koppelhus & Dam (2003) constructed a palynological zonation of Lower – Middle Jurassic strata in East Greenland based on the entire palynological assemblages: pollen, spores, dinoflagellate cysts, acritarchs and fresh water algae. Only the biozones

based on pollen and spores are compared with the biozonation in this study.

Assemblage Zone 4 (Bisaccates) of Koppelhus & Dam (2003) has its base defined by the first sample that is overwhelmingly dominated by bisaccate pollen, the top is defined as being below the first abundant occurrence of *Spheripollenites subgranulatus*. The zone is characterized by poor preservation and a lack of marine microplankton, and the suggested age is late Pliensbachian. This zone correlates with Biozone A herein based on the dominance of bisaccate grains (62%).

The early – late Toarcian Assemblage zone 5 (*Spheripollenites subgranulatus* – *Cerebropollenites macroverrucosus* – *Luehndea spinosa*) of Koppelhus & Dam (2003) has its base defined by the first abundant occurrence of *Spheripollenites subgranulatus*. The top of the zone is defined as below a peak in the abundance of *Perinopollenites elatoides*. Characteristic for the zone are also *Cerebropollenites macroverrucosus* and *Corollina torosus*. The zone is Toarcian? – middle Aalenian in age and correlates well with Biozone B herein, based on the zonal criteria above.

The base of Assemblage Zone 6 (*Perinopollenites elatoides*) of Koppelhus & Dam (2003) is defined as the peak abundance of *Perinopollenites elatoides* together with an abundance of *Chasmatosporites hians* and *C. major*. The upper boundary of the zone is below a high abundance of *Botryococcus*. *Staplinisporites caminus* and *Sestrosporites pseudoalveolatus* have their first occurrences in the zone, as well as the dinoflagellate cysts *Phallogocysta eumekes*, *Dissiliodinium* spp. and *Wallogocysta laganum*. The suggested age is early – late Aalenian. The assemblage partly correlates with Biozone C herein, which is late Aalenian – early Bajocian in age and also begins with a peak in the *Perinopollenites elatoides* abundance and the first occurrence of *Wallogocysta*, *Phallogocysta*, and *Staplinisporites caminus*. The first abundant occurrence of *Dissiliodinium* is herein just below Biozone C, as is the high abundance of *C. hians*.

7.2 Ammonite zonation versus palynostratigraphy

When comparing the interpreted ages from the biozonation herein with the ammonite biozonation, there are several similarities but also some differences. Biozone E and the upper part of Biozone D herein have interpreted ages that are consistent with the estimated ages of the strata. The lower part of Biozone D as well as Biozone C and the upper part of Biozone B herein have interpreted ages that are consistent with the ammonite zonation. In Biozone A and the lower part of Biozone B, however, there are some differences. The palynomorphs in Biozone A herein indicate late Pliensbachian, while the sample comes from the early Pliensbachian IbeX Zone. As the samples in Biozone A are poorly preserved and the qualitative

analysis were difficult there are a certain degree of uncertainty. The results may, however, indicate a older FO for some taxa, e.g. *Dissiliodinium* spp., *Monolites couperi*, *Susadinium* spp. To clarify which of these possibilities are correct further studies should be carried out.

The lower part of Biozone B is interpreted as being early Toarcian – Toarcian in age. The ammonite zonation gives a middle Toarcian – late Toarcian age.

The biozonations from the Danish Subbasin and Greenland are to the larger extent dated with ostracods and dinoflagellate cysts (Nielsen 2003). The ostracod record in post-Pliensbachian within this interval is poor or barren (Nielsen 2003). This means that the age of the palynozones above this level have a high degree of uncertainty.

7.3 Ecology and climate

The temperature and humidity curve for coastal and lowland have a high degree of uncertainty in the interval earlier than early/middle Toarcian due to, among other reasons, the small amount of coastal and lowland elements. The samples (WS26 – WS29) in this interval (IbeX Zone to Bifrons Zone) are also poorly to very poorly preserved and only a few have been quantitatively analysed. The hiatus between these samples are occasionally very large. These samples have also been collected from marine environments in which the lithology may have had a strong influence on the sporomorph assemblage (Chaloner & Muir 1968; Muller 1959; Traverse 2007). Due to these facts, the climatic interpretation starts in the Toarcian Bifrons Zone (sample WS30).

The high relative abundance of upland pollen and spores deposited in Pliensbachian and Toarcian is interpreted as a result of the depositional environment (marine) and not as an ecological indicator. The change to a palynoflora more dominated by lowland and coastal elements is interpreted to show a change in depositional environment to more near shore.

When comparing coastal temperatures with lowland temperatures herein, as well as with lowland precipitation it is possible to correlate the different graphs with each other and give interpretations on the climate from these.

In late Toarcian both coastal and lowland elements show a warm and wet climate. It becomes gradually cooler until there is a brief interval of cool and wet climate in the middle Aalenian Scissum Zone. After this there is a period of warmer, drier climate with a peak around the Aalenian/Bajocian boundary. This coincides with the peak of coastal elements in the environmental graph. The increase in the relative amount coastal elements does however not need to be directly connected with changes in the climate, it can be related to sea level changes. According to Morton (1987) there is a small sea level maximum just before the Aalenian – Bajocian boundary. However, the increase in coastal elements

begins already in the middle Aalenian Scissum Zone. There is another sea level maximum in the late Toarcian (Morton 1987), but this and the increase of coastal elements do not correlate. There are also an additional number of sea level maxima interpreted by Morton (1987), but none that correspond with an increase in coastal elements. Hence, this explanation is considered to be possible, but not probable. The excellent match between the warm maximum and the coastal maximum suggests a connection.

The climatic trends through the rest of Bajocian, as well as the early Bathonian are a little more difficult to interpret, as the coastal environment shows a strong cooling trend, while the lowland environment shows a weaker warming trend. The humidity is relatively stable with a small drier dominance. In middle/late Bathonian the climate is interpreted as cooler and more humid.

In the late Bajocian and early Bathonian there is an increase and maximum in the upland elements. This coincides with a gradual cooling, displayed by the coastal elements, and a more humid climate. The interpreted depositional environment is brackish/lagoonal, not an environment which would be prepositioned to have a higher relative amount of upland pollen and spores. It is therefore likely that the alteration in the SEG:s are a response to climatic or geographical change. The decrease of the lowland and coastal SEG:s could indicate a less dense vegetation in these environments.

When comparing the results of the environment and climate assessment with the lithology of the samples, no relationship can be detected. This strengthens the opinion that the results of the assessment are a result of changes in environment and climate and not dependent of changes in lithology.

In Abbink (2001) the climatic study begins in Callovian while this study ends in the middle/late Bathonian. It is therefore not possible to correlate these two studies with each other directly. It is, however, possible to compare the result of the palaeoclimate curves in the very end of this study to the result in the very beginning of Abbink (2001). The climate according to Abbink (2001) in the Callovian is relatively cool and humid. This may correlate well with the results of this study which suggests that the climate in the middle/late Bathonian is also cool and humid.

In Buchardt (2003) (in Poulsen & Riding 2003) a climate curve, warmer/cooler, for Sinemurian (early Jurassic) to post Kimmeridgian (late Jurassic) in North Europe, has been compiled. The palaeotemperatures in that climate curve have been assembled by Buchardt (2003) (in Poulsen & Riding 2003) mainly from older work and are calculated from oxygen isotope data from Jurassic fossils in Northwest Europe. The graph shows a cool maximum in the late Pliensbachian with a strong warming trend through the Toarcian and the Aalenian, and a temperature maximum in the late Toarcian/early Ba-

jocian. There is a rapid cooling in the Bajocian with a temperature minimum in the late Bajocian. Throughout the rest of the Middle Jurassic the climate curve shows minor fluctuations in the cool end of the spectra. This correlates well with the results of this study (fig. 8).

8. Conclusions

This palynological investigation of the Early – Middle Jurassic (Pliensbachian – Bathonian) of the Hebrides basin, Scotland has revealed a diverse, if not always well preserved, palynoflora. The studied interval has been biostratigraphically divided into five biozones (A – E) (fig. 3) based on the presence and absence of certain miospore key taxa as well as their relative quantitative abundance. Biozone A (Pliensbachian) is defined by the presence of several long ranging taxa as well as the very scarce presence of *Spheripollenites subgranulatus*, while Biozone B (late Toarcian-early Aalenian) is defined by the abundant presence, of *Spheripollenites subgranulatus*. Biozone C (late Aalenian - early Bajocian) is defined by the first co-occurrence of *Callialasporites dampieri*, *C. turbatus* and *C. minus*. Biozone D (middle Bajocian - early Bathonian) is defined by the first occurrence of *Neoraistrickia gristhorpensis*, and Biozone E (middle/late Bathonian) is defined by a significant increase in the abundance of *Perinopollenites elatoides* and *Araucariacites australis*. The results of the study are correlated with Riding's (1991) palynological study over the Hebrides Basin with a good result. The biozones herein also correlate fairly well with the biozonations of Dybkjær (1991), and Koppelhus and Dam (2003) of the Danish Subbasin and Greenland. The present ammonite correlated palynozonation has implications for the suggested ages of the palynozones of the Danish Subbasin, and Greenland.

The depositional environments in this study are interpreted to have been marine (Pliensbachian – Toarcian), near shore marine (Aalenian – Bajocian) and brackish/lagoonal to terrestrial (Bathonian). This is consistent with previous studies within this interval in the area.

The identified sporomorphs have been divided into ecological and climatic assemblages, and graphs have been drafted after their relative abundances. The result is shown in figures 7 and 8. The interpretation of the ecological graphs shows that the high dominance of upland elements in Pliensbachian is the result of lithology, while the coastal dominance in late Aalenian and the upland dominance in early Bathonian are due to climatic or geographical changes. The interpretation of the climatic graph commences in late Toarcian, due to the Neves effect and poor preservation. The interpreted climate graphs indicate a warm and humid climate in the late Toarcian with a change to a warmer and drier climate in the late Aalenian – early Bajocian. The studied interval then ends with a change to a cooler and more humid climate in the Bathonian. These results

correlate well with the palaeotemperature curve based on oxygen isotope data compiled by Buchardt in Poulsen & Riding (2003).

9. Suggestions for further studies

It would be interesting to analyse samples covering the major hiatus in the studied interval to be able to more precisely determine ages for biozone boundaries and other important events. This would require further sampling.

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Appendix 1: List of identified palynomorphs with ecological and climate preferences. Climate preferences are illustrated by Humidity (wetter or drier)/Temperature (cooler or warmer) (Abbink 1998; Guy-Ohlson 1989; Koppelhus & Dam 2003; Rding & Thomas 1992).

Appendix 1

Tidal

Alisporites thomasi (Couper) Nilsson 1958
Densoisporites spp.
Densoisporites velatus Weyland & Krieger 1953
Retitriletes spp. Pierce 1961
Retitriletes austroclavatidites (Cookson) Döring, Krutzsch, Mai & Schultz 1963
Retitriletes clavatidites (Couper) Döring, Krutzsch, Mai & Schultz 1963

Coastal

/C *Araucariacites australis* Cookson 1947
 /C *Callaialasporites dampieri* (Balme) Dev 1961
 /C *Callaialasporites minus* (Tralau) Guy 1971
 /C *Callaialasporites turbatus* (Balme) Schultz 1967
 /C *Callialasporites* spp. Sukh Dev 1961
 /C *Callialasporites trilobatus* (Balme) Dev 1961
 /W *Corollina* spp. Maliavkina 1949 emend. Cornet & Traverse 1975
 /W *Corollina torosa* (Reissinger) Klaus 1960, emend. Cornet & Traverse 1975

Lowland

W/W *Baculatisporites comaumensis* (Cookson) Potonié 1956
 W/W *Calamospora tener* (Leschik) de Jersey 1962
 D/C *Chasmatisporites apertus* (Rogalska) Nilsson 1958
 D/C *Chasmatisporites elegans* Nilsson 1958
 D/C *Chasmatisporites hians* Nilsson 1958
 D/W *Deltoidospora* spp. Miner 1935
 D/W *Deltoidospora australis* Couper 1953
 D/W *Deltoidospora concavus* (Bolkhovitina) Dettmann 1963
 D/W *Deltoidospora minor* Couper 1953
 D/W *Deltoidospora toralis* (Leschik) Lund 1977
 D/W *Exesipollenites tumulus* Balme 1957
 W/W *Ischyosporites* spp. Balme 1957
 W/W *Ischyosporites variegatus* (Couper 1958) Schultz 1967
Leptolepidites spp.
Leptolepidites equatibossus (Couper) Tralau 1968
Leptolepidites macroverrucosus Schultz 1967
Leptolepidites major Couper 1958
Leptolepidites paverus Levet-Carette 1964
 D/W *Monosulcites* sp.
Neoraistrickia gristhorpensis (Couper) Tralau 1968

W/W *Osmundacidites wellmannii* Couper 1953
 W/C *Perinopollenites elatoides* Couper 1958
 W/W *Punctatisporites* spp.
 W/W *Punctatisporites globosus* Couper 1958
 W/W *Punctatisporites major* Couper 1958
Staplinisporites caminus (Balme) Pocock 1962
Staplinisporites telatus (Balme) Döring
Stereisporites hauerivensis Döring 1966
 D/W *Striatella* spp. Mädler 1964 emend. Filatoff & Price 1988
 D/W *Striatella scania* (Nilsson) Filatoff & Price 1988
 D/W *Striatella seebergensis* Mädler 1964 emend. Filatoff & Price 1988
Uvaesporites argenteiformis (Bolkhovitina) Schultz 1967
Uvaesporites puzzlei Guy 1971

River

Vietrisporites bjuvensis Nilsson 1958
Vitreisporites spp.

Upland

Alisporites spp.
Alisporites radialis (Leschik) Lund 1977
Alisporites robustus Nilsson 1958
 Bisaccate pollen indet.
 Bisaccate sacci indet.
Pinuspollenites minimus (Couper) Kemp 1970
Pinuspollenites pinoides (Nilsson) Lund 1977
Pinuspollenites spp.
Podocarpidites sp. Cookson 1947 ex Couper 1953
Quadraeculina anellaeformis Maliavkina 1949

Other

Acanthotriletes varius Nilsson 1958
Anapiculatisporites sp.
Anapiculatisporites telephorus (Pautsch) Jansonius 1962
Apiculatisporites sp.
Cadargasporites sp.
Calamospora mesozoica Couper 1958
Cerebropollenites spp. Nilsson 1958
Cerebropollenites macroverrucosus (Thiergart) Schultz 1967
Cerebropollenites thiergartii Schultz 1967
Chasmatisporites major (Nilsson) Pocock & Jansonius 1958
Chasmatisporites spp. Nilsson 1958, emend. Pocock & Jansonius 1969
Chordasporites spp.
Cibotiumspora juriensis (Balme) Filatoff 1975

Conbaculatisporites spp.
Contignisporites problematicus Dettman 1963
Concavissimisporites verrucosus Delcourt & Sprumont 1955
Chordasporites spp.
Eucommiidites granulatus Schultz 1967
Exesipollenites cf.
Exesipollenites scabrosus
Foraminisporis sp.
Foraminisporisa jurassicus Schultz 1967
Cycadopites nitidus (Balme) Pocock 1970
Granuloperculatipollis rudis (reworked)
Kekryphalospora distincta Fenton & Riding 1988
Kraeuselisporites reissingerii (Harris) Morbey 1975
Manumia delcourtii (Pocock) Dybkjær 1991
Marattisporites sp.
Monolites couperi Tralau 1968
Pilasporites couperi Hunt 1986
Podosporites amicus Scheuring 1970 (reworked)
Polypodiisporites polymicroforatus (Orłowska-Zwolinska) Lund 1977 (reworked)
Porcellispora longdonensis (Clarke) Scheuring 1970 emend. Morbey 1975 (reworked)
Retitriletes semimuris (Danzé-Corsin & Laveine) McKeller 1974
Rhaetipollis germanicus Schultz 1967 (reworked)
Riccisporites tuberculatus Lundblad 1954 (reworked)
Simeozoontriletes artuatis
Spheripollenites psilatus Couper 1958
Spheripollenites subgranulatus Couper 1958
Tigrisporites spp.
Trachysporites cf.
 Unidentified

Dinoflagellate cysts

Carpathodinium credae (Beju 1971) Drugg 1978
Ctenidodinium cornigera (Valensi 1953) Lentin & Williams 1978
Ctenidodinium continuum (Valensi 1953) Jan du Chên et al. 1958
Ctenidodinium sellwoodii (Sarjeant 1975) Stover & Evitt 1978
Dissiliodinium spp.
Ellipsoidictyum gochtii Fensome 1979
Energlynia acollaris (Dodekov 1975) Sarjeant 1978
Eyachia prisca Gocht 1979
 Dinoflagellate cyst fragments indet.
Gongylodinium hocneratum Fenton et al. 1980
Hapsidaulax margarethae Sarjeant 1978
Jansonia sp.
Leptodinium sp. cf. *L. subtile* Klement 1960

Mancodinium semitabulatum Morgenroth 1970
Meiourogonyaulax planoseptata Riding 1987
Mendicodinium groenlandicum (Pocock & Sarjeant) Davey 1979
Nannoceratopsis spp.
Nannoceratopsis ambonis Drugg 1978 emend. Riding 1984
Nannoceratopsis spiculata Stover 1966
Pareodinia antennata (Gitmaez & Sarjeant 1972) Wiggins 1975
Pareodinia aphelia
Pareodinia prolongata Sarjeant 1959
Parvocysta nasuta Bjaerke 1980
Phallocysta eumekes Dörhöfer & Davies 1980
Scriniocassis weberi Gocht 1964
Sentusidinium pelionense Fensome 1979
Sirmiodiniopsis orbis Drugg 1978
Susandinium spp.
Susandinium scrofoides Dörhöfer & Davies 1980
 Unidentified dinoflagellate cyst indet.
Valensiella ovulum (Deflandre 1947) Eisenack 1963
Valvaeodinium spinosum (Fenton & et al. 1980) Below 1987
Wallodinium cylindricum (Habib 1970) Duxbury 1983
Wallodinium krutzschii (Alberti 1961) Habib 1972
Wallodinium laganum Feist-Burkhardt & Monteil 1994

Algae and acritarchs

Marine

Micrhystridium spp. Deflandre 1937, emend. Lister 1970
Tasmanites spp. Newton 1875

Freshwater

Lecaniella foveata Sing 1971
Tetraporina compressa Kondratév 1963
Botrycoccus braunii Kützing 1849

Chytroeisphaeridia sp.
Chytroeisphaeridia cerastes
Chytroeisphaeridia chytroeides (Sarjeant 1962) Downie & Sarjeant 1965

Other

Foraminiferal lining
 Insect
 Fungi

Appendix 2: A list of all identified palynomorphs with their distribution in the studied interval (Koppelhus & Dam 2003; Riding & Thomas 1992; Batten & Koppelhus 1996; Koppelhus & Batten 1996; Guy-Ohlson 1986).

		Pliensbachian		Toarcian		Aalenian		Bajocian		Bathonian										
		ibex		bifrons		opal-mure		condiscit		humphresianum										
		26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44
	amount	miospores		154		155	71	97	214	211	237	215	167	217	206	95	122	302	174	129
	%	miospores		36,0		48,7	14,9	19,3	36	43,7	44,8	63	52,8	71,9	66	15,7	20	56	27,9	20,6
Pollen and spores		total amount palyno		428		318	476	502	597	483	529	341	316	302	311	605	619	539	623	625
<i>Acanthotriletes varius</i>	%	amount						?												
<i>Alisporites</i>	spp.	%				0,6					0,4									
	amount	x	x			1					1	x	x		x	x	x	x	x	x
<i>Alisporites radialis</i>	%	amount		0,6							0,8	3,7	0,6	0,9	1,5	1,1	0,8	1,3	1,7	
	amount			1							2	8	1	2	3	1	1	4	3	x
<i>Alisporites robustus</i>	%	amount		1,9		2,6		0,5	0,5	0,4	0,9	0,6	2,8	1,5	1,1			1,7	1,7	
	amount			3		4		1	1	1	2	1	6	3	1			5	3	
<i>Alisporites thomasi</i>	%	amount				0,6			0,5	1,7	4,2	1,8	1,4	1,5		0,8	2,0	4,6	0,8	
	amount					1			1	4	9	3	3	3		x	1	6	8	1
<i>Anapiculatisporites</i>	spp.	%																		
	amount								x											
<i>Anapiculatisporites telephorus</i>	%	amount									0,4									
	amount			x							1		x							
<i>Apiculatisporites</i>	spp.	%									0,4									
	amount										1			x						
<i>Araucariacites australis</i>	%	amount						4,1	0,5	2,4	2,1	4,7	5,4	1,4	1,9	6,3	6,6	12,6	5,2	7,0
	amount			x				4	1	5	5	10	9	3	4	6	8	38	9	9
<i>Baculatisporites</i>	cf.	%								0,5					0,5					0,6
	amount	?	?					?		1					1	?	?		1	
<i>Baculatisporites comauensis</i>	%	amount															3,3			0,8
	amount	x											x		?		4			1
<i>Bisaccat</i>	%	amount		15,6		2,6	1,4		3,3	3,8	6,8	8,4	4,8	4,6	2,4	3,2	0,8	3,6	6,9	7,8
	amount			24		4	1		7	8	16	18	8	10	5	3	1	11	12	10
<i>Bisaccat sack</i>	%	amount		39,0		32,3	1,4		7,0	9,5	16,9	31,2	29,3	40,1	39	18,9	20,5	2,0	9,2	8,5
	amount			60	x	50	1		15	20	40	67	49	87	80	18	25	6	16	11
<i>Cadargasporites</i>	spp.	%																		
	amount											x								
<i>Calamospora mesozoica</i>	%	amount							x	x										
	amount							5,6	4,1	0,5	1,9	1,3	0,5	3,0	0,9	0,5	5,3	0,8	1,3	0,6
<i>Calamospora tener</i>	%	amount						4	4	1	4	3	1	5	2	1	5	1	4	1
	amount							4	4	1	4	3	1	5	2	1	5	1	4	1
<i>Callialasporites dampieri</i>	%	amount						x	2,1	1,9	x	2,5	3,7	3,0	2,8	1,0	4,2	3,3	2,6	4,6
	amount								2	4		6	8	5	6	2	4	4	8	8
<i>Callialasporites minus</i>	%	amount							6,2	0,9	0,9	0,8	2,8	2,4	1,8	1,5	x	0,8	1,7	1,1
	amount								6	2	2	2	6	4	4	3		1	5	2
<i>Callialasporites trilobatus</i>	%	amount									0,8								0,3	
	amount										2		x				x	?	1	
<i>Callialasporites turbatus</i>	%	amount							2,1	0,9	0,5	1,3	0,5	1,8	0,9	1,0	3,2	0,8	3,3	3,4
	amount								2	2	1	3	x	1	3	2	3	1	10	6
<i>Callialasporites</i>	spp.	%							x		x									
	amount								x		x									
<i>Cerebropollenites</i>	spp.	%																		
	amount	x	x	15,6		4,5	8,5	5,2	0,9	5,7	11,4	0,9	2,4	0,9	4,4	5,3	3,3	7,3	0,6	3,9
	amount	x	x	24		7	6	5	2	12	27	x	2	4	2	9	5	4	22	1
<i>Cerebropollenites macroverucosus</i>	%	amount									1,0	1,4	5,9	3,3	0,9	1,9			1,3	0,6
	amount	x									1	3	14	7	x	2	4		x	4
<i>Cerebropollenites thiergartii</i>	%	amount		0,6							2,1	1,4	1,3	4,2	0,6	0,5	0,5		0,8	1,1
	amount			1							2	3	3	9	1	1	1		1	2
<i>Corollina</i>	spp.	%																		
	amount	x	x	5,2		9,0	9,9	12,4	37	10,4	2,1	0,5			1,0	1,1	2,5	1,3	2,3	
	amount	x	x	8	x	14	7	12	80	22	5	x	1		x	2	1	3	4	
<i>Corollina torosa</i>	%	amount																		
	amount																			
<i>Corollina torosus</i>	%	amount																		
	amount																			
<i>Chasmatosporites</i>	spp.	%																		
	amount					?				x										
<i>Chasmatosporites apertus</i>	%	amount		0,6						1,4	0,9	0,4		0,6	0,9	0,5		0,8		0,8
	amount			1		?		x	3	2	1			1	2	1		1		1
<i>Chasmatosporites elegans</i>	%	amount																		
	amount					?														
<i>Chasmatosporites hians</i>	%	amount		2,6			7,0	2,1	4,2	1,4	2,5		0,6	1,8	1,9		1,6	1,3		1,6
	amount			4	x	x	5	2	9	3	6		1	4	4		2	4	x	2
<i>Chasmatosporites major</i>	%	amount		1,3										0,5			0,8			
	amount			2										1			1			
<i>Cibotiumspora juriensis</i>	%	amount																		
	amount									x										
<i>Combaculatisporites</i>	spp.	%																		
	amount									x										
<i>Contignisporites problematicus</i>	%	amount																		
	amount							x												

		P liensbachian														Toarc					Aalenian				Bajocian				Bathonian				
				ibex		biffo		opal		murc		cond		dis		cite		humphresianum															
		26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45												
	amount pollen an			154		155	71	97	214	211	237		215	167	217	206	95	122	302	174	129												
	%miospores			36,0		48,7	14,9	19,3	36	43,7	44,8		63	52,8	71,9	66	15,7	20	56	27,9	20,6												
Pollen and spores	total amount			428		318	476	502	597	483	529		341	316	302	311	605	619	539	623	625												
<i>Connavis simisporites verrucosus</i>	%																																
	amount										x																						
<i>Cordasporites</i>	spp %																			0,3													
	amount	x																		1													
<i>Deltoidospora</i>	spp %								1,4						0,5																		
	amount								3			x	x	x	1			x			x												
<i>Deltoidospora australis</i>	%								0,5	0,5					0,5	1,5			0,8	0,3													
	amount				x	?			1	1					x	1	3	x	1	1	x												
<i>Deltoidospora concavus</i>	%																																
	amount									x																							
<i>Deltoidospora minor</i>	%							6,2	4,7	2,4	1,3		1,9	1,2	2,8	1,5		1,6	2,6		3,1												
	amount		x		x	x		6	10	5	3	x	4	2	6	3	x	2	8	x	4												
<i>Deltoidospora toralis</i>	%									0,5					?	1,0			1,0	0,6	0,8												
	amount			?		x				1		x	x		2		x		3	1	1												
<i>Densosporites</i>	spp %										0,4							0,8	0,3														
	amount										1		x				x	1	1	x													
<i>Densosporites velatus</i>	%															?																	
	amount								x	x									x	x													
<i>Eucommidites granulosus</i>	%																																
	amount					?																											
<i>Exesipollenites</i>	cf. %						25,4																										
	amount						18																										
<i>Exesipollenites scabrosus</i>	%										1,4									0,7													
	amount										3			x	x					2													
<i>Exesipollenites tumulus</i>	%						2,8	2,1	0,5	7,1	3,0	2,3	4,8	4,1	4,9	4,2	2,5	2,6	1,1	4,7													
	amount	x	x				2	2	1	15	7	5	8	9	10	4	3	8	2	6													
<i>Eyachia prisca</i>	%																																
	amount						?																										
<i>Foraminisporites</i>	cf. %										1,4							0,8		0,6													
	amount										3							1		1													
<i>Foraminisporites jurasicus</i>	%														0,4																		
	amount	?													1		x		?														
<i>Ginkgocycadophytus nitidus</i>	%									0,5				1,8		4,2	4,1	0,3	1,7	1,6													
	amount								x	1				3		4	5	1	3	2													
<i>Granuloperculatipollis nudis</i>	%																																
	amount										x																						
<i>Kchyosporites</i>	spp %												0,9		0,5		1,6	0,3															
	amount												x	2		x	1		2	1	x												
<i>Kchyosporites variegatus</i>	%																																
	amount							x	x																								
<i>Kekryphallospora distincta</i>	%						1,4													0,3													
	amount				??		1													1													
<i>Kraeuselisporites reisingeri</i>	%																																
	amount					?																											
<i>Leptolepidites equaibosus</i>	%								0,5																								
	amount								1																								
<i>Leptolepidites macroverrucosus</i>	%														0,8																		
	amount														2																		
<i>Leptolepidites major</i>	%						2,8																										
	amount						2																										
<i>Leptolepidites paverus</i>	%																																
	amount									x																							
<i>Leptolepidites sp</i>	%								0,9	0,9	0,8		0,9																				
	amount						x		2	2	2	x	2	x	x					x	x												
<i>Manumia delcourtii</i>	%							2,1	4,2	2,4	1,3		0,5	0,6						1,0													
	amount					x	x	2	9	5	3	x	1	1	x	x			x	3	x												
<i>Marattisporites</i>	cf. %									1,4																							
	amount									3			x																				
<i>Monoletes couperi</i>	%										0,8		0,5		1,0																		
	amount										2		1		2		x																
<i>Monosulcites</i>	sp. %												0,9			2,1		2,6	x	x													
	amount												2,0			2,0		8,0															
<i>Neorais trickia grithopensis</i>	%														1,7					0,7													
	amount														4	x				2	x												
<i>Osmundacidites wellmanii</i>	%					0,6	2,8		0,9	0,9	1,3		0,9					7,4			0,8												
	amount	x	x	R		1	2		2	2	3		2	x	x	xR		9		x	1												
<i>Perimpollenites elatoides</i>	%			1,3			9,9	14,4	4,7	9,0	4,2		2,8	5,4	8,3	5,8	14,7	9,8	20,9	23,6	13,2												
	amount			2	x		7	14	10	19	10		6	9	18	12	14	12	63	41	17												
<i>Pilasporites couperi</i>	%																																
	amount						?			?																							

		P liensbachian										Toarc					Aalenian					Bajocian					Bathonian									
		ibex					bifron					opal					murg					cond					discite					humphresianum				
		Sample (WS)	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45														
	amount	miospores					154	155					71	97	214	211	237	215	167	217	206	95	122	302	174	129										
	%	miospores					36,0	48,7					14,9	19,3	36	43,7	44,8	63	52,8	71,9	66	15,7	20	56	27,9	20,6										
Pollen and spores		total amount					palyn	428	318					476	502	597	483	529	341	316	302	311	605	619	539	623	625									
<i>Pinus pollenites minimus</i>	%						3,9								2,3	0,5		2,3		5,5	4,9	2,1		0,3	2,9	0,8										
	amount						6								4	1		5		12	10	2		1	5	1										
<i>Pinus pollenites pinoides</i>	%																									0,3										
	amount																										1									
<i>Pinus pollenites</i>	spp	%						1,3								0,8		2,8	0,6	1,4		2,1		1,0	2,9											
	amount	x						?	2								2		6	1	3	x	2	K	3	5										
<i>Podocarpidites</i>	sp.	%						0,6																		0,3										
	amount						1																			1										
<i>Podosporites amicus</i>	%																																			
	amount																																			
<i>Polydiisporites polymicroforatus</i>	%																																			
	amount														?																					
<i>Porcellispora longdonensis</i>	%																0,4																			
	amount																	K																		
<i>Punctatisporites globosus</i>	%						0,6	2,8						3,3	1,9	3,0	1,9	2,4	1,4	1,9		2,5	2,6	3,4	2,3											
	amount						1	2						7	4	7	4	4	3	4		3	8	6	3											
<i>Punctatisporites major</i>	%														1,4	1,7	0,5	1,2		1,0		2,5	1,3	4,6	1,6											
	amount														?	3	4		1	2	x	2	x	3	4	8	2									
<i>Quadraculina anellaeformis</i>	%						1,3	0,6						0,9	1,9			0,6	0,9	1,9	2,1		1,3	0,6												
	amount						2	1						2	4			1	2	4	2		4	1												
<i>Retiriletes</i>	spp	%													0,9	1,4	0,4				0,5															
	amount	?	x				x						2	3	1	x				1																
<i>Retiriletes austroclavitudites</i>	%													0,5	0,9	0,8	0,5							1,0												
	amount	x				x						1	2	2	1	x				x			x	3												
<i>Retiriletes clavitudites</i>	%													0,5	0,8																					
	amount	?	x				x						x	x	1	2																				
<i>Rhaetipollis germanicus</i>	%																																			
	amount						?																													
<i>Riccisporites tuberculatus</i>	%																																			
	amount																																			
<i>Spheripollenites psilatus</i>	%						0,6	23,9	8,5	24,7	2,8	4,3	3,8	2,3	1,2	1,4		3,2	3,3	0,7		4,7														
	amount	?	1	x	37	6	24	6	9	9	x	5	2	3	x	3	4	2		6																
<i>Spheripollenites subgranulatus</i>	%						4,5	1,4	2,1	0,5																										
	amount						x	7	1	2	x	1																								
<i>Staplinisporites caminus</i>	%													0,5		0,4																				
	amount													1		1																				
<i>Staplinisporites telatus</i>	%													0,5											0,6											
	amount													1											1											
<i>Stereisporites hauterivensis</i>	%																																			
	amount																																			
<i>Striatella</i>	spp	%																																		
	amount																																			
<i>Striatella seebergensis</i>	%													0,5			0,5																			
	amount													1			1																			
<i>Tigrisporites</i>	spp	%																								0,6										
	amount	?													x			x	x		x				x	1										
<i>Trachysporites</i>	cf.	%													0,5																					
	amount						x	x		x	1	x		x	x		x																			
<i>Unidentified</i>	%						9,74	12,9	8,5	7,2	8,9	17,1	11,4	8,4	23,4	10,1	11,7	15,8	13,1	13,2	12,6	23,3														
	amount						15	20	6	7	19	36	27	18	39	22	24	15	16	40	22	30														
<i>Uvaesporites argenteaeformis</i>	%																																			
	amount													x																						
<i>Uvaesporites puzzlei</i>	%																																			
	amount																																			
<i>Vietrisporites bjuvensis</i>	%													0,5								0,8														
	amount													1								1														
<i>Vitreisporites</i>	spp	%						2,6																												
	amount						4																													
<i>Fragment</i>							152	148	30	93	86	89	68	85	140	84	99	102	178		133	171														

	P liens bachian		archian		Aalenian		Bajocian		Bathonian											
	ibex		ifer bifron		opal		murci cond		dis citd		humphresianum									
	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45
Dino flagellats																				
<i>Carpathodinium credae</i>									1											1
<i>Ctenodinium comigera</i>															6	6	x			13
<i>Ctenodinium continuum</i>															1					
<i>Ctenodinium selwoodii</i>															6					
<i>Disilodinium</i> spp.			1			9		2	6					5	5	7	14	6	1	
<i>Ellipsoidictyum gochtii</i>																				2
<i>Energynia acollaris</i>									1				I		1		3			
Fragment	X	X	103	X	6	252	280	259	119	156		20	7		273	214		162	210	
<i>Gongylocladus hocrneratum</i>								x							1	x				
<i>Hapsidaulax margarethae</i>																				1
<i>Jansonia</i> sp.																x	x			
<i>Leptodinium cf subtile</i>						1										2				
<i>Mancodinium semitubulatum</i>					x	5	4		4	10						2	1	R	R	
<i>Meiurogonya ulax planoseptata</i>																1	x			
<i>Mendocodium groenlandicum</i>			?	x		13	4	5	10	6		4		x	1	3	x	13	1	4
<i>Nannoceratopsis</i> spp.						1	x	x									x			
<i>Nannoceratopsis ambonis</i>										1										
<i>Nannoceratopsis spiculata</i>						x														
<i>Pareodinia antennata</i>																	5	2		
<i>Pareodinia apheia</i>			1				2	1	1						4	7	70	110	4	
<i>Pareodinia prolongata</i>															1		2		x	
<i>Parvocysta nasuta</i>						4										1				
<i>Phallosysta aumekes</i>							x													
<i>Scrinio cassis weberi</i>										8										
<i>Sentusidinium pelionense</i>						2	x			2					2	2				1
<i>Simiodiniopsis arbis</i>						1	2								1	5				
<i>Susandinium</i> spp. ?																				
<i>Susandinium scrofoides</i>						4	2													
Unidentified			3		4	59	4	16	28	10		16			97	59	121	31	85	
<i>Valensiaella ovulum</i>							3										1			?
<i>Valveodinium spinosum</i>							?													
<i>Wallocladus cylindricum</i>						7	?	2	1						3	1	3		x	
<i>Wallocladus laganum</i>						11	1			2					4	4	2	x	x	
<i>Wallocladus krutzschii</i>						1		x	1	1					x					
Algae and acritarchs																				
<i>Chytrioisphaeria</i> sp.						?														
<i>Chytrioisphaeria cerastes</i>																3		1		
<i>Chytrioisphaeria chytrioeides</i>																				1
<i>Lecaniella foveata</i>																				
<i>Micrhytridium</i> spp.			7		2	4	8	11	11	1		1								
<i>Tasmanites</i> spp.			3	x			x		1	2										
<i>Tetraporina compressa</i>				?			1		1	2						1				
Other																				
<i>Foraminiferal lining</i>			1			1	1		2	2						1		2	2	
Insect										1										
Fungi			3		3			1	3	13				1	1			1		

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