Sedimentology and palynofacies analysis of Jurassic rocks Eriksdal, Skåne, Sweden

Muhammad Saeed

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Cover Picture: Photograph showing field area, Eriksdal, Skåne.

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Abstract: A sedimentlogical and palynological study of samples from the Middle Jurassic Fuglunda Member, Mariedal Formation at Eriksdal, Skåne, Sweden, has been carried out. The section is dominated by sandstone with minor units of coal, claystone, siltstone and conglomerate. The depositional environment has been interpreted as a coastal setting, perhaps a delta system with mixed influences of fluvial, tidal and wave processes. Twenty-four samples processed for the palynological study revealed rich and well-preserved assemblages of dispersed organic matter but their composition varies significantly. Forty-two pollen and spore species were identified. Wood remains, amorphous organic matter, cuticles and fungal spores were also recorded in the samples. The coal samples have almost the same palynomorph content as samples from adjacent clastic sediments, except 23A and 23B, which are devoid of pollen and spores. The Fuglunda member palynoflora is dominated by gymnosperms, most notably *Perinopollenites elatoides*. Most of the species are long-ranging; however, a few species are stratigraphically significant (*Neoraistrickia gristhorpensis, Todisporites minor, Callialasporites microvelatus*). These index taxa suggest that the studied samples are of Bajocian–Bathonian (Middle Jurassic) age. The occurrence of the key environmental indices *Gleicheniidites senonicus, Cyathidites, Classopollis* and *Perinopollenites* suggests a warm and humid palaeoclimate for the Eriksdal area. The composition of the Fuglunda member palynoflora, together with its Thermal Alteration Index (TAI = 2) and Spore Colour Index (SCI = 4), reveal that the organic matter is gas-prone and is immature to produce hydrocarbons.

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Keywords: Fuglunda member, Jurassic, pollen, spores, palynomorph, gymnosperms

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Sedimentologi och palynofacies analys av jurassiska avlagringar, Eriksdal, Skåne, Sverige

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Sammanfattning: En sedimentlogisk och palynologisk studie av sedimentprover från det mellanjurassiska Fuglundaledet, Mariedalformation vid Eriksdal, Skåne, Sverige har utförts. Avsnittet domineras av sandsten med mindre enheter av kol, lersten, siltsten och grus. Paleomiljön har tolkat som en kustnära miljö, troligen ett deltasystem med stark påverkan av vågprocesser. Dessutom förekommer fluviala- och tidvattensavlagringar. Sammanlagt 24 prover preparerades för palynologiska studier och palynomorferna identifierades. Studien visar på en välbevarad palynologisk association uppvisande en hög mångfald, men den procentuella sammansättningen av olika palynomorfgrupper varierar signifikant mellan de olika proverna. Sammanlagt 42 arter av pollen och sporer identifierades. Dessutom utfördes en palynofaciesanalys som visar att proverna även innehåller ved, amorft organiskt material (AOM), kutikula och svampsporer. De palynologiska associationerna härrörande från kolavlagringarna har ett liknande innehåll som de andra proverna. Min studie visar att vegetationen dominerades av gymnospermer. Dessa är främst representerade av pollenarten *Perinopollenites elatoides*. De flesta arterna har en lång vertikal utbredning men det finns även flera arter som kan användas som nyckeltaxa (t.ex. *Neoraistrickia gristhorpensis, Todisporites mino* och *Callialasporites microvelatus*). Åldern på de undersökta prover från Fuglundaledet tolkas här som bajoc–bathon (mellanjura) baserat på nämnda pollen och sportaxa. Närvaron av följande miosporer; *Gleicheniidites senonicus*, *Cyathidites*, *Classopollis* och *Perinopollenites* tyder på ett varmt och fuktigt paleoklimat för Eriksdalsområdet. Färgen på sporer förändras med ökande begravningsdjup och därmed mognadsgrad, vilket anges på en skala som mäter färgförändringen, s.k. ”Thermal Alteration Index” (TAI) och ”Spore Colour Index” (SPI). Min studie visar att palynomorferna i det studerade materialet uppvisar ett TAI-index på 2 och SCI på 4 vilket innebär att det organiska materialet är för omoget för att alstra kolväten.

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Nyckelord: Eriksdal, Fuglunda-ledet, jura, pollen, sporer, gymnospermer, paleoekologi, klimat.

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1. Introduction

The subsurface Mesozoic succession of SW Skåne, southern Sweden has been investigated since the 1940's for the exploration of hydrocarbons, although commercial quantities of hydrocarbon have not been recorded (Alhberg & Olsson 2001). The Mesozoic succession resembles the successful plays in other parts of NW Europe (e.g., the North Sea and Norwegian Shelf), but exploration surveys have so far given negative results for commercial hydrocarbons in Skåne.

In Sweden, Jurassic sedimentary rocks are known only from the southernmost province, Skåne. These Jurassic sedimentary rocks mostly consist of sandy to muddy siliciclastics, with interlaminated coal and, in some places, carbonate-rich beds. Each area reflects a different depositional and tectonic setting because these rocks were deposited in areas that are structurally and tectonically complex. Middle and Upper Jurassic exposures occur at Eriksdal in the Vomb Trough (Norling et al. 1993). Here Upper Jurassic sediments lie directly beneath a thick cover of Quaternary deposits. Subsurface studies show that further deposits of this age occur beneath the Cretaceous and Paleogene sedimentary deposits in the Danish Embayment, the Vomb Trough and off-shore in Hanö Bay (Guy-Ohlson and Norling 1988).

The Middle and Upper Jurassic deposits in the Eriksdal section are exposed as a result of mining activities. Most of the data not only comes from these outcrops and exposures but also from subsurface sections acquired from quarries, bore-holes and wells. Extensive seismic surveys of the area have also been carried out and their results add much to our knowledge. The geological setting of the Eriksdal area has been described by Nilsson (1953) from a lithological and stratigraphical point of view. Fossils in these deposits consist mainly of palynomorphs, foraminifers and ostracodes (Erlstöm et al. 1991).

1.1 Aims and Objectives

The purpose of this study is to learn the methodologies of palynofacies analyses and investigate the palynological content; i.e. pollen, spores and the organic matter in the Middle Jurassic Mariedal formation of Eriksdal, Sweden. The main objective was to determine the diversity of Jurassic palynofacies in the Eriksdal deposits, to compare the different coal- and non coal-bearing intervals, with respect to palynofacies assemblages. The sedimentology of the exposed succession was also studied in order to provide additional constraints on the depositional settings of the sampled beds. Integration of the sedimentology and palynology aimed to determine the depositional environment, climate and vegetation changes through the succession. A secondary aim of this study was to determine the thermal alteration index of the strata based on spore color.

The outcomes of the study will have implications for understanding the geological history of the area in terms of its vegetation, paleoenvironment and depositional processes The study of these Jurassic of Sweden is important since they represent some of the nearest exposed correlative strata of the hydrocarbon-rich Jurassic succession in Norway. The Swedish succession, therefore, can serve as a model for the composition and facies relationships of the Norwegian reservoir-rocks.

2. Background

2.1 Palynofacies Analysis

Since Combaz (1964) introduced the word palynofacies for the first time, there have been several discussions as to how palynofacies should be studied and interpreted. The palynofacies approach deals with the recovery of acid-resistant organic matter from sediment or sedimentary rocks by normal palynological processing using HCl or HF, followed by investigation of the composition of the residue via light microscopy. Spores, pollen, dinocysts, acritachs and other palynomorphs are included in palynofacies (Fig. 1). Acid-resistant residues also include some non -palynomorphs that are called palynodebris. In recent years the use of palynology has ranged from its primary applications of descriptive taxonomy, biostratigraphy and phylogeny to its direct application in hydrocarbon exploration. In hydrocarbon exploration, palynology is used for the dating of sediments and high-resolution biostratigraphy has enabled ever finer zonation and recognition of sedimentary hiata (Ram 2007). Palynology also plays an important role in the correlation of terrestrial and marine sediments, sequence biostratigraphy,

Group	SUBGROUP			DESCRIPTION
Phytoclast	Fragments of Tissues Derived from Higher Plants or Fungi	Opaque		Equidimensional, Lath, corroded, black in color, sharp or diffuse outline, irregular.
		Non-Opaque	Fungal Hyphae	Fragments of hyphae, brown in color, filaments of fungi.
			Cuticle	Epidermal tissue of higher plants, leaves, roots and stems, pale yellow to light brown in color .
			Membranes	Pale Yellow in color, thin, sheet like, irregular.
Palynomorph	Spore			Triangular or circular form palynomorphs, Trilete mark or monolete , produced by Pteridophytes, Bry ophyte and Fungi.
	Pollen			Circular or oval form, Tetrads, produced by Gymnosperms and Angiosperms.
	Algae			Irregular or rounded colonies, Aquatic algal remain mainly Pediastrum.
	Marine Palynomorphs			Dinoflagellate cysts, Acritarchs and chitinous organic linnings to calcareous shells of forimin iferal tests.
Amorphous Organic Matter	AOM			Structureless, yellowish -amber to brown masses often has palynomorph and pyrite inclusion.
	Resin			Unstructured, hyaline, usually round, homogenous , produced in by terrestrial higher plants in tropical climate.

Fig. 1. Detailed classification of the different components of Palynofacies analysis modified after Mendonça Filho et al. (2012).

evaluation of hydrocarbon source potential, kerogen analysis and palaeogeographic reconstruction.

A palynofacies is the total distinctive assemblage of microscopic organic constituents in a body of rock interpreted to reflect a specific set of environmental conditions and to characterize a specific potential for hydrocarbon-generating (Tyson 1995).

2.2 Thermal Alteration Index

The variation in color of pollen and spores in coal beds has been known since the 1920s (Gutjahr 1966). The Thermal Alteration Index (TAI) was first used by Staplin (1969) to quantify the relative opacity of organic matter under a microscope. With increasing burial depth, temperature and pressure, spores and pollen in sediment are subjected to a series of changes both chemically and physically during diagenesis and metamorphism. Physical properties of the palynomorph such as color, reflectance and fluorescence reflect these changes with increasing burial depth. Measurement of these properties of organic matter, especially for palynomorphs is widely used to calibrate a palyomorph assemblage against the standard Thermal Alteration Index (TAI) scale. This helps in the assessment of coal rank and degree of hydrocarbon maturation, and thus petroleum generating potential (Ujiie 2000).

Spores and pollen contain a highly resistant biomacromolecule in the outer wall named Sporopollenin. It can preserve its morphology in sediments for over hundreds of millions of years (Ujiie et al. 2003) Sporopollenin is an oxygenated hydrocarbon composed of long chain fatty acids, amino acids and phenols (Guilford et al. 1988). The exines of modern and shallowly buried plants have a pale yellowish colour in transmitted light because they have not been subjected to deep burial and high temperatures. However, during deep burial process, the exines are heated and the color changes from lighter color to dark black due to the loss of volatile components and reduction of long-chain polymers to shorter-chain molecules in the sporopollenin (Traverse 2007)

The 10 increment color-scale corresponding to the TAI (Fig. 2) is based on color variation of spores and pollen and was presented by Pearson (1984). Traverse (2007) refined and replicated this diagram. The numerical Spore Color Index (SCI) is used to simply determine the color variation between spores, whereas the Thermal Alteration Index employs the color differences between spore-pollen assemblages to determine source rock maturation (Traverse 2007).

Spores colour	TAI	SCI	Organic Thermal Maturity
Pale yellow	1	1	Immature
Pale yellow- lemon yellow	1+	2	Immature
Lemon yellow	2-	3	Immature
Golden yellow	2	4	Immature
Yellow orange	2+	5	Mature Main Phase Of Liquid Petroleum Generation
Orange	3-	6	Mature Main Phase Of Liquid Petroleum Generation
Orange brown	3	7	Mature Main Phase Of Liquid Petroleum Generation
Dark brown	3+	8	Dry Gas Or Barren
Dark brown- black	4-	9	Dry Gas Or Barren
black	4	10	Dry Gas Or Barren

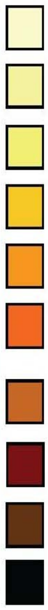

Fig. 2. Modified from Traverse et al. (2007) & Almash-ramah (2011) showing spores colour indicating the dif-ferent Thermal Alteratation Index and Spore Colour Index

2.3 Previous Works

The Eriksdal area has been investigated both from a sedimentological and stratigraphical point of view. There are various palynological reports on the Upper Jurassic of Sweden, but the Eriksdal area has not been discussed in much detail.

Nilsson (1953) undertook lithological and stratigraphical studies in the Eriksdal area. His studies were further expanded by Christensen (1968) to include the study of ostrocode material. Hägg (1940) also performed studies upon the molluscan fauna at Eriksdal. Some of the material sampled and described by Nilsson (1953) was further investigated by Ekström (1985) for microfossils. Erlström et al. (1991) studied the ostrocode fauna in the Fyledal clay at Eriksdal. Their study indicated a Kimmeridgian–Berrisian age. However, an Oxfordian-Kimmeridgian age was interpreted from the palynomorph stratigraphy and foraiminferal fauna (Guy-Ohlson and Norling 1988; Norling 1972). The results also suggest that the Vitabäck Clay incorporates sediments of younger age in NW Scania than at Eriksdal.

Norling (1970) undertook a stratigraphical analysis of the Rydebäck-Fortuna borings in southern Sweden and compared that succession with the Eriksdal beds. In particular, he correlated the beds occurring in Rydebäck-Fortuna borings with the clayey sand and silt with coal seams in the Eriksdal succession. Tralau (1968) described a Middle Jurassic microflora from the informally defined Mariedal Formation of Eriksdal, southern Sweden. He systematically described the microspores from samples collected from several beds in this unit. He also described the geographical and stratigraphical distributions of the species and their evident botanical affinities. Tralau (1966) also studied some plant macrofossils from the Mesozoic deposits at Eriksdal. He found several plant taxa and noted their resemblance to the Jurassic floras of Yorkshire, UK.

3. Geological settings

3.1 Regional Geology

The Middle and Upper Jurassic strata of Sweden are preserved between the East European platform and NW European area of subsidence. The Middle and Upper Jurassic sedimentary rocks of Skåne (Fig. 3) were originally deposited at the margin of the Fennoscandian Shield in an elongate trough-like, depression. This depression is developed as several down-faulted blocks (Guy-Ohlson and Norling 1988).

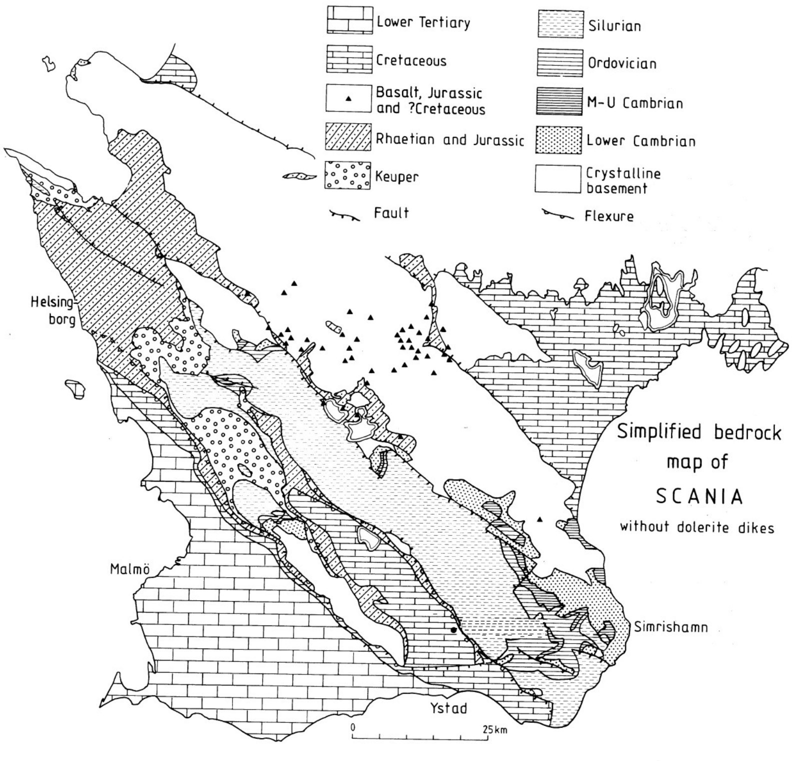

Fig. 3. Geological map of Skåne showing the location of the study area Eriksdal (Bergström 1982)

This was followed by an inversion process, which started as a result of compressional deformation during late Santonian/Campanian time (Norling & Bergström 1987) and continued during the Cenozoic. As a result of inversion, shallow marine deposits that were previously deeply buried were uplifted and exposed to erosion.

3.2 Paleogeography

During the Jurassic several regionally important events occurred, including the initial breakup phase of Pangea, the closing of the Tethys and the opening of the North Atlantic, the latter of which was linked to the block faulting in Skåne (Ziegler 1990). Block faulting played an important role in southern Sweden during the Jurassic. In Northwest Europe, the Early Alpine tectonic phases caused the reactivation of the Tornquist Zone, which was established during the Palaeozoic Era (Norling and Bergström 1987; Erlström et al. 1997). In general, the Jurassic successions of Skåne were influenced by tectonism, which actively controlled deposition and erosion. As a result, there are markedly different patterns of deposition and degree of subsidence in each tectonic sub-basin (Ahlberg et al. 2003).

During the Jurassic, Skåne was influenced by a warm and humid climate. The coastal plains were extensively covered by vegetation which locally accumulated in peat swamps to form coal beds (Tralau 1968). The development of kaolinitic clays also reflect a warm humid climate (Hallam 1994; Manspeizer 1994). The climatic conditions favoured low-pH weathering during pedogenesis. Therefore, mineralogically mature sandstone and clay-rich facies dominate the Jurassic of Skåne. Consequently, limited evaporate minerals were precipitated under the warm climatic regime during the Jurassic (Ahlberg et al. 2003).

3.3 Vomb Trough

The Vomb Trough is a narrow, asymmetric graben bounded by complex tectonic structures, having an approximate length of 80 km and a width ranging from 7 to 11 km from the northern to southern part. The eastern boundary of the Vomb Trough in the Eriksdal area is influenced by complex tectonism. Lower Paleozoic rocks are exposed along the western boundary of a plateau (Norling et al. 1993). The basin is bordered by the Romeleåsen Horst to the west and it extends offshore from Skåne to the south.

The Vomb Trough region was subject to intense erosion during the late Paleozoic and Triassic followed by deposition during the Jurassic and Cretaceous (Norling 1982). Rocks deposited in the Vomb trough are predominantly of Late Triassic, Jurassic, Late Cretaceous and Middle to Late Paleogene age (Norling 1982). The Vomb trough incorporates many faults which resulted in the formation of several open and wedge-shaped minor troughs and uplifts. The sedimentary succession shows substantial variations in thickness as a result of these tectonic movements. The Compressional forces along the trough through the Late Cretaceous and Cenozoic have caused inversion movements, which produced the present shape of the Vomb Trough.

3.4 Local Geology

The Eriksdal exposures are typical of the Jurassic succession exposed in Sweden. Eriksdal lies on the NE border of the Vomb Trough. At Eriksdal, the Jurassic sequence has an average thickness of 400–600 m and is vertically tilted or slightly overturned due to basin inversion. The strike of the strata on average is N40◦W and the beds dip at an angle of 80◦NE i.e., 10◦ overturned (Norling et al. 1993).

Bergström and Norling (1986) have previously explained the geological and tectonic framework of the Eriksdal area and the surrounding Kurremölla Valley.

There are four main lithostratigraphic units (Fig. 4 & 5) exposed in the Eriksdal area. The Röddinge Formation (Lower Jurassic) is exposed in the Kurremölla Valley (Norling et al. 1993). The Middle Jurassic Fuglunda and Glass Sand members of the informal Mariedal formation are exposed in the northeastern and central parts of the Fyleverken sand pit and the Upper Jurassic Fyledal Clay of the informal Annero formation is represented to the southwest beneath a thin veneer of Quaternary deposits.

The Lower Jurassic Rödding Formation consists of ferruginous sandstones which are limonitic, chomositic and sideritic (Norling 1982). The Fugulunda Member of Middle Jurassic age consists of 100 m thick alternating succession of sand, clay and coal (Fig. 5). The lower portion consists of thinly laminated sand, clay and coal beds whereas the upper 40 m part consists of 5–6 m of thick beds of the same lithologies but with cross-bedding in the sandstones (Norling et al. 1993). The Glass Sand Member of Middle Jurassic age is composed of white quartz sand with streaks and bands of ferruginous concretions and heavy minerals. The sand is medium grained and is dominated by cross-bedding. Due to its unique content of silica (>99%), the sand has been quarried by the Fyleverken Company (Norling et al. 1993). The Fyledal Clay Member is composed of alternating greenish and greyish black argillaceous beds. Two nodular limestone layers occur in the uppermost part. Sedimentary structures other than flat lamination are absent due to the dominance of argillaceous material. The lowermost part contains some rootlet horizons (Erlstöm et al 1991). The Nytorp Sand is composed of mix-coloured, partly clayey, coarse and fine- grained

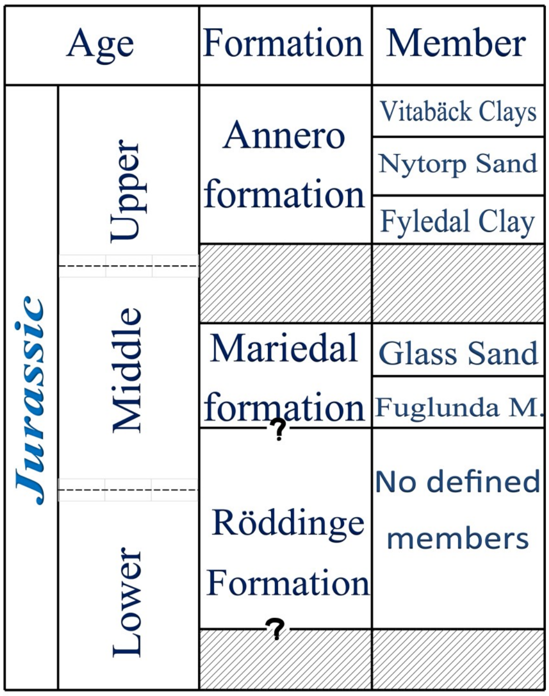

Fig. 4. Jurassic stratigraphy of Eriksdal. (Modified from Norling et al. 1993)

sandstones with interbeds of uncemented sand, silt and siltstones (Guy-Ohlson & Norling 1988). The Vitabäck Clays are composed of an irregular succession of mixed-coloured and varied argillaceous beds. This unit is no longer exposed in the Eriksdal area due to the excavation of the quarry and cover of the outcrops by spoil dumps. Several paleosol horizons are found in this unit.

4. Correlative hydrocarbon bearing rocks of Norway

Along the Norwegian coast and continental shelf, the lower and Middle Jurassic deposits consist of thick units of sandstone interbedded with mudstone. Such sandstone units dominate the Norwegian Shelf (Ramberg et al. 2008). These sandstone units are very porous and host substantial oil and gas reserves – constituting the largest hydrocarbon reservoirs in the region (Partington et al. 1993). The North Sea and the Norwegian and Barents seas were occupied by humid swamplands during Early Jurassic. Coal beds found in these sediments derive from peats that accumulated in these swamplands. During the Early and Middle Jurassic, mainland Norway and its shelf areas were gently subsiding due to crustal cooling following Permian and Triassic rifting in the North Atlantic – North Sea region (Johannessen & Embry 1989).

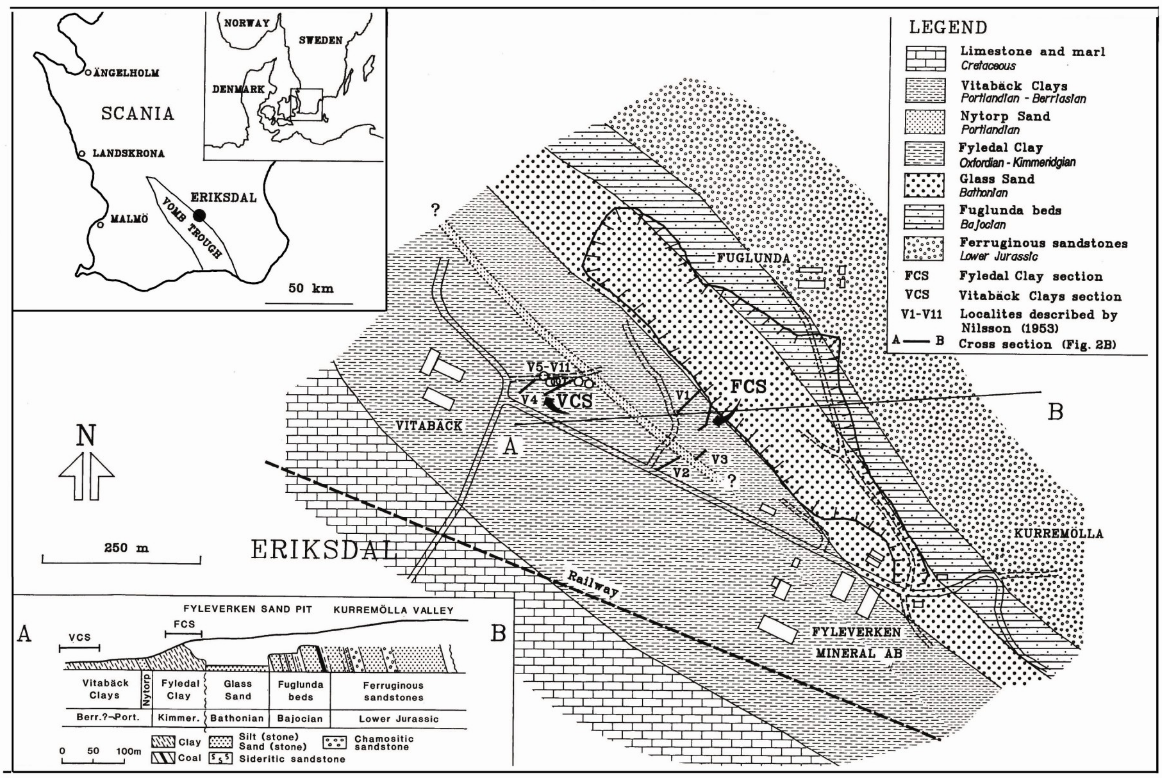

Fig. 5. Geological map of the Eriksdal area and schematic cross-section (A-B) (Erlström et al. 1991)

During the Jurassic, the climate was warm and became more humid as evidenced by replacement of Early to Middle Triassic arid deposits by coal-bearing units; the coals having accumulated in densely vegetated swamp forests. Increased weathering and erosion of the older sediments and basement rocks were favoured by the warm and humid climate. Consequently, enormous amounts of gravel, sand and mud were carried out into the shelf basins. The Lower and Middle Jurassic successions are dominated by fluvio-deltaic sandstones.

During the Late Jurassic, major geological events occurred resulting in changes to the geological structure of the region. A great offshore continental shelf was formed by continued crustal sag and fragmentation (Rattey & Hayward 1993; Vajda & Wigforss-Lange 2009). Firstly, thick successions of organic-rich material were deposited across the shelf. Simultaneously, the Middle Jurassic basins were fragmented into narrow sub-basins by regional fracturing and differential subsidence associated with tectonic break-up. Due to a lack of oxygen at the sea floor, organic materials were not oxidized and these organic-laden sediments accumulated in great thicknesses before being eventually buried by overburden. With progressive burial, the organic material was transformed into oil and gas at high temperatures (Ramberg et al. 2008). Secondly, thick layers of sands were deposited above and intercalated with the organic-rich sediments. These sandstones are highly porous and constitute excellent reservoirs for hydrocarbons. Thirdly, crustal fragmentation resulted in the formation of fault blocks and flexures. The sand units were tilted in these fault blocks and later subsided. Fine-grained sediments were deposited over these blocks and acted as impermeable cap rocks, so that the hydrocarbons in the underlying reservoir sandstones cannot escape. All these processes occurred during Jurassic, making this time period critical for the formation and entrapment of huge oil reserves in Norway (Johannessen & Embry 1989).

5. Material and Methods

5.1 Sedimentology

Field studies involved compiling a measured section from the basalmost exposure of the Fuglunda Member to the uppermost accessible bed. Measured sections were compiled by traversing the outrcrop and measuring the thickness of individual beds with a tape measure. For each bed the character of the upper and lower boundaries, lithology, thickness, sedimentary structures, colour and fossil content was recorded. Laboratory work included lithological classification of hand specimens based on color, grain size and porosity. The results were compiled in a graphic section.

5.2 Palynology & palynofacies

Thirty-two samples were collected one from each major bed in the measured profile (Fig. 7), out of these twenty-four samples were selected for palynological and palynofacies analysis, among which 12 samples were processed at Global Geolab limited, Alberta, Canada, using standard palynological techniques. The remaining samples were processed according to Vidal’s (1988) standard palynological processing method in the palynology laboratory at the department of Geology, Lund University. Two *Lycopodium* tablets were added to each sample thus allowing the pollen and spore concentration to be calculated based upon the *Lycopodium* spores counted. Around 10-15 grams of rock sample were first treated with dilute hydrochloric acid (HCl) to remove the calcium carbonate ($CaCO_3$) and later macerated by leaving the sample in cold hydrofluoric acid (HF) of 40–60% concentration overnight. Using a 12 µm mesh, the organic matter was sieved and subsequently the residue was mounted in epoxy resin on glass slides. The sample slides were then studied using transmitted light microscopy and all palynomorphs per slide were identified and counted. Specimens were identified primarily by using the descriptions of Erlström et al. (1991), Guy-Ohlson (1971 & 1978) and Vajda & Wigforss Lange. (2006). Palynofacies analysis involved grouping the palynomorphs into the following categories: spores, pollen, fungi, algae, wood and amorphous organic matter. The organic matter particles ranged in abundance between 5 and 10000 per slide.

6. Results

6.1 Sedimentology

The principle lithologies of the Fuglunda Member measured in the field are sandstones, siltstones, claystones and coals. The total thickness of the section measured is 52.74 meters and the section is structurally overturned (about 110˚ rotation from the original attitude of the bedding). Individual descriptions of each bed interval are given below (Fig. 7). Sampling positions refer to the stratigraphic height above the base of the measured succession.

Bed#ES-1 is measured at the top of the hill but represents the basal exposed bed of the stratigraphic succession. The total thickness of the bed is 42 cm and the upper contact is gradational. The lithology consists of massive fine-grained sand with some very fine-grained sand lenses and some local cross-bedding (Fig. 6B). Iron oxide nodules are also present. The sample was taken at a level of 0.1 m above the base of the succession.

Bed#ES-2 is 22 cm thick. The lithology consists of dark-grey laminated claystone. Plant roots are present. The upper boundary of the bed is sharp. For palynofacies analysis, a sample was taken at a level of 0.5 meters.

Bed#ES-3 is 17 cm thick. The bed consists of dull black coal composed of unidentifiable organic matter. The upper boundary of the bed is sharp and the sample was taken at a level of 0.65 meters.

Bed#ES-4 consists of thinly laminated organic-rich dark grey claystone with some fragmentary leaf impressions. The thickness of the bed is 17 cm and the sample was taken at a level of 0.9 meter. The upper boundary of the bed is sharp.

Bed#ES-5 is composed of interlaminated thin sand and coal layers. In the fine-grained sand layers, there are local lenses consisting of yellow sand of medium grain size. The bed is 90 cm thick and the sample was taken at a level of 1.5 meters. There are no plants roots at the bottom of the bed but some occur 10 cm from the top of the bed. A weak paleosol is developed in this bed. The upper boundary of this bed is sharp.

Bed#ES-6 is dominated by claystone which is laminated and has dark grey color. Plant roots are present. The total thickness of the bed is 16 cm and the sample was taken at a level of 1.95 meters.

Bed#ES-7 is quite similar to bed 5. It's composed of fine sand and silt with sparse sand lenses. The thickness of the bed is 25 cm and the sample was taken at a depth of 2.25 meters. The base is gradational and upper boundary is irregular. Bedding is wavy and the upper boundary is convoluted by soft sediment deformation.

Bed#ES-8 consists entirely of coal, with dirty (clay-rich) coal at the bottom and cleans towards the top. The total thickness of the bed is 70 cm and the sample was taken at a level of 2.5 meters.

Bed#ES-9 consists of irregular beds of white sand and dark grey claystone. A few sandy lenses are recorded but they are not continuous. Some of these sandy lenses are quite yellow. Lumps of coal are locally present. Current ripples are recorded (Fig. 6C), which suggest that flooding events laid down these layers. The bed thickness is 117 cm and the sample was taken at a level of 3.55 meters.

Bed#ES-10 is composed of irregular and interlaminated layers of sand and silt. The sand grades into very fine sand to silty sand. Very small pieces of coal are also present. Black (coalified) roots are present, which penetrate from the upper part of the bed. The upper boundary is sharp to irregular. The bed is 52 cm thick and the sample was taken at 4.3 meters.

Bed#ES-11 is dominated by brittle dull coal with some obvious wood fragments. The bottom of the coal is sharp to irregular. The bed is weakly laminated. Iron nodules are also recorded. The upper boundary is sharp. The bed is 38 cm thick and the sample was taken at a level of 5.25 meter.

Bed#ES-12 is dominated by very finely laminated, dark organic rich clays and some sand layers that are lenticular whilst some are continuous. Sandy layers are about 2 cm thick and show cross-lamination. Almost 6.0% of the bed adjacent to the lower boundary is concealed by overburden. The bed is 32 cm thick and the sample was taken at a level of 5.25 meters.

Bed#ES-13 is dominated by coal. Some laminations and a blocky fracture pattern are recorded from the bed. Some woody material is present at the base and some leafy matter at the top of this unit. The upper boundary is irregular. The bed thickness is 70 cm and the sample was taken at the 5.8 meter level.

Bed#ES-14 is composed of sandy layers with some dark grey clay lenses and some weakly interlaminated fine-grained sandstone. Additionally, there are a few small isolated quartz pebbles in the sandstones. The bed is 2.25 m thick and the sample was taken at a level of 7.95 meters.

Bed#ES-15 is composed of well laminated carbonaceous shale with the development of coal in a few places. Sulphate minerals and gypsum are also present. A small number of burrows are also recorded. at the top. The bed is 1.6 m thick and the sample was

The upper boundary is gradational and the bed is sharp

Bed#ES-16 has a lithology consisting of interlaminated claystone to fine-grained sandstone. The grain-size variation in the sandstone suggests that it was deposited in environments ranging from low energy to high energy. The upper boundary is sharp. The thickness of the bed is 76 cm and the sample was taken at a level of 10.5 meters.

Bed#ES-17 consists of sandstones with thin sparse interbeds of claystone. The grain size of the sandstone varies within the bed. The sandstone is fine-grained at the bottom but the upper 10 m is medium grained. At the extreme top of the bed, the sandstone again grades into fine grained material. At about 8.7 m, a 10 cm thick conglomerate layer is present. Iron-stained lenses (Fig. 6A) and iron concretions are also recorded. The total thickness of this bed is 12.7 m and the sample was taken at a level of 18.5 meter.

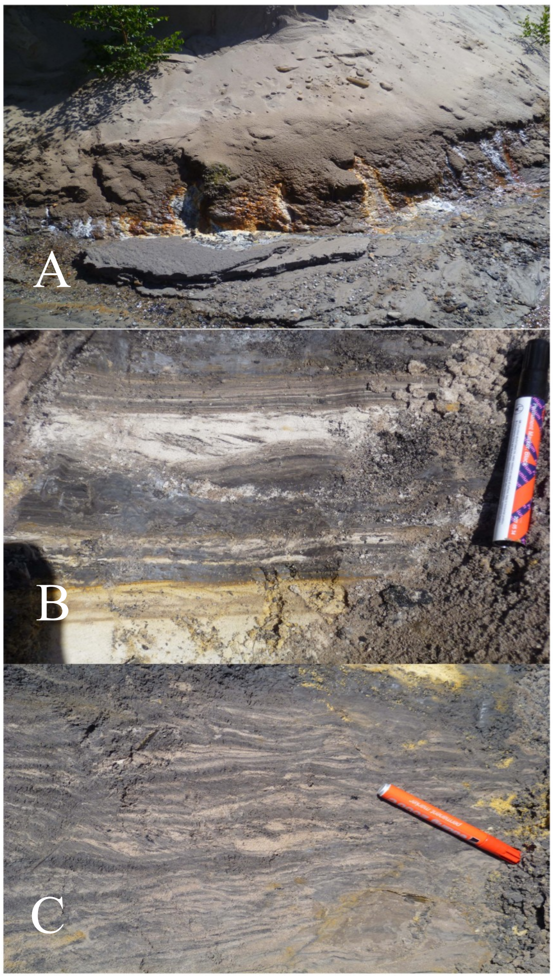

Fig. 6. Field photograph showing A) Iron statining. B) Cross bedding. C) Ripple marks.

Bed#ES-18 consists of dark grey claystone, which is thinly laminated in places. The lower boundary is irregular and the upper boundary is interbedded with thin fine sand. Iron nodules are also present. Fossil leaves, possibly of *Ginkgo* are also present. The thickness of the bed is 1.1 m and the sample was taken at a level of 24 meters.

Bed#ES-19 is dominated by sandstone with sparse interbeds of claystone. Iron staining is evident at 20–25 cm above the base. The sand is fine grained in the upper part of the package. The thickness of the bed is 6.7 m and the sample was recorded at 28.5 meter.

Bed#ES-20 is dominated by medium- to coarse-grained sandstone and is 11.1 m thick. The bed incorporates conglomerate (gravel) bands at several intervals. One at 250 cm is 15 cm thick, another at 370 cm is 10 cm thick and a further one at 6 m is also 10 cm thick. Pebble conglomerate beds are lenticular and weakly fine upwards. The lower gravel bed is matrix supported. Low angle cross-beds are present. Iron staining is also locally developed. The sample was recovered at about 36.5 meters.

Bed#ES-21 consists of dark organic-rich clays at the bottom but these give way to more sandy laminae towards the top. Ripple marks, burrows and some vertical roots were recorded from the top part of the bed. The bed is 2.1 m thick and the sample was recovered at 43.7 meters.

Bed#ES-22 consists of medium-grained sandstone, incorporating thinly interlaminated flasers of clay and organic matter. Burrows and wavy cross-lamination are also evident in the sandstone. The upper boundary of the package is gradational. The bed is 2.5 m thick and the sample was recovered at about 46.5 meters.

Bed#ES-23 consists of brittle glossy coal. The upper and lower boundaries are both sharp. The total thickness of the bed is 20 cm and two samples were recovered at different intervals (46.9 m and 47.1 m) for palynological investigation.

Bed#ES-25 has a lithology consisting of dark organic-rich claystone and thinly interlaminated sandy layers. Root burrows are absent from this bed. A small component of gypsum is present at the base. The bed is 1 m thick and the sample was recovered at a level of 48 meters.

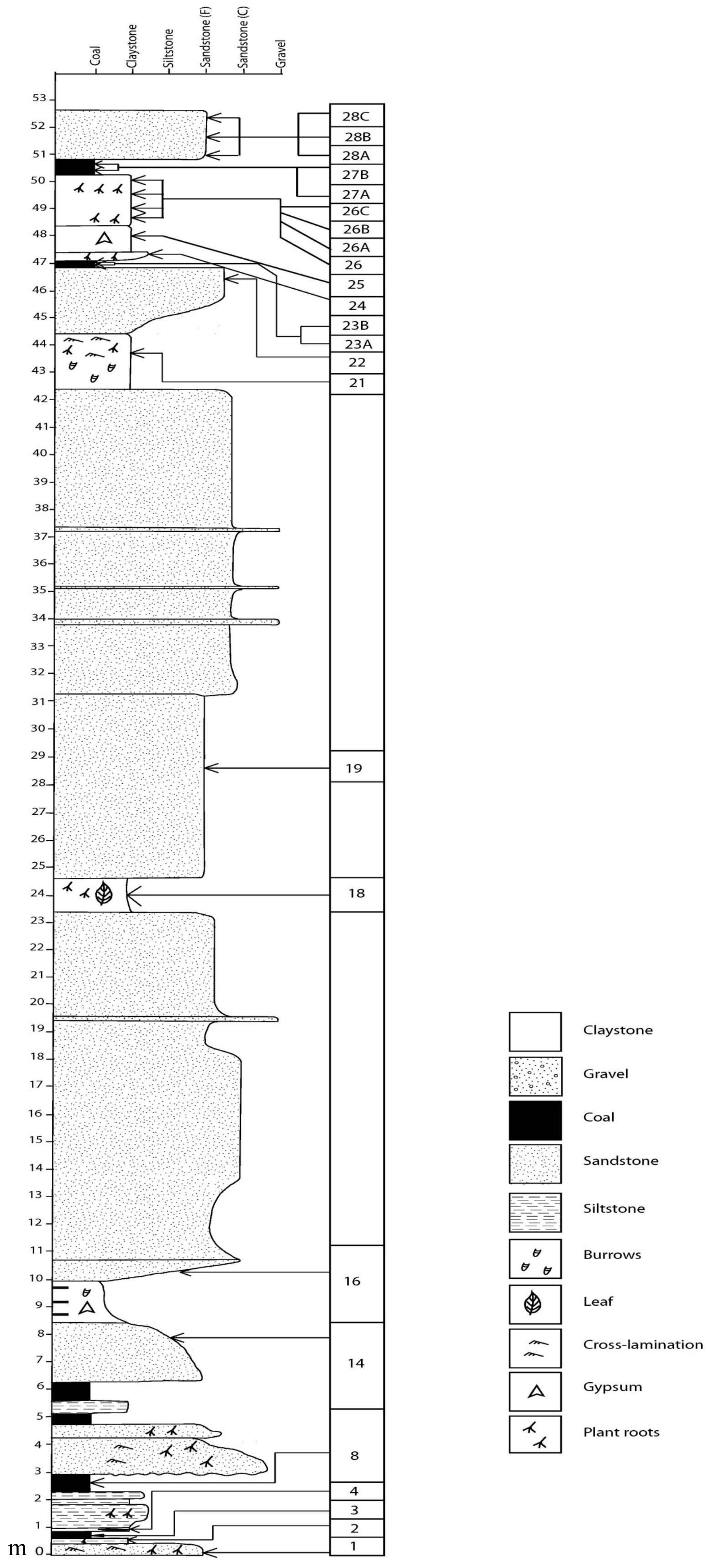

Fig. 7. Lithological log of the studied area, Eriksdal, Skåne.

Bed#ES-26 consists of fine sand with interlaminated dark carbonaceous claystone and is 1.9 m thick. Roots occur in the top part of the bed. The bed was divided into three subsections in order to obtain a more detailed palynological signature of the bed. Four samples were taken at different intervals: 48.75 m, 49 m, 49.5 m and 50.25 m for detailed palynological investigation.

Bed#ES-27 has a lithology dominated by bituminous coal and the bed is 55 cm thick. A few concretions of pyrite were noted. There are some root traces in the bed. Two samples at different intervals (50.54 m and 50.76 m) were taken for detailed palynology.

Bed#ES-28 occurs near the current water limit of the quarry and is the uppermost bed stratigraphically. The bed is 1.9 m thick and is dominated by well-sorted, fine to very fine sand. The bed contains some local cross bedding. Three samples were taken at different intervals: 51.05 m, 50.52 m and 50.25 m for detailed palynology.

6.2 Palynofacies

The results from this study show that the samples have rich and well-preserved palynological assemblages but the composition of the assemblages varies significantly between samples. Most of the samples are dominated by AOM and wood remains. Pollen, algae, and fungi are present in low amounts. Cuticle sheets are also found in the samples. The palynomorphs are grouped into seven main categories: pollen, spores, algae, cuticles, wood, fungi, and amorphous organic matter. To calculate the abundance of organic particles in each sample, the *Lycopodium* spores that had been introduced to each sample were also counted. The results of the palynofacies analysis are shown below.

The bottom of lowermost sample is at a depth of 52.74 m and derives from a bed of fine sandstone with local-cross bedding. Among the 32 samples initially recovered, 24 were selected for palynofacies analysis. Each sample number corresponds to the equivalent bed number (Fig 7). The samples were numbered in ascending stratigraphic order throughout the unit.

Sample#ES-1: The palynological sample contains 39.9% wood, 30.05% AOM, 14.53% cuticles and 5.91% palynodebris with some minor fraction of spores, pollen and fungal spores.

Sample#ES-2: The palynological sample contains 21.53% wood, 33.63% AOM, 27.72% cuticle, 9.72% spores and 5.9% palynodebris with some minor amount of pollen and fungal spores.

Sample#ES-3: This sample contains 57.6% wood, 9.36% AOM, 15.5% cuticle and 8.77% spores with some minor pollen, palynodebris and fungal spores in the palynological sample.

Sample#ES-4: The sample hosts a palynological assemblage of 42.03% wood, 26.92% AOM and 14.84% cuticles with some minor quantity of palynodebris, spores, pollen and fungal spores.

Sample#ES-8: The palynological sample consists of 42.34% wood, 21.45% AOM, 18.38% cuticles and 10.86% palynodebris. Spores and pollen are present in small amounts.

Sample#ES-14: The palynological sample is dominated by wood 43.97%, cuticles 26.81%, AOM 7.77% and palynodebris 13.4%. Spores, pollen and fungal spores are low in abundance.

Sample#ES-16: The palynological sample is dominated by wood 69.28%, cuticle 21.99% with a small proportion of palynodebris, spores, pollen and fungal spores.

Sample#ES-18: The palynological sample consists of 53.08% wood, 9.09% AOM and 21.11% cuticle. Palynodebris, spores, pollen and fungal spores are low in abundance.

Sample#ES-19: The palynological sample consists of 39.18% wood, 12.33% palynodebris, 22.74% cuticles and 13.97% AOM with some minor fraction of spores and pollen.

Sample#ES-21: The palynological sample is largely dominated by wood 43.45%, AOM 25% and cuticles 21.73% with a small fraction of spores, pollen and palynodebris. Fungal spores are absent in the sample.

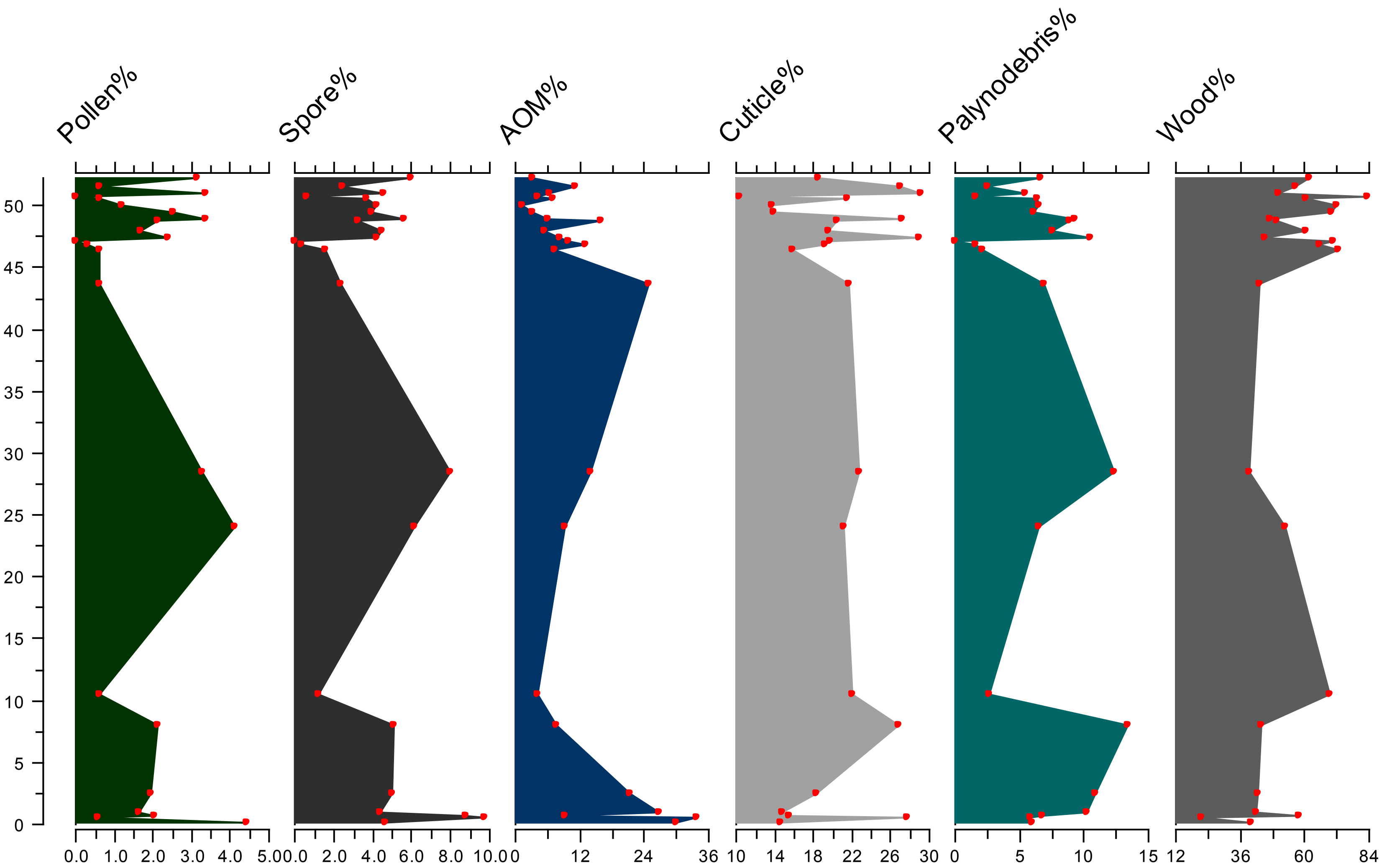

Fig. 8. Quantitative representation and relative abundance of dispersed organic matter and palynomorphs in the studied samples.

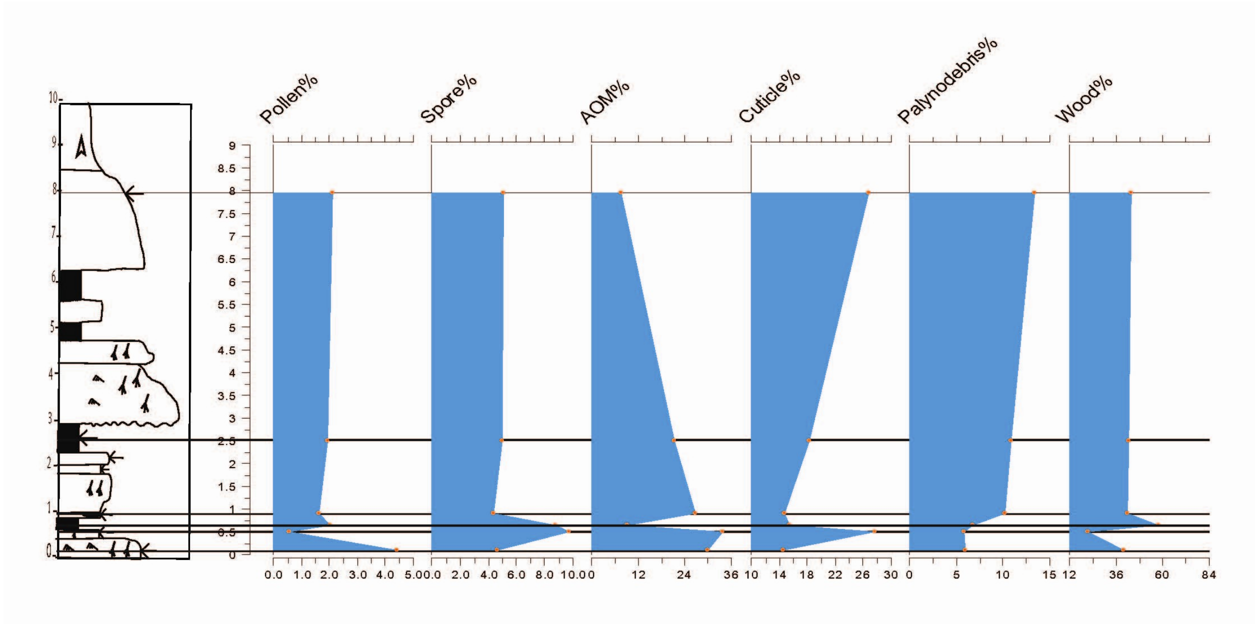

Fig. 9. Relative abundance digram over palynological groups found in the lower part 0-9 m.

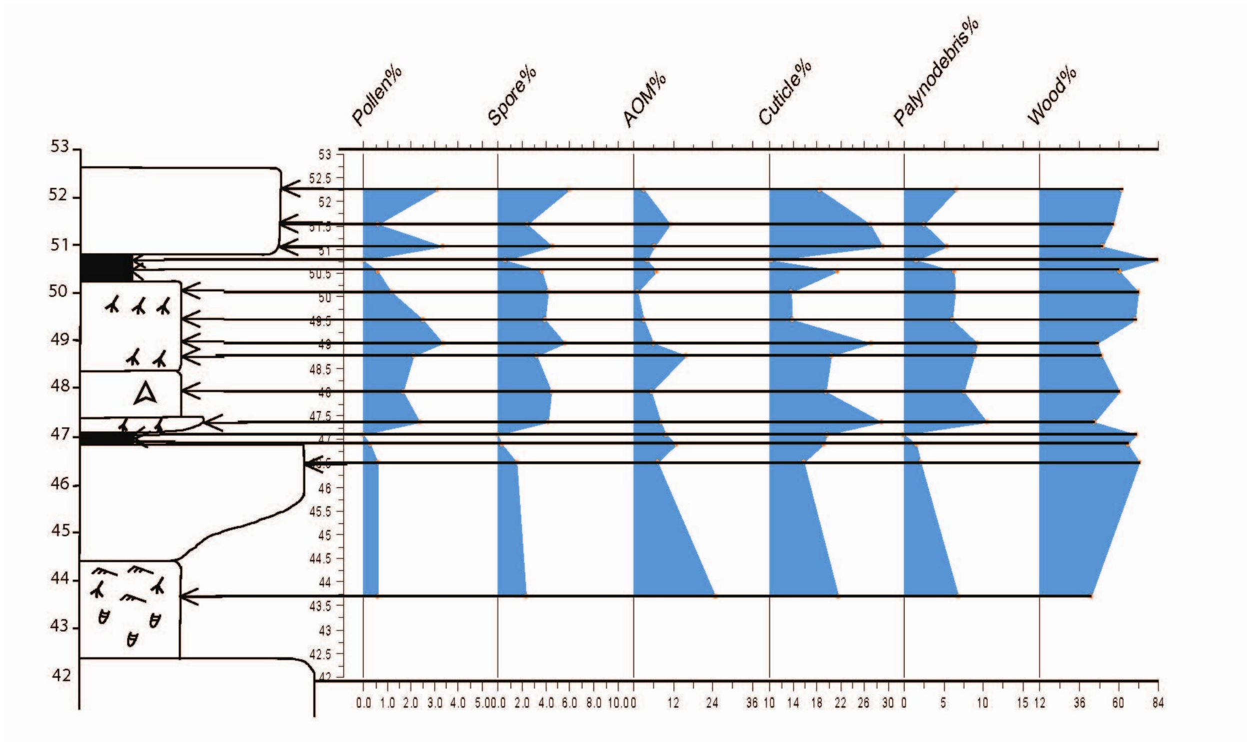

Fig. 10. Relative abundance digram over palynological groups found in the upper part 42-53 m.

.**Sample#ES-22**: The palynological sample is dominated by 72.27% wood, 15.89% cuticles and 7.48% AOM. Pollen, spores, palynodebris are found in minor fractions.

Sample#ES-23: Two samples were used for palynological investigation, to assess variation within the coal bed.

- **23A** is the lower sample dominated by 65.41% wood, 13.21% AOM and 15.89% cuticles with a minor fraction of palynodebris. Pollen, spores and fungal spores are absent.
- **23B** is the upper sample dominated by 70.47% wood, 9.85% AOM and 19.69% cuticles. Spores, pollen, palynodebris and fungal spores are absent.

Sample#ES-24: The palynological sample contains 45.18% wood, 10.54% palynodebris, 28.92% cuticles and 8.13% AOM. Spores, pollen and fungal spores are present in small amounts.

Sample#ES-25: The palynological sample consists of 60.34% wood, 19.55% cuticles and 7.54% palynodebris. Spore, pollen, AOM and fungal spores are present in small fractions.

Sample#ES-26: The subsamples, in stratigraphic order below, are characterized by different palynoassemblages.

- **26** dominated by 49.33% wood, 20.38% cuticles, 8.85% palynodebris and 15.82% AOM. There is a small amount of spores, pollen and fungal spores.
- **26A** is dominated by 46.78% wood, 6.16% AOM, 27.17% cuticles and 9.24% palynodebris. Spores, pollen and fungal spores are found in small fractions.
- **26B** is dominated by 69.83% wood, 13.97% cuticles and 6.15% palynodebris. Spores, pollen, AOM and fungal spores are found in small fractions.
- **26C** is dominated by 71.64% wood, 13.73% cuticles and 6.57% palynodebris. Small fractions of spores, pollen, AOM and fungal spores are also present.

Sample#ES-27: The bed was divided into two sub-sections that were sampled individually for palynology.

- **27A** is dominated by 60.49% wood, 21.58% cuticles, 6.99% AOM and 6.38% palynodebris with a small fraction of pollen and spores. The sample is devoid of fungal spores.
- **27B** is dominated by 83.13% wood, 10.43% cuticles and 4.29% AOM% with a small portion of spores, pollen and palynodebris.

Sample#ES-28: For detailed palynological investigations the bed was divided into three subsections.

- **28A** is dominated by 50.46% wood, 29.05% cuticles and 6.42% AOM with some fraction of pollen, spores and palynodebris.
- **28B** is dominated by 56.35% wood, 26.93% cuticles and 11.15% AOM. Pollen, spores and palynodebris are found in small fractions.
- **28C** is dominated by 61.76% wood, 18.5% cuticles and 6.58% palynodebris with a small fraction of spores, pollen, AOM and fungal spores.

6.3 Thermal Alteration Index

By matching the colour of the fossil spores and pollen with the colour scheme employed by Pearson (1984) and Traverse (2007), the Thermal Alteration Index has been determined to 2 (TAI) and 4 (SCI) (Fig. 2). It indicates the sediments have been through the later stages of diagenesis and only into the early stage of the “oil window’’. This means that the organic matter in the sediments is thermally immature to produce hydrocarbons.

7. Stratigraphical ranges of the pollen and spores

All samples yielded some palynomorphs except samples 23A and 23B, in which no pollen or spores were found. The pollen and spore taxa identified in this study vary in their stratigraphical ranges within the section (Fig. 12) however most of the identified taxa are long ranging. From the recorded distribution of palynomorphs (Fig. 11) the following general information can be inferred:

i. 42 species were documented in total, but the diversity per sample is low.

ii. Stratigraphically, it is evident that there is a significant difference in diversity between the samples throughout the section.

iii. Most of the species have been recorded previously from the same location (e.g., by Tralau 1968); however, some taxa were not possible to identify due to poor preservation.

The species found in the samples have been arranged according to their known published stratigraphical ranges (Fig. 12). It is evident from these distributions that almost half of the species found are long-ranging. However, the known international stratigraphical ranges of some species start in the Middle Jurassic and are restricted to that interval, thus allowing the age of the strata to be determined. Considering the results outlined above (Figs. 11 and 12), several observations can be made:

- Fourteen species are long-ranging, hence they have little importance in dating the deposits.
- The species *Neoraistrickia gristhorpensis* is limited to the Middle Jurassic and is thus a key taxon for constraining the age of the deposits (Tralau 1968).
- *Todisporites minor* is also an index fossil for the Middle Jurassic in Yorkshire (UK) (Couper 1958).
- *Callialasporites microvelatus* is also considered to be a key form from the Middle Jurassic, having been recorded from Germany and Vilhelmsfält (Sweden) (Guy-Ohlson 1971).
- *Lycopodiumsporites semimuris* is not reported from Late Jurassic but is present in Middle Jurassic sediments of Sweden (Guy-Ohlson 1971).

Based on the above distributions, the whole assemblage of the Fuglunda Member may be regarded as Middle Jurassic (Bajocian–Bathonian) in age.

8. Discussion

8.1 Sedimentological interpretation

Based on the sedimentary features recorded in section 6.1, the depositional setting of the studied interval can be interpreted independently of its fossil content. The key sedimentological characteristics of the succession enable the following interpretations:

-

- The succession contains a mix of coarse and fine lithologies with variable sharp (erosional) to gradational contacts, which indicates a broad range of sediment transport energy levels. If the contact is not well defined, it means that the depositional transition between the lithologies was gradual. Where a lithological contact is sharp and truncated, then it implies there was a rapid increase in water energy resulting in scouring and erosion (Nichols 2009).
- Several coal seams, carbonaceous claystones and siltstones are present in the succession (from bed #ES-21 to #ES-27) suggesting a predominantly continental depositional setting with sufficient moisture levels to support rich plant communities, and the accumulation of organic remains in stagnant mires.
- Both plant roots and burrows are relatively common in the sediments, particularly below coal seams (below bed #ES-3, 11, and 27), indicating that the coals probably accumulated from autochthonous vegetation and not from transported organic matter. The presence of plant roots and burrows is commonly noted below coals in other regions where peat accumulated from vegetation that was produced locally (Wust et al. 2003).
- The lowermost 10 meters of the section, i.e., from bed #ES-21 to #ES-28, reveals three successive fining-upward packages of beds, grading from cross-bedded sands to coals. This suggests deposition within fluvial conditions, probably point bars of meandering or anastomosing streams (Ahlberg 1990). Braided rivers tend to have a much higher percentage of coarse-grained sediments, and less regular fining-upward cycles (Boggs 1987). Meandering streams are mostly associated with channel-margin (point bar) sand deposits, whereas anastomosing steams have lesser sand and are associated with extensive distal mud-sheet deposits (Marriott et al. 2009). Clear distinction between meandering versus anastomosing river settings cannot be resolved for the Eriksdal deposits on the basis of this study alone.
- Some beds containing well-preserved leaves (#ES-18) and thinly laminated clays with soft-sediment deformation (#ES-7) may indicate deposition within lacustrine settings subject to episodic. seismic activity (Montenat et al. 2007). Seismites are the result of soft-sediment deformation due to the over-pressuring of satu-

-ration water during seismic events (Montenat et al. 2007). These sedimentary structures show features of discharge and/or inoculation of earlier fluidized flow.

- Sediment maturity depends both on the nature of the source rocks in the area and the length of time the sediment was in the sedimentary cycle (Wiltje et al. 2004). The scarcity of conglomerate beds (only a few thin beds with clasts reaching pebble size, i.e., bed #ES-20), and the rounded nature of the clasts suggests that the sediments of the Fuglunda Member are relatively mature and were deposited in the distal part of a fluvial system, a long way from the sediment source area.

- Although there are no shelly fossils, the presence of wavy and flaser bedding, burrows and pyrite concretions, particularly in the upper part of the succession suggests that there was some tidal influence on sedimentation. The origin of wavy and flaser bedding relates to the alternation of currents or wave action and slack water (Nichols 2009). The current action forms sand ripples and during slack water conditions mud is deposited in the ripple troughs or as drapes on ripple crests. These processes reflect tidal activity (Reineck and Wunderlich 1968). The presence of a high amount of pyrite in the Eriksdal coal also suggests that the sediment accumulated close to marine environments where sulfur levels are enriched (Berner 1970).

- The presence of thick sandstones with low-angle cross beds, together with the fact that the Fuglunda Member is immediately overlain by the shallow marine Glass Sand Member, suggests that some of the uppermost beds in the section were deposited in beach environments (Ahlberg 1990).

Taking all these features together, it suggests a coastal depositional setting for the Fuglunda Member – perhaps a delta system with a mix of fluvial, tidal and wave (beach) influences on depositional processes, together with extensive delta-top blankets of organic deposits (peats).

8.2 Palynofacies interpretations

The investigated samples from the Fuglunda Member at Eriksdal contained well-preserved palynomorphs, mainly wood, amorphous organic matter and cuticles. Other groups present in the palynological assemblage are relatively low in abundance and include pteridophyte spores, pollen, fungal spores and palynodebris (Fig. 9). Cuticles sheets are also found in the assemblage. Forty-eight established species were identified and there were more unidentified forms in the samples. Among the spores and pollen in the assemblage, most are long ranging and thus have little value as stratigraphic markers (Fig. 12). However, a few key taxa occur that are useful biostratigraphic indices and help to date the deposits.

The increase in the number of pollen and spores from the base up to 2 m is followed by a massive increase in wood, cuticle and amorphous organic matter (Fig. 11). The middle part of the section, i.e., 10–27 m, shows an increase in pollen and spore abundance but also an increase in cuticle and wood. The topmost part of the section shows an interesting feature (Fig. 10). There is a slight decrease in the relative abundance of pollen, spores, AOM and cuticle and an increase in relative abundance of wood. Most of the samples are dominated by wood, cuticle and amorphous organic matter.

Four plant groups dominate the spore-pollen assemblages as follows:

- Most of the samples are dominated by gymnosperms. Twenty-six species of gymnosperms were identified. The gymnospermous pollen and spores are dominated by *Perinopollenites elatoides, Podocarpidites* ssp., *Cerebropollenites macroverrucosus, Eucommiidites troedssonii, Spheripollenites scabratus Protopinus scanicus, cf. Brachysaccus microsaccus Ginkgocycadophytus nitidus* and *Classopollis chateaunovi*. The other gymnospermous pollen are present in minor amounts and include *Araucariacites australis, Alisporites robustus, Alisporites thomasi, Callialasporites microvelatus, Cerebropollenites mesozoicus, Quadraeculina anellaeformis, Parvisaccites enigmatus, Pinuspollenites minimus* and *Vitreisporites pallidus.*

- The second plant group is the Pteridophyta represented by twelve species. The three species, *Cyathidites minor, Cyathidites australis* and *Gleicheniidities troedssonii* are common among most of the samples.

- Lycopods are the next in abundance and they were mostly concentrated in the upper part of the section. Only six species were identified, among which *Densoisporites* ssp., *Lycopodium austro-clavatoides and Calamospora* ssp. are the most common.

- Bryophyta are present in very low amounts and only two species were identified in the samples. *Stereisporites* ssp., are common in some samples.

Eriksdal	1	2	3	4	8	14	16	18	19	21	22	23A	23B	24	25	26	26A	26B	26C	27A	27B	28A	28B	28C	
Bryophytes																									
Stereisporites aulosenesis																	x								
Stereisporites spp.				x															x	x	x				
Pteridophyta																									
Baculatisporites spp.	x							x									x								
Cyathidites australis	x	x	x	x	x	x	x		x	x					x			x			x				
Cyathidites minor	x	x	x	x														x		x	x	x			
Gleicheniidites senonicus	x	x			x	x					x						x	x			x	x		x	
Todisporites major			x												x				x						
Todisporites granulatus		x																							
Undulatisporites concavus		x																							
Deltoidospora spp.						x	x								x										
Leptolepidites spp.	x																x								
Leptolepidites bossus																	x		x						
Matonisporites crassiangulatus																				x					
Cyathidites concavus																				x					
Lycopods																									
Densoisporites spp					x									x					x						
Lycopodiumsporites austroclavatoides																	x		x	x	x				
Lycopodiumsporites reticulumsporites																	x				x				
Lycopodiumsporites semimuris																	x								
Calamospora spp.		x	x												x				x		x	x			
Neoraistrickia gristhorpensis																							x		
Gymnosperms																									
Araucariacites australis																								x	
Alisporites thomasi								x										x			x				
Alisporites robusts									x																
Callialasporites microvelatus															x										
Cerebropollenites macroverrucosus						x											x	x	x		x				
Cerebropollenites mesozoicus			x														x								
Classopollis chateaunovi	x			x	x	x			x					x								x			
Eucommiidites troedssonii				x		x		x	x							x	x	x	x						
Gingkocycadophytus nitidus	x				x		x	x									x	x	x						
Perinopollenites elatoides	x		x			x		x	x					x	x	x	x	x	x	x		x	x		
Podocarpidites spp.	x			x	x										x		x		x						
Podocarpidites cf. ellipticus	x				x												x								
Quadraeculina anellaeformis																					x				
Spheripollenites scabratus			x															x			x	x			
Parvisaccites enigmatus																x									
Pinuspollenites minimus		x							x							x									
Calliallasporites trilobatus																	x								
Cf. Brachysaccus microsaccus						x		x								x		x				x			
Chasmatosporites hians						x									x				x						
Protopinus scanicus		x						x								x		x			x				
Vitreisporites pallidus						x		x													x				
Exesipollenites tumulus																		x							
Bisaccate spp.				x			x	x	x							x	x	x	x	x	x	x		x	
Trilete spp.	x	x	x	x	x	x	x	x	x	x				x			x	x	x	x	x	x	x	x	

Fig. 11. Distribution of palynomorphs found in the samples from Fugulunda Member.

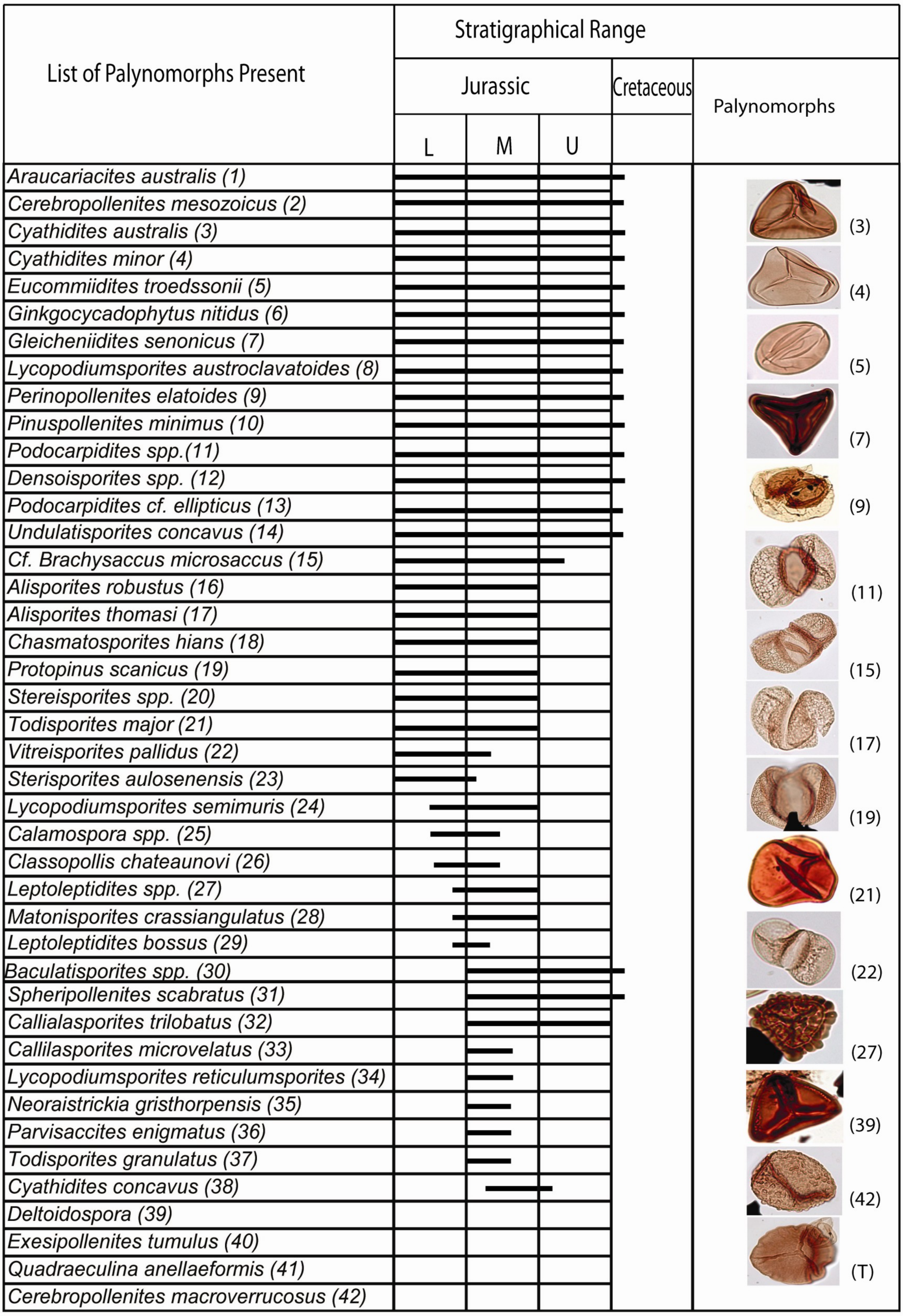

Fig. 12. Stratigraphical ranges of palynomorphs found in Fugulunda Member (Guy-Ohlson 1971 & 1978; Erlström et al. 1991)

8.3 Paleoclimatological interpretations

The palynoflora of Eriksdal area is diverse and abundant and reflects a moist, temperature climate (Vajda & Wigforss-Länge 2006). These conditions allowed the development of extensive and persistent vegetation in the area that could help bind sediments in fluvial floodplain and deltaic settings. Buchardt (2003) developed a climatic curve, highlighting warmer/ cooler, conditions for the Early to Late Jurassic in North Europe. Paleotemperatures were calculated from oxygen isotope data from Jurassic fossils in Europe. Coastal and lowland areas experienced a warm and wet climate during the late Toarcian, however, in the middle Aalenian there was a short interval of cool and wet climate. This was followed by an interval of warmer, drier climate (Stefanowicz 2008).

Based on dispersed spore-pollen records, the vegetation at Eriksdal during the studied time interval was dominated by gymnospermous plants. The pteridophyta are represented mainly by the *Cyatheaceae* and *Gleicheniaceae*. Lycophytes are dominated by *Calamospora* spp., which is commonly found in tropical regions, whereas bryophytes are represented by low abundances of *Sterisporites* spp. *Cyatheaceae* are tree-ferns and, today, are found in warm and humid tropical to subtropical regions, the *Gleicheniaceae* also occur in tropical and subtropical areas but in some areas they extend into temperate heathlands and cool montane habitats. They commonly live in forest understory, riverine, or marshy heathland habitats. *Podocarpidites* pollen derives from podocarp conifers. These are woody shrubs to large trees, distributed in tropical, subtropical and southern temperate regions. *Cycadopites*-type monosulcate pollen was produced by a range of Mesozoic plants. The most common groups in the Northern Hemisphere at that time were Bennettitales, Cycadales and Ginkgoales (Tralau 1968; Pott & McLoughlin 2009, 2011). Bennettites are extinct and were cosmopolitan; modern cycads are found in tropical and semi-tropical regions (Jiang & Wang 2002); *Ginkgo* is today a relictual genus of cool montane regions.

The presence of *Classopollis* and *Perinopollenites* in the Fuglunda Member assemblage suggests that deposition of the sediments took place in continental coastal areas under warm, and potentially saline climatic conditions (Watson 1988; Vajda 2001). Therefore, they may be indicative of coastal marshes or estuarine environments. The presence of pteridophyte spores indicates more or less humid conditions. Although ferns can thrive in tropical to cool temperate environments, they are restricted to habitats where at least consistent seasonal water is available for spore germination, gametophyte growth and the exchange of sex cells (Abbink et al. 2004). The Eriksdal palynoflora is well represented by spores of *Cyathaeaceae, Baculatisporites, Todisporites* and *Deltoidospora.* Ferns found in the European Jurassic flora are diverse and reflect lush vegetation characteristic of floodplains and river banks (Pelzer et al. 1992). Therefore, it is suggested that the Eriksdal ferns may have occupied marshy or river-bank communities in distal fluvial or deltaic environments (Abbink et al. 2004). *Vitreisporites pallidus* is considered to be a seed-fern pollen; the parent plants grew in deltaic environments during the Jurassic and Cretaceous (Harris, 1964). This is consistent with warm, wet fluvial conditions at Eriksdal in the Jurassic (Pelzer 1984). Gymnospermous pollen such as *Podocarpidites* and *Quadraeculina anellaeformis* are found in subtropical to temperate areas and reflect generally moist forest conditions. They are sometimes considered to be indicative of upland environments (Vakhrameev 1991). *Araucariacites* and *Callialasporites* spp. derive from araucariacean conifers. Today these trees grow mostly in tropical to subtropical moist forests, but a few grow in coastal areas of south Pacific islands. They were much more diverse in the Mesozoic and some may have grown more extensively in coastal forests under warm climates. Therefore, their presence does not exclude a coastal depositional setting for the Eriksdal sediments (Haaris 1979; Vakhrameev 1991). The majority of bryophytes such as *Stereisporites* grow in humid conditions and near water. Therefore, their presence is consistent with a fluvial environment and humid vegetation regime (Abbink et al. 2004).

8.4 Paleonvironmental summary

The basal part of the section is marked by the presence of the species *Araucariacites australis* (Jurassic to Lower Cretaceous), *Gleicheniidites senonicus* (Upper Triassic to present), *Podocarpidites* spp. (Middle Jurassic) and *Neoraistrickia gristhorpensis* (Middle Jurassic). Here the lithology consists of very fine sandstone and siltstone, which implies that the sediments were deposited in low-energy conditions (point bar to flood basin deposits). The presence of iron staining (from the oxidation of pyrite) shows that the coal bed between the sandstone units probably formed in a reducing environment. The strong representation of the ferns *Gleicheniidites senonicus* and *Neoraistrickia gristhorpensis* is consistent with the predominantly moist floodbasin settings interpreted for this interval.

The middle part of the section is marked by the presence of various species including *Alisporites robustus* (Lower–Middle Jurassic), *Cyathidites australis* (Jurassic to Lower Cretaceous), *Eucommiidites troedssonii* (Triassic to Cretaceous), and *Perinopollenites elatoides* (Liassic to Lower Cretaceous). The lithology is dominated by sandstone with interbeds of finely laminated claystone, which indicates a succession deposited in fluvial channels with episodic lake (abandoned channel) settings. The presence of several families of gymnosperm pollen (*Alisporites robustus*, *Eucommiidites troedssonii* and *Perinopollenites elatoides*) mixed with ferns in this part of the succession is consistent with this interval being dominated by channel deposits incorporating organic debris from a wide range of sources.

The top of the section is marked by the presence of *Baculatisporites* spp. (Upper Triassic to Cretaceous), *Cyathidites australis* (Middle Jurassic), *Cyathidites minor* (Jurassic to Lower Cretaceous), *Classopollis chateaunovi*, *Podocarpidites* spp. (Middle Jurassic) and other gymnosperm pollen and spores. This interval is composed of alternating beds of coal and sandstone with some flasers of organic-rich clay and silt, which reflects deposition in lower energy conditions similar to those of the basal part of the section, but under a tidal influence. The return to a strong representation of fern spores (*Baculatisporites* and *Cyathidites* spp.), together with the presence of the xerophytic cheirolepidacean conifer, *Classopollis chateaunovi*, is consistent with this uppermost interval representing coastal deposits with plant communities adapted to disturbance.

8.5 Regional similarities in the palynoflora

The pollen and spore taxa recovered from the Fuglunda Member are widespread in the Middle Jurassic deposits of Eurasia and North America. The palynoflora of the Fuglunda member contains most of the long-ranging taxa, however some are more age-diagnostic. For example, *Todisporites minor* is among the index fossils for the Middle Jurassic, and was first reported from the Middle Jurassic Bajocian of Yorkshire (Couper 1958). *Stereisporites granulatus* is reported from Middle Jurassic Bajocian of China (Jiang & Wang 2002). *Gleicheniidites, Vitreisporites* and *Quadreculina enigmatus* are reported from the Middle Jurassic of Canada and Western Europe (Couper 1958; Pocock 1970). *Cyathidites australis* and *Cyathidites minor* are reported from Jurassic and Lower Cretaceous in New Zealand and England (Couper 1953 and 1958).

The palynoflora of Eriksdal has been compared with those from others parts of Sweden and NW Europe. The dominant constituents are pollen grains and spores in these areas. The assemblage described from the Kurremölla section 641.0–642.50 m by Guy-Ohlson (1982) shows strong similarity to that of the Fuglunda member at Eriksdal. This Kurremölla assemblage is dated as Berriasian to Hauterivian due to the presence of some key younger palynomorphs (Guy-Ohlson 1982). Due to its broad similarity with the Kurremölla assemblage, the playnoflora from Eriksdal was named as ''The Kurremålla Flora'' by Möller and Halle (1913).

Comparison of the pollen and spore assemblages recovered from the Fuglunda member at Eriksdal with those collectively obtained from the Karindal area (Guy-Ohlson and Norling 1988) shows general similarity amongst the long-ranging taxa. However, there is a little resemblance in terms of shared index taxa. There is a broad similarity between the palynoflora of Eriksdal and the Karindal zone C assemblage (Guy-Ohlson and Norling 1988).

There is a great similarity between the Jurassic palynomorphs in Yorkshire (UK) and Eriksdal (Couper 1958). Comparison of the Eriksdal palynoflora with those of the Lower and Middle Purbeck Formations, Southern England, reveals that suites B and C found by Norris (1969) show similar abundances of palynofloral groups. However, the abundance of *Classopollis* species at Eriksdal is generally low, whereas it is dominant in comparative aged deposits of Southern England.

Batten's (1968) study of the NW European continental shelf area recorded the dominant gymnosperm pollen as being *Perinopollenites elatoides, Cerebropollenites mesozoicus, Classopollis, Araucariacites australis,* and *Calliasporites*. These taxa are also present at Eriksdal and suggest the assemblages are of equivalent age.

Further afield, the palynoflora of Eriksdal can also be compared with palynofloras from other regions such as China (Jiang & Wang 2002), Canada (Pocock 1970), New Zealand (Jadwiga 2006) and Libya (Thusu et al. in El-Arnauti et al. 1988). All these palynofloras show broadly similar representations of palynomorphs.

9. Implications for hydrocarbon exploration

The Jurassic rocks of Sweden are similar to those of Norway in some aspects but there are significant differences in terms of hydrocarbon potential. The source rocks at Eriksdal are immature and have never been buried deeply enough to produce oil (Ahlberg 1996). The thermal alteration index results showed that, the sediments have been through the later stages of diagenesis but have not yet reached the ''Oil window''. Furthermore, the organic matter in the Jurassic succession of Sweden is mostly gas-prone (Kerogen Type III: woody material), hence has low potential to produce oil. Although the studied deposits have not been buried deeply enough for burial heat to reach thermal maturity, it is possible that correlative rocks buried more deeply elsewhere in Skåne have indeed reached the oil window. Volcanic activity spanning the Triassic to Cretaceous may also have locally enhanced thermal maturity of the sediments. However, extensive faulting may also have served as possible escape paths for the migration and loss of hydrocarbons (Ahlberg 1996; Ahlberg and Olsson 2001). The vertically tilted potential source rocks exposed at Eriksdal lack appropriate cap rocks (hydrocarbon seals) and any hydrocarbons that might have been generated are likely to have been lost by groundwater flushing.

Therefore, the Jurassic source rocks in Skåne have shown negative results in most of the previous surveys conducted for hydrocarbon exploration. Nevertheless, these rocks (their lithologies and stratigraphic relationships) can serve as good models for petroleum geologists to understand the facies relationships in coeval deposits in Norway.

10. Conclusions

- Based on field studies of the Fuglunda Member, the sediments are interpreted to have been deposited in a coastal setting, perhaps a delta system that was strongly influenced by fluvial, tidal and wave processes.
- The palynological investigation carried out on the sediments from Fuglunda Member revealed a well-preserved palynological assemblage. Forty-three species were identified belonging to four different major plant groups. The most common species in the assemblage is *Perinopollenites elatoides.*
- The best preserved and most diverse palynomorph assemblages are mostly represented in the upper and lower parts of the section. The middle part is dominated by sandstones and yields only minor assemblages of palynomorphs.
- The coal samples show a similar abundance of pollen and spores to the non-coal bearing samples, except 23A and 23B, which were barren of pollen and spores.
- Based on the pollen and spore assemblage, the paleoclimate of the Eriksdal area during the Middle Jurassic was warm and humid.
- Based on the palynomorph assemblages, the age of the Fuglunda member can be assigned to the Bajocian–Bathonian of the Middle Jurassic.
- The palynomorph assemblages from the Jurassic of Skåne show various similarities with Jurassic palynofloras of China, New Zealand, Canada, Libya and Yorkshire (UK).
- The thermal alteration index (TAI) and Spore color index (SCI) results show that the organic matter is gas-prone and is immature to produce hydrocarbons.

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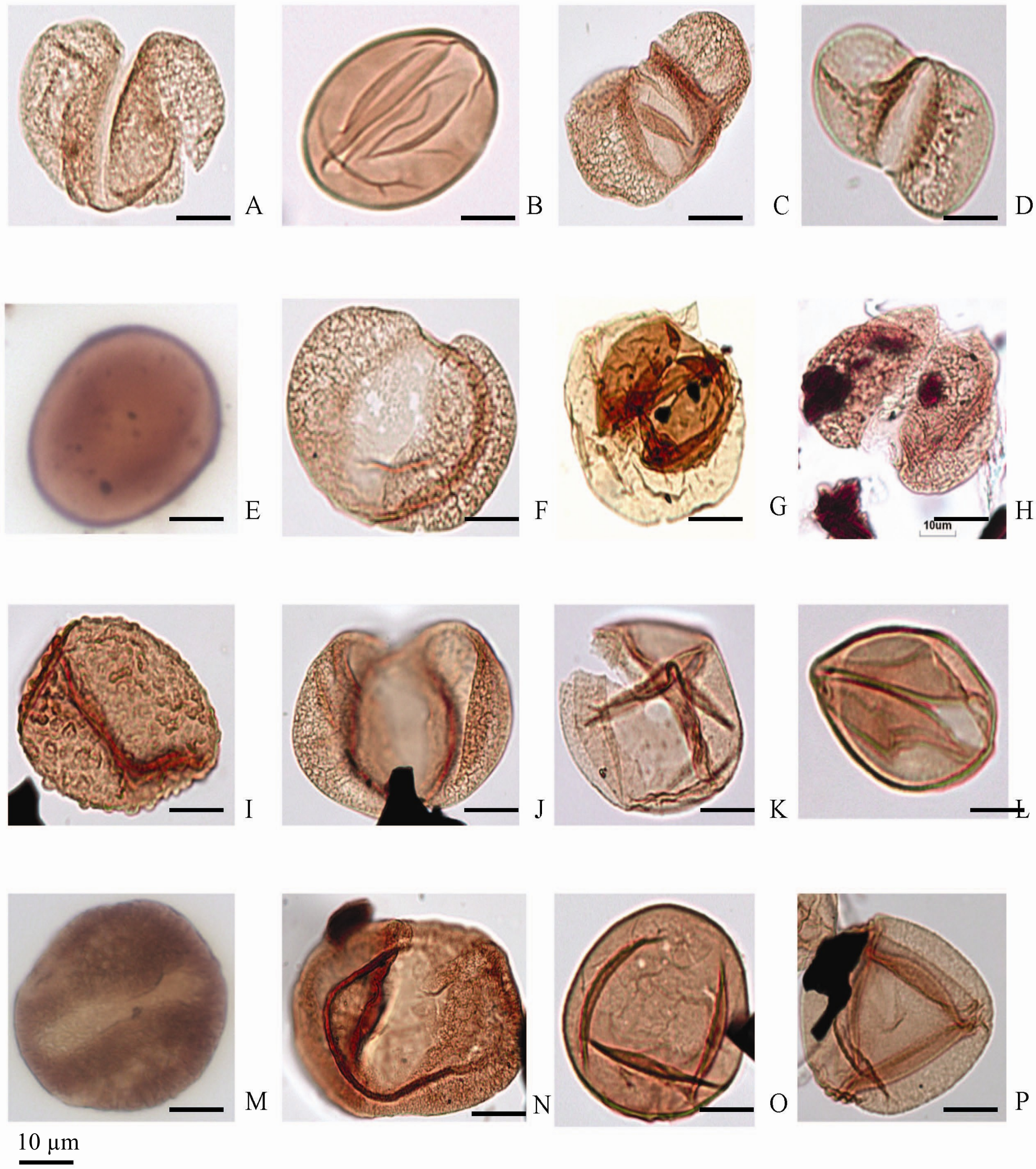

Plate 1. A, *Alisporites thomasii*. **B**, *Eucommiidites troedsonii*. **C**, *Cf. Brachysaccus microsaccus*. **D**, *Vitreisporites pallidus*. E, *Classopollis*. **F**, *Pinuspollenites minimus*. **G**, *Perinopollenites elatoides*. **H**, *Podocarpidites cf. ellipticus.* **I**, *Cerbropollenites macroverrucosus*. **J**, *Protopinus scanicus*. **K**, *Calamospora.* **L**, *Chasmatosporites hians.* **M,** *Quadraeculina anellaeformis*. **N**, Bisaccate pollen. **O**, *Spheripollenites scabratus.* **P**, *Calliallasporites trilobatus*.

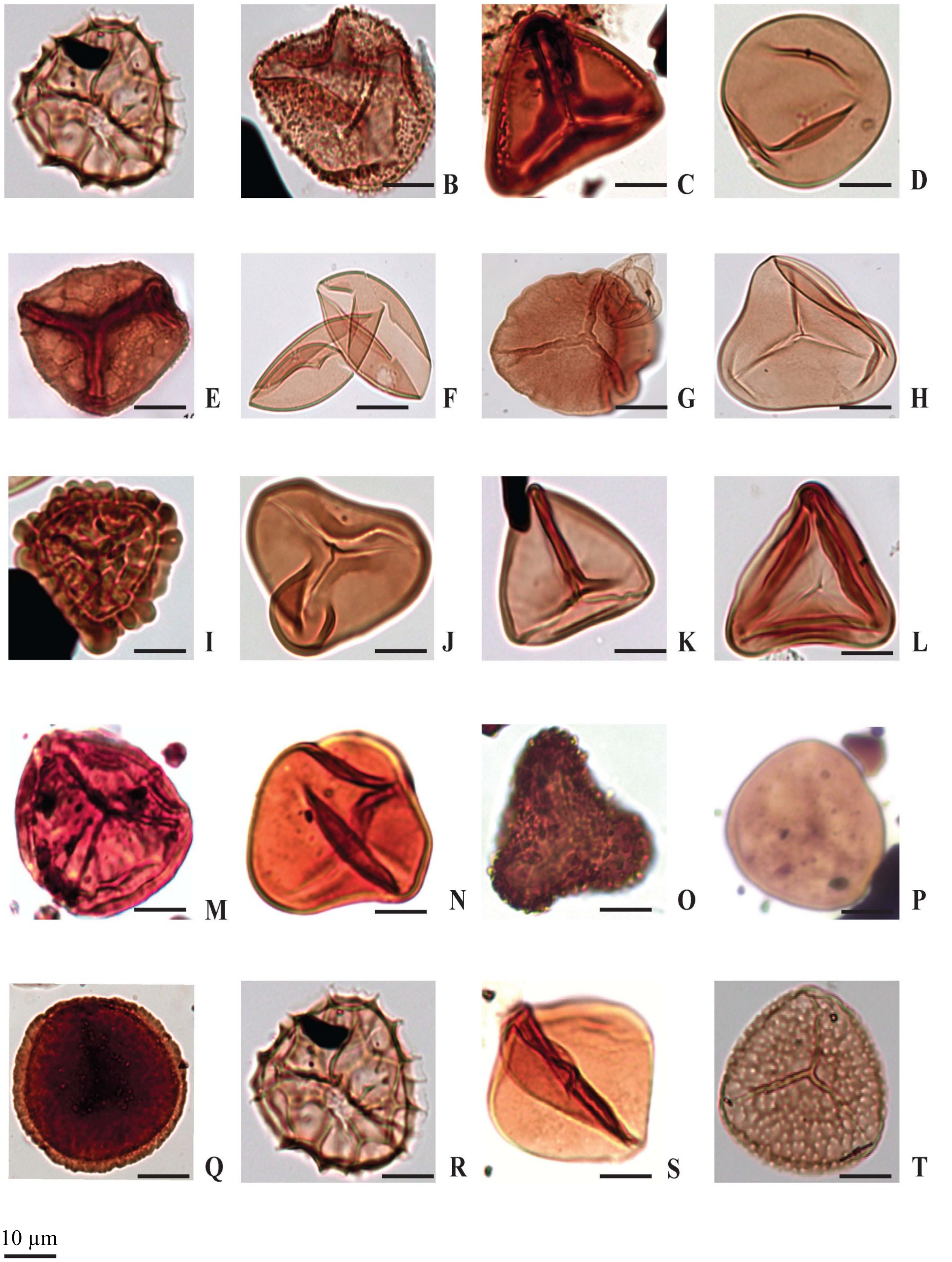

Plate 2. **A**, *Lycopodiumsporites reticulumsporites* **B,** *Baculatisporites*. **C,** *Deltoidspora*. **D**, *Todisporites*. E, Trilete spore. F, *Gingkocycadophytus nitidus*.**G**, Trilete spore. **H,** *Cyathidites minor*. **I**, *Leptoleptidites* ssp. **J,** *Matonisporites crassiangulatus*. **K**, *Cyathidites minor*. **L,** *Gleicheniidiites senonicus*. **M**, *Densoisporites*. **N**, *Todisporites major.* **O,** *Acanthotriletes* spp. **P**, *Sterisporites* spp. **Q,** *Calliallasporites microvelatus*. **R**, *Lycopod -iumsporites semimuris*. **S,** *Cyathidites australis*. **T,** *Stereisporites aulosenesis*.

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