Early and Middle Jurassic mires of Bornholm and the Fennoscandian Border Zone: a comparison of depositional environments and vegetation

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Suitable climatic conditions for peat formation existed during Early–Middle Jurassic times in the Fennoscandian Border Zone. Autochthonous peat and allochthonous organic matter were deposited from north Jylland, south-east through the Kattegat and Øresund area, to Skåne and Bornholm. The increase in coal seam abundance and thickness from north Jylland to Bornholm indicates that the most favourable peat-forming conditions were present towards the south-east. Peat formation and deposition of organic-rich muds in the Early Jurassic coastal mires were mainly controlled by a continuous rise of relative sea level governed by subsidence and an overall eustatic rise. Watertable rise repeatedly outpaced the rate of accumulation of organic matter and terminated peat formation by lacustrine or lagoonal flooding. Organic matter accumulated in open-water mires and in continuously waterlogged, anoxic and periodically marine-influenced mires. The latter conditions resulted in huminite-rich coals containing framboidal pyrite. The investigated Lower Jurassic seams correspond to peat and peaty mud deposits that ranged from 0.5–5.7 m in thickness, but were generally less than 3 m thick. It is estimated that on Bornholm, the mires existed on average for *c*. 1200 years in the Hettangian–Sinemurian and for *c*. 2300 years in the Late Pliensbachian; the Early Jurassic (Hettangian–Sinemurian) mires in the Øresund area existed for *c*. 1850 years. Aalenian uplift of the Ringkøbing–Fyn High and major parts of the Danish Basin caused a significant change in the basin configuration and much reduced subsidence in the Fennoscandian Border Zone during the Middle Jurassic. This resulted in a more inland position for the Middle Jurassic mires which on occasion enabled peat accumulation to keep pace with, or temporarily outpace, watertable rise. Thus, peat formation was sometimes sustained for relatively long periods, and the mires may have existed for up to 7000 years in the Øresund area, and up to 19 000 years on Bornholm. The combination of the inland position of the mires, a seasonal climate, and on occasion a peat surface above groundwater level caused temporary oxidation of the peat surfaces and formation of inertinite-rich coals. The spore and pollen assemblages from coal seams and interbedded siliciclastic deposits indicate that the dominant plant groups in both the Early and Middle Jurassic mires were ferns and gymnosperms. However, significant floral differences are evident. In the Lower Jurassic coals, the palynology testifies to a vegetation rich in cycadophytes and coniferophytes (Taxodiaceae family) whereas club mosses were of lesser importance. Conversely, in the Middle Jurassic coals, the palynology indicates an absence of cycadophytes, a minor proportion of coniferophytes (Taxodiaceae) and a significant proportion of club mosses. These variations are probably related to adaptation by different plants to varying environmental conditions, in particular of hydrological character.

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In contrast to the Permo-Carboniferous and Cenozoic, the Jurassic is not considered to be a time of major peat formation. However, the Jurassic succession of Northwest Europe, and in particular the Middle Jurassic, contains significant coal-bearing strata showing that favourable conditions for peat formation were fulfilled at many times. In the Danish area, coal-bearing strata are generally restricted to the Central Graben in the North Sea and the Fennoscandian Border Zone. Well-developed Lower–Middle Jurassic coals are found from the Øresund area to the island of Bornholm in the Baltic Sea indicating climatic and geological conditions suitable for the accumulation and preservation of organic matter (Fig. 1).

The importance of coal beds in stratigraphic analysis is emphasised by the fact that coal seams may represent a considerable proportion of the time represented by coal-bearing successions. Thus, this paper views the peat-forming environments on Bornholm and in the Fennoscandian Border Zone in a broad geological perspective and discusses the variability in peat-forming conditions in the area in an attempt to explain the principal compositional differences between the Lower and Middle Jurassic coal seams. In addition, the paper pre-sents palynological data from the coals and adjacent sediments and discusses the palynological evidence of the peat-forming vegetation compared to the evidence from the coal composition.

Geological setting

The Fennoscandian Border Zone is a major tectonic structure that separates the Baltic Shield from the Danish Basin and Polish Trough (Fig. 1). The border zone is divided into the stable Skagerrak–Kattegat Platform and the highly block-faulted Sorgenfrei–Tornquist Zone, which has been tectonically active at least since late Palaeozoic times (Sorgenfrei & Buch 1964; Norling & Bergström 1987; EUGENO-S Working Group 1988; Michelsen & Nielsen 1991, 1993; Mogensen 1994). Towards the south-east, the Sorgenfrei–Tornquist Zone continues into the Teisseyre–Tornquist Zone via the Rønne Graben, west of Bornholm in the Baltic Sea. The Rønne Graben pull-apart basin was formed by Late Carboniferous – Early Permian dextral wrench-faulting (Vejbæk 1985; Liboriussen et al. 1987). Continued Triassic
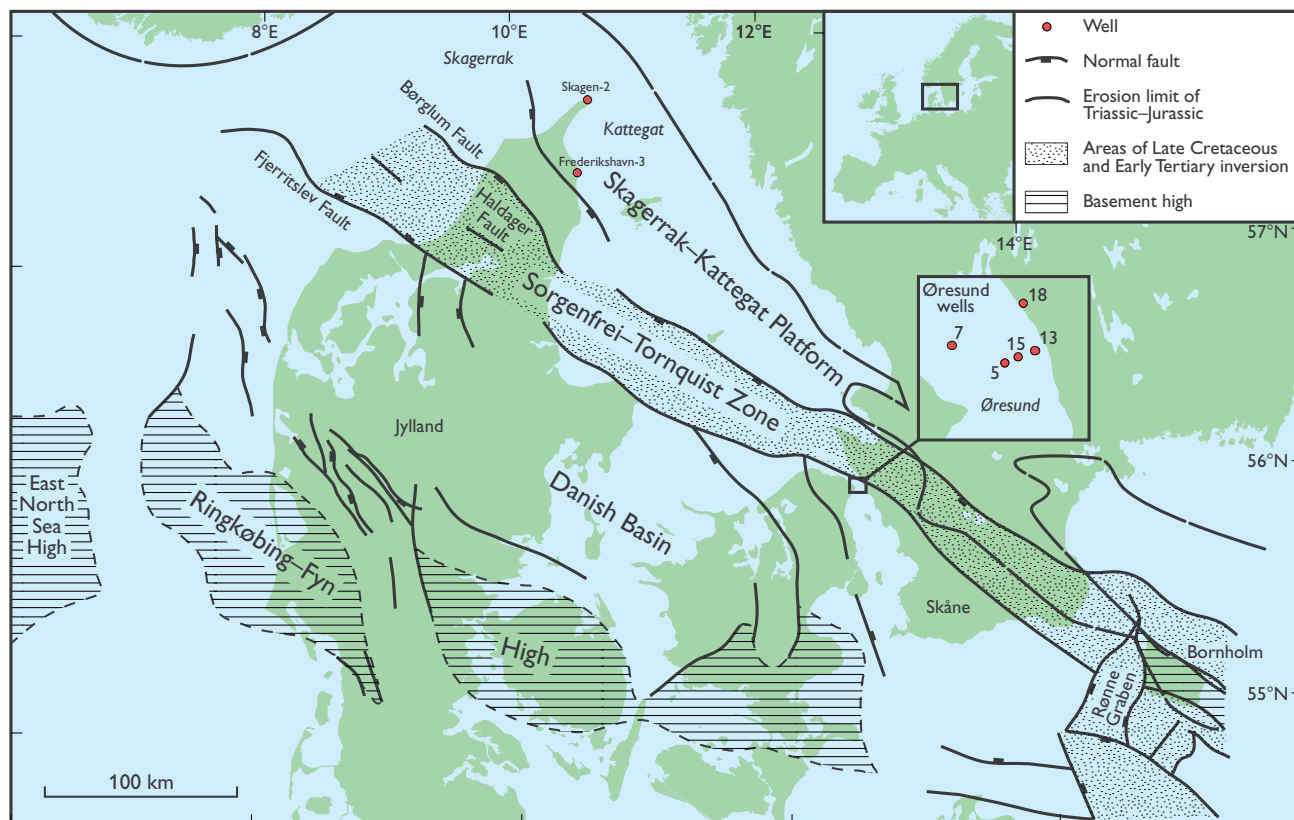

Fig. 1. Map showing the structural outline of the Fennoscandian Border Zone and the location of Bornholm and the Øresund, Skagen-2 and Frederikshavn-3 wells. Modified from Liboriussen *et al.* (1987) and EUGENO-S Working Group (1988).

– Early Cretaceous wrench faulting resulted in fault-controlled subsidence and tilting of fault blocks in the Sorgenfrei–Tornquist Zone. Compressional tectonism in the Late Cretaceous – Palaeogene led to inversion of fault blocks in the Sorgenfrei–Tornquist Zone and regional Neogene–Pleistocene uplift resulted in erosion of the Mesozoic sediments (Gry 1969; Michelsen & Nielsen 1991, 1993; Japsen 1993; Petersen *et al.* 2003, this volume).

Northwards transgression from the Tethys during Early Jurassic times due to an overall rise in sea level combined with continued subsidence of the North Sea area and the Danish Basin, created an extensive epicontinental sea in Northwest Europe (Hallam 1988, 1992; Ziegler 1988). The north-eastern margin of the sea coincided with the Fennoscandian Border Zone. Coastal and delta plains were established along the margin of the sea, and Hettangian–Sinemurian coal-bearing strata were deposited on Bornholm (Rønne Formation), in the Øresund area, Skåne (Helsingborg Member), and in the Kattegat and north Jylland (Gassum Formation; Troedsson 1951; Gry 1969; Bertelsen 1978; Gravesen *et*

al. 1982; Pieńkowski 1991; Petersen 1993, 1994; Nielsen 1995; Surlyk *et al.* 1995).

Fully marine conditions were established across the entire area in the Early Pliensbachian, but due to a Late Pliensbachian regression, deposition of coal-bearing strata (Sorthat Formation) was resumed on Bornholm until an Early Toarcian transgression terminated peat formation (Fig. 2–3; Koppelhus & Nielsen 1994; Petersen & Nielsen 1995). In the Danish Basin, deposition of marine clays and sands continued until the Aalenian (Michelsen 1989; Michelsen & Nielsen 1991; Nielsen 1995).

Continental conditions were re-established during the Middle Jurassic and coal-bearing strata were deposited in lake-dominated peatlands and small alluvial fans on Bornholm (Bagå Formation; Gry 1969; Gravesen *et al.* 1982; Petersen 1993; Koppelhus & Nielsen 1994), in lake-dominated peatlands in the Øresund area (Petersen 1994), and in deltaic environments in Skåne (Fuglunda Member; Rolle *et al.* 1979; Norling *et al.* 1993). Thin coaly muds, lacustrine clays and fluvial sands were deposited in north Jylland (Haldager Sand Formation; Koch 1983; Nielsen 1995).
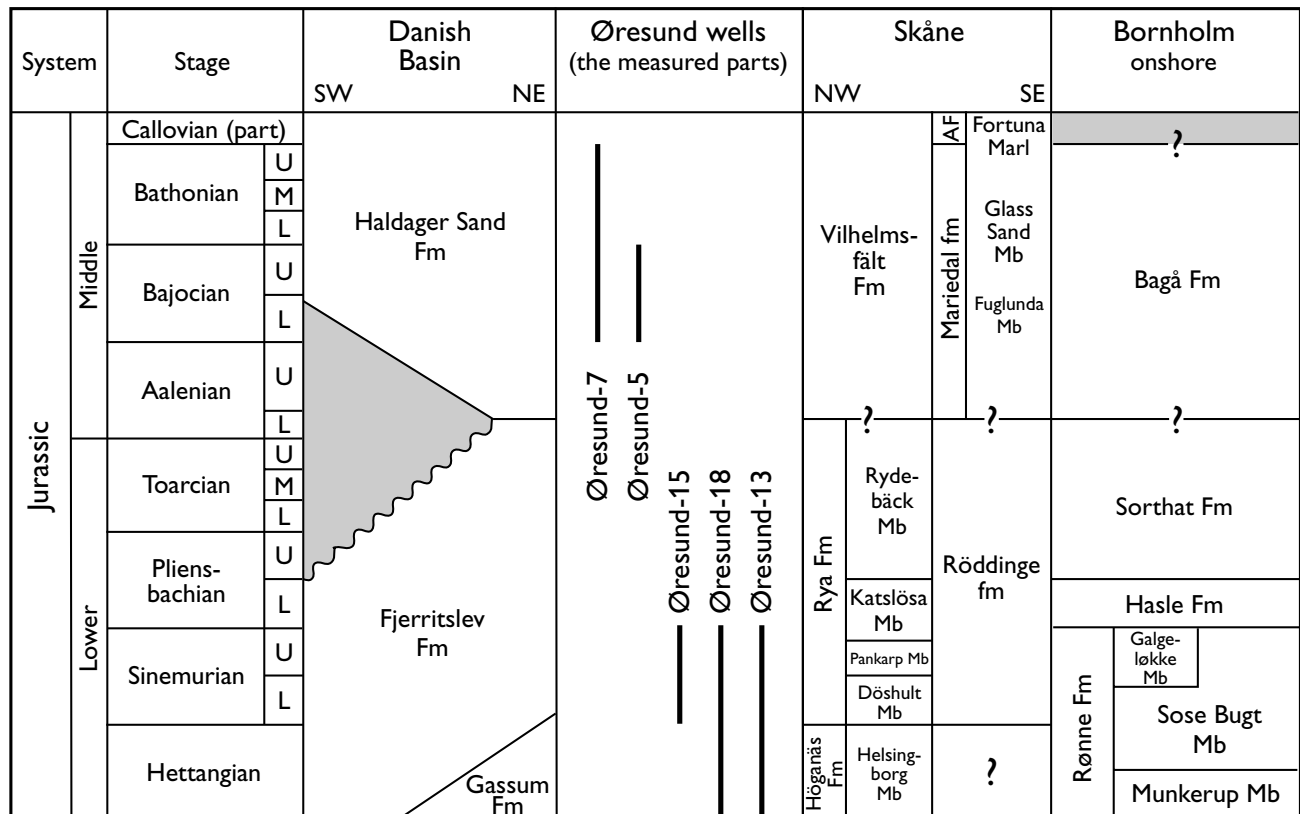

Fig. 2. The Lower and Middle Jurassic stratigraphy in the study area; **AF,** Annero Fm. Compiled from Michelsen (1978), Gravesen *et al.* (1982), Sivhed (1984), Ahlberg *et al.* (2003, this volume) and Michelsen *et al.* (2003, this volume). Note that the age range of the Øresund-5 and -7 wells is poorly constrained.
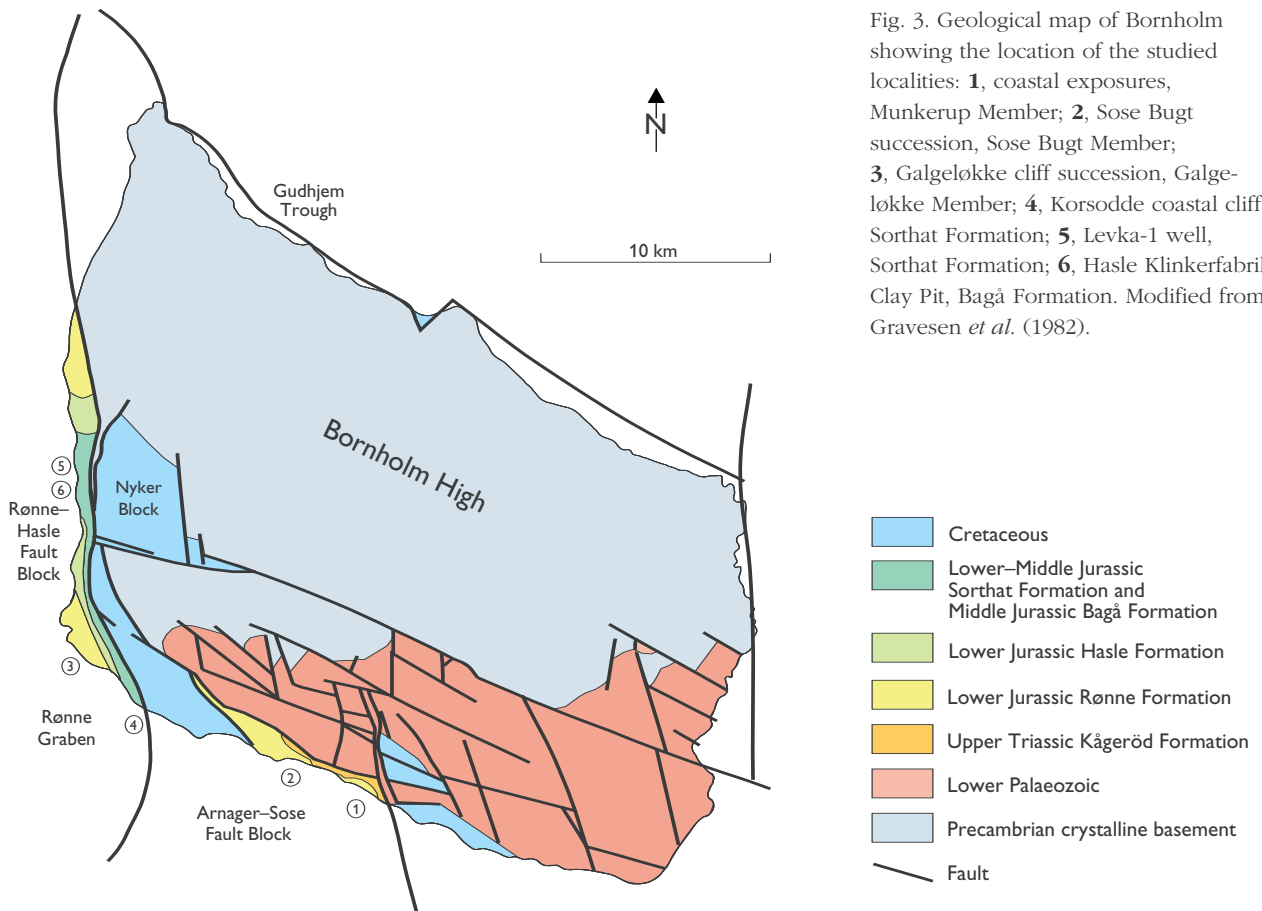
Fig. 3. Geological map of Bornholm showing the location of the studied localities: **1**, coastal exposures, Munkerup Member; **2**, Sose Bugt succession, Sose Bugt Member; **3**, Galgeløkke cliff succession, Galge-løkke Member; **4**, Korsodde coastal cliff, Sorthat Formation; **5**, Levka-1 well, Sorthat Formation; **6**, Hasle Klinkerfabrik Clay Pit, Bagå Formation. Modified from Gravesen *et al.* (1982).

Early–Middle Jurassic climate

Establishment of peat-forming mires and preservation of peat are mainly controlled by a complex interaction of climate, subsidence and eustasy. The breakup of Pangea and northwards drift of Laurasia during the Mesozoic into a warm-temperate to subtropical climatic zone at approximately 40°N, and the creation of a large epicontinental sea in northern Europe in the Jurassic, resulted in a substantial increase in humidity and rainfall compared to the hot and arid conditions that had dominated the Permian and most of the Triassic periods (Parrish *et al.* 1982; Ziegler 1982; Hallam 1984; Scotese 1994). The interaction of precipitation and temperature, and in particular seasonality of rainfall, has a strong influence on peat formation, because probably the single most important factor controlling peat distribution is continuity in rainfall (Ziegler *et al.* 1987; Calder & Gibling 1994; Lottes & Ziegler 1994). Seasonally wet conditions north of Tethys (western Europe) in

Jurassic times has been suggested by Hallam (1985), and reconstructed rainfall maps for the Pliensbachian suggest a moderate rainfall in the Danish region (Parrish *et al.* 1982).

Plant fossil assemblages from the Rhaetian and Lower Jurassic of Sweden, Germany, Bornholm and Jameson Land, East Greenland, indicate that the climate was sufficiently uniform to establish a northern floral province with relatively uniform plant communities (Harris 1937; Florin 1958). Warm conditions are suggested by the large number of plant species from Jameson Land, and thin cutinised leaves of *Podozamites* and Equisetales comparable in size to modern subtropical bamboos are thought to reflect favourable conditions for plant growth (Harris 1937). Investigations of clay mineralogy and palaeosols of the Jurassic on Bornholm indicate a warm, humid climate (Graff-Petersen & Bondam 1963; Arndorff 1993), and the taxonomic composition of miospore assemblages from the Hettangian–Sinemurian Sose Bugt section on Bornholm lends support to the interpretation

Levka-1

Gamma-ray

Gamma-ray

Shoreface

Lagoon

Lagoon

Lake

Swamp & lake

Fluvial channel

Crevasse delta

Lake

Lagoon

Shallow submerged inter-fluvial areas

Lake & swamp

Stacked crevasse deltas & swamps

Lagoon

Three stacked fluvial channel fills

Three stacked fluvial channel fills

Swamp

Lagoon

Shallow submerged inter-fluvial areas

Lake & swamp

Fluvial channel

Crevasse delta

Lake

Fluvial channel

Seam 6

Seam 4/5

Seam 3

Seam 2

Seam 15

Seam 12/13

Seam 9

m
100

110

120

130

140

150

160

m
20

30

40

50

60

70

80

90

Clay Si Sand 2 4 8 mm

Clay Si Sand 2 4 8 mm

Lithology
▬ Mudstone
▭ Siltstone
▱ Silty sandstone
▨ Sandstone
■ Coal

Sedimentary structures
〜 Erosional surface
▤ Horizontal bedding/ lamination
◸ Cross-bedding with mud drapes
◿ Cross-lamination
〜 Wave ripples
◿ Low-angle cross-bedding

⬳ Small-scale hummocky cross-stratification
◡ Flaser and wavy bedding
▤ Lenticular and silt-streaked bedding
▭ Load structure
Ⅴ Small-scale water escape structures
Ⴑ Synaeresis cracks
◿ Disturbed bedding

✳ Iron concretions
☆ Pyritic concretions
◗ Carbonaceous detritus

Biogenic structures
ᵴ–ᵴᵴᵴ Degree of bioturbation
⦶ Teichichnus
Ⓤ Diplocraterion
Ⓤ Equilibrichnia
〜 Horizontal burrows
⅄ Rootlets

Fossils
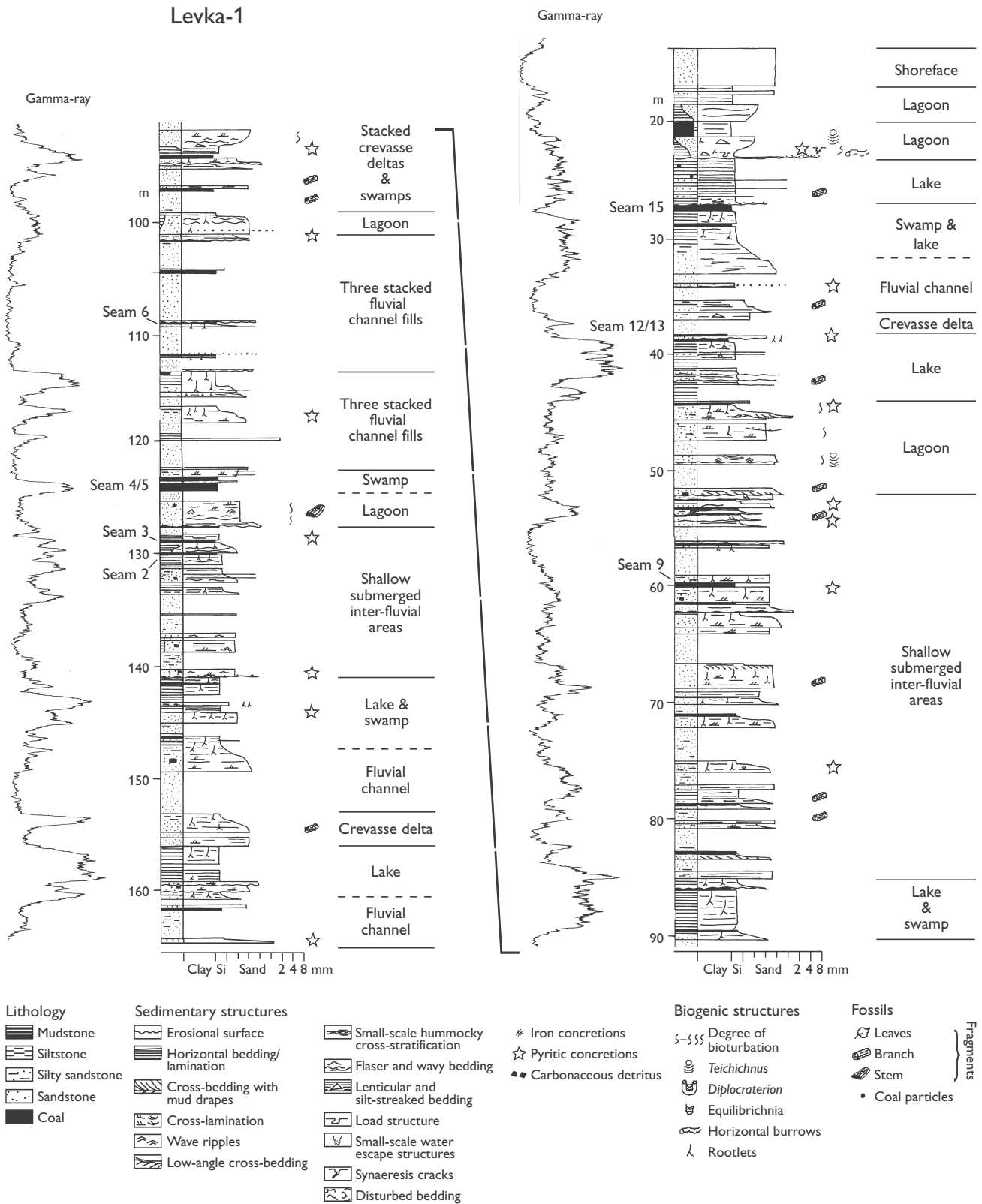⬳ Leaves
⬳ Branch
⬳ Stem
• Coal particles

Fragments

Fig. 4. Sedimentological core-log of the Upper Pliensbachian – Lower Toarcian part of the Sorthat Formation in the Levka-1 well (reference level: metres below surface). The investigated coal seams are indicated. The accompanying legend refers also to Figs 5, 10, 11, 14, 15. Intervals with no core recovery (lithology shown only) are interpreted on the basis of gamma-log data. Modified from Koppelhus & Nielsen (1994).
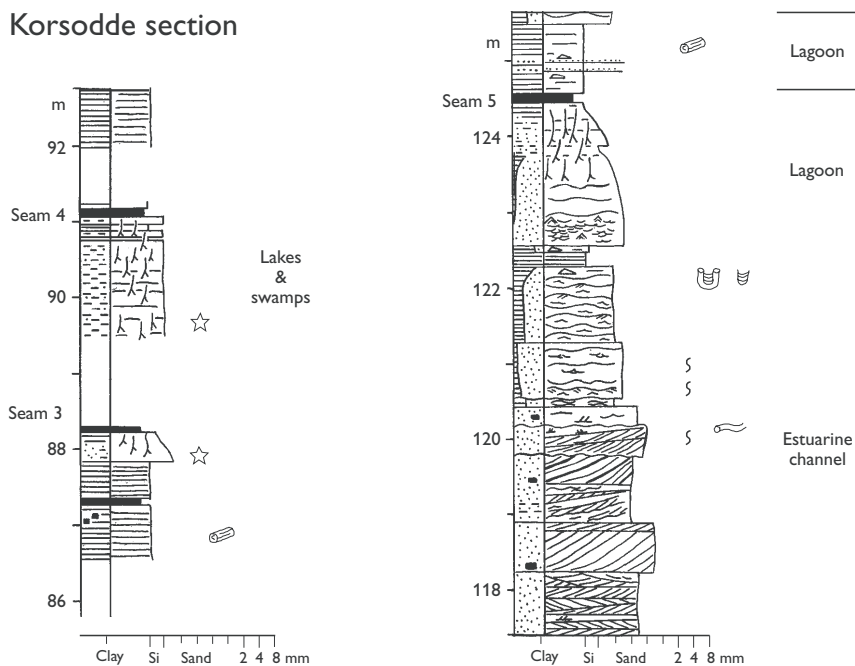
Korsodde section

Fig. 5. Sedimentological log of selected coal-bearing intervals from the Korsodde coastal cliff succession (Sorthat Formation); reference level: metres above base of section. Modified from Koppelhus & Nielsen (1994); for legend, see Fig. 4.

of a wetter climate, in particular compared to areas further to the west, for example around the British Isles (Batten *et al.* 1994). However, seasonal variations are indicated by annual rings in tree trunks from the Rhaetian of Skåne (Ahlberg & Arndorff 1994), in gymnospermous wood from Jameson Land (Harris 1937), and in tree-stumps from the Hettangian and Bajocian–Bathonian on Bornholm (Höhne 1933; Nielsen 1995; Surlyk *et al.* 1995). Parts of the Hettangian–Sinemurian succession in the Øresund-18 and -15 wells are characterised by thinly-stratified light grey silty claystones and dark grey claystones or thin graded layers with a silty base and a darker, more clayey upper part. The thin layering may reflect seasonal fluctuations in sedimentation rates, possibly due to unevenly distributed rainfall through the year, as suggested by Hamilton & Tadros (1994) for similar stratified lacustrine mudstones with coal seams in the Gunnedah Basin, Australia.

Lower Jurassic coal-bearing strata

Sorthat Formation, Bornholm

Fully marine conditions prevailed in early Jurassic times over most of the Danish Basin (Michelsen 1975). On Bornholm, however, coastal plain environments lasted until the Late Sinemurian; a transgression caused deposition of marine sandstones in the Early Pliensbachian (Gravesen *et al.* 1982; Surlyk *et al.* 1995). A Late Pliens-

bachian regression re-established a coastal plain environment with peat-forming mires on Bornholm until the regional Early Toarcian sea-level rise caused a renewed transgression (Koppelhus & Nielsen 1994). The Upper Pliensbachian – Lower Toarcian sediments of the Levka-1 well and the lower part of the Korsodde section (included in the Sorthat Formation) were deposited in an overall coastal plain environment (Figs 3–5; Koppelhus & Nielsen 1994; Petersen & Nielsen 1995; Michelsen *et al.* 2003, this volume). The Levka-1 well section represents fluvial channels, floodplain areas with shallow lakes and lagoons, and small crevasse deltas (Fig. 4). Coalified wood fragments and stems occur frequently. Coal seams 2, 3, 6 and 9 represent peat-forming mires established on top of abandoned sandy channel fills and on heavily rooted crevasse and lake deposits in shallow inter-fluvial areas. Seams 4 and 5 represent peat accumulation on top of lagoonal sediments showing wave-ripples, wavy and flaser bedding, bioturbation and transported *Equisetites* stems. A well-oxidised palaeosol that developed upon the fill of a coastal lake, is overlain by seams 12 and 13 which are separated by a thin sandy, rooted parting. The clay of the lake-fill contains a palynomorph assemblage dominated by spores and pollen, together with a few acritarchs and *Tasmanites*. Seam 15 is interpreted to represent an infilled-lake peat mire.

The lower 133 m of the Korsodde section consists of fluvial channel sand interbedded with heterolithic fining-upwards units of clay and silt and laminated to

almost massive clay beds topped by coal seams that overlie rooted horizons (Fig. 5). The fining-upwards units contain pyrite nodules, coalified wood fragments, and mixed palynomorph assemblages of spores, pollen, acritarchs, freshwater algae and marine dinoflagellate cysts, and were deposited in small coastal lakes and protected lagoons (Batten *et al.* 1994; Koppelhus & Nielsen 1994).

Coal seam composition and peat-forming environments

The studied coal seams of the Sorthat Formation are between 0.08 and 0.57 m thick (Figs 4, 5). Those from the Levka-1 well and seam 4 from the Korsodde section are dominated by very high contents of huminite (seam-average ranges from 80–90 vol.%), and only minor amounts of inertinite, liptinite and minerals (Petersen & Nielsen 1995). Pyrite occurs in several of the seams. Seams 3 and 5 from the Korsodde section differ in petrographic composition from the rest of the investigated seams. Seam 3 contains significant amounts of minerals (seam-average 37 vol.%) and seam 5 contains a high proportion of inertinite (seam-average 30 vol.%). Both seams contain pyrite.

Reflected-light microscopic analysis of a sample from seam 2 in Levka-1 reveals that it contains 2 vol.% pyrite and 6 vol.% of other minerals (Petersen & Nielsen 1995). The composition of the inorganic components in the sample was further investigated by computer controlled scanning electron microscopy (CCSEM). Inorganic par-
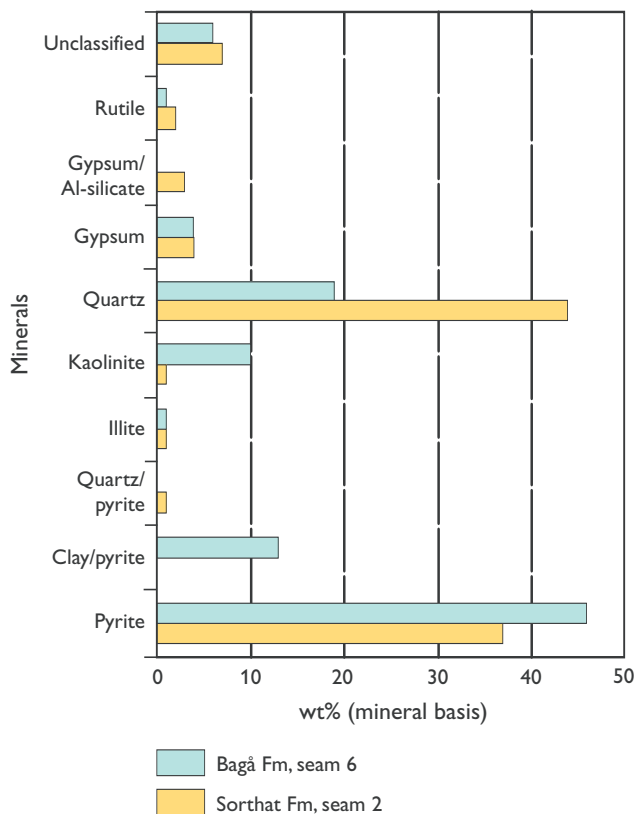

Fig. 6. Composition (wt% on a mineral basis) of the mineral matter in the upper part of seam 2, Sorthat Formation (Levka-1 well) and in seam 6 (interval 125–135 cm) in the upper Bagå Formation. The group 'unclassified' includes minerals which constitute less than 1 wt% of the inorganic fraction.
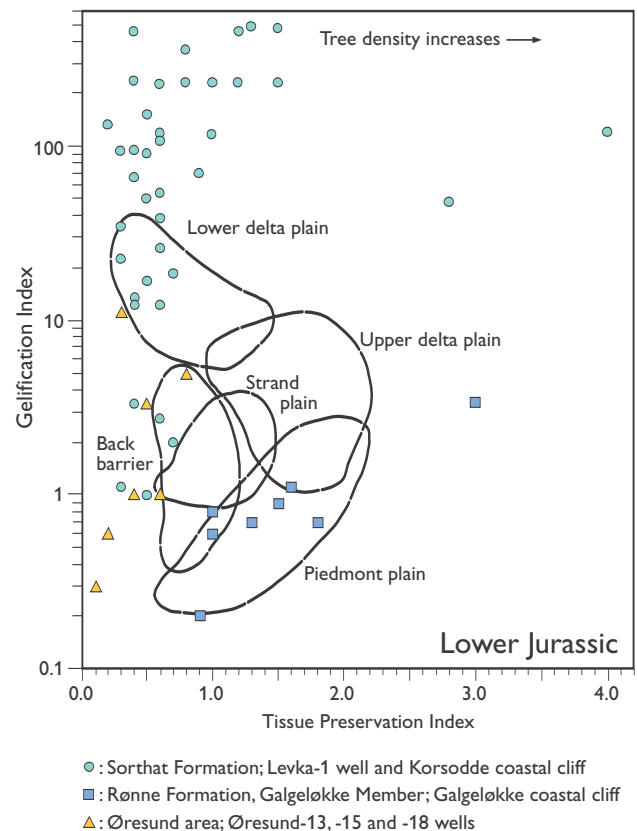

Fig. 7. Coal samples from the Lower Jurassic of Bornholm and the Øresund area plotted on the Tissue Preservation Index (TPI) vs. Gelification Index (GI) diagram of Diessel (1986). The strand plain area is after Kalkreuth & Leckie (1989; see also Diessel 1992). Notable are the low GI values of the Galgeløkke Member coal suggesting oxidizing conditions during deposition of the peat (domed bog), and the very high GI values of the Upper Pliensbachian – Lower Toarcian Sorthat Formation coals suggesting anoxic, waterlogged conditions during peat deposition.
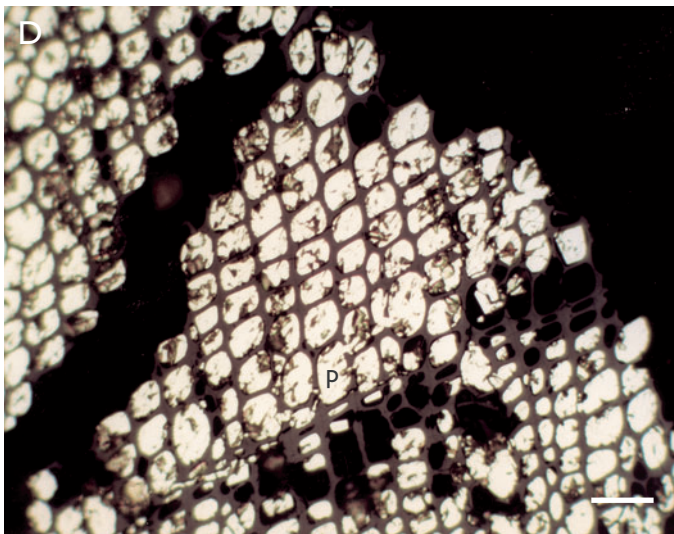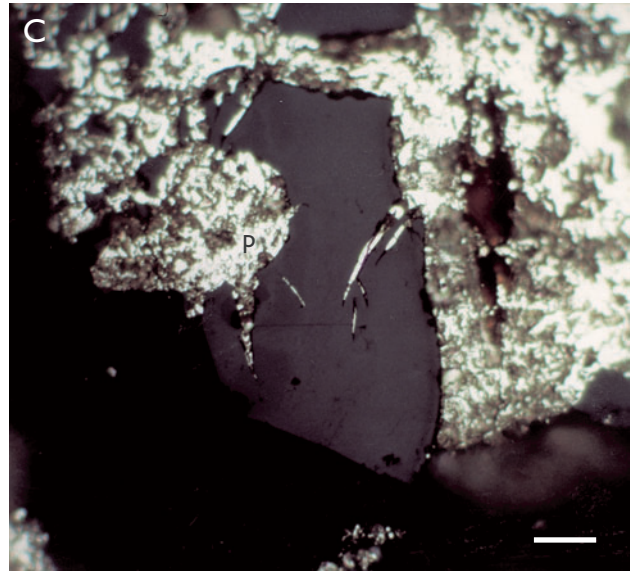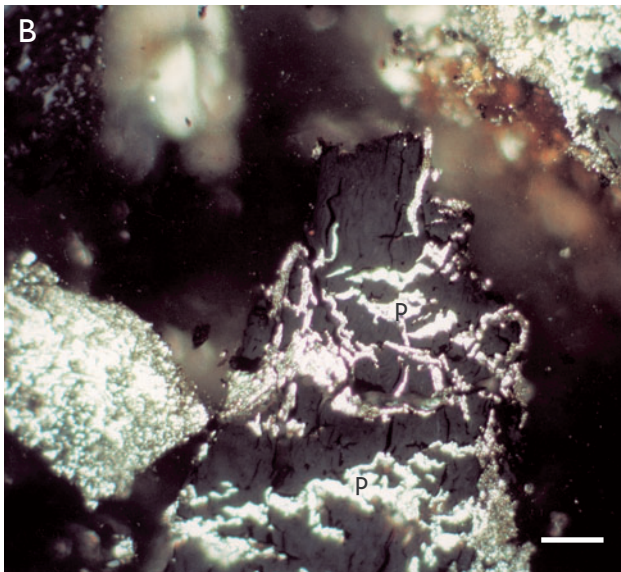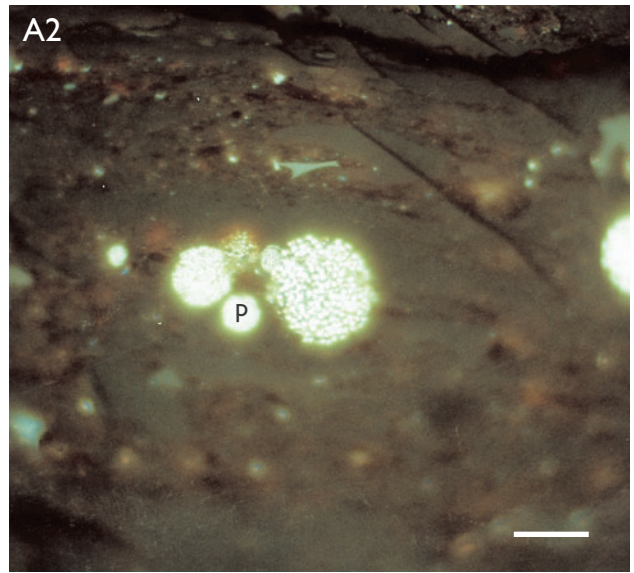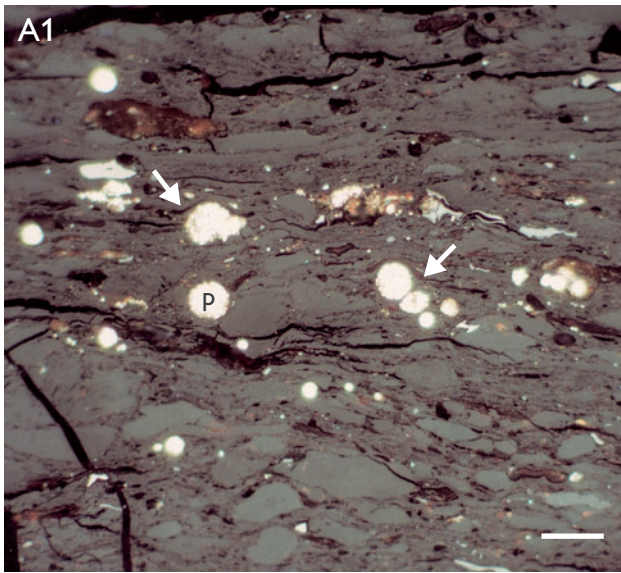
Fig. 8. Colour photomicrographs of pyrite (reflected white light, oil immersion, scale bar *c*. 30 µm, except A2: scale bar *c*. 20 µm). **A1**: Framboidal pyrite (**P**) in ulminite in coal seam 2, Sorthat Formation. Note how the sporinite (**arrows**) 'flows' around the pyrite, suggesting precipitation of the pyrite (syngenetic) prior to compaction (seam 2, sample 291934; Levka-1 well). **A2**: Framboidal pyrite (**P**) in the same sample. **B**: Pyrite (**P**) filling cleats in ulminite in seam 8 in the upper Bagå Formation, suggesting epigenetic pyrite precipitated after gelification of the organic matter (seam 8, sample B-9.2, Hasle Klinkerfabrik Clay Pit). **C**: Pyrite (**P**) filling cleats in macrinite in seam 8 in the upper Bagå Formation, suggesting epigenetic pyrite precipitated after gelification and oxidation of the organic matter (seam 8, sample B-9.2, Hasle Klinkerfabrik Clay Pit). **D**: Pyrite (**P**) precipitated in cell lumens in fusinite in seam 5, upper part of the Bagå Formation (seam 5, sample B-6.3, Hasle Klinkerfabrik Clay Pit).

ticles below 1 μm and organically bound elements are not detected. The CCSEM analysis indicates that the inorganic fraction is dominated by 45 wt% quartz with subordinate pyrite and minor proportions of gypsum and clay minerals (Fig. 6). In general, the quartz is in the size range of clay and silt with the major part being fine-grained silt (4–16 μm). The pyrite crystals are mainly within the size limits of silt followed by very fine-grained and fine-grained sand. Framboidal aggregates may account for the larger particles.

The peats accumulated mainly in anoxic and fully water-saturated freshwater mires as indicated by the very high content of humified organic matter in all of the seams in the Levka-1 section (high Gelification Index values, GI = huminite/inertinite, Fig. 7; Petersen & Nielsen 1995). The high content of humocollinite and the abundance of hopanoids in the coals indicate pronounced bacterial activity reflecting abundance of nutrients and a relatively high pH level (Teichmüller 1989; Waples & Machihara 1991; Peters & Moldowan 1993). The significant amounts of pyrite in seams 2 and 4 and minor amounts in several other seams suggest occasional brackish – marine influence on the mires (Cohen *et al*. 1984; Phillips & Bustin 1996a). The pyrite occurs in association with fusinite and inertinite, and as framboidal aggregates and minute crystals in huminite (Fig. 8A). It is interpreted to be mainly syngenetic. However, some of the pyrite, e.g. in seam 4, occurs infilling cleats in huminite and macrinite, thus suggesting that precipitation of pyrite also took place after gelification. The very small grain size of the mineral matter (clay to fine-grained silt) suggests that the mineral matter was deposited from suspension or may have been windborne.

Three coal seams, seams 3, 4 and 5, from the Korsodde succession have been investigated in detail (Fig. 5; Petersen & Nielsen 1995). Seam 4 is petrographically very similar to the seams from the Levka-1 well and represents a wet, anoxic, and probably rheotrophic, nutrient-rich peat-forming environment. The seam overlies sediments from a shallow, vegetated coastal lake, that occasionally was flooded by the sea. Seam 3 also overlies coastal lake deposits, and the high mineral content in the seam reflects the development of the lake into a frequently inundated open mire. A peat mire failed to develop although rootlets indicate that *in situ* plants contributed to peat accumulation. Seam 5 overlies a lagoonal unit and constitutes the final, regressive phase in the evolution of an estuarine complex. The precursor peat was subjected to desiccation, possibly linked to a decreased rate of watertable rise.

Palynological evidence of the peat-forming vegetation

Palynological analyses were carried out on five coal samples from seams 2 and 15 in Levka-1 and three samples from the sediment immediately below the coal seams. Although the parent plant affinities of palynomorphs from the Jurassic are uncertain in most cases, it has been possible to discriminate several groups of plants: ferns (pteridophytes) of the order Filicales (Class: Filicopsida), cycadophytes of the order Cycadales (Class: Gymnospermopsida), coniferophytes of the order Coniferales (Class: Gymnospermopsida), mosses (Division: Bryophyta), and microplankton-like acritarchs, marine green-algae (*Tasmanites* spp.) and a freshwater green-algae (*Botryococcus* spp.; Table 1).

The palynomorph assemblage of the sediment sample below seam 2 in the Levka-1 well is dominated by cycadalean pollen (*c*. 25%, *Chasmatosporites hians*, *C. minor*, *C. apertus*) and Jurassic species of the family Pinaceae (*c*. 50%, mainly *Cerebropollenites thiergartii*) (Table 1). The content of ferns is likewise pronounced (18%). Moving up to the two coal samples, several pollen types that have affinities with conifers disappear, while *Chasmatosporites hians,* whose affinity lies with the order Cycadales (van Konijnenburg-van Cittert 1971), and *Cerebropollenites thiergartii,* whose affinity lies with the family Pinaceae, increase significantly in number upwards in the seam (Cycadales and Pinaceae pollen increases to 14% and 19% in the uppermost sample, respectively). However, the pollen *Corollina torosus,* the affinity of which is considered to lie with the large conifer Cheirolepidaceae (Srivastava 1976) and which constituted an important part of the Jurassic coniferous forests (Stewart 1983), appears in the lower coal sample. The occurrence of these larger gymnospermous plants is in agreement with the considerable content of the maceral subgroup humotelinite in the lower coal sample. The diversity of spores whose affinities lie with the ferns, in particular the family Osmundaceae, increases from the underlying sediment up into the coal. In the lower coal sample, the proportion of ferns reaches 56%, suggesting a mire with a pronounced herbaceous vegetation. The generally high content of degraded organic matter (humodetrinite) in both coal samples correlates with a high proportion of these small plants. Spores related to mosses constitute a significant proportion of the coal assemblages. The palynomorph diversity is lower in the uppermost coal sample, possibly due to the influence of marine water as interpreted from the coal petrology and the occur-

Table 1. Peat-forming plants based on palynological evidence

Locality	Seam	Sample	Sample type	Filicopsida %	Lycopsida %	Gymnosperms % Cycadales	Coniferales P*	T†	G‡	Micro-plankton§ %	Bryophyta %	n*
Øresund-13	1	6368	coal	64.3	5.1	3.5	11.2	0.5	15.4	0	0	196
	2 cm below seam 1	247948	black clay	14.0	4.2	13.5	19.2	8.2	37.9	3.0	0	209
Øresund-18	4 cm above seam 1	247943	clay/silt	5.1	6.2	1.1	10.7	14.1	58.2	4.6	0	178
	1	6371	coal	16.0	2.5	7.3	14.1	25.6	33.5	0.5	0.5	206
	1	6373	coal	23.7	1.7	5.1	8.5	30.5	23.7	1.7	5.1	59
	1	6372	coal	41.7	0	16.7	0	8.3	16.6	12.5¶	4.2	24
	1	6369	coal	0	0	0	40.0	0	40.0	0	20.0	5
	2 cm below seam 1	247944	light clay	73.9	0	4.3	0	0	5.9	14.4	1.5	69
	4 cm below seam 1	247945	light clay	71.4	0	4.4	1.1	3.3	11.0	4.4	4.4	91
	2	6375	coal	61.4	2.6	1.3	18.6	1.3	14.8	0	0	75
	2	6374	coal	46.0	9.8	2.0	6.9	2.0	32.3	1.0	0	102
	2 cm below seam 2	247947	dark clay	20.3	8.8	14.7	10.4	4.7	36.0	5.1	0	193
Levka-1	2	291934	coal	10.8	0	13.5	18.9	0	32.5	5.4	18.9	37
	2	291932	coal	56.1	0	8.4	6.3	6.3	12.5	0	10.4	48
	3 cm below seam 2	247938	coaly clay	18.0	0	24.6	50.2	0.6	6.6	0	0	167
	15	6386	coal	33.3	0	28.5	12.4	4.9	19.7	0	1.2	81
	15	6383	coal	24.5	0	40.0	11.1	3.3	14.4	0	6.7	90
	15	6379	coal	28.9	0	42.0	8.1	1.6	11.3	0	8.1	62
	2 cm below seam 15	247940	clay	43.5	0	11.9	33.7	2.0	8.9	0	0	202
	3 cm below seam 15	247941	clay	43.4	0	18.2	31.5	0.5	6.4	0	0	203
Bagå Clay Pit	1	B-1.1	coal	62.7	13.2	0	14.2	0	5.5	0	4.4	91
	2	B-2.1	coal	31.3	9.7	0	25.7	8.3	20.8	0	4.2	144
	3	B-3.2	coal	50.9	10.5	0	12.3	0	24.6	0	1.7	57
	3	B-3.1	coal	54.1	16.2	0	2.7	2.7	21.6	2.7	0	37
	4	B-4.1	coal	53.3	22.3	0	22.2	0	2.2	0	0	45
	5	B-6.9	coal	24.7	31.1	0	24.6	0	19.6	0	0	61
	6	B-7.2	coal	30.7	3.6	0	19.8	0	45.9	0	0	111
	few cm below 6	B-7.1	black clay	36.2	21.3	0	27.5	0	12.5	0	2.5	80

* Pinaceae.
† Taxodiaceae.
‡ Other gymnospermous pollen.
§ Mainly acritarchs, some *Tasmanites* and *Botryococcus*.
¶ Three dinoflagellates.
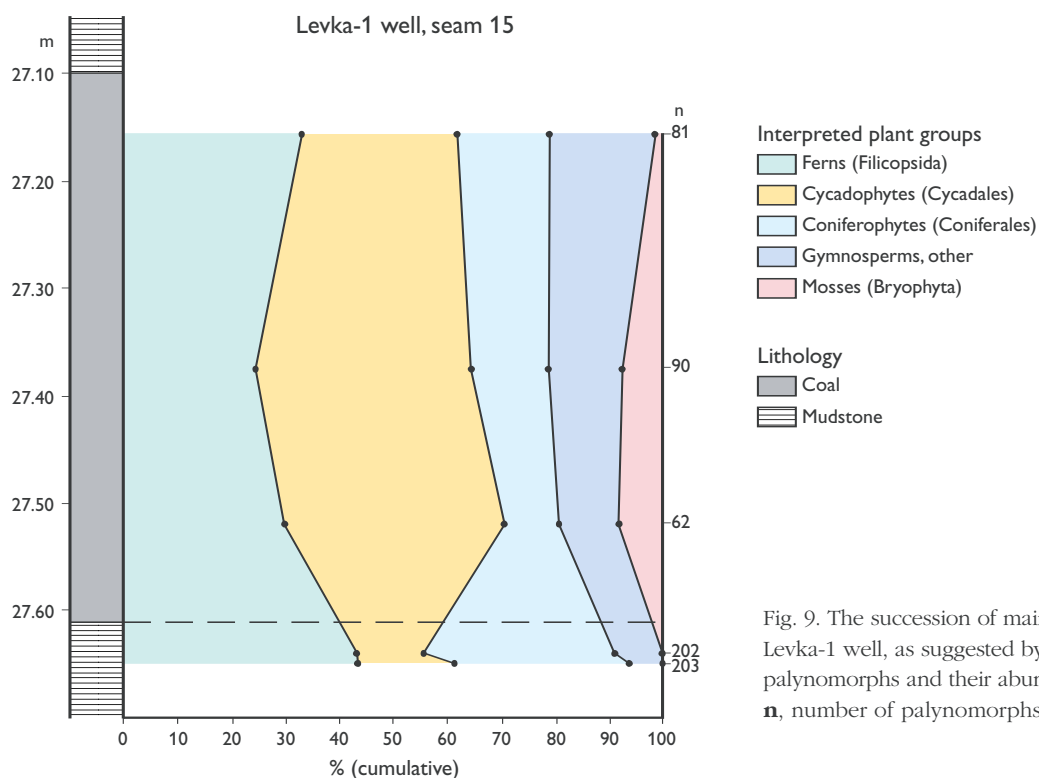★ Number of palynomorphs counted.

Fig. 9. The succession of main plant groups in seam 15, Levka-1 well, as suggested by the botanical affinities of palynomorphs and their abundance in percentages. **n**, number of palynomorphs counted.

rence of a probable acritarch species (*Lecaniella foveata;* Batten *et al.* 1994; Petersen & Nielsen 1995).

The clay samples taken immediately below seam 15 in the Levka-1 well contain a significant content of the same pollen species identified in seam 2 whose affinities lie with the order Cycadales and Jurassic species of the family Pinaceae (Fig. 9; Table 1). Fern spores are present below seam 15 in considerable amounts (43%, mainly *Deltoidospora* spp.), and the diversity of spores related to ferns is greater than in the sediment sample below seam 2. The most pronounced changes in the palynomorph assemblages in seam 15 compared to the underlying sediment are a significant decrease in the proportion of pollen whose affinities are with the family Pinaceae, a decrease in the amount of fern spores, and a considerable increase in the proportion of pollen whose affinities are with the cycadophytes (Fig. 9; Table 1). Despite differences in types and amounts of the recorded pollen species among the three coal samples in seam 15, they display a rather uniform composition. The coal petrographic composition is also uniform, conforming with studies on recent peat deposits, which have shown a correlation between peat vegetation and peat composition (Cohen & Spackman 1977; Phillips & Bustin 1996b). Thus, the mire vegetation may have been dominated by gymnospermous plants and a secondary proportion of ferns characterised by the genera *Dicksonia* or *Coniopteris* and the family Osmundaceae (Tralau 1968; van Konijnenburg-van Cittert 1978). This might correlate with the dominance of humotelinite over humodetrinite in the seam. The lowermost coal sample has both the smallest amount of gymnospermous pollen and the lowest proportion of humotelinite of the three coal samples. In general, the palynomorph assemblages suggest that the peat-forming vegetation of seam 15 was of higher diversity than that of seam 2, which may be explained by the influence of saline water in the precursor mire of seam 2.

Duration of peat formation

The compaction ratio for peat to bituminous coal varies between 4.1:1 and 30:1 (Ryer & Langer 1980). A peat:coal compaction ratio of 10:1 may be assumed for the sub-bituminous coals in this study (see also McCabe 1991). The tropical Batang Hari River peat deposit in Sumatra has an accumulation rate of *c.* 1.8 mm/yr, whereas the cold temperate peat deposit in Maine has been accumulating at a rate of *c.* 0.6 mm/yr (Cameron *et al.* 1989). An average accumulation rate of 1 mm/yr may thus be

a reasonable assumption for the warm temperate to subtropical Jurassic climate. Using this assumption, the Late Pliensbachian – Early Toarcian peat-forming mires on Bornholm existed between 800 and 5700 years, with an average of *c.* 2300 years.

Other Lower Jurassic coal-bearing strata in the Fennoscandian Border Zone

Hettangian–Sinemurian mires are represented by coal and coaly mudstones within the Munkerup Member and the Sose Bugt Member of the Arnager–Sose Fault Block on the south coast of Bornholm (Figs 2, 3). The poorly exposed Munkerup Member consists primarily of lake deposits (Gry 1969; Gravesen *et al.* 1982; Koppelhus 1991). Periodically, the lacustrine environment developed into mires. Increasing deoxygenation of the lakes and encroachment of vegetation is evident
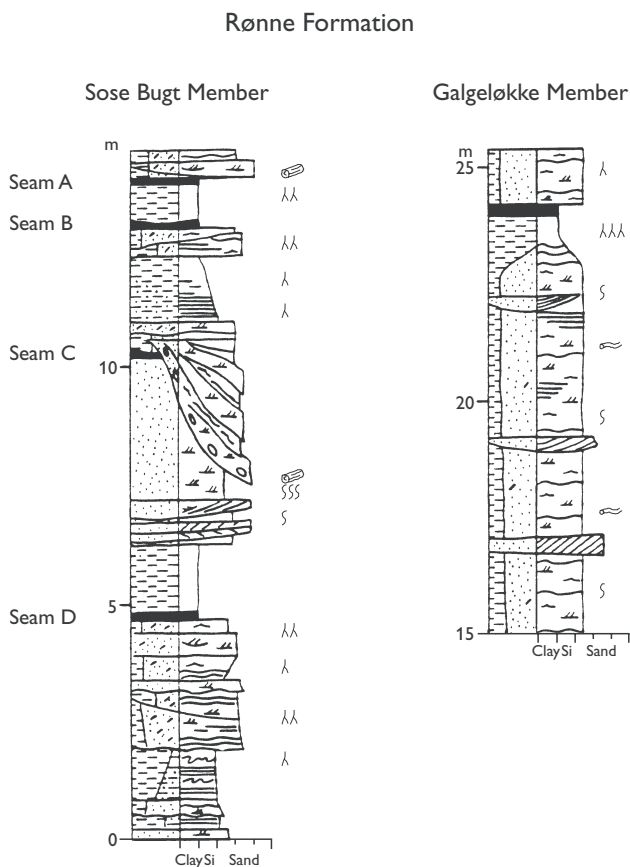

Fig. 10. Sedimentological log of the coastal Sose Bugt succession (Hettangian–Sinemurian Sose Bugt Member) and Galgeløkke cliff section (Sinemurian Galgeløkke Member). After Gravesen *et al.* (1982); section heights refer to the original sections of Gravesen *et al.* (1982). For legend, see Fig. 4.
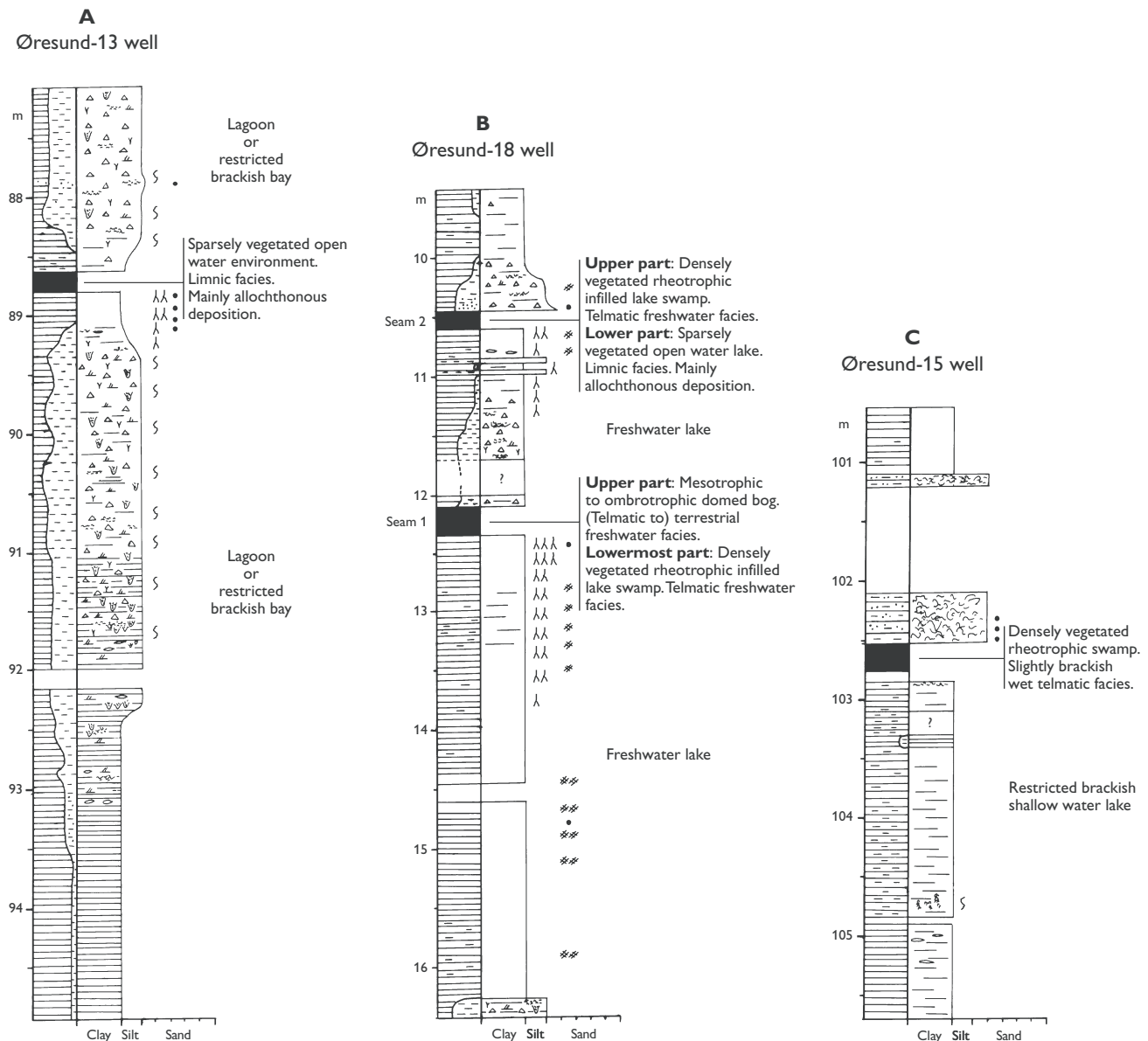
Fig. 11. **A**: Sedimentological core-log of the studied Hettangian–Sinemurian part of the Øresund-13 well. **B**: Sedimentological core-log of the studied Hettangian–Sinemurian part of the Øresund-18 well. **C**: Sedimentological core-log of the studied Sinemurian part of the Øresund-15 well. Modified after Petersen (1994); reference level: metres below sea level. For legend, see Fig. 4.

from the gradual transition from clayey, rooted sediments to the overlying coaly mudstones. The coaly mudstones are inertinite-rich, contain pyrite, and are to a large extent allochthonous, reflecting deposition in freshwater to brackish, open water environments (Petersen 1993). The Sose Bugt Member consists of lacustrine, fluvial, lagoonal, and restricted marine shoreface to offshore sediments (Figs 2, 3, 10; Surlyk *et al.* 1995). The occurrence of marine palynomorphs at certain levels within the terrestrial part of the succession indicates occasional marine incursions. The four 0.12–0.30 m thick, mainly allochthonous, mineral-rich coaly mudstones were deposited in shallow lakes on a coastal plain

(Petersen 1993; Surlyk *et al.* 1995). The mires developed largely under freshwater conditions, but may have periodically been influenced by marine water.

In the neighbouring Rønne–Hasle Fault Block, the Rønne Formation is dominated by lagoonal units with coal seams deposited in an overall coastal plain environment (Nielsen 1995). The exposed section of the Sinemurian Galgeløkke Member consists of sandy and muddy lagoonal, tidal flat and tidal channel complex deposits (Figs 3, 10; Sellwood 1972; Gravesen *et al.* 1982). An inertinite-rich coal seam, 0.10–0.35 m thick, overlies wavy- and flaser-bedded tidal flat heteroliths. The seam represents a dominantly freshwater peat bog

with a domed surface (Fig. 7, GI values < 1), implying a significant change from the tidal flat environment that prevailed prior to peat formation (Petersen 1993), and the possible presence of a diastem below the coal seam. Siliciclastic deposition may have occurred contemporaneously nearby, but the elevated peat surface hindered flooding of the peat deposit (e.g. Staub & Esterle 1994; Phillips & Bustin 1996b). The high content of well-preserved pyrofusinite, which represents fossil charcoal (Scott 1989), indicates that wildfires occurred in the bog. This resulted in a high inertinite content in the seam as shown by low GI values in the TPI versus GI diagram (Fig. 7). The coal seam contains small amounts of pyrite towards the top, which probably was precipitated due to migration of sulphate ions into the peat from the overlying brackish sediments after peat formation was terminated.

Similar paralic depositional environments existed in the Øresund area in Hettangian–Sinemurian times (Fig. 1). The bioturbated heteroliths underlying a 0.18 m thick, inertinite- and mineral-rich coal seam in the Øresund-13 well represent deposition in a shallow, restricted bay or lagoon (Fig. 11A ; Petersen 1994). After the shallow area was filled, it became vegetated and accumulation of mainly allochthonous organic matter resistant to degradation during transportation took place in an open freshwater mire. Both seams 1 (0.25 m) and 2 (0.15 m) in the Øresund-18 well overlie lake fill sediments (Fig. 11B; Petersen 1994). The presence of rooted claystones below the seams demonstrates that the gradual fill of the lakes promoted plant growth. Both seams represent rheotrophic, probably nutrient-rich freshwater mires, although the precursor peat of seam 1 may temporarily have evolved to a more domed state.

Sinemurian coal-bearing strata occur in the Øresund-15 well, and the claystones underlying the coal seam were deposited in a shallow, weakly brackish lake situated in a coastal plain (Fig. 11C). The preserved stratification and absence of trace fossils suggest a poorly oxygenated sediment. The 0.16 m thick, huminite-dominated coal seam represents an occasionally slightly brackish, nutrient-rich swamp established on top of the lake-fill.

A *c*. 3 cm thick coaly mudstone occurs in the uppermost Lower Jurassic in the Skagen-2 well in north Jylland (referred to as the Fjerritslev Formation by Michelsen 1978). The coaly mudstone represents an allochthonous deposit, which is emphasised by the high content of the mineral-rich microlithotype carbominerite (71 vol.%), microlaminated detrital macerals, and macerals resistant to degradation during transportation (inertinite: 39 vol.%; liptinite: 9 vol.%). Oxidised cutinites may reflect oxidation of the organic matter during transportation. The occurrence of pyrite (2 vol.%) suggests that the open water environment was brackish or periodically influenced by marine water. The peat mire was situated in a coastal environment, consistent with the position of the bed within a thin unit that correlates with transgressive marine mudstones further to the west (i.e. basinwards; Nielsen 1995).

Palynological evidence of the peat-forming vegetation in the Øresund area

A total of twelve samples were analysed from the Øresund-13 and -18 wells; these comprise seven coal samples, four samples from the sediment immediately below the coal seams, and one sample immediately above a seam. In addition to the plant groups mentioned from the Sorthat Formation coals, club mosses (Class: Lycopsida) were identified in these coals (Table 1).

A sample was taken from the coal seam in the Øresund-13 well and from the black clay about 2 cm below the seam. The latter shows a higher diversity than the coal sample. Acritarchs (*Lecaniella foveata*, *Leiosphaeridia* spp. and a possible *Cymatiosphaera* spp.), *Tasmanites* spp. and a possible dinoflagellate cyst (? *Mancodinium semitabulatum*) occur only in the sediment sample. This is consistent with the interpretation of the sedimentary environment as a lagoon or brackish restricted bay and the seam as a freshwater deposit (Petersen 1994). Spores related to ferns, in particular *Deltoidospora* spp., whose affinities lie with the two fern genera *Coniopteris* or *Dicksonia* (Tralau 1968), are common in the clay. However, coniferalean and cycadalean pollen are more abundant. Bisaccate species and a pollen of unknown affinity are also abundant. In combination, the pollen related to gymnosperms constitute 78% of the palynomorph assemblage in the clay sample (Table 1).

In contrast, in the coal sample the proportion of gymnosperm pollen is only 31%. In particular, the proportions of the species *Chasmatosporites hians* and *Perinopollenites elatoides*, whose affinities are with the Cycadales and the coniferophyte family Taxodiaceae (Guy-Ohlsson 1986) respectively, are significantly lower. However, spores whose affinities lie with the order Lycopodiales, the fern genera *Dicksonia* and the fern family Osmundaceae (van Konijnenburg-van Cittert 1978) are more abundant. In total, the proportion of fern-related spores increases to approximately 64% in the coal sample. Thus, the palynomorphs indicate a change
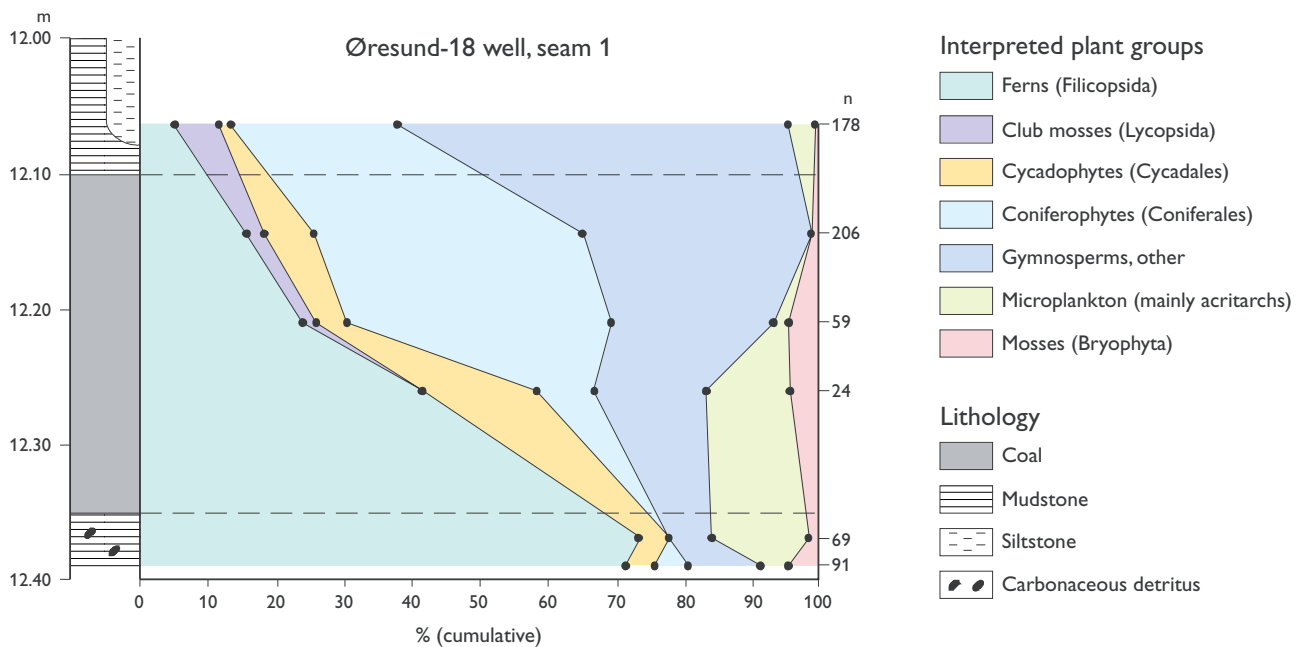
Fig. 12. The succession of main plant groups in seam 1, Øresund-18 well, as suggested by the botanical affinities of palynomorphs and their abundance in percentages. **n**, number of palynomorphs counted.

in the composition of the vegetation from the silici-clastic environment to the mire environment. The sparse mire vegetation probably consisted to a large extent of herbaceous plants.

The sediment samples below seam 1 in the Øresund-18 well are dominated by fern spores (71–74%, mainly *Deltoidospora* spp.) and up to 15% acritarchs (Fig. 12; Table 1). Upwards through the coal seam, spores related to ferns decrease and constitute only 16% in the uppermost sample. Club mosses (*Retitriletes clavatoides*) were probably present in the late peat stages corresponding to slightly wetter conditions. Most notable compared to the underlying clay is the significant content of taxodiaceous pollen (*Perinopollenites elatoides*) and bisaccate pollen related to unknown gymnosperm plants. Pollen and spores also show that plants belonging to the Cycadales (*Chasmatosporites hians*, *C. apertus*), the Pinaceae (*Pinuspollenites minimus*, *Cerebropollenites macroverrucosus*, *C. thiergartii*), and the Bryophyta constituted parts of the original mire vegetation (Fig. 12; Table 1). An evolutionary link between the parent plant of *C. macroverrucosus* and the extant *Tsuga* has recently been suggested, although the parent plant of the former probably became extinct during the Cretaceous (Batten & Dutta 1997). Acritarchs and dinoflagellates are present. The composition of the vegetation cannot be directly correlated to the maceral composition of the seam, which may be due to the

high proportion of oxidised organic matter (inertinite), particularly inertodetrinite. The occurrence of club mosses in the upper part of the seam may correspond to a return to more wet and nutrient-rich conditions, which would be consistent with the increased content of mineral matter. In contrast, the occurrence of microplankton in the seam is of particular interest. No indications of saline water influence, such as pyrite, have been observed in the seam, and the sediments have been interpreted as freshwater deposits (Petersen 1994). However, the occurrence of acritarchs suggests, at least temporarily, brackish conditions. On the basis of the palynomorph assemblage, the mire may have been covered with a dominantly gymnospermous vegetation and a significant, subordinate proportion of ferns and club mosses.

Spores (mainly *Deltoidospora* spp.) probably derived from ferns increase from *c*. 20% in the dark clay immediately below seam 2 in the Øresund-18 well to 61% in the upper part of the seam, whereas the proportions of cycadalean pollen and pollen with unknown gymnosperm affinities decrease significantly upwards (Table 1). The contribution of the Taxodiaceae family was much less important in the precursor mire of seam 2 than in that of seam 1. The mire may have been characterised by a prominent herbaceous vegetation, and the highest proportion of spores derived from club mosses occurs in the lower part of the seam representing wet,

open-water conditions. The contribution of plant tissue from ferns together with club mosses in the precursor mire is compatible with the high content of detrital organic matter (humodetrinite) in the coal.

Duration of peat formation

The coaly mudstones from the Sose Bugt Member are very low in rank (Petersen *et al.* 2003, this volume), and a compaction ratio of 4:1 for peat:lignite (Esterle & Ferm 1994) may provide a better estimate than that adopted for the sub-bituminous coals (see above). Using this value and ignoring the relatively high content of mineral matter, the original carbonaceous deposits were between 0.5 and 1.2 m thick, and organic matter accumulation lasted for about 500–1200 years. The Hettangian Munkerup Member is located in the same fault block as the Hettangian–Sinemurian Sose Bugt Member. The boundary between the two members is not exposed (Gry 1969; Gravesen *et al.* 1982), but the thickness of the sediment package between the seams of the two members is insignificant with regard to coalification. Thus, although the Munkerup Member coals yield higher reflectance values than the Sose Bugt Member seams (Petersen *et al.* 2003, this volume), the 4:1 compaction ratio is also applied to the Munkerup Member coals. Using this compaction ratio, the original peat deposits of the Munkerup Member were also between 0.5 and 1.2 m thick, and peat accumulation lasted for about 500–1200 years. The original peat deposit represented by the coal seam in the Galgeløkke coastal cliff section in the Rønne Graben had a maximum thickness of 3.5 m (peat:coal compaction ratio: 10:1), corresponding to 3500 years of peat accumulation. On average, the mires represented by the investigated seams in the Rønne Formation thus existed for *c.* 1200 years.

Assuming a 10:1 compaction ratio for the Lower Jurassic coal seams in the Øresund area, the original peat thickness was 1.5–2.5 m and the duration of peat accumulation was 1500–2500 years. On average, the peat mires existed for 1850 years.

Middle Jurassic coal-bearing strata

Bagå Formation, Bornholm

The lower to middle part of the Bagå Formation in the Hasle Klinkerfabrik Clay Pit is a heterogeneous, clay-rich succession about 60 m thick that is characterised by stacked units (*c.* 10 m thick) of laminated, grey – dark grey clay with silt and sand laminae and subordinate beds of cross-bedded or laminated sandstones, often showing rootlets (Koppelhus & Nielsen 1994). These units are separated by coaly mudstones or coal seams, associated with rooted horizons that record the periodic establishment of peat-forming mires. Fossil plant fragments, small logs, stems, and leaves are common in the clay. The palynomorph assemblages are all non-marine and dominated by pteridophyte spores and gymnosperm pollen (Hoelstad 1985; Koppelhus & Nielsen 1994), and the total sulphur content in the coaly mudstones and coal seams is generally less than 0.80 wt%, indicating a freshwater environment (Casagrande 1987). Thus, the clay was deposited in freshwater lakes, which were gradually filled and transformed into open-water or peat-forming freshwater mires. The sand beds represent crevasse splays and channel deposits. The upper part of the Bagå Formation becomes more sandy, with some very poorly sorted sand beds, occasionally with large kaolinised granite boulders deposited by debris flows that originated from the granite horst located immediately to the east (Gry 1969; Gravesen *et al.* 1982; Nielsen 1995). Pyrite nodules are common in the sand beds. Based on the clastic facies and the proximity to the major graben fault against the granitic basement, a small alluvial fan environment with deposition from sheet wash and mud flows is envisaged.

Coal seam composition and peat-forming environments

Eight coal seams, 0.05–1.90 m thick, have been investigated in the upper part of the Bagå Formation (seams 1–8 of Petersen 1993). The seams are petrographically complex, with varying amounts of inertinite (1–72 vol.%; 74% of the studied coal samples contain 20–60 vol.%) and huminite (16–89 vol.%; 71% of the studied samples contain more than 30 vol.%), and often a considerable content of minerals (2–57 vol.%; 57% of the studied samples contain 10–20 vol.%; Petersen 1993). Fusinite is a prominent component of the inertinite maceral group (up to 41 vol.%). Pyrite occurs in seven of the eight seams. Framboidal pyrite has not been observed, although in several of the seams significant amounts of pyrite (up to 36 vol.%) fill cell-lumens of fusinite, occur as massive pyrite or fill cleats in gelified organic matter (Fig. 8B, C, D; Petersen 1993).

Analysis of a sample from seam 5 by CCSEM shows that the inorganic fraction is dominated by pyrite (46 wt%),
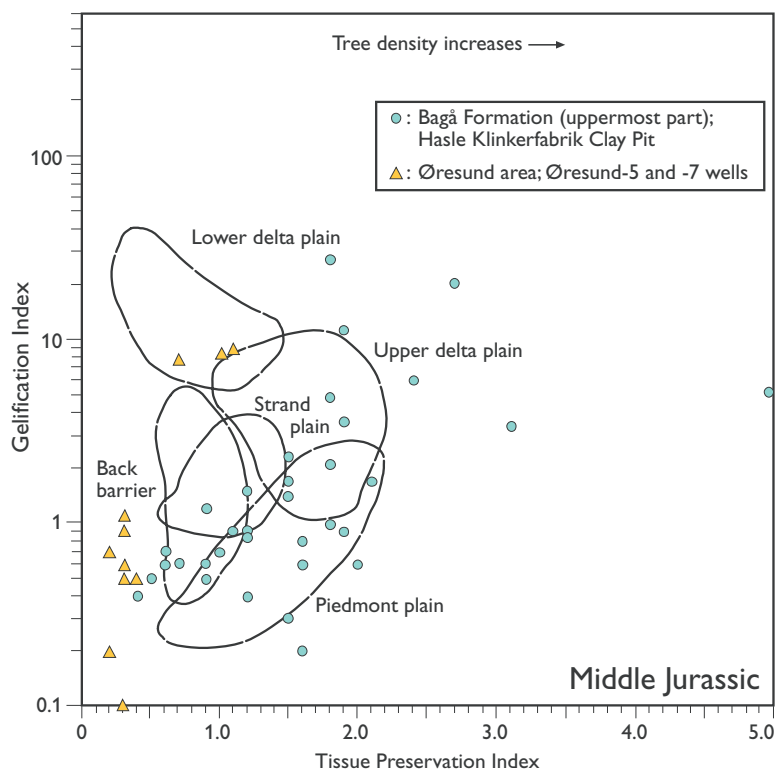
Fig. 13. Coal samples from the Middle Jurassic on Bornholm and the Øresund area plotted on the TPI vs. GI diagram (Fig. 7). Most of the samples from the upper Bagå Formation plot within the field of the piedmont plain.

followed by quartz (19 wt%), clay associated with pyrite (13 wt%) and kaolinite (10 wt%; Fig. 6). The majority of the quartz is in the grain-size range of silt (in particular coarse silt, 32–64 μm), to fine-grained sand, whereas most of the pyrite is of fine-grained sand grade.

The eight coal seams from the upper part of the Bagå Formation were formed in freshwater swamps, that occasionally were established on the alluvial plain. The occurrence of several well-defined root horizons below a thick coal seam (seam 5 of Petersen 1993) indicates repeated episodes of siliciclastic deposition followed by colonisation of the sediments by plants. A level coloured by humus substances below each root horizon was possibly formed by a low-standing watertable, which together with the petrography of seam 5 imply an unstable watertable. Most of the samples from seam 5 plot in the field of the piedmont plain in the TPI versus GI diagram (Fig. 13), consistent with the alluvial fan interpretation. Varying amounts of detrital minerals in the seams is attributed to periodic outwash from the nearby granitic horst. In addition to pyrite and clay associated with pyrite, the inorganic fraction in the 125–135 cm interval in seam 5 is characterised by quartz, primarily of coarse silt to fine-grained sand size, and kaolinite. The comparatively high content of kaolinite is probably related to the proximity of the mires to the weathered granitic basement of the Bornholm High to the east. A large proportion of impure coals and an abundance

of inertinite-rich lithotypes occur in piedmont coal seams in the Springhill coalfield of Nova Scotia, where peatlands were nourished by groundwater discharge from alluvial fans and basin-margin fault-fed springs (Calder 1993, 1994). A similar small-scale scenario is envisaged for the sand-dominated, upper part of the Bagå Formation. Formation of dull coals due to severe oxidation in the piedmont plain setting has also been noted by Diessel (1986), and most of the upper Bagå Formation coals contain much inertinite. The inertinite may have formed due to a fluctuating watertable in the precursor mires, an inertinite-forming process known from recent peat-forming environments (Cohen & Stack 1996; Moore *et al*. 1996). Fluctuations were probably related to seasonality as indicated by the occurrence of annual rings in wood from the coal seams in the Bagå Formation (Höhne 1933). A peat-forming flora dominated by cellulose-rich plants (shrubs, herbs) is suggested by the maceral composition.

Palynological evidence for the peat-forming vegetation

Seven coal samples and one clay sample were analysed from coal seams 1–6 (Petersen 1993) in the upper part of the Bagå Formation. It is possible to discriminate several plant groups: ferns (Order: Filicales; Class:

Filicopsida), club mosses (Class: Lycopsida), coniferophytes (Order: Coniferales; Class: Gymnospermopsida) and mosses (Division: Bryophyta; Table 1). Pollen related to cycadophytes were not found, although Höhne (1933) identified cycadophytes in the coals.

A sample from the lowermost part of seam 1 is characterised by a high diversity of spores, which are related to ferns of the family Osmundaceae and the genera *Dicksonia* or *Coniopteris* (Tralau 1968; van Konijnenburg-van Cittert 1978), to the orders Lycopodiales and Selaginellales, and to bryophytes. Fern-related spores constitute 63% and club mosses 13% of the assemblage (Table 1). Pollen whose affinities lie with the Cheirolepidaceae and Pinaceae are also present. Compared to seam 1, seam 2 is characterised by a higher diversity and a larger proportion of pollen whose affinities are with the families Pinaceae, Taxodiaceae, and other gymnosperms (Table 1). The spore assemblage has a different composition from that of seam 1 and makes up a smaller proportion of the total palynomorphs. It implies, however, a rather similar overall composition of the herbaceous vegetation. Based on coal petrography, Petersen (1993) suggested that the vegetation in the mires represented by seams 1 and 2 was generally small-sized and consisted of abundant herbaceous plants, small trees, shrubs and tree ferns. Palynological evidence of tree ferns has not been found in the coals, and the abundance of spores whose affinities are with herbaceous plants indicates that ferns and club mosses were more common in these mires than deduced from the maceral composition, which has a rather high content of humotelinite.

The rest of the samples from seams 3–6 are rather similar. The diversity of spores related to ferns is considerably lower than in seams 1 and 2; however, they still constitute up to 54% of the assemblages (Table 1). Ferns in particular seem to have been abundant in the mires represented by seams 3 and 4. The most abundant is *Deltoidospora* spp., whose affinity is with the genera *Dicksonia* or *Coniopteris* (Tralau 1968). The proportion of club mosses was significant in the mires, and the spores (mainly *Retitriletes austroclavatoides*, *R. clavatoides*, *R. semimuris*, *Sestrosporites pseudoalveolatus*) amount to 22% and 31% in seams 4 and 5, respectively. These spores are particularly associated with mineral-rich levels in the coals implying that the plants favoured wetter and more nutrient-rich conditions. The pollen species *Cerebropollenites macroverrucosus* which is related to the gymnosperm genus *Tsuga* of the family Pinaceae (Tralau 1968; Batten & Dutta, 1997), is abundant. In the coal sample from seam 6, the pollen

Vitreisporites pallidus is abundant. The affinity of this pollen is with the Caytoniales (van Konijnenburg-van Cittert 1971), a gymnosperm order of uncertain relationship (Stewart 1983).

A peat-forming vegetation consisting of abundant herbaceous and shrubby plants and some larger trees was suggested by Petersen (1993). To some extent this is supported by the palynomorph assemblages, but the proportion of gymnospermous trees may have been greater than deduced from the maceral composition. Plants belonging to the family Pinaceae were present. Reconstruction of the gymnospermous vegetation in the mires is difficult due to the high proportion of pollen of unknown affinity (Table 1).

Duration of peat formation

Assuming a peat accumulation rate of 1 mm/yr and a peat:coal compaction ratio of 10:1 (see above), the original peat deposits represented by the coal seams in the upper part of the Bagå Formation were between 0.5 and 19.0 m thick, and peat accumulation occurred in the mires for between 500 and 19 000 years.

Other Middle Jurassic coal-bearing strata in the Fennoscandian Border Zone

Several seams, 0.16–0.70 m thick, are present in the Øresund-5 and -7 wells, overlying parallel-laminated to homogeneous claystones deposited in freshwater lakes (Figs 14, 15; Petersen 1994). The abundance of coalified plant remains and the upwards-increasing content of organic matter, coal particles, coal streaks and rootlets in the claystones towards the coal seams record the gradual fill of the lakes and deterioration of the oxygen supply in the mires. The lower part of the Øresund-5 seam represents a drier mire environment, whereas the upper part of the seam is a carbonaceous claystone deposited in an open freshwater environment. This indicates that the rising groundwater level gradually outpaced organic matter accumulation, and peat formation was terminated by lacustrine flooding. Seams 1, 3 and 4 in the Øresund-7 well contain a higher inertinite content as shown by low GI values (Fig. 13), and they represent bogs that were probably subjected to a fluctuating watertable (Petersen 1994). The mire represented by seam 2 was also established after a lake had been filled with sediment. However, the mire was continuously water-saturated and anoxic, and probably nutrient-rich and rheotrophic.
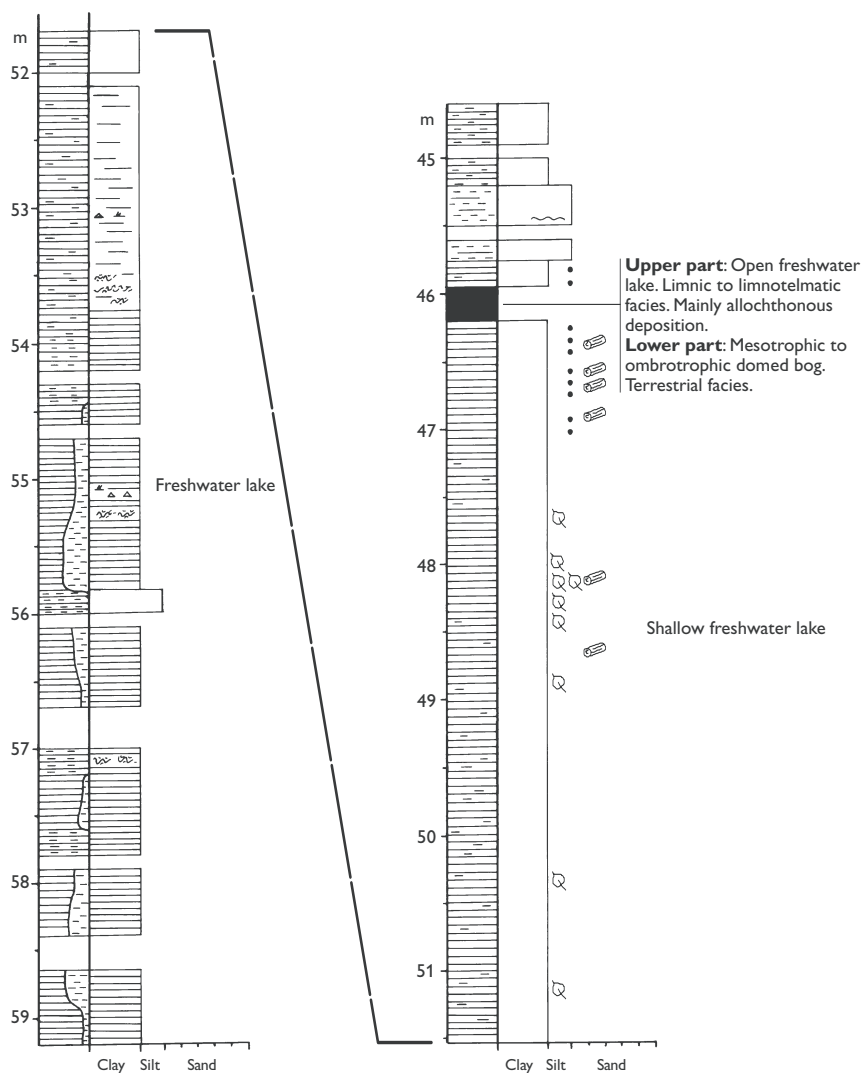
Øresund-5 well

Fig. 14. Sedimentological core-log of the Jurassic succession of the Øresund-5 well. Modified after Petersen (1994); reference level: metres below sea level. For legend, see Fig. 4.

Upper part: Open freshwater lake. Limnic to limnotelmatic facies. Mainly allochthonous deposition.

Lower part: Mesotrophic to ombrotrophic domed bog. Terrestrial facies.

Freshwater lake

Shallow freshwater lake

The Middle Jurassic peat-forming freshwater mires in the Øresund area were thus located in an overall lake-dominated wetland with a prolific flora indicated not only by the coal seams but also by the abundance of coalified leaves and branches in the claystones. There is no evidence of marine influence, and the continental sedimentation kept pace with the subsidence-induced base-level rise.

In north Jylland, thin coal seams and carbonaceous mudstones are present in the Middle Jurassic Haldager Sand Formation. Analysis of a 4 cm thick seam in the Frederikshavn-3 well shows that it is inertinite- and mineral-rich (75 vol.% and 17 vol.%, respectively), which may indicate an allochthonous origin. However, black carbonaceous clay and rootlets below the seam indicate a gradual change to oxygen deficient, low energy conditions and the establishment of vegetation. Degraded liptinite components suggest fungal and/or bacterial attack under well-oxidised conditions. This and the

scarcity of huminite (1 vol.%) may imply that the seam was severely oxidised, possibly due to a fall in the watertable following the accumulation of the organic matter. Minerals are easily incorporated into a thin layer of organic matter, and the carbonaceous seam is probably autochthonous and was deposited in a shallow, slightly brackish area, as suggested by the presence of pyrite (4 vol.%). The seam is overlain by coaly matter associated with quartz grains, and poorly sorted dark-brown clay and sand, indicating a gradually rising watertable.

Duration of peat formation

The original peat deposits in the Øresund area were between 1.6 and 7.0 m thick and the peat-forming environments existed for between 1600 and 7000 years using the assumptions discussed above. Although some

Øresund-7 well

Fig. 15. Sedimentological core-log of the Jurassic succession of the Øresund-7 well. Modified after Petersen (1994); reference level: metres below sea level. For legend, see Fig. 4.
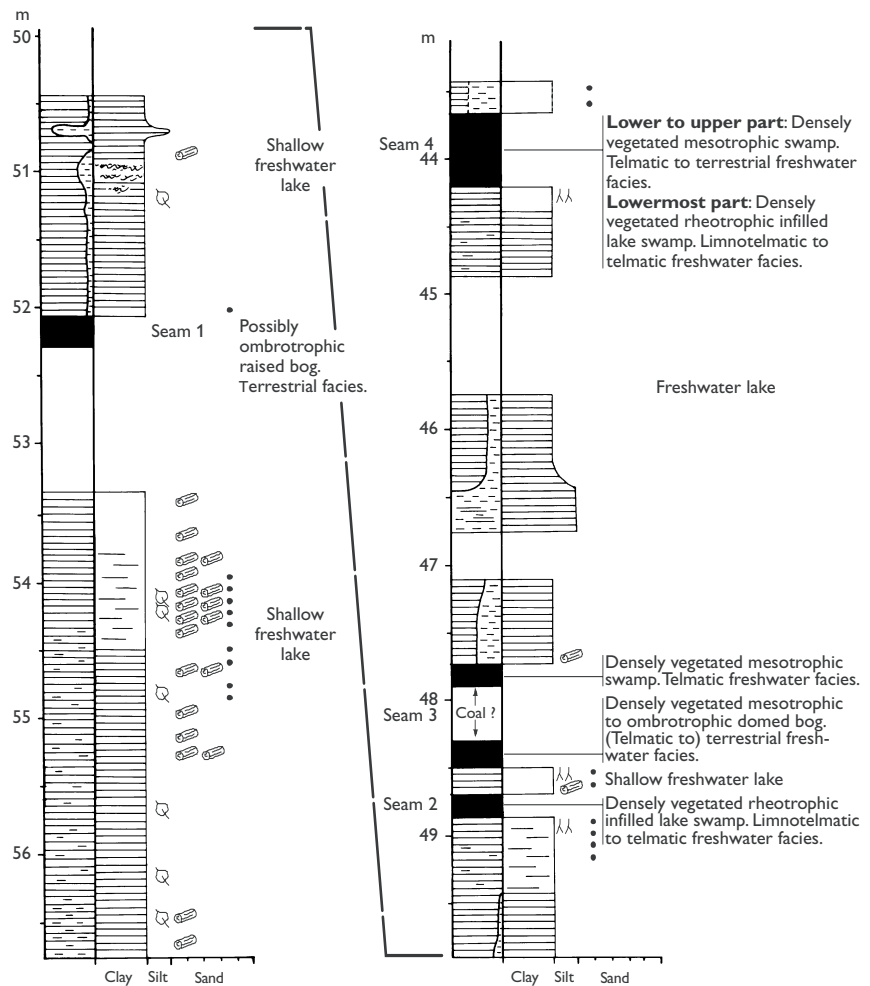
of the mires were rather short-lived, the data demonstrate that certain of the Middle Jurassic peat mires in the Øresund area were able to exist for longer periods than the Early Jurassic mires in the same area.

Discussion

Factors controlling peat formation

Peat formation occurred in the Fennoscandian Border Zone from north Jylland, through Øresund and Skåne to Bornholm during Early–Middle Jurassic times. The conditions for peat accumulation were most favourable to the south-east as indicated by an increase in number and thickness of the seams from north Jylland to Bornholm.

The Upper Pliensbachian – Lower Toarcian Sorthat Formation coals differ from the Bathonian upper Bagå Formation coals in terms of composition, thickness and palynological content. The Lower Jurassic coal seams

represent peat accumulation in low-lying interchannel and abandoned channel mires on a lower coastal plain in an overall transgressive setting (Petersen & Nielsen 1995). In paralic settings, rising relative sea-level causes a rise in the groundwater table and a more landwards ponding of coarse sediments, which may result in the formation of extensive peatlands (Diessel 1994; Petersen & Andsbjerg 1996; Petersen et al. 1998). Peat accumulation in the Sorthat precursor mires was favoured by a continuously high-standing watertable and anoxic conditions, and only small amounts of very fine-grained detrital mineral particles reached the mires. The mires were probably rheotrophic and periodically saline-water influenced, and the resulting coals are generally very huminite-rich. The limited thickness of the seams (up to 0.57 m, but generally between 0.08 m and 0.26 m) reflects a rather short duration of peat accumulation (average for all seams of 2300 years), determined by a fairly rapid relative sea-level rise. The sea-level rise was governed by an overall eustatic rise (Hallam 1988; Haq et al. 1988) and a subsidence rate of c. 30 m/my (Petersen

& Nielsen 1995). Most of the coal seams represent the boundary between two succeeding lake/lagoonal successions, i.e. they were deposited during the transition from a period of relatively slow rise in the watertable to a period during which the watertable rose more rapidly. Peat formation began when the lake/lagoon or abandoned channel was filled and turned into low-lying mires. Peat accumulation probably continued during the initial phase of the succeeding faster rise in watertable, as accumulation of organic matter may have been favoured by sediment starvation due to upstream ponding of clastic sediments. Peat formation was terminated by lacustrine or lagoonal flooding of the mires, when the watertable rise outpaced the rate of organic matter accumulation. Similarly, the formation and duration of the Hettangian–Sinemurian coastal mires in the Fennoscandian Border Zone was strongly controlled by a relative sea-level rise, and the peats obtained thicknesses of only 0.5–3.5 m. On average, the investigated mires in the Rønne Formation existed for c. 1200 years and the mires in the Øresund area for 1850 years.

The principal controlling factor on the development of the Early Jurassic mires in the Fennoscandian Border Zone was thus a general rise of the groundwater table that favoured the development of waterlogged, possibly rheotrophic and nutrient-rich mires, and hindered the development of domed bogs in most cases. This resulted in the dominance of huminite-rich coals and carbonaceous claystones. A similar mechanism has been presented for the Westphalian A in the Warrior Basin, Alabama, where domed peat formation may have been hindered due to extremely rapid basin subsidence in spite of a suitably warm and humid climate (Eble *et al.* 1994). Hunt (1989) suggested that eastern Australian Permian delta plain coals are consistently high-vitrinite coals, because the peats formed under high watertables principally controlled by a high subsidence rate.

During the Middle Jurassic, the subsidence rate was much lower as clearly shown by thinner Middle Jurassic sediment packages (up to 200 m in c. 21 Ma; Gradstein *et al.* 1994) in the Danish Basin and Fennoscandian Border Zone compared to those in the Lower Jurassic (up to 1000 m in c. 26 Ma). The marked change in subsidence rate and basin configuration was caused by uplift of the Ringkøbing–Fyn High and the Danish Basin south-west of the Sorgenfrei–Tornquist Zone (Nielsen 1995, 2003, this volume). These changes may have been related to thermal doming centrally in the North Sea area (Underhill & Partington 1993) and to an important Middle Jurassic volcanic event in central Skåne that was possibly associated with, or preceded by, uplift in the form of a rift dome (F. Surlyk, personal communication 1997). The reduced subsidence rate coupled with a more stable eustatic sea level (Hallam 1988; Haq *et al.* 1988) resulted in a more inland position for the Middle Jurassic mires in the Fennoscandian Border Zone and on Bornholm than that for the Early Jurassic mires. The proximity of the Bathonian mires (upper Bagå Formation) on Bornholm to granitic basement is reflected in the coarser grain size of the quartz particles and a much higher kaolinite content than observed in the Sorthat Formation coals. The thickest of the upper Bagå Formation coal seams (1.9 m) corresponds to a precursor peat thickness of 19 m and an estimated 19 000 years of peat accumulation. From the Øresund area, a maximum of 7000 years is estimated. This suggests that on occasion peat accumulation was able to keep pace with the increase in accommodation space for a relatively long period of time. At other times, the rate of peat accumulation may have outpaced the rate of watertable rise resulting in the development of domed peats. As noted above, this style of peat development probably resulted from the combination of a low subsidence rate and a stable eustatic sea level, which worked together to limit flooding controlled by relative sea-level rise.

The coal petrography indicates that most of the investigated Middle Jurassic mires were exposed to fluctuations in the groundwater table, probably controlled by a seasonal climate; such periodic falls in the watertable level favoured oxidation of the peat surfaces. In contrast, the seasonal climate probably had a more limited influence on the level of the watertable in the Early Jurassic coastal mires, where a high-standing watertable was governed by a more or less continuous rise of relative sea level. Oxidation of the organic matter on the Middle Jurassic peat surface implies that the estimates of peat accumulation periods may be a rough minimum. The combined effect of a seasonal climate and possibly peat accretion above the watertable level resulted in coal seams with a higher content of inertinite. A low subsidence rate has been similarly inferred to account for oxidation of the precursor peats of Permian high-inertinite coals in eastern Australia (Hunt 1989; Hunt & Smyth 1989). The fluctuating watertable in the Middle Jurassic mires may have favoured wildfire frequency and the formation of fire-derived inertinite; however, the nature of the inertinite, particularly in the coals from the Øresund area, is indicative of derivation by oxidation. The presence of inertinitic maceral precursors formed by oxidation in recent peat deposits (Cohen & Stack 1996; Moore *et al.* 1996), makes this suggestion likely.

The peat-forming vegetation based on palynological evidence

The palynological evidence of the peat-forming vegetation suggests a Lower Jurassic flora with a prominent proportion of ferns together with cycadophytes, coniferophytes from the families Pinaceae and Taxodiaceae, unknown gymnospermous plants, and bryophytes. Although the overall composition of the plant communities seems to have been rather uniform, variations in the composition of the palynomorph assemblages (and coal composition) in the seams and between seams may reflect variations in the peat-forming plant communities. These variations are probably related to specific environmental conditions in the mires as demonstrated in recent peat systems (Cohen 1973; Esterle & Ferm 1994; Phillips & Bustin 1996b). The limited knowledge of the ecology and environmental tolerance of the plants restricts the understanding of the palaeoecological differences between the mire systems as indicated by various palynomorph assemblages. The Middle Jurassic seams from the upper Bagå Formation are characterised by the common occurrence of spores whose affinities lie with the order Lycopodiales and the absence of pollen related to the order Cycadales. Club mosses are particularly abundant in mineral-rich levels corresponding to wet, nutrient-rich conditions in the precursor mires, or common inundations. Bryophytes seem to have been present, together with ferns and coniferophytes. Of particular note is the absence of pollen related to Cycadales in the Middle Jurassic coals, particularly in view of their common occurrence in the Lower Jurassic samples. According to Lapo & Drozdova (1989), cycadophytes are rarely found in Jurassic coals because they preferred drier habitats. However, Höhne (1933) noted the presence of cycadophytes in the Bagå Formation coals, although this may have been stratigraphically lower in the succession. It is notable that the genus *Nilssonia*, considered to represent the foliage of cycadophytes, occurs in Lower Jurassic claystones on Bornholm (Möller 1903). Hence the palynomorphs from the Lower Jurassic seams whose affinities are with the Cycadales could have originated from vegetation outside the mires.

In general, there is a relatively good correspondence between the interpretation of the peat-forming vegetation based on macerals and the palynological evidence of the peat-forming vegetation. In order to strengthen the interpretations based on macerals, however, it is necessary to acquire specific knowledge of the peat-forming plants, i.e. the stature, structure and the wood content of the tissues; furthermore, the degradational conditions should also be considered (Pierce *et al.* 1995). Biological aspects of the parent plants should be incorporated, if possible, in particular to account for the variation in spore/pollen production by different species, but also to account for spores and pollen that may have been transported into the mires from the hinterland. It is clear that multidisciplinary studies of coals integrating palaeobotanical data with petrographic results provide the most detailed picture of the mire floras (see discussion by Scott 1991; DiMichele & Phillips 1994).

Origin and environmental significance of pyrite in the coals of the Sorthat and Bagå Formations

The framboidal pyrite in the Sorthat Formation coals is interpreted to be syngenetic. Framboidal pyrite is normally considered to indicate the influence of saline water during peat formation because organic sulphur inherited from the peat-forming flora only accounts for low contents of sulphur and pyrite in freshwater environments (Cohen *et al.* 1984; Casagrande 1987; Phillips & Bustin 1996a). However, the nature of the pyrite in the Bagå Formation coals and the lack of other evidence for marine influence suggest that this pyrite is mainly epigenetic in origin. It is therefore necessary to identify an external source of sulphur to account for the high content of pyrite in fairly well-defined intervals in the coals and the abundant pyrite concretions in the sand beds. The coal-bearing strata are faulted against the graben bounding fault, and sulphate-enriched porewater expelled from deeper levels may have migrated up through the fault zone and into the highly permeable sand beds and coal seams. Sulphate-rich porewater is associated with anhydrite deposits, and Zechstein and Triassic deposits with anhydrite and a very low content of organic matter are present in the Rønne Graben. Sulphate-rich porewater is known from Triassic strata in the Danish Basin (Gustafson & Anderson 1979; Laier 1982). The pyrite nodules in the sand beds in the Bagå beds are often associated with coal particles. This suggests that the reduction of the sulphate and the precipitation of pyrite occurred where the local environment was reducing due to enrichment in organic matter. In the coal seams, pyrite is often found associated with fusinite, suggesting that precipitation was favoured by the higher porosity of the fusinite compared to the huminite (Fig. 8D). An analogous situation has been described from Carboniferous coal seams in a non-

marine succession from Nova Scotia, Canada, where epigenetic pyrite fills fusain lenses, fractures and cleats (Beaton *et al*. 1993). The Carboniferous coal measures are in fault contact with rocks containing gypsum, anhydrite, carbonates, halite and potash salts, which are interpreted to be the source of the sulphur.

Conclusions

The development of the Early–Middle Jurassic mires in the Fennoscandian Border Zone occurred in a humid, warm-temperate to subtropical, weakly seasonal climate. During the Early Jurassic, mires were established on coastal plains facing the open sea to the west. Peat formation was mainly controlled by an overall fairly rapid rise of relative sea level governed by the general eustatic rise and a relatively high subsidence rate causing repeated lacustrine or lagoonal flooding of the mires. The Early Jurassic mires were relatively short-lived, averaging 1200 years (Rønne Formation), 1850 years (Øresund area) and 2300 years (Sorthat Formation), because watertable rise outpaced the rate of peat accumulation. The Lower Jurassic coals and coaly mudstones in the Fennoscandian Border Zone and on Bornholm represent peat deposits that were between 0.5 and 5.7 m thick, but generally were less than 3 m thick.

The Upper Pliensbachian – Lower Toarcian Sorthat Formation coals originated in continuously waterlogged, anoxic mires, and the high-standing watertable and the periodic marine influence on the mires favoured the formation of huminite-rich coals and the precipitation of framboidal pyrite. In addition to pyrite, the mineral matter is dominated by clay and fine-grained silt-sized quartz.

Uplift of the Ringkøbing–Fyn High and the main part of the Danish Basin south of the Sorgenfrei–Tornquist Zone in Aalenian times changed the basin configuration and influenced the accumulation of peat. The uplift, which may have been related to the formation of a large thermal dome in the central North Sea, and possibly also in Skåne, caused a strongly reduced subsidence rate within the Fennoscandian Border Zone. The low subsidence rate coupled with a relative stable eustatic sea level, resulted in a general regression such that the Middle Jurassic mires developed farther inland than those of the Early Jurassic. The setting enabled peat accumulation in the Middle Jurassic mires to keep pace with and occasionally outpace the watertable rise. Thus, some of the Middle Jurassic peat mires existed for relatively long periods. It is inferred from coals in the Øresund area that peat accumulation occurred for up to 7000 years and upper Bagå Formation coals testify that at certain times during the Bathonian, peat accumulation may have occurred on Bornholm without significant interruption for up to 19 000 years. The combination of an inland position of the Middle Jurassic mires, a seasonal climate, and periodic peat accretion above the groundwater level caused temporary oxidation of the peat surfaces and the formation of inertinite-rich coals. Watertable fluctuations within the upper Bagå Formation mires on Bornholm may further have been promoted by the generally sandy substrate of the alluvial plain. The proximity of these mires to the granitic basement areas to the east on Bornholm is reflected by a larger grain size of quartz particles and a higher kaolinite content than observed in the Sorthat Formation coals. The pyrite in the upper Bagå Formation coals is interpreted to be mainly epigenetic in origin, precipitated out of sulphate-enriched porewater expelled from underlying Zechstein–Triassic strata.

Palynological data indicate variations in the peat-forming plant communities between coal seams. Variations within individual seams also suggest subtle changes in the mire environment, probably mainly of hydrological character, reflecting the evolution of the mire. The Hettangian–Sinemurian mires represented by the seams in the Øresund-18 well were characterised by an abundance of ferns, cycadophytes and at certain levels significant proportions of coniferophytes of the family Taxodiaceae. Club mosses were also represented. The Late Pliensbachian – Early Toarcian mires (seams 2 and 15 in the Levka-1 well, Sorthat Formation) were also characterised by an abundance of ferns. In contrast to the Sinemurian mires in the Øresund area, however, cycadophytes were more abundant, while coniferophytes of the family Taxodiaceae were much less common and club mosses were probably absent. The Bathonian mires represented by the seams in the upper Bagå Formation differ in particular from the Early Jurassic mires by the complete absence of cycadophytes and the abundance of club mosses, and by the rare occurrence of coniferophytes of the family Taxodiaceae. Ferns were significant components of the mires, as were Jurassic species of Pinaceae. It is tempting to relate the difference in the plant communities of the mires represented by the Sorthat and Bagå Formation coal seams to the distinctly different depositional settings represented by these seams. The Early Jurassic mires were waterlogged, anoxic and periodically marine-influenced, whereas the Bathonian mires developed under fresh-

water conditions and were situated inland, where in particular the seasonal climate was important in promoting a fluctuating watertable. In general, there appears to be a relationship between the petrographic composition of the coals and the composition of the peat-forming vegetation, as deduced from palynological evidence. Thus, the overall coal seam composition was controlled not only by allogenic factors but also by differences in vegetational input from the various peat-forming plant communities, which may account for the more subtle petrographic variations in the coal seams.

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