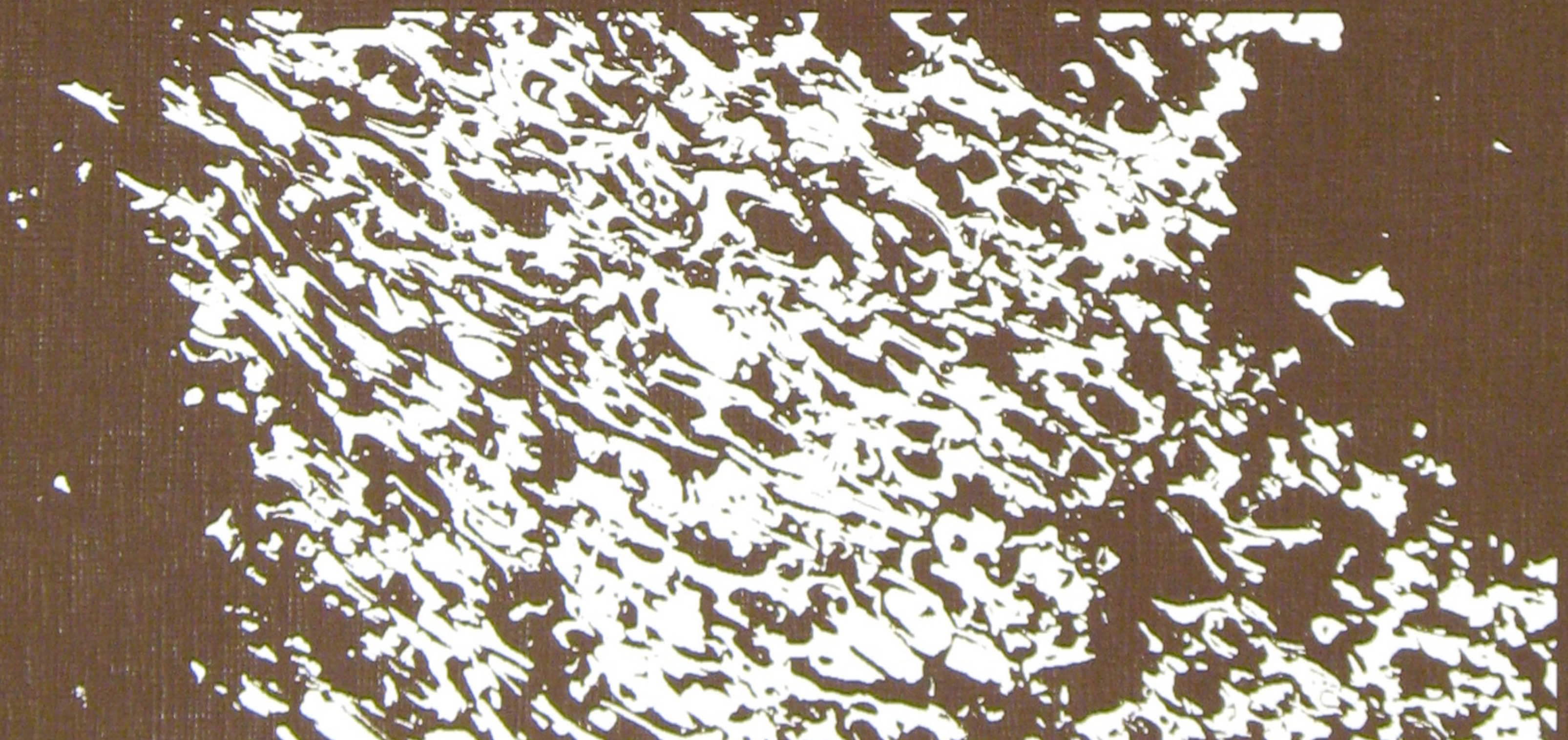
DANMARKS GEOLOGISKE UNDERSØGELSE • DGU SERIE A • NR. 33
MINISTRY OF ENVIRONMENT AND ENERGY • DGU SERIES A • NO. 33

Depositional environments of coals and associated siliciclastic sediments in the Lower and Middle Jurassic of Denmark

The Øresund -5, -7, -13, -15 and -18 wells

BY
HENRIK INGERMANN PETERSEN



Geological Survey of Denmark • Copenhagen 1994

ERRATUM

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Page 25, right hand column, the last two sentences should read as follows:

"The lake was gradually filled by sediments, and a mire was established during increased growth ***of plants. Coal seam 2 is represented by a (limnotelmatic)/telmatic*** facies"

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Key words:
Øresund wells, Lower and Middle Jurassic, coal, Lignite, peat, swamps, peat bogs, clastic sediments, organic geochemistry.

With 6 plates

Vignette:
Fusinite
Seam 1, Øresund-5 well, Denmark

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Contents

Abstract

Five cored wells located in the Fennoscandian Border Zone in the Øresund area, Denmark, encountered Lower or Middle Jurassic coal-bearing strata; the coal seams are Lignite to Sub-bituminous A/High Vol. Bituminous C in rank.

A number of shallowing-upward units are recognized in the five wells. Each unit is capped by a coal seam. Correlation of these shallowing-upward units between wells is difficult on the basis of available biostratigraphy and log data. Seven of the coal seams result from establishment of peat-forming conditions due to infilling of fresh water lakes, whereas the last two of the coal seams result from peat accumulation on top of restricted brackish lagoon or bay sediments. However, only one of the latter two seams accumulated in an environment influenced by saline water. Hence, the investigated coals represent almost entirely fresh water peat-forming environments.

Three main types of environments are defined: 1) Type 1 is a sparsely vegetated open water swamp; it is represented by a limnic facies. The deposit is typically a carbonaceous claystone with a high content of allochthonous organic matter; 2) Type 2 is a densely vegetated rheotrophic, nutrient-rich and anoxic swamp; it is represented by a limnotelmatic to telmatic facies. The coal has a very high content of humified organic matter; 3) Type 3, subdivided into the types 3a and 3b, is the driest environment of the three types. Type 3a is a desiccated ombrotrophic raised bog represented by a terrestrial facies. It is strongly influenced by a fluctuating watertable. The coals contain a high content of inertinite that generally shows a low reflectance. Type 3b is a mesotrophic to ombrotrophic domed bog; the environment alternates between dry oxidizing conditions and wet conditions. It is represented by a telmatic to terrestrial facies.

In general, the three types of environments form ecosystems characterized by the groundwater influence, nutrient supply, and vegetation. Successions representing the hydrological evolution towards drier conditions due to vertical peat accretion are recognized in some of the seams.

The vegetation was small-statured and consisted of a prominent herbaceous type of flora, shrub-like plants, smaller arboreous plants and, to a lesser extent, larger plants.

Introduction

The aim of this paper is to characterize Lower and Middle Jurassic coal seams in the Øresund area based on coal petrographical and organic geochemical analysis techniques. Furthermore an attempt is made to define the environments under which the coals were formed. This study, together with other recently completed investigations (Petersen, 1993; Petersen & Nielsen, in press; Surlyk et al., in press) of Lower and Middle Jurassic coal seams on the island of Bornholm, contributes to the characterization of Jurassic peat-forming environments in the Fennoscandian Border Zone at the margin of the Fennoscandian Shield (Fig. 1). This zone formed the northeastern margin of the Danish Basin during the Jurassic. Accumulation and preservation of organic matter necessitates specific environmental conditions which differ significantly from those under which the associated clastic sediments were deposited. Study of the coal seams and interpretation of the original peat-forming environments thus contributes to a more detailed understanding of the changing sedimentary regimes.

The analyses are carried out on coal material (polished blocks, particulate pellets) sampled from cored coal seams from the Øresund-5, -7, -13, -15 and -18 wells. These wells were amongst a total of 19 wells drilled in 1964 along two transects across the Øresund between Helsingør and Hälsingborg by the Geotechnical Institute (Fig. 2). The aim of these wells was to investigate the geology of the Øresund prior to the construction of a transport link between Denmark and Sweden. The results of these studies were published by Larsen et al. (1968).

The Øresund-18 well was drilled onshore on the Swedish Øresund coast whereas the other 4 wells are located offshore. The 5 investigated boreholes are shallow wells that encountered sediments of Quaternary and/or Jurassic age.

Sedimentological core logs were measured and 20 coal samples were taken from 9 cored coal seams ranging in thickness from 0.15 m to 0.70 m. (The thicknesses of the coal seams are the true thicknesses calculated from x = a cos v, where "x" is the true thickness of the seam, "a" the measured thickness and "v" the inclination of the seam). The Øresund-7 well contains four coal seams, the Øresund-13 well three coal seams, the Øresund-18 well two coal seams and the Øresund-5 well one coal seam. In the Øresund-13 well only the lowermost seam was investigated. The coal seams are named seam 1, seam 2 etc. from the lowermost to the uppermost seam in each well. Determination of the rank as well as the facies interpretations were obtained using optical and organic geochemical analysis techniques. The analyses provided a large amount of information concerning the composition of the coal seams which makes it possible to present a detailed petrographic/chemical characterization and facies interpretation of each coal seam.

Geological setting, palaeogeography and stratigraphy

Geological setting

During the Mesozoic, the Fennoscandian Border Zone was divided into the Sorgenfrei-Tornquist Zone to the west and the Skagerrak-Kattegat Platform to the east (Fig. 1) (Sorgenfrei & Buch, 1964; EUGENO-S Working Group, 1988; Michelsen & Nielsen, 1991, 1993). The Øresund wells are situated at the margin of the Sorgenfrei-Tornquist Zone which represents a highly complex block faulted tectonic structure (Fig. 1). Tectonic activity within the zone has probably been going on from the Early Palaeozoic to Recent times (Liboriussen et al., 1987). The Sorgenfrei-Tornquist Zone is regarded as the northern branch of the Teisseyre-Tornquist Zone which comprises a block faulted structure extending from the Black Sea through Poland to Bornholm. The Fennoscandian Border Zone, the Rønne Graben and the Teisseyre-Tornquist Zone separate the stable Fennoscandian-Baltic Shield from the subsiding Danish Basin and the Polish Trough. These structures form one of the most prominent tectonic systems in northern Europe. During Triassic to Early Cretaceous times, the Sorgenfrei-Tornquist Zone was affected by dextral wrench faulting and tensional stress resulting in subsidence and tilting of the fault blocks. Pienkowski (1991) suggested that eustatic sea-level changes were more important during the Early Jurassic in Scania than the influence exerted by local tectonism, whereas tectonic activity becomes the main influence during the Middle Jurassic.

Late Cretaceous to initial Tertiary compressional tectonism led to inversion of the fault blocks resulting in erosion of the Mesozoic sediments (Liboriussen et al., 1987; Norling & Bergström, 1987; Michelsen & Nielsen, 1993).

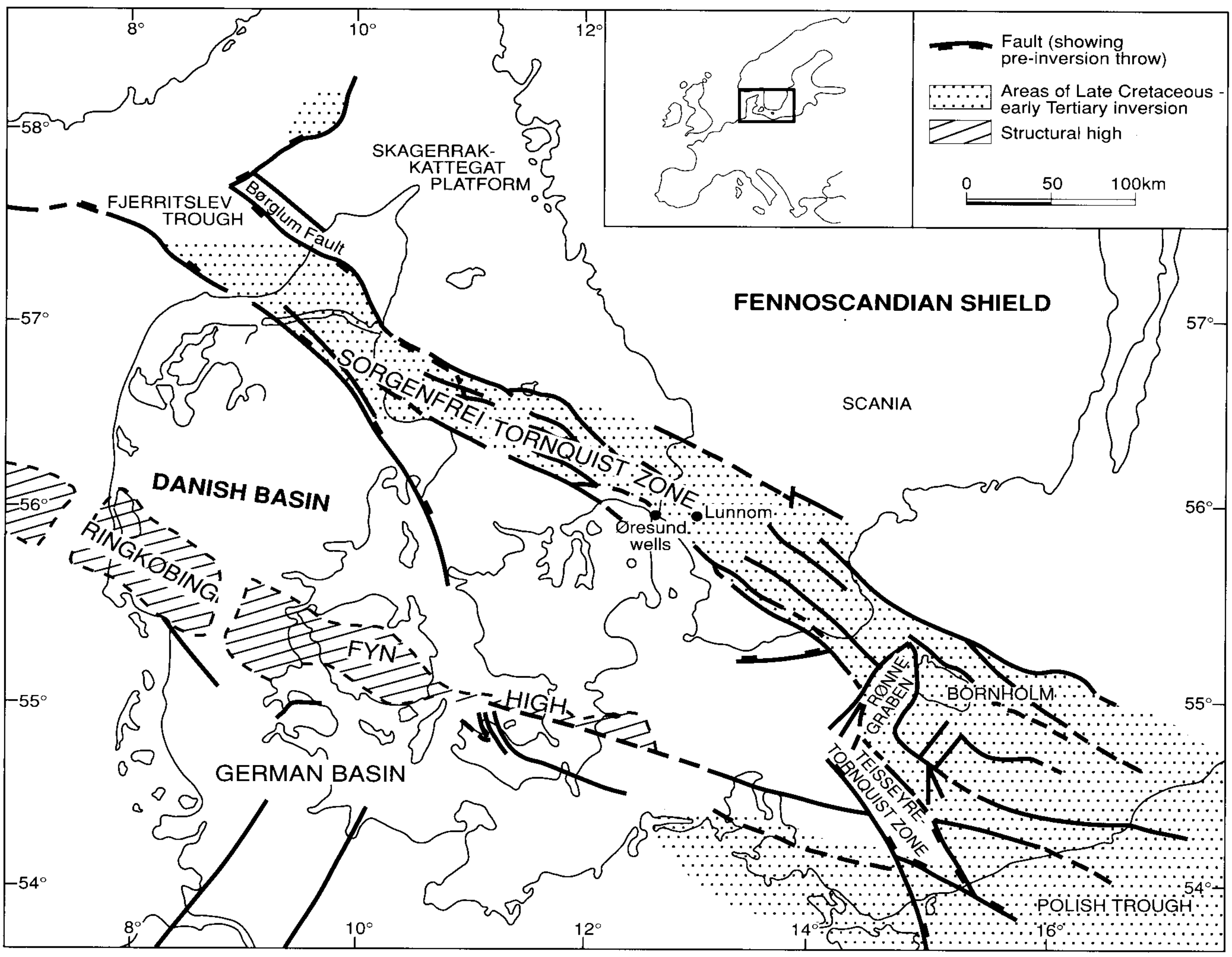

Fig. 1: Structural map of the Fennoscandian Border Zone and adjacent areas (Modified from Liboriussen et al., 1987 and EUGENO-S Working Group, 1988).

Lower and Middle Jurassic peat-forming environments in the Fennoscandian Border Zone

At the end of the Triassic (Rhaetian), the climate changed from the hot and arid conditions that had dominated the Permian and most of the Triassic to more humid conditions. This is demonstrated by a shift from mainly red sandstones, claystones and evaporites to deposition of greyish sediments and coal beds during the Rhaetic and Jurassic. The mid-Rhaetic succession at Lunnom, northwest Scania, contains two coal seams which were deposited in a deltaic environment (Fig. 1) (Norling & Bergström, 1987; Svensson, 1989). The lower coal seam is mainly autochthonous and represents a fresh water environment within the lower to upper delta plain (Therkelsen, 1992). The vegetation was mainly shrub-like with a subordinate component of trees and herbaceous type of plants.

A northward transgression from the Tethys during the Early Jurassic created an epicontinental sea in northern Europe. The northeastern margin of this sea coincided with the Fennoscandian Border Zone and was characterized by a variety of marginal marine and coastal plain environments influenced by relative sea-level changes.

In the Danish Basin, Bajocian to Bathonian braided river plain sediments and Callovian to Oxfordian meandering flood-plain system sediments with allochthonous coal laminae unconformably overlies Lower Jurassic to Aalenian marine shelf mudstones (Koch, 1983). In northern Jutland, northeast of the Børglum fault, the strata consists of deltaic coal-bearing sediments (Rolle et al., 1979), and further to the southeast coal-bearing strata are recognized in the Øresund wells and in Scania.

The Lower Hettangian succession in western and northwestern Scania include brackish to marine nearshore sediments, deltaic sandy and clayey sediments, and coal seams and plant fossils from the Thaumatopteris flora deposited in a mainly fresh water environment (Troedsson, 1951; Pienkowski, 1991). During the Late Hettangian, sedimentation occurred primarily in deltaic/delta plain environments. Troedsson (1951) recognised 9 sedimentary cycles in the Hettangian which he attributed to tectonic activity. From the Sinemurian to the Aalenian, marine conditions prevailed in Scania. The Upper Aalenian to Bajocian succession represents deltaic to limnic deposits and consists of interbedded sands and clays with several coal seams. The coal seams, the marine intercalations and the cyclic deposits probably indicate a delta-top environmnent (Rolle et al., 1979; Norling & Bergström, 1987). Bathonian and younger Jurassic deposits are not coal-bearing.

Lower Jurassic sediments are encountered in the Øresund-13, -15 and -18 wells and Middle Jurassic sediments in the Øresund-5 and -7 wells (Fig. 3). During the Early Jurassic, peat-forming environments existed in the Hettangian (Øresund-13) and the Sinemurian (Øresund-15 and -18). The coal seam in the Øresund-5 well was probably deposited in the Bajocian, whereas the coal seams in the Øresund-7 well were deposited in the Middle Jurassic. The depositional environments of the clastic sediments and the coal seams, as well as a more detailed stratigraphy of these coal-bearing strata, are discussed later.

The island of Bornholm is situated in the Baltic Sea in the southern part of the Sorgenfrei-Tornquist Zone (Fig. 1). The Lower Hettangian comprises lacustrine sediments with plant fossils from the Thaumatopteris flora (Gravesen et al., 1982; Koppelhus, 1991). Allochthonous shaly coal/detrital coal was deposited in a fresh water lake with a scattered vegetation (Petersen, 1993). During the Late Hettangian, a delta plain/coastal plain was established and sand, sandy clay, clay and four seams consisting of carbonaceous clay were deposited (Gravesen et al., 1982; Surlyk et al., in press). The seams are predominately allochthonous; they were deposited in mainly open fresh water environments with sparse vegetation (Petersen, 1993). During the Sinemurian a tidal coastal environment was established. Tidal sediments and an autochthonous coal seam representing a raised bog was deposited (Sellwood, 1972; Gravesen et al., 1982; Petersen, 1993). On Bornholm, marine conditions only prevailed in the Early Pliensbachian. Marginal marine, coastal plain conditions were re-established in the Late Pliensbachian and deposition of coal-bearing strata resumed and occurred until the end of the Bathonian period

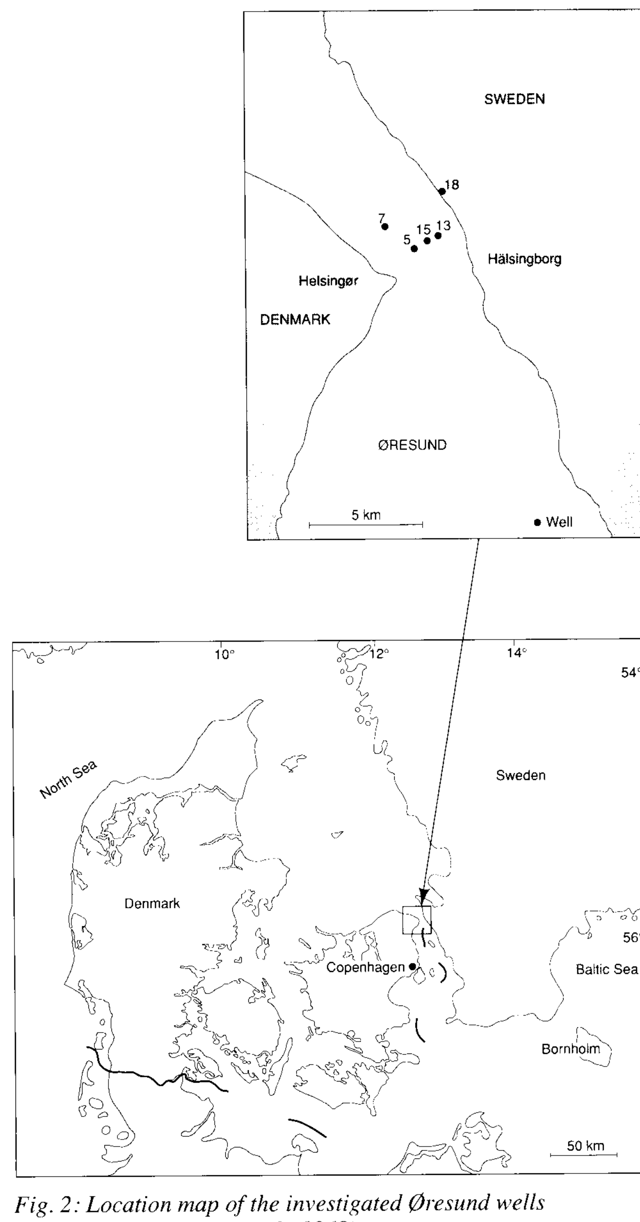

Fig. 2: Location map of the investigated Øresund wells (Modified from Larsen et al., 1968).

(Koppelhus & Nielsen, 1994). During the Late Pliensbachian-Early Toarcian huminite-rich coals accumulated in low-lying flood basins in a coastal plain environment (Petersen & Nielsen, in press). These fresh water swamps were densely vegetated. 8 coal seams from the Bathonian part of the succession were deposited in an upper delta plain /alluvial fan environment. The backswamps were essentially fresh water (Petersen, 1993). They were dominated by a shrub-like vegetation with arboreous plants and a well-developed herbaceous type of flora.

According to Pienkowski (1991), the Lower Jurassic section from Scania and Bornholm are very similar to the coeval deposits in the Holy Cross Mountains and Pomerania in Poland.

Stratigraphy

The stratigraphy and age of the strata penetrated in the Øresund wells was established by Larsen et al. (1968), but has been re-investigated (N. E. Poulsen, Geol. Surv. Den., unpubl. data). The new datings and the revised stratigraphy is used here.

Coal-bearing Hettangian sediments are encountered in the Øresund-13 well (Fig. 3). These sediments are age-equivalent to the lowermost part of the Fjerritslev Formation and upper part of the Gassum Formation in the Danish Basin, the Helsingborg Member of the Höganäs Formation in Scania and the Munkerup and Sose Bugt Members of the Rønne Formation on Bornholm (Fig. 3). The Øresund-15 and Øresund-18 wells encounter coal-bearing Sinemurian sediments (Fig. 3). The coal-bearing strata are age-equivalent to the lower part of the Fjerritslev Formation and the uppermost part of the Gassum Formation, the Döshult and Pankarp Members of the Rya Formation in Scania and the Galgeløkke Member of the Rønne Formation on Bornholm.

The coal-bearing deposits encountered in the Øresund-5 well possibly belong to the Bajocian (Fig. 3). The sequence can thus be correlated to the lower part of the Haldager Sand Formation in the Danish Basin, the Fuglunda Member ("Eriksdal Beds") in Scania and the upper part of the Bagå Formation on Bornholm. Due to the limited biostratigraphic data from the Øresund-7 well, the section is assigned a general Middle Jurassic age and thus cannot be precisely compared with other localities (Fig. 3).

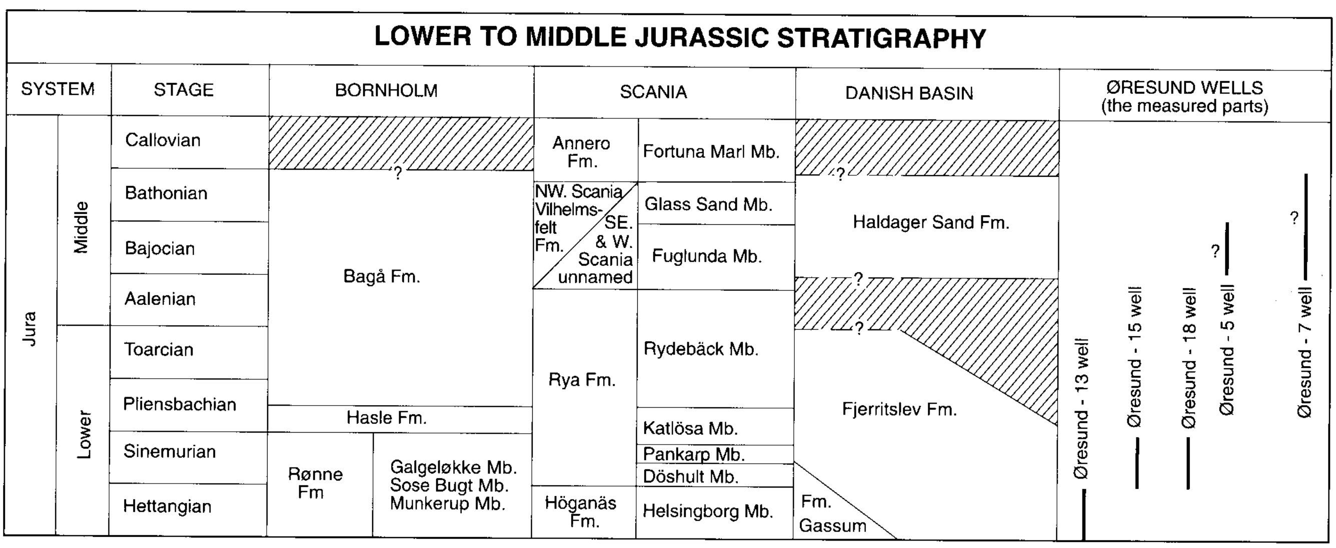

Fig. 3: The Lower to Middle Jurassic stratigraphy of the island of Bornholm, Scania and the Danish Basin together with the stratigraphy of the measured parts of the Øresund wells (Compiled from Bergström et al., 1982; Gravesen et al., 1982; Koppelhus & Nielsen, 1994; N. E. Poulsen, Geological Survey of Denmark, unpublished data).

Description and interpretation of the coal seams and the coal-bearing strata

A number of shallowing-upward units between 0.2 m and 13 m thick are recognized in the five wells. The units are separated by lacustrine flooding surfaces. Each unit is capped by a coal seam. The strata are typically comprised of one or two shallowing-upward units, with a maximum of four units occurring in the Øresund-7 well. Correlation of these shallowing-upward units between wells is difficult on the basis of biostratigraphy and log data. The units are described and interpreted, and named after the capping coal seams.

The rank of the coal seams

The rank was determined by means of random reflectance measurements on the maceral eu-ulminite. The huminite reflectances range from 0.36 %Rm to 0.51 %Rm and from these values a rank of Lignite to Sub-Bituminous A/High Vol. Bituminous C is inferred (Table 1). The relatively wide range of the reflectance values may partly be attributed to the fact that reflectance is a rather poor rank indicator in low rank coals (McCartney & Teichmüller, 1972). Hence, the coals are immature brown coals, and this is supported by several organic geochemical parameters (see Organic Geochemistry section).

HUMINITE REFLECTANCE MEASUREMENTS			
Well	Coal seam	Sample no.	%Rm
Øresund-5	Seam 1	6365	0.39
Øresund-7	Seam 1	6357	0.42
	Seam 2	6358	0.45
	Seam 3	6360	0.46
	Seam 4	6363	0.41
		6364	0.42
Øresund-13	Seam 1	6368	0.46
Øresund-15	Seam 1	6367	0.36
Øresund-18	Seam 1	6372	0.51
	Seam 2	6375	0.51

Table 1

Principles of coal facies interpretation

The facies interpretations in this section are based on the maceral and the microlithotype composition of the coal seams together with an evaluation of the underlying and overlying clastic sediments (chemical data are discussed in another section). The macerals recorded in the analyses are listed in Table 2, and the microlithotype classification used is shown in Table 3.

It is important to note that the term "facies" is used here in a broad sense to refer to the subenvironment within which the specific coal types accumulated. This is the standard usage of "facies" in coal petrology, in contrast to the more descriptive use of "facies" (or lithofacies) adopted by sedimentologists (see discussion in Reading, 1986). Three facies are defined based on the petrographic composition of the coal seams.

Limnic facies

Description: The facies is characterized by a high content of minerals together with a high proportion of the macerals inertodetrinite, sporinite and liptodetrinite. The macerals are often oriented parallel to the bedding (microlamination), and the inertodetrinite is generally well-sorted. Carbominerite is a prominent microlithotype of the facies, and durite may also characterize the microlithotype composition. The limnic facies is represented by carbonaceous claystones.

Interpretation: The high content of macerals that are resistant to transportation and are characteristic of a limnic facies (Stach, 1982; Teichmüller, 1982; Teichmüller & Teichmüller, 1982a), indicates allochthonous deposition within an open water environment. The relative well-sorted inertodetrinite indicates redeposition of a desiccated peat surface and/or redeposition of incomplete fusinized charcoal; furthermore, oxidation of the sparse in situ herb-aceous type of vegetation may partly be responsible for the inertodetrinite formation (see also "Terrestrial facies") (Diessel, 1982; Hagelskamp & Snyman, 1988; Marchioni & Kalkreuth, 1991). Carbominerite is a prominent microlithotype of open water deposits and durite may be formed within an open water environment (Hacquebard et al., 1967; Teichmüller, 1982). In the present study, the limnic facies represents mainly fresh water lakes/open water swamps characterized by deposition of very organic-rich clay.

MACERAL ANALYSES

Well	Coal seam	Sample no.	% Huminite										% Liptinite					% Inertinite				% Minerals	
			Humotelinite				Humodetrinite		Humocollinite														
			T	Tu	Eu	Ul	At	De	Po	Eg	Co	Ge	Sp	Cu	Li	Re	Su	Fu	Sf	In	Ma	Py	Mi
Øresund-5	Seam 1	6365	0.2	0.0	10.2	2.6	4.0	12.0	0.0	0.0	0.0	1.0	1.4	0.2	2.2	0.0	0.0	7.6	2.0	48.8	4.4	0.2	3.2
		6366	0.0	0.0	1.8	1.2	2.4	4.0	0.8	0.0	0.0	1.8	1.8	0.4	3.0	0.4	0.0	5.2	0.8	42.6	5.2	0.4	28.2
Øresund-7	Seam 1	6356	0.0	0.0	5.2	2.0	2.0	1.6	0.2	0.4	0.0	0.0	0.6	0.4	0.8	0.0	0.0	11.2	2.8	68.8	3.2	0.0	0.8
		6357	0.0	0.0	11.0	1.6	5.2	8.2	1.0	0.8	0.0	1.8	1.8	0.4	1.0	0.2	0.0	6.0	3.4	54.8	1.8	0.0	1.0
	Seam 2	6358	0.8	1.6	35.2	3.0	5.4	23.6	0.4	0.4	0.0	1.4	1.2	0.2	1.0	0.2	0.0	0.6	0.0	7.4	0.2	0.0	17.4
		6359	1.0	3.4	32.6	3.8	10.4	25.6	0.8	0.0	0.8	1.8	1.0	0.4	1.4	0.4	0.0	1.0	0.2	8.2	0.2	0.0	7.0
	Seam 3	6360	0.0	0.0	13.4	3.2	2.2	12.0	1.2	0.0	0.0	2.0	0.6	0.4	3.0	0.0	0.0	2.0	0.8	50.4	1.6	0.2	7.0
		6361	0.0	0.0	10.6	3.8	4.0	21.6	3.6	0.6	0.0	2.6	0.6	0.2	1.4	0.0	0.0	5.8	1.2	38.8	4.4	0.0	0.8
	Seam 4	6362	1.4	0.2	19.8	3.2	11.0	23.4	9.6	0.0	0.2	6.2	1.4	1.0	0.8	0.2	0.0	2.6	0.4	5.6	1.0	0.2	11.8
		6363	1.4	0.4	4.6	4.0	6.4	16.0	13.0	0.8	0.0	3.0	0.4	0.2	1.6	0.0	0.0	3.8	3.0	36.0	3.8	0.0	1.6
		6364	0.2	0.0	6.6	3.4	4.0	20.0	1.8	0.6	0.4	4.8	0.4	0.4	0.4	0.0	0.2	4.0	2.0	43.8	4.4	0.0	2.6
Øresund-13	Seam 1	6368	0.2	0.0	1.6	3.2	5.4	0.8	0.2	0.0	0.6	2.6	6.6	2.2	3.8	0.0	0.0	1.6	0.2	45.0	6.0	0.0	20.0
Øresund-15	Seam 1	6367	0.0	0.2	29.4	1.6	2.2	36.6	0.2	0.0	1.4	3.8	1.8	0.4	1.4	0.0	0.0	5.2	1.0	8.6	0.6	2.4	3.2
Øresund-18	Seam 1	6369	0.0	0.0	22.4	1.2	3.0	36.0	0.0	0.0	0.8	4.4	2.4	0.0	5.6	0.4	0.0	2.4	1.2	15.2	1.8	0.0	3.2
		6370	0.0	0.2	6.4	2.0	2.4	13.2	0.6	0.0	0.4	3.0	7.2	0.8	7.8	0.2	0.0	2.2	0.4	43.6	4.8	0.2	4.6
		6372	0.0	0.0	6.8	0.6	0.6	9.2	0.0	0.0	0.0	1.6	3.8	1.6	6.4	0.2	0.0	1.2	1.2	61.4	2.8	0.0	2.6
		6373	0.0	0.2	15.2	1.8	1.0	25.2	0.4	0.2	0.6	1.8	1.8	0.2	0.8	0.0	0.2	13.2	2.0	25.6	5.2	0.0	4.6
		6371	0.0	0.0	9.0	1.4	0.4	22.4	0.6	0.2	1.0	1.6	4.6	1.0	4.8	0.0	0.0	9.6	0.4	25.4	2.8	0.0	14.8
	Seam 2	6374	0.0	0.0	2.8	0.8	2.4	5.6	0.0	0.0	0.2	1.4	10.0	0.6	5.6	0.0	0.0	1.4	0.8	33.6	4.6	0.4	29.8
		6375	0.2	0.4	14.6	2.0	3.8	47.0	1.0	0.0	1.0	6.8	5.2	0.6	1.6	2.0	0.0	0.2	0.0	6.6	0.2	0.0	8.6

At : attrinite Co : corpohuminite Cu : cutinite De : densinite Eg : eugelinite Eu : euulminite Fu : fusinite Ge : gelinite
In : inertodetrinite Li : liptodetrinite Ma : macrinite Mi : other minerals Po : porigelinite Py : pyrite Re : resinite Sf : semifusinite
Sp : sporinite Su : suberinite T : textinite Tu : textoulminite Ul : ulminite

Table 2

Limnotelmatic/telmatic facies

Description: The facies is characterized by a high content of huminite. Occasionally a high content of strongly gelified plant tissues (humocollinite) is observed. The content of inertinite and minerals varies, but is generally <10 vol. %. If the inertinite content is high it usually consists of fairly well-sorted inertodetrinite or pyroinertinite. The microlithotypes vitrite, clarite, duroclarite and huminite dominated vitrinertite are prominent constituents of the microlithotype composition. Huminite-rich carbominerite can likewise be common.

Interpretation: The facies is interpreted to represent peats that accumulated under mainly anoxic conditions which favoured humification of the organic matter. A high proportion of humocollinite can be related to wet conditions, as oxygenated water, an abundance of nutrients, and a relative high pH level promote biochemical gelification due to increased bacterial activity (Teichmüller, 1982, 1989). The inertinite within the coals may have originated from charring of subaerial plant parts during peat formation or it may be allochthonous/hypautochthonous inertodetrinite. In the latter case, the coal is often microlaminated (fairly well-sorted inertodetrinite and liptinite is oriented parallel to the bedding). Hence, a high inertinite content may characterize the facies, but it does not indicate aerobic conditions during peat accumulation. The content of minerals depends on the density of the swamp vegetation, the location of the swamp relative to clastic input and

DIFINITION OF THE MICROLITHOTYPES

MICROLITHOTYPE	MACERAL GROUP COMPOSITION
Vitrite	vitrinite > 95%
Liptite	liptinite > 95%
Inertite	Inertinite > 95%
Clarite	vitrinite + liptinite > 95%
Vitrinertite	vitrinite + inertinite > 95%
Durite	inertinite + liptinite > 95%
Trimacerite	vitrinite, inertinite, liptinite > 5%
Duroclarite	vitrinite > inertinite, liptinite
Clarodurite	inertinite > vitrinite, liptinite
Vitrinertoliptite	liptinite > vitrinite, inertinite

Table 3

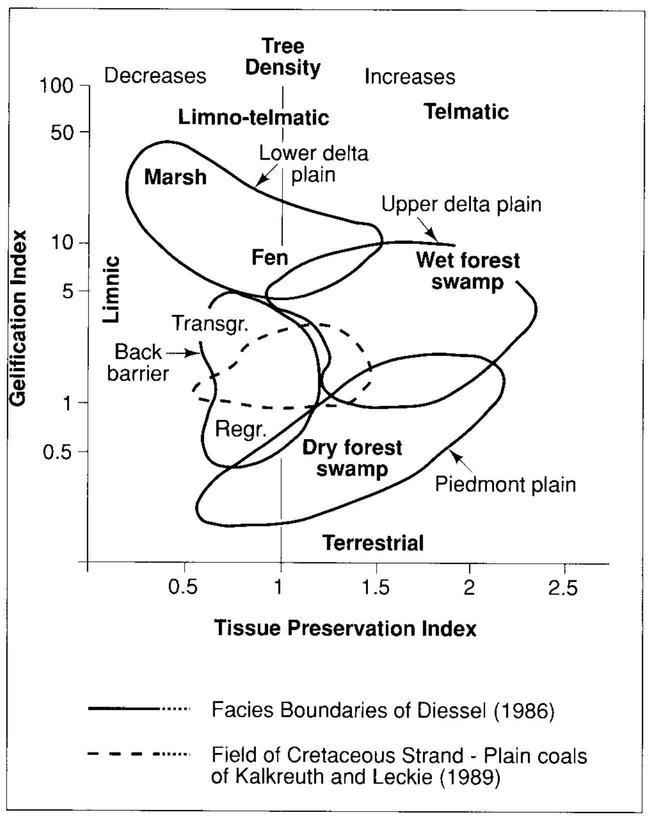

Fig. 4: The TPI versus GI facies diagram proposed by Diessel (1986) indicating facies boundaries (From Marchioni & Kalkreuth, 1991)

the frequency of inundations of the swamp. The main microlithotypes (vitrite, clarite) are related to a telmatic forest swamp facies (Hacquebard et al., 1967; Hacquebard & Donaldson, 1969; Teichmüller, 1982, 1989). In this study the limnotelmatic/telmatic facies represents a densely vegetated infilled-lake swamp characterized by autochthonous peat formation under anoxic conditions.

Terrestrial facies

Description: The facies is characterized by a high content of relative low reflecting inertinite and, in particular, a very high proportion of poorly sorted and angular inertodetrinite. The amount of minerals is generally very low. Inertite, clarodurite and inertinite-dominated durite and vitrinertite are the main microlithotype constituents of the facies.

Interpretation: This facies represents accumulation of the peat under relatively dry conditions. The petrographic composition is typical of an autochthonous, rainfed, raised bog. The high proportion of low reflecting inertinite is attributed to a fluctuating watertable which favoured periodic desiccation and oxidation of the organic matter at the peat surface (e.g. Diessel, 1982; Teichmüller, 1982; Hagelskamp & Snyman, 1988; Hunt & Smyth, 1989; Marchioni & Kalkreuth, 1991; Demchuk et al., 1993). Infrequent precipitation generated the fluctuating watertable. The proportion of angular and poorly sorted inertodetrinite is prominent which is related to in situ oxidation of herbaceous type of plants and/or mechanical disintegration of larger fusinite particles at the peat surface. The mire evolution towards diminishing groundwater influence due to vertical accretion may have been accompanied by decreasing fertility and nutrient supply which promoted stunting of the vegetation resulting in an increase of the herbaceous plant community (Smith, 1968; Anderson, 1983; Calder, 1993; Pierce et al., 1993). The dry conditions favoured wildfires, that have been a feature of terrestrial ecosystems since the Late Devonian; hence, charring of plant tissues probably accounts for the high reflecting pyroinertinite within the coals (Cohen, 1973; Cope & Chaloner, 1985; Scott, 1989). Inertinite formed by wildfires can be found in the other two facies types as well. The most abundant microlithotypes indicate a periodically dry oxidizing peat environment (Hacquebard et al, 1967; Teichmüller, 1982; Styan & Bustin, 1983; Bustin et al., 1985). Inertite, clarodurite and inertinite-rich durite can form due to a fluctuating watertable, whereas inertinite-rich vitrinertite is attributed to flooding by oxygenated water followed by periods of desiccation. A high proportion of huminite within the microlithotypes vitrinertite and clarodurite suggests that these microlithotypes are the result of temporary wet anoxic conditions alternating with drier aerobic conditions. Such a situation probably accounts for the very complex and intimately associated huminite and inertinite macerals which may be observed within the coals. Thus, a gradation with respect to dryness exists within the terrestrial facies.

Raised bogs maintain their own watertable and are able to

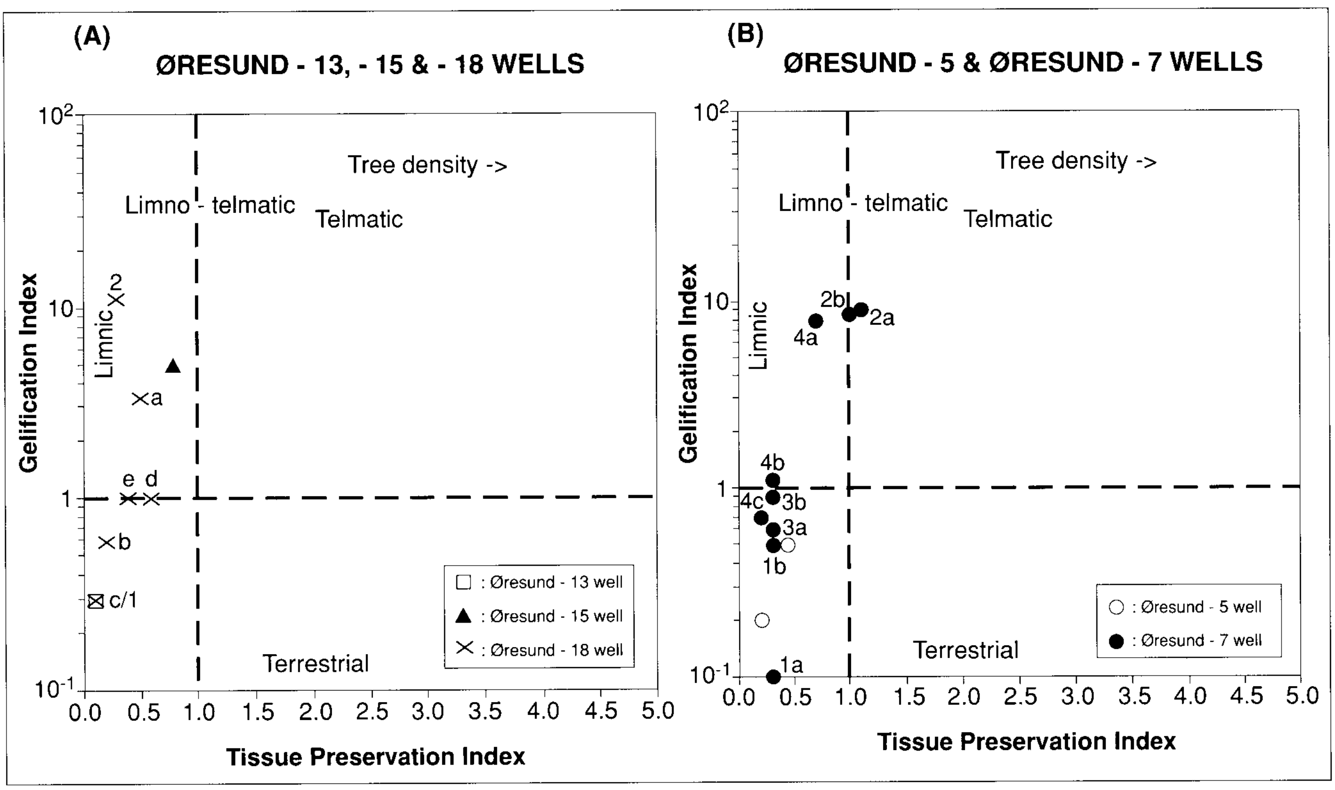

Fig. 5: TPI versus GI facies diagram for (A) the coal samples from the Øresund-13, -15 and -18 wells (Samples a (base) to e (top) are from seam 1, Øresund-18 well: a=6369, b=6370, c=6372, d=6373, e=6371; Samples 1-2 are from seam 2, Øresund-18 well: 1=6374, 2=6375; see also Figures 12 and 13), and (B) the coal samples from the Øresund-5 and -7 wells (Sample nos. refer to the four coal seams from the Øresund-7 well: Seam 1, 1a=6356 and 1b=6357; Seam 2, 2a=6358 and 2b=6359; Seam 3, 3a=6360 and 3b=6361; Seam 4, 4a=6362, 4b=6363 and 4c=6364; See also Figures 16 and 17) (Diagram modified from Diessel, 1986). See text for further explanation.

accrete vertically which prevents flooding of the peat surface (McCabe, 1984, 1987). This accounts for the very low content of minerals in the resulting coal.

A terrestrial facies can be distinguished from an inertinite-rich telmatic/limnotelmatic facies by the angular, poorly sorted inertodetrinite and a generally lower content of minerals and carbominerite.

Petrographic composition related to the peat-forming vegetation

The low rank of the coals enables a more detailed interpretation of the huminite macerals compared to higher rank coals due to a lower degree of transformation of the plant tissues in the former. They can, therefore, contribute to a more detailed facies interpretation of the peat-forming environments. The decomposition of ligno-cellulosic cell walls within the peatigenic layer (mainly humification) and during the early coalification stage (mainly biochemical gelification) is due to active degradation by microorga -nisms and chemical processes (Teichmüller, 1968, 1989; Teichmüller & Teichmüller, 1982b; Stout and Spackman, 1987). The early degradation of resistant lignin-rich tissues requires more aerobic conditions and is possibly not completed until the geochemical gelification (vitrinization), which takes place between the brown coal stage and the hard coal stage. Therefore, within the present study the mainly strong gelification of the woody plant remains (high content of eu-ulminite) is related to less resistant cellulose-rich wood with a minor content of the relative stable lignin. These woody plant remains are related to a vegetation consisting mainly of shrub-like plants and smaller arboreous plants. The occasional occurrence of textured huminite (textinite, textoulminite) suggests the presence of larger plants with more of the less degradable lignified

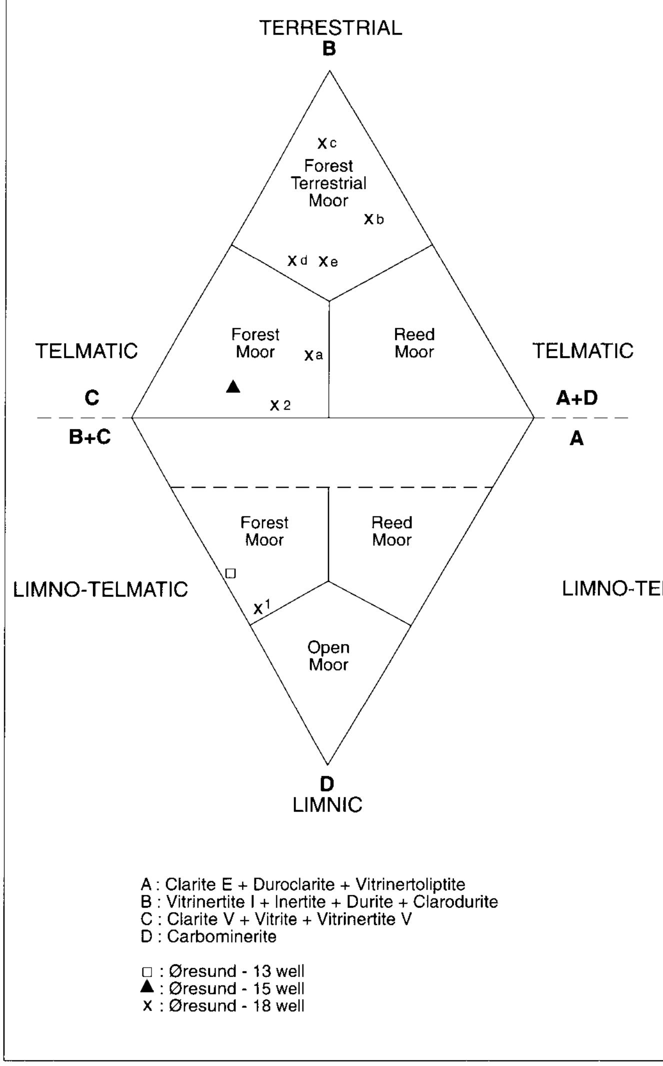

Fig. 6: Four-component facies diagram for the coal samples from the Øresund-13, -15 and -18 wells
(Samples a (base) to e (top) are from seam 1, Øresund-18 well: a=6369, b=6370, c=6372, d=6373, e=6371; Samples 1-2 are from seam 2, Øresund-18 well: 1=6374, 2=6375; See also Figures 12 and 13) (Diagram modified from Hacquebard & Donaldson, 1969). See text for further explanation.

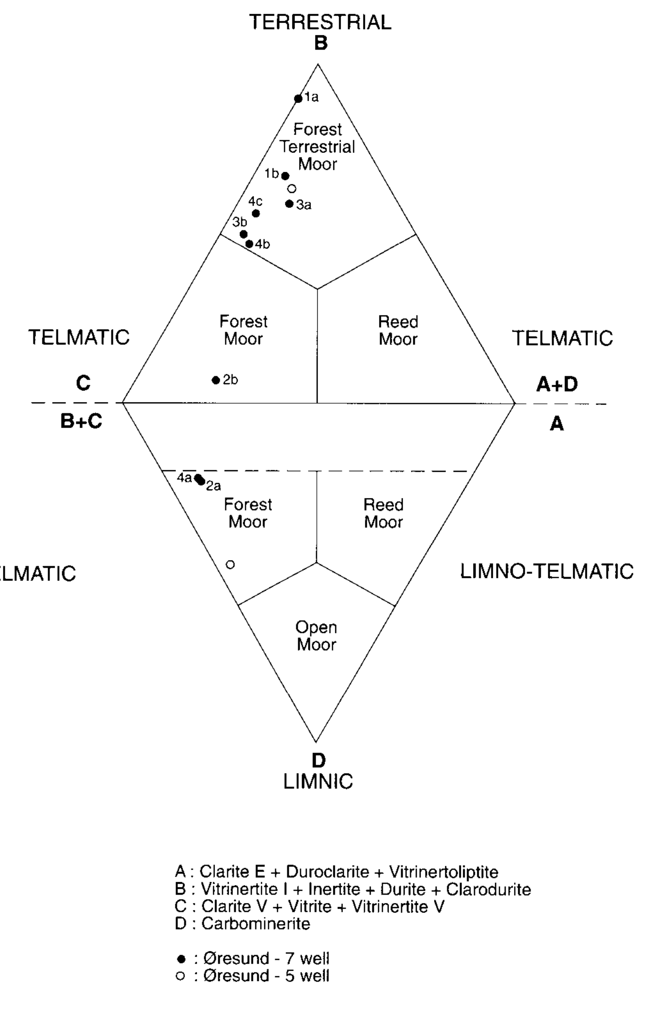

Fig. 7: Four-component facies diagram for the coal samples from the Øresund-5 and -7 wells
(Sample nos. refer to the four coal seams from the Øresund-7 well: Seam 1, 1a=6356 and 1b=6357; Seam 2, 2a=6358 and 2b=6359; Seam 3, 3a=6360 and 3b=6361; Seam 4, 4a=6362, 4b=6363 and 4c=6364; See also Figures 16 and 17) (Diagram modified from Hacquebard & Donaldson, 1969). See text for further explanation.

wood among the swamp vegetation.

Humodetrinite constituting finely dissiminated humic matter (attrinite, densinite) is supposed to originate from decomposition of a fragile cellulose-rich vegetation (Teichmüller, 1982, 1989; Styan & Bustin, 1983; Calder, 1993). During the Jurassic, prior to the evolution of angiosperms, such vegetation was represented by herbaceous type of plants.

Facies diagrams

Two types of facies diagrams are used to support the interpretations. One is based on the maceral composition and the other on the microlithotype composition.

The former was first proposed by Diessel (1985, 1986) and is defined by the Tissue Preservation Index (TPI) and the Gelification Index (GI) (Fig. 4). The TPI is a measure of the relationship between tissue (more or less structured macerals) and groundmass (unstructured macerals) in the coal, which may reflect the ratio between the shrubby/arboreous vegetation and the herbaceous type of vegetation in the original mire. The GI compares gelified tissues to oxidized tissues and the GI is thus a measure of the humidity or oxidation in the mire. The original TPI and GI formulae have been modified by Petersen (1993) (Fig. 5):

TPI = tex+texto+eu+ul+semif+fus/at+den+inert

GI = huminite/inertinite

where: tex=textinite; texto=textoulminite; eu=eu-ulminite; ul=ulminite; semif=semifusinite; fus=fusinite; at=attrinite; den=densinite; inert=inertodetrinite.

The high content of inertodetrinite in most of the samples is the major problem in this context. The inertodetrinite may be formed by fusinitization of a herbaceous type of flora and/or it may be the result of fragmentation of fusinite (derived from larger plants) due to desiccation of a peat surface or due to transportation. The inertodetrinite maceral is placed in the denominator of the TPI, and because of the high content of the maceral in many of the samples it has a great influence on the TPI value. Therefore, to evaluate the TPI correctly, the genetic origin of the inertodetrinite must be considered. For example, a TPI below 1 may not necessarily indicate a dominantly herbaceous type of vegetation, but rather reflect disintegrated fusinite/semifusinite initially derived from larger plants due to desiccation of a peat surface (Fig. 5). Other parameters must be considered to obtain the most valid interpretation.

MICROLITHOTYPE - GROUP COMPOSITION

Well	Coal seam	Sample no.	% A	% B	% C	% D	A + D % < 20 % D	B + C % > 20 % D
Øresund-5	Seam 1	6365	5	63	25	7	12	-
		6366	3	42	7	48	-	49
Øresund-7	Seam 1	6356	0	90	10	0	0	-
		6357	8	67	25	0	8	-
	Seam 2	6358	8	8	61	23	-	69
		6359	10	7	73	10	20	-
	Seam 3	6360	6	59	28	8	13	-
		6361	6	50	44	0	6	-
	Seam 4	6362	7	7	64	22	-	70
		6363	5	47	44	4	9	-
		6364	2	56	38	4	6	-
Øresund-13	Seam 1	6368	3	49	3	45	-	52
Øresund-15	Seam 1	6367	10	9	69	12	22	-
Øresund-18	Seam 1	6369	32	18	45	5	37	-
		6370	22	57	11	10	32	-
		6372	5	78	12	5	10	-
		6373	14	45	36	5	19	-
		6371	11	45	28	16	27	-
	Seam 2	6374	5	33	7	55	-	40
		6375	19	4	61	16	36	-

A : % clarite E + % duroclarite + % vitrinertoliptite
B : % vitrinertite I + % inertite + % durite + % clarodurite
C : % clarite V + % vitrite + % vitrinertite V
D : % carbominerite

Table 4

The second facies diagram is based on the "four-component facies diagram" originally proposed by Hacquebard and Donaldson (1969) (Figs 6 & 7). The diagram is based on four groups of microlithotypes which are considered to represent four different coal facies. Table 3 shows the definition of the microlithotypes. The composition of the groups listed in figures 6 and 7 is modified relative to the original facies diagram of Hacquebard and Donaldson (1969).

The microlithotype-group composition of the studied seams is shown in Table 4. "A" represents a telmatic to limnotelmatic reed moor facies, whereas "C" represents a telmatic to limnotelmatic forest moor facies. Many of the coal seams discussed here are considered to have been exposed to periodic desiccation. Therefore, it is assumed that the microlithotypes inertite and durite were mainly formed by inertinization at the peat surface. They indicate a relative dry environment and together with vitrinertite I and clarodurite they make up group "B", indicative of a terrestrial forest moor facies. The terms "forest moor" and "reed moor" are here not considered to represent specific moor types but rather as indicators of the vegetation type: the former suggests a larger and more dense vegetation compared to the latter. Group "D" represents a limnic open moor facies. If "D" comprises less than 20 % of the microlithotype composition (note that not all microlithotypes are used in the facies diagram; therefore the values are corrected to make up 100 %) "D" is added to "A" and the uppermost triangle of the diagram is used. If "D" comprises greater than 20 % of the microlithotype composition the lowermost triangle is used, and if such is the case "B" is added to "C".

The Øresund-13 well

Only the lowermost c. 8 m (94.95-87.09 m) of the Øresund-13 well was logged. The section contains one unit, 6.33 m thick, that consists of claystone and heterolithic clay and siltstone that is overlain with a gradual contact by a 0.18 m thick coal seam (Fig. 8). The beds dip approximately 10°.

Unit 1: 94.95-88.62 m

Sedimentological description: The unit begins with approximately 1.40 m of light grey to dark grey silt-streaked and parallel-laminated claystone. The succeeding c. 4.50 m consist mainly of siltstone-dominated heterolith. The lower part of the heterolith is mainly parallel-lami-

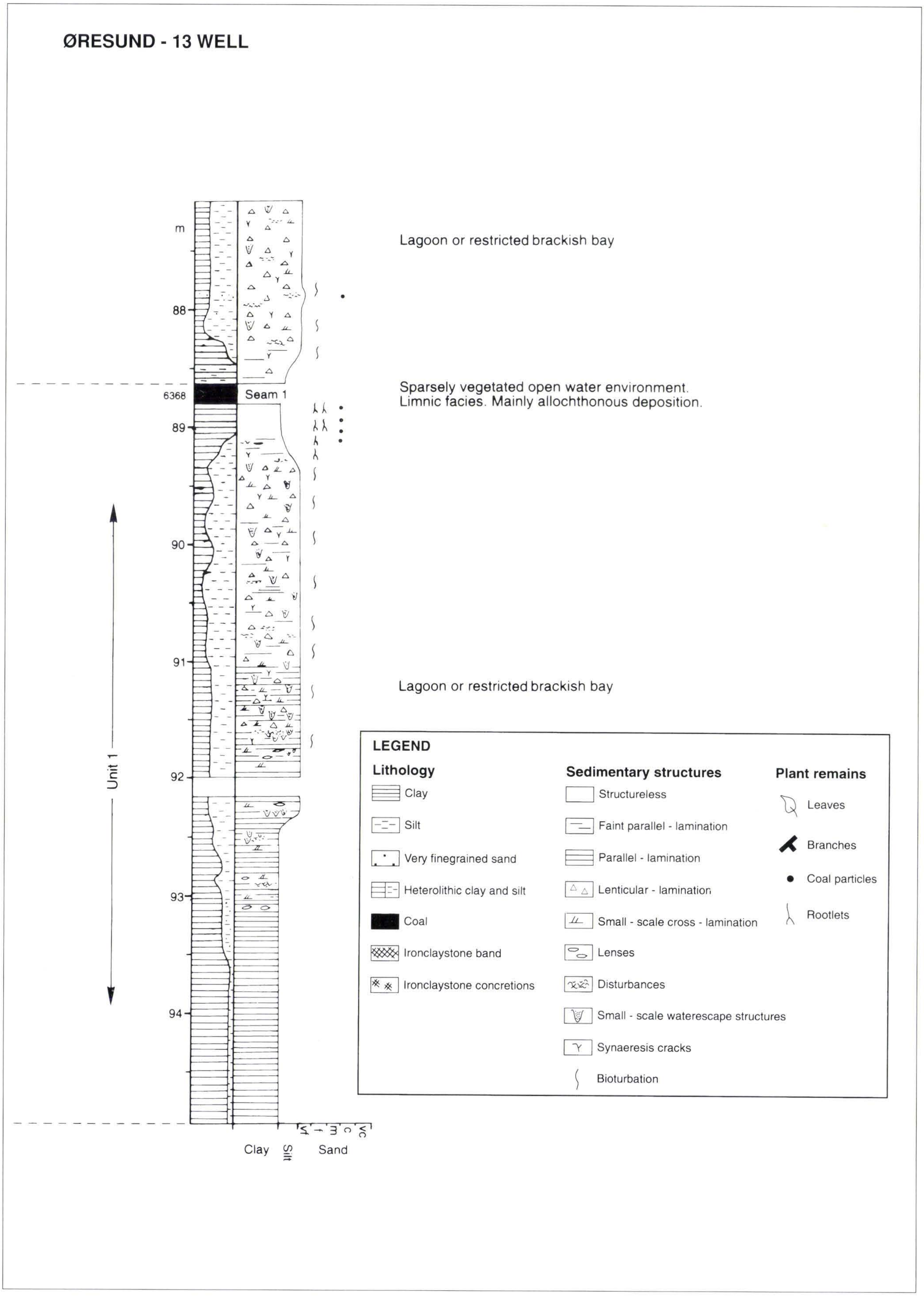

Fig. 8: Lithological log of the investigated part of the Jurassic succession of the Øresund-13 well.

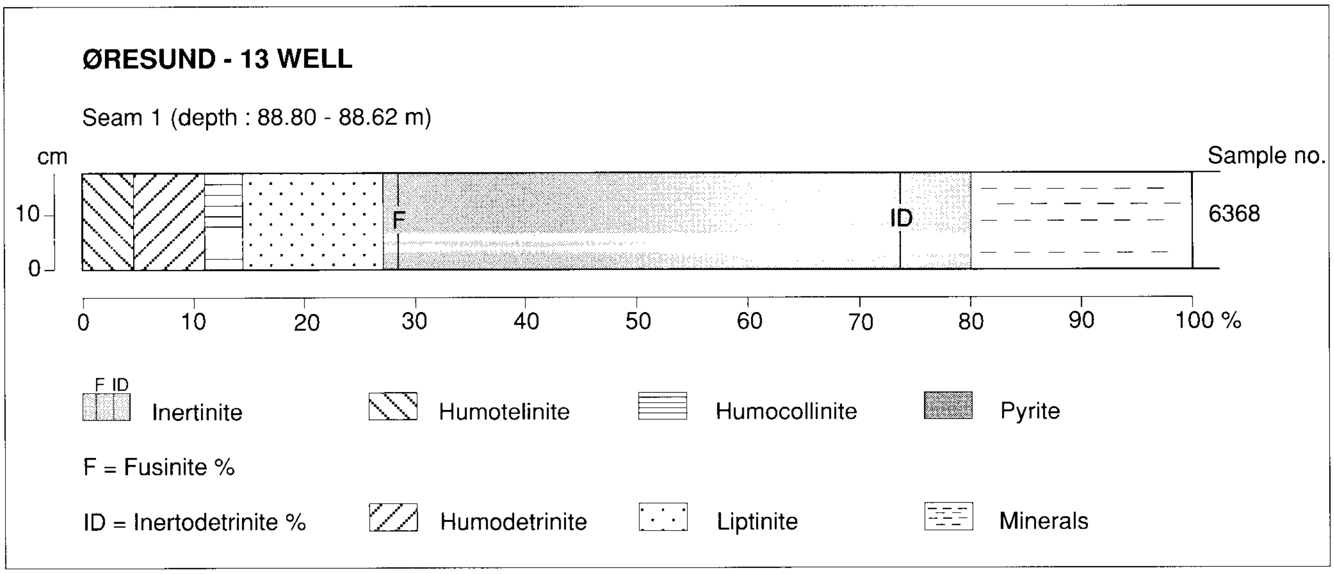

Fig. 9: The coal petrographic composition of the seam from the Øresund-13 well.

nated, whereas the overlying part is increasingly dominated by faint parallel-lamination to irregular or lenticular lamination. The siltstone lenses are cross-laminated. Small-scale water escape structures and synaeresis cracks are present, together with other signs of sediment disruption, probably including bioturbation. The transition from the heterolith to the black, structureless rooted claystone underlying the coal seam is distinct. The claystone contains coal particles.

Characterization of coal seam 1: The seam is c. 0.18 m thick. Macroscopically is it a black, homogeneous, hard and compact coal. The TOC content is 40.50 wt-% (Table 5).

The polished coal block shows microlamination consisting of approximately 300 microns thick laminae. Two types of lamination are recognized (Plate 1, A). The first type is characterized by very well-sorted macerals generally < 5 microns (Plate 1, B), whereas the other type mainly consists of larger macerals (10-20 x 30-40 microns), although particles < 10 microns are also abundant (Plate 1, C). The macerals are mainly inertinite, but rounded and oblong huminite macerals are present. A fusinized very small twist is observed (Plate 1, D).

The seam is very rich in inertinite (52.8 vol.%) (Fig. 9). A general feature of the inertinite macerals is the relatively low reflectance. Inertodetrinite is the most prominent maceral of the inertinite maceral group, followed by macrinite (Table 2). The huminite content amounts to only 14.6 vol.% and the three submaceral groups are roughly evenly represented. Attrinite is the dominant maceral of the huminite maceral group. Macerals of the liptinite group are abundant (12.6 vol.%) and are represented by sporinite, liptodetrinite and cutinite. The seam meets the definition of a carbonaceous claystone as the mineral matter content is 20.0 vol.% (Fig. 9).

Mineral- and inertinite-rich carbominerite is the most significant microlithotype and, together with clarodurite and inertinite-dominated durite and vitrinertite, constitutes the greater part of the coal seam.

The seam is overlain by alternating laminae of claystone and silty claystone followed by a lenticular-laminated heterolith of siltstone and claystone with cross-lamination. The coal/sediment transition is distinct.

Interpretation: The lowermost part of unit 1 was deposited under very low energy conditions, as shown by the claystone dominated parallel-laminated heterolith. The increasing content of siltstone and the gradual change from parallel-lamination to faint parallel-lamination and lenticular-lamination with increasing frequency of small-scale cross-lamination indicates fluctuating energy levels and the presence of weak currents. This is in agreement with the occurrence of bioturbation showing that the environment was well-oxygenated. The synaeresis cracks probably formed due to fluctuations in salinity (Plummer & Gostin, 1981; Wightman et al., 1987), which suggests that deposition took place under brackish conditions. The absence of agglutinated foraminifera indicates a restricted environment with low salinities; fully marine conditions were never established (Larsen et al., 1968). The gradual infilling of the water body finally resulted in deposition of massive black clay with coal particles indicating decreased availability of oxygen. The increasing anoxia favoured accumulation and preservation of organic matter. Rootlets indicate low water depth and the establishment of a sparse swamp vegetation. The unit is thus interpreted as a shallowing-upward succession deposited in a restricted bay or lagoon, that evolved into a sparsely vegetated swamp.

The maceral and microlithotype composition of the seam indicates that it represents a limnic facies. The microlamination and sorting of the organic matter is the result of transportation and deposition in the swamp probably together with redeposition within the swamp due to weak currents. As emphasized by Petersen (1993) the TPI vs. GI facies diagram does not confirm the allochthonous origin of inertinite-rich and mineral matter rich coals (Fig. 5). Based on the TPI vs. GI diagram the seam may equally be interpreted as a desiccated peat surface. This bias is attributed to the way the GI is calculated; i.e. it does not distinquish allochthonous inertinite from autochthonous inertinite, and it does not include the content of minerals.

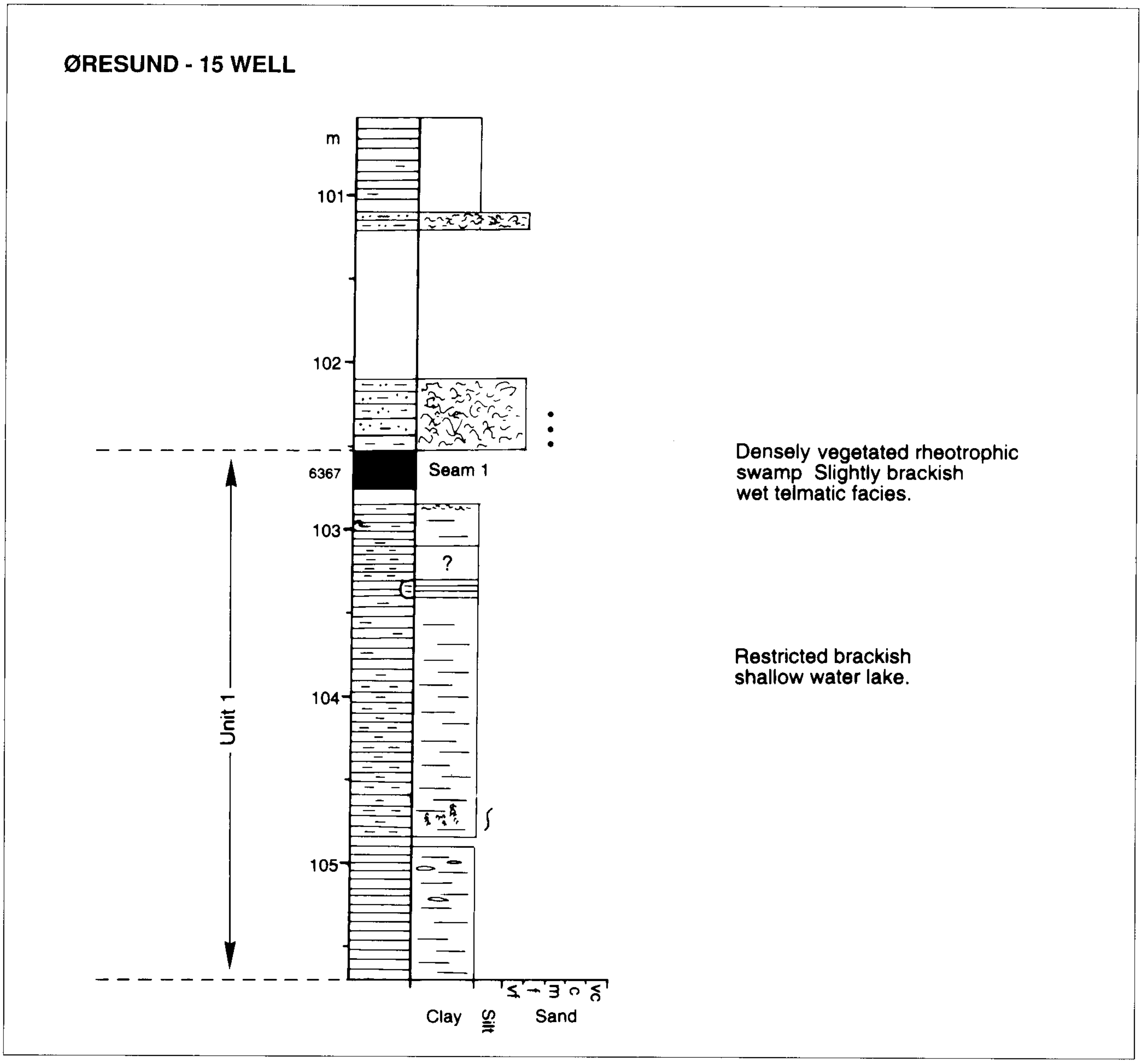

Fig. 10: Lithological log of the investigated part of the Jurassic succession of the Øresund-15 well. Legend, see Figure 8.

The probably sparse in situ vegetation contributed to a minor extent to peat formation. Decomposition of the plant tissues formed huminite and the infiltration of the mainly allochthonous inertinite by the humic substances formed the vitrinertite and clarodurite. The sample from the coal seam plots within the field of the limnotelmatic forest moor facies in the four-component facies diagram suggesting a wet depositional environment (Fig. 6). However, durite and clarodurite are considered to be mainly of allochthonous origin; hence, if they are added to "D" in the four-component facies diagram, as originally proposed by Hacquebard & Donaldson (1969), the sample plots within the limnic open moor facies, thus indicating an allochthonous origin of the seam.

In conclusion, unit 1 represents sedimentation within a restricted bay or lagoonal environment; decreasing water depth favoured plant growth and the wet-land became sparsely vegetated. The increasing anaerobic conditions promoted the accumulation and humification of the organic matter, though most was derived from redeposition of peat from adjacent areas. Salinity fluctuated initially but was subsequently low, as indicated by the absence of pyrite within the coal seam. The seam represents a sparsely vegetated open water environment protected from marine influence but with restricted connection to nearby fluvial systems. The mire may have been located within the coastal plain environment. Increased input and deposition of siliciclastics caused by changes in the surrounding hydrological systems ended the accumulation of organic matter.

The Øresund-15 well

The lowermost 5.15 m (105.70-100.55 m) has been measured (Fig. 10). Generally the core quality is poor. The measured section includes one shallowing-upward unit, 3.17 m thick, that consists of claystone capped by a 0.22 m thick coal seam. The beds dip approximately 45°.

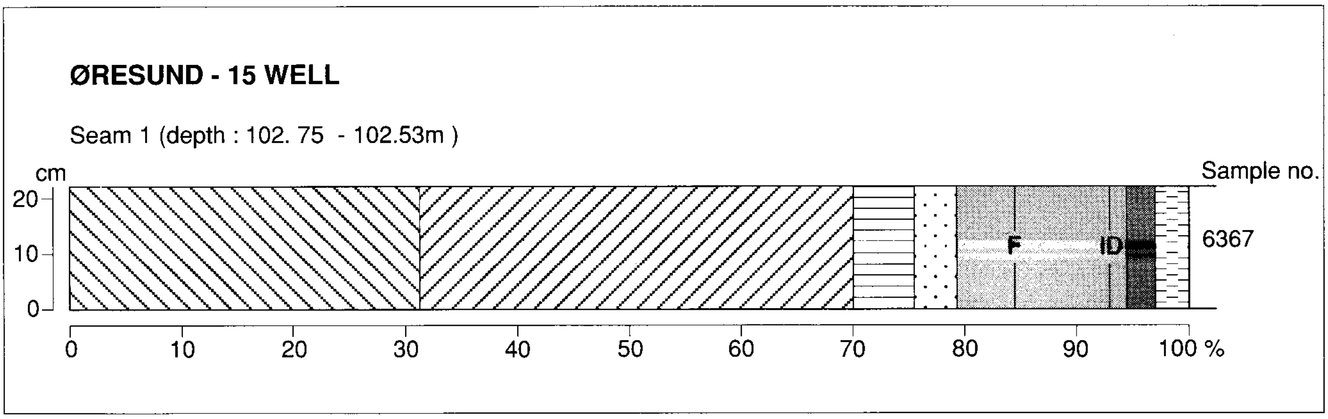

Fig. 11: The coal petrographic composition of the seam from the Øresund-15 well. Legend, see Figure 9.

Unit 1: 105.70-102.53 m

Sedimentological description: The unit begins with a grey, faintly parallel-laminated claystone with silty laminae; in the lowermost part siltstone lenses occur. No systematic change between clay and silt laminae is observed. Graded laminae (approximately 1 cm thick) define a thin stratification; such laminae are light grey and probably more silty at the base and become darker upwards probably due to an increased clay content. The transition from one lamina to another is sharp and erosive in places. The unit becomes darker and more massiv upwards with few siltstone-streaks.

Characterization of coal seam 1: The c. 0.16 m thick (corrected thickness) coal seam is poorly cored. The coal seam has a TOC content of 44.90 wt-% (Table 5). Macroscopically, much gelified tissue is recognizable, which is confirmed by the maceral analysis showing a huminite content of 75.4 vol.% (Fig. 11). Densinite and eu-ulminite are the dominant macerals of the huminite maceral group (Table 2). The inertinite maceral group amounts to 15.4 vol.% and the dominant macerals are inertodetrinite and fusinite. The content of liptinite and mineral matter is low, 3.6 vol.% and 5.6 vol.% respectively. Pyrite forms nearly half of the mineral content.

The microlithotype composition is dominated by vitrite, clarite and vitrinertite with huminite as the most significant constituent of the latter two bimacerites. The carbominerite content is also prominent.

The coal seam is overlain by highly disrupted laminated claystone with discrete siltstone/fine-grained sandstone laminae. Coal particles are present.

Interpretation: The sediments were deposited under low energy conditions. The preserved stratification and the absence of trace fossils indicate that deposit feeders were missing, thus suggesting a poorly oxygenated sediment. The absence of plant remains within the clastic sediments and the occurrence of pyrite within the coal seam suggest a restricted brackish shallow-water lake within a coastal plain setting. The lake and the swamp was influenced by saline water, but they were not affected by severe inundations. The presence of pyrite is considered to be indicative of marine-influenced swamps since these provide the optimum conditions for pyrite formation: the availability of sulphate ions, the presence of iron minerals, the high concentration of organic matter and the presence of sulphate-reducing anaerobic bacteria (e.g. Berner, 1981; Mackowsky, 1982; Postma, 1982; Teichmüller & Teichmüller, 1982a; Styan & Bustin, 1984; Casagrande, 1987; Diessel, 1992).

The coal seam represents a limnotelmatic-telmatic facies. The vegetation consisted mainly of herbaceous type of plants, but a more woody vegetation was also common. These were mainly shrub-like plants, arboreous plants such as smaller trees and, to a lesser extent, large plants with more lignified wood. Corpohuminite was probably derived from gymnospermous plants.

The interpretation is further supported by the high content of the microlithotypes vitrite, clarite and vitrinertite V. This is compatible with the telmatic forest moor facies indicated by the four-component facies diagram and also with the mainly herbaceous type of plant community and limnotelmatic facies indicated by the TPI vs. GI diagram (Figs 5 & 6). The inertinite may have originated from oxidation of the in situ vegetation by oxygenated water and/or by wildfires.

The peat-forming environment was established on top of lake-fill sediments. The seam represents a swamp within a coastal plain setting. The plant community was dominated by a herbaceous type of vegetation together with abundant cellulose-rich shrubby plants and small trees. The swamp was presumably slightly brackish. Increased input of siliciclastic sediments interrupted peat formation.

The Øresund-18 well

Approximately 7 m of core (16.43-9.41 m) has been measured (Fig. 12). The section contains two units: unit 1, 4.33 m thick, consists mainly of claystone overlain by a 0.25 m thick coal seam, whereas unit 2, 1.65 m thick, consists mainly of a heterolith overlain by a 0.15 m thick coal seam.

Unit 1: 16.43-12.10 m

Sedimentological description: With the exception of the heterolithic basal part, the unit consists of a grey to dark grey, generally structureless claystone locally with occasional siltstone streaks. However, stratification is defined by alternating light grey and dark grey claystone laminae in the interval 14.45-13.00 m. The light grey laminae appear to be slightly more silty. The lower half of the unit contains several reddish/brownish iron claystone bands whereas the

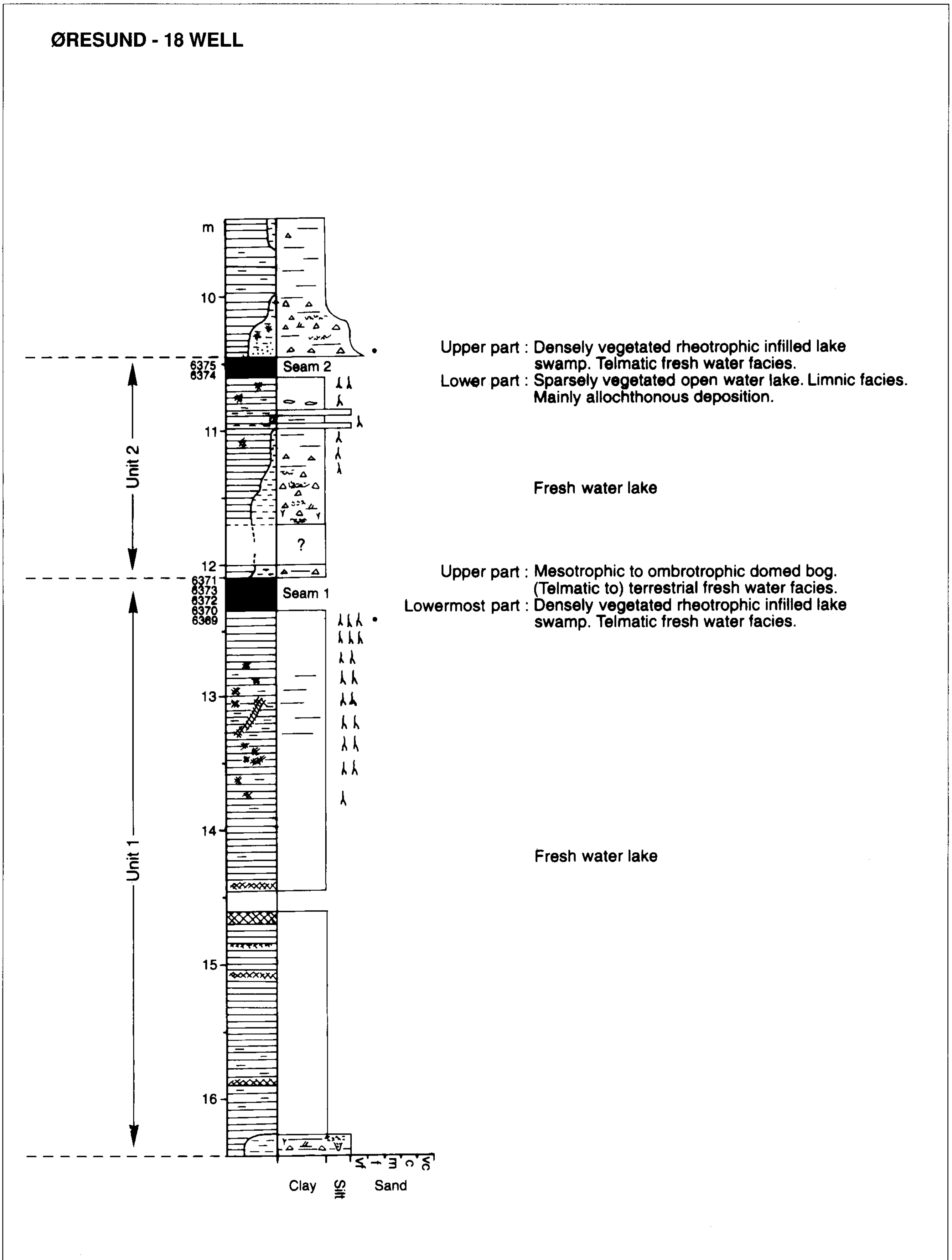

Fig. 12: Lithological log of the investigated part of the Jurassic succession of the Øresund-18 well. Legend, see Figure 8.

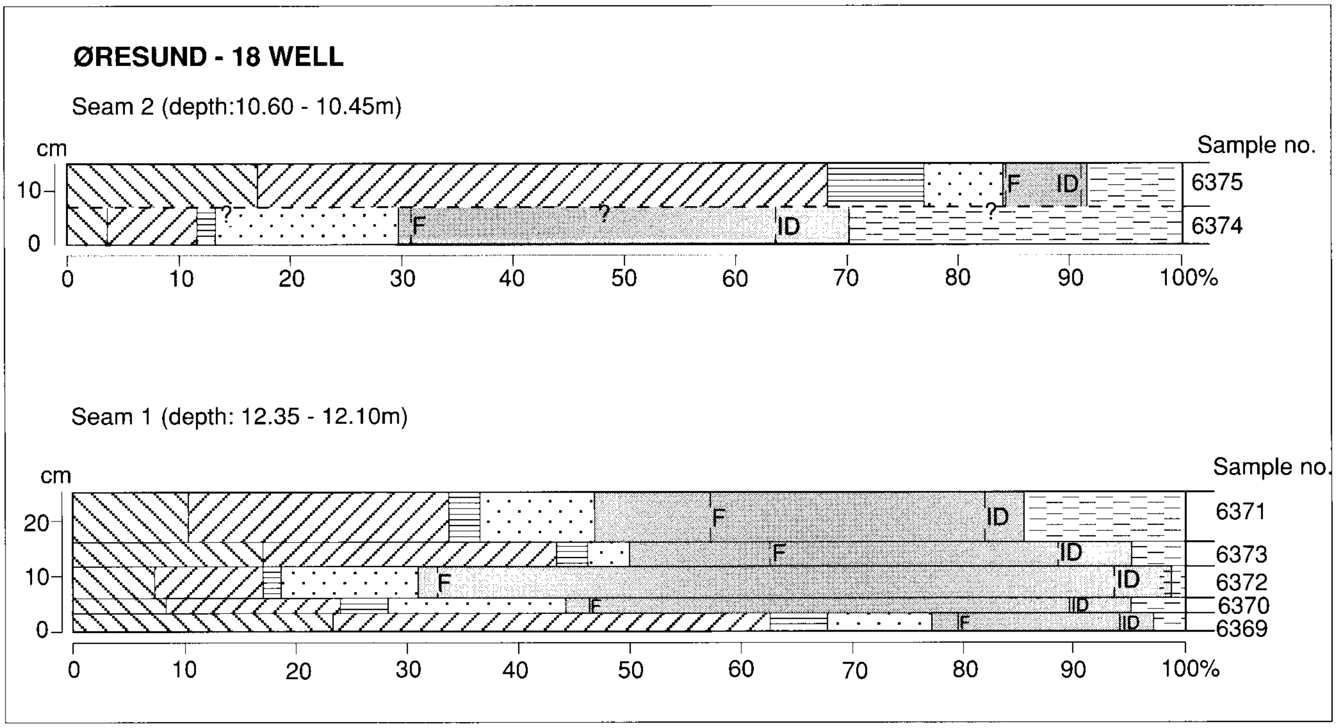

Fig. 13: The coal petrographic composition of the seams from the Øresund-18 well. Legend, see Figure 9.

upper half contains small iron concretions. Rootlets increase in frequency upwards, towards the base of the coal seam, and coal particles are present immediately under the seam.

Characterization of coal seam 1: The seam is c. 0.25 m thick and comprises black, hard and compact coal with TOC contents between 57.30 wt-% and 69.10 wt-% (Table 5). A polished coal block (sample 6370) from the interval 3-6 cm above the base of the seam shows laminae consisting of varying reflecting and relative poorly sorted and rounded inertodetrinite particles associated with liptinite, mainly liptodetrinite and sporinite (Plate 2, A). The laminae contain stringers of huminite. These laminae alternate with laminae composed of much larger concentrations of inertinite, e.g. fusinite (Plate 2, B). The organic matter forming the inertinite seems to have been partly gelified before it was oxidized. Another polished coal block (sample 6372) from the interval 6-12 cm is very similar to the sample described above. Pyrofusinite and pyroinertodetrinite is present (Plate 2, C). The poorly sorted and rounded inertinite may occur in close association with huminite, mainly densinite (Plate 2, D, E).

The seam has a varying content of huminite with the highest content at the base of the seam (67.8 vol.%) and the lowest value in the interval 6-12 cm (18.8 vol.%) (Fig. 13). Humodetrinite dominates over humotelinite, and the most prominent macerals are densinite and eu-ulminite ranging between 9.2-36.0 vol.% and 6.4-22.4 vol.% respectively (Table 2). In general, a decrease in the content of huminite is accompanied by an increase in the content of inertinite. The inertinite shows varying reflectance and consists mainly of inertodetrinite together with macrinite, fusinite and semifusinite. The liptinite content is high (maximum value: 16.0 vol.%) and is dominated by the liptodetrinite and sporinite macerals (Fig. 13, Table 2). With the exception of the uppermost part of the seam, the mineral content is very low, i.e. not exceeding 4.8 vol.%. Quartz grains are a common constituent of the mineral matter in the uppermost part.

The microlithotype composition is complex; all of the microlithotypes, except liptite, are present in varying amounts throughout the seam. But two trends can be demonstrated: vitrite, vitrinertite V and duroclarite are significant microlithotypes in the huminite-rich intervals (0-3 cm and 12-16 cm) of the seam, whereas the microlithotypes durite, clarodurite and inertite constitute a major part of the inertinite-rich intervals of the seam.

Interpretation: The major part of the unit was deposited under very low energy conditions, shown by the homogeneous, generally structureless claystone. The claystone is interpreted to represent lake deposits. The increasing abundance of roots upwards shows, that the lake was gradually overgrown and a swamp was established. Within the swamp environment, tissues from the in situ plants accumulated, resulting in an autochthonous peat/coal deposit.

The lowermost part of the seam represents a limnotelmatic/telmatic facies. The very low content of minerals is attributed to (1) a generally low input of siliciclastics, and (2) a dense vegetation dominated by herbaceous type of plants together with abundant larger plants which hindered inundation of the peat swamp. The lower to middle part of the seam represents a dry terrestrial facies, whereas the upper part represents a slightly wetter terrestrial facies. The high content of poorly sorted and poorly rounded inertodetrinite indicates that the inertodetrinite was formed in situ during the drier events. Thus, most of the coal seam indicates that peat formation occurred within a domed bog. The liptinite was probably derived from in situ plants and the predominance of liptodetrinite is attributed to the degradation processes at the peat surface. The TPI vs. GI diagram suggests a fluctuating watertable and shows an evolution from a limnotelmatic swamp facies (sample 6869) dominated by a herbaceous type of vegetation to a terrestrial facies represented by a raised bog (samples 6370 to 6373) (Fig. 5). This mire evolution is further indicated by the microlithotypes. The lowermost part of the seam is dominated by microlithotypes characteristic of a forest swamp environment, whereas microlithotypes indicating a dry oxidizing environment are prominent in the lower to middle part of the seam. The upper part represents slightly wetter conditions than the lower and middle part. This is suggested by the increased content of vitrite and clarite and also of vitrinertite V in the interval 12-16 cm (sample 6373) in association with a decreased content of clarodurite and inertinite-dominated durite. The four-component facies diagram supports this interpretation (Fig. 6). The lowermost sample plots within the field of the telmatic forest moor facies close to the field of the telmatic reed moor facies. The rest of the seam plots within the field of the terrestrial forest moor facies thus indicating a raised bog deposit. The uppermost samples plot closer to the field of the telmatic forest moor facies, which is in accordance with the slightly wetter conditions (Fig. 6).

Unit 1 represents the infill of a fresh water lake isolated from marine influence. Decreasing water depth promoted plant growth and a swamp dominated by a herbaceous type of flora was established. Abundant larger plants with cellulose-rich wood were also present. The peat became more domed and a dry terrestrial facies was established, followed by a somewhat wetter terrestrial facies. Stunting of the vegetation might have occurred. The peat accumulation was terminated by gradual drowning of the mire (see below).

Unit 2: 12.10-10.45 m

Sedimentological description: A few cm of black carbonaceous claystone immediately overlies coal seam 1. The clay is overlain by a lenticular-laminated heterolith consisting of siltstone and claystone. Cross-lamination is observed in the siltstone lenses. The siltstone is light-colored whereas the claystone is brownish and reddish due to iron-staining. Small-scale water escape structures are present. Upwards the heterolith becomes faintly parallel-laminated and rooted. Two thin yellowish siltstonebeds separated by iron-stained clay with rootlets overlies the heterolith. The uppermost 0.25 m of sediment underlying the coal seam is a dark grey to black, structureless and rooted claystone with rare siltstone lenses and concretions of iron claystone.

Characterization of coal seam 2: This seam is c. 0.15 m thick. The lower part is composed of dull coal with a TOC content of 33.50 wt-% (Table 5); the upper part consists of black, hard coal with a TOC content of 55.60 wt-%.

The lower part contains 30.2 vol.% minerals (Fig. 13; Table 2). Inertodetrinite makes up most of the 40.4 vol.% inertinite. The high content of liptinite (16.2 vol.%) is dominated by sporinite and liptodetrinite, 10.0 vol.% and 5.6 vol.%, respectively. The content of huminite is very low (13.2 vol.%), especially compared to the upper part of the seam where it amounts to 76.8 vol.%. In the upper part, densinite is the dominant maceral of the huminite maceral group followed by eu-ulminite. The content of liptinite, inertinite and mineral matter has decreased relative to the lower part to 7.6 vol.%, 7.0 vol.% and 8.6 vol.%, respectively (Fig. 13, Table 2).

The maceral composition is reflected in the microlithotype composition of the seam; carbominerite, durite and inertite dominate the lower part of the seam, while vitrite, duroclarite and huminite-rich clarite and carbominerite are important constituents of the upper part.

Interpretation: Increased water depth and input of siliciclastics temporarily ended the peat-forming environment that formed seam 1. The black, organic rich claystone suggests that the boundary between coal seam 1 and the overlying clastic sediments is gradual rather than erosive. A return to diminished deposition of siliciclastics combined with a decreasing water depth within the depositional area promoted accumulation of organic matter.

The lower part of seam 2 represents deposits from an open fresh water lake. The presence of rooted sediments below the base of the seam indicates that a sparse vegetation was present. This interpretation is supported by the carbominerite- and durite-dominated microlithotype composition, and is also suggested by the plot close to the field of the limnic open moor facies in the four-component facies diagram (Fig. 6). The plot is somewhat biased in this case, however, due to the allochthonous origin of the durite. Durite should be added to component "D", which would move the plot inside the field of a limnic open moor facies. The TPI vs. GI diagram does not support the inferred depositional environment, due to the allochthonous nature of the lower part of the seam (Fig. 5).

The upper part of the coal seam represents a telmatic facies. The mineral content indicates periodically inundations of the swamp; such events are compatible with a strong gelification of plant tissues (humocollinite). The nutrient-rich conditions favoured a luxuriant plant community. Herbaceous type of plants dominated over shrub-like and more arboreous plants. Although eu-ulminite is a common maceral of the huminite maceral group, and indicates abundance of plants with cellulose-rich wood, the increased gelification may bias this interpretation as the decomposition of lignified wood from larger plants like-wise is enhanced. The four-component diagram indicates a telmatic forest moor facies (Fig. 6). The TPI vs. GI diagram suggests a limnic to limnotelmatic facies (Fig. 5). The GI value indicates anoxic conditions within the swamp, which is in agreement with the above interpretation. The high content of humodetrinite accounts for the very low TPI, and thus for the probably too wet facies indicated by the plot.

Like unit 1, unit 2 represents the gradual infill of a lake and the establishment of a swamp environment. The peat and the clastic sediments were deposited in fresh water. The initial limnic coal facies was succeeded by a telmatic coal facies. The swamp vegetation was luxuriant and probably dominated by a herbaceous type of flora. The peat represented by seam 2 never evolved to a raised bog as did the peat represented by seam 1.

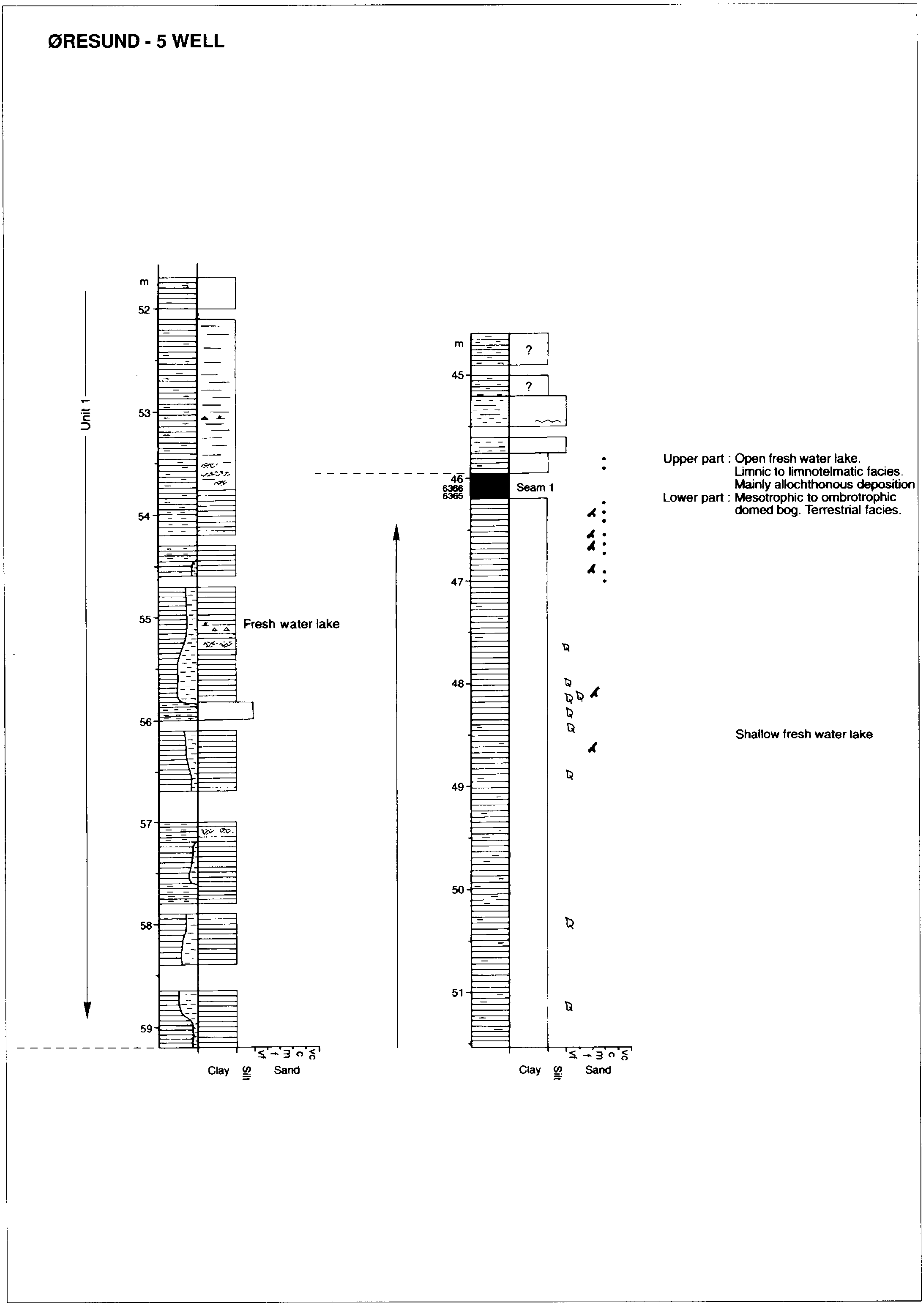

Fig. 14: Lithological log of the Jurassic succession of the Øresund-5 well. Legend, see Figure 8.

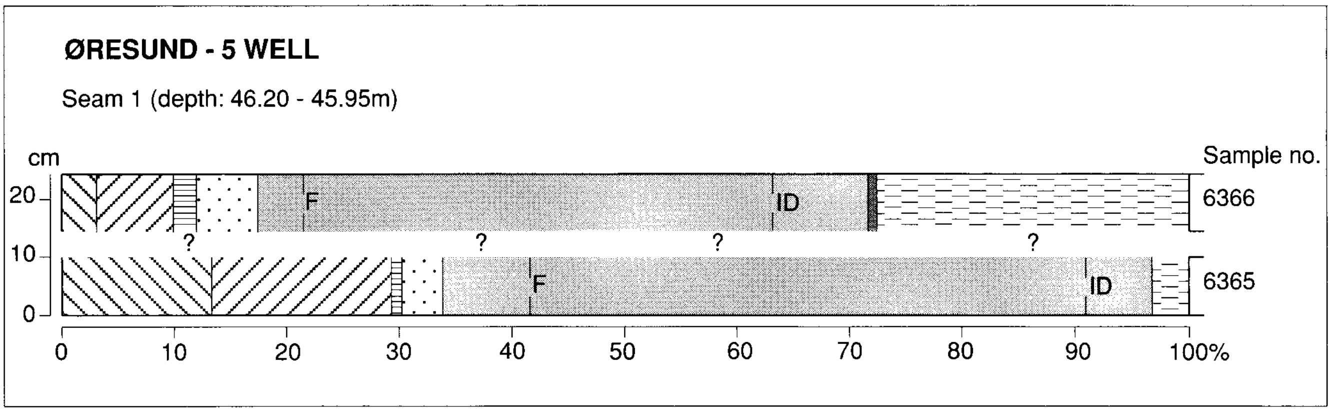

Fig. 15: The coal petrographic composition of the seam from the Øresund-5 well. Legend, see Figure 9.

The Øresund-5 well

The Jurassic succession in the well was measured (59.20-44.60 m) (Fig. 14). The section contains one unit, 13.25 m thick, dominated by claystone and a 0.25 m thick coal seam. The beds dip about 25°-30°.

Unit 1: 59.20-45.95 m

Sedimentological description: The lowermost 4.75 m of the unit consists of a parallel-laminated heterolith of claystone and siltstone. The claystone is dark brown, the siltstone light brown. Lenticular-bedding and cross-lamination is recognized and small-scale disturbances occur locally. The silt content decreases upward, grading up into a parallel-laminated to faintly parallel-laminated claystone with siltstone-streaks. Upwards, the silt content decreases further and the lamination disappears rather abruptly. The claystone becomes dark brown to black and structureless. Coal-streaks are present and, together with coal particles, may be abundant in the upper part. The coal particles have no preferred orientation. Larger and smaller branches and leaves are found throughout the upper c. 5.0 m.

Characterization of coal seam 1: The seam is c. 0.22 m thick (corrected thickness) and comprises black, dull and structureless coal and carbonaceous claystone. The seam has a TOC content of 52.10 wt-% in the lower part and 33.70 wt-% in the upper part (Table 5).

The lower part of the seam contains 62.8 vol.% inertinite (Fig. 15). Inertodetrinite is the primary maceral of the inertinite maceral group (48.8 vol.%), but fusinite, macrinite and semifusinite are also present (Table 2; Plate 3, A, B). Densinite (12.0 vol.%) and eu-ulminite (10.2 vol.%) dominate the huminite maceral group (30.0 vol.%) (Fig. 15). The content of liptinite and mineral matter is low.

In the upper part of the seam, inertodetrinite (42.6 vol.%) is still dominant in the inert fraction (53.8 vol.%) of the coal (Fig. 15, Table 2). Nearly all of the inertinite macerals are relative low reflecting. Compared to the lower part, the mineral matter content increases significantly to 28.6 vol.%, whereas the huminite content decreases to only 12.0 vol.%.

The basal part of the seam is characterized by the microlithotypes inertite, clarodurite and inertinite-dominated vitrinertite and durite. Furthermore, vitrite is a prominent constituent. Carbominerite is the most significant microlithotype in the upper part of the seam. Other important microlithotypes are inertite, durite and vitrinertite.

The coal seam is overlain by a black structureless claystone with coal-streaks and coal particles. Approximately 0.20 m above the coal seam the sediments become more silty, passing up into a structureless siltstone with claystone-streaks.

Interpretation: The siliciclastic sediments of unit 1 record the gradual infill of a lake. The absence of bioturbation and synaeresis cracks suggests a fresh water lake. The increasing content of preserved organic matter indicates deterioration of the oxygen sypply in the swamp water. Furthermore, the presence of abundant plant remains suggests that a vegetation existed close to the lake.

Roots are not recognized below the base of the coal seam and this, combined with the high content of macerals resistant to degradation by transportation, may suggest a limnic facies. On the other hand, the overall composition of the lower part of the seam suggests a terrestrial facies representing domed bog. The coal composition reflects alternating oxidizing and reducing conditions during deposition of the peat. Together with gelified tissues, the inertinite formed the prominent content of vitrinertite (Styan & Bustin, 1983). The four-component facies diagram and the TPI vs. GI diagram indicate a dry depositional environment as sample 6365 plots within the field of the terrestrial forest moor facies and the terrestrial dry forest swamp facies, respectively (Figs 5 & 7).

The detailed interpretation of the mire evolution from the lower to the upper part is somewhat speculative, because the middle part of the seam is very poorly cored. The upper part of the seam represents a limnic facies. Approximately 100 % of the inertinite exhibits low reflectance which may indicate redeposition of a raised bog surface. Sample 6366 falls within the field of the limnotelmatic forest moor facies of the four-component facies diagram (Fig. 7). If durite and inertite are regarded as allochthonous, the plot would move inside the field of the limnic open moor facies, thus supporting the interpretation. The plot on the TPI vs. GI diagram is biased by the high content of allochthonous inertinite, and wrongly indicate a terrestrial dry forest swamp facies (Fig. 5).

The mire evolution shown by the seam is peculiar. A "normal" mire evolution is from a planar mire towards a raised bog (Calder et al., 1991; Calder, 1993). This seam shows the opposite evolution. This suggests that peat accumulation rapidly exceeded the rate of water level rise. Desiccation, flooding and a fluctuating watertable formed the very inertinite-rich and mineral poor peat at the base of the seam. The upper part of the seam suggests that the rate of water level rise exceeded the rate of peat accumulation and allochthonous carbonaceous clay was deposited in an open fresh water environment.

The Øresund-7 well

The entire Jurassic succession of the well was measured (56.75-41.43 m) (Fig. 16). The section contains four units, between 0.40 m and 4.68 m thick, each consisting mainly of claystone, capped by a coal seam. The seams are between 0.18 m and 0.77 m thick. The beds dip approximately 20°-30°.

Unit 1: 56.75-52.07 m

Sedimentological description: This basal unit consists of a dark grey to dark brown parallel-laminated claystone with occasional siltstone-streaks. The claystone gradually becomes structureless upwards towards the coal seam. Thin coal-streaks, branches and leaves are present throughout the unit but are particularly abundant in the upper half, together with coal particles, up to 2 cm long and 0.5 cm thick.

Characterization of coal seam 1: The seam is at least 0.20 m thick (corrected thickness) but the true thickness is uncertain due to poor core recovery. The TOC content varies between 53.10 wt-% and 57.10 wt-% (Table 5).

The content of inertinite is very high, 86.0 vol.% in the lower part and 66.0 vol.% in the upper part (Fig. 17, Table 2). The inertinite has a varying but mainly low reflectance. Inertodetrinite is the most prominent maceral of the inertinite maceral group (68.8 vol.% and 54.8 vol.%, respectively) followed by fusinite, macrinite and semifusinite. The huminite content amounts to 11.4 vol.% in the lower part of the seam, but increases to 29.6 vol.% in the upper part (Fig. 17, Table 2). Eu-ulminite is the dominant maceral of the huminite maceral group. Humodetrinite is more abundant in the upper part of the coal seam than in the basal part. The liptinite content is very low, and the mineral content is extremely low (ranging from 0.8-1.0 vol.%).

The microlithotype composition of the seam is clearly influenced by the high content of inertinite as inertite and inertinite-dominated vitrinertite are the most significant microlithotypes. Clarodurite and inertinite-dominated durite are likewise common constituents. Duroclarite is not observed in the lower part of the seam, but is common in the upper part together with vitrite.

Interpretation: The brown to black, parallel-laminated to structureless claystone with abundant preserved plant remains and coal particles is interpreted to indicate deposition under low energy conditions in a fresh water lake.

It is likely that only the upper part of the coal seam is preserved, precluding detailed elucidation of mire evolution. The coal seam represents a terrestrial facies. This is supported by the angular particles and large grain size variation of the inertodetrinite. The increased content of huminite at the top of the seam indicates wetter conditions compared to the underlying part and possibly a wetter terrestrial facies. Probably shrub-like plants, more arboreous plants and herbaceous type of plants were present in equal proportions.

The microlithotype composition corroborates the interpretation. Styan & Bustin (1983) suggested that vitrinertite is formed by flooding by oxygenated water followed by desiccation of the peat surface, but the negligible mineral content indicates that flooding was not an important process in the formation of this peat. The considerable content of fusinite suggests fusinitization before gelification of the organic matter, indicating that wildfires contributed to the formation of the inertinite. The four-component diagram and the TPI vs. GI diagram suggest a dry environment of peat formation (Figs 5 & 7). The two samples plot within the field of the terrestrial forest moor facies of the former diagram (sample 6356 very close to apex "B") and within the field of the terrestrial dry forest swamp facies of the latter (sample 6356 on the TPI axis).

Unit 1 represents a fresh water lake which was slowly filled by muds and plant remains. A mire was established and organic matter accumulated in anoxic swamp waters. Towards the top of the coal seam, the original peat had evolved to a raised bog. The plant community consisted of herbaceous type of plants, shrub-like plants and arboreous plants in roughly equal proportions. The bog was situated beyond the reach of saline waters.

Unit 2: 52.07-48.70 m

Sedimentological description: The lower 2.65 m of the unit comprises a parallel-laminated dark grey to light- colored heterolith of claystone and siltstone. Few fusinite particles are observed in the lowermost part. Upwards, towards the coal seam, the unit changes to a dark grey, structureless to faintly parallel-laminated claystone with minor siltstone-streaks. The content of coal particles increases and rootlets are present immediately under the seam.

Characterization of coal seam 2: The seam is approximately 0.16 m thick (corrected thickness) and is a black, hard coal with a TOC value of 47.60 wt-% in the lower part and a TOC value of 44.20 wt-% in the upper part (Table 5).

The huminite content increases from 71.8 vol.% in the lower part to 80.2 vol.% in the upper part of the seam, which is mainly caused by an increase in the amount of humodetrinite (Fig. 17). Eu-ulminite, densinite and attrinite are the principal macerals of the huminite maceral group (Table 2; Plate 4, A, B). The amount of structured huminite (textinite and textoulminite) increases from 2.4 vol.% to 4.4 vol.% from the base to the top of the seam. The liptinite content is a minor component of the seam. Inertinite generally shows low reflectance, and is dominated by inertodetrinite; the content of inertinite does not vary significantly (8.2-9.6 vol.%) (Fig. 17; Table 2). In the lower part of the seam the mineral matter content reaches 17.4 vol.% but in the upper part it decreases to 7.0 vol.%.

Vitrite is the most important microlithotype in the coal seam. In the lower part carbominerite is second followed by huminite-dominated vitrinertite, clarite and duroclarite.

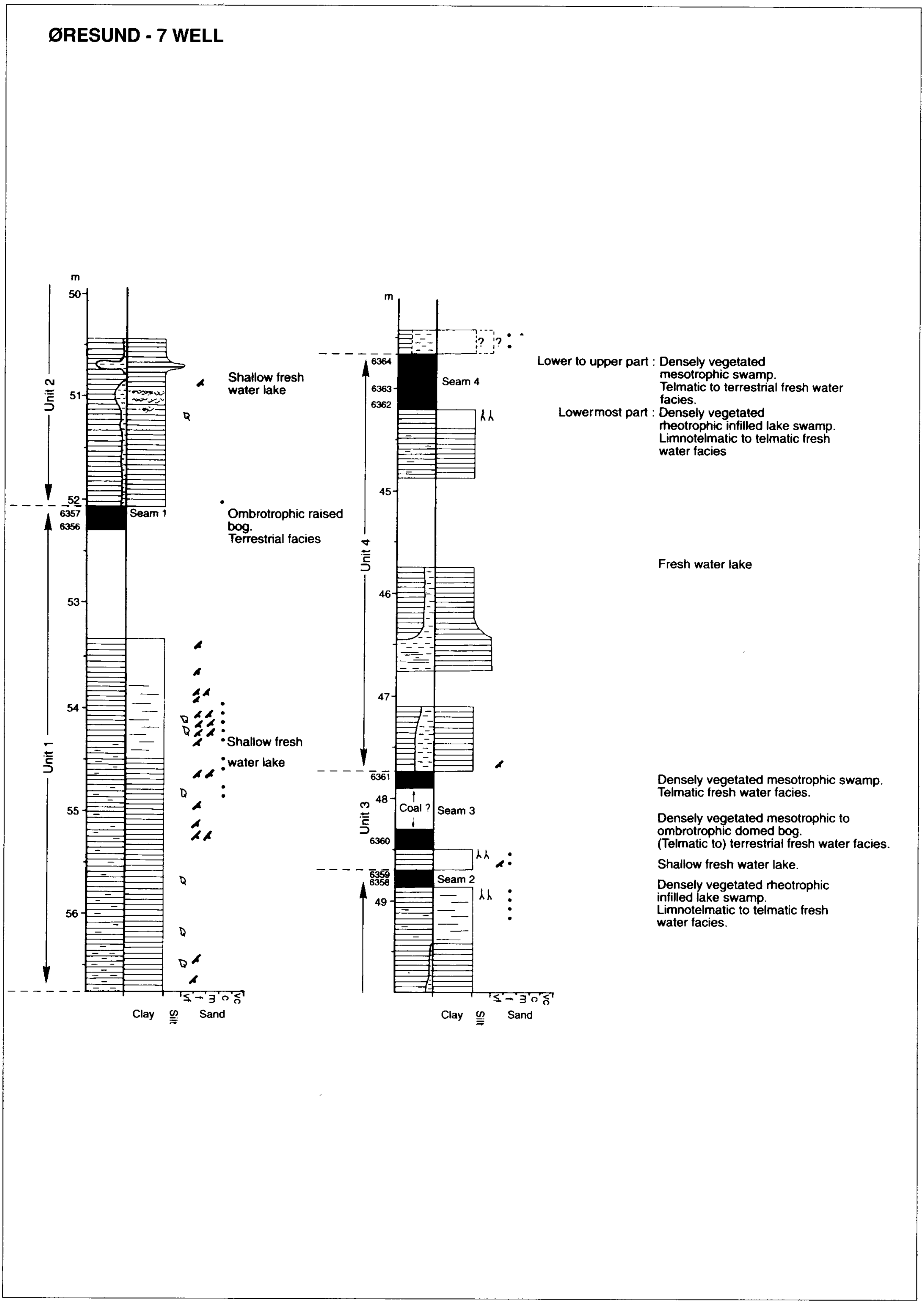

Fig. 16: Lithological log of the Jurassic succession of the Øresund-7 well. Legend. see Figure 8.

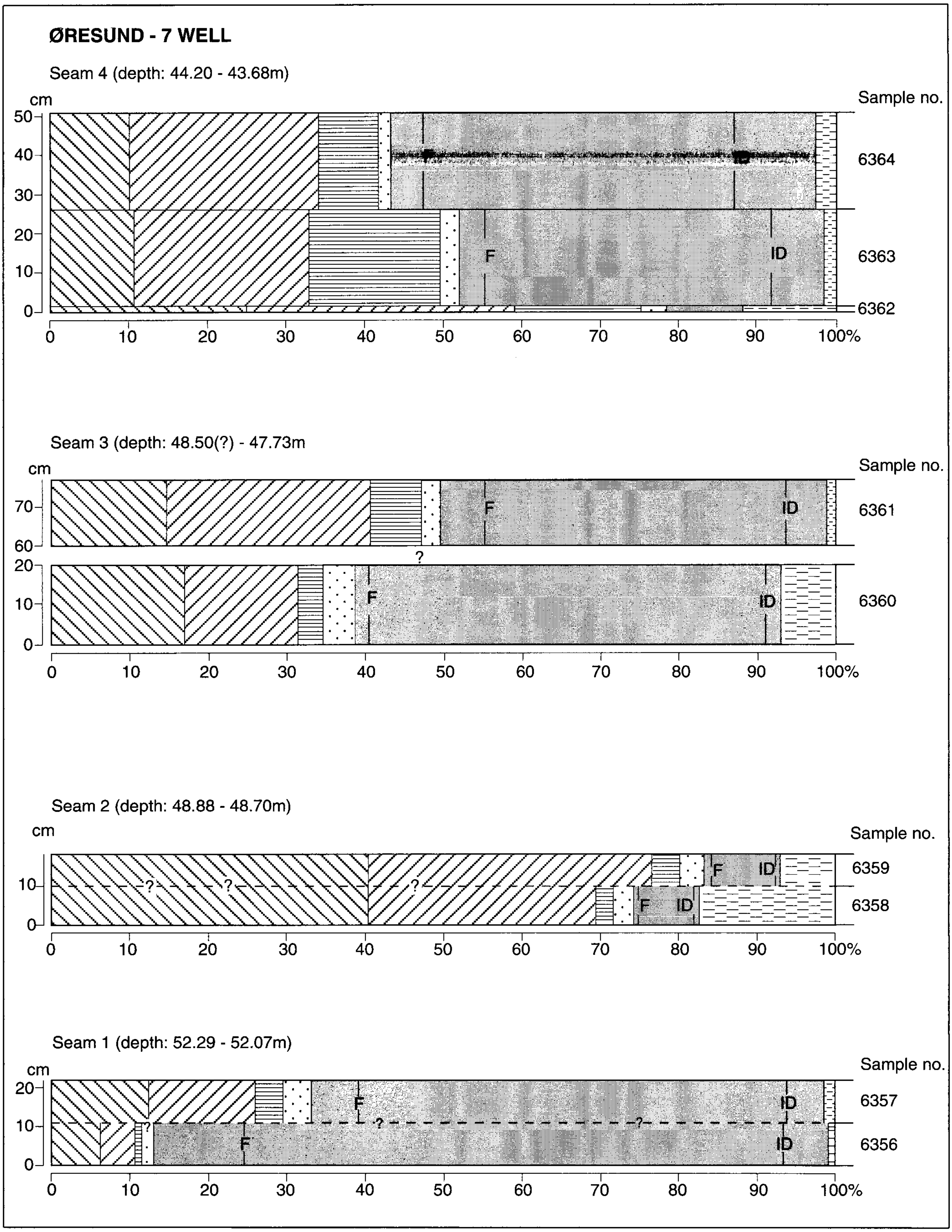

Fig. 17: The coal petrographic composition of the seams from the Øresund-7 well. Legend, see Figure 9.

In the upper part of the seam, the most abundant microlithotypes following vitrite are huminite-dominated clarite, carbominerite, and huminite-dominated vitrinertite and duroclarite. The last two are equally represented.

Interpretation: The peat-forming environment represented by seam 1 was destroyed due to the re-establishment of the fresh water lake. The lake was gradually filled by sediments, and a mire was established during increased growth facies. The content of huminite suggests that the swamp was densely vegetated. Shrub-like and smaller arboreous plants together with other plants with cellulose-rich wood dominated the vegetation. Plants with more lignified wood were present. A herbaceous type of flora was likewise abundant. The relative high content of minerals, especially in the lower part of the seam, suggests inundations of the swamp. The high content of gelified tissues indicate dominantly anaerobic conditions within the swamp.

The most abundant microlithotypes are all attributed to a wet forest swamp facies which is in good agreement with a telmatic facies. This is also supported by the four-component diagram as it shows an evolution from a limnotelmatic forest moor facies (sample 6358) to a telmatic forest moor facies (sample 6359) (Fig. 7). The TPI vs. GI diagram suggests a limnotelmatic facies (Fig. 5). The seam thus represents a densely vegetated fresh water swamp.

Unit 3: 48.70-47.73 m

Sedimentological description: A 0.2 m thick bed of grey and structureless claystone with coal particles, branches and rootlets separates coal seams 2 and 3.

Characterization of coal seam 3: The thickness of the seam is uncertain due to the poor core recovery between the two samples (Fig. 16), but it may be about 0.70 m thick (corrected thickness). The two samples, representing the base and the top of the seam, both consist of black coal with TOC values of 50.40 wt-% and 50.70 wt-%, respectively (Table 5).

The base of the coal seam contains 54.8 vol.% inertinite, dominated by inertodetrinite (50.4 vol.%) (Fig. 17; Table 2). The inertinite macerals show mainly low reflectance. Huminite amounts to 34.0 vol.% and approximately equal amounts of humotelinite (16.6 vol.%), dominated by eu-ulminite (13.4 vol.%), and humodetrinite (14.2 vol.%), dominated by densinite (12.0 vol.%), are present. The content of liptinite reaches 4.0 vol.% while the mineral matter content is 7.2 vol.%.

The top of the seam is characterized by 50.2 vol.% inertinite of which 38.8 vol.% is very poorly sorted and rounded inertodetrinite (Fig. 17; Table 2; Plate 5, A, B). Fusinite, macrinite and semifusinite are also present (Table 2; Plate 5, C). The macerals of the inertinite maceral group has a varying reflectance. The huminite content is 46.8 vol.%. The detrital huminitic matter (densinite 21.6 vol.% and attrinite 4.0 vol.%) is intimately associated with the macerals of the inertinite group (Plate 5, A, B, D). Humocollinite constitutes 6.8 vol.% of the top of the coal seam (Fig. 17), dominated by porigelinite (3.6 vol.%) and gelinite (2.6 vol.%) (Table 2; Plate 5, E). Macerals of the liptinite group and the mineral matter together comprise only 3.0 vol.%.

The four main microlithotypes of the base of the seam are inertite, vitrite and inertinite-dominated vitrinertite and durite, thus reflecting the high content of inert material within the coal seam. Other important microlithotype components are clarodurite and inertinite-dominated carbominerite. Three microlithotypes characterize the top of the seam. The most significant is huminite-dominated vitrinertite, followed by inertite and vitrite.

Interpretation: A rising watertable ended the peat formation represented by seam 2 and the fresh water lake was re-established. The structureless mudstone with plant remains was deposited under very low energy conditions. Sedimentation exceeded the lake level rise and the lake became vegetated.

The lower part of seam 3 represents a slightly wet terrestrial facies, whereas the top represents a telmatic to wet terrestrial facies. Probably herbaceous type of plants and shrub-like plants together with smaller arboreous plants were equally represented within the lower part of the seam, whereas the herbaceous type of flora dominated in the upper part. The decreasing content of minerals towards the top of the seam may be attributed to a denser vegetation. The organic matter was partly gelified before oxidation and fragmentation at the peat surface. Hence, the intimate association of inertinite and huminite was produced by periodic oxidation of the peat surface alternating with temporary establishment of anoxic conditions within the swamp. The relatively high content of macrinite within the upper part of the seam supports this interpretation, as macrinite (and semifusinite) indicates gelification before oxidation (Shibaoka, 1983).

The microlithotype composition also indicates alternating dry and wet peat-forming conditions. The very high content of vitrinertite within the upper part may suggest increased flooding of the peat. The four-component facies diagram indicates a terrestrial forest moor facies, and the TPI vs. GI facies diagram a terrestrial dry forest swamp facies (Figs 5 & 7). This is in agreement with the above interpretation, particularly considering that the upper sample 6361 plots towards the field of the limnic to limnotelmatic facies of the TPI vs. GI diagram. This corresponds to the wetter swamp environment dominated by herba-ceous type of plants within the upper part of the seam.

The unit represents the gradual infill of a fresh water lake and the establishment of a raised bog. The peat composition was formed by a complex interplay between flooding and desiccation due to a fluctuating water level within the mire.

Unit 4: 47.73-43.68 m

Sedimentological description: The lower part of the unit is a dark grey parallel-laminated heterolith of claystone and siltstone. This is followed by c. 0.30 m of light siltstone with common dark grey to black clay-streaks and clay-laminae. It is overlain by a heterolith dominated by claystone. The uppermost clastic part of the unit is a dark grey parallel-laminated claystone with siltstone-streaks. The claystone becomes structureless below the coal seam. The sediments immediately underlying the coal seam are rooted.

Characterization of coal seam 4: The seam is approximately 0.47 m thick (corrected thickness) and is composed mainly of black coal with a TOC content ranging from 42.40 wt-% to 48.50 wt-% (Table 5).

The basal part of the seam contains a high content of huminite (75.0 vol.%) (Fig. 17). The major part is humodetrinite (34.4 vol.%) which may be intimately associated with inertodetrinite and macrinite (Plate 6, A). Humotelinite constitutes 24.6 vol.% and is dominated by eu-ulminite (19.8 vol.%) (Table 2). Humocollinite amounts to 16.0 vol.% and noticeable is the high content of porigelinite (9.6 vol.%) (Fig. 17; Table 2; Plate 6, B). The content of inertinite amounts to 9.6 vol.% and inertodetrinite is the most abundant maceral of the inertinite maceral group. Liptinite is only a minor component of the basal part of the seam whereas the mineral matter amounts to 12.0 vol.%.

The remaining part of the seam is characterized by a decreasing huminite content towards the top (Fig. 17). The content of humotelinite and humodetrinite decreases (10.4-10.2 vol.% and 22.4-24.0 vol.%, respectively) and the most prominent maceral of these two submaceral groups is densinite, ranging between 16.0 vol.% and 20.0 vol.% (Fig. 17; Table 2). The humocollinite content remains at c. 16 vol.% within the middle part of the coal seam but decreases to 7.6 vol.% towards the top. Porigelinite (13.0 vol.%) is a significant component of the middle part of the seam. The porigelinite may show a high reflectance that can make it difficult to distinguish between porigelinite and very fine-grained inertodetrinite. Compared to the base of the seam, the content of inertinite is significantly higher within the rest of the coal seam. The inertinite macerals exhibit a variable but low reflectance (Plate 6, C, D). Inertodetrinite is the dominant maceral of the inertinite maceral group (36.0-43.8 vol.%) (Fig. 17). Macerals of the liptinite group together with the mineral matter content are subordinate constituents of the coal seam.

Vitrite is the dominating microlithotype within the basal part of the seam, thus reflecting the high content of huminite. Subordinate components are carbominerite and huminite-dominated vitrinertite and clarite. The trimacerites are only minor components of the microlithotype composition.

The majority of the coal seam is dominated by vitrinertite with a high content of both huminite and inertinite. Vitrite is still abundant within the middle part of the seam but inertite and clarodurite are also prominent constituents. Towards the top, the content of vitrite decreases whereas the content of inertite increases further. Clarodurite and inertinite-dominated durite are also important microlithotypes within the upper part of the seam.

Interpretation: The peat-forming environment represented by seam 3 was destroyed due to a rising watertable and an increased input of siliciclastic sediments, and the establishment of a fresh water lake. The presence of roots below the coal seam 4 indicate that the lake was overgrown and that accumulation of organic matter from in situ plants commenced.

The lowermost part of seam 4 represents a limnotelmatic/telmatic facies in a densely vegetated swamp. The vegetation consisted of a mainly herbaceous type of flora, but larger plants with cellulose-rich wood were common. The mineral content indicates periodic inundations of the mire. These inundations might have infiltrated the mire with nutrient-rich and to a certain degree oxygenated water, which favoured the growth of plants but also the decomposition of the organic matter. Notable is the very high content of porigelinite. The mode of genesis of this maceral is uncertain, but it may be attributed to a combination of favourable chemical conditions within the swamp water and the composition of the plant community. The oxygen content within the swamp was not able to increase the content of inertinite significantly, thus suggesting restricted oxic conditions. The microlithotype composition supports the maceral based interpretation of the lowermost part of the seam, since all the dominant microlithotypes are attributed to a wet forest swamp facies. The sample plots within the field of the limnotelmatic forest swamp facies on the four-component diagram (Fig. 7). The TPI vs. GI diagram likewise shows a limnotelmatic facies (Fig. 5).

The rest of the seam is characterized by a lower huminite content and a higher inertinite content compared to the lowermost part. It is represented by a telmatic to terrestrial facies. Peat accumulated in a raised bog that was covered by a vegetation dominated by herbaceous type of plants. Shrub-like plants and smaller arboreous plants were present. The content of porigelinite is very high, but part of it shows higher reflectance than observed in the lowermost part of the seam. The increased reflectance may be related to partial oxidation during exposure of the peat surface, since granular porigelinite is easy oxidized due to its large surface area (Shibaoka, 1983).

The four-component facies diagram suggests that the facies changes from limnotelmatic to telmatic in the basal part of the seam to telmatic to terrestrial in the remaining part (Fig. 7). The plots within the TPI vs. GI diagram also support this conclusion, as the samples plot within or close to the field of the terrestrial dry forest swamp facies (Fig. 5). The fresh water bog was protected against major influence from clastic depositional systems.

Organic geochemistry

Organic geochemical data on Lower and Middle Jurassic coals are few in the literature. The organic geochemical analyses were performed to obtain knowledge of the chemical composition on the coal material. The chemical composition provides information of the type of organic matter and of the depositional environment (e.g. fresh water or marine, reducing or oxidizing conditions), as well as on the state of thermal maturity or rank. Rock-Eval pyrolysis, Gas Chromatography and Gas Chromatography/Mass Spectrometry was used in this study.

Rock-Eval pyrolysis

Rock-Eval pyrolysis has been developed for source-rock evaluation, and is commonly used in the oil industry to determine maturity and kerogen types. Experience has shown that the kerogen can be subdivided into three types, which with respect to the composition roughly correspond to the three maceral groups in the van Krevelen diagram, and which follow similar evolutionary pathways (van Krevelen, 1961; Tissot & Welte, 1984).

The screening data of the coal samples are tabulated in Table 5 and the samples are plotted in Tmax versus HI diagrams (Fig. 18). The Tmax lies between 416°C and 428°C suggesting immature low rank coals (Waples, 1985). The Hydrogen Indices indicate predominantly type IV organic matter, that is inert terrestrial coal parent matter, with a low hydrocarbon generative potential. Minor differences are recognizable between the Hydrogen Indices. The values for the Middle Jurassic coal seams (Øresund-5 and -7 wells) are in general lower than for the Lower Jurassic seams (Øresund-13, -15 and -18 wells) (Fig. 18; Table 5). This may be attributed to the general significantly lower content of liptinite macerals in the Middle Jurassic seams (Figs 9, 11, 13, 15, 17; Table 2). The higher Hydrogen Indices seem to be related to a high content of liptinite (mainly sporinite and liptodetrinite) combined with a high content of huminite and/or minerals. The huminite and mineral matter contents may also influence the Hydrogen Index by containing disseminated lipid material which is not recognizable under the microscope. Sample 6372 shows a low Hydrogen Index (Table 5), although the liptinite content amounts to 12.0 vol.%; but compared to the other samples both the huminite and mineral matter contents are low, whereas the inertinite content is high (Table 2). Hence, the low Hydrogen Index is explained by the presence of a large proportion of inert carbon.

Gas Chromatography

The saturated, aromatic and polar fractions of each of the solvent extracts of the coal samples are listed in Table 6. The NSO-compounds constitute the major part of all the solvent extracts, but the solvent extracts of the samples from the Øresund-7 well contain more heterocompounds and a minor content of the saturated and aromatic fractions than the extracts of the samples from the Øresund-13 and Øresund-18 wells. This may be attributed to the lower content of lipid compounds (liptinite) within the coal samples from the Øresund-7 well combined with a slightly lower rank of these coals (see below).

Generally, the GC-traces of the saturated fractions display a unimodal distribution of the n-alkanes and a dominance of the heavy n-alkane fraction, with a predominace of the nC_{23} to nC_{27} range (Fig. 19). The pristane peak is likewise conspicuous. This composition is in agreement with other analyses of low rank coals (e.g. Clayton et al., 1991; Ducazeaux et al., 1991, their coal type B). The proportion of unresolved material is moderate, but samples 6356 and 6361 from the Øresund-7 well contain considerable proportions. Furthermore, a general feature is the dominance of odd carbon numbered compounds over even carbon numbered. The prominent heavy-end fraction of the n-alkanes and the dominance of odd carbon numbered compounds is a characteristic feature of organic matter derived from terrestrial higher plants (Eglinton & Hamilton, 1967; Han & Calvin, 1969; Tissot & Welte, 1984; Waples, 1985).

SCREENING DATA

Well	Coal seam	Sample no.	TOC wt-%	Tmax °C	S2 mg HC/g rock	HI
Øresund-5	Seam 1	6365	52.10	419	26.06	50
		6366	33.70	423	30.39	90
Øresund-7	Seam 1	6356	53.10	417	16.15	30
		6357	57.10	416	36.42	64
	Seam 2	6358	47.60	422	26.31	55
		6359	44.20	419	32.97	75
	Seam 3	6360	50.40	418	36.18	72
		6361	50.70	418	17.89	35
	Seam 4	6362	42.40	422	34.73	82
		6363	48.50	417	25.96	54
		6364	48.10	416	14.98	31
Øresund-13	Seam 1	6368	40.50	426	49.48	122
Øresund-15	Seam 1	6367	44.90	419	31.18	69
Øresund-18	Seam 1	6369	69.10	427	114.14	165
		6370	64.60	425	92.10	143
		6372	61.30	426	47.06	77
		6373	67.50	424	52.69	78
		6371	57.30	424	53.54	93
	Seam 2	6374	33.50	427	51.47	154
		6375	55.60	428	71.87	129

Note: For further explanation, see Organic Geochemistry section and Appendix

Table 5

A measure of the predominance of odd carbon numbered n-alkanes is the Carbon Preference Index (CPI) calculated over a specified range (Bray & Evans, 1961; Cooper & Bray, 1963). In the present case the range is from nC_{22} to nC_{32}:

$$CPI = 2(nC_{23}+nC_{25}+nC_{27}+nC_{29}+nC_{31}) / (2(nC_{24}+nC_{26}+nC_{28}+nC_{30})+nC_{22}+nC_{32})$$

The CPI values of the samples from the Øresund-7 well are in the range 2.98-6.49 (Table 6), which is typical for organic matter derived chiefly from terrestrial higher plants. The CPI values of the samples from the Øresund-13 and Øresund-18 wells are lower, 1.87-1.97 (Table 6). A slightly higher rank of the former samples may account for this as increasing maturity seems to minimize the CPI due to cracking of the hydrocarbons and dilution of the odd carbon numbered n-alkanes (Radke et al., 1980). Hence, the CPI is also used as a maturity parameter as the CPI tends to an equilibrium of 1 with increasing maturation.

Another shorter expression is the Philippi ratio (Philippi, 1965):

$$\text{Philippi ratio} = (2nC_{29}) / (nC_{28} + nC_{30})$$

The Philippi ratios, 1.32-3.80, likewise confirm the immaturity of the samples (Table 6). The lowest value (1.32, sample 6375) testifies to the highest obtained rank by huminite reflectance measurements (0.51 %Rm, Table 1).

The pristane/phytane ratio is used here as an indicator of oxidation and depositional environment. It is assumed that phytol (C_{20}) derived from the side chain of chlorophyll may transform to pristane (C_{19}) due to oxidation and subsequent decarboxylation within a normal or oxidizing environment (Tissot & Welte, 1984). The conversion to phytane is favoured within a highly reducing environment. Thus, a high pristane/phytane ratio is probably indicative of a depositional environment with oxygen accessibility. According to Waples (1985) a pristane/phytane ratio greater than 3 is indicative of coal, which is in agreement with the pristane/phytane ratios obtained from the saturated fraction of the extracts of the coal samples (Table 6). Pris-

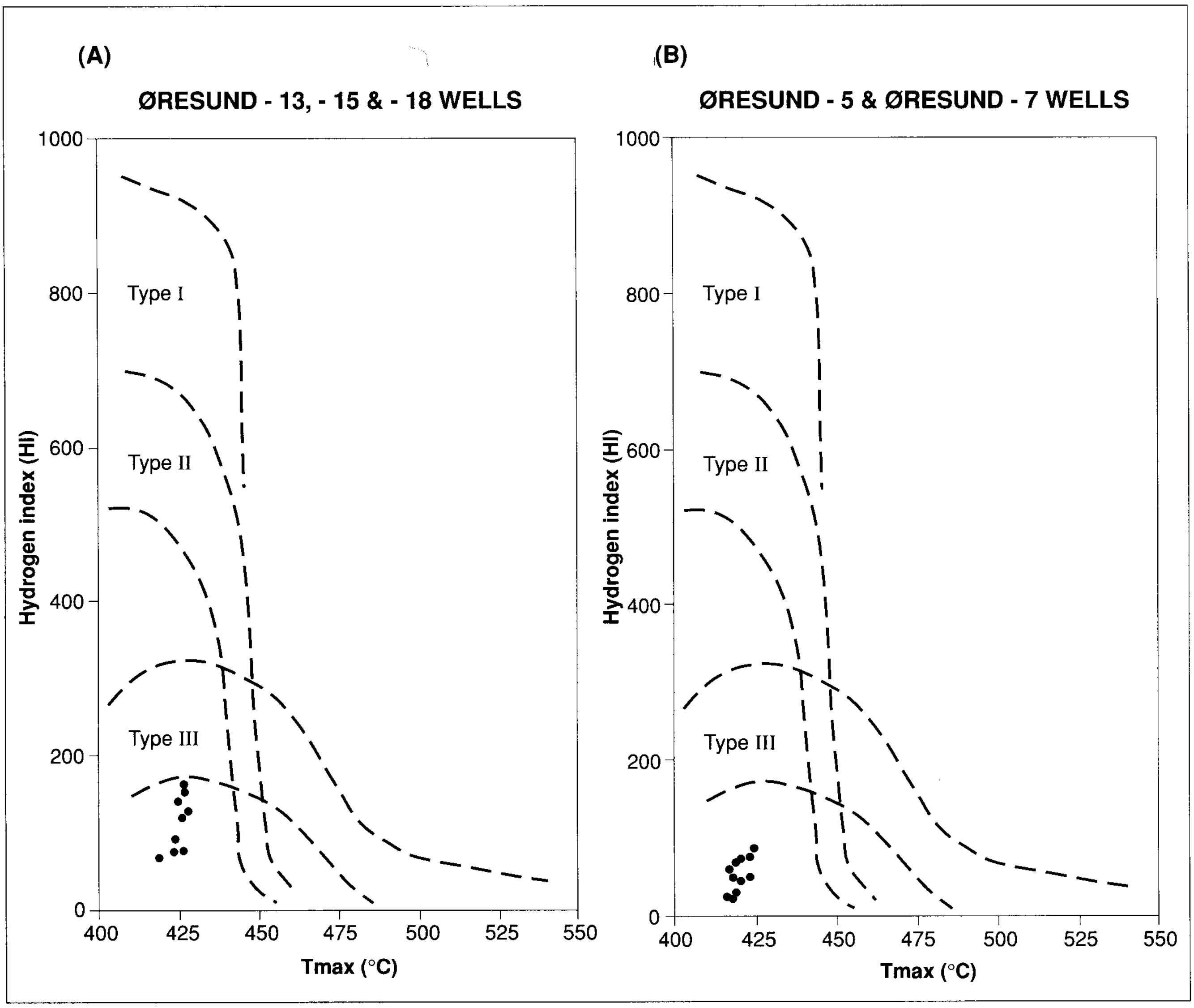

Fig. 18: Tmax versus Hydrogen Index diagrams for (A) the coal samples from the Øresund-13, -15 and -18 wells, and (B) the coal samples from the Øresund-5 and -7 wells. For comparison the evolutionary paths for Types I, II and III kerogens during coalification are shown. See text for further explanation.

ØRESUND - 7 WELL COAL EXTRACTS															
SAMPLE	EXTR.(ppt)	ASPH. (%)	SAT(%)	ARO(%)	NSO(%)	PR/PH	PR/C17	PH/C18	BIAS	WAX	CPI	PHILIPPI	IP18%	PR%	PH%
6356	18.4	56.2	8.5	6.4	85.1	3.99	1.96	0.54	0.44	0.80	2.98	2.78	9.58	72.29	18.13
6359	42.6	68.3	5.6	4.5	89.9	2.46	1.79	0.48	0.26	0.54	3.86	3.02	11.46	62.92	25.62
6361	28.3	61.4	7.2	9.6	83.1	3.22	1.83	0.88	0.21	1.47	3.19	1.42	9.26	69.26	21.49
6362	38.2	57.9	5.1	5.1	89.8	6.13	3.30	0.51	0.14	0.40	5.66	3.80	8.20	78.92	12.88
6363	46.9	65.1	2.7	8.8	88.5	5.40	2.48	0.44	0.13	0.42	6.49	1.92	7.25	78.26	14.49

ØRESUND - 13 & ØRESUND -18 WELLS COAL EXTRACTS															
SAMPLE	EXTR.(ppt)	ASPH. (%)	SAT(%)	ARO(%)	NSO(%)	PR/PH	PR/C17	PH/C18	BIAS	WAX	CPI	PHILIPPI	IP18%	PR%	PH%
6368	26.5	73.3	11.3	11.3	77.4	4.61	2.49	0.48	0.47	1.00	1.87	2.23	13.00	71.49	15.51
6370	62.1	50.7	6.5	8.7	84.8	4.61	2.16	0.42	0.28	0.67	1.91	1.38	11.60	72.65	15.75
6374	32.3	60.7	13.0	15.2	71.8	4.60	1.70	0.34	0.73	0.19	1.93	1.58	12.53	71.84	15.63
6375	40.8	66.1	9.8	14.8	75.4	5.20	2.77	0.48	0.87	0.06	1.97	1.32	10.76	74.85	14.39

Table 6

tane can originate from other sources (e.g. Didyk et al., 1978), hence the interpretations must be qualified, in particular if the pristane/phytane values are below 3 to 5 (Philp, 1994). Püttmann et al. (1986) argued that high amounts of sporinite and partly also resinite tend to increase the pristane/phytane ratio. Considering the narrow rank range and the varying amount of sporinite in the samples analysed in the present investigation, the sporinite-resinite-effect should be expected to be noticeable. This seems not to be the case, thus the results obtained from these 9 low rank coals do not indicate such a connection.

The interpretation of pristane, phytane and n-alkane distributions has proven valuable in that they provide general information on biodegradation, maturity and deposi-

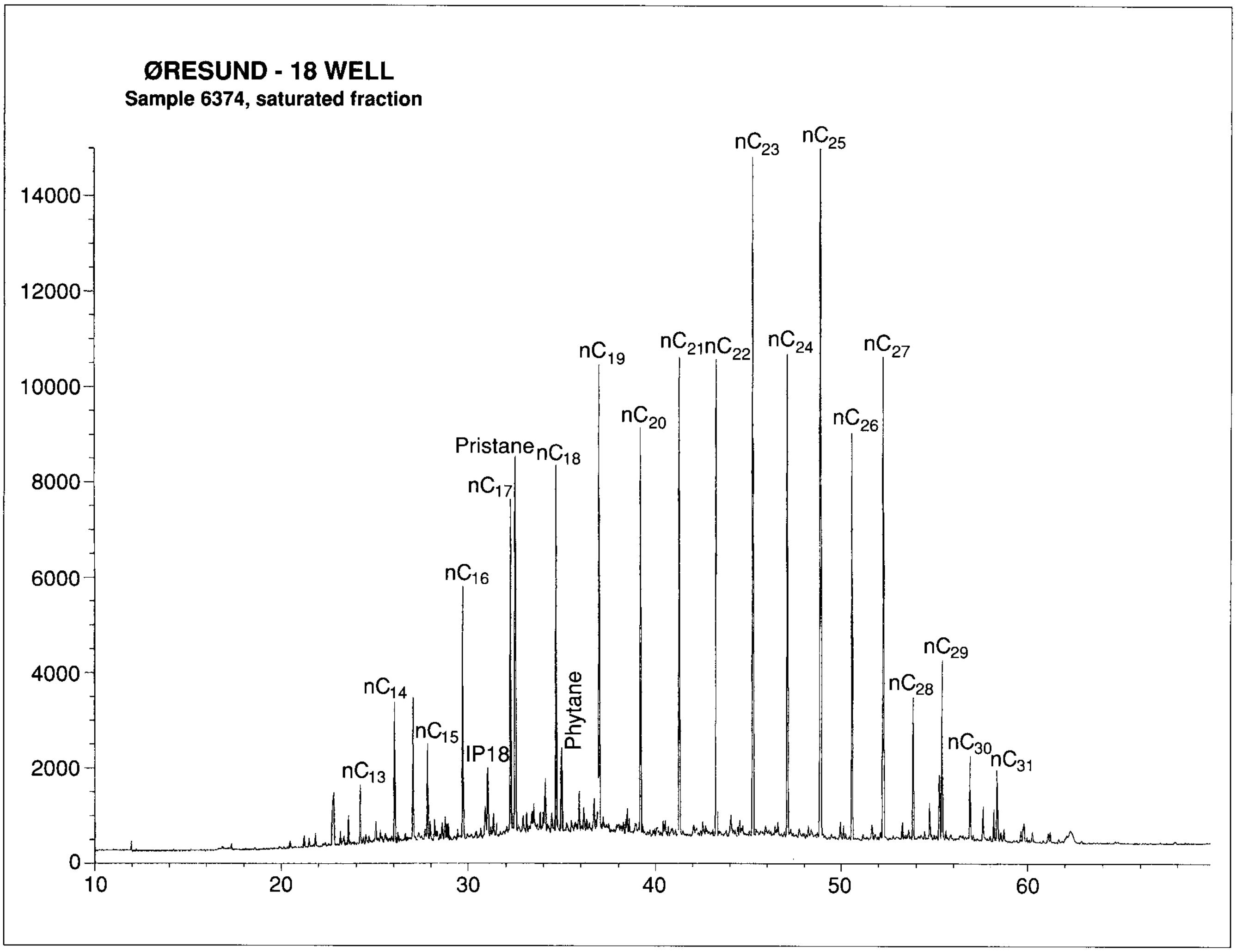

Fig. 19: An example of an annotated GC-chromatogram (saturated fraction; sample 6374, seam 2, Øresund-18 well). See text for further explanation.

tional environment (Fig. 20). During maturation of the organic matter n-alkanes are generated faster than pristane and phytane thus decreasing the ratios, whereas enhanced biodegradation removes the n-alkanes faster thus increasing the ratios (Waples, 1985). The plot of the coal samples testifies to terrestrial peat deposition with restricted oxygen supply.

Gas Chromatography/Mass Spectrometry

Biomarkers (biological markers) are a group of organic compounds which can be referred to as chemical fossils due to their molecular skeleton inherited from the biogenic precursor molecule (Philp 1985; Waples, 1985). The biomarkers fragment in a regular manner, which facilitates the identification of a specific compound by detecting its fragmentation ions.

A well-known biomarker group is the triterpanes which are cyclic saturated hydrocarbons. The source of triterpanes is probably triterpenoids from bacteria and certain higher land plants like ferns (Philp, 1985; Waples & Machihara, 1991). The most common and most frequently used triterpanes are the pentacyclic hopanes, but tetracyclic and tricyclic triterpanes do exist. The most characteristic fragment ion of the hopanes is m/z 191. The hopanes normally contain between 27 and 35 carbon atoms. The molecule containing 30 carbon atoms is simply called hopane, whereas the C_{27} to C_{29} homologs are referred to as norhopanes. Hopanes with more than 30 carbon atoms are referred to as homohopanes or extended hopanes (Waples & Machihara, 1991). The hopanes constitute a series with the 17α(H),21ß(H) configuration and the 17ß(H),21α(H) configuration; the latter are called moretanes. Finally, 17ß(H),21ß(H) forms and hopenes (hopanes with a double bond) exist in immature organic matter.

The m/z 191 mass chromatograms are characterized by significant amounts of ßß-forms and hopenes, which confirms the immaturity of the coals (Fig. 21).

Increasing maturity of the organic matter is accompanied by conversion in the configuration of the hopane molecule at the C_{17}, C_{21} and, within the homohopanes, the C_{22} positions to form more stable forms (Philp, 1985; Waples, 1985). Several ratios are used to monitor the maturity of the organic matter.

The presence of 29-norneohop-13(18)-ene and 30-neohop-13(18)-ene (% 29-norneohop-13(18)-ene against all C_{29} forms and % 30-neohop-13(18)-ene against all C_{30} forms) in the samples emphazises the immaturity of the samples as the hopenes are converted to hopanes early during coalification (Figs 22 & 23). The samples from the Øresund-13 and Øresund-18 wells seem to be slightly more mature due to the lower ratios, that is they contain a lower content of hopene.

The 17ß(H),21ß(H) forms are only present at low maturity due to conversion to αß-forms with increasing coalification and their presence thus indicates immaturity. The 30ßß/(30αß + 30ßα + 30ßß) and 31ßß/(31αß + 31ßα + 31ßß) ratios are used to obtain a qualitative estimation of the maturity of the samples (Figs 22 & 23). The sensitivity of the ßß-forms clearly reveals the slightly higher maturity of the samples from the Øresund-13 and Øresund-18 wells as the ratios are significantly lower than the ratios obtained from the samples from the Øresund-7 well.

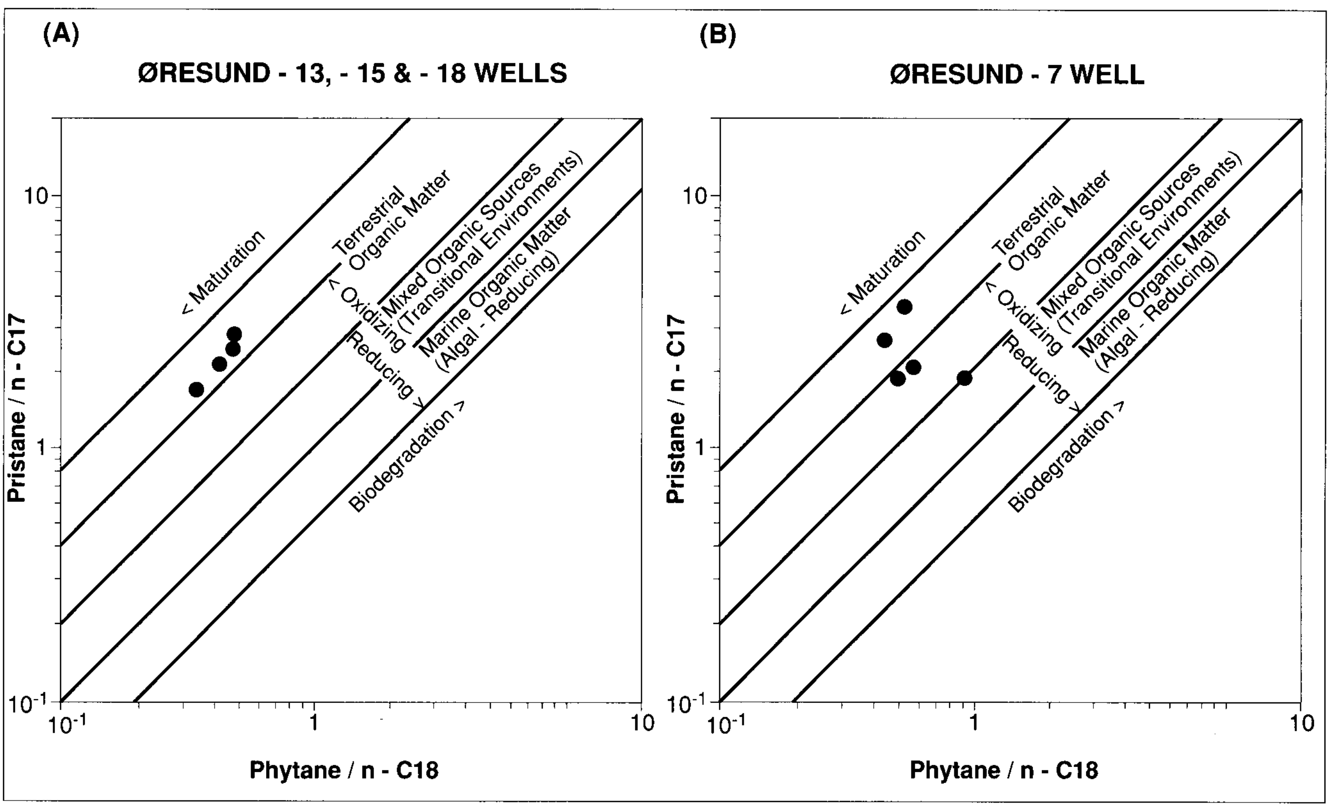

Fig. 20: Phytane/nC18 versus Pristane/nC17 diagram for (A) four coal samples from the Øresund-13 and -18 wells, and (B) five coal samples from the Øresund-7 well. See text for further explanation.

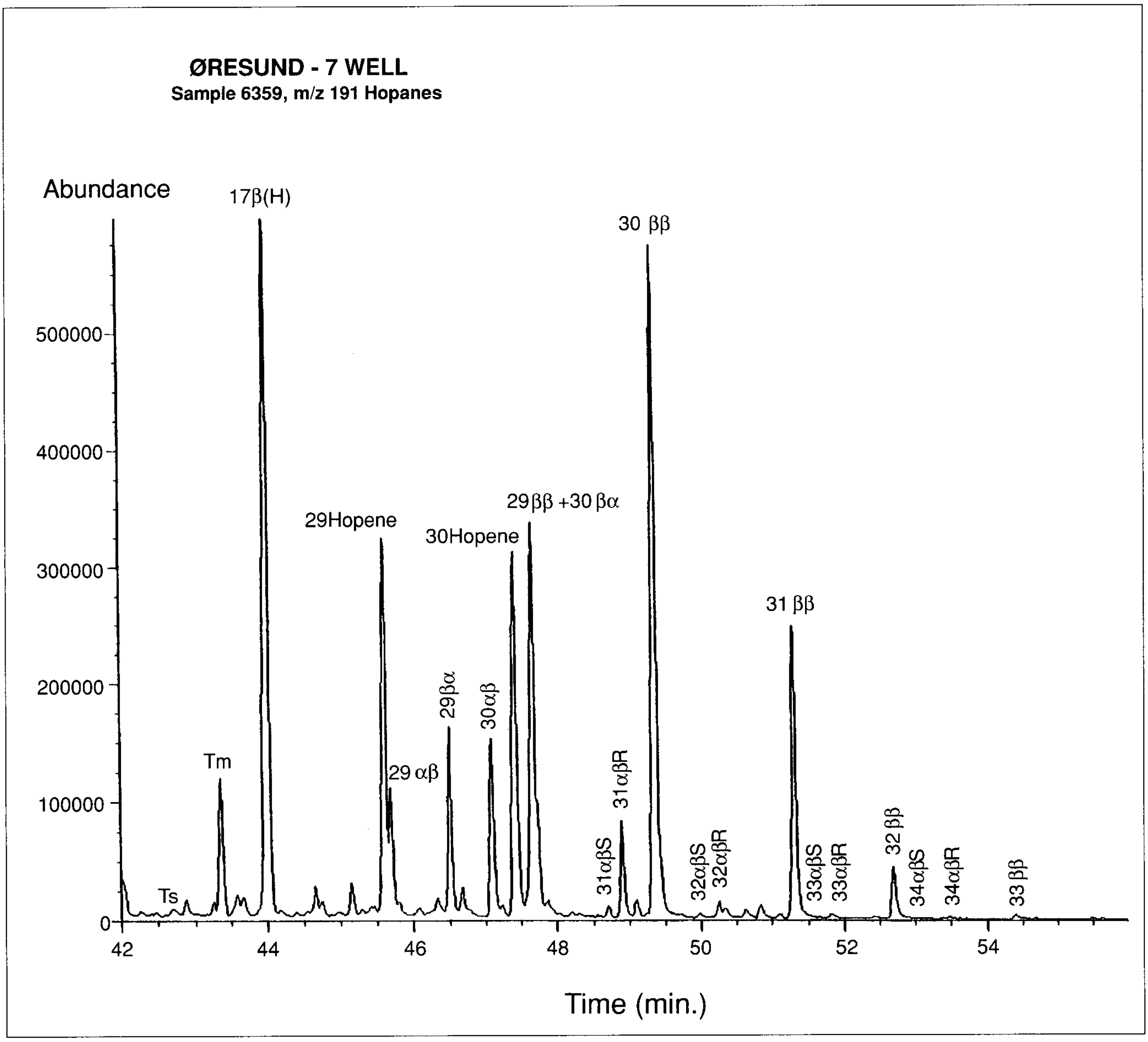

Fig. 21: An example of an annotated m/z 191 ion (Hopanes) fragmentogram (saturated fraction; sample 6359, seam 2, Øresund-7well).

The 22S/(22R+22S) epimer ratios of the homohopanes are also useful in this respect. C_{31} and higher extended hopanes only occur as 22R epimers in living organisms, but after entering the geosphere and with increasing maturity part of the 22R epimers are transformed into 22S forms. The process is ongoing until an equilibrium of approximately 55-60 % 22S and 40-45 % 22R epimers is reached (Philp, 1985; Waples & Machihara, 1991). The samples from the Øresund-7 well show very low ratios of 31αß 22S/(22S + 22R) which suggests limited isomerization (Fig. 23). In contrast, the higher ratios of the samples of the Øresund-13 and Øresund-18 wells reflect increased maturity, which supports the slightly higher rank of these samples indicated by other rank parameters (see elsewhere) (Fig. 22). Sample 6375 is tending to equilibrium (approximately 42 % 22S epimer), which is in good agreement with the highest measured huminite reflectance of all samples (0.51 %Rm).

The Tm/(Tm + 17ß(H)) ratio (Tm = trisnorhopane, C_{27}) is likewise a maturity parameter. The ratio approaches 1 as the 17ß(H) is converted to Tm with increasing maturity. Again the significantly higher ratios of the samples from the Øresund-13 and Øresund-18 wells testify to a slightly higher rank of these samples compared to the Øresund-7 samples (Figs 22 & 23).

Steranes is another commonly used biomarker group. The source of steranes is sterols that are found in higher land plants and algae, and the principal precursor sterols contain 27, 28, 29 and 30 carbon atoms (e.g. Waples & Machihara, 1991). The m/z 217 and m/z 218 mass chromatograms show the steranes. Due to the low maturity of the samples the mass chromatograms for the steranes are dominated by the αααR-forms. Typically for terrestrial organic matter, the humic coals show a strong predominance of the C_{29} sterane (e.g. Waples & Machihara, 1991; Peters & Moldowan, 1993). The C_{30} sterane, and in particular 24-n-propylcholestanes, may be indicative of a marine influence in the peat-forming swamp (Peters & Moldowan, 1993). In the mass chromatograms a pronounced m/z 218 peak is observed at the same time as the C_{30} sterane elutes. How-

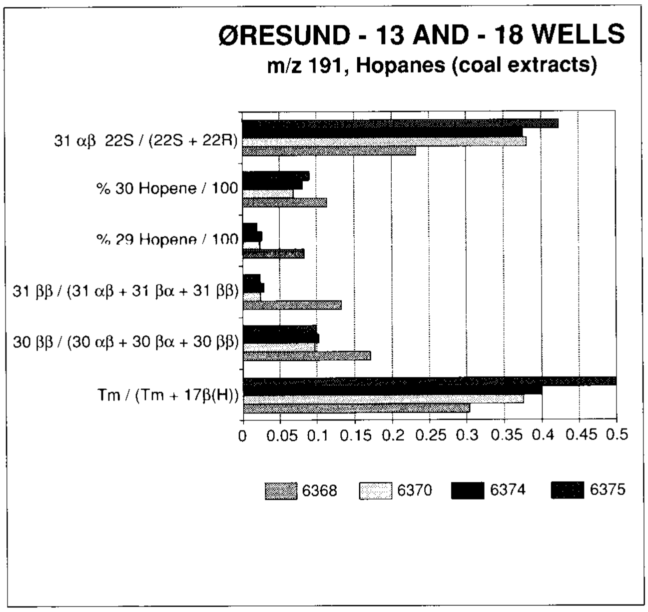

Fig. 22: Maturity parameters based on the m/z 191 ion (Hopanes) fragmentograms.

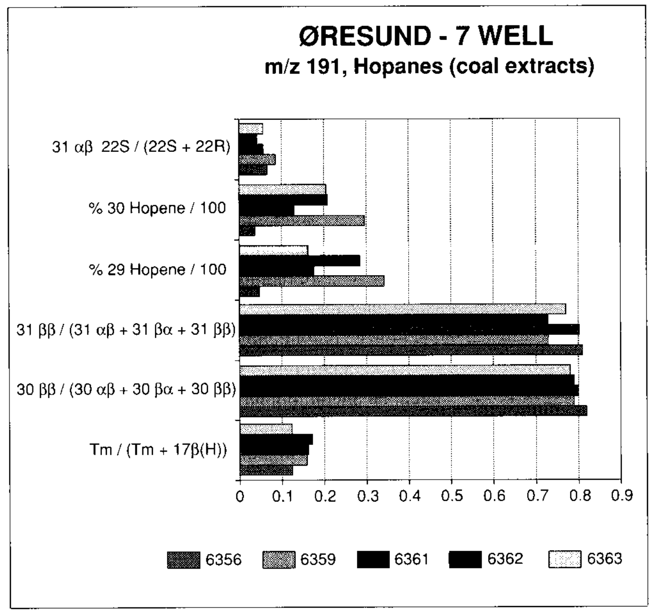

Fig. 23: Maturity parameters based on the m/z 191 ion (Hopanes) fragmentograms.

ever, mass spectra show that the m/z 218 ion fragment is derived from the considerable amounts of hopenes present, and due to this coelution the identification of C_{30} steranes is very questionable. Thus, the applicability of the m/z 218 and m/z 217 mass chromatograms to identify a marine influence is probably not possible in these low rank coals.

Definition of mire environments

Most of the coal seams encountered in this study are the result of peat-forming conditions established due to the infill of fresh water lakes. A few were established on top of restricted brackish lagoon or bay sediments. With the exception of the peat-forming environment represented by the seam within the Øresund-15 well, the peat-forming environments were fresh water. Thus, peat deposition took place within a wetland primarily dominated by fresh water lakes. The investigated coal seams are generally rich in inertinite and often also durite, which are formed mainly in lake and lower delta plain environments (Teichmüller, 1989).

Three general types of environments are defined based on the maceral/microlithotype composition of the coal seams. Basically, the petrographic composition is supposed to reflect the groundwater influence, the nutrient supply, and the vegetation in the original mire. The three types may thus be regarded as mire ecosystems. This is in accordance with Moore (1987) who suggested that the classification of ancient mires should be based on the same factors that are used in the classification of recent mire systems. Successions of the environments are recognized in a few of the seams (Fig. 24). It would probably be possible to further subdivide each type into plant community based subenvironments by means of palynological analyses.

Type 1 environment: Sparsely vegetated open water lakes/swamps represented by a limnic coal facies. Anoxic conditions prevailed in the environment which promoted accumulation of organic matter. The organic matter is mainly allochthonous and dominated by rounded and well sorted inertodetrinite together with sporinite and liptodetrinite. The content of allogenic inorganic components is high (> 20 vol.%) and the resulting deposit is typically a carbonaceous claystone.

Type 2 environment: Low-lying and mainly anoxic peat swamps represented by a limnotelmatic to telmatic facies. The swamps were generally isolated from active clastic depositional systems and were only occasionally inun-

PEAT-FORMING ENVIRONMENTS

Stage	Øresund-13 well Seam 1	Øresund-15 well Seam 1	Øresund-18 well Seam 1	Øresund-18 well Seam 2	Øresund-5 well Seam 1	Øresund-7 well Seam 1	Øresund-7 well Seam 2	Øresund-7 well Seam 3	Øresund-7 well Seam 4
Callovian									
Bathonian									
Bajocian					Type 1 Type 3a	Type 3a	Type 2	Type 3b	Type 3b Type 2
Aalenian									
Toarcian									
Pliensbachian									
Sinemurian		Type 2	Type 3b Type 3a Type 2	Type 2 Type 1					
Hettangian	Type 1								

Fig. 24: The environments recorded in the studied coal seams. For type description, see "Definition of peat-forming environments".

dated. Therefore, the resulting coal contains a varying content of minerals. However, the siliciclastic partings and dispersed minerals in the coal seams indicate a significant groundwater influence. Hence, the swamps were probably rheotrophic and nutrient-rich (eutrophic). They could support a dense vegetation, which together with the anoxic conditions accounts for the usually very high content of huminite in the resulting autochthonous coal. The huminite composition is dependent on the original peat-forming plant community and the degree of degradation of the organic matter. The abundance of gelified tissues is not an absolute indicator of rheotrophic conditions (Calder, 1993). The huminite content is > 50 vol.%, the inertinite content is < 40 vol.% and the mineral content < 20 vol.%. Inertinite-rich coals may be interpreted to represent a Type 2 environment (Type 2(I)) if considerable amounts of the inertinite is allochthonous, hypautochthonous or in situ formed pyroinertinite. Evidence for transportation is microlamination formed by fairly well-sorted inertodetrinite and lipti-nite. Another evidence is the occurrence of micrograded inertodetrinite. Likewise may a considerable content of minerals lower the content of huminite and inertinite in the coal below the stated limits (Type 2(M)). In this study, the swamps were infilled lake swamps.

Type 3 environment: This environment is the driest of the three types. It can be divided into two subenvironments. Type 3a is a thoroughly exposed and desiccated raised bog represented by a terrestrial facies. The organic matter is dominantly low reflecting and poorly sorted, angular inertodetrinite. Wildfires may have been a common feature of these dry bogs. The huminite content is < 30 vol.% and the inertinite content > 60 vol.%. Type 3b is a raised bog with alternating dry oxidizing conditions and wet anoxic conditions. This favoured the generation and preservation of significant amounts of humified organic matter together with oxidized organic matter. Due to the wetter conditions a minor part of the inertinite can be allochthonous. Type 3b is represented by a telmatic to terrestrial facies. The huminite content is between 30-50 vol.% and the inertinite content between 40-60 vol.%.

Thus, the coal of the Type 3 environment is very inertinite-rich. The coals represent bogs that had rised above the influence of local groundwater and evolved towards rainfed systems. Type 3a was probably solely rainfed and thus ombrotrophic and nutrient-poor (oligotrophic), whereas Type 3b was mesotrophic to ombrotrophic (e.g. Calder et al., 1991; Calder, 1993).

The discrimination between an inertinite-rich coal representing a Type 2 environment and a coal representing a Type 3b environment is only possible by a careful examination of the petrographic composition of the coal, and in particular of the inertinite macerals.

In this study the inertinite-rich coals represent a Type 3 environment.

The percentage values indicated are tentative. Several situations can complicate the interpretation; for instance few inundations of thin peats may have a large influence on the peat composition due to deposition of minerals (McCabe, 1984). This may raise the mineral content considerably in an otherwise inertinite-rich coal representing a Type 3 environment. Furthermore, wildfires can increase the inertinite content in all the types of environments. If high contents of liptinite is present modification of the definitions may be necessary.

Conclusions and discussion

The successions of the three types of environments seen within some of the seams generally show a development from a very wet groundwater and rainfall influenced environment towards a dryer peat swamp (Fig. 24). Ultimately, the peat accreted vertically beyond the groundwater table and evolved to a solely rainfed nutrient-poor raised bog. This evolutionary trend to less groundwater influence may have affected the vegetation. It is noteworthy that the Middle Jurassic seams presumably evolved to a more "mature" peat-forming stage. This may likewise be reflected in the seam thickness.

Based on the sedimentary characteristics of the underlying sediments and the coal composition it is suggested that the Lower Jurassic peats accumulated in mires (infilled lakes) within a coastal plain setting. The peats represented by the coal seams in the Øresund-7 well indicate drier peat-forming conditions. These peats were deposited upon fresh water sediments rich in plant remains. Hence, a depositional site further landward is suggested. During peat accumulation compaction of the underlying clay may have caused a temporary local rise in the watertable. This may have been important in promoting vertical peat accretion and the formation of a rain-fed domed bog as the rise in the watertable ceased. The actual distance of the Middle Jurassic peat-forming environments from the coast is very difficult to estimate due to limited data. Coals from low-lying mires further inland generally contain lower mineral content than coals from more coast-near low-lying mires. However, raised bogs with a low mineral content may develop within less than 10 kilometres of a shoreline making raised bogs difficult to use in interpretation of the position of the peat relative to the coast (Robinson Roberts & McCabe, 1992).

Special attention is often paid to the question whether a specific coal petrographic composition can be related to a specific clastic depositional system. A number of factors influence the peat composition: the evolutionary stage of the vegetation, the peat-forming plant community, the level of peat evolution (rheotrophic to ombrotrophic) and the degree of degradation of the organic matter. These factors are not unique to specific clastic environments. Therefore, the coal composition is basically independent of the clastic depositional environment, thus emphazising the independence between a clastic and a peat-forming environment. Comparison of coals of the Orange Free State, South Africa, with Permian coals from the Cooper Basin, Australia, shows that coals can be similar irrespective of the clastic depositional environment (Stavrakis & Smith, 1991). Likewise, no connection is observed between the clastic depositional environment and the coal composition of the Lower and Middle Jurassic coal seams on Bornholm (Petersen, 1993). Diessel (1992) concludes, that the coal composition is governed by timing of peat accumulation relative to the balance between sediment supply and sea-level variations resulting in marine transgressions and regressions.

The generally prominent proportion of humodetrinite within the huminite maceral group and the generally strongly gelified humotelinite in the Jurassic seams indicates the presence of a plant community with much cellulose-rich wood (e.g. Teichmüller, 1982, 1989). This assumption is valid due to the low rank of the coals which precludes a significant influence of geochemical gelification. Hence, the coal seams are probably mainly derived from a vegetation consisting of herbaceous type of plants, shrub-like plants and smaller arboreous plants. Guerra-Sommer et al. (1991) found a correspondance between mainly ferns and gelocollinite and desmocollinite in a study of a Permian coal seam, whereas Pierce et al. (1991, 1993) correlated detrital macerals and gelocollinite with small lycopsid and tree fern miospore patterns in a study of a Carboniferous coal seam. Furthermore, Pierce et al. (1993) found a much greater abundance of tree ferns, small ferns and small lycopsids, that is small-statured and ground-cover plants, in connection with a raised bog. These studies were performed on Permian and Carboniferous coal seams, but the plant groups were still in existance in the Jurassic. Thus, it is probably valid to relate the maceral composition of the Øresund coal seams to a vegetation consisting of similar plant groups, although no palynological or palaeobotanical studies have been carried out on the Øresund coal seams to confirm this. Other investigations of Jurassic coals revealed a very similar small-statured vegetation (Lapo, 1978; Lapo & Drozdova, 1989; Miao et al., 1989). However, this unidimensional model based on petrographic data alone may be debatable (e.g. DiMichele & Phillips, 1994).

The low content of liptinite observed in the Middle Jurassic coal seams in the Øresund-5 and -7 wells is similar to the low contents in the Middle Jurassic coal seams on Bornholm (Petersen, 1993). The Lower Jurassic coal seams in the Øresund-13, -15 and -18 wells contain a significantly higher content. Likewise, a higher content of liptinite is observed in the seams from the Lower Jurassic part of the Bagå Formation (Petersen & Nielsen, in press). This is probably controlled by the vegetation type, although the exact difference in the flora between the former and the latter peat-forming environments is unknown.

The occurrence of high reflecting porigelinite which is very similar to micrinite within some of these low rank coals is noticeable. This supports the conclusions of Shibaoka (1983) who claimed that granular high reflecting organic material within coal may originate from oxidation of porigelinite or may simply represent very tiny inertodetrinite particles and thus not necessary micrinite. Recently Faraj and Mackinnon (1993) redefined micrinite in Southern Hemisphere sub-bituminous and bituminous coals as fine-grained kaolinite. The micrinite in these coals occurs as streaks, cell fillings and as bands. The bright appearence is due to the rough surface and fine grain size of the micrinite which produces primarily diffuse reflected light and hence high brightness. This indicates that the term micrinite includes both organic and inorganic components and clearly many problems concerning micrinite and its origin still have to be solved.

Finally, the geochemical analyses have provided information on the composition of the relatively unknown low rank Jurassic coals. The results have proven successful in demonstrating the slightly higher rank of the Lower Jurassic coal seams compared to the Middle Jurassic seams. Likewise, the analyses have shown that the terrestrial organic matter of the coals corresponds to kerogen type IV, and that the hydrocarbon generative potential of the coals is very low. Sterane C_{30} cannot be used in the present study as an environmental indicator because coelution of m/z 218 ions from hopene makes the identification of the sterane questionable.

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APPENDIX

Sampling and methods

Sedimentological core logs, sampling and sample preparation

The Øresund wells are cored throughout but the more silty sections are poorly consolidated and thus poorly preserved in core. Furthermore, some of the coal seams show poor core recovery. Sedimentological core logs were measured through the Jurassic sequence in the Øresund-5 and Øresund-7 wells, whereas only a limited part of the coal-bearing Jurassic sediments in the remaining three wells were measured (Figs. 8, 10, 12, 14, 16).

All visible lithological variation within the coal seams was sampled (crushed core samples, channel core samples) and, if possible, the samples were collected as column core samples. The samples were dried for 24 hours at 60 °C and polished blocks, and particulate pellets suitable for optical analyses were prepared. Particulate pellets were prepared by crushing the coal samples (crushed core samples, channel samples) to a grain size between 63 microns and 1000 microns. If the fraction < 63 microns amounted to more than 10 % of the 63 microns to 1000 microns fraction, approximately 20 % of the sample < 63 microns was blended with the analysis fraction. Approximately 20 ml of the homogenized, dried coal sample was embedded in epoxy under vacuum. The sample was then cut vertically into two pieces and the "new" face was ground and polished using ¼ micron diamond powder for the final polish to obtain a smooth surface. The preparation procedure thus takes into account the grain size and density induced separation during embedding and follows the standards described in the International Handbook of Coal Petrography (1963, 1971, 1975) and Stach et al. (1982). The high quality of the cored coal seam from the Øresund-13 well and seam 1 from the Øresund-18 well made it possible to prepare three polished block samples perpendicular to the bedding of the coal seam.

A portion of all samples was crushed to a grain size < 250 microns for screening analyses (Total Organic Carbon = TOC; Rock-Eval); nine samples selected for extraction and further chemical analysis were crushed to a powder (grain size < 63 microns). The samples for TOC measurements were treated with 2 N HCl to remove carbonate-bonded carbon. About 200 mg of the coal sample was used. For the Rock-Eval analysis, a 5 mg untreated coal sample was used.

Samples for further chemical analyses (Gas Chromatography, Gas Chromatography/Mass Spectrometry) were soxtex extracted with dichloromethane/methanol 93/7 vol. %/vol.%. Firstly, the samples were boiled for 1 h in the solvent and afterwards rinsed for 3 hrs. The solvent was finally removed by evaporation in a rotary evaporator. Deasphaltating the extracts was achieved by precipitation with n-hexane. The deasphaltened extracts were fractionated into saturated, aromatic and NSO fractions by means of Medium Performance Liquid Chromatography (MPLC). The obtained amount of each fraction in the coal extracts is listed in Table 6.

Rank determination

The rank of the coal samples was determined by random reflectance measurements on eu-ulminite B, the brown coal equivalent of the hard coal maceral telocollinite. This is in accordance with the standards outlined in Stach et al. (1982). The equipment used was a Leitz MPV-SP system. A total of 100 random reflectance measurements per sample conducted in monochromatic light and in oil immersion was considered sufficient. In a few samples, it was not possible to obtain 100 measurements due to the coal composition. The Leits system was calibrated against a standard with a reflectance value of 0.515 %Rr. The calculated arithmetric means are listed in Table 1.

Combined maceral-microlithotype analysis

The combined maceral-microlithotype analysis was carried out in oil immersion using a Zeiss incident light microscope equipped with visible and ultraviolet light sources, and a Swift point counter. A 20 point graticule was inserted in the eye piece and an intersection was chosen as fixpoint which was used to maceral group identification. Two conversions were fulfilled during the microlithotype analysis which gives a quantitative estimation of the maceral associations in the coal (Stach et al., 1982): 1) the band width of the microlithotype must be 50 microns and 2) a maceral group represented by less than 5 % by volume was disregarded.

To be recorded as a microlithotype at least 10 intersections had to fall within the particle while the fixpoint determined which maceral group had to be counted. If the fixpoint fell outside the particle the microlithotype was recorded as a "observed microlithotype" but if the fixpoint fell within a maceral without 10 intersections situated inside the particle the maceral was recorded as a "maceral at the boundary". The fixpoint situated on a maceral < 30 microns was registered as an "isolated maceral". Depending on whether the intersections fell on 1, 2 or 3 maceral groups various microlithotypes were identified (Table 3). A particle containing between 20 and 60 % by volume of minerals (at least 4 intersections on minerals) was termed a carbominerite. As these limits are based on densities only 5 % by volume of pyrite is sufficient to define a carbopyrite due to the high density of the pyrite mineral.

A total of 500 microlithotypes were counted in each sample in the combined maceral-microlithotype analysis.

Maceral analysis

The maceral identification followed the standards described in the International Handbook of Coal Petrography (1963, 1971, 1975) and Stach et al. (1982). The same equipment as the above was used. The rank determinations indicated low rank coals and therefore the brown coal terminology was used. 500 points were recorded in each sample and 19 different macerals plus pyrite and "other minerals" were identified (Table 2).

Screening analyses: Total Organic Carbon (TOC) and Rock-Eval

A LECO IR-212 carbon determinator was used to estimate the content of organic carbon. The HCl treated sample was heated to 2000 °C and oxygen was supplied to ensure complete combustion. The evolved CO_2 was measured and the amount of organic carbon (in % by weight) was estimated. The TOC values together with the Rock-Eval data are presented in Table 5.

Rock-Eval pyrolysis was performed on a Delsi Rock-Eval II equipment. The analysis was carried out to determine the type of organic matter and the hydrocarbon generative potential of the coal. The sample was heated 3 min. at 300 °C in an inert helium atmosphere. During this heating, the free and absorbed hydrocarbons were released and detected by the FID detector as the S_1 peak. The sample was then heated from 300 °C to about 600 °C with a heating rate of 25 °C/min. The organic matter was broken down to smaller hydrocarbons during this thermal cracking process and the released hydrocarbons were detected as the S_2 peak. The temperature at which maximum pyrolysis occurred is referred to as Tmax. Tmax increases with increasing maturity of the organic matter. The Rock-Eval analytical technique is adopted from the petroleum geology; the method is described by e.g. Espitalie et al. (1977a, 1977b), Tissot & Welte (1984) and Peters (1986).

The results are plotted in a modified van Krevelen diagram where the H/C ratio is replaced by the Hydrogen Index (HI) calculated from the ratio S_2/TOC. The S_2 peak (mg hydrocarbons/g rock) is used as an approximate estimation of the amount of atomic H in the sample (Waples, 1985). The O/C ratio is replaced by the Tmax. Correlation between vitrinite reflectance and Tmax has been established by Espitalie (1986). Rock-Eval pyrolysis is an efficient and simple method to obtain an overall characterization of the kerogen composition and the hydrocarbon potential of the organic matter. The method is equally applicable to coal characterization.

Gas Chromatography (GC) analysis

The saturated fraction of the extracts of the coal samples was injected into a Hewlett Packard 5890 gas chromatograph equipped with a FID detector and fitted with a 25 m HP-1 WCOT (Wall Coated Open Tube) column. After 2 min. heating at 30 °C the temperature programme heated the sample from 30 °C to 290 °C with a heating rate of 4.5 °C/min. and finally the temperature was kept at 290 °C for 10 min. Splitless injection was used. Separation of the extracts during this process was archieved according to molecular weight and volatility.

Gas Chromatography/Mass Spectrometry (GC/MS)

The GC/MS analyses were run on a Hewlett Packard HP 5890 series II gas chromatograph equipped with a 25 m HP-5 WCOT column coupled to a Hewlett Packard 5971A quadropole mass spectrometer operated at 70 eV. The carrier gas was helium 6.0. The saturated fractions of the extracts were dissolved in dichloromethane and splitless injected at 70 °C. The following temperature programme was run: 30 °C/min. from 70 °C to 100 °C, then 4 °C/min. from 100 °C to 300 °C and finally the temperature was kept at the 300 °C for 12 min. The components emerging from the gas chromatograph were scanned for preselected fragment ions (Selected Ion Monitoring, SIM) and in this study special attention was paid to the m/z 191 fragment ion of hopanes and the m/z 217 and m/z 218 fragment ions of steranes.

PLATES 1 – 6

PLATE 1
Øresund - 13 well
Coal seam 1

A: Transition from a fine-grained well-sorted lamina (bottom) to a coaser grained lamina (top). The main part of the laminae are composed of low reflecting inertodetrinite (Sample 6368, core sample, polished block, oil immersion; scale bar = 28 microns).

B: The fine-grained laminae are composed of very small, low reflecting and well-sorted inertodetrinite particles together with liptinite and minerals (Sample 6368, core sample, polished block, oil immersion; scale bar = 28 microns).

C: Part of a coarse-grained lamina. Larger, low reflecting inertodetrinite particles together with huminite, liptinite and mineral matter are characteristic of the coarse-grained laminae (Sample 6368, core sample, polished block, oil immersion; scale bar = 28 microns).

D: A very small piece of fusinized wood (Sample 6368, core sample, polished block, oil immersion; scale bar = 28 microns).

PLATE 1

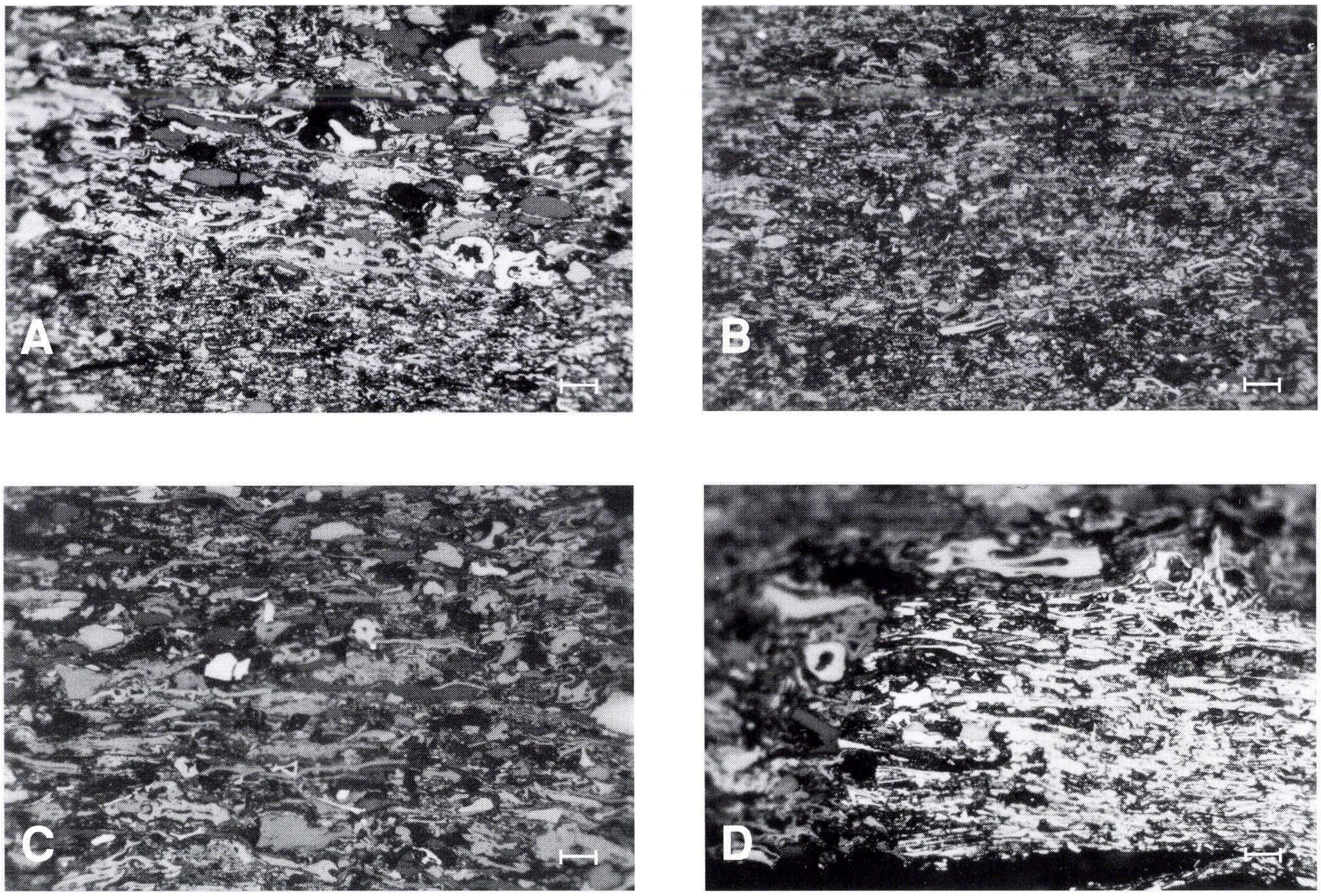


PLATE 2
Øresund - 18 well
Coal seam 1

A: Eu-ulminite, densinite and low reflecting inertodetrinite/macrinite (Sample 6370, 3-6 cm, core sample, polished block, oil immersion; scale bar = 28 microns).

B: Low reflecting fusinite showing "bogen" structure (Sample 6370, 3-6 cm, core sample, polished block, oil immersion; scale bar = 28 microns).

C: Fusinite (lower part) together with low reflecting fusinite, inertodetrinite and macrinite and minor proportions of huminite and sporinite (Sample 6372, 6-12 cm, core sample, polished block, oil immersion; scale bar = 28 microns).

D: Mainly low reflecting, angular and poorly sorted inertodetrinite and macrinite intimately associated with densinite. Sporinite and liptodetrinite is likewise present (Sample 6373, 12-16 cm, core sample, particulate pellet, oil immersion; scale bar = 28 microns).

E: Mainly low reflecting inertodetrinite and macrinite together with sporinite and liptodetrinite in a groundmass of densinite. The inertinite particles are angular and poorly sorted (Sample 6373, 12-16 cm, core sample, particulate pellet, oil immersion; scale bar = 28 microns).

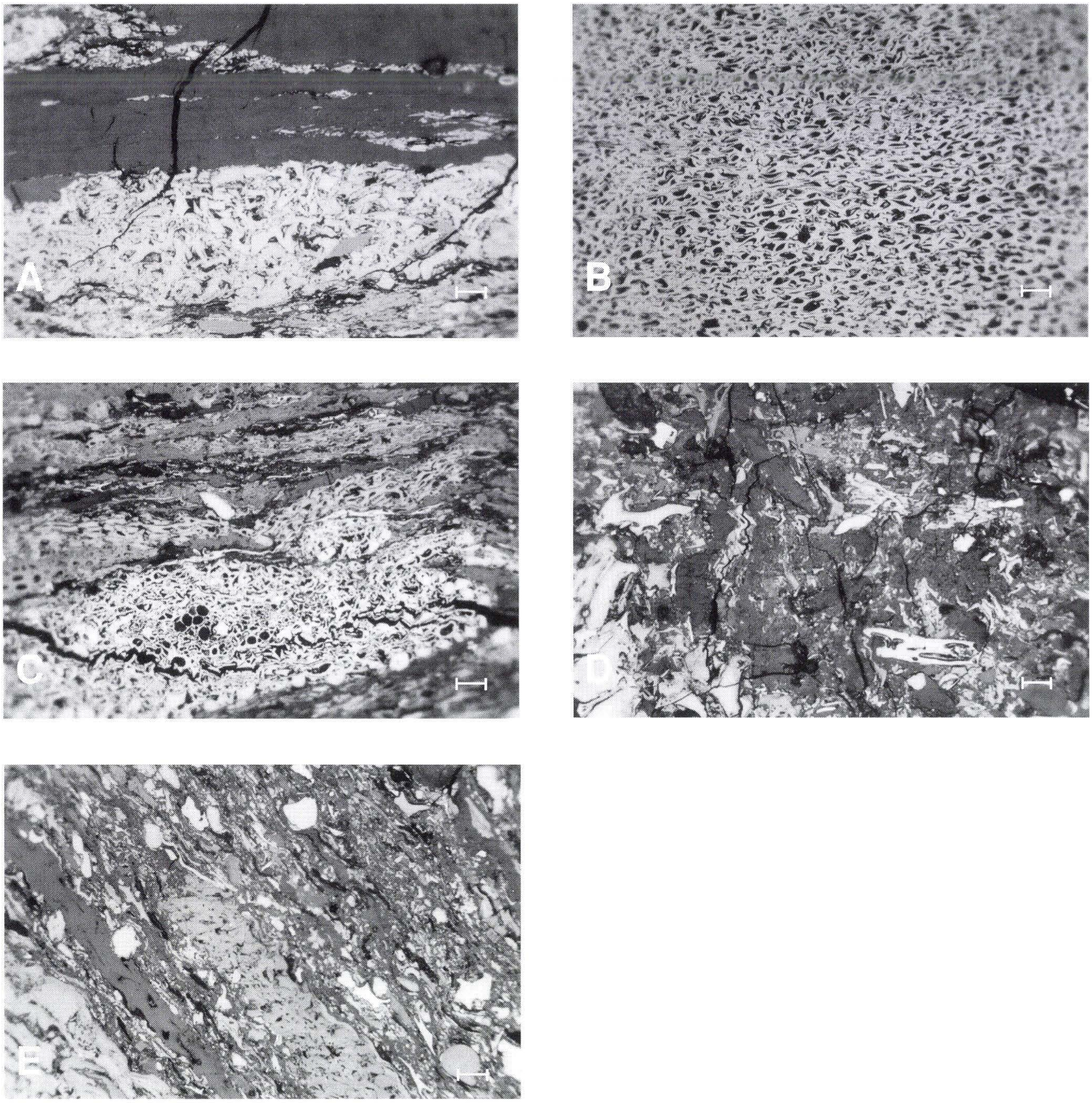

A
B
C
D
E

PLATE 3
Øresund - 5 well
Coal seam 1

A: Fusinite with fusinized corpohuminite (macrinite) (Sample 6365, base (?), crushed core sample, particulate pellet, oil immersion; scale bar = 28 microns).
B: Fusinite (oxidized textinite) and macrinite (oxidized corpohuminite) (Sample 6365, base (?), crushed core sample, particulate pellet, oil immersion; scale bar = 28 microns).

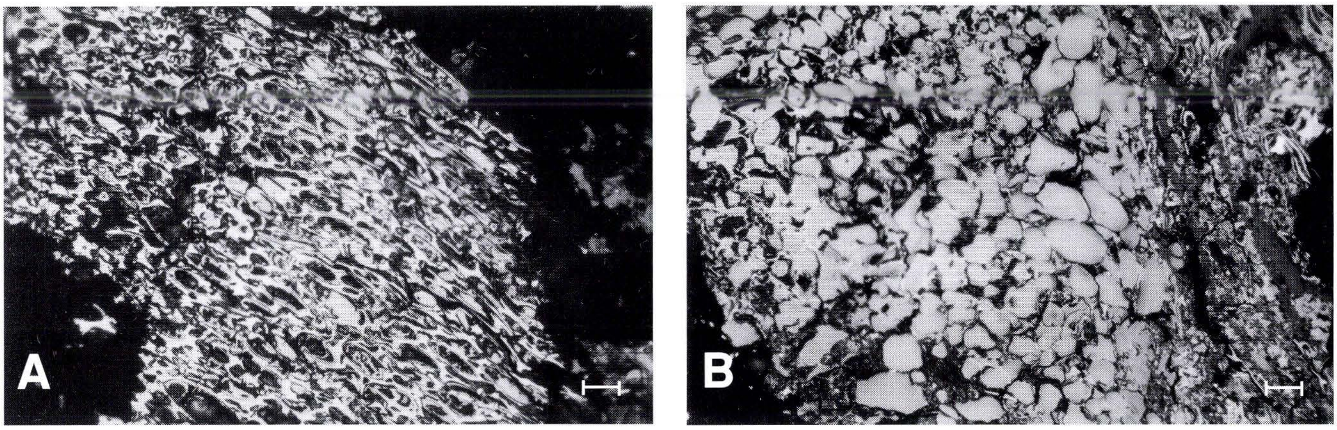

A
B

PLATE 4
Øresund - 7 well
Coal seam 2

A: Textoulminite with cell lumens partly infilled by gelinite (Sample 6359, top (?), crushed core sample, particulate pellet, oil immersion; scale bar = 28 microns).

B: Mainly intimately associated textinite, gelinite and densinite together with cutinite and sporinite (Sample 6359, top (?), crushed core sample, particulate pellet, oil immersion; scale bar = 28 microns).

PLATE 4

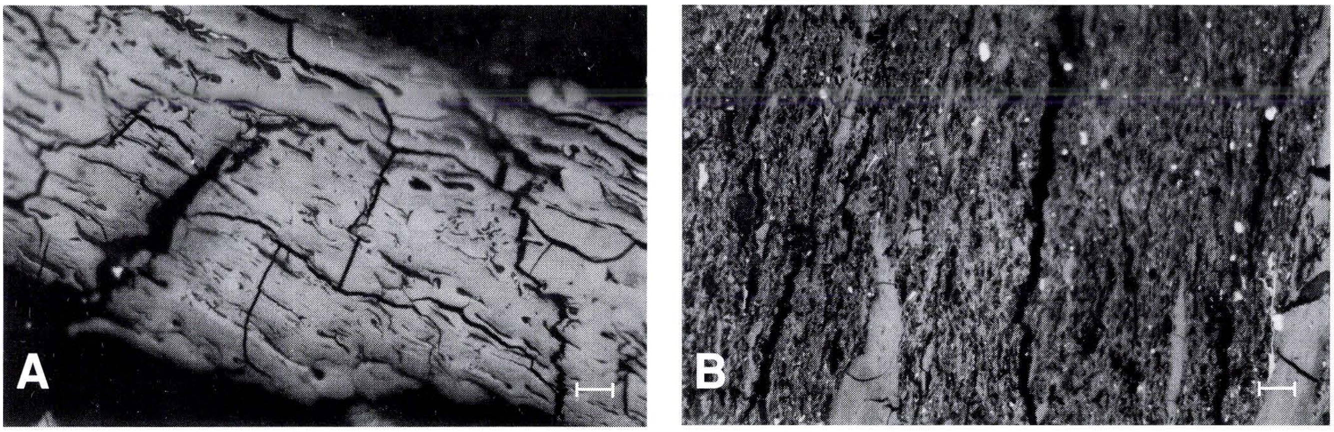


PLATE 5
Øresund - 7 well
Coal seam 3

A: Angular and poorly sorted low reflecting inertodetrinite and macrinite together with oxidized porigelinite (or very fine-grained inertodetrinite), and minor amounts of ulminite and liptodetrinite (Sample 6361, top (?), crushed core sample, particulate pellet, oil immersion; scale bar = 28 microns).

B: Angular and poorly sorted low reflecting inertodetrinite, macrinite and semifusinite/fusinite together with irregular bands of densinite (Sample 6361, top (?), crushed core sample, particulate pellet, oil immersion; scale bar = 28 microns).

C: Low reflecting macrinite, semifusinite and inertodetrinite (Sample 6361, top (?), crushed core sample, particulate pellet, oil immersion; scale bar = 28 microns).

D: Low reflecting inertodetrinite and macrinite together with minor proportions of liptodetrinite and sporinite in a groundmass of densinite, porigelinite and gelinite (Sample 6361, top (?), crushed core sample, particulate pellet, oil immersion; scale bar = 28 microns).

E: Porigelinite and gelinite (lower to middle part of the photo) and eu-ulminite (upper part of the photo) (Sample 6361, top (?), crushed core sample, particulate pellet, oil immersion; scale bar = 28 microns).

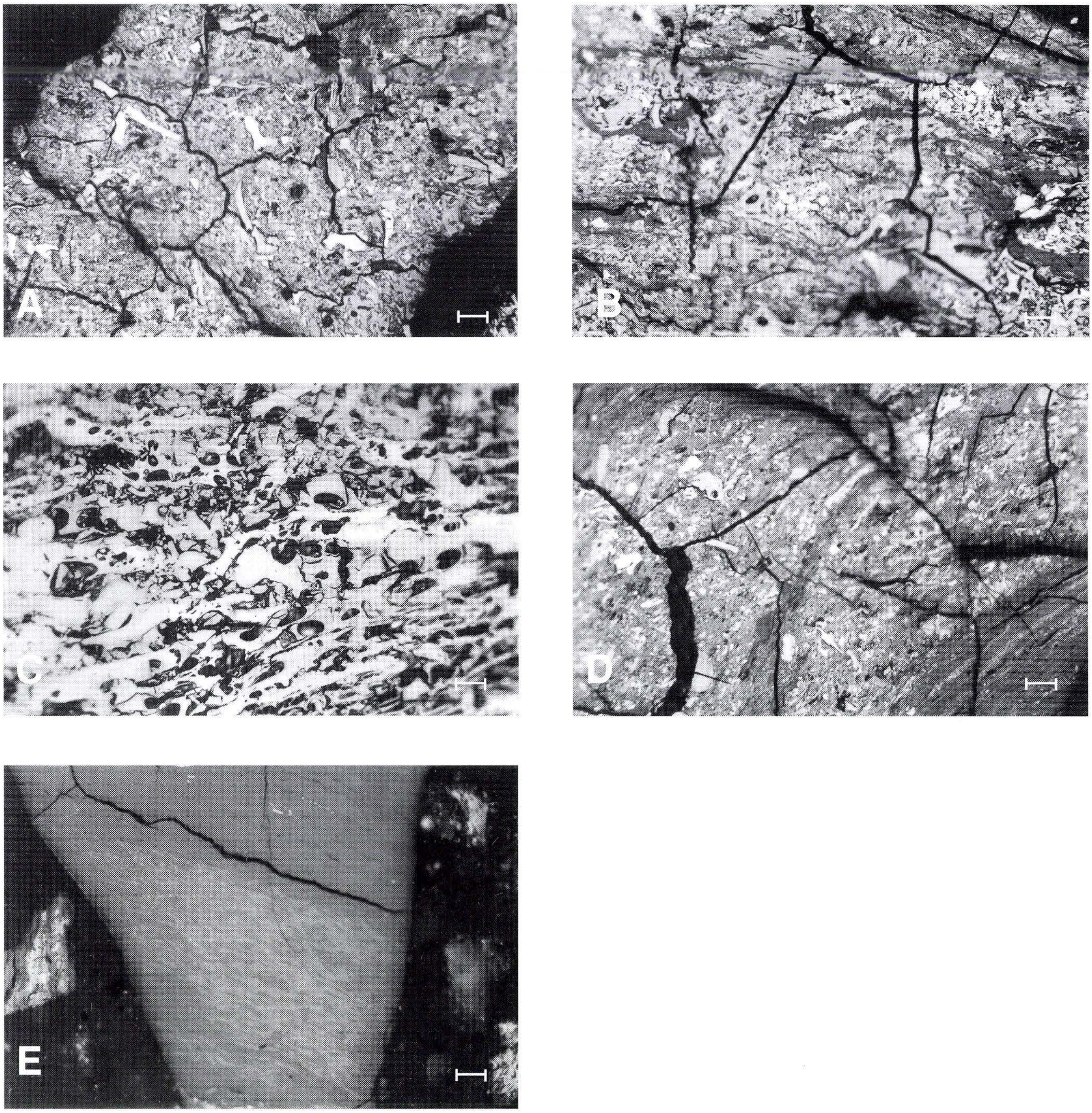

A
B
C
D
E

PLATE 6
Øresund - 7 well
Coal seam 4

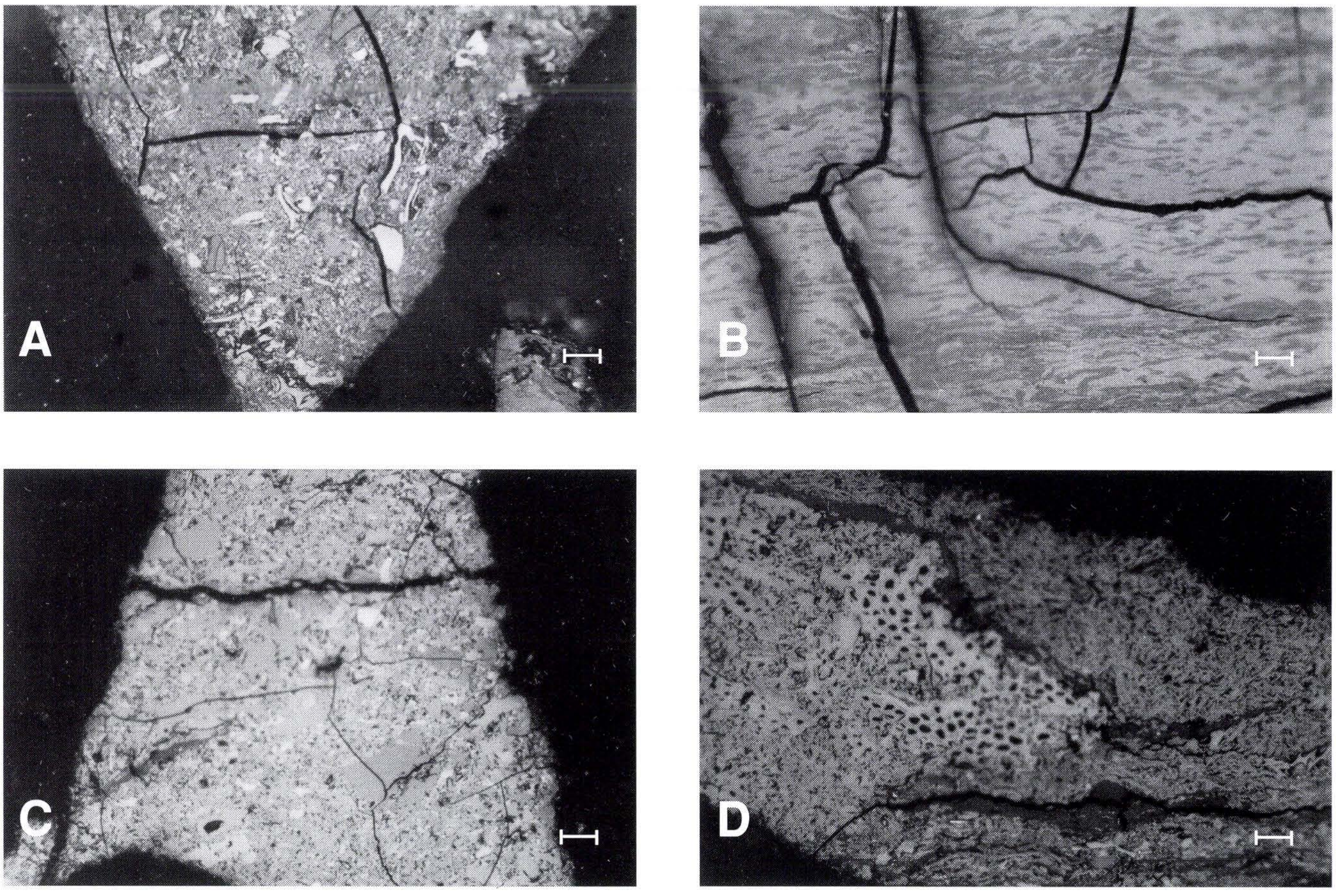
A: Mainly low reflecting inertodetrinite and macrinite together with liptodetrinite, sporinite and cutinite in a groundmass of densinite and porigelinite (Sample 6362, base, crushed core sample, particulate pellet, oil immersion; scale bar = 28 microns).

B: Porigelinite and gelinite (Sample 6362, base, crushed core sample, particulate pellet, oil immersion; scale bar = 28 microns).

C: Low reflecting and generally angular and poorly sorted inertodetrinite and macrinite (Sample 6364, upper part, crushed core sample, particulate pellet, oil immersion; scale bar = 28 microns).

D: Low reflecting semifusinite, inertodetrinite and macrinite together with irregular bands of huminite (Sample 6364, upper part, crushed core sample, particulate pellet, oil immersion; scale bar = 28 microns).

PLATE 6



Lower and Middle Jurassic coal seams and associated siliciclastic sediments from the Øresund area, east Denmark, are investigated by means of coal petrology, organic geochemistry, and sedimentology.
The depositional environments of the coal-bearing strata are presented together with a detailed facies study of the coal seams. Three main types of peat-forming mires are defined based on the petrographic composition of coal seams.

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