

## INVESTIGATION ON THE SOURCE ROCK POTENTIAL OF DENMARK<sup>1</sup>

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### ABSTRACT

Thomsen, E., H. Lindgreen & P. Wrang 1983 Investigation on the source rock potential of Denmark. In: J. P. H. Kaasschieter & T. J. A. Reijers (eds.): Petroleum geology of the southeastern North Sea and the adjacent onshore areas (The Hague, 1982) - Geol. Mijnbouw 62: 221-239.

Source rock analyses are carried out at the Geological Survey of Denmark using mineralogical, coal petrographical and organo-chemical methods. Investigations have been concentrated on Mesozoic deposits from the Danish part of the Central Graben and on Palaeozoic and Mesozoic deposits from the Danish onshore area. The results from the Central Graben indicate that the Kimmeridgian deposits are the principal source rocks for the known oil fields in the Danish sector, but with regional variations with respect to richness and maturity, the northern part of the study area being the most promising. From the Danish onshore area coal petrographical analyses indicate that Rhaetian-Jurassic-Early Cretaceous deposits are mainly immature-premature with respect to oil generation. Combined mineralogical and coal petrographical analyses on a limited number of samples from the Palaeozoic indicate post-mature Early Palaeozoic deposits, while Carboniferous and Permian sediments have been found to be in a premature-mature stage.

### INTRODUCTION

For several decades Mesozoic and Upper Palaeozoic deposits have been the objects for the search for commercial hydrocarbons in Denmark. So far the onshore activities have proved unsuccessful, while the offshore activities have led to the discovery of several promising fields in the North Sea.

Concerning the source rock potential of the Danish offshore area, results have only been published by WEISSMAN (1979) who reported that Upper Cretaceous and Tertiary did not generate hydrocarbons in significant amounts. Source rock investigations in adjacent concession areas indicate that the Late Jurassic Kimmeridge Clay and equivalent formations are the main source rocks in the North Sea (see BARNARD & COOPER, 1981). Apart from a report submitted by the Geological Survey of Denmark (LINDGREEN & THOMSEN, 1982) nothing has been published about the source rock potential of the Danish onshore area. Cambrian oil source rocks are known in the Baltic Syncline (MAKSIMOV ET AL., 1974; GURARI ET AL., 1976). In the Danish area Cambro-Silurian deposits are exposed in a system of fault blocks on the southern part of Bornholm (Fig. 1). Up to 350 m of Lower Palaeozoic have

been drilled in a few wells in onshore Denmark (POULSEN, 1969, 1974; CHRISTENSEN, 1971, 1973). However, according to MICHELSEN & ANDERSEN (1981) seismic data indicate a thick Lower Palaeozoic sequence in the Skagerrak, northern Jutland and the Kattegat area.

Approximately 500 m of Early Carboniferous limestones, shales and minor sandstones have been drilled in the Ørsløv 1 well on Falster (MICHELSEN, 1971; BERTHELSEN, 1972). Late Carboniferous coal-bearing deposits, which are the source for the gas occurrences in Germany and Poland, have not been drilled in the Danish area. Oil fields probably sourced from bituminous intervals in the Zechsteinkalk and the Hauptdolomite are known in Poland and Eastern Germany (GURARI ET AL., 1976; USPENKAJA, 1976). In the Danish area possible equivalents to the Zechsteinkalk and the Hauptdolomite have been recorded in a few wells. The Kupferschiefer has only been drilled in the Rønne 1 well (JACOBSEN, 1971) in Jutland, oil shows were recorded in carbonates in the wells Åbenrå, Hønning 1 and Tønder 1 in southern Jutland. No commercial accumulations have been drilled.

During the Rhaetian-Jurassic-Early Cretaceous more than 2000 m of dark marine shales and claystones alternating with non-marine claystones and sandstones with coal occurrences were deposited (LARSEN, 1966; BERTHELSEN, 1978; MICHELSEN, 1978). Compared with areas adjacent to Denmark, the most likely source rocks are shales of Jurassic and Early Cretaceous

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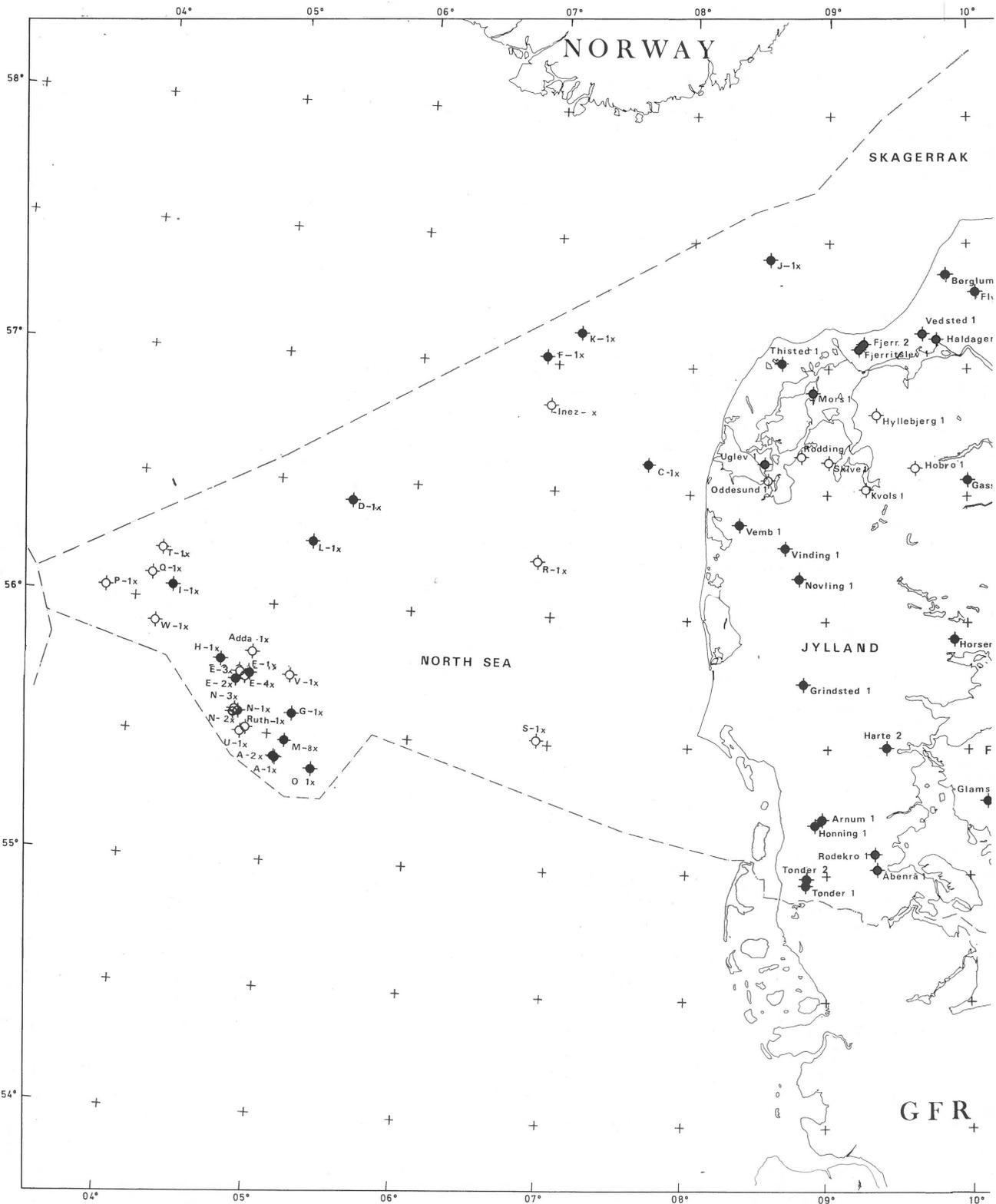
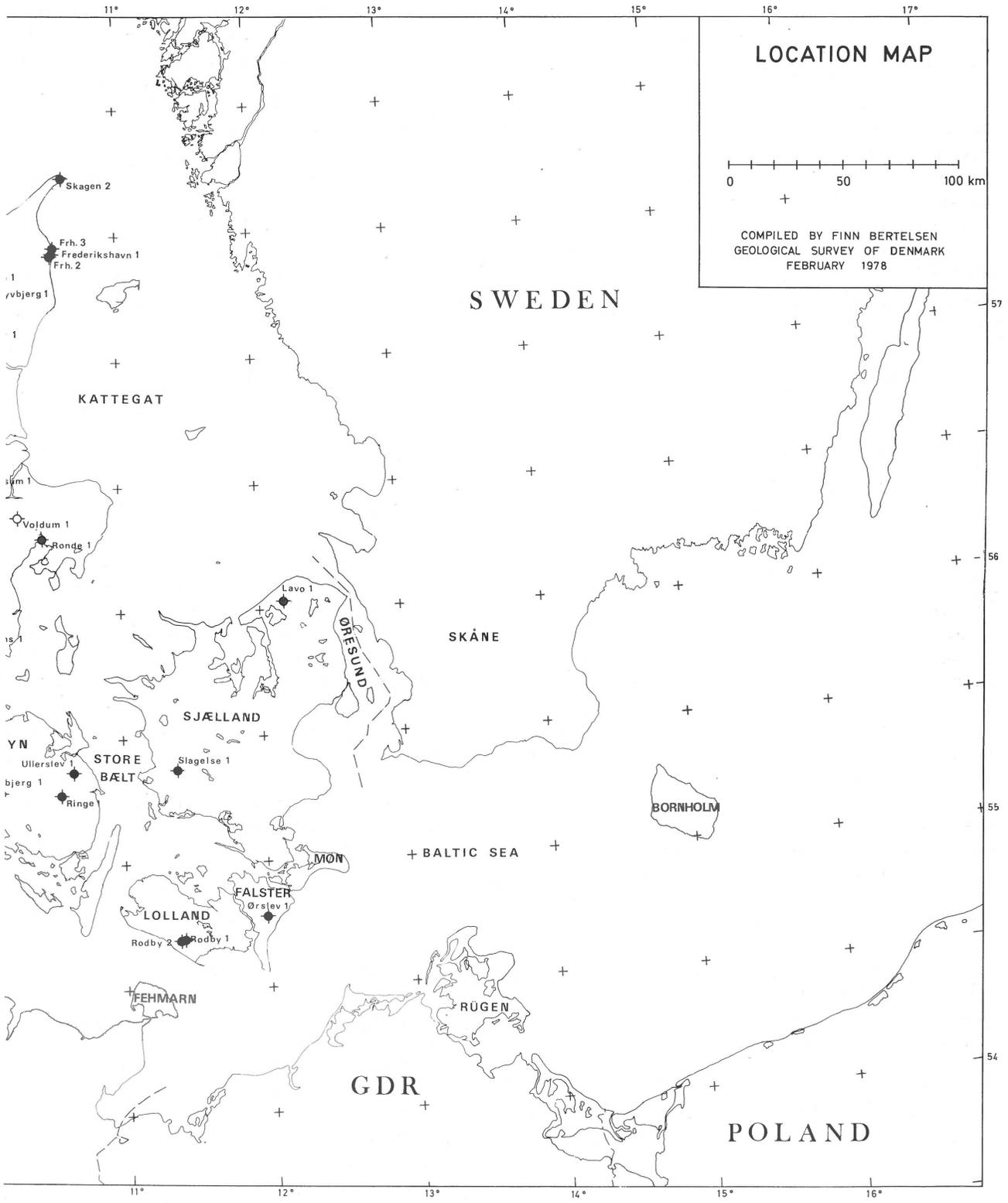
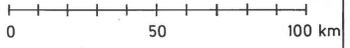


Fig. 1  
Location map.



LOCATION MAP



COMPILED BY FINN BERTELSEN  
GEOLOGICAL SURVEY OF DENMARK  
FEBRUARY 1978

SWEDEN

KATTEGAT

SKÅNE

ÖLAND

SJÆLLAND

STORE BÆLT

BORNHOLM

BALTIC SEA

FALSTER

LOLLAND

FEHMARN

RÜGEN

GDR

POLAND

age (SCHOTT, 1982). In 1977-78 the Danish Government initiated source rock investigations by coal petrographical, mineralogical and organic geochemical methods. The results obtained so far are reported in the present article.

Concerning the geological and structural setting of the Danish area and its relation to surrounding areas reference is made to the papers by ZIEGLER (1978), SURLYK (1980) and MICHELSEN & ANDERSEN (1981). A detailed account of the geology of the Danish part of Central Graben is presented by MICHELSEN (1982). Well data are accessible in a paper by SORGENFREI & BUCH (1964) and in the Well Data Summary Sheets Vol. 1 and 2 (1981) and Vol. 3 (1982) issued by the Danish Geological Survey. The location of the wells investigated is shown in figure 1.

## MATERIAL

The material available for the investigation were cutting samples (intervals 10 to 30'), a few sidewall cores and, from onshore wells, conventional cores.

## METHODS

The source rock analyses have been performed by mineralogical, coal petrographical and organochemical methods.

Optically, the organic matter was rated qualitatively in reflected light supplemented by blue-light induced fluorescence. The rank of the organic matter was determined by vitrinite reflectance measurements using the principles outlined in STACH ET AL. (1975). Supplementary rank determinations have been carried out on several samples using quantitative fluorescence measurements and TAI index determinations. Fluorescence measurements, i.e. red/green ratio determinations, were carried out according to the suggestions by OTTENJANN ET AL. (1974) and TEICHMÜLLER & OTTENJANN (1977).

In selected Mesozoic samples from the onshore area, TAI index values were determined according to a modified version of the scales published by STAPLIN (1969) and BURGESS (1974). Approximate threshold values for the onset of oil generation, oil expulsion and the peak zone of oil generation, have been used according to the suggestions by HOOD ET AL. (1975), DOW (1977) and TISSOT & WELTE (1978).

Semiquantitative mineralogy and clay mineralogy were determined by X-ray diffraction on powdered bulk samples and on clay fractions pretreated for removal of organic matter, carbonates, free iron and aluminium oxides, saturated with magnesium or potassium, heated or glycerolated, and oriented. Qualitative and, for carbonates and sulfides, quantitative mineralogy was determined by differential thermal analysis on powdered bulk samples with detection of evolved CO<sub>2</sub>, H<sub>2</sub>O and SO<sub>2</sub>. The oxidation state and mineralogical positions of iron was determined by Mössbauer spectroscopy

on powdered bulk samples. Specific surface areas were determined on a gas adsorptometer with gases N<sub>2</sub>, H<sub>2</sub>O and Kr. The clay mineral compositions were calculated as relative reflection intensities, the total clay reflection area being equalled 100% (HELING, 1979). Illite crystallinity was calculated after TEICHMÜLLER ET AL. (1979).

Total carbon (TC) and total organic carbon (TOC) were measured on a Leco carbon analyser. TOC was measured after pretreatment with hot, concentrated HCl. Soluble organic matter (SOM) was determined from the extract from a Soxhlet extraction of the crushed sample with methylenchloride in 24 hours. The separation of SOM was performed by column-chromatography with hexane, methylenchloride and methanol as eluents. Gas liquid chromatography (GLC) of the alifate fraction was performed on a OV 1 capillary column. Pyrolysis was performed on a Rock-Eval instrument (ESPITALIÉ ET AL., 1977).

## RESULTS AND DISCUSSION

### *Danish onshore area*

Source rock studies have been carried out by combined mineralogical and coal petrographical methods on Palaeozoic sample material. Rhaetian-Jurassic-Early Cretaceous material has been studied by coal petrographical methods.

*Cambro-Silurian deposits* – Selected samples from the wells Nøvling 1, Rønde 1 and Slagelse 1 have been investigated. Analyses have been carried out on samples from outcrops and cores from shallow drilling (Vasagaard) on the island of Bornholm.

Before evaluating the geological significance of the results, it should be emphasized that the carbonaceous matter has been treated as if it were vitrinite, although higher land plant material is absent, in sediments of Cambrian to Early Silurian age. However, TEICHMÜLLER ET AL. (1979) and KISCH (1980) found a good correlation between illite crystallinity and 'vitrinite' reflectance in Early Palaeozoic deposits. Hence, the method has been used assuming that the carbonaceous matter responds to increasing coalification as vitrinite *sensu stricto*. In the Slagelse 1 well 'vitrinite' reflectance indicates that the Cambro-Silurian sequence is in a post-mature stage with respect to oil generation. The values are generally in the range 2.4 - 3.0% R<sub>0</sub>, indicative of sediments equivalent to semi-anthracitic – anthracitic coal rank (Table I). A common characteristic is a high scatter of the reflectance values, which in part is attributed to analytical principles. Due to lack of larger grains suitable for determination of the maximum reflectance, only mean random reflectance measurements (R<sub>0</sub>) have been carried out. The corresponding rank ranges have been determined using the classification scheme published by TEICHMÜLLER ET AL. (1979). Investigations of organic concentrates in transmitted light show that the organic matter



ratio of 3.3. X-ray and electron diffraction on a kerogen concentrate from the sample revealed a graphite structure with  $D(002)$   $3.43\text{\AA}$  and  $L_c$   $30\text{\AA}$ , corresponding to the onset of low metamorphism, WINKLER (1974), or the onset of greenschist facies after TURNER (1968), according to KWIENCINSKA (1980). The kerogen concentrates from Vasagaard 1 showed similar sharp DTA peaks at  $495^\circ$  and  $570^\circ$  for the two samples, but the C/H ratios were 0.7 and 0.1, indicative for a lower degree of metamorphism or for the influence of weathering.

The high content of organic matter in Slagelse 1 (Alum Shale) may have retarded the mineralogical transformations, as the Alum Shale only contains a mica but unlike the Ordovician-Silurian samples no chlorite.

The Ordovician-Silurian samples from Nøvling and Rønde contain a well-crystalline hematite. Clay mineralogically they contain a mica, which in most samples is a well-crystalline  $2M_1$  muscovite, as well as a chlorite. The X-ray pattern for the chlorite resembles the ripidolite investigated by BORGGARD ET AL. (1982), and as the  $\text{Fe}^{2+}$  situated in clay minerals must be placed in this chlorite, its identification as a ripidolite seems valid (Table III).

The occurrence of a well-crystalline  $\text{Fe}^{2+}$ -chlorite and a mica, which in most samples can be identified as a  $2M_1$  muscovite, in all Ordovician-Silurian rocks, combined with the absence of kaolinite and smectite, points to an onset of low metamorphism in accordance with HOWER ET AL. (1976) after WINKLER (1974), or the onset of greenschist facies after TURNER (1968).

Chlorites in Early Palaeozoic deposits in Norway and Great Britain are reported by BJØRLYKKE (1974) and PERRIN (1971). BJØRLYKKE believed the chlorite in the hematite-free Oslo deposits to be due to short-distance clastic sediments. However, the chlorite detected in the present investigation most probably is authigenic, since a  $\text{Fe}^{2+}$ -chlorite is very susceptible to weathering. Furthermore, hematite with no kaolinite or illite is a product of intense weathering (MAIGNIEN, 1966; MILLOT, 1970). Also, the recrystallization of separate phases of muscovite and chlorite corresponds to a low level of metamorphism, whereas illite with varying amounts of expandible layers is typical for the zone of diagenesis (MILLOT, 1949). Therefore, a calculation of illite crystallinity in rocks of this metamorphic grade with a  $2M_1$  muscovite as the only mica mineral is meaningless (see also MILLOT, 1970).

The results of the combined investigations show that lower rank conditions are prevailing in the Cambro-Silurian deposits on Bornholm as compared with similar deposits in the Slagelse 1 well. However, there is a discrepancy between the results of the coal petrographic analyses indicating late diagenetic grades and the mineralogical investigations pointing to low metamorphic grades. This discrepancy is currently under investigation. However, both methods show that the Cambro-Silurian deposits investigated so far are in a post-mature stage with respect to oil generation. Compared with the Slagelse 1 well, the lower rank recorded on Bornholm points to a higher gas-potential. However, only dry gas is to be expected.

Table III  
Mineralogy of Ordovician – Silurian samples. Legend, see Table II.

Well, sample, stratigraphy	Total sample											Clay fraction					Iron minerals						
	% organic C	organic C/H	dolomite	ankerite	calcite	quartz	feldspars	anhydrite	pyrite	kaolinite	mica	$2M_1$ Muscovite	chlorite	kaolinite	mica	mixed-layer mica-smec.	smectite	chlorite	$\text{Fe}^{3+}$ in hematite	$\text{Fe}^{2+}$ in layer silicates	$\text{Fe}^{2+}$ in pyrite	$\text{Fe}^{2+}$ in ankerite	$\text{Fe}^{2+}$ in siderite
Ord.-Sil.																							
Slagelse 1:																							
2812.5 m	0.1	—	—	—	+	+	—	—	—	—	++	++											
2855.8 m	0.4	—	—	—	++	+	—	—	—	—	++	++							+	++	—	—	—
2905 m	0.3	—	—	—	++	+	—	—	—	—	++	++											
Nøvling 1:																							
11600'	0.1	64	—	—	+	—	++	—	—	—	—	—							++	++	—	—	—
11615'	0	—	13	—	+	+	—	—	—	—	+	+							+	++	—	+	—
11932'	0.1	—	—	23	++	++	—	—	—	—	++	++							+	++	—	—	—
12132.5'	—	—	—	++	++	+	—	—	—	—	++	++							++	++	—	—	—
Rønde 1:																							
17164'	0	—	—	11	+	+	—	—	—	—	+	+							++	++	—	—	—

*Carboniferous-Permian deposits* – Early Carboniferous deposits from the well Ørslev 1 have been investigated. Permian deposits from the wells Nøvling 1, Rønne 1, Slagelse 1, Tønder 1 and Ørslev 1 are under study and, therefore, only a few results are available as yet.

The results of vitrinite reflectance measurements are illustrated in Table I. The measurements have been supplemented with a limited number of red/green ratio determinations (Q). The results show that the Lower Carboniferous in the Ørslev 1 well is in a mature stage with respect to oil generation, i.e. at the beginning of the oil-window. This is sustained by the red/green ratio determinations, indicative of sediments with a rank range comparable to a vitrinite reflectance of 0.55 - 0.70%  $R_0$  (OTTENJANN, pers. comm.). Apart from the Rønne 1 well, the number of specimens or particles suitable for measurements is low in the Permian samples. This highly reduces the validity of the data. However, the preliminary results indicate the Permian deposits in the wells Nøvling 1 and Tønder 1 to be mature for oil generation. The interval investigated in the Rønne 1 well encompasses the Kupferschiefer, which is mature, but the measurements have been carried out on what has tentatively been regarded as vitrinite. Since several of the particles show the character of former mobile compounds, they could in fact represent solid bitumen. The Permian deposits in the Ørslev 1 and the Slagelse 1 wells are immature to premature with respect to oil generation. The results are sustained by the red/green ratio determinations.

The Carboniferous samples investigated from Ørslev 1

have a high content of calcite or ankerite (Table IV). The  $Fe^{2+}$  in sample 7740' is probably situated in mica. The presence of kaolinite and mixed-layers smectite-illite and the absence of smectite together with the degree of illite crystallinity indicate a stage of late diagenesis (FOSCOLOS ET AL., 1976).

The Permian samples from the Slagelse 1 well consist predominantly of dolomite associated with a low content of carbon (Table IV). In Ørslev 1 the sample investigated consists of quartz, hematite, kaolinite and illite, which are stable in a tropical climate with alternating dry and humid seasons (MILLOT, 1970). Furthermore, mixed-layers smectite-illite is present, which may have formed during diagenesis. The carbonates and sulfates are either evaporites or diagenetic products. No metamorphic minerals were detected. The illite crystallinity indicates a late degree of diagenesis (TEICHMÜLLER ET AL., 1979).

In summary, it is interesting to note that there is a marked coalification jump between Permian and Silurian deposits in the Slagelse 1 well. The Carboniferous deposits in the Ørslev 1 well exhibit rank values not indicative for major thermal influences. The late diagenetic stage indicated mineralogically in the Permian and Carboniferous samples in the Ørslev 1 well should be compared to the mineralogically indicated low-metamorphic stage of the Silurian samples from the wells Slagelse 1, Nøvling 1 and Rønne 1 as well as the Cambrian samples from the well Slagelse 1. Hence, the high degree of transformation found in the Early Palaeozoic deposits most likely is due to a pre-Carboniferous event, probably the

Table IV  
Mineralogy of Upper Palaeozoic samples. Legend, see Table II.

Well, sample, stratigraphy	Total sample													Clay fraction					Iron minerals					Illite crystallinity
	% organic C	organic C/H	dolomite	ankerite	calcite	quartz	feldspars	anhydrite	pyrite	kaolinite	mica	2M <sub>1</sub> Muscovite	chlorite	kaolinite	mica	mixed-layer mica-smec.	smectite	chlorite	Fe <sup>3+</sup> in hematite	Fe <sup>2+</sup> in layer silicates	Fe <sup>2+</sup> in pyrite	Fe <sup>2+</sup> in ankerite	Fe <sup>2+</sup> in siderite	
Permian																								
Slagelse 1:																								
2596.7 m	0.3	80	—	—	—	—	—	—	—	—	—	—	10	60	—	—	30							
2601 m	0.6	78	—	—	—	—	—	—	—	—	—	—	10	30	30	—	30							
Ørslev 1:																								
6852'	—	—	+	++	+	—	++	—	+	+	—	—	20	70	10	—	—						4.8	
Carbonif.																								
Ørslev 1:																								
7688'	0.9	—	—	50	+	+	—	1	+	+	—	—	20	20	60	—	—						5.6	
7736'	1.0	—	24	++	+	+	—	1	+	+	—	—	20	20	50	—	10	—	—	++	+	—	4.8	
7740'	1.2	—	—	++	+	+	—	1	+	+	—	—	20	40	30	—	10	—	+	++	—	—	4.0	

Caledonian orogeny, as also proposed by GAERTNER (1960) and could indicate a northward extension of the eastward bend of the Caledonian deformation front as proposed by ZIEGLER (1981). According to this proposal, less transformed foreland deposits of Early Palaeozoic age might be expected in the northern Jutland, northern Kattegat and Skagerrak area (for more details see LINDGREEN & THOMSEN, 1982).

*Rhaetian-Jurassic-Early Cretaceous deposits* – From the Danish Subbasin coal petrographical analyses have been carried out on samples from the deep wells Skagen 2, Frederikshavn 1, Haldager 1, Vedsted 1, Fjerritslev 2, Gassum 1, Rønde 1, Horsens 1, Vinding 1, Ullerslev 1 and Lavø 1 (Fig. 1). The analyses comprised vitrinite reflectance measurements, red/green ratio (Q) determinations and evaluations of the spore colour index (TAI). Table V illustrates the range of huminite/vitrinite reflectance values, red/green ratios and TAI values recorded in the study area. There is a high degree of correspondence between the various rank parameters applied, i.e. a reflectance range of 0.36 - 0.58%  $R_0$ , Q range for sporinite of 0.70 - 1.40 (OTTENJANN, pers. comm.) and a range of TAI values of 1 - 2+. It can be concluded that the rank range in the investigated part of the Danish Subbasin corresponds to lignitic-high volatile bituminous C coal rank.

Although the number of samples analysed does not permit a detailed mapping of the regional rank conditions, the reflectance values clearly illustrate the basin nature and reflect the influence of increasing temperature with increasing depth of burial. Towards the centre of the Danish Subbasin the rank increases, reflecting increasing depth of burial, while the lowest rank conditions are encountered towards the Fennoscandian Border Zone and the Ringkøbing - Fyn High indicating shallow burial conditions. A composite plot of huminite/vitrinite reflectance against depth for the wells investigated is shown in figure 2. As shown on this graph, the Gassum 1 well shows a distinctly different trend, while the remainder of the investigated wells demonstrate a similar rank increase with depth. According to TEICHMÜLLER & TEICHMÜLLER (1968) the rank gradient increases at varying rates in

the different rank ranges. In low rank ranges, such as the range of the Danish Subbasin, the increase with depth can be regarded as nearly linear (KOCH, 1974). With exception of the results from Gassum 1, a linear regression analysis shows a very high degree of correlation ( $r = 0.963$ ) with a rank gradient of 0.09%  $R_0$ /km. The gradient encountered in the Gassum 1 well is more than double as high, i.e. 0.21%  $R_0$ /km. The gradient is a function of the geothermal gradient, as well documented in studies of Tertiary sediments from the Upper Rhine Graben (DOEBL ET AL., 1974; TEICHMÜLLER, 1979). In the investigated part of the Danish Subbasin a regional geothermal gradient in the order 18 - 25°C/km has been recorded (MADSEN, 1975, 1978). Local anomalies are recorded in wells situated on saltstructures, i.e. the Gassum 1 well with a geothermal gradient of 36°C/km. The high rank gradient recorded in this well is attributed to the special thermal conditions around salt structures (RASHID & McALARY, 1977; BALLING, 1978). For the rest of the wells investigated the influence of salt structures is regarded as insignificant (THOMSEN, 1980; LINDGREEN & THOMSEN, 1982). According to MADSEN (1978) geothermal gradients in the order of 26 - 28°C/km are to be expected in the centre of the Danish Subbasin in areas unaffected by salt structures. Since none of the investigated wells is located in the centre of the basin, the average rank gradient of 0.09%  $R_0$ /km must be regarded as a minimum average value for the Rhaetian-Jurassic-Early Cretaceous sequence in the Danish Subbasin.

Several of the investigated wells have passed a maturity level corresponding to a vitrinite reflectance of 0.50%  $R_0$ , the value commonly cited as the threshold value for the onset of oil generation. However, no hydrocarbons have been encountered. Our North Sea experience shows that the composition of source rock hydrocarbons only become crude-like in a reflectance range of 0.60 - 0.70%  $R_0$ , which is in good accordance with the findings of HOOD ET AL. (1975) and DOW (1977). The discrepancies concerning the definition of the oil 'birth' line probably results from use of different extraction methods. However, the main source of variation is due to the type of organic matter, since different types of organic matter have a

Table V

Range of mean huminite/vitrinite reflectance values ( $R_0$ ), red/green ratios (Q) and thermal alteration index values (TAI) recorded in Rhaetian-Jurassic-Lower Cretaceous samples from deep wells drilled in the Danish Subbasin. Number in brackets refers to number of samples analysed.

Well	Depth interval (m)	Range of $R_0$	Range of Q	Range of TAI
Skagen 2	214 - 564	0.36 - 0.41 (16)	0.70 - 1.03 (7)	1 (4)
Frederikshavn 1	358 - 980	0.39 - 0.44 (13)	0.82 - 0.93 (3)	1 (4)
Haldager 1	417 - 1521	0.41 - 0.46 (19)	0.99 - 1.21 (9)	1 - 1+ (4)
Vedsted 1	457 - 2065	0.42 - 0.52 (7)	1.03 - 1.23 (6)	1+ - 2- (6)
Fjerritslev 2	299 - 2326	0.42 - 0.57 (14)	0.78 - 1.40 (7)	1 - 2+ (7)
Gassum 1	997 - 1710	0.42 - 0.55 (16)	1.00 - 1.40 (8)	1 - 2 (6)
Lavø 1	1940 - 2365	0.54 - 0.57 (2)	1.25 (1)	n.d.
Rønde 1	1985 - 2805	0.51 - 0.58 (11)	1.10 - 1.15 (2)	n.d.
Vinding 1	1292 - 1720	0.44 - 0.48 (4)	1.06 - 1.10 (2)	n.d.
Horsens 1	1165 - 1642	0.46 - 0.49 (2)	1.09 - 1.10 (2)	n.d.
Ullerslev 1	826 - 978	0.40 (1)	0.94 - 1.07 (2)	n.d.

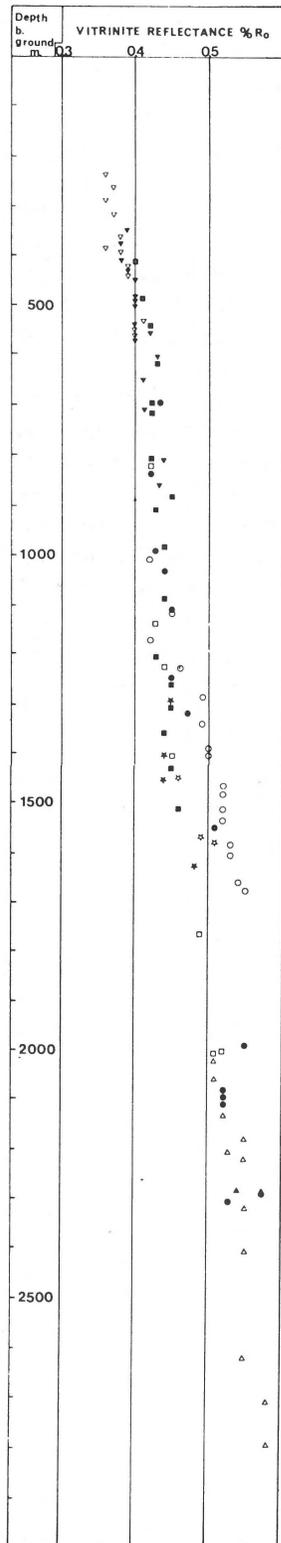
RHAETIAN — JURASSIC —  
 LOWER CRETACEOUS


Fig. 2  
 Composite plot of huminite/vitrinite reflectance values against depth for Rhaetian-Jurassic-Lower Cretaceous deposits investigated in wells from the Danish Subbasin.

- ▽ SKAGEN 2
- ▽ FREDERIKSHAVN 1
- HALDAGER 1
- VEDSTED 1
- FJERRITSLEV 2
- GASSUM 1
- △ RØNDE 1
- \* VINDING 1
- ◇ HORSSENS 1
- + ULLERSLEV 1
- ▲ LAVO 1

different composition and thus a different rate of transformation with increasing temperature (TISSOT & WELTE, 1978; HUNT, 1979). Optical investigations in transmitted and reflected light indicate that fair amounts of the three main kerogen types can be found in the investigated sequence. However, the most mature Rhaetian-earliest Jurassic deposits seem to be dominated by the more unfavourable humic type of organic matter, which according to the threshold value for type-III kerogen (TISSOT & WELTE, 1978) must be rated immature-premature (THOMSEN, 1980; LINDGREEN & THOMSEN, 1982).

According to DOW (1977) a semi-logarithmic plot of vitrinite reflectance values versus depth in a continuously subsiding basin will show a straight line, the 'maturation gradient' which allows estimates of the maturity levels with depth. Using a rank gradient of 0.09%  $R_0$ /km and reflectance values of 0.60 and 1.30%  $R_0$ , the oil 'window' is to be expected from ca. 2700 - 6000 m (discussed in detail by LINDGREEN & THOMSEN, 1982). The inherent errors by using this method are manifold. The method requires in fact a basin which has been under continuous subsidence since the basin was initiated, uninterrupted by major tectonic episodes and with no major changes of the geothermal conditions. The rank conditions recorded in the Late Palaeozoic deposits fit with this plot, which could represent a fair expression of the rank conditions in Mesozoic-Late Palaeozoic deposits in the Danish Subbasin. However, the limited number of samples analysed so far from the Upper Palaeozoic do not permit any general conclusions.

### Central Graben

The Mesozoic-Cenozoic sequence in the wells M-8 (Dan field), E-1 (Thyra-field) and I-1 has been studied. The results of the mineralogical investigations are shown in figures 3 - 5; the porosities of the shales in Table VI. The porosities and specific surface areas show that the claystone is open to diffusion of inorganic and organic ions and molecules. In agreement with MILLOT (1970), DUNOYER DE SEGONZAC (1970), SARKISYAN (1972) and HANCOCK & TAYLOR (1978), the kaolinite is probably formed during early diagenesis from fresh-water

Table VI  
 Porosities of Central Graben samples.

Well, sample	Specific surface area, $m^2/g$	Pores $<400\text{Å}$ , $cm^3/g$
E-1:		
11280' - 300'	24	0.03
12900' - 920'	18	0.03
I-1:		
11280' - 290'	14	0.06
11520' - 530'	16	0.05
M-8:		
9090' - 120'	34	0.06
10680' - 710'	38	0.05

solutions, whereas the mixed-layers and the illite are largely formed during late diagenesis by potassium interlayering in expandible layers. The potassium may originate from migrating salt-water solutions during late diagenesis. The late diagenesis as used here corresponds to mesodiagenesis plus telodiagenesis of FOSCOLOS ET AL. (1976) and to catagenesis plus metagenesis of TISSOT & WELTE (1978).

In M-8 the late diagenetic stage is reached at 10 000' with the disappearance of smectite minerals in the lowermost part of the Oxfordian section. The increase in degree of diagenesis is seen through the regularly increasing amounts of illite with depth and the maximum in the mixed-layers smectite-illite at 8000' in the uppermost part of the Oxfordian section. From the presence of fair amounts of kaolinite and smectite as well as from the increasing amounts of illite and mixed-layers illite-smectite through the Lower Cretaceous and Upper Jurassic of E-1 it can be concluded that both sections are still in the stage of early diagenesis. The smectite, however, might have originated from bentonites in the drilling mud, and then the increase in the amounts of mixed-layers might be an indication of the onset of late diagenesis. In I-1 the regular increase in the amounts of illite with depth through the Lower Cretaceous and Upper Jurassic sections and the disappearance of smectite at the base of Lower Cretaceous indicates that the Lower Cretaceous is in the early diagenetic stage, whereas the

Upper Jurassic is in the late diagenetic stage.

The degree of clay mineral diagenesis for Late Jurassic formations varies with maturity of the organic matter more than with depth, in agreement with BURST (1969), DUNOYER DE SEGONZAC (1970), MILLOT (1970), SARKISYAN (1972), HELING & TEICHMÜLLER (1974), FOSCOLOS ET AL. (1976), HOWER ET AL. (1976), FOSCOLOS & POWELL (1979), HELING (1979) and TEICHMÜLLER ET AL. (1979).

The regular variations in M-8 in clay mineralogy with depth through several Jurassic formations indicate rather uniform detrital material, the only exceptions being the predominantly, smectitic clays of the samples 7560 and 7620': These smectitic may originate from weathered volcanic ash (DUNOYER DE SEGONZAC, 1970; MILLOT, 1970)

In I-1, E-1 and M-8 increasing amounts of dolomite and ankerite are seen with depth, and for M-8 also decreasing amounts of calcite with depth, a pattern seen also by HOWER ET AL. (1976) in the Gulf Coast Tertiary. This increase in the ratio of dolomite+ankerite/calcite with an increasing degree of clay diagenesis has also been noted by BROCKAMP (1979) and MUFFLER & WHITE (1969). The dolomite and ankerite formation has been described by MGHARGUE & PRICE (1982) for several claystone formations. In source rock reports of the Danish Geological Survey it has been used as an additional parameter for maturity.

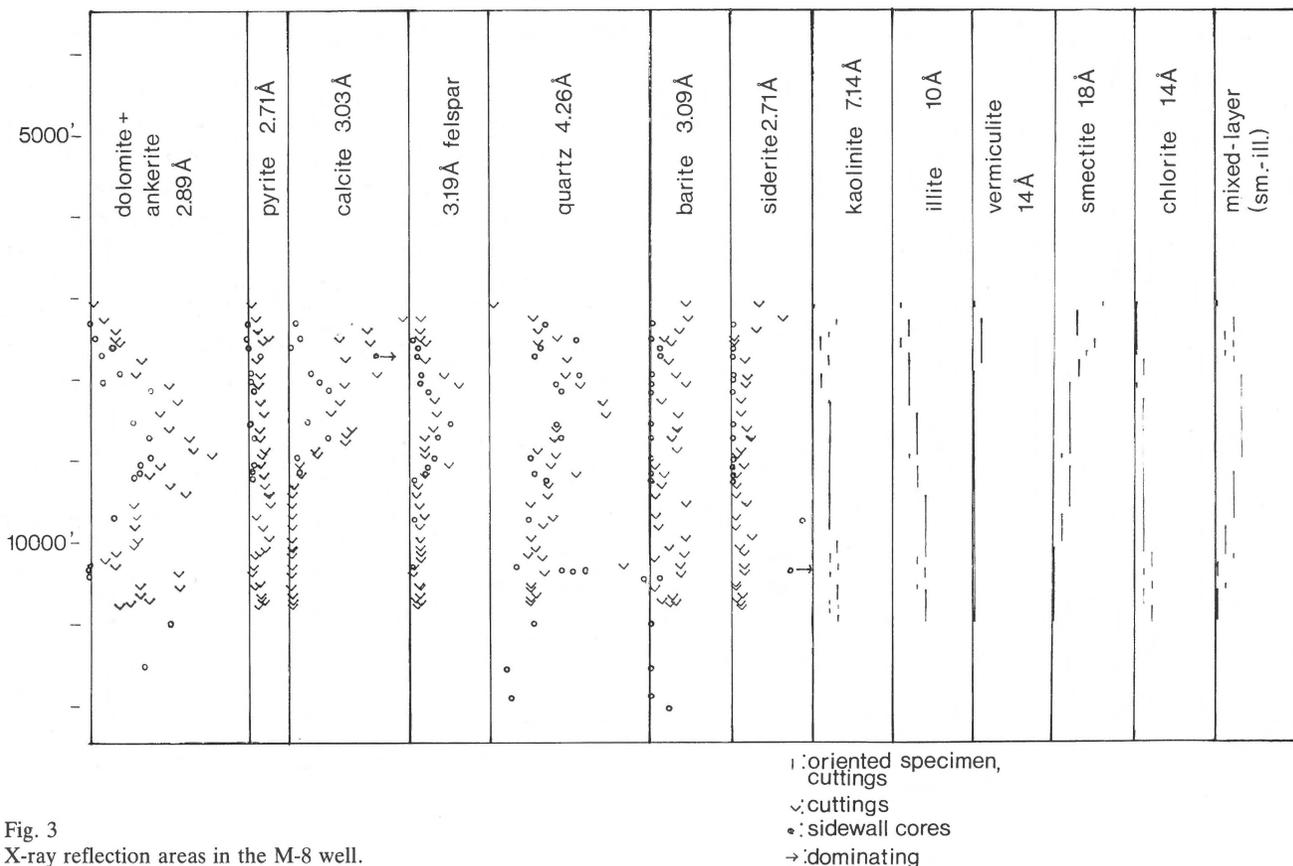


Fig. 3  
X-ray reflection areas in the M-8 well.

Fig. 5  
X-ray reflection areas in the I-1 well. Legend, see figure 3.

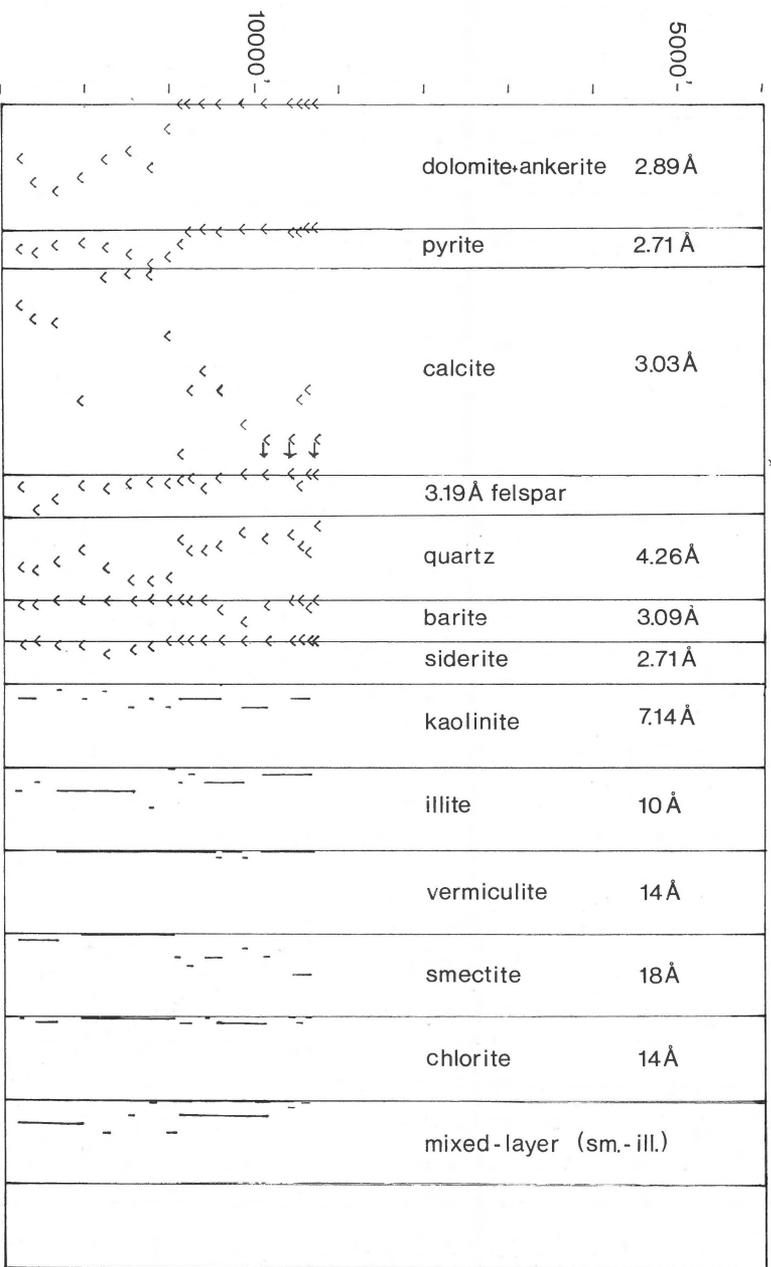
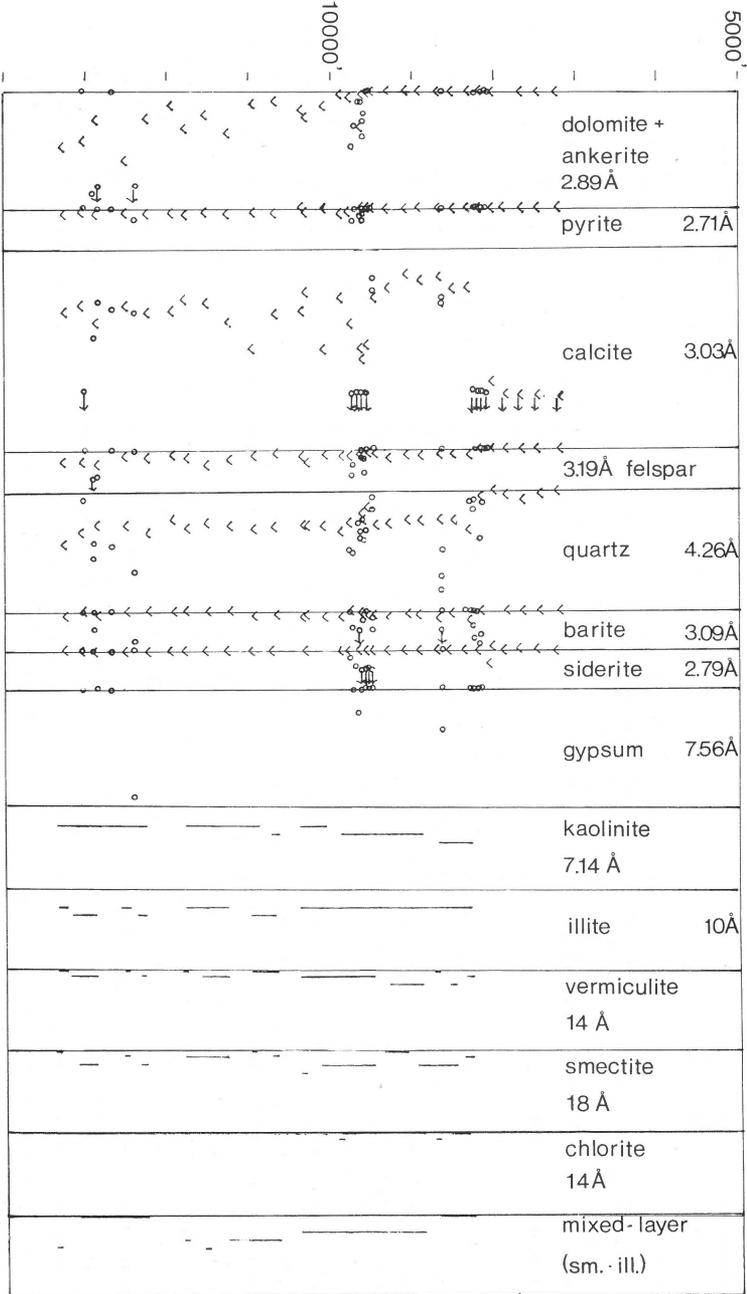


Fig. 4  
X-ray reflection areas in the E-1 well. Legend, see figure 3.



*Organochemical investigations* – Table VII shows the results primarily from the Jurassic levels in M-8.

A very high content of organic carbon (TOC) is measured in samples from 8670, 8790, 9240, 10590 and 10620'. This is due to heavy contamination from mud additives. The highest levels 7110 and 7170' are dominated by carbonate, and show no source rock potential at all.

Apart from two samples TOC has values between 1% and 2% from 7300 to 10200', which is a minimum for a good source rock (BARNARD & COOPER, 1981). Below that level the TOC is significant higher, about 2.5% average. One exception is the level 10260' which is extremely rich in organic matter (>11%). This is reflected in the amount of extract from the samples (SOM), which generally shows low values (<1000 ppm) until a depth of 10200', and values between 1000 and 2000 ppm below 10500'.

The relative values (mg SOM/g TOC) do not differ much throughout the well, and are rather low. This means, that despite some levels (e.g. 10260') have produced considerable amounts of oil (>5000 ppm), significant migration will probably not have taken place.

The pristane/phytane ratio increases down to 10260' after which a significant decrease takes place. The high values indicate an increasing input of oxidized material (e.g. higher

landplants) from 9000' to 10300' (RASHID, 1979; IKAN ET AL., 1975; POWELL ET AL., 1975; DIDYK ET AL., 1978).

Apart from some levels with biodegradation, the decreasing pristane/n-C<sub>17</sub> ratio reflects increasing maturity with depth. The value is rather high, indicative for low maturity.

T<sub>max</sub> increases slightly with depth reflecting increasing maturity. Notice the very low values for T<sub>max</sub> and high values for S1, S2 and S3 together with the very low values for mg/g TOC in the contaminated levels. The results from the pyrolysis indicate that most of the organic matter contains significant amounts of type-III material.

Figure 6 shows the gas-chromatograms from the alifate fraction together with the alifate fraction from the Dan Field oil. The latter shows the characteristic pattern for a partly biodegraded oil, a specific decrease in the n-alkanes resulting in a naphthenic type of oil (BAILEY ET AL., 1973; DEROO ET AL., 1974; BURNS ET AL., 1975; HO ET AL., 1974). The sample 7560' is dominated by naphthenic compounds with a great hump in the steroid region typical for immature algal material (POWELL ET AL., 1975). The high pristane/phytane ratio, together with the dominance of n-alkanes in 10260', indicates non-marine sediments. The sample at 10830' is clearly dominated by terrestrial material. The overall pattern shows that only few levels can be of interest as possible source rocks, viz., 7560'

Table VII  
Organochemical data from the M-8 well. TC = total carbon, TOC = total organic carbon, SOM = soluble organic matter, HC = hydrocarbons, pr = pristane, ph = phytane, PI = S1/(S1+S2), PC = 0.083(S1+S2), HI = 100S2/TOC, OI = 100S3/TOC.

feet	%		ppm						mg/g TOC		pyrolysis (ROCK EVAL)									
	TC	TOC	SOM	HC	AlI	Aro	Het	SOM	HC	pr/C <sub>17</sub>	pr/ph	T <sub>max</sub>	S1	S2	S3	PI	S <sub>2</sub> /S <sub>3</sub>	PC	HI	OI
6480			1800	1100	730	400	340			2.5	1.4	421	.39	.8	1.5	.32	.6	.10		
7110	9.07	.35	180	88	64	24	52	51	25	.7	1.3	-	.02	.1	1.3	.20	.1	.01	26	370
7170	7.55	.65	320	120	72	44	94	49	18	.6	1.4	414	.06	.3	1.3	.19	.2	.03	38	200
7320	3.46	1.07	290	150	92	54	85	27	14	-	-	421	.09	.5	1.8	.15	.3	.05	47	170
7470	2.05	.62	280	140	96	40	56	45	22	1.2	2.1	421	.07	.4	.9	.15	.5	.04	69	150
7560	2.96	2.09	1300	860	560	300	240	64	41	1.6	1.6	427	.43	5.6	.9	.07	6.0	.50	270	44
7620	2.58	1.65	630	400	260	140	100	38	24	1.6	2.0	430	.16	2.4	.9	.06	2.6	.21	142	54
7830	2.43	1.12	440	-	-	-	-	-	-	429	.31	.9	1.0	.26	.9	.10	.81	.92		
8010	2.70	1.40	590	320	210	110	120	42	23	1.2	1.8	429	.20	1.7	.9	.10	2.0	.16	115	59
8130	2.53	1.06	600	-	-	-	-	-	-	1.2	1.1	429	.16	1.0	.8	.13	1.4	.10	98	73
8340	3.97	1.36	970	370	260	110	400	71	27	-	-	435	.39	1.4	1.3	.22	1.1	.15	100	92
8490	2.18	1.02	540	240	110	130	160	53	24	-	-	428	.14	.6	1.0	.19	.6	.06	59	100
8670	5.96	2.76	650	330	140	190	110	23	12	1.0	1.2	423	2.1	5.1	4.8	.29	1.1	.59	180	170
8790	11.67	7.02	840	390	240	150	140	12	6	1.1	1.3	333	11.5	14.	11.8	.44	1.3	2.2	210	170
8940	5.17	1.23	530	220	120	100	140	43	18	.9	1.3	432	.19	1.4	1.4	.12	1.0	.13	113	110
9000	3.28	1.50	750	310	130	180	260	50	21	1.1	-	431	.29	1.9	1.2	.13	1.5	.18	126	82
9120	2.36	1.17	450	220	96	130	96	38	19	1.1	-	431	.15	.9	.9	.14	1.0	.09	78	79
9240	8.42	6.31	580	-	-	-	-	-	-	-	-	336	8.15	12.1	11.8	.40	1.0	1.68	190	190
9360	2.42	1.4	750	430	230	210	140	53	31	1.1	2.5	432	.26	1.4	1.7	.16	.8	.14	99	120
9480	2.06	1.19	710	390	150	250	160	60	33	1.0	2.2	432	.21	.9	1.2	.2	.7	.09	72	98
9600	1.92	1.78	870	360	160	200	160	49	20	1.2	2.4	431	.28	1.0	1.0	.23	1.0	.10	54	55
9750	1.92	1.23	1080	680	320	360	190	88	55	1.1	3.0	433	.24	1.0	.8	.20	1.3	.10	78	63
9870	1.91	1.31	970	600	260	340	160	74	46	1.2	3.0	435	.24	1.0	.8	.20	1.3	.10	75	58
9990	1.74	1.3	990	500	170	330	100	76	39	1.1	3.5	431	.21	.7	.6	.23	1.2	.08	55	46
10140	1.99	1.3	970	400	130	270	240	75	31	.9	2.9	436	.24	1.0	.8	.20	1.3	.10	75	58
10200	2.16	1.35	1000	640	230	410	160	82	47	1.0	3.2	439	.26	1.0	.7	.20	1.5	.11	76	50
10260	12.10	11.27	5500	2600	950	1600	370	48	23	1.5	5.1	443	2.90	17.	1.0	.14	17.	1.65	150	9
10350	3.72	2.91	1900	1000	360	670	330	65	36	1.2	3.6	443	.63	2.5	.9	.20	2.9	.26	87	30
10440	3.37	2.61	2400	1300	370	930	420	92	50	.6	1.9	439	.62	3.2	.8	.16	4.3	.32	120	29
10590	14.40	10.80	1530	950	480	470	330	14	9	.6	1.0	329	17.5	19.4	19.3	.47	1.0	3.0	180	180
10620	8.10	6.15	1100	620	280	340	290	18	10	.6	1.4	325	6.4	8.5	9.3	.43	.9	1.23	140	150
10710	4.37	3.31	1700	1100	360	700	310	50	32	.9	2.5	434	1.8	5.4	4.5	.25	1.2	.59	160	140
10770	2.46	1.8	1500	820	330	500	400	85	46	.6	1.8	439	.56	3.7	2.6	.13	1.4	.35	200	140
10800	2.93	2.03	1700	1000	420	610	310	84	51	.7	2.2	433	.68	2.8	2.9	.20	1.0	.29	140	140
10830	3.31	2.39	1200	460	130	340	410	50	19	.5	1.9	434	.69	3.1	3.4	.18	.9	.31	130	140
10860	3.15	2.50	1400	540	170	370	430	56	22	.5	1.7	433	.63	3.4	3.5	.15	1.	.34	140	140

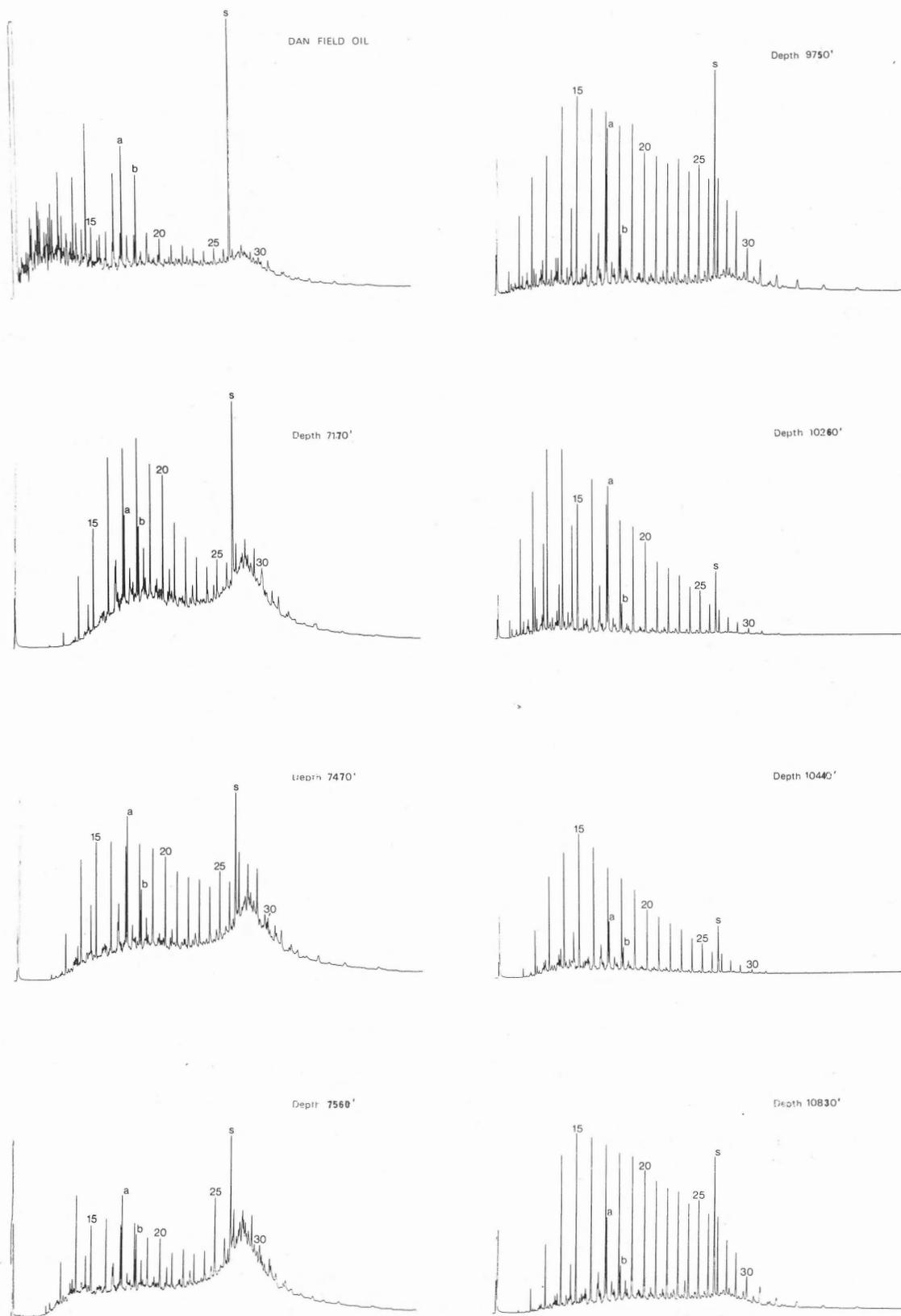


Fig. 6  
Gas-chromatograms from the M-8 well. a = pristane, b = phytane, s = squalane (internal standard).

and 10260' - 10440'. The levels below 10440' might have some potential but contain much oxidized material: 7560' must be regarded as a immature source rock, while 10260' is marginal mature.

Comparison with the Dan Field oil is difficult due to the biodegradation, but the pristane/phytane ratios point to a formation corresponding to 7560', but more mature, as the source rock. A more detailed investigation of this problem is necessary, and will be carried out in the near future.

Similar studies on the well I-1 indicate that apart from the horizon at 9620', the TOC is below 1% down to 11000' (Table VIII). Below 11000' the TOC is very high. The amount of extract reflects the organic carbon content and is much higher than in M-8. Below 11000' the values for mg SOM/g TOC are

nearly constant near the maximum value for a well-mature source rock for oil (150-200).

The high value for mg SOM/g TOC at the level 9620' indicates migrated oil. This is confirmed by the composition of the extract, high alifate fraction and very low heterofraction (SALLE & DEBYSER, 1976). Pyrolysis gives a high S2 peak indicating an significant source rock potential.

The pristane/phytane ratio below 9500' is rather constant with values around 1.3, indicating non-oxidized material. The high value of pristane/n-C<sub>17</sub> ratio at the levels 9420 and 10180' reflects biodegradation presumably due to meteoric water. The low value below 11000' shows a much higher maturity than in the M-8 well.

The results from the pyrolysis clearly confirm the levels

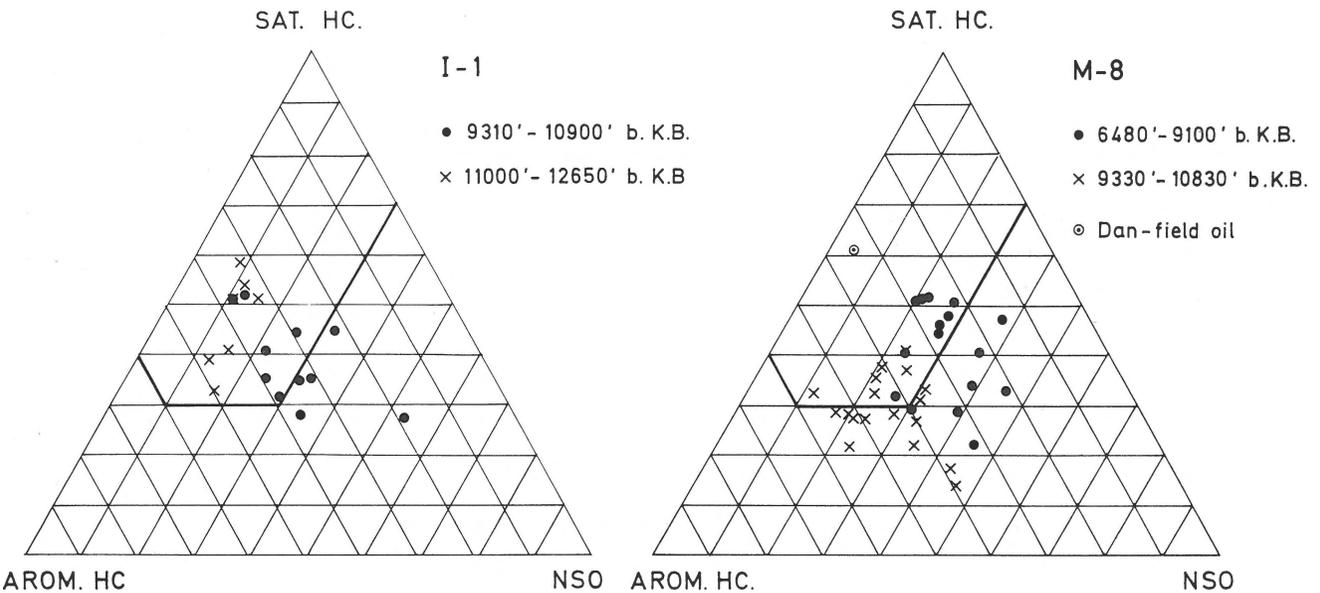


Fig. 7 Composition of extracts of the I-1 and M-8 wells. SAT. HC = saturated hydrocarbons, AROM. HC. = aromatic hydrocarbons, NSO = hetero-compounds.

Table VIII Organochemical data from the I-1 well.. Legend, see Table VII.

feet	% TOC		ppm			mg/gTOC		pr/C <sub>17</sub> pr/ph		T <sub>max</sub>	pyrolysis (ROCK.EVAL)									
	TC	TOC	SOM	HC	Alf	Aro	Het	SOM	HC		S1	S2	S3	PI	S <sub>2</sub> /S <sub>3</sub>	PC	HI	OI		
9320	7.48	.60	450	180	100	75	200	75	29	1.2	1.8	432	.08	.4	1.6	.17	.3	.04	63	260
9420	1.86	.81	550	270	120	150	140	68	34	2.3	2.8	422	.10	.4	.9	.22	.4	.04	44	110
9550	3.30	.79	1900	1000	700	340	500	240	130	1.0	1.4	422	.11	.3	1.1	.29	.3	.03	34	140
9620	8.69	2.69	9000	6000	3500	2400	840	340	220	.7	1.1	427	2.3	6.5	1.2	.26	5.4	.73	240	45
9930	3.51	.84	1000	640	330	300	200	120	76	.6	1.5	422	.16	.4	1.0	.29	.4	.05	46	120
10180	4.18	.80	1100	620	330	290	280	140	77	2.7	1.3	422	.17	.4	1.4	.32	.3	.04	45	170
10470	2.87	.49	670	390	210	180	180	140	80	1.7	1.3	366	.13	.2	1.0	.43	.2	.02	35	200
10650	2.78	.50	1100	570	340	230	190	220	110	.8	1.6	352	.24	.3	.9	.46	.3	.04	56	170
10810	3.60	.64	720	430	210	220	140	110	68	.5	1.4	425	.08	.3	1.0	.24	.3	.03	41	160
10940	3.22	.42	360	210	98	110	90	85	51	1.1	1.5	-	.06	.1	.8	.35	.1	.01	26	190
11060	9.39	8.32	14100	8300	4100	4200	1500	170	100	.5	1.3	432	4.2	31.	1.9	.12	16.8	3.0	377	22
11290	7.21	5.62	8400	6200	2800	3400	990	150	110	.6	1.6	434	2.7	14.	2.7	.16	5.2	1.4	250	48
11530	6.25	2.69	4200	2300	920	1400	460	160	86	.6	1.3	439	1.0	3.6	2.6	.23	1.4	.4	130	96
11820	4.18	2.86	4800	4000	2600	1400	380	170	140	.6	1.2	441	1.5	3.7	1.5	.29	2.4	.42	128	54
12100	4.64	2.53	4500	3100	1800	1300	340	180	120	.4	1.4	441	1.0	2.8	1.1	.27	2.7	.32	110	41
12400	4.38	2.42	3900	3100	1800	1200	370	160	130	.4	1.3	441	1.0	2.4	1.1	.30	2.1	.29	100	47
12650	4.34	2.48	3800	2700	1600	1100	520	150	110	.4	1.5	441	.94	2.7	1.1	.26	2.4	.30	110	45

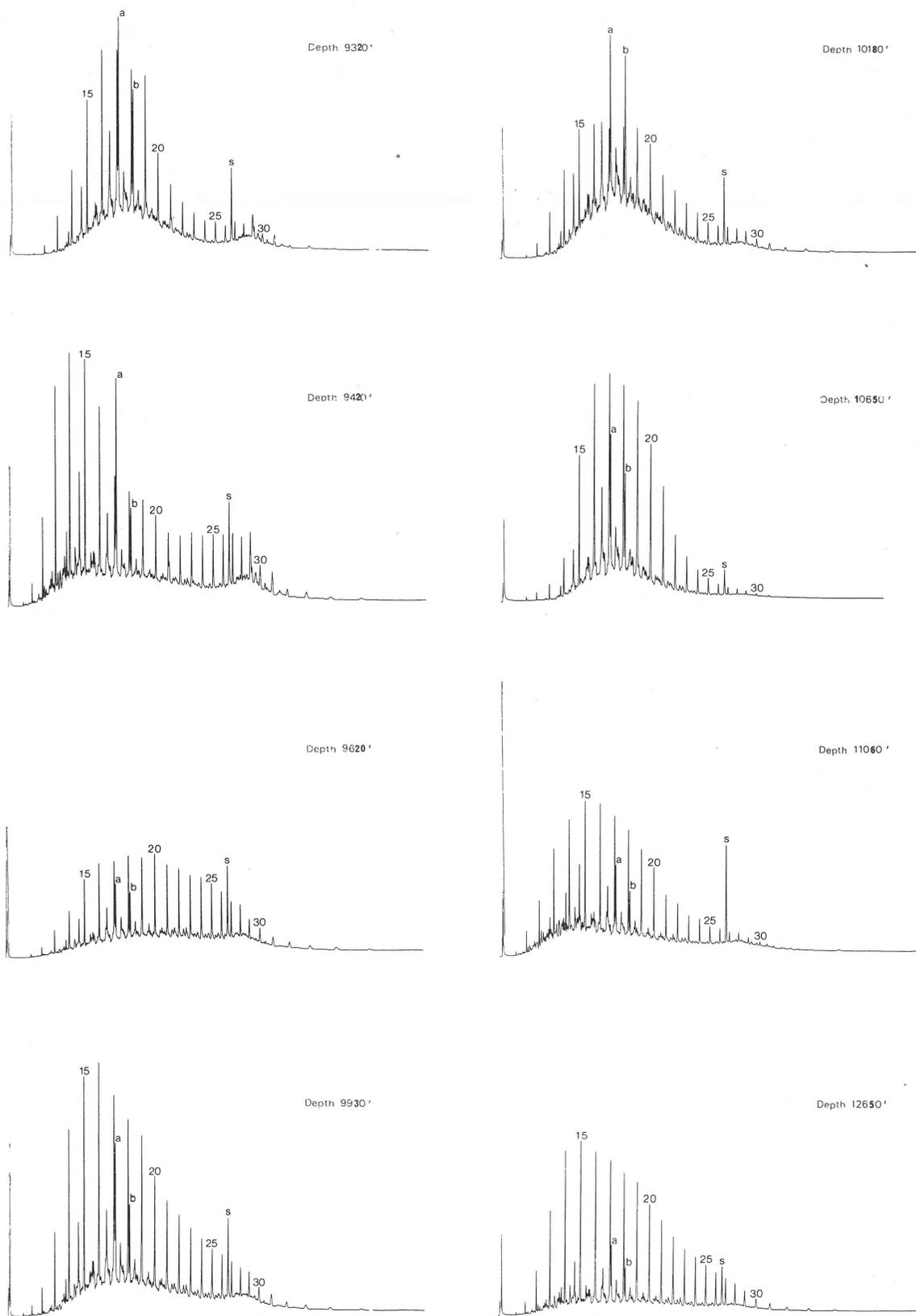


Fig. 8  
Gas-chromatograms from the I-1 well. a = pristane, b = phytane, s = squalane (internal standard).

below 11000' as excellent mature source rocks for oil.  $T_{max}$  and S1 are significant higher than in M-8 and the type of material is better.

Figure 8 shows the gas-chromatograms from the I-1 well. Apart from the horizon at 9620', the extract is dominated by light components. At 10180' the pattern of biodegradation is clearly seen. From 11060 to 12650' mature material from algal origin seems to dominate the extract. The formation below 11000' is regarded as the best source rock in the examined wells.

Investigation of the E-1 well shows that the well contains source rocks. The quality is rated between that of the source rocks in M-8 and I-1, which seems to indicate better source rock possibilities in the northern part of the Danish Central Graben.

*Coal petrographical investigations* – Figure 9 shows vitrinite reflectance trends for three wells located on a north-south line through the Danish Central Graben with the I-1 well representing the northernmost location (Fig. 1).

The results show significant differences in the rank conditions. The highest rank is attained in the Upper Jurassic in the

I-1 well. Compared with the southern well M-8, this could be interpreted as a result of greater depth of burial of the Jurassic in the I-1 well. The reflectance trend of the I-1 well shows a major coalification break at a depth of about 2850 m, which suggests an originally greater depth of burial of the Mesozoic deposits. However, the Mesozoic rank gradient in the E-1 well is lower as compared with the I-1 well, while the M-8 well has an intermediate rank gradient.

For sediments of approximately similar age and rank ranges, different rank gradients reflect variations of the geothermal gradients, which could indicate major regional differences of the rank conditions in the study area. However, a regional comparison can only be made with due respect to the abnormal heat flow conditions at or near salt structures and faults.

The M-8 well is drilled on a salt structure whereas the I-1 well is drilled on a structure of unknown character. The E-1 well is located in an area unaffected by major structures, hence abnormal heat flow conditions are not to be expected. Thus the high and intermediate rank gradients observed in the I-1 and M-8 wells are tentatively attributed to local heat flow anomalies.

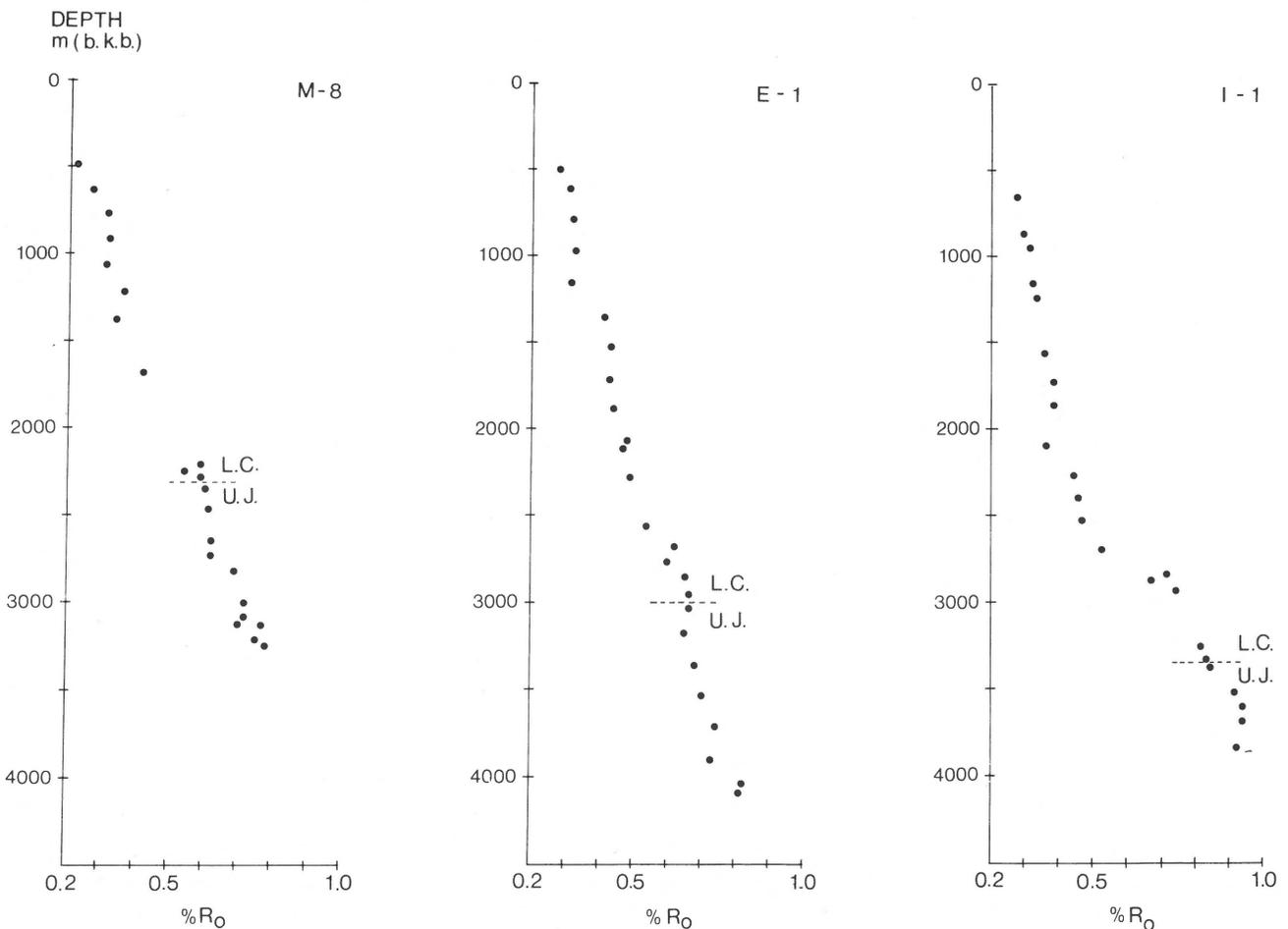


Fig. 9  
Vitrinite reflectance trends in the M-8, E-1 and I-1 wells. The Lower Cretaceous-Upper Jurassic boundary is marked

Favourable type of organic matter is mainly found in the Upper Jurassic where horizons rich in liptinite, mainly alginite, have been recorded. Apart from these intervals of (?) Kimmeridgian age, Early Jurassic deposits and sapropelic deposits in the Middle Jurassic could represent potential source beds as judged from the optical investigations (LINDGREEN ET AL., 1982).

It can be concluded that the northernmost well I-1 is the most promising in terms of maturity conditions, because favourable Late Jurassic sediments attain higher maturity levels than sediments of similar age in the wells investigated in the central (well E-1) and the southern (well M-8) part of the study area. In all the wells investigated the Cenozoic deposits are immature.

Compared with the Mesozoic deposits that so far have been investigated in the Danish Subbasin, significantly higher rank conditions have been encountered in similar deposits in the Danish Central Graben. This is attributed to a larger depth of burial and a higher regional value of the geothermal gradient, i.e. 32°C/km as opposed to values in the order 18 - 25°C/km recorded in the investigated part of the Danish Subbasin (MADSEN, 1975, 1978).

## CONCLUSIONS

### *Central Graben*

The limited number of wells investigated makes a general source rock evaluation for the Central Graben area impossible. There are however some trends, which should be noted. The low content of organic matter found in most Cretaceous samples indicate poor source rock potential for these formations. The Upper Jurassic formation equivalent to Kimmeridge is regarded as a principal source rock for oil in the study area. It is of a considerable thickness, the amount and type of organic matter being favourable.

Data from the northern (I-1) well, the central (E-1) and the southern (M-8) well show that: 1) The organic matter is mainly of algal origin, 2) the amount of organic matter is rich to extremely rich in the northern well and good to rich in the central and the southern wells. In the northern well the entire formation is within the zone of maximum oil generation. In the central well the upper part of the unit is just within the zone of oil generation, whereas the lower part of the unit is within the zone of maximum oil generation. In the southern well the unit is just approaching this zone. Therefore, the formation has to be regarded as a better oil source rock in the northern well. However, assuming sufficient burial as seen in the M-8 well the upper part of the formation is still a good source rock in the southern area. The investigations show that the study area is complex with respect to the amount of organic matter as well as the maturity conditions.

### *Danish onshore area*

The results of the combined mineralogical and coal petrographical analyses that so far have been carried out indicate that the investigated Cambro-Silurian sequence is in a post-mature stage with respect to oil generation. The problem of timing has not been treated, but is probably a pre-Carboniferous event. The question of the maturity conditions in Early Palaeozoic deposits in the northern part of the Kattegat and Skagerrak areas is regarded as a question of timing, i.e. time of marked subsidence. The Carboniferous and Permian deposits are in a premature-mature stage with respect to oil generation, while the investigated Rhaetian-Jurassic-Early Cretaceous deposits are premature-immature and apparently dominated by unfavourable types of organic matter in the premature intervals. However, it should be emphasized that no results at present are available from the basin centre. Hence, the possibility of oil occurrences sourced by Mesozoic deposits cannot be excluded.

Outside the depocentre the generally immature nature of the Rhaetian-Jurassic-Early Cretaceous deposits exclude oil generation from this interval.

## ACKNOWLEDGEMENTS

The present study has been possible due to grants from the Danish Ministry of Energy and the Danish Natural Science Research Council. Thanks are due to Dr. M. Teichmüller, Professor Dr. M. Wolf and technician K. Ottenjann for training in coal petrography and valuable discussions. Our thanks are also due to our laboratory technicians G. Berthelsen, K. Fries, C. Guvad, L. L. Nielsen and B. Keis.

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