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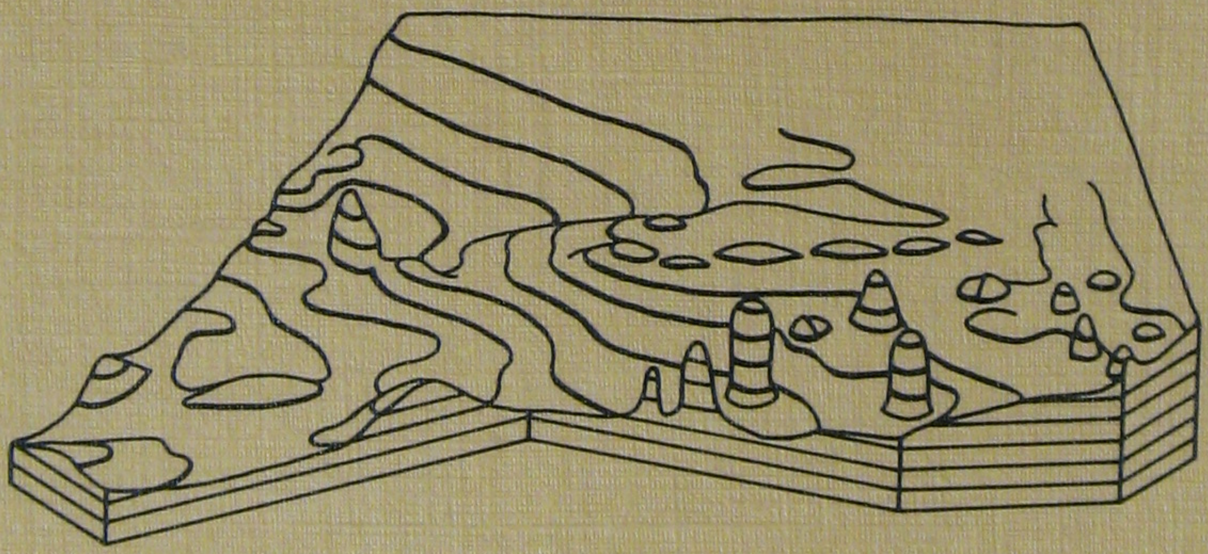
Geology of the Danish Central Graben

Editor
Olaf Michelsen



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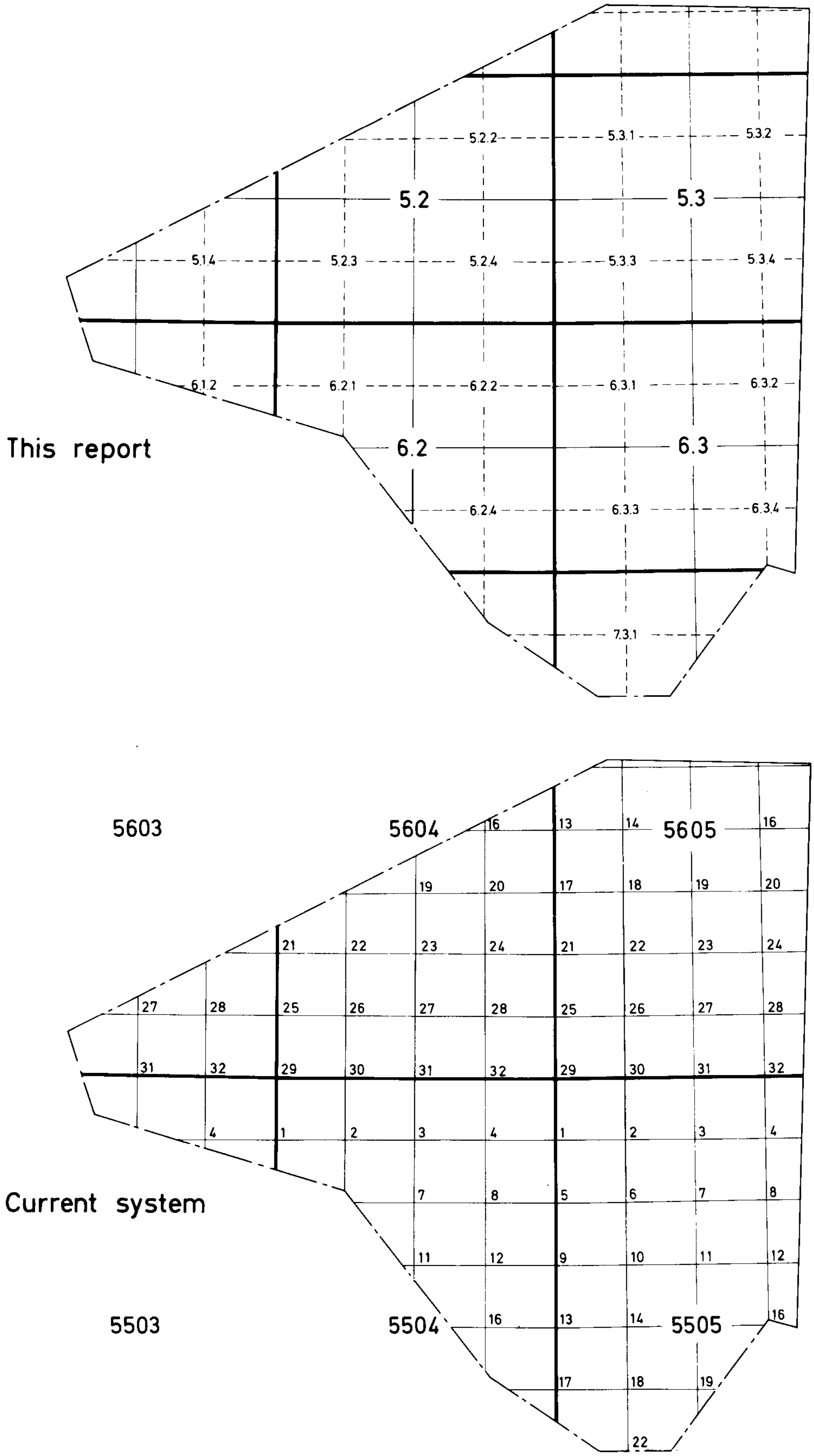
Comparison of the block number system used in this report and the current system, October 1982.



Longitude and latitude lines coincide in the two systems.

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Vignet:
Block diagram constructed from seismic mapping and showing the generalized relief of Top Chalk. – By *Erik Nygaard.*

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Contents

Summary

The publication provides a description of the geological, sedimentological and tectonic history of the Danish Central Graben area related to potential reservoir bodies and hydrocarbon traps. Special emphasis has been placed on hydrocarbon-relevant parameters and on the presentation of a dynamic model for the structural unit covering the Central Graben area.

The structural outline is dealt with in chapter 2.1. The Graben is subdivided into seven subregions (fig. 47), of which the Northern and Southern Salt-dome Provinces and the Tail End Graben are the most well documented.

Chapter 2.2 includes a description of the structural development. The most prominent and well documented features are the indications of the Caledonian basement and the Rotliegendes volcanism, and the recognition of the Cimmerian tectonic phases, the pronounced subsidence during Late Jurassic, the Late Cretaceous to Early Tertiary inversion tectonics, and the pronounced subsidence during Late Tertiary.

All lithostratigraphical units documented by well data are descibed in chapter 3. A correlation of the units to the chronostratigraphy is given in fig. 2.

A preliminary temperature investigation in six wells is presented in chapter 4.

In a few wells, the source rock potential has been investigated by means of mineralogical, organo-chemical, and coal petrographical methods (chapter 5). A Late Jurassic clay formation is regarded as the principal source rock for oil.

Referring to four areas of different structural styles (fig. 47) the occurrence of potential hydrocarbon traps is discussed in chapter 6.

A review of drilled potential reservoir rocks is given in chapter 7. The evaluation is based primarily on the wire line logs, since only few cores have been cut and very few tests have been performed.

1.0 Introduction

In September 1966 hydrocarbon show was encountered in Danian limestone in the A-1 well in the Danish Central Graben. This well was the first exploration well drilled in the Danish North Sea sector and the oil show was the first ever recorded in the entire North Sea.

During the last 15 years a total number of 24 exploration wells have been drilled on 21 different closed structures. All of these wells except one discovered oil or gas shows at one or more stratigraphic levels (fig. 1).

Five commercial fields produce, or are planned to produce, from Maastrichtian-Danian chalk reservoirs. This stratigraphic level has been the main objective of the exploration work conducted until now. However, a great number of hydrocarbon shows have been

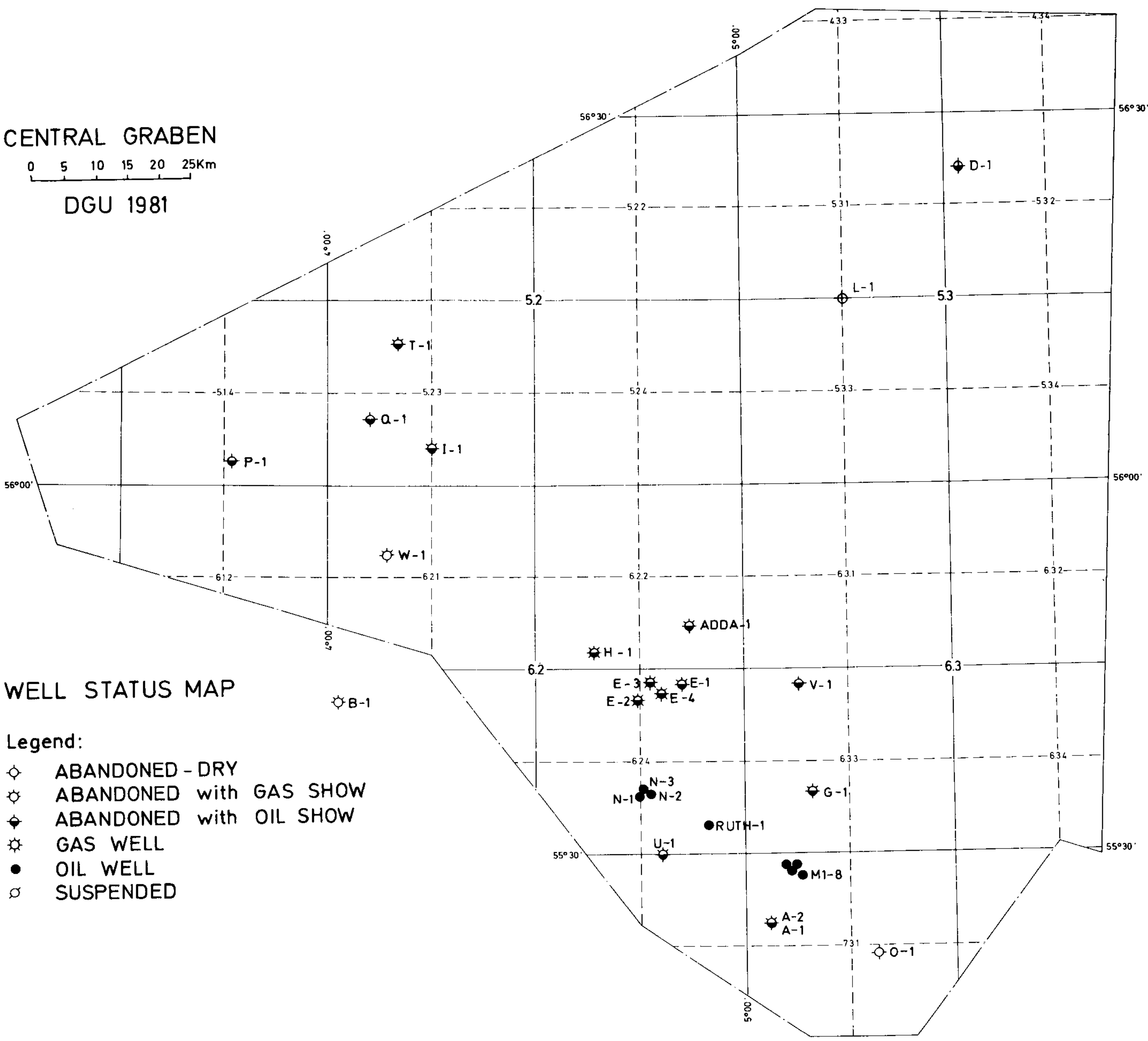


Fig. 1: Location of wells mentioned in the present publication, and the status of the wells by October 1st, 1981.

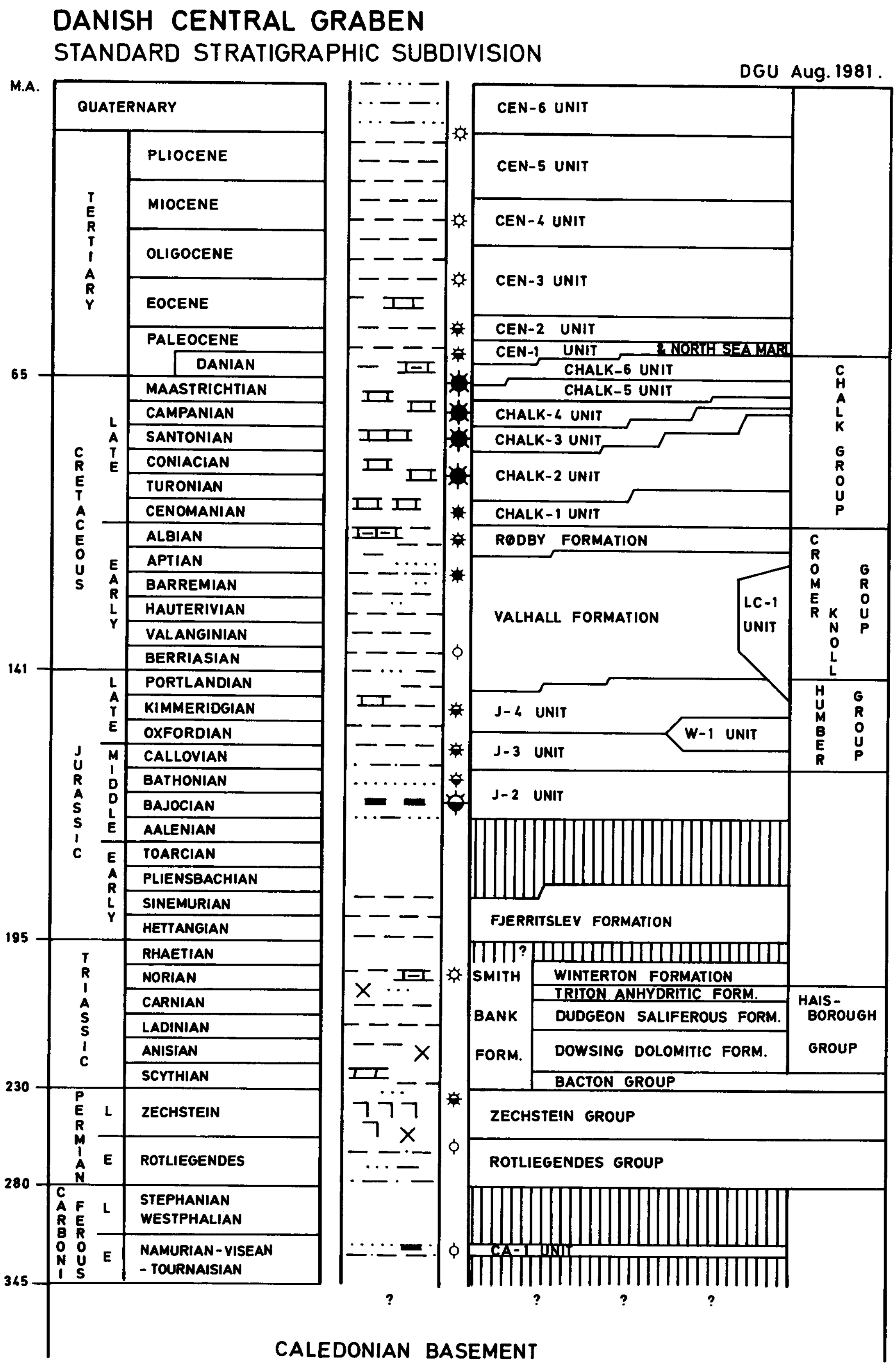


Fig. 2: Standard stratigraphic subdivison of formations in the Danish Central Graben with indications of oil and gas shows.

encountered in Middle and Upper Jurassic, Lower Cretaceous and Tertiary stratigraphic intervals in the Danish Central Graben (fig. 2).

All wells have been covered by a confidentiality period of five years, and published information on released data from the Danish off-shore area is limited (Bertelsen 1975, 1978; Childs & Reed 1975, Larsen 1972, Madsen 1975, Michelsen 1975, 1978; Rasmussen 1974, 1978).

During the autumn of 1981 a working group under supervision of the editor interpreted and compiled released data of the Danish Central Graben for an internal report, which is presented in the present report. Each chapter is written by various authors and the publication therefore appears with different styles of presentation.

Besides the professional staff mentioned as authors of the different chapters, a large group of persons have provided assistance of significant importance.

Torben Bistrup, Carsten Clausen, Peter Japsen, Kurt Damtoft Poulsen, Søren Priisholm, Torben Rex Sørensen, Ole Vejbæk, and Anatol Winter have supported with scientific evaluations.

Technical assistance was given by Lasse Gudmundsson, Per E. Andersen, Helle Zetterwall, Torben Krintz, Einar S. Christensen, Kirsten Fries, Birgitte Keis, and Ole Haslund. The drafting work was carried out by Eva Melskens and Kirsten Andersen, and the typing by Vibeke Hermansen, Dorthe Plougmann, Lene Kristensen, and Vibeke Bøgh. I. and C. Torres made the photographic work.

The English manuscript was corrected by Olivia Collin.

An editorial group of Olaf Michelsen, Erik Nygaard, Naja Mikkelsen, and Arne Buch, prepared the written contributions for publication.

The report is based on an evaluation and compilation of all available data, including those presented by different companies (Core Laboratories UK Ltd., DeGolyer & MacNaughton, Exploration and Production Services (North Sea) Ltd., Paleoservices Ltd., Robertson Research Int. Ltd., Schlumberger, and others).

It must be emphasized that both the block units and the number system are provisional.

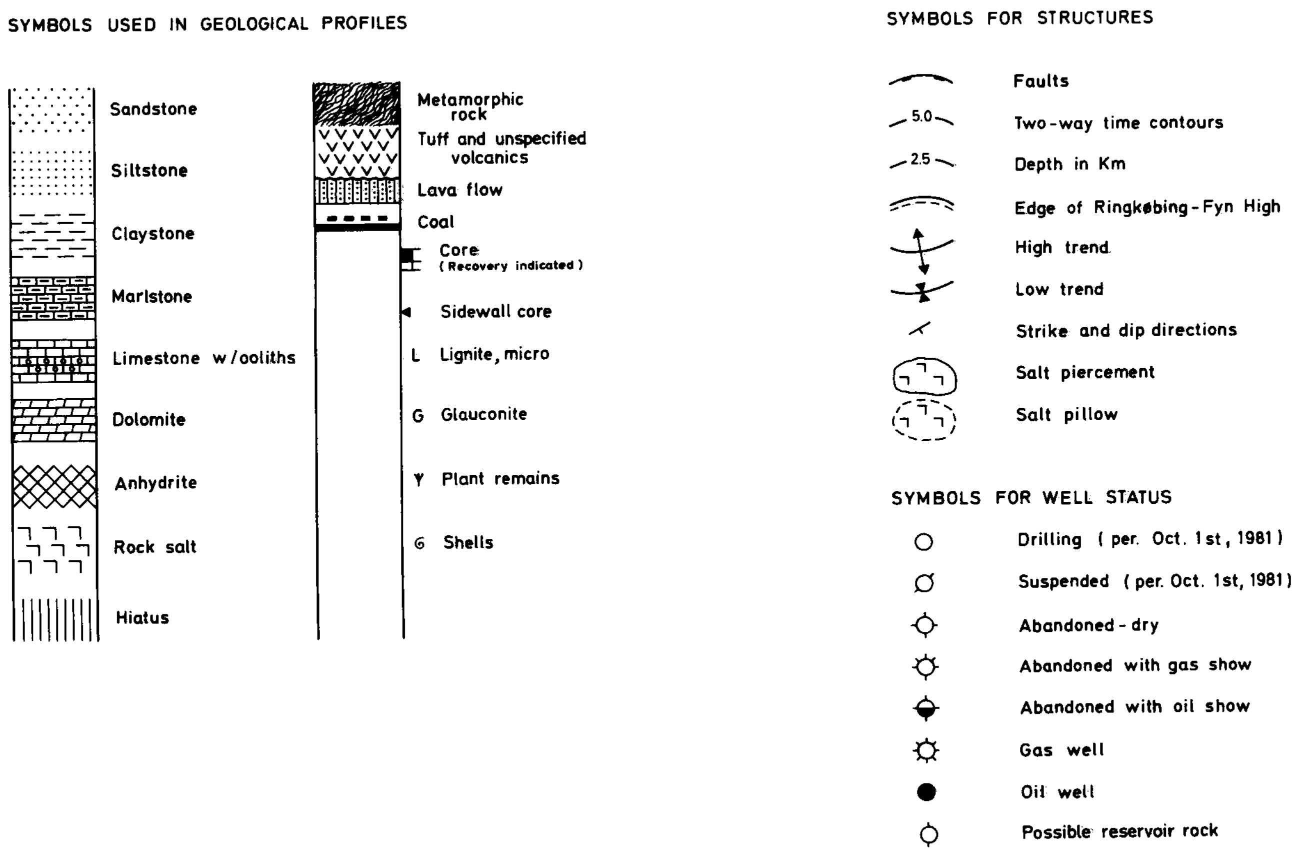


Fig. 3: Legend of symbols used for a) lithology, b) structures, and c) wells.

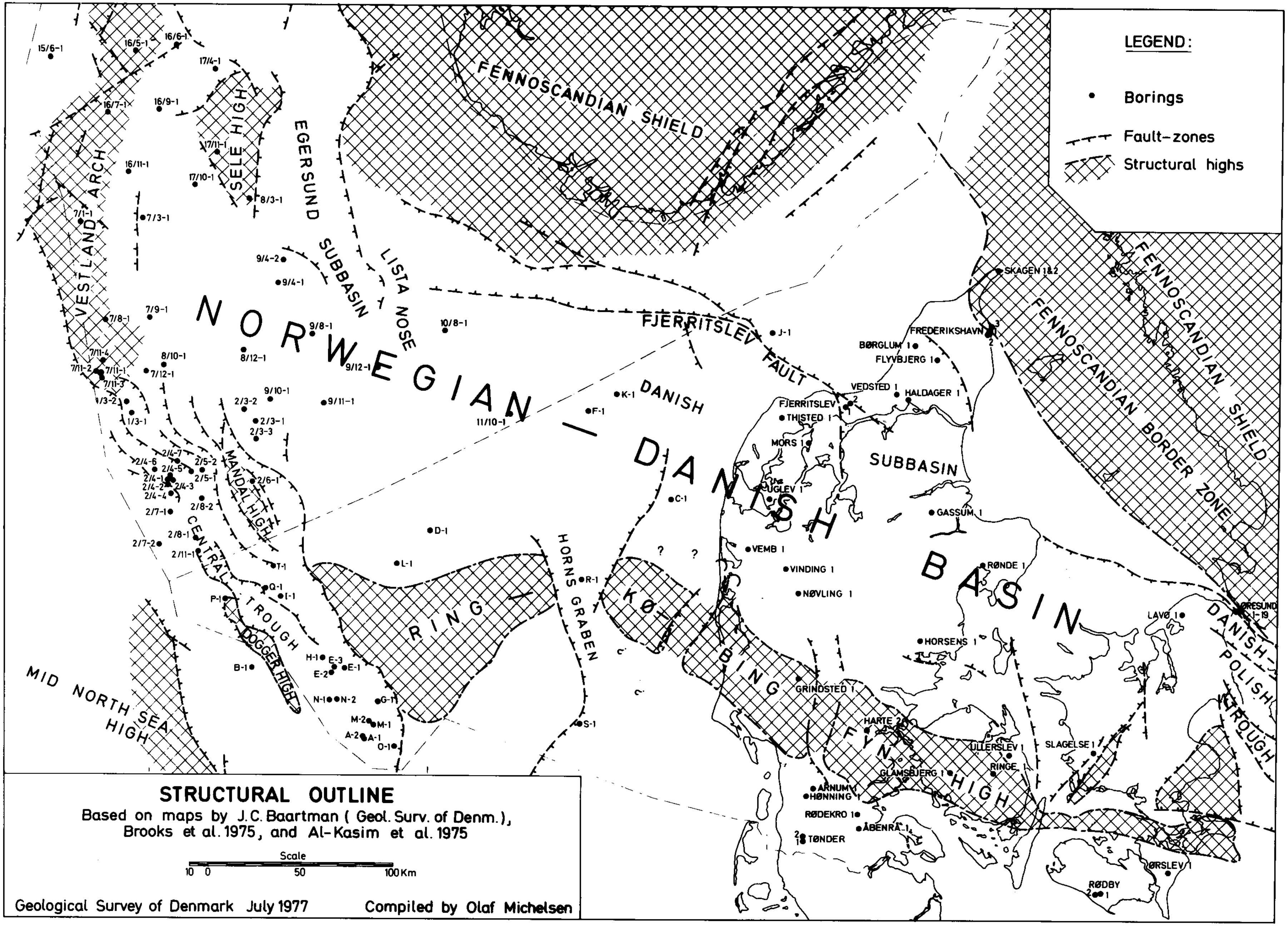


Fig. 4: Structural outline of the Danish area (from Michelsen 1978b).

2.0 Structural outline and development

By Claus Andersen, Jens Christian Olsen, Olaf Michelsen & Erik Nygaard

The Central Graben is a broad, complex trough with a long history of differential subsidence. It was probably initiated in the Permian and was controlled by major rifting during the Mesozoic.

To the south in the Dutch sector the trough is divided into two parts. From here it passes northwards and divides the southern North Sea Basin into the Anglo-Dutch Basin and the Northwest German Basin. It also separates the Mid North Sea High from the Ringkøbing-Fyn High. These highs form broad, east-west trending, relative stable ridges.

The further continuation of the Central Graben is to the northwest, towards the centre of the North Sea, where it passes into the Viking Graben and the Moray Firth Basin at about 58° N.

Where the Central Graben divides the two major highs, there is an elongate central narrow horst, the Dogger High, which is the southernmost of a row of mid-Graben highs. Both sides of the Graben are clearly defined by normal rotational faults that were intermittently active from Triassic to Early Cretaceous times.

2.1 Structural outline

The structural outline of the Central Graben within the Danish North Sea sector is well illustrated by the Bouguer gravity map and by the structural outline map at base Zechstein level (fig. 5).

A number of geo-sections based on the interpretation of seismic sections are given (figs. 7 to 13) in order to illustrate the structural style of various parts of the Danish Central Graben.

On the gravity map the pronounced slope in the eastern part marks the position of the boundary fault zone to the Ringkøbing-Fyn High. The adjacent elongate trend of minima below 260 mgal coincides with the axial depression of the Central Graben. The kink from a north-south orientation of the Graben in the southern part, into a northwest-southeast orientation in the central and northern part, is likewise well illustrated from the gravity picture.

The centre of the Dogger High is indicated by the gravity high above 280 mgal (fig. 5). This maximum is part of a trend of gravity highs extending northwestwards into the very little known part of Central Graben.

The fault pattern of the base Zechstein level (fig. 5) demonstrates the overall picture at this level of pull-apart tectonics, typical of a rift setting.

Partly based on this map, it is possible to subdivide the Danish Central Graben into the following, in part overlapping, structural subunits:

A. A Southern Salt-dome Province south of 55° 40' N, where Zechstein evaporites have undergone halokinesis. Doming of Upper Cretaceous-Danian chalk caused by halokinetic movements of underlying salt is the trap-building mechanism of the declared and established oil fields (Dan, Gorm, and Skjold). It is noteworthy that only few salt domes have actually pierced through and displaced the brittle limestones of the Chalk Group.

The growth of the salt structures appears in some cases to have started late in the Triassic and continued locally into the Quaternary. Development of rim-synclines becomes important during Late Jurassic.

In contrast to the majority of the halokinetic structures which are most certainly caused by migration of Zechstein evaporites, the salt pillow below the Dan field is interpreted as formed by flow of Triassic evaporites. The Ryan structure (O-1) may have a similar genesis.

B. A Northern Salt-dome Province including the area around the North Arne structure in the northeastern part of the Danish Central Graben area, and belonging to the so-called Northern Zechstein Basin.

The southern tip of the Norwegian Hod structure extending into Danish sector is probably also caused by halokinesis.

C. The Tail End Graben forms the axial depression of the Central Graben adjacent to the boundary fault zone of the Ringkøbing-Fyn High and extends into the northern as well as the Southern Salt-dome Provinces. The area is characterized by a pronounced gravity low. The depth to base Zechstein/top Rotliegendes is in the order of 10-11 km. This makes Tail End Graben one of the major depocentres of the whole Central Graben complex (Day et al. 1981). The Jurassic sequence is especially thick in this area, locally exceeding 4000 m (fig. 14).

The structural style in the central part of the Tail End Graben does not appear to have been influenced by salt flowage to any large extent. Differential subsidence, controlled by rotational fault blocks, in the

Mesozoic and especially Late Jurassic, was followed by inversion tectonics in the Cretaceous and Early Tertiary. This was most likely caused by a change into an oblique strike-slip regime, and together the dynamic factors seem to control the present structural configuration in this subarea.

The configuration and development of the boundary fault zone to the Ringkøbing-Fyn High can not be fully evaluated from geophysical data. It is , however, a very prominent feature with depths to base Zechstein in the order of 10 km in the adjacent Graben floor, in contrast to a depth to the basement of about 3 km on the high.

D. The western margin of Tail End Graben is characterized by a major fault zone extending from the South Arne structure southeastwards through the area around the H-1 well into the Southern Salt-dome Province where it is masked by the dominant halokinetic structures. At the Cretaceous levels some of these faults have been interpreted as having reverse components (geo-section, line 5423, fig. 7), believed to be caused by compressional strike-slip. Overpressured shales and shale-flow phenomena appear to be an important element in this zone. Whether it is associated with a flow of deeply seated salt or not is impossible to tell from existing data.

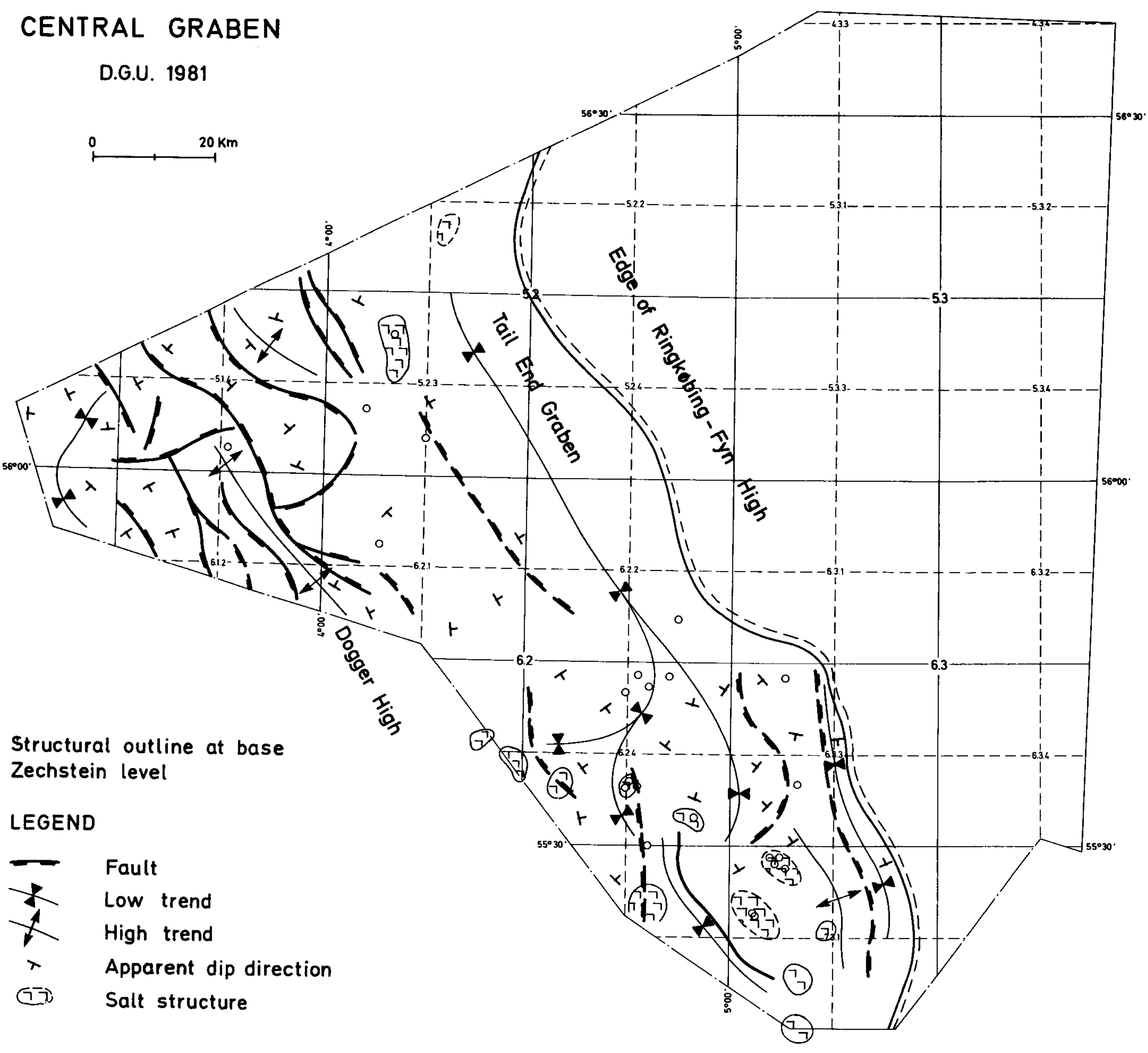


Fig. 5: a) Structural outline of the Danish Central Graben at the base Zechstein level.

E. The region west of the Tail End Graben: Resolution of available seismic data, below the pronounced Late Cimmerian Unconformity to the west of the fault zone just mentioned, is usually poor. Well data from W-1 and Q-1 indicate a relatively thin Triassic-Jurassic sedimentary sequence resting on volcanics of a possible Rotliegendes age.

F. The Dogger High extends northwestwards from the German North Sea sector into the Danish sector up to a position around the P-1 well. It is a rather complex horst structure on which the Mesozoic section below the Late Cretaceous limestones is missing. In P-1 Rotliegendes sediments and volcanics were found immediately below the Chalk Group at about 3100 m b.MSL. Underneath the Rotliegendes, Early Carboniferous sediments, overlying Caledonian greenschists, were encountered. It is uncertain, whether the older Mesozoic sediments were ever deposited on the central part of the Dogger High, or whether they have been removed by erosion during Cimmerian or later tectonic events.

G. The area to the north and west of the Dogger High in the direction of the British and Norwegian sectors is the least known part of the Danish Central Graben

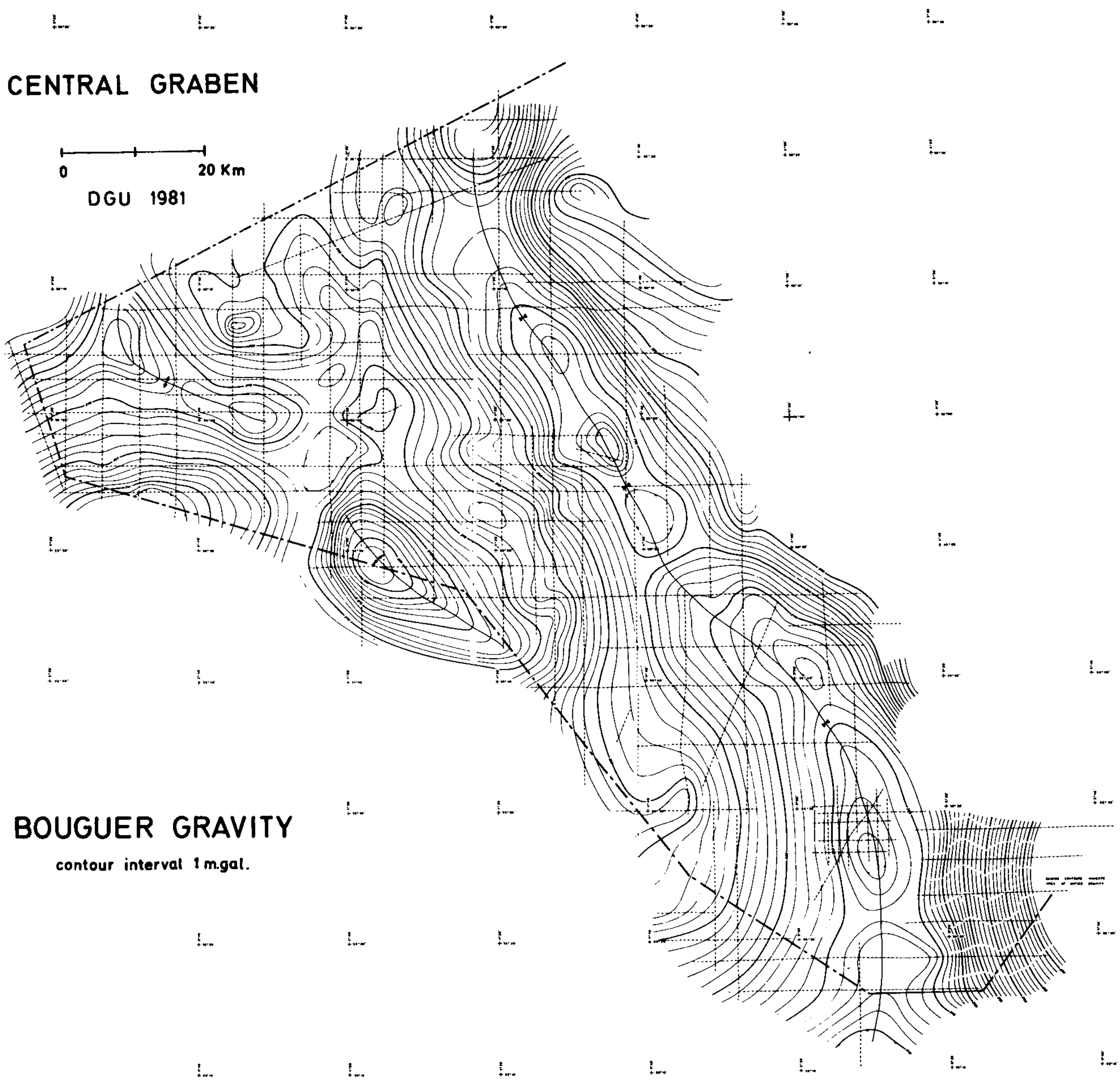


Fig. 5: b) Bouguer gravity map of the Graben area (after Edcon).

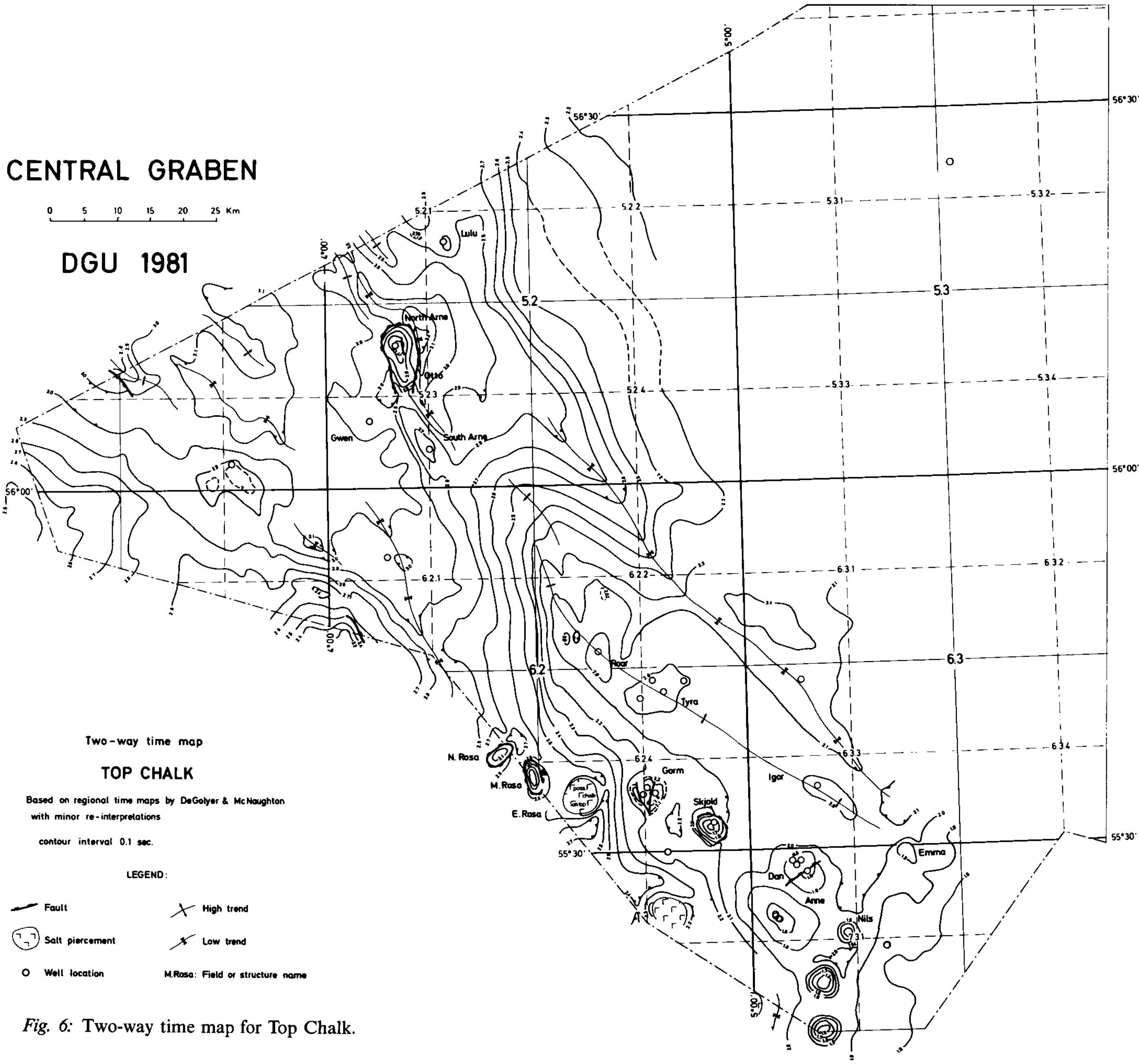


Fig. 6: Two-way time map for Top Chalk.

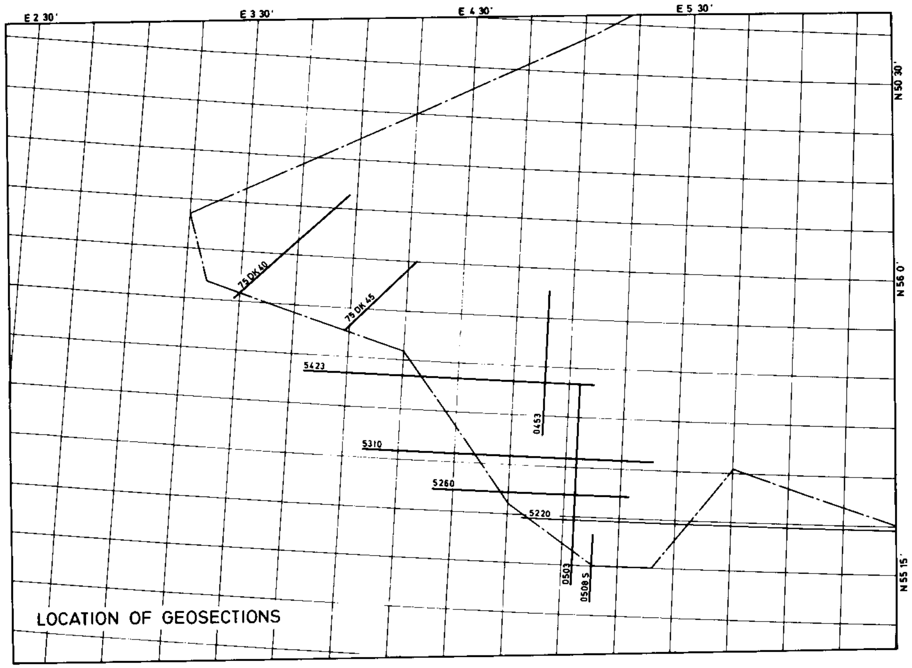
area. There is no well control and only a moderate seismic coverage.

2.2 Structural development

The development of the Central Graben, as presented here, is based on a considerable interdiciplinary reinterpretation of basic data as well as on papers by Bertelsen (1978, 1980), Day et al. (1981), Deegan & Scull (1977), Fyfe et al. (1981), Michelsen (1978), Rhys (1974), and Ziegler (1981) and those cited in the text. The development is treated in stratigraphic order (fig. 2), and referred to the general structural outline on fig. 5. The chapter is focused on the evolution within the area under consideration rather than the history of the entire basin and the major plate tectonic framework.

Knowledge of the structural development of the Danish Central Graben area prior to the Mesozoic rifting is incomplete and the documenting data sparse. Therefore the outline of this part of the section is brief and general. Conversely, far more is known about the Mesozoic-Cenozoic eras.

The location of the Caledonian basement is indicated by wells in Poland, Danish onshore, North Germany, and the North Sea. The boundary between



LEGEND FOR GEOSECTIONS AND SEISMIC LINES

TMM	Top Middle Mirocene
TCh	Top Chalk Group
BUC	Base Upper Cretaceous
TLC	Top Lower Cretaceous
BLC	Base Lower Cretaceous
TJ	Top Jurassic
inJ	Internal Jurassic
BJ	Base Jurassic
TT	Top Triassic
TZ	Top Zechstein
BZ	Base Zechstein

(a)	Potential structural arch trap
(f)	Potential structural fault trap
(p)	Potential primary stratigraphic trap.
(s)	Potential secondary stratigraphic trap.

The off-set of wells from seismic lines is given in Km.

GEOSECTION, LINE 5423

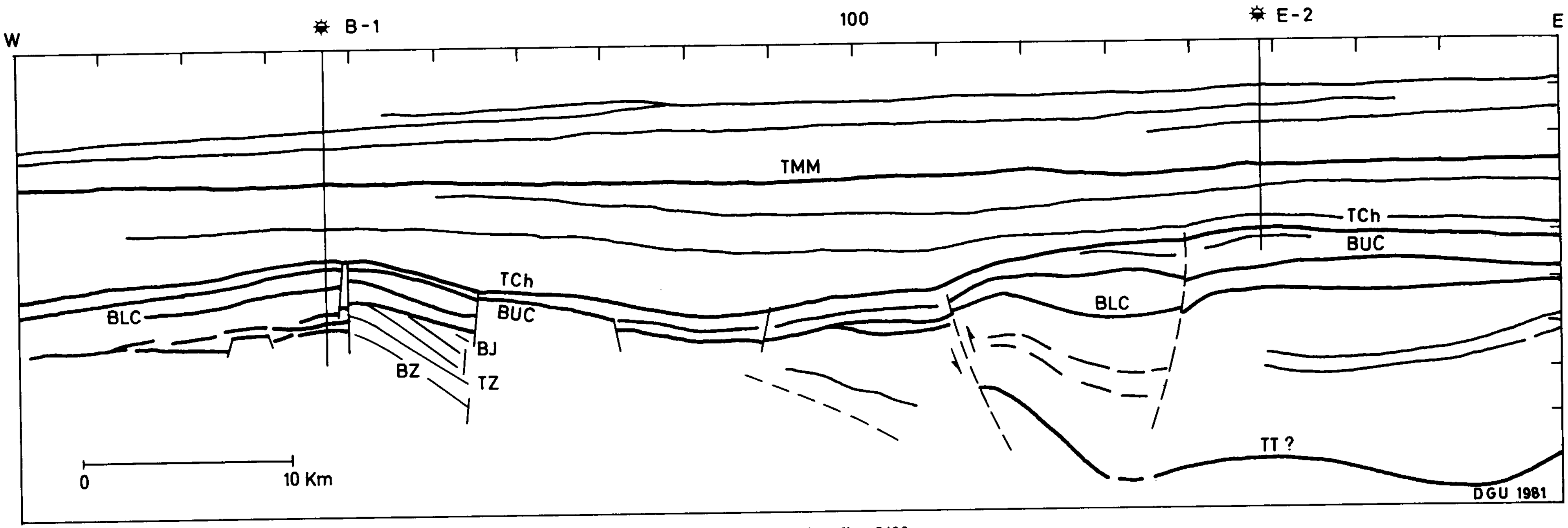


Fig. 7: a) Location map and legend of geosections presented in figs. 7 to 13 and b) Geosection, line 5423.

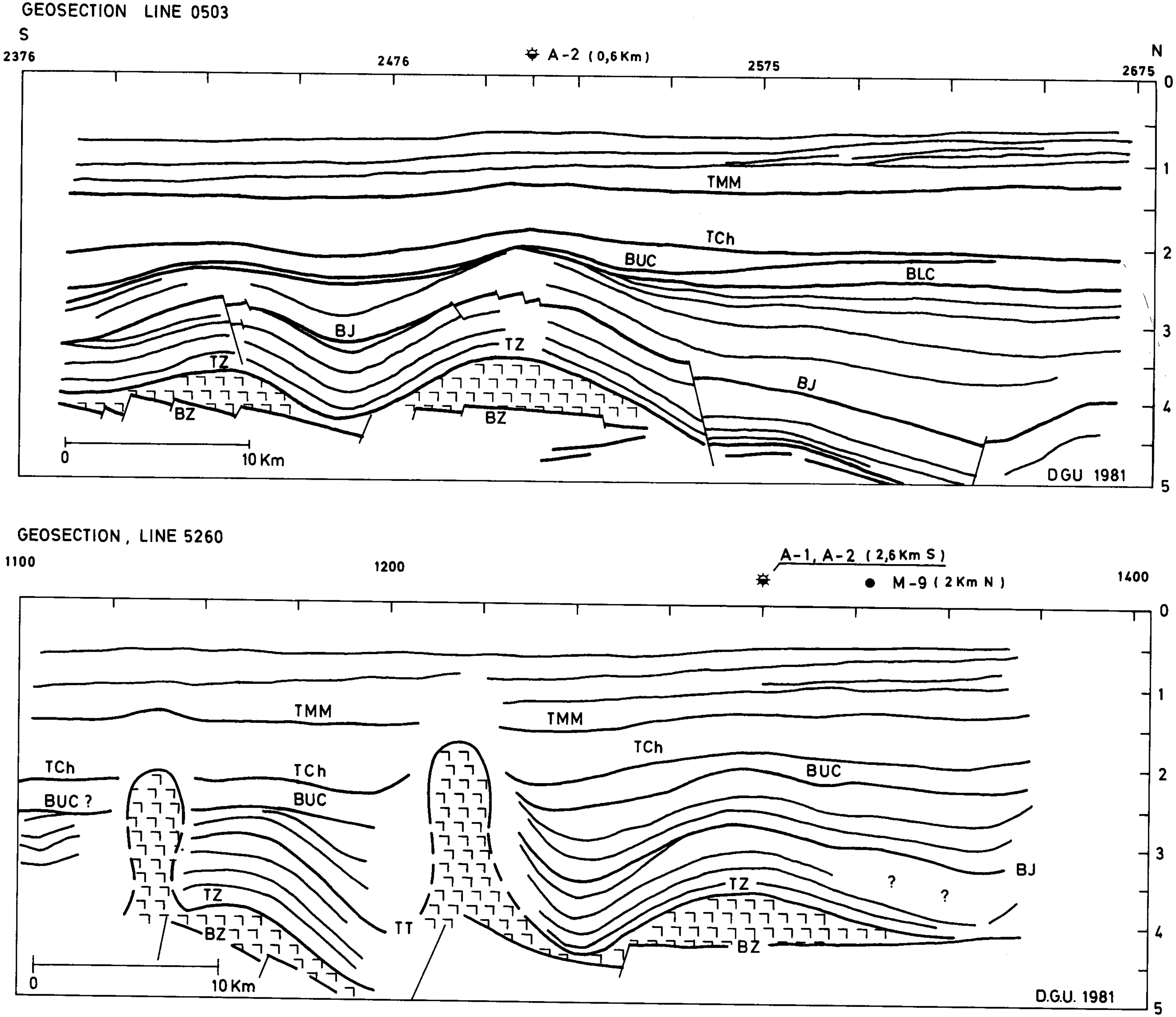
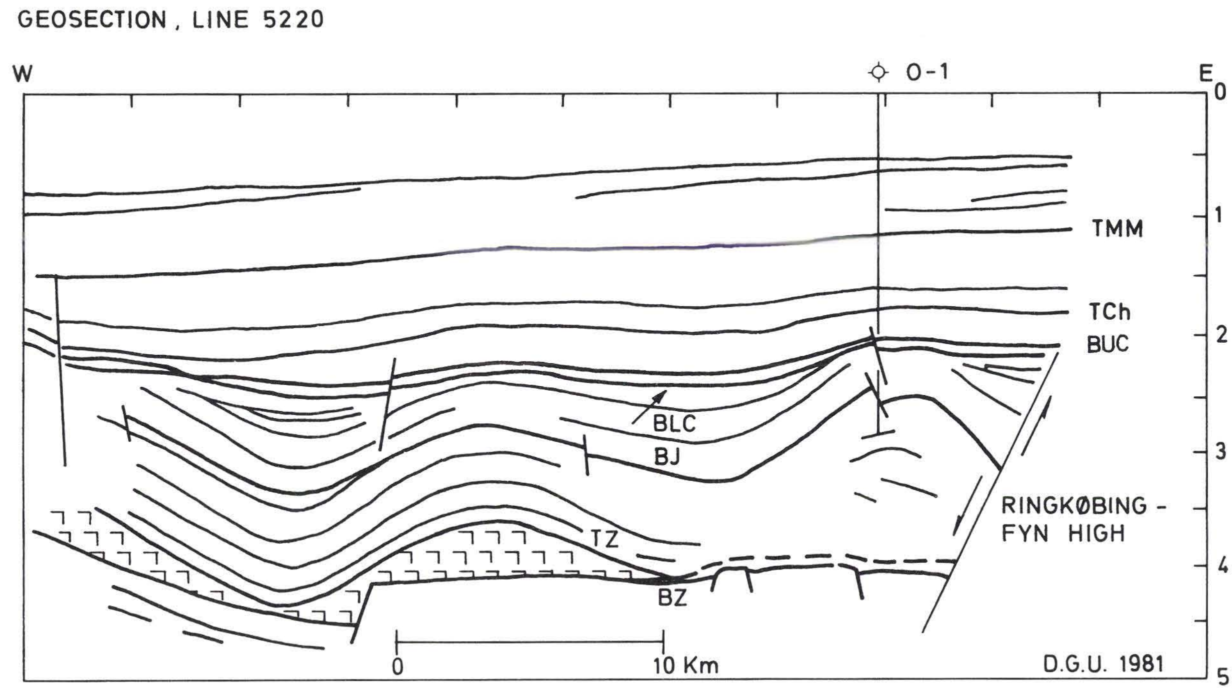


Fig. 8: Geosections a) line 0503 and b) line 5260. – For location and legend, see fig. 7.



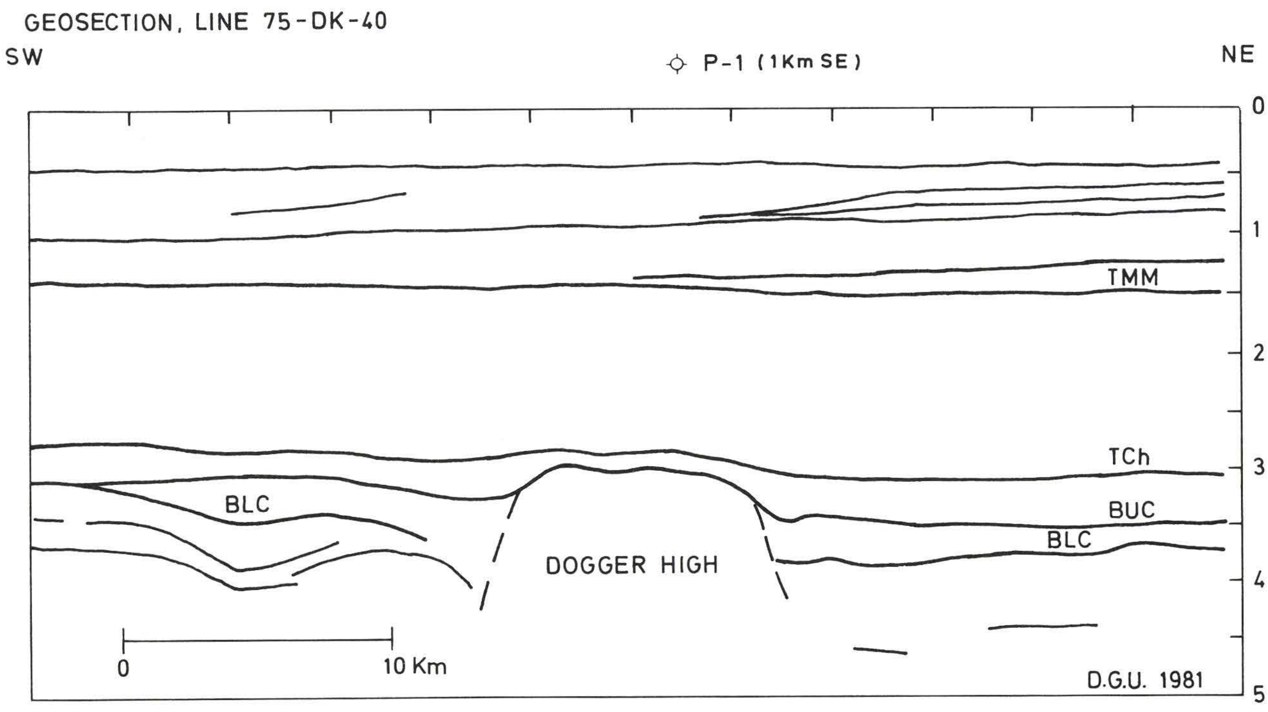
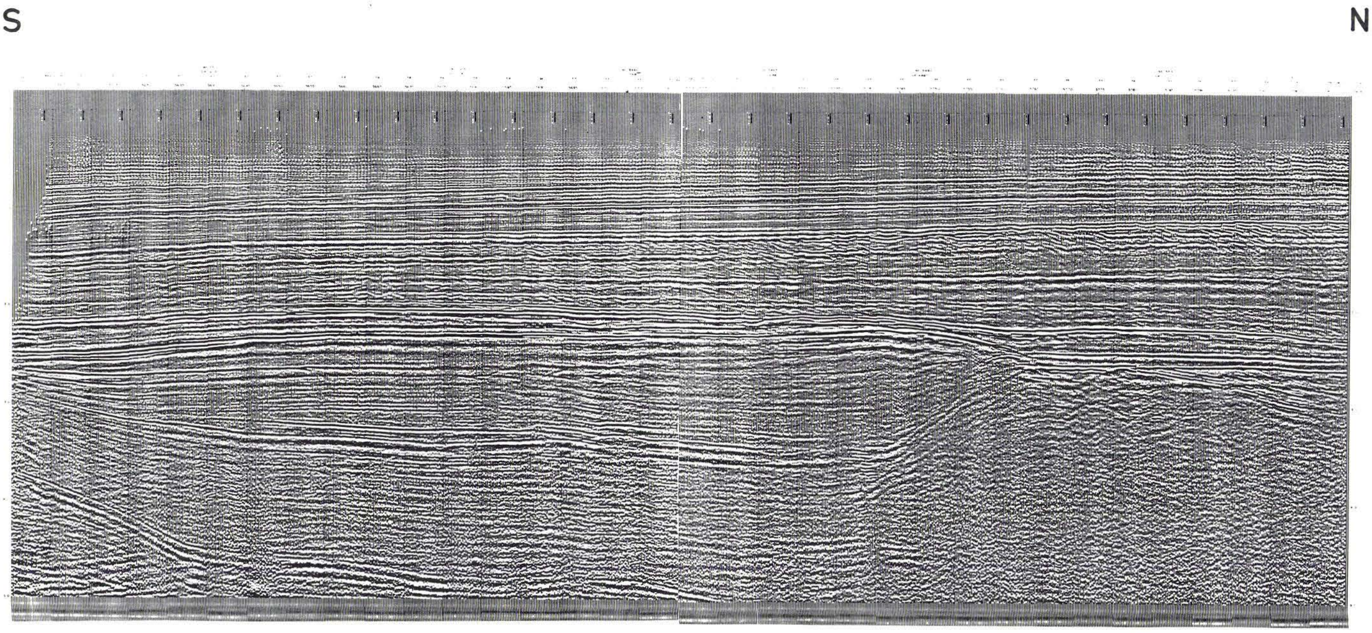
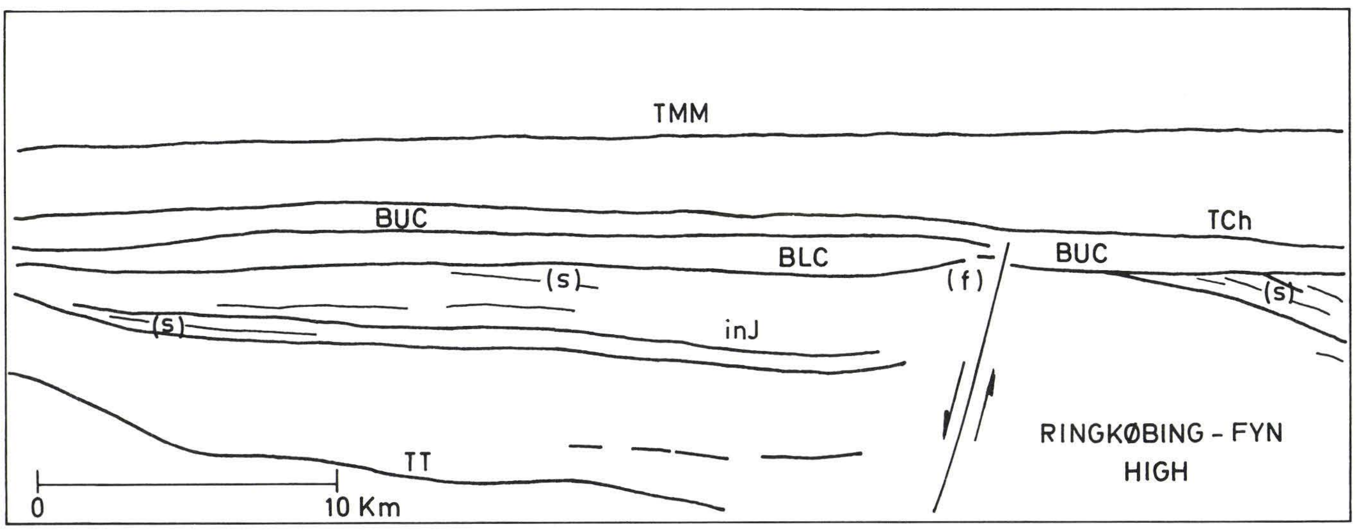


Fig. 9: Geosections a) line 5220 and b) line 75-DK-40. – For location and legend, see fig. 7.

CENTRAL GRABEN

Geosection, line 0453





D.G.U. 1981

Fig. 10: Line 0453 a) seismic section b) geosection. – For location and legend, see fig. 7.

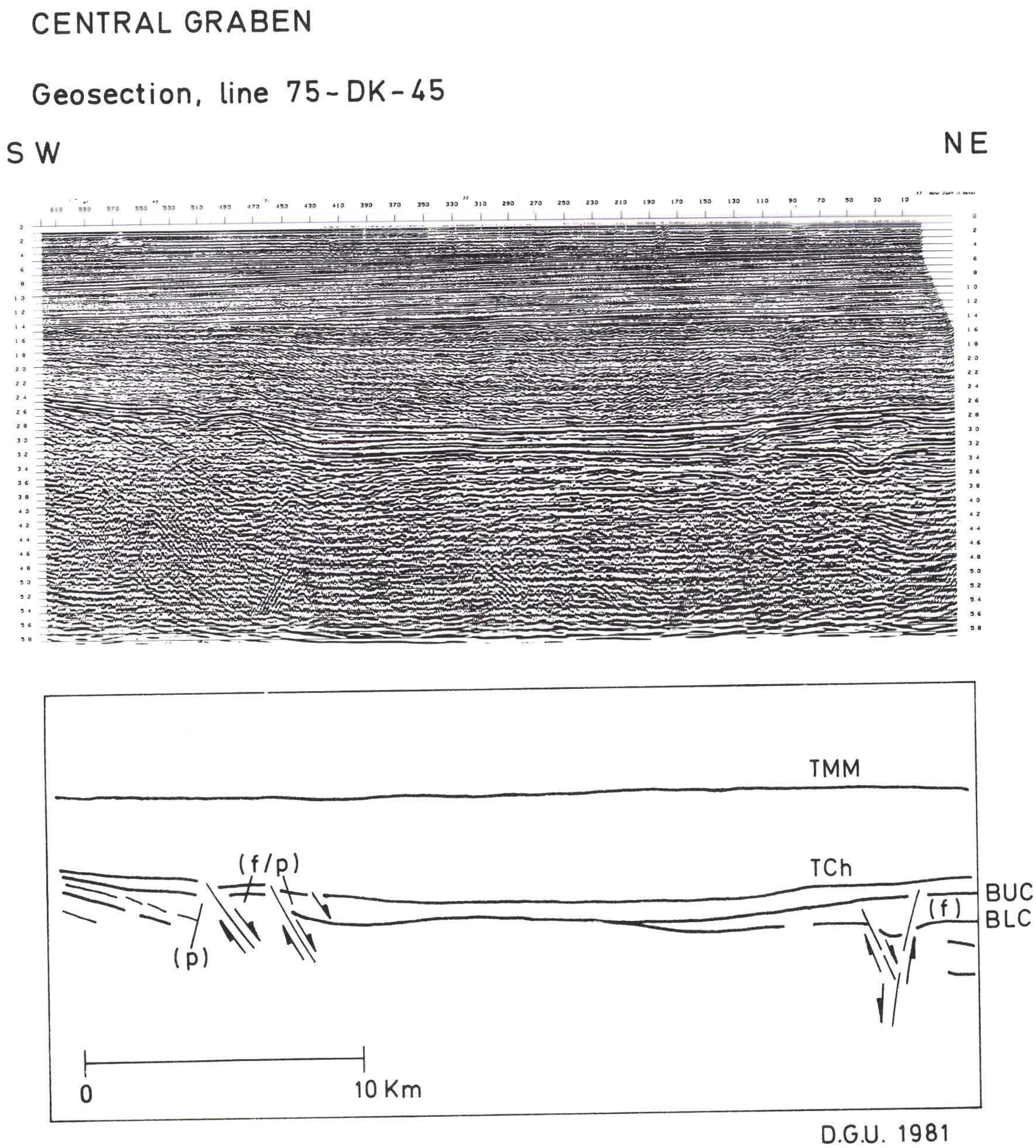


Fig. 11: Line 75-DK-45 a) seismic section b) geosection. – For location and legend, see fig. 7.

this Caledonian fold belt and the undeformed foreland to the north and east is not well defined. The Ringkøbing-Fyn High is known to be Precambrian basement, in parts covered by Lower Palaeozoic sediments which also cover Sjælland, Kattegat, and Jylland.

The greenschists found in the P-1 well, located on the northern part of the Dogger High, have Caledonian radiometric ages (Frost et al. 1981). Thus the Polish-German Caledonian deformation front , linking up with the Scottish-Norwegian Caledonian Mobile Belt, appears in the Danish sector to be located more or less at the same position as the later formed Central Graben.

Devonian and Carboniferous

So far Devonian deposits have not been drilled in Danish areas, whereas Carboniferous is present in the P-1 well. The palaeogeographic pattern based on wells elsewhere in the North Sea suggests the presence of Devonian strata. During the Devonian an extensive basin covered large parts of the North Sea including the Central Graben. The sediments that can be expected in the Danish sector are dominated by redbeds but, centrally, deposits of Limestones , in a possible fault controlled sea arm extending northwards from the Rhenish Basin, are likely to be present.

CENTRAL GRABEN

Geosection, line 0508 S

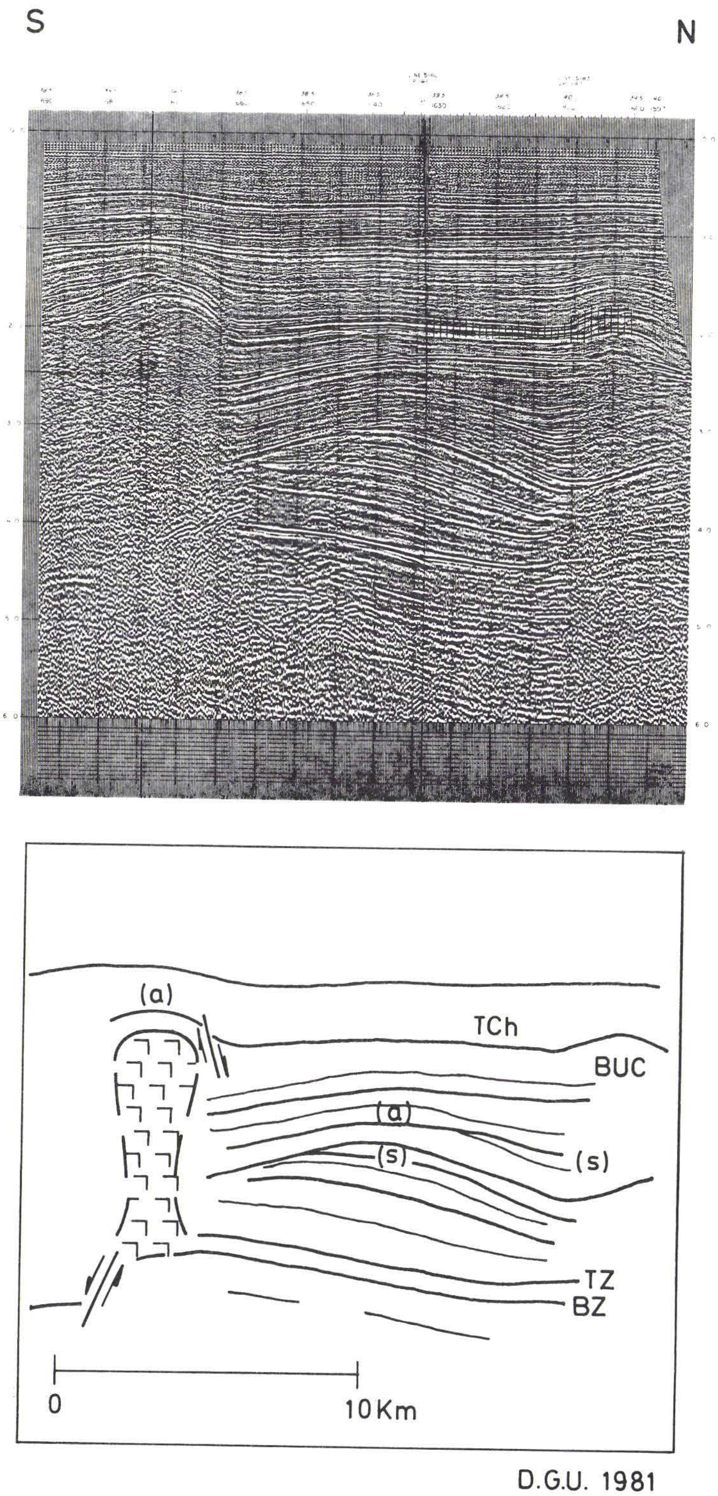


Fig. 12: Line 0508S a) seismic section b) geosection. – For location and legend, see fig. 7.

Geosection, line 5310

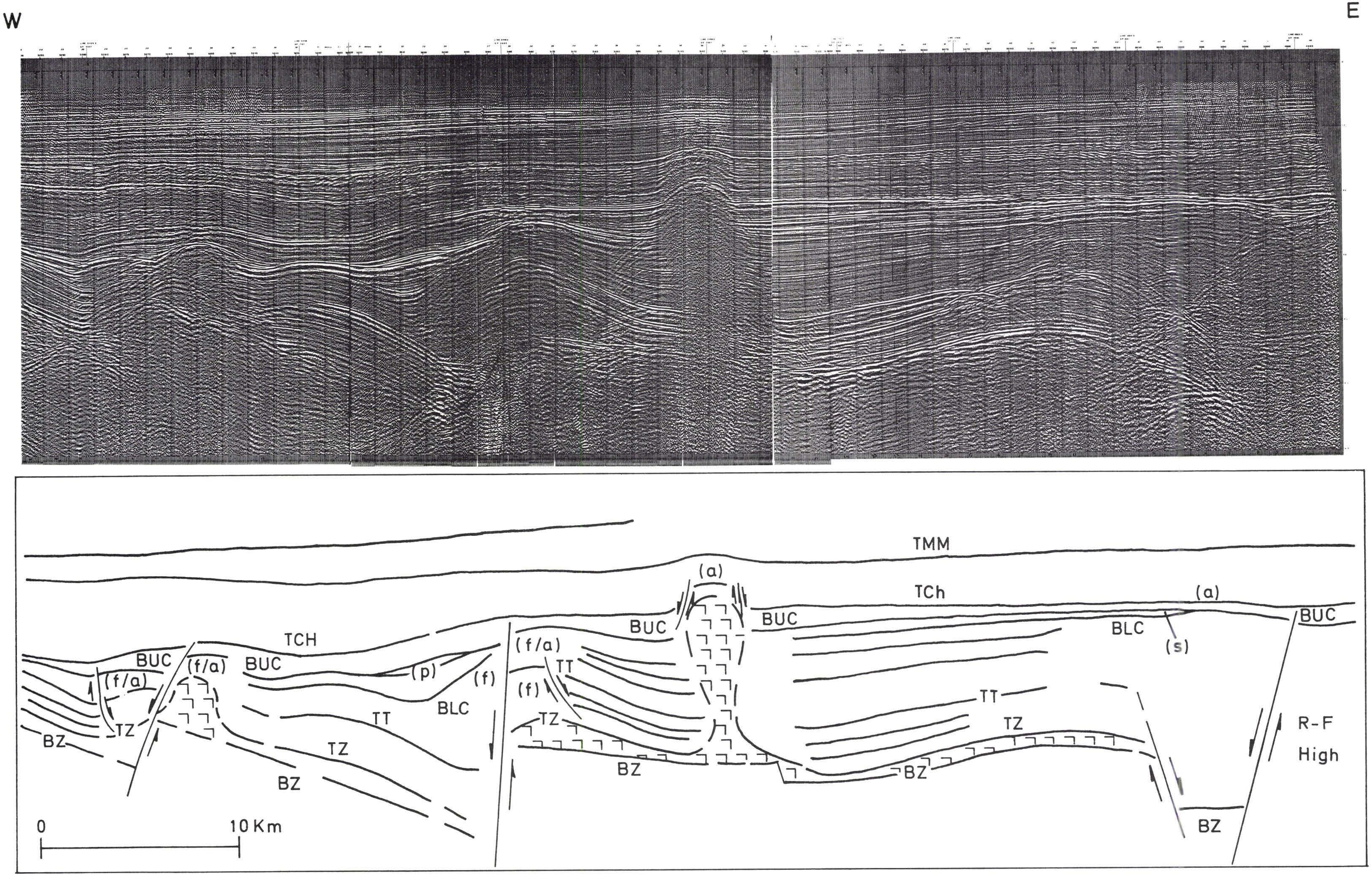


Fig. 13: Line 5310 a) seismic section b) geosection. – For location and legend, see fig. 7.

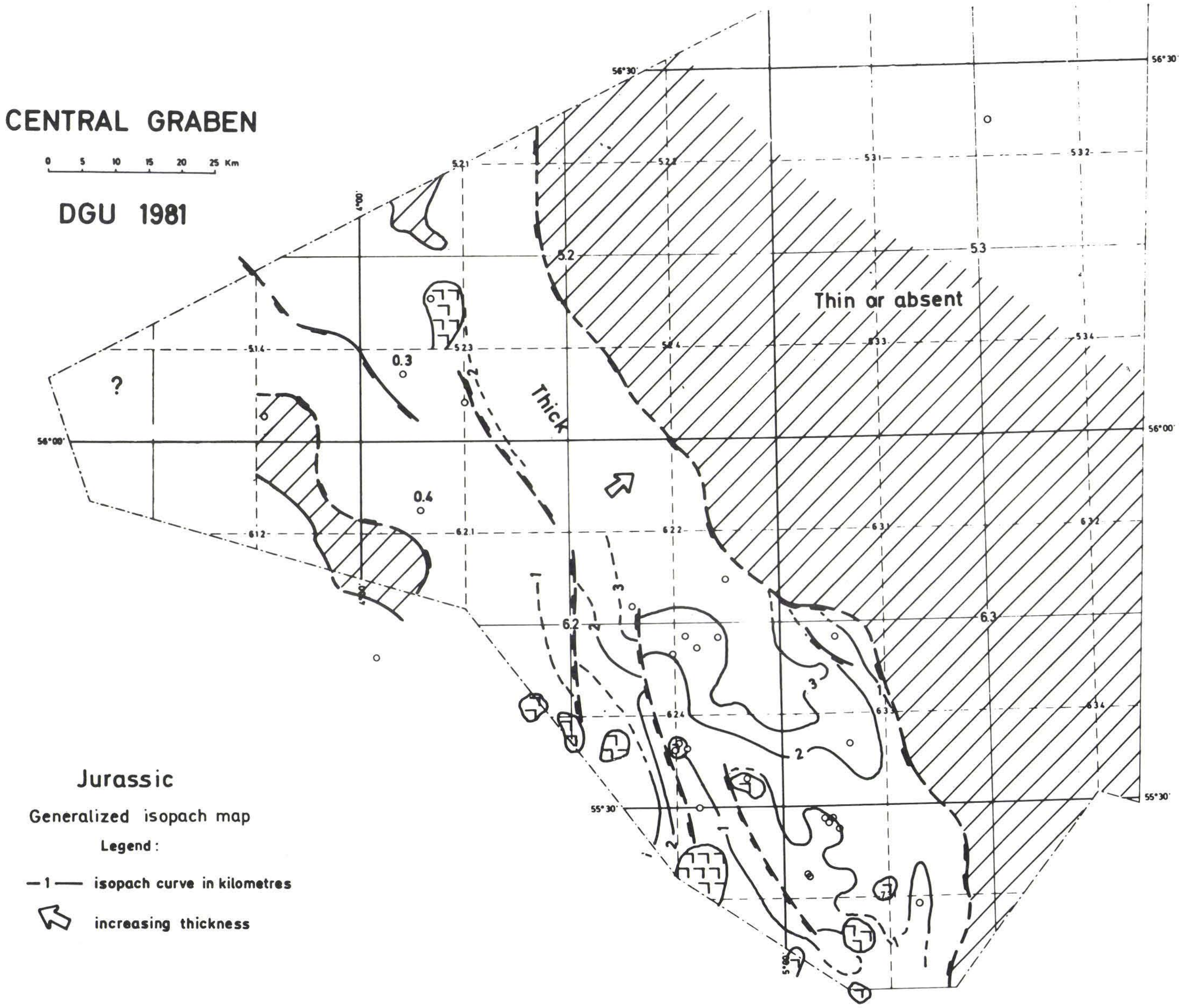


Fig. 14: Generalized isopach map of the Jurassic sequence.

Marine Early Carboniferous platform deposits are known as far north as the Danish P-1 well in the Central Graben, and the Moray Firth Basin. P-1 may well be located in a marginal belt which, together with the North British and the North German occurrences, delimites the occurrence to the north.

Late Carboniferous coal bearing series were until recent only known from the southern North Sea, where they form an east-west depositional belt. The central North Sea and the Danish onshore area is generally accepted as the source region for clastic supply to this depositional basin. The new discovery of marine Late Carboniferous sediments in the Oslo Graben area (cf. Olaussen 1981) gives valid reasons for changing the palaeogeographic picture. Of two postulated connecting sea arms (Eva Paproth 1981, pers. comm.) the one passing Kattegat, Skåne, and the Baltic may be preferred to the other through Skagerrak and northwards through the North Sea. Until further data are available , the conclusion will be that Carboniferous sediments, might be present in the Kattegat, Skagerrak, and the Central Graben, and even on the westernmost block of the Ringkøbing-Fyn High.

The structural understanding of the Carboniferous in the study area will be likewise rather poor. Dipping seismic reflections in the Dogger High area (fig. 11) below the Chalk Group may tentatively be correlated with Devonian-Carboniferous events. Similar dipping reflectors are seen on the Ringkøbing-Fyn High and in the area north of the Adda structure (fig. 10).

Permian

Late Carboniferous to Early Permian tectonic movements strongly affected the Northwest European region.

Following the uplift after the Variscan Orogeny in central West Europe, formation of horsts, basins, and grabens were initiated in Northwest Europe by right-lateral faulting. Thick volcanic piles usually accumulated at intersections of fault trends (i.e. northern Germany), and dyke swarms were intruded in Scania and the northern part of the British Isles. A part of this system may have been the WNW-ESE trend of highs across the North Sea, including the Mid North Sea High and Ringkøbing-Fyn High, which probably already existed in Late Carboniferous-Early Permian times. It also seems reasonable to relate the formation of both the Oslo Graben, the Horns Graben and the associated volcanism to the same tectonic phase. The Rotliegendes sequence in the Danish part of Central Graben is dominated by volcanics with subordinate intercallated sediments, and it has been drilled in the B-1 and P-1 wells and possibly in Q-1 and W-1. Possible Rotliegendes volcanics occur in the adjacent parts of the British and Norwegian sectors. The tectonic activity in the early part of Early Permian created a separate Southern and a Northern Permian Basin. In these basins red beds with interbedded sand and clay were deposited later in Rotliegendes. Due to missing well-control, neither the geometry of the northern basin nor the distribution and thickness of the red beds in the Central Graben are well known. Red beds are likely, however, to be rather widely spread both on the Dogger High and on the Graben floor.

In Late Permian, Zechstein time, the sea transgressed into the Northern and Southern Permian Basins mentioned above.

South of 57° N, the Zechstein facies in the North Sea are clearly structurally related. Shallow water carbonates and anhydrites predominate around the basin margins particularly on the Mid North Sea High and the Schillbank High, whereas thick evaporite sequences were deposited in the subsiding Northern and Southern Zechstein Basins. Evaporites were also deposited in the subsiding Central Graben. Day et al. (1981) propose that the evaporite sequence is continuous through the Central Graben although probably thin over the median part.

Ziegler (1981) in contrast is in favour of a model where the central part of the Danish Central Graben is dominated by deposition of thin carbonate and anhydrite shelf sequences similar to the deposition pattern of the adjacent structural highs.

No proof for selecting the right model is as yet at hand since Zechstein, because of its depth, is not recorded on available seismic sections and therefore cannot be traced in the Tail End Graben area. The absence of the Zechstein evaporites in the W-1 and Q-1 wells is, following the arguments of Day et al. (1981), explained by salt withdrawal associated halokinetic movements.

Triassic

The structural framework, created during the Late Palaeozoic, which made up the fundament for the Triassic, Jurassic, and Early Cretaceous sedimentation, suffered rifting during the Triassic. In the Northern and Southern Permian Basins in Northwest Europe the onset of the Triassic was marked by a regional regression and a return to a continental depositional regime. Continued subsidence caused a gradual burial of the Mid North Sea High and the Ringkøbing-Fyn High. Generally the continental sedimentation rates kept pace with subsidence and rising sea level.

The Triassic depositions in the North Sea may generally be divided into two parts, a northern and a southern. The Danish Central Graben seems to be located in a transition zone between these. The northern area is dominated by accumulations of heterogenuous and rather coarse-grained material shed into the basin from the northeast. The southern region is characterized by more fine-grained material deposited in a cyclical succession reflecting regressions and transgressions from the south. Well control in the Danish Central Graben is limited to the Southern Salt-dome Province and the B-1 and Q-1 wells.

The thickness of the Triassic sequence in the south is 1500-2000 m, but rather wide variations caused by erosion during the Early Cimmerian or perhaps the Mid Cimmerian tectonic events, do occur. This observation is in accordance with well information, indicating that Rhaetian sandstones of the Winterton Formation, normally present in the Netherlands part of the Central Graben, are missing in the Danish sector. The base Jurassic seismic reflection is often developed as a rather distinct unconformity surface.

Variations in thickness of the Triassic sequence in the Southern Salt-dome Province may locally be explained by the onset of halokinesis of Zechstein evaporites in the Late Triassic. Towards the German part of the Dogger High the thickness of the Triassic sequence is generally reduced and the angular unconformity on top becomes much more distinct.

In the northern parts of the Danish Central Graben, very little can be said about distribution and structural setting of the Triassic. This is due to scarcity of data, both with respect to well control and to resolution of the seismics.

Jurassic

The thickness of the Jurassic sequence, predominantly Late Jurassic shales, exceeds 4000 m in parts of Tail End Graben. In the Southern Salt-dome Province the thickness rarely exceeds 1600 m and usually only in connection with development of rim-synclines around salt structures. West of the fault zone delineating the Tail End Graben, the Jurassic is much reduced in thickness, and it is totally absent on the crest of the Dogger High. An understanding of the Jurassic in the northern area adjacent to the Norwegian sector is difficult to obtain due to lack of well control and released seismic sections. A generalized isopach map of parts of the Central Graben is given in fig. 14.

Unconformities are rather frequently recorded in the Jurassic sequence especially on seismic sections from the northern part of the Southern Salt-dome Province.

It is tentatively suggested that the major part of the Tail End Graben subsided as one large rotational fault block in the Late Jurassic with the boundary fault zone of the Ringkøbing-Fyn High acting as a major synthetic fault.

The Early Jurassic sedimentation of Northwest Europe took place during a sea-level rise. In the North Sea region relatively shallow-water marine clay- and marlstones were deposited. Deposition of sand and silt took place only in marginal regions, e.g. along the northeastern margin of the Danish Subbasin and in the East Shetland Basin.

The Early Jurassic sediments are preserved only in local basins within the North Sea region, probably as a result of the Mid Cimmerian events (see below). It is believed that the Early Jurassic sea covered the entire Danish area, and that the main depocentres were primarily in the Danish Subbasin and secondarily in the southern Central Graben. In the Danish Central Graben, the claystone series is referred to the Fjerritslev Formation, which is known from the Danish Subbasin, equivalent with the Dunlin Unit in the northern North Sea.

At the end of the Early Jurassic a rifting phase, the Mid Cimmerian phase, took place. It affected the Northwest European Graben systems by renewed block faulting, and it was accompanied by a general lowering of the sea level and subsequent erosion. In the central North Sea a large rift dome was uplifted, and volcanic activities took place north of the Danish area. In the Central Graben the erosion is not yet known to have affected strata older than Early Jurassic. Due to the accentuated relief, clastic sediments were shed into the basins. Generally the deposition took place in fluviatile and deltaic environments. Interbedded sand, clay, and coal, equivalent to the Haldager Sand in the Danish Subbasin and the Brent Sand to the north, were deposited in the Central Graben.

During the Middle Jurassic, the Central North Sea rift dome began to subside and a general sea level rise took place. The area was flooded and, except for certain highs, the sea covered the main part of the North Sea region. The rate of subsidence in the Central Graben exceeded the rate of sedimentation, so clay-dominated sediments were laid down in a deep water marine environment. The Late Jurassic period is a main subsiding period for the Central Graben. The thickness of the Late Jurassic claystone series within the Graben varies, due to differentiation of the subsidence and deposition on individual rotational fault blocks, but it markedly exceeds that of the equivalent series on the surrounding flanks.

At the transition Jurassic to Cretaceous, a tectonic pulse, the Late Cimmerian phase, affected the entire Northwest European region, and it was accompanied by a sea level drop. A regional unconformity was developed in the Graben system, and shallow marine arenaceous sediments were deposited in marginal areas, e.g. the Frederikshavn Member in the Norwegian-Danish Basin. The unconformity is believed to be largely of sub-marine nature, and continuous sedimentation in the deeper parts of the Graben systems is found elsewhere in the North Sea. In the Danish Central Graben, the unconformity hiatus represents varying parts of the Late Jurassic-Early Creaceous.

In the Southern Salt-dome Province, the distinction of separate subsiding Late Jurassic fault blocks is attenuated by contemporaneous salt movements.

The sand of the W-1 Unit shows indications of having originated from a near source. It is therefore suggested that the Dogger High horst block remained partly elevated during Late Jurassic times and acted as a source area for clastic deposits along the margins of the graben floor.

The Late Cimmerian rifting phase gave rise to an unconformity which can be mapped in most of the North Sea area. This unconformity is diachronous due to a complex interplay of tectonic activity and eustatic changes (Fyfe et al. 1981).

In the Danish Central Graben, the top of the Jurassic sequence frequently shows an angular unconformity to the overlying Early Cretaceous in the area to the east of the Dogger High. In a zone along the Ringkøbing-Fyn High stretching from Tyra and Adda to the south of Igor, the top Jurassic is difficult to map seismically. Distinct unconformities are usually not observed and there appears to be very little contrast in acoustic impedance between the shales of Late Jurassic and Early Cretaceous ages.

The depth to the Top Jurassic marker is usually less than 2500 m in the southeastern part of Central Graben. Minimum depth to the Top Jurassic (about 2200 m) is recorded on top of the Anne structure, while the maximum depth (more than 4500 m) is found towards the north close to the Norwegian sector.

Early Cretaceous

The Late Cimmerian tectonic phase led to a framework of differentially subsiding rotational fault blocks which was only little changed during Early Cretaceous. The general transgressional sedimentation lead to onlap sequences and maximum deposition in the graben floor.

In the central North Sea sedimentation of marine clay, well known from the Norwegian sector, was the dominating feature. In the Danish Central Graben this sedimentary sequence is referred to as the Valhall Formation, which is time equivalent with the Vedsted Formation and the upper part of the Frederikshavn Member in the Norwegian-Danish Basin. Along the highs, sand bodies or sandy marl fans were deposited which are interpreted as beds deposited by density currents activated by fault activity. The LC-1 Unit in the Danish area is probably equivalent to the Devils Hole Formation. A minor regression associating the Asturian tectonic phase, seems to have broken the general transgressional trend. In the Danish region this could be indicated by minor unconformities. As the Cretaceous transgression continued the highs were drowned. The Rødby Formation, dominated by reddish marl, covers large parts of the North Sea area, as well as the Ringkøbing-Fyn High.

The distribution and thickness of the Early Cretaceous sequence within the Danish Central Graben is illustrated on the generalized isopach map of the Early Cretaceous (fig. 15). The thickness of the Early Cretaceous sequence exceeds 500 m in the central and northern parts in the elongated, partly fault-controlled troughs. A maximum thickness more than 900 m is found in a trough at the northern extension of a major Cimmerian normal fault.

The thickness of the Early Cretaceous sequence is less than 250 m in the Southern Salt-dome Province, except for a few peripheral sinks around salt diapirs in the southernmost part.

Early Cretaceous is thin or absent on the Ringkøbing-Fyn High and there is a gradual decrease in thickness in the Graben towards the boundary fault zone.

Likewise Early Cretaceous is thin or absent in the Dogger High area.

'Onlap sequences' are characteristic features on seismic sections and internal unconformities occur locally close to the fault zone at the western margin of Tail End Graben suggesting that this zone was active during Early Cretaceous times.

In the northern part of the Danish Central Graben area and around Dogger High, the top of the Early Cretaceous sequence is marked by an unconformity. The area around the P-1, W-1, Q-1, and I-1 wells was uplifted and part of the Early Cretaceous eroded prior to the deposition of the Late Cretaceous Chalk Group.

Late Cretaceous

The dominating factor for the Late Cretaceous sedimentary evolution in Northwest Europe was a global sea level rise during which the marginal areas, such as Scania, were transgressed. Due to the transgression and changes in climatic conditions, the influx of clastic material was radically reduced, and chalk was deposited.

In Late Cretaceous times the active central North Sea rift system ceased to exist. More than 1500 m of the chalk was deposited in the Norwegian part. On the Graben flanks the chalk thicknesses usually are in the order of 250-500 m.

Comparing the generalized isopachs of the Lower Cretaceous sequence and the Chalk Group, one observes that areas of thick Lower Cretaceous are often overlain by relatively thin Upper Cretaceous and vice versa. This phenomenon is associated with a system of antiformal and synformal gentle flexures arranged in en echelon pattern. These are believed to be the effects of Late Cretaceous and Early Tertiary inversion tec-

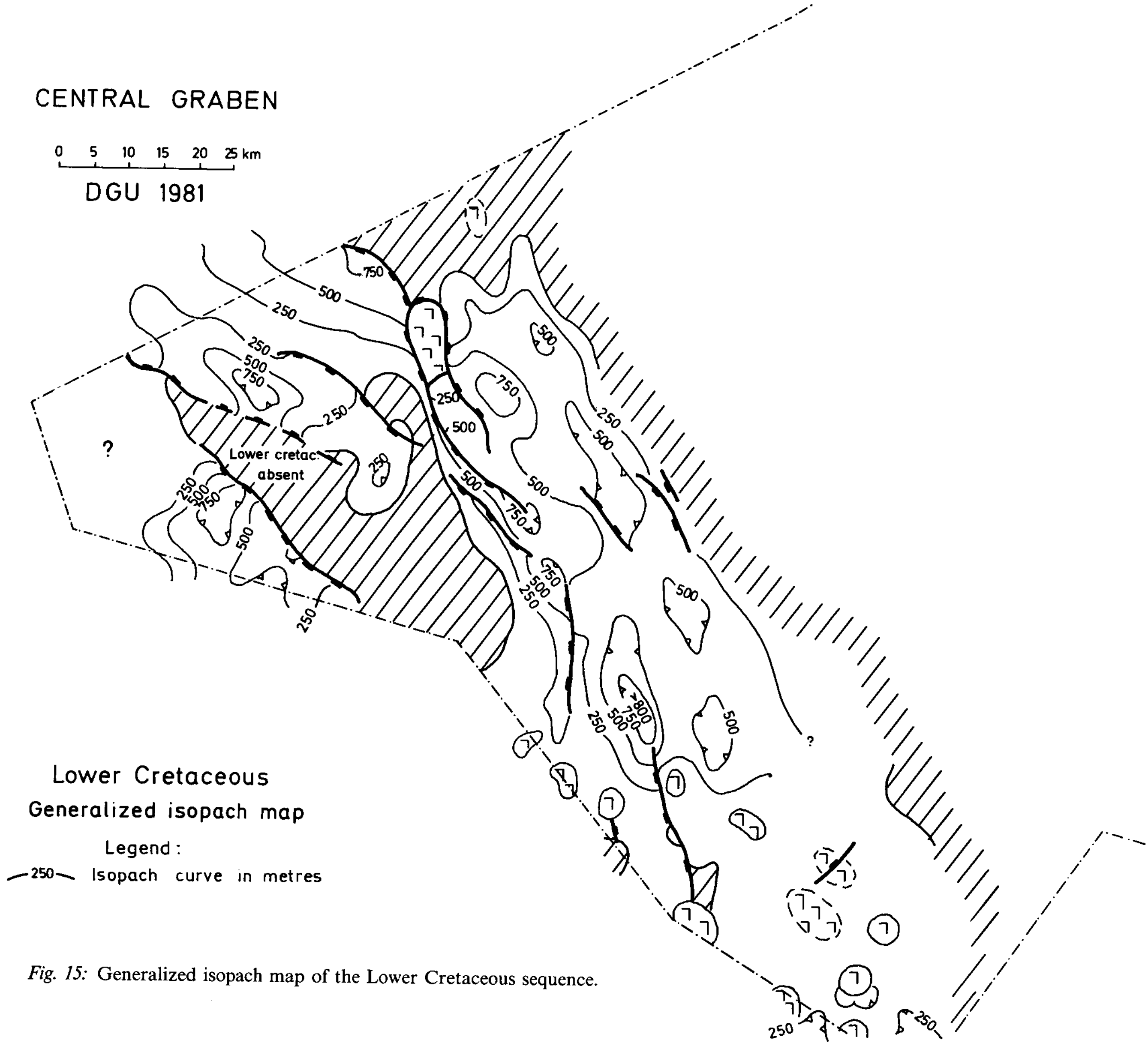


Fig. 15: Generalized isopach map of the Lower Cretaceous sequence.

tonics caused by a compressional strike-slip stress regime.

The change from rifting to a phase of gradual subsidence was thus accompanied by inversion tectonics whereby previously tensional basins were deformed by compressional and wrench forces. The basin fill was folded and uplifted and may even have been subjected to erosion.

The inversions are believed to be caused by Sub-Hercynian or possible Laramide orogony.

A generalized isopach map of the Chalk Group is given in fig. 16, and a two-way time map to Top Chalk is given in fig. 6.

The thickness of the Chalk Group outside the halokinetic structures varies considerably, from less than 250 m in the south, to more than 1250 m in the northern part of the Danish Central Graben, close to the Late Cretaceous regional depocentre in the Norwegian sector.

The effect of active Late Cretaceous salt diapirism and possible shale flow along the western margin of the Tail End Graben can be read from the generalized isopachs and the fault pattern.

The relative thickness distribution of the various chalk units, based on well information, shows a complicated depositional pattern throughout the Central Graben area (fig. 26). This indicates a differential structural evolution of the Graben subunits. The well data seem to indicate that the Dogger High area and the western margin of the Tail End Graben were

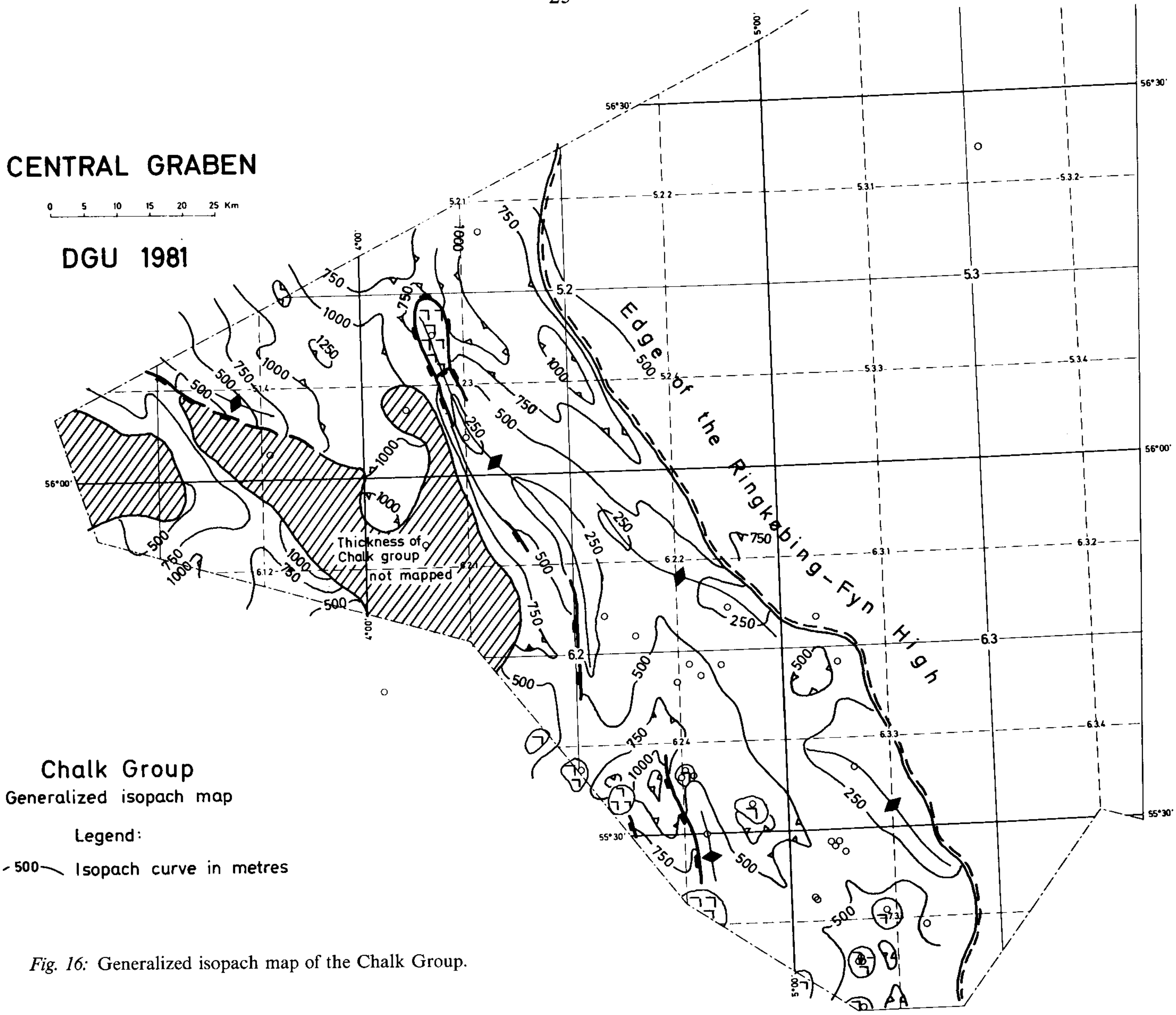


Fig. 16: Generalized isopach map of the Chalk Group.

uplifted during deposition of the Chalk-1, 2, and 3 Units. The Chalk-4 Unit was deposited all over the Central Graben although it is thin at the eastern margin of the Tail End Graben close to the boundary fault zone. This area may have remained relatively uplifted during deposition of this Unit.

The Chalk-5 Unit is also relatively thin in the Tail End Graben and its western margin. These areas probably became inverted during deposition of this Unit.

The Chalk-6 Unit of Danian age was probably deposited throughout the Central Graben area. It has its maximum thickness along the flank of the Ringkøbing-Fyn High and may be absent locally along the western margin of the Tail End Graben.

Tertiary and Quaternary

In the beginning of the Tertiary, the Laramide tectonic phase, associated with a regression in the marginal areas and a change of the climate, altered the sedimentary pattern into a clastic dominated regime. After this event the North Sea Basin became a part of a large Northwest European sedimentary basin, the main sedimentary source region of which was situated to the east. During the Tertiary the basin subsided evenly and rapidly, and was affected only by minor tectonic events and locally by halokinetic movements. In the Early Tertiary, sedimentation clay dominated, while sand and silt intercalations characterize the Late Tertiary accumulation.

During the entire Cenozoic, characterized by a gradual and rapid subsidence pattern in the Central North Sea area except for mild Laramide inversions in the former Graben areas, more than 3000 m of sediments accumulated in the northern part of the Central Graben. Only the Early Tertiary lithological units vary significantly in thickness, and these deposits become thicker in the northern part.

The central part of Dogger High showed a separate subsidence pattern during the Early Tertiary. Fig. 11 shows that sediments prograded eastwards from this high into the basin to the east. The base of the Upper Miocene is locally developed as a weak angular unconformity and marks the shift from an Early Tertiary, predominant-shale sedimentation into a more sandy, Late Tertiary sedimentation. This indicates that sedimentation rates probably started to exceed subsidence rates.

The Late Tertiary sedimentary sequence shows uniform progradation from the east. The fairly monotonous and uniform Tertiary evolution is interrupted only locally by continued salt diapirism.

The thickness of the Quaternary cover is up to 600 m in the Central Graben area.

3.0 Description of the formations

All formations recorded by drilling in the Danish Central Graben area are listed and described in the present chapter. The descriptions are based on a compilation of information available in the DGU files. This basic material is of a heterogeneous character as it comprises analyses and reports worked out by various companies and by DGU. The descriptions given below are, therefore, to be regarded as preliminary, and further investigations must be carried out to elucidate certain stratigraphic and depositional aspects. Thus, the majority of the lithostratigraphic units are treated and named here informally. Only for the Triassic, Lower Jurassic, and Lower Cretaceous units sufficient knowledge has been established to refer these to formal lithostratigraphic units. All lithostratigraphic units are defined on wire-line log characteristics.

A review of the present standard stratigraphic subdivision is given in fig. 2. The bio- and chronostratigraphic correlation is generally at the same level of documentation. This stratigraphic concept will probably be revised through supplementary biostratigraphic studies.

As a rule, the lithology of each unit or formation is described, as interpreted from various sample descriptions and from wire line logs. The diagnostic log motifs and formation boundaries are treated. Furthermore, the thickness, distribution, geological age, depositional environment, source rock potential, reservoir potential, and sealing potential are described. The evaluation of thickness and distribution is partly based on seismic data. The formation descriptions are accompanied by palinspastic profiles and generalised formation maps comprising thickness and distribution. Tables on such primary data as depth, thickness, porosities etc. are presented in chapters 8 and 9.

Well locations are given on a map (fig. 1). Legends for signature on maps, palinspastic profiles, and well sections are given in fig. 3.

3.1 Pre-Permian

By Jørgen Gutzon Larsen & Olaf Michelsen

Data on Pre-Permian rocks are reported only from the P-1 well, which was bottomed in Caledonian basement. The geology of this formation in the western part of the Danish sector is, therefore, poorly known. According to the age determinations performed and reviewed by Frost et al. (1981), the North German-Polish Caledonides extend under most of the North Sea and join the Scottish-Norwegian Caledonides, whereas most of the Ringkøbing-Fyn High is underlain by Precambrian basement.

Caledonian basement

The P-1 well, situated on the western extension of the Dogger High, was bottomed in a sequence of greenschists, believed to be meta-tuffs between 11259-11464' b.KB. In some of these beds, phenocrystal relics of clinopyroxene, titanite and apatite may be abundant, whereas green biotite (?primary), zircon and brown amphibole are scarce. The amphibole is surrounded by a clinopyroxene reaction zone - a relation, which is believed to be of igneous origin, e.g. caused by resorption of amphibole phenocrysts or xenocrysts by lowering of the water pressure or increase in temperature in a crystallizing magma. Light grey to reddish, thin beds are intercalated with the meta-tuff. They are rich in albite-oligoclase, forming fragmental to more or less rounded relics, together with scattered grains of the

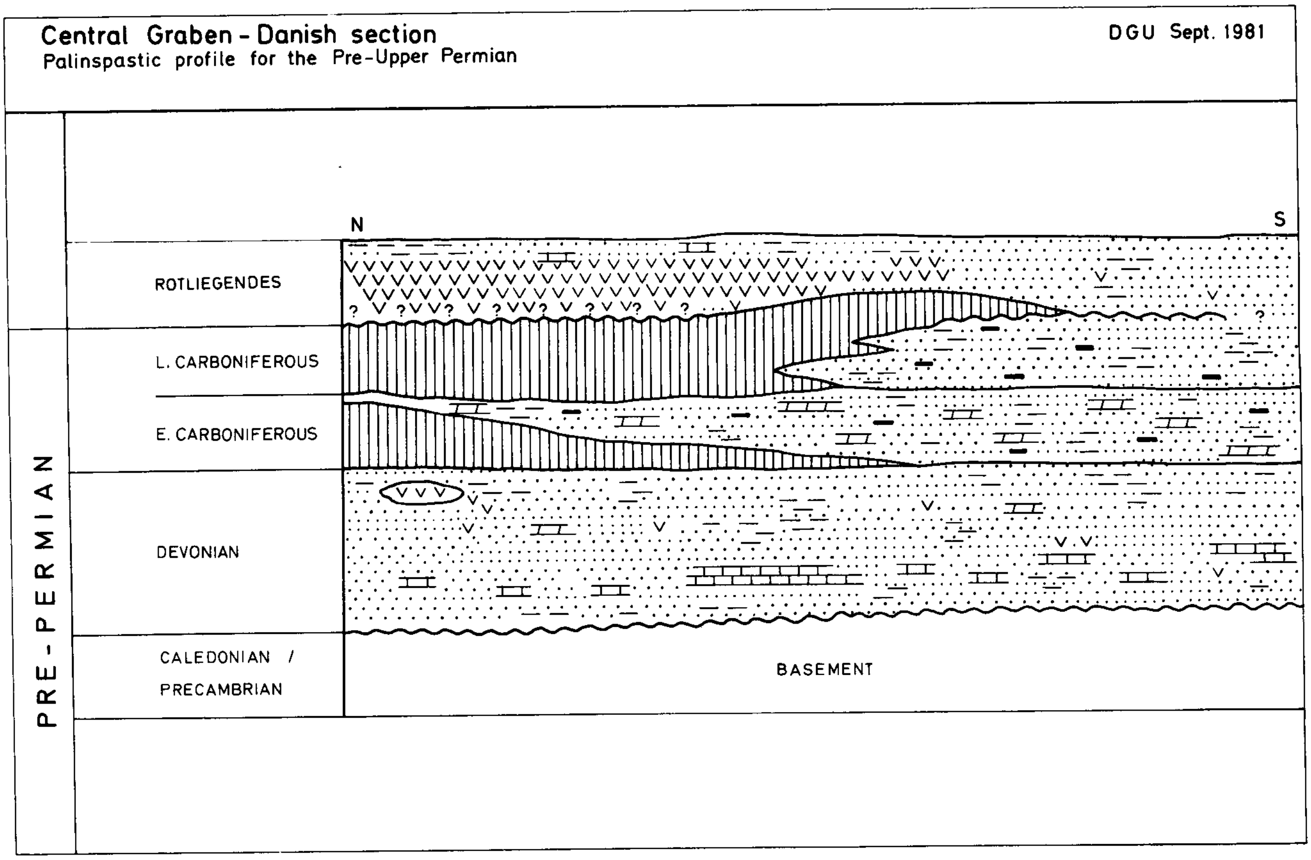


Fig. 17: Palinspastic profile of Pre-Upper-Permian deposits. For legend, see fig. 3.

minerals mentioned above in a cataclastic quartz-feldspar matrix. Settling texture in one of these light beds has been observed, but does not give certain evidence of their origin. They may be volcanogenic greywackes or salic crystalline tuffs. The phenocrystal assemblage described above suggests the presence of an alkaline, trachytic, volcanism (see Gaida et al. 1978). Argon 39/40 step heating ages of 436 +/- 4 Ma can be related to the Caledonian metamorphism with an Early Permian 271 +/- 6 Ma overprint (Frost et al. 1981). Combined results from K/Ar and Rb/Sr-age determinations agree with this conclusion (Ole Larsen, written com.).

Carboniferous

During the Carboniferous, the Danish Central Graben area was in a transitional position between a northern land mass and the shelf of the Variscian geosynclinal to the south. The substratum is supposed mainly to be the Caledonian basement or Devonian sediments (fig. 17). Only the Danish P-1 well has been drilled in the Carboniferous within the Central Graben. Just south of the Danish region, and further to the northwest pronounced Carboniferous series have been drilled.

CA-1 Unit *(informal name)*

The Lower Carboniferous series, the CA-1 Unit, drilled in the Danish P-1 well, indicates that more than one formation may be present, but the lack of usable reference wells makes it unreasonable to establish formal formational units.

Type section: The Danish P-1 well, 11038-11259' b.KB.

Thickness: 67 m in the P-1 well, but the regional thickness may well exceed this figure according to the thicknesses known from the area south of the Mid North Sea High (see Rhys 1974).

Lithology: The drilled sequence is an interbedded series of shale and sandstone. Minor coal seams occur in the sandstones, as do dolomitic limestone in the shale (Bertelsen 1978).

Log characteristics: The gamma ray changes between low and high readings reflect the mentioned layering of sandstone and shale. The sonic velocity is generally high and the log motif is nervous and undifferentiated.

Boundaries: The lower boundary is primarily marked by the sonic velocity which is high and uniform in the underlying metamorphic greenstone, and relatively lower and nervous in the present series. The upper boundary is between the present mainly greyish series and the overlying reddish series of assumed Rotliegendes age. The log motifs are not significant, but the change from high gamma ray readings above to relatively lower below is used for location of the boundary.

Distribution: The Early Carboniferous deposits are probably present in major parts of the Danish Central Graben, but due to lack of data (seismic mapping is critical), a delineation of the extension is not possible.

Geological age: Based on studies of the miospores, part of the series is dated to Early Carboniferous, Late Visean or Early Namurian (Bertelsen 1978). - The lower part of the series has not been dated, thus it may be of Carboniferous or Devonian age.

Depositional environment: It is a marginal fluvially dominated environment with minor coal swamps. The occurrence of thin limestone beds with foraminifera, ostracods, and crinoid fragments shows that short marine transgressions periodically flooded the area.

Source rock potential: Probably poor for oil since the Rotliegendes volcanism and/or depth of burial-temperature increase may have led to overcooking. No studies have been carried out in the Danish region.

Reservoir potential: Limited reservoirs in form of porous sandstones may be expected.

Sealing potential: The series is probably not sealed, being overlain by the Rotliegendes. The Carboniferous shale beds will possibly be able to act as seals.

3.2 Permian

By Fritz Lyngsie Jacobsen & Jørgen Gutzon Larsen

In North-West Europe two mega-basins began their development during Late Carboniferous to Early Permian: The South Permian Basin stretching from eastern England into Poland , and the North Permian Basin reaching from Scotland into Denmark. These two basins were separated by the Mid North Sea High and the Ringkøbing-Fyn High which came into existance early in Permian. The initial phase of subsidence was accompanied by extensive subaerial volcanism. This was followed by a period of oxidation and erosion under desert conditions and deposition of redbeds and sabkha sediments in the two Permian basins (fig. 19). These rocks are included in the Rotliegendes Group as originally established by Werner (1786). Continuous subsidence and transgression of the sea, but with a restricted connection to the ocean, lead to the formation of the evaporites of the Zechstein Group.

Rotliegendes Group

Autunian

Type section: For the present being the P-1 well, 10541-10865' b.KB may suffice as a reference for the Rotliegendes volcanics and underlying sediments belonging to the Autunian stage. However, it should be noted that this correlation is based purely on lithostratigraphical evidence.

Thickness: The volcanic rocks and interbedded sediments form a 99 m thick pile in the P-1 well, but in all other wells of the Danish off shore sector, the base of the volcanic rocks has not been penetrated. Therefore only minimum thicknesses of 44 m in B-1, 148 m in W-1, 71 m in Q-1 can be given. The underlying sediments in P-1 well comprises 33 m of redbrown sandstone, siltstone, claystone, and marlstone (Bertelsen 1978).

Lithology: The lithology is summarized in fig. 18. The volcanic sequences are classified as lava flows with interbedded agglomerates, tuffs and detrital sediments. The lava flows are generally a few metres in thickness or less, may be of the pahoehoe type, but flows up to 7 m in thickness occur. Presumably some of the 'agglomerates' noted in the mudlog may originate from scoriaceous or vesicular top zones. The cores and cuttings indicate, together with the log data, especially gamma ray, the predominance of basalts; but more differentiated rocks occur in the P-1 and W-1 wells. From the latter well these rocks are described as andesites and rhyolites (mudlog). They may occur as lava flows and pyroclastic beds. Most of the rocks look rather oxidized and they are often cut by secondary veins. The interbedded sediments are mostly (silty) claystone but a 28 m thick metamorphosed limestone occurs in W-1.

Log charactetistic: The volcanic rocks are characterized by cyclic variations in the sonic velocity, and

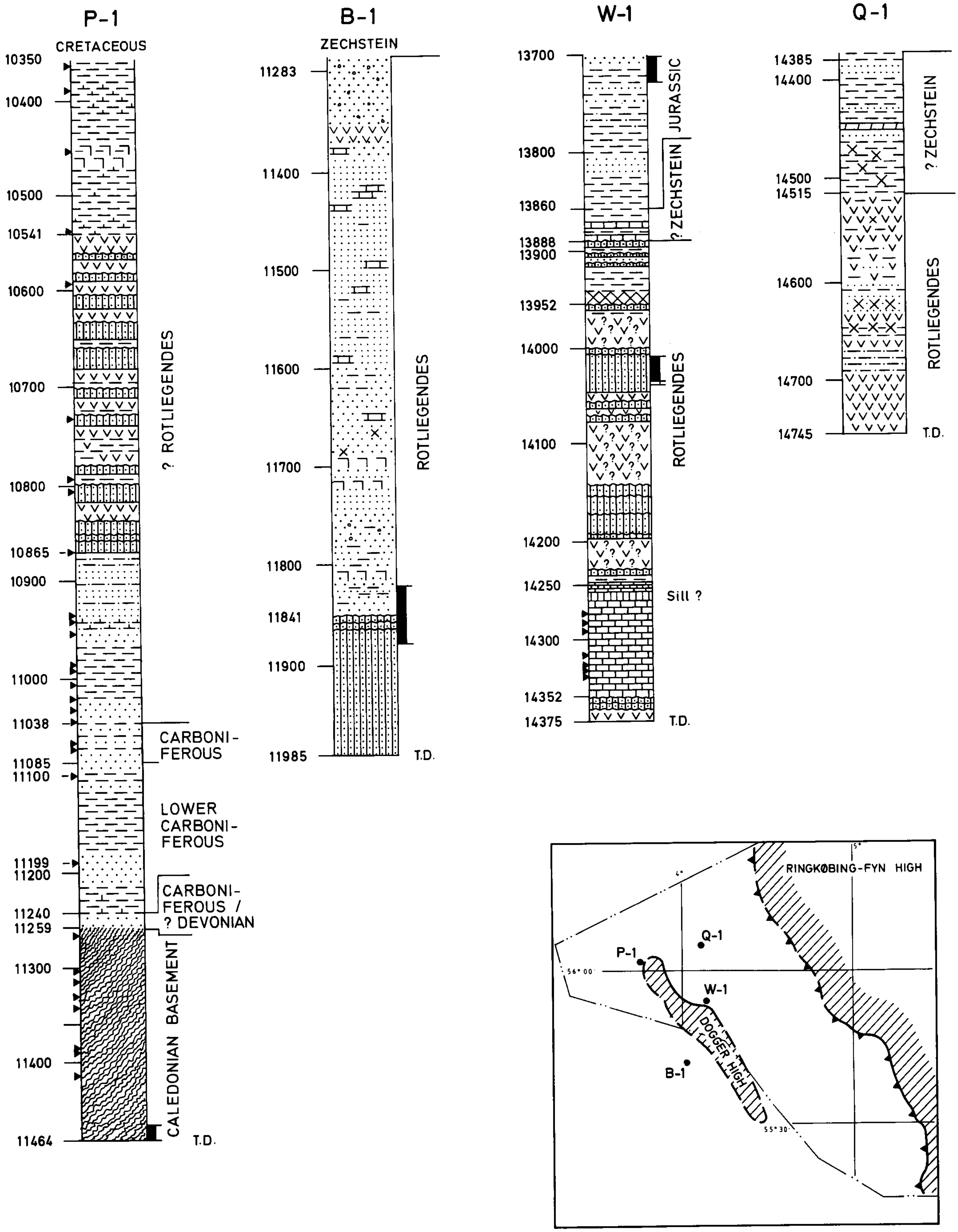


Fig. 18: Lithological profiles of the Rotliegendes deposits. For legend, see fig. 3.

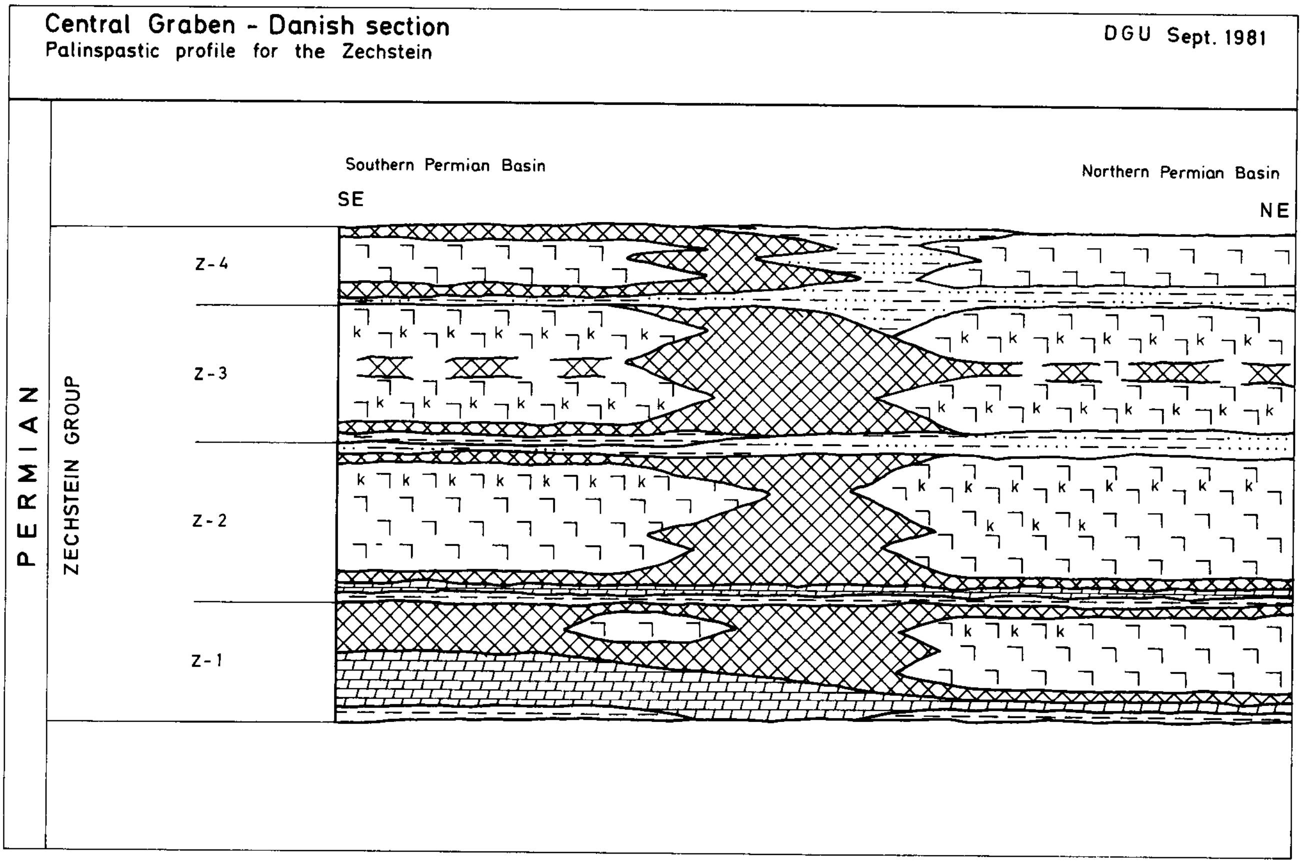


Fig. 19: Palinspastic profile of the Zechstein deposits. For legend, see fig. 3.

by formation density logs with high values in the massive besaltic lava flows, and lower values in the interbedded deposits or porous top zones. The gamma ray intensity is variable but generally relatively low especially in the massive basalt lava flow. Massive lava flows with high gamma ray intensities and lower densities may be rhyolites. The lithologies of the B-1, W-1, Q-1, and P-1 wells based on the geophysical logs and the mudlog are shown in fig. 18. The differentiated rock types are not indicated as they await more detailed examination. They form a smaller portion of the massive flows, but could be more frequent among the intrabasaltic deposits.

Geological age: At present radiometric age determinations have been performed on the B-1 well, giving 212 +/- 14 Ma (K/Ar by Larsen 1972) and on the W-1 well, where a large spread is observed, 89-230 Ma (Geological Dating Services). This age is regarded as updated, due to metamorphism, and the volcanics are overlain by Upper Permian sediments. Permian volcanic rocks also occur in the North Permian Basin, i.e. in the D-1 well, dated to 237 +/- 16 Ma; the C-1 well, 281 +/- 8 Ma (Larsen 1972, Rasmussen 1974); the L-1 well overlain by marginal Zechstein deposits; and the 2/7-2 well of the Norwegian sector (Dixon et al. 1981). Unfortunately the ages of the volcanic rocks recorded within the Central Graben (P-1, Q-1, W-1) are uncertain as they are not overlain by dated, typical Zechstein sediments (see fig. 18). In this connection it should be mentioned that Triassic(?) and Jurassic volcanics are known from the triple junction between the Viking Graben and the Moray Firth Basin (Woodhall & Knox 1979).

Petrography: So far only a few petrographic descriptions are available. Dixon et al. (1981) recorded plagioclase and scattered clinopyroxene and altered olivine phenocrysts in the B-1 basalts, which are similar to those of the C-1 and D-1 well of the North Permian Basin. Altered plagioclase phenocrysts occur in the cored basalt of W-1. Rhyolites have only been described from the R-1, associated with the Horn Graben. The secondary minerals of the basalts include among others: calcite, anhydrite, epidote, chlorite, serpentine, haematite, goethite, and quartz, possibly originating from the thermal rise associated with the volcanism.

Chemical analyses of the basalts of B-1 show that they can be classified as transitional olivine tholeiites grading into hawaiites, typical for the Permian volcanism north of the variscian fold belt. In contrast the younger volcanic rocks in the region appear to be more alkaline: the ?Middle Triassic - Middle Jurassic, alkaline basalts of the east Moray Firth Basin (Woodhall & Knox 1979); the Permian - Middle Jurassic alkaline dykes of Sunnhordland, West Norway (Faerseth et al. 1976); the nephelinitic lavas of the Egersund Basin east of the Viking Graben (Dixon et al. 1981); and the Lower Cretaceous phonolites, leucite bearing lavas and trachytes of Zuidwal-1 in North-West Holland (Cottencon et al. 1975). Alkaline basalts are, however, also known from the initial Permian volcanism in the Oslo Graben.

Extension: The extension and thickness of the (?)Rotliegendes volcanics within the Danish Central Graben have not been mapped due to scarcity of data. A palinspastic profile for the Rotliegendes Group is given in fig. 17. Volcanic rocks presumably cover the floor of the Central Graben and the Horns Graben, as shown by the deepest wells (B-1, P-1, Q-1, W-1, and R-1). Volcanic rocks have been reached north and south of the Ringkøbing-Fyn High (C-1, D-1, L-1, and in Rødby-2 and Rødekro-1 respectively), but neither on the high itself nor in the Danish Subbasin east of the C-1 well. In the deepest parts of the subbasin, however, no well has penetrated the Zechstein salt. Restricted areas with Permian volcanic rocks occur in the British, Norwegian, and German sectors adjacent to the westernmost Danish sector. The present distribution presumably represents down faulted remnants of a much larger cover, which was eroded away before the Zechstein submergence. It is likely that volcanic rocks have been preserved in the Graben zones and in the basins which were associated with the volcanism, i.e. the Oslo-Bamble-Horn Graben system and/or the North and South Permian Basins. It is unknown whether the initial formation of the Central Graben was associated with volcanism.

Saxonian

Type section: The B-1 well at 11283-11841' b.KB is chosen as reference well for the Rotliegendes sediments; however, it should be noted that these sediments may be contemporaneous with the volcanism in other areas.

Rotliegendes sediments: Most data on the Rotliegendes sediments originate from southern North Sea and the North German Basin (Ziegler 1981 and Marie 1976). They consist of desert sand and sabkha- to playa-type deposits. Degradation of the Variscian foldbelt to the south caused influx of fanglomerates and braided stream (wadi) deposits along the southern margin of the basin. The desert sand dune deposits in the southern part of the basin are the main reservoirs of the Rotliegendes gas play. In the centre of the basin, sabkha shales and evaporites were deposited in thicknesses above 1000 m (North Germany) to 300 m (eastern part of the British sector). Along the northern boundary of the basin, a basal conglomerate, overlain by red shales, siltstone and thin sandstones, forms a marginal facies derived from the Ringkøbing-Fyn High.

Rotliegendes sediments reach about 100-200 m in the Norwegian-Danish Basin. The sediments show a general coarsening towards the north and northeast, in agreement with data from the British sector, pointing towards a northern source area.

In the Danish wells of the Central Graben Rotliegendes sediments are only identified with certainty in the B-1 well (Rasmussen 1974), where silty sandstone with thin beds of evaporites are underlain by dated Permian volcanics and overlain by Zechstein evaporites.

In the W-1, Q-1, and P-1 wells, the typical basinal Zechstein Group is missing (fig. 18), and it is not certain whether the shaly facies with dolomite, anhydrite and rock salt belongs to Rotliegendes or to a Zechstein (or younger, ?Triassic) marginal facies shown in fig. 18. Intercalations of volcanic material near the top of the Rotliegendes sediments (B-1) indicate that the volcanism was active until the end of Rotliegendes time.

Zechstein Group

The Zechstein Group, as originally established by Werner (1786) for the South Permian Basin, has been subdivided into four cyclic series (Richter-Bernburg 1955). This division can also be applied to the North Permian Basin in the Danish North Sea sector (fig. 19). At present, however, it is not possible to make a certain stratigraphical correlation to the Central Graben area.

Type section: No type well can be given for the Danish Central Graben area due to the fact that drilling here penetrates only few metres into cap rock, or just into the rock salt below. The nearby B-1 well, with a marginal facies relation to the South Permian Basin, and the D-1 well, representing a basinal facies of the North Permian Basin, are used as reference sections for the structural high and deeper sections of the Central Graben respectively.

Thickness: The thickness of the Zechstein Group within the Central Graben is poorly known, due to halokinesis, to the scarcity of deep wells, and to uncertain stratigraphy above the ?Rotliegendes volcanics in wells P-1, Q-1, and W-1 (see the interpretation in fig. 19). Furthermore, seismic evidence to characterize the Zechstein deposits has not yet been evaluated. For these reasons, thicknesses of zero to several km (in the salt diapirs) are expected.

Lithology and distribution: The lithology of the Zechstein Group varies in accordance with distance to land: the Ringkøbing-Fyn High, Dogger High and Mid North Sea High are fringed by sabkha sediments and lagoonal evaporites dominated by limestone, dolomite, and anhydrite, as in B-1 and L-1 outside the Graben. These marginal deposits grade into the thick basinal facies dominated by rock salt with the basal kupferschiefer, and interbedded with salt, clay, dolomite, anhydrite, and K-Mg salt forming up to four evaporite cycles. Zechstein deposits have not yet been identified with certainty by the wells on the structural highs in the central part of the Danish Central Graben nor by seismic methods in the deeper parts here. Rocks of the marginal facies presumably frame the salt deposits in the northern and southern part of the Graben where the thick salt deposits have formed salt domes and diapirs.

In the idealized profile of the evaporites (fig. 19) in the eastern part of the North Sea, a tentative lithostratigraphic correlation is given. To the south, there is a well established succession controlled by data from several wells. To the northeast, the profile is based on the Danish D-1 well and the Norwegian 17/4-1 well. The differing evolution of the four cycles of evaporites in the two mega-basins is shown: in the South Permian Basin, Z-2 is the major cycle, and in the North Permian Basin, both Z-1 and Z-2 and partly Z-3 are major cycles and Z-4 subordinate.

3.3 Triassic

By Finn Jacobsen

Deposition during the Triassic continued in the basinal areas developed during the Permian, but in Early Triassic the highs were also gradually covered by sediments. The pattern of sedimentation in the two mega-basins is analogous to that of the Rotliegendes,

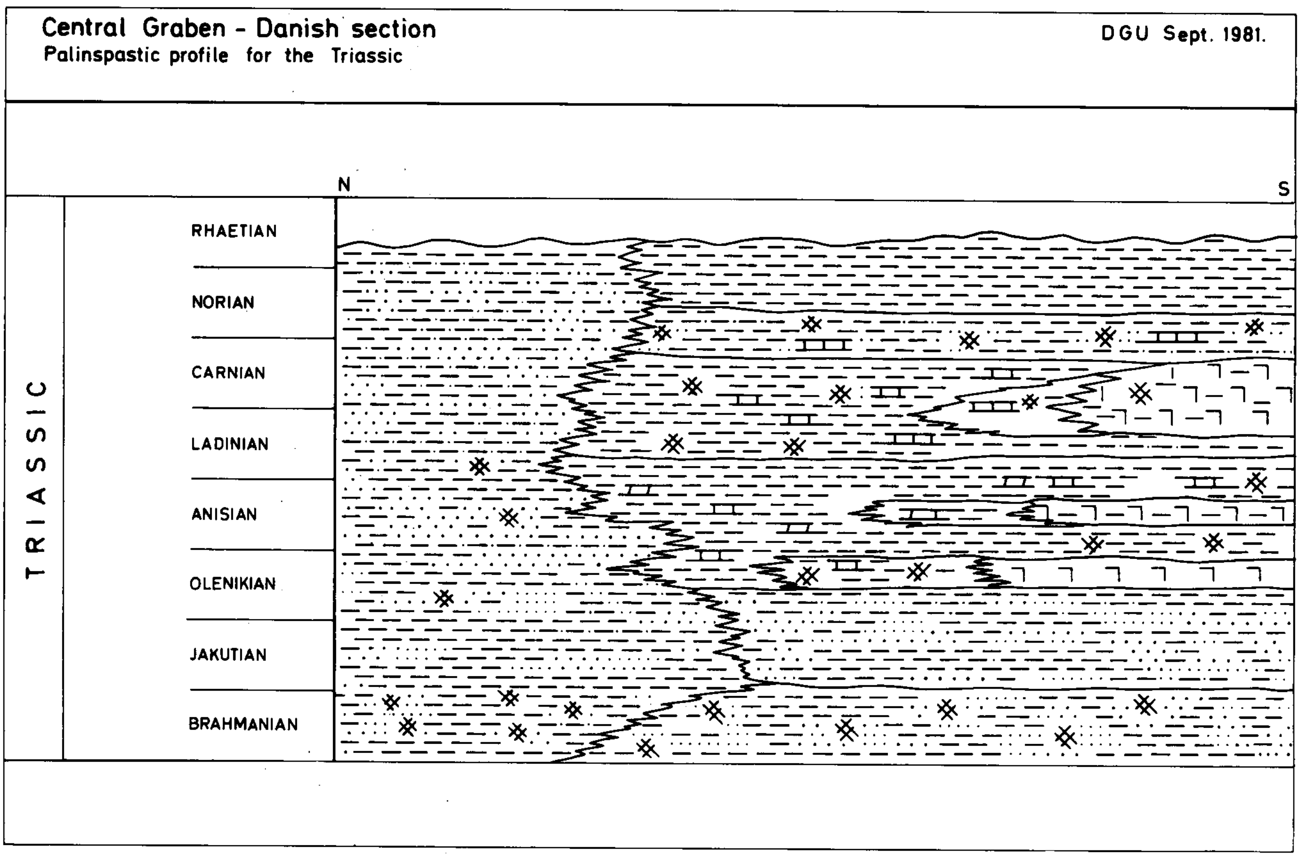


Fig. 20: Palinspastic profile of the Triassic deposits. For legend, see fig. 3.

i.e. with a pronounced, more coarse-grained clastic infill in the northern basin (fig. 20). The Triassic represents a regressive period in the North Sea area, with dominant continental sedimentation of sandstone, shale, and evaporites in red bed facies. Strong subsidence is recorded in the center of the Danish Subbasin with more than 5000 m Triassic sediments, and in the Horn Graben with approximately 3000 m. In the Danish Central Graben the Triassic has not yet been mapped, but thicknesses of about 2000 m or more are expected locally.

Bacton Group Rhys 1974

The Bacton Group was defined by Rhys (1974) as the sequence of red beds, with a relatively low content of anhydrite and carbonate, forming the lowermost unit of the Triassic series in the Southern North Sea Basin.

The Group consists of a lower pelitic formation, the Bunter Shale, and an upper arenaceous formation, the Bunter Sandstone. A tentative subdivision based on the wire line logs is proposed for the Danish Central Graben area.

Type section: Conoco Group 49/21-2 well, British North Sea sector (see Bertelsen 1980). Here the thickness is 571 m.

Reference sections: The Formation is found only incompletely developed in the B-1 (9990-10190' b.KB) and U-1 (14651-16045' b.KB) wells.

In the Q-1 well the section from 13921' to 14385' may represent the Bacton Group, but it seems more reasonable to refer the section to the Smith Bank Formation, described by Deegan & Scull (1977). This Formation is not treated in the present publication.

Thickness: The contact with the underlying Zechstein is only found in the B-1 well. The thickness here is 51 m, but the Formation seems to be incomplete due to erosion of the uppermost part.

The uppermost part of the Formation is reached in the U-1 well. The thickness here is more than 425 m. Seismic evaluation in the southern part of Central Graben indicates greater thicknesses near the highs.

Lithology: The Formation is dominated by red brown to brown, occasionally silty, anhydritic, and calcareous claystone with minor silt- and sandstone beds.

Due to the general lack of sandstone, it has not been feasible to divide the Group, based on lithology.

Log characteristics: The Formation is characterized by very uniform log motifs indicating laminated clay/siltstone. The sandstone beds show distinct log readings.

A tentative subdivision of the Group in the U-1 well is attempted from the log motifs. The very uniform log motif below the base of a sandstone bed at 4672.6 m may correspond to the Bunter Shale Formation. This log motif is similar to the log motifs in Danish onshore wells.

The more irregular log motif in the section from 4437 m to 4672.6 m is more or less similar to the Bunter Sandstone Formation in the type section and may therefore represent this formation.

Boundaries: The upper boundary is placed at the base of the overlying evaporites. The lower boundary is placed at the top of the uppermost massive Zechstein anhydrite bed. Both boundaries are distinctive on the log pattern.

Distribution: The Group is known only from two wells (B-1 and U-1) in the southern part of the Danish Central Graben. As seen from the seismic evaluation, the Group is present in this part. In the middle and northern part of Danish Central Graben, the Triassic cannot be deliniated on the seismic profiles and the occurrence of the Triassic is therefore undeterminable. To the north the Group may pass into the Smith Bank Formation in the Q-1 well (fig. 20).

Geological age: No biostratigraphical data are available but the sequence can probably be referred to the Scythian Series (Bertelsen 1980).

Depositional environment: The Group is considered to have been deposited in supratidal and continental (alluvial) environments that are placed on a supposed extensive and flat continental plain fringing the northern margin of the southern mega-basin.

The low sand content recorded is explained by the distal position of the area in relation to the main source area, which is believed to have been situated to the north. Some material may have originated in the suggested positive area, which has been exposed to erosion during the Late Carboniferous and Permian periods.

Source rock potential: Probably poor, but this has not yet been studied.

Reservoir potential: Poor due to the thin deposits of the sand beds. In areas around highs, sand beds may be thicker.

Sealing potential: The Formation itself may have a fair sealing potential, while the overlying evaporites may even have a better one.

Dowsing Dolomitic Formation Rhys (1974)

The Formation was established by Rhys (1974) on the basis of the relative importance of dolomite. The Central Graben area is slightly influenced only by the Muschelkalk transgression. Therefore the lithostratigraphy proposed may not fit the northern part of the Central Graben.

Type section: Conoco Group 49/21-2 well, British North Sea sector (Bertelsen 1980). The thickness here is 92 m.

Reference well: Danish U-1 well (13074-14651' b.KB).

Thickness: The total Formation is represented in the U-1 well only, where the thickness is 480 m. In areas with halokinetic movements (the A-2 well), the top of the Triassic, including the uppermost Dowsing Dolomitic Formation, is eroded. The thicknesses in A-2 and V-1 are 333 m and 175 m respectively.

Lithology: The Formation consists of variegated, dark reddish-brown, grey and grey green calcareous (dolomitic) claystone with two members of halite surrounded by, and with interbeds of, light grey to greenish grey marlstone/claystone and anhydrite. Subordinate siltstone beds may occur. The halite members grade laterally into marlstone and calcareous grey claystone (the V-1 well).

Subdivision: In the U-1 well it is possible to subdivide the Formation into five members:
Unnamed member: 13074-13443' b.KB (3956-4069 m b.MSL): Claystone, dark reddish-brown, occ. grey to green and grey, calcareous (dolomitic). Some anhydrite. Marlstone increasing downward.
Unnamed member: 13443-13528' b.KB (4069-4095 m b.MSL): Marlstone or claystone, very calcareous (dolomitic), light grey to grey to greenish interbedded with anhydrite.
Muschelkalk Halite Member: 13528-13728' b.KB (4095-4156 m b.MSL): Rock salt, clear, colourless interbedded with marl- and claystone, light grey.
Unnamed member: 13728-14478' b.KB (4156-4385 m b.MSL): Claystone, silty, dark reddish-brown and variegated greyish, calcareous, interbedded with thin greyish to reddish silt beds and marlstone. At the base, claystone and marlstone, light grey, anhydrite and some dolomite.
Röt Halite Member: 14478-14651' b.KB (4385-4436 m b.MSL): Rock salt, clear, colourless to orange with small content of limestone and marlstone. A potash-rich bed is found in this member.

Log characteristics: The evaporite sections are characterized by rather uniform straight sonic velocity and gamma ray readings, occasionally with distinct peaks reflecting dolomitic and potash-rich beds.

The variable lithology of claystone, siltstone, marlstone, and anhydrite in the other members is seen as rather irregular serrate log motifs.

Boundaries: The lower boundary of the Formation is placed at the base of the Röt Halite Member. The upper boundary of the formation is indistinct and is based mainly on changes in the carbonate content.

Distribution: Hitherto the Formation has been drilled only in the southern part of the Danish Central Graben area, so the northern limit is unknown. Northwards the formation probably grades (laterally) into parts of the Smith Bank Formation. Facies changes in the halite members towards marly/anhydritic equivalent beds suggest limitation of the northern outlines of Röt and Muschelkalk salt (fig. 20).

Geological age: The upper halite member has been dated to Anisian by means of palynology in the A-2 and V-1 well (Bertelsen 1975). The lower halite member is considered more or less contemporaneous with the Röt deposits of Poland and Germany, Late Olenikian-Early Anisian (Bertelsen 1975).

Depositional environment: The deposits were formed under conditions which were highly controlled by the connection to the Tethys Sea. The southern megabasin most probably had the character of one large lagoonal area. The lowermost deposits represent a transgressive period in the Triassic. Due to a high degree of evaporation and a low influx of fresh water, salinity was high. In the centres of the basin, halites were precipitated in playa-like conditions, while large-scale coastal sabkhas seem to have fringed the basin in which anhydrite claystone was deposited.

Continental plain deposits of fluvial lacustrine origin replaced the salt lake. A new transgression resulted in the Muschelkalk Halite Member. In the Central Graben area, brackish conditions with deposition of dolomitic mudstone have prevailed.

As seen from the fossils and sediment characteristics, the climatic conditions during the deposition of the Formation seem to have been arid to semi-arid and rather hot.

Source rock potential: Probably poor, but this has not yet been studied.

Reservoir potential: Poor.

Sealing potential: Fair.

Dudgeon Saliferous Formation Rhys 1974

The Formation was defined by Rhys (1974) in the Southern North Sea Basin to comprise the halite-bearing claystone sequence found between the dolomitic claystone of the Dowsing Dolomitic Formation (below) and the mainly anhydritic claystone of the Triton Anhydritic Formation (above). The lithological development in the Danish area during the Middle and Late Triassic is comparable to that of the southern North Sea, and therefore the formation name of Rhys (1974) has been adopted for this sequence.

Type section: Conoco Group 49/21-2 well, British North Sea sector. The thickness is 276 m.

Reference section: Danish U-l well, 12159-12074' b.KB.

Thickness: The Formation has been drilled only in the southern area. It is penetrated in the U-l well (279 m) and drilled in the O-l (166 m) and M-8 (131 m) wells.

Lithology: The Formation consists of silty, dark reddish-brown, brick-red and grey-green calcareous, and sporadically anhydritic claystone.

A prominent halite member is present in the O-l and M-8 wells, whereas equivalent deposits of mainly grey coloured marlstone, dolomite, and anhydrite are encountered in the more marginally situated U-l well.

Subdivision: In the U-l well the Formation can be subdivided into four members:
Unnamed member: 12159-12428' b.KB (3678-3760 m b.MSL): Claystone, brick-red to dark reddish-brown, calcareous and anhydritic. In the lower part, reddish marlstone.
Unnamed member: 12428-12550' b.KB (3760-3797 m b.MSL): Claystone, silty, dark reddish-brown to violet. Varying content of calcareous material, but commonly anhydritic.
Unnamed member: 12550-12674' b.KB (3797-3825 m b.MSL): Marlstone, light grey to greenish-grey, rare reddish/violet dolomitic and anhydritic. (This evaporite-dominated member is proposed to be the marginal equivalent to the Keuper Halite Member described by Rhys (1974)).
Unnamed member: 12674-13074' b.KB (3835-3957 m b.MSL): Claystone, occasionally siltstone, reddish-brown, grey or greenish-grey, micaceous and generally calcareous. Minor beds of limestone may occur.

Log characteristics: The variable lithology of claystone, siltstone, anhydrite, and limestone is reflected as irregular serrate log motifs, but in the different wells with a variable evaporite and carbonate content.

Boundaries: The lower boundary is indistinct but defined by the higher gamma ray and lower sonic velocity in this formation, probably due to the lower carbonate content than in the formation below.

The upper boundary in the type well and the O-1 well is defined as the top of the Keuper Halite Member, which is easily recognizable on the gamma ray and sonic velocity. In wells with imperfectly developed or missing halite beds (e.g. U-1), the upper boundary is set at the shift from high sonic velocities below to lower above.

Distribution: The Formation is drilled only in the southern area. Here the Keuper Halite is more restricted in the lateral extension than the above-mentioned Röt and Muschelkalk halites (fig. 20).

In the middle and northern part of the Central Graben, neither well nor seismic data are available.

Geological age: The occurrence of the miospores *Ovalipollis ovalis* and *Porcellispora longdonensis* indicates a Carnian age of the Formation (Bertelsen 1975).

Depositional environment: The lithology indicates continental sabkha deposits. Soluble salts are precipitated in the basin center, whereas the less soluble sulphates and carbonates are found in fringing facies belts.

Source rock potential: Probably poor, but this has not yet been studied.

Reservoir potential: Poor.

Sealing potential: Fair.

Triton Anhydritic Formation Rhys 1974

The Triton Anhydritic Formation was proposed by Rhys (1974) for the uppermost, anhydrite bearing part of the Triassic red bed sequence of the Southern North Sea Basin. The Formation is recognizable without any difficulties in the Danish sector.

Type section: Conoco Group 49/21-2 well, British North Sea sector. The thickness is here 214 m.

Reference section: The Danish O-1 well, 10401-11193' b.KB (Bertelsen 1980). The formation is also fully drilled in the U-1 and M-8 wells (see chapter 8).

Thickness: The recorded thicknesses of the Formation vary from approximately 230-280 m to zero - due to erosion on halokinetic structures.

Lithology: A threefold division of the Formation can be made with :

A lower section of dark reddish-brown and grey-green, slightly calcareous to non-calcareous, micaceous claystone with some anhydrite.

A middle section (Keuper Anhydritic Member) of grey to reddish-brown variegated or brick-red, calcareous, and anhydrite-bearing claystone with some silt- and marlstone intercalations.

An upper section of calcareous, light grey, greenish-grey, or reddish marlstone and claystone.

Log characteristics: The log motif shows a separate configuration. The Middle Keuper Anhydritic Member is characterized by many distinct peaks on the sonic velocity, density and resistivity responses corresponding to the individual anhydrite layers.

Boundaries: The lower boundary is described above (see Dudgeon Saliferous Formation). The upper boundary is placed at the basal claystone of the Winterton Formation and it is very distinct in the gamma ray and sonic velocity readings.

Distribution: Unknown, only drilled in the southern part of the area. Seismic evaluation is not yet possible in the northern and middle parts.

Geological age: No palynomorphs or other microfossils have been recovered from the Formation in the Danish sector. It is, however, thought to correspond to the upper part of the Oddesund Formation (Bertelsen 1980), which means a Carnian to Early Norian age.

Depositional environment: The predominant environment seems to have changed from distal flood plains through continental coastal sabkha to distal flood plains.

Source rock potential: Investigations of one well section (M-8) indicate no source rock potential for oil.

Reservoir potential: Poor.

Sealing potential: Fair-good because of the anhydrite content.

Winterton Formation Rhys 1974

The Formation is proposed by Rhys (1974) to replace the North Sea 'Rhaetic' because this sequence is not compatible with the British onshore Rhaetic, where the grey to green shales are missing from its lower part.

Contrary to the definition by Bertelsen (1980) of the Winterton Formation in the Central Graben, the Formation includes only the pure claystone in the present report. This revision was made because of the lithological similarity between the upper part of the former Winterton Formation and the overlying Early Jurassic section.

The Rhaetic Sandstone Member recognized in the Southern North Sea Basin is not present in the Danish wells. Seismic events, however, seem to indicate sandy layers in connection with erosional areas.

Type section: Conoco Group 49/21-2 well, British North Sea sector. The thickness here is 76 m.

Reference section: The Danish 0-1 well, 10347-10401' b.KB (Bertelsen 1980). The Formation is drilled also in the U-1 and M-8 wells (see chapter 8).

Thickness: Only small thicknesses are recorded. In the O-1 well the thickness is 16 m, in the U-1 well 12 m, and in the M-8 well 7 m. The above-mentioned wells are all placed on structures. It is therefore possible that greater thicknesses may be found in other parts of the area.

Lithology: Dark grey to black grey, non-calcareous, relatively pure, sticky claystone.

Log characteristics: The log motif is characterized by very low sonic velocity and high gamma ray readings, which separate the Formation from the ones above and below.

Boundaries: The lower and upper boundaries are defined at the base and top of the pure and soft claystone (see the log characteristics).

Distribution: The distribution may be as in the underlying formation (fig. 20). Due to the halokinetic movements the Formation may be absent locally.

Geological age: An ostracod assemblage of *Emphasia* ssp. (Michelsen 1978a) and the presence of *Ricciisporites tuberculatus* miospores indicate a Rhaetian age (Bertelsen 1978).

Depositional environment: The deposits are interpreted as being formed as the underlying sediments. A very characteristic kaoline content in the Formation seems to indicate weathering. This corresponds to the seismic information about the relatively elevated position of the drilled Formation and the probability of more sandy members along these areas.

Source rock potential: Data insufficient for an evaluation.

Reservoir potential: Poor in the claystone. May be fair to good in the sandy members.

Sealing potential: Probably poor due to the sandy sections.

3.4 Jurassic

By Jens Ole Koch, Lise Holm & Olaf Michelsen

During Early Jurassic time, deposition continued in the basinal areas occupied by Triassic sedimentation. The Danish Central Graben subsided strongly and more than 4000 m of sediments were deposited during Jurassic time (fig. 14). North of the area the thickness seems less than 2000 m and, in the Norwegian-Danish Basin, approximately 1200 m. The rythm of sedimentation corresponds closely to what is known from adjacent areas in the Northwest European sedimentary region.

During the Early Jurassic, relatively uniform marine claystone series, the Fjerritslev Formation, were deposited all over the North Sea region, including the main part of the highs. Large areas were uplifted and eroded during the Mid Cimmerian phase (fig. 23), accompanied by a general eustatic lowering of the sea level. During the Middle Jurassic period, deltaic or fluvial conditions prevailed in the main part of the North Sea, and coal-bearing sand bodies, the J-2 Unit, were deposited. During the Late Jurassic a general subsidence took place, but more restricted areas were transgressed by the sea than in the Early Jurassic. Thick marine claystone series (the J-3 and J-4 Units) were deposited in the main part of the basin. Near marginal highs, only minor sand bodies (the W-1 Unit) were laid down. The Late Jurassic is a period of main subsidence for the Central Graben. Figs. 21 and 23 show the distribution of Jurassic sediments.

Fjerritslev Formation Larsen 1966 and Michelsen 1978b

The Formation was established by Larsen (1966) and later revised and subdivided by Michelsen (1978b) into four members (F-I, F-II, F-III, and F-IV). The type well (Fjerritslev-2) is situated in northern Jylland in the northwestern part of the Danish Subbasin, in which the Formation is widely distributed.

On the basis of the assumption that the Lower Jurassic claystones present in the Central Graben and in the Danish Subbasin originally formed one coherent sediment body, which during the Mid Cimmerian tectonic episode was differentially eroded (see e.g. Michelsen 1978b, fig. 12), the name Fjerritslev Formation has also been assigned to the Lower Jurassic claystones in the Danish Central Graben.

The Fjerritslev Formation corresponds to the Dunlin Unit in the northern North Sea (Deegan & Scull 1977).

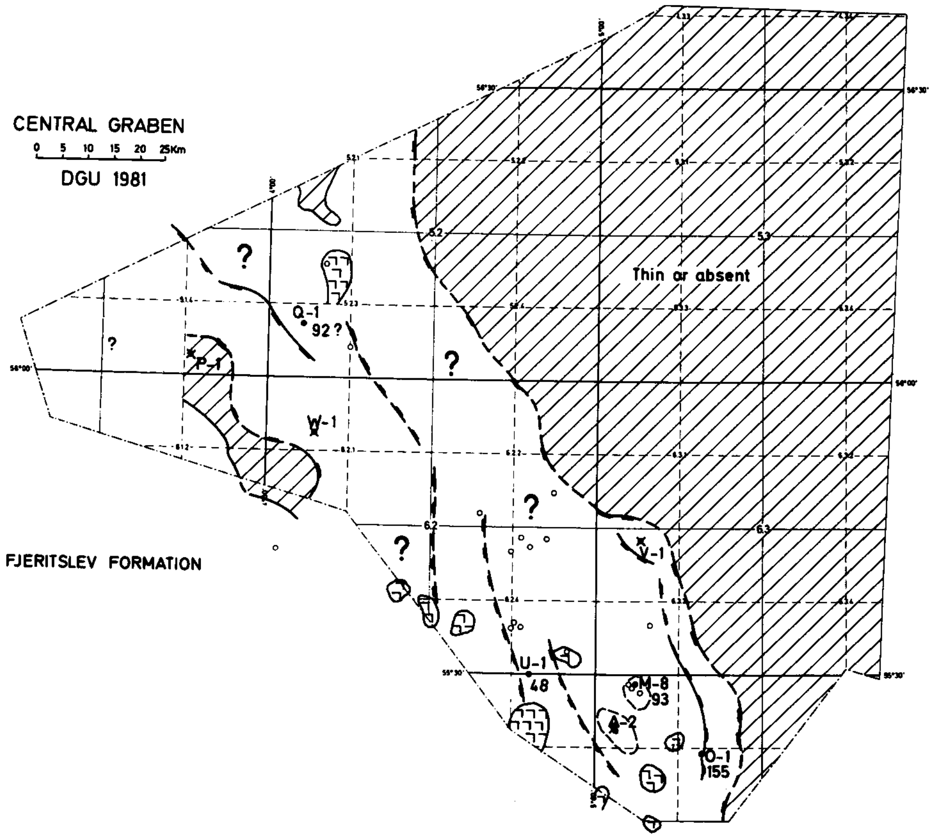
Type section: The Fjerritslev-2 well in northern Jylland from 1314 m to 2225 m b.MSL.

Reference sections: The O-1, U-1, and M-8 wells in the southern part of the Danish Central Graben (see chapter 8).

Thickness: The thickness of the Fjerritslev Formation is 155 m (O-1), 93 m (M-8), and 48 m (U-1).

In the Danish Central Graben, the Formation is rather thin in comparison to the type section. This is partly due to Mid Cimmerian erosion of the top of the Formation. The O-1 and M-8 wells are situated on domes induced by the flow of Triassic salt (or shale), but the thickness of the Fjerritslev Formation is probably unaffected by halokinesis. In the U-1 well the thickness might be slightly reduced due to Early Jurassic halokinesis in the underlying Zechstein salt pillow.

Lithology: The Fjerritslev Formation consists mainly



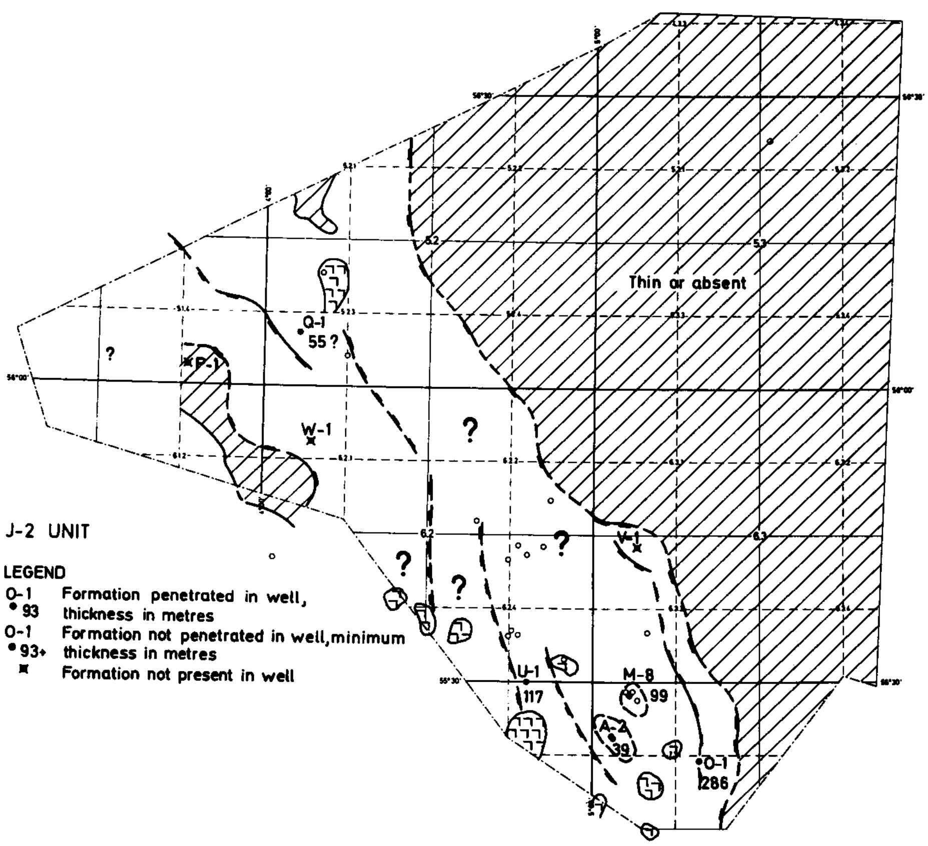
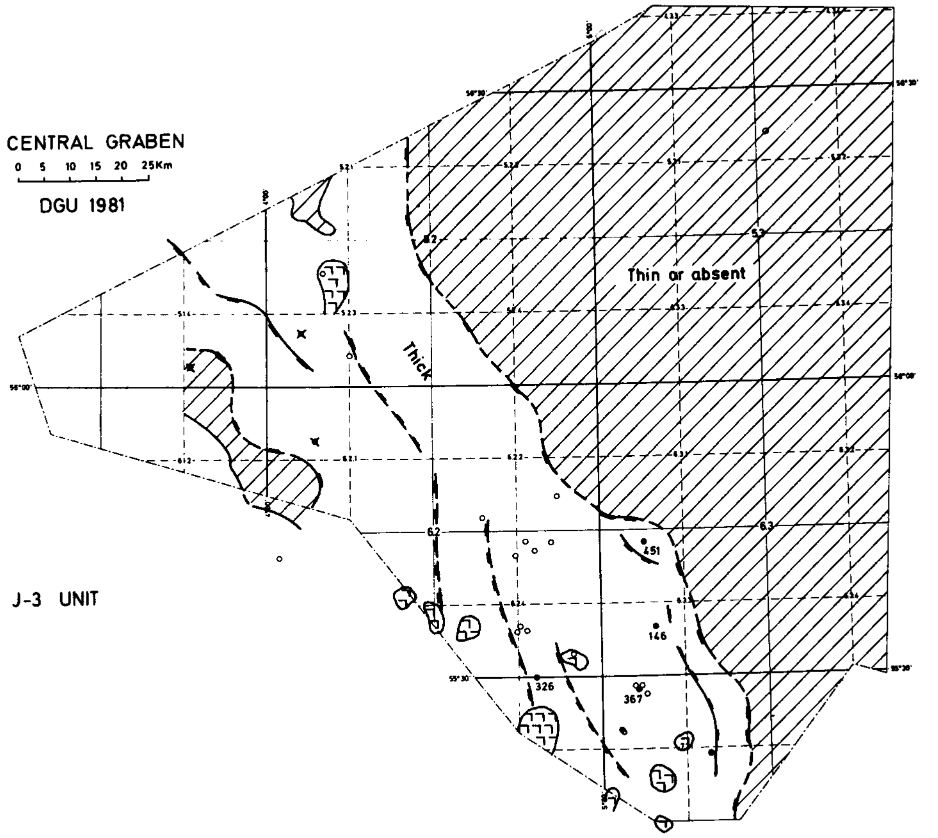


Fig. 21: Distribution and thickness of a) the Fjerritslev Formation and b) the J-2 Unit.



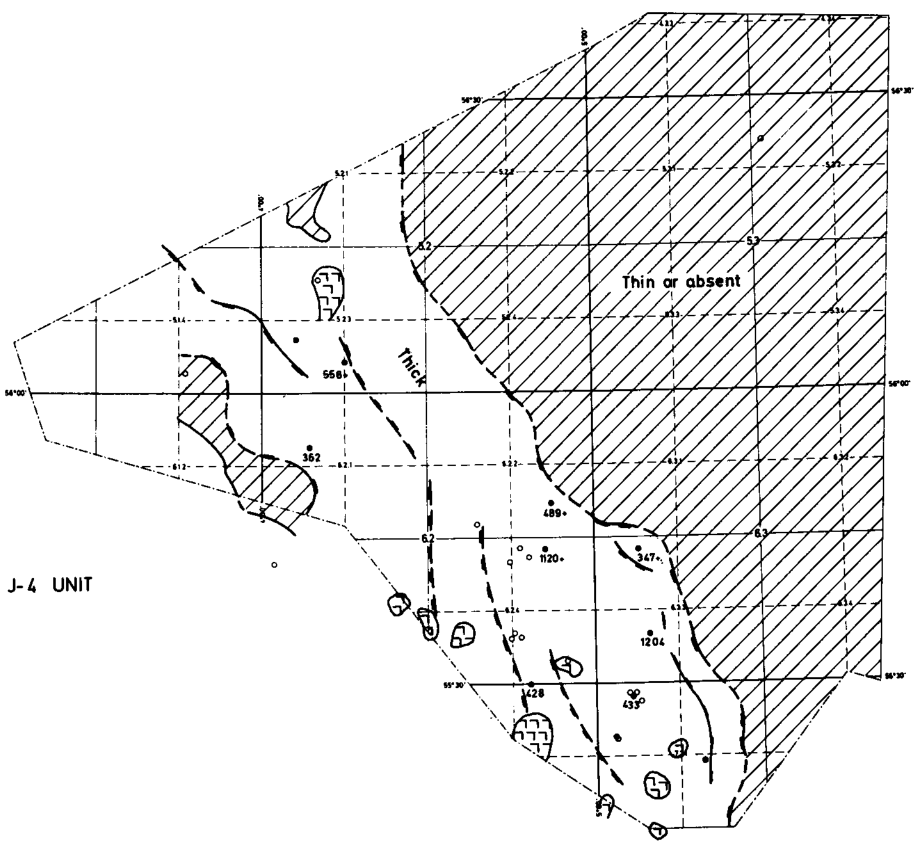


Fig. 22: Distribution and thickness of the a) J-3 Unit and b) the J-4 Unit. – For legend, see fig. 21.

of hard, dark grey, slightly calcareous, silty claystones with pyrite, becoming fissile in places. Downwards the claystones are interbedded with thin, light grey, silty, calcareous claystones and soft marlstones.

Subdivision: On the basis of log correlations the Formation tentatively has been subdivided into three members.

Log characteristics: The Formation is characterized by regular high-level gamma ray readings and a relatively regular sonic velocity pattern. Downwards the sonic velocity becomes more irregular, reflecting more abundant occurrence of thin soft marls and hard silty claystones.

Boundaries: The lower boundary of the Fjerritslev Formation is the contact to the underlying Winterton Formation which is characterized by a very low sonic velocity and a high gamma radiation. This boundary is thus marked by breaks both in the gamma ray and the sonic velocity.

The Fjerritslev Formation is unconformably overlain by the sandy J-2 Unit which is characterized by a low, irregular gamma radiation and a very irregular sonic velocity. Thus the upper boundary of the Fjerritslev Formation also is well marked by characteristic breaks in the sonic velocity as well as in the gamma ray response.

Distribution: Seismic mapping of reflectors below the 'Late Cimmerian unconformity' has not yet been completed. However, the Fjerritslev Formation has been penetrated by the O-1, U-1, and M-8 wells which are situated in the southern part of the Danish sector (fig. 21).

On the basis of log correlations and datings of the three drilled sections, it is suggested that the Fjerritslev Formation has been differentially eroded during the Mid Cimmerian tectonic episode and that it is unconformably superposed by the J-2 Unit. The Fjerritslev Formation is thickest near the border faults of the Ringkøbing-Fyn High (east of the O-1 well) which probably was syn-sedimentarily active. In the A-2, W-1, Q-1, and V-1 wells, which are situated on domal features in the Central Graben, the Fjerritslev Formation has been almost entirely eroded or possibly never deposited. Hence, on some of these domal features the J-2 Unit directly overlies Triassic or older rocks.

The remaining wells in the Danish sector, either

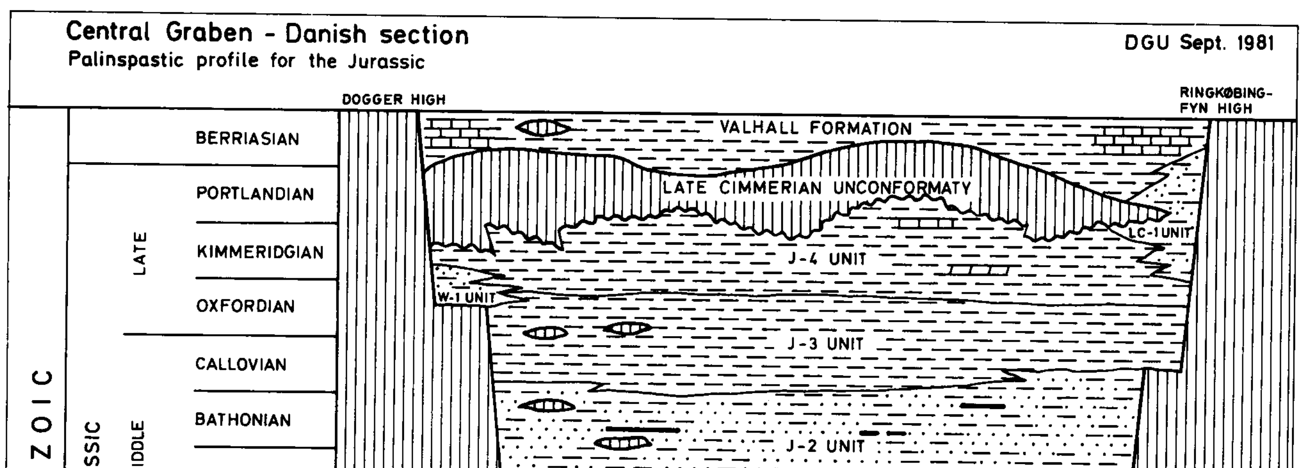


Fig. 23: Palinspastic profile of Jurassic deposits. For legend, see fig. 3.

meet the salt well above the level of the Fjerritslev Formation or they have not been drilled deep enough to reach it. However, seismic mapping and the presence of the Fjerritslev Formation on top of three domal structures in the southern part suggests that the Formation is present in between the domes, at least in the southern part of the Danish sector of the Central Graben.

North of the Danish sector the Fjerritslev Formation was encountered in the Norwegian 7/9-1 well. This might indicate that the Formation may also be present in the northern part of the Danish sector between the domes.

Geological age: On the basis of ostracods and sporomorphs, the Formation is dated to the Hettangian-Sinemurian in the U-1 and O-1 wells (Michelsen 1978a) and to the Sinemurian-Lower Pliensbachian in the M-8 well.

The J-2 Unit unconformably overlies the Fjerritslev Formation. The two formations are separated by a Pliensbachian-Toarcian-Aalenian hiatus.

Depositional environment: The fine-grained sediments and flora/fauna content suggest that the Fjerritslev Formation was deposited by the settling out of suspension of clay and silt below wave-base in a marine water body.

The upwards decreasing content of silt- and marlstone beds points to a decreasing silt influx into the basin, or to an increasing distance to the basin margin. This might be a response either to the general Early Jurassic eustatic sea level rise or to differential subsidence of the Central Graben basin, or to a combined effect of both mechanisms.

It has been argued that the Fjerritslev Formation and the equivalent Dunlin Unit (Deegan & Scull 1977, p. 14) should have been deposited in the pro-delta and delta-front environments of the overlying Haldager and Brent Formations. This model, however, implies that the two formations were deposited at the same time and in the same basin. This assumption appears to be erroneous because of the large hiatus between the two formations. It is more likely that the Fjerritslev Formation represents a calm influx of sediments into the subsiding basin during the Early Jurassic eustatic sea level rise, while the superposed Middle Jurassic J-2 Unit was deposited in response to the Mid Cimmerian tectonic episode.

Source rock potential: Investigations of the Fjerritslev Formation in the M-8 well have shown that the organic material is mainly marine, but some terrestial material does occur. The Formation is regarded as a good source rock for oil and gas. Further investigations are needed.

Reservoir potential: Poor, due to the lack of porous permeable intervals.

Sealing potential: Good.

J-2 Unit *(informal name)*

The J-2 Unit is penetrated by the A-1, O-1, M-8, and U-1 wells in the southern part of the Danish Central Graben, and probably also by the Q-1 well in the northern part. The Unit is equivalent to the Haldager Formation (Larsen 1966 and Michelsen 1978b) in the Danish Subbasin and to the Brent Unit (see Deegan & Scull 1977) in the northern North Sea.

Type section: The Danish O-1 well, 8901-9840' b.KB.

Reference sections: The M-8, U-1, and A-2 wells (see chapter 8).

Thickness: The thickness of the J-2 Unit is 286 m (O-1), 117 m (U-1), 99 m (M-8), 39 m (A-2), and 55 m (Q-1).

The above mentioned wells are all situated on domal structures. The influence of halokinesis on the thickness of the Unit has not yet been evaluated.

Lithology: The Unit consists of interbedded clean sandstones, claystones, and heterolithic sand-siltstones with coal seams.

The clean sandstones are white to grey-brown, hard to friable, fine- to medium-grained, slightly calcareous with fair primary porosity.

The heterolithic sand- and siltstones consist of interlaminated light sand- or siltstones and dark claystones, occasionally wavy bedded or showing slump, flame, and ball structures.

Usually the claystones are dark grey to black, moderately hard, slightly silty and sideritic.

The coal seams most frequently are 0.5 to 1 foot thick, but seams up to 8 feet occur. The coals are black and lignitic.

Subdivision: In most of these wells, two members can be recognized (see chapter 8). The lower member consists of interbedded thick sandstones, claystones, and heteroliths. The upper member comprises interbedded claystones, sandstones, heteroliths, and coal seams, in most wells showing an upward decreasing occurrence of sandstone beds.

Log characteristics: The J-2 Unit is characterized by very irregular sonic velocity and gamma ray patterns. The thick sandstone bodies separated by thin claystones or coal seams occasionally give the sonic velocity curve a blocky appearance.

Boundaries: The J-2 Unit rests unconformably on rocks of Triassic and Early Jurassic age. The lower boundary therefore tends to be relatively sharp, and it is usually easily recognized on the gamma ray and sonic velocity responses.

The upper boundary is usually recognized as a break in the sonic velocity due to the lower velocity of the overlying claystones of the J-3 Unit.

Distribution: Interpretation of seismic reflections below the Late Cimmerian unconformity has not yet been completed. The J-2 Unit is known from the sections presented in fig. 21. Nevertheless, it may possibly cover most of the Central Graben area.

Geological age: A Bajocian? age is indicated in the A-2 well, and the Unit is assigned to the Bathonian-Bajocian in the U-1 well on the basis of palynomorphs.

Depositional environment: The coal seams in the upper member were probably formed by autochthonous accumulation of plant material in a shallow water swamp environment in a warm, humid climate. The heterolithic nature of the silt- and claystones indicates regular fluctuations in flow regime, e.g. caused by deposition in the intertidal zone or by deposition from fluctuating river discharges.

Dipmeter analysis of sandbeds in the O-1 well shows a concentration of decreasing dip, with depth patterns centering around a dip axis of 215°. A secondary concentration is found with westerly to northerly dip directions.

It has been suggested by several authors (e.g. Ziegler 1978 and Eynon 1981) that the Middle Jurassic sedimentation in the Danish Central Graben was entirely continental, due to the Mid Cimmerian uplift of the volcanic centre in the triple junction between the Central Graben, Viking Graben, and the Moray Firth Basin. Skarpnes et al. (1980), however, suggest a marine connection through the Central Graben in Middle Bathonian time, and Ziegler (1981) has included a small Middle Jurassic marine basin in the southernmost part of the Central Graben.

On the basis of the available data it is difficult to tell whether the J-2 Unit was deposited in a fluvial valley-system, which now and then was invaded by the sea, or if the Unit was accumulated by progradation of a deltaic system into a marine basin. However, it does not appear to be unreasonable to apply the delta model, and consequently interpret the lower member as having been deposited as pro-delta clays and distributary mouthbar sands, while the upper member represents deposition in interdistributary bays and coastal swamps on the subaerial-intertidal deltaplain. Although the dipmeter analysis from the O-1 well most likely points to transport directions towards SW, it is still highly speculative whether the delta system advanced from the north to the south into the West Netherlands Basin, from the south to the north, or simply was spread from the margins into the central part of the Central Graben.

Source rock potential: The claystone beds from the M-8 well were examined in detail. They were found to contain algae-rich organic material which is favourable for oil formation, and the beds were classified as rich source rocks.

Reservoir potential: The J-2 Unit contains several up to 6 metre thick sand- and siltstone beds with good reservoir characteristics.

The sand- and siltstone intervals are listed in the reservoir data sheets along with log porosity evaluations. The log porosity varies between 4 and 45%, the average (chapter 9) being around 20%.

Most wells had gas shows in the J-2 Unit, and tests were performed in the M-8, and U-1 wells.

Sealing potential: Individual claystone beds might be quite impermeable, but the lateral extension is most likely limited. Generally the sealing potential is believed to be poor.

W-1 Unit *(informal name)*

Until now this Unit only has been penetrated by the Danish W-1 well, which is situated on the northeastern flank of the Dogger High. The Unit might be equivalent to the Piper Formation of Deegan & Scull (1977) from the Northern North Sea.

Type section: The Danish W-1 well, 13521-13860' b.KB.

Reference sections: None.

Thickness: 97 m (318') in the type well.

Lithology: The Unit consists of grey to white sandstones, minor siltstones, and conglomerates interbedded with dark grey claystones and heterolithic siltstones and claystones. The sandstones are grey to white, fine-grained, firm, in part friable, moderately sorted, moderately argillaceous, in part conglomeratic. They consist mainly of rounded to sub-angular grains of quartz but contain glauconite and are slightly carbonaceous and calcareous. Loose medium-grained sand beds of clear to milky quartz occur. The conglomerates comprise rounded granular clasts of milky chalcedony and quartz, some dolomitic and granitic clasts, and minor occurrences of light grey siltstone clasts in a medium-grained sand matrix. The interbedded claystones are light to dark grey, soft to firm, slightly silty, and occasionally grading into or interbedded with argillaceous siltstones, blocky to subfissile, slightly to moderate calcareous, micaceous, carbonaceous with traces of glauconite. The claystones and siltstones occasionally contain carbonized plant remains, pyrite, and large bivalves (*Ostrea* sp.).

Log characteristics: The W-1 Unit is characterized by a low gamma ray record and a relative regular sonic velocity pattern. The occurrence of thin claystones interbedded with thicker sandstones and conglomerates, or thin sandstones interbedded with thicker claystones, gives the gamma ray response a somewhat blocky appearance.

Boundaries: In the type section, the Unit rests unconformably on red-brown, probably Permian claystones and volcanics. Downwards the boundary has been defined by a shift to higher sonic velocities in the probably harder Permian rocks. The upper boundary is easily recognized in the type well, as strong breaks occur both in the gamma ray readings and in the sonic velocities because of the shift to the overlying radioactive and soft J-4 Unit.

Distribution: The Unit is known only from the W-1 well. Seismic mapping of the horizon has not yet been performed in the area. However, it is believed that the W-1 Unit is distributed along the northeastern margin of the Dogger High which most probably acted as the source area of the sandstones.

Geological age: No detailed biostratigraphical data are available at present. A completion log, provided by the concessionaires, states that the W-1 Unit and the overlying J-4 Unit span the chronostratigraphic interval Late Oxfordian - Early Kimmeridgian.

Depositional environment: The content of glauconite and bivalves (*Ostrea* sp.) suggests that the Unit was deposited in marine waters. A shallow marine coastal environment is the most likely possibility. The sandstones might represent barrier bars or other shallow marine coastal sand bodies, stacked on top of each other and interbedded with claystones representing more offshore or lagoonal sedimentation.

More detailed sedimentological information is needed for conclusive evidence.

Source rock potential: The claystones might serve as an intraformational source rock, but they contain terrestric plant remains and the net thickness is only approximately 20 metres. No detailed investigations have been performed.

Reservoir potential: Three major sandstone intervals occur in the W-1 Unit in the type section. The net sand thickness is approximately 67 m (219') with a neutron porosity of 12-15% (chapter 9). Two Formation Interval Tests were performed, but no conclusive calculations of the permeability can be made.

Sealing potential: Probably poor.

J-3 Unit *(informal name)*

This Unit is penetrated by the Danish A-2, G-1, M-8, O-1, and U-1 wells, and is probably present in the V-1 well. The Unit might be analogous with the Heather Formation of Deegan & Scull (1977) from the northern North Sea and parts of the central North Sea.

Type section: The Danish M-8 well, 8940-10143' b.KB.

Reference section: The Danish U-1 well, 9595-10665' b.KB.

Thickness: 367 m in the type section. This order of thickness is known from the wells penetrating the Unit. However, from seismic data the thickness is expected to be much greater in the Tail End Graben.

Lithology: Claystone, often slightly silty, dark grey, brownish-grey, grey, slightly calcareous, with micro-lignite, plant remains, and traces of pyrite. Siltstone, medium to coarse-grained, greyish-brown, and marlstone, light greyish-brown, occur subordinately.

Log characteristics: The J-3 Unit is characterized by a fairly constant high gamma ray response and low sonic velocity.

Subdivision: At the moment no subdivision has been carried out.

Boundaries: In the southern well sections, the J-3 Unit rests on the J-2 Unit. The lower boundary here is defined on the sonic log as a decrease in the velocity from the J-2 to the J-3 Unit.

The upper boundary is marked by an increase in the sonic velocity and a small decrease in the gamma ray response in the J-4 Unit. In the V-1 well, the Upper Jurassic sediments rest unconformably on Triassic rocks. The presence of a J-3 Unit here is proposed but the log-pattern is not typical.

Geological age: Based on ostracods and palynomorfs, the Unit is dated to Oxfordian and probably Callovian.

Depositional environment: The fine-grained nature of the J-3 Unit and the flora/fauna content suggests that the Unit was deposited by the settling out of suspension of clay and silt below wave base in a marine water body. The presence of siltstone and plant remains shows that the basin margin was not too far away. The open marine claystone of the J-3 Unit represents the condition that prevailed after the transgression which followed the Mid Cimmerian uplift.

Distribution: Seismic mapping of the internal reflectors in the Jurassic has not yet been carried out. Further, as the J-3 Unit is known only from few wells, all situated in the southern part of the Danish Central Graben, no accurate distribution can be mapped. However, based on the general regional pattern, the Unit is thought to be present in most parts of the Danish Central Graben basin (fig. 22).

In the Q-1 and W-1 wells, both situated on domal features, the J-3 Unit has been totally removed or never deposited, and the J-4 Unit directly overlies the J-2 Unit and the W-1 Unit respectively.

Source rock potential: Only the M-8 well has been investigated. The Unit is not a promising source rock for oil, due to an unfavourable type of organic matter. It might be a potential gas source rock. In M-8 the Unit is just within the zone of oil generation.

Reservoir potential: Poor, due to the absence of porous layers within the clay sequence.

Sealing potential: Good, due to the thick and homogeneous claystone sequence.

J-4 Unit *(informal name)*

The J-4 Unit is known from 13 wells in the Danish sector, of which 8 penetrated the Unit. It is equivalent to the Kimmeridge Clay Formation described by Deegan & Scull (1977) and known from most of the North Sea area.

Type section: In order to cover the main part of the Unit, two well sections have been established as type sections. The Danish G-1 well (8088-12037' b.KB) is the type well for the lower part of the Unit. The Danish E-1 well (9727-13403' b.KB) is the type well for the upper part.

Reference section: The Danish U-1 well, 8190-9595' b.KB.

Thickness: See below.

Lithology: Claystone, shaly, laminated, dark grey, slightly silty, calcareous, with mica, microlignite, and pyrite. The organic carbon content is normally high and of marine origin. Numerous thin lime- and dolostone beds are characteristic according to the gamma ray and sonic velocity responses. The uppermost part of the Unit is characterized by a highly radioactive shale.

Log characteristics: The J-4 Unit is characterized by a high gamma ray response and a low sonic velocity, often with many high velocity peaks. The uppermost part has a very high gamma response.

Subdivision: In one well (E-1) the uppermost part of the J-4 Unit has a very high radioactivity, but no formal subunits have at present been established for this interval.

Boundaries: The J-4 Unit rests in the main part of the Central Graben on the J-3 Unit, and the lower boundary is marked by an increase in sonic velocity and a small decrease in the gamma ray response. The upper boundary is an unconformity (the Late Cimmerian unconformity), normally overlain by Early Cretaceous sediments of varying age. The Cretaceous sediments normally have a higher sonic velocity and lower radioactivity than the J-4 Unit, so there are often strong log breaks at this boundary.

Geological age: The Unit ranges from Late Oxfordian to Portlandian in age.

Depositional environment: The fine-grained sediment, the flora/fauna, and the high organic content suggest that the J-4 Unit was deposited in a marine environment with high organic productivity and restricted bottom circulation, probably deeper shelf.

Distribution and thickness: Seismic mapping of the internal reflectors in the Jurassic sequence has not yet been carried out. A two way time to the Top Jurassic has been mapped, but no depth conversion has been made. This means that the regional depths and thicknesses mentioned below are only very approximate.

The J-4 Unit is present in most of the area (fig. 22). Only on salt structures and on structural highs is it likely to be absent. In the southern part of the Danish Central Graben, the thickness is several hundred metres and the Unit lies within the depth interval 2 1/2 to 5 kilometres, depending on its location in relation to the salt structures. The Unit is thinnest and situated highest on the structures, while in the rim-synclines it is thickest and deepest situated.

In the Tail End Graben the J-4 Unit reaches its greatest thickness. In the G-1 well, situated in the transition zone between the southern part of Central Graben and the Tail End Graben, the thickness is 1204 m .The thickness is expected to increase northwards in the Tail End Graben. Locally it might exceed two thousand metres. The depth to the top of the Unit is 3 kilometres in the southern part of the Tail End Graben, and the top dips to 4 kilometres towards the north.

In the areas north and south of the Dogger High, the depth to the Top Jurassic is generally from 3 to 4 kilometres and it can exceed 5 kilometres locally. The thickness of the J-4 Unit in these areas is not yet known.

Source rock potential: Investigations of the M-8 and I-1 sections have shown that the J-4 Unit must be regarded as the most important source rock for oil generation. It is potentially good in M-8, and rich to extremely rich in I-1. It is immature in M-8, but probably mature in the adjacent basinal areas of this structure. It is mature in I-1.

Reservoir potential: Generally poor, but hydrocarbon shows have been reported from the lime- and dolostone stringer, which thus might have reservoir characteristics.

Sealing potential: Good, due to the thick and homogeneous claystone sequence.

3.5 Early Cretaceous

By Jens Morten Hansen & Arne Buch

The Early Cretaceous sea primarily covered the same basinal regions as the Late Jurassic sea but, late in the Early Cretaceous the sea also covered Late Jurassic land masses. During Early Cretaceous time the topography of the North Sea region became gradually buried. The following major transgression comprises the transition Early/Late Cretaceous. At the Jurassic/Cretaceous transition, the Late Cimmerian unconformity is a significant feature (fig. 24), known from large parts of the North Sea region. The subsequent transgression and sedimentation of marine clay (the Valhall Formation), and marine sand (the LC-1 Unit), started late in Late Jurassic. Therefore, the formations described in the present chapter also comprise sediments of Late Jurassic age. Thicknesses of the Lower Cretaceous sediments are given in fig. 15.

LC-1 Unit *(informal name)*

The LC-1 Unit has been established in order to treat the Early Cretaceous - Late Jurassic sandstones in the V-1 well. These sandstones cannot be considered to be a part of any other formation known from the Central Graben, but they are probably equivalent to the Devil's Hole Formation (see Deegan & Scull 1977).

Type section: The Danish V-1 well, 8947-9462' b.KB.

Reference section: None at present.

Thickness: The Unit interfingers with other formations and comprises only sandstones, siltstones, carbonate-cemented siltstones (?marls), and marls. The total thickness of these sandstones, siltstones, and marly beds (excluding clay beds) is 61.5 m in V-1.

Lithology: Sand- and siltstones, silty sandstones, sandy siltstone, and sandy marl. It is grey to dark grey with thin subordinate grey to dark grey shales and clays. Calcareous and pyritic.

Log characteristics: The Unit is characterized by low gamma ray readings and very irregular sonic velocities.

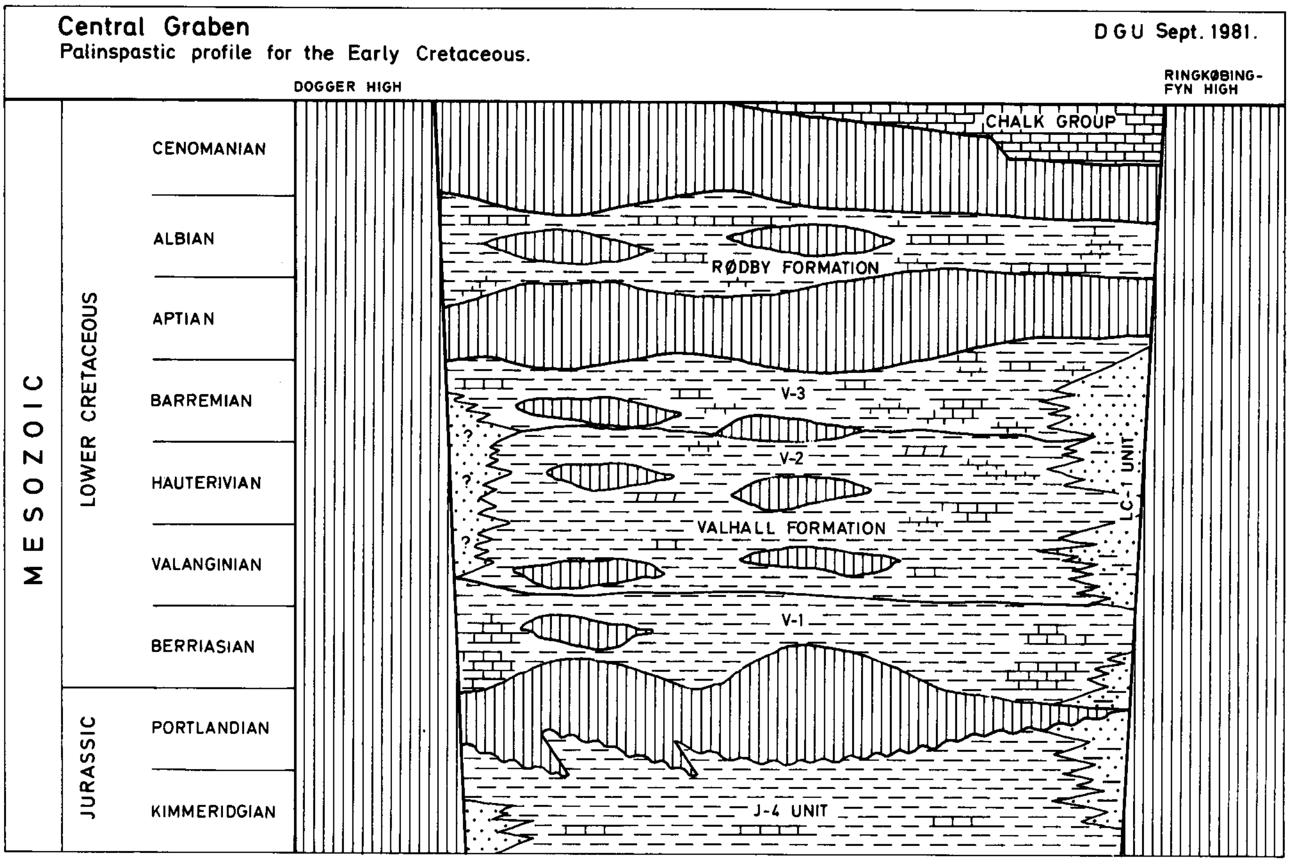


Fig. 24: Palinspastic profile of Early Cretaceous deposits. For legend, see fig. 3.

Boundaries: In the type section the boundaries are marked by a clear break in the gamma ray readings from high values in the Valhall Formation to lower values in the LC-1 Unit.

In the type well the LC-1 Unit is believed to interfinger with the J-4 Unit from 9114' to 9462' b.KB, where the lowermost sandstone beds occur.

Distribution: The LC-1 Unit is known only from the V-1 well, which is situated comparatively close to the southwestern margin of the East North Sea Block of the Ringkøbing-Fyn High. Consequently the distribution is speculative. However, the depositional environment of the Unit indicates, that it has been deposited along the southwestern margin of the Ringkøbing-Fyn High (fig. 24). There is no evidence for similar deposits along the northern and southern margins of the High, although such deposits might be present. The LC-1 Unit is analogous to the W-1 Unit east of the Dogger High (see chapter 3.4) as well as to the Devil's Hole Formation (Deegan & Scull 1977) in the British sector of the central North Sea.

Depositional environment: Palaeontological data indicate a deep-water, marine environment. The content of microfossils indicates that, to some extent, these have been reworked from older strata. A study of the dipmeter log indicates that the sandstones are neither cross-bedded nor channelled, but apparently form sand sheets which are parallel to the interbedded thin clay layers. This information indicates that the sand was transported by, and deposited from density currents, and not by water currents. Furthermore, the thickest sand sequence (8972-9114') shows a still steeper dip downhole. At the top of the sand sequence, the dip is about 10°, while at the bottom it is about 20°, which could indicate a 10° syn-sedimentary rotation of the fault block on which the Unit was deposited. The plunge of the dip is towards NE, i.e. towards the southwestern margin of the Ringkøbing-Fyn High.

These observations indicate that the LC-1 Unit was deposited from density currents originating from uplifted parts of the Ringkøbing-Fyn High during periods of rotational faulting within the Central Graben area.

Geological age: Biostratigraphical studies on foraminifera as well as on dinoflagellates indicate a Kimmeridgian to mainly Hauterivian/Barremian age for the sandstones.

Source rock potential: Poor.

Reservoir potential: No cores have been cut and no tests have been performed in the Unit. The neutron porosity varies between 3 and 35% and averages 20-25% in the upper thick sandstone.

Valhall Formation Deegan & Scull 1977

The Formation was established by Deegan & Scull (1977), who stated that the Formation is widely distributed in the central North Sea and is thin or absent only on structural highs. It may be equivalent to the Speeton Clay Formation in the southern North Sea and to the Vedsted Formation in the Norwegian-Danish Basin (Larsen 1966). The Devil's Hole Formation (British sector of the central North Sea) and the LC-1 Unit are time equivalent to the Formation. These, however, are fault-scarp controlled sandstone bodies.

Type section: Norwegian 2/11-1 well (southernmost part of the Norwegian sector) 2910-3540 m b.KB; thickness is 630 m.

Reference sections: The Formation is most completely developed in the following reference wells:

G-1 (7410- 8088' b.KB, thickness 207 m),
E-1 (8297- 9727' b.KB, thickness 436 m), and
I-1 (9508-11018' b.KB, thickness 459 m).

Thickness: The thicknesses listed above for the reference wells appear to be 'normal', i.e. from areas where Early Cretaceous halokinesis has not severely affected the accumulation of sediments.

As reflected by the seismic mapping, the 'Early Cretaceous Formations' (also including a minor series of the Upper Jurassic) exhibit a complex structural development which, particularily in the western and middle part of the Danish Central Graben, appears to have been controlled by syn-sedimentary growth of salt domes, faulting, and possibly also by shale flow in underlying sediments. Hence, the maximum thicknesses of the Early Cretaceous formations (mainly the Valhall Formation) are obtained in rim-synclines to salt domes and in the downwarped side of the Tail End Graben. The seismic thickness may locally exceed 700 m and possibly reach 1200 m (fig. 15). However, the Formation has not been drilled in any of these areas.

Lithology: In the type well the Formation is a soft, grey, calcareous mudstone, which grades into a marl. The colour may be light grey to reddish-grey. In other Norwegian wells, mudstones dominate. In the Danish sector, grey and dark grey mudstones and shales predominate, but abundant limestones, marls, and siltstone beds may occur. Generally speaking, siltstones are most abundant in the lower part, while calcareous beds are most abundant in the upper part. In addition to the grey mudstones, greenish and reddish mudstones, shales, and calcareous beds may occur mainly in the upper part.

Log characteristics: On the basis of logs, the Formation can be divided into three members: Valhall-1, 2, and 3. The lower member (Valhall-1) has a comparatively low gamma ray reading and correspondingly a comparatively high sonic velocity. The middle member (Valhall-2) has the highest gamma ray and the lowest sonic velocity of the Formation and it also exhibits the most regular log pattern of the Formation.

The upper member (Valhall-3) shows a more irregular pattern than the lower and middle members. These log characteristics may indicate an alternation between shales and siltstones in Valhall-1, a comparatively clean mudstone in Valhall-2, and a mixture of mudstone, shales, siltstones and marls in Valhall-3.

Boundaries: The boundaries to the underlying J-4 Unit as well as to the overlying Rødby Formation are generally difficult to distinguish on the basis of log motifs alone. However, depending on the magnitude of the hiatus between the J-4 Unit and the Valhall Formation (corresponding to the Late Cimmerian unconformity), the log breaks may be more or less easily distinguished.

In general the lower boundary is marked by a higher, sometimes much higher gamma ray reading, and higher sonic velocity in the J-4 Unit than in the Valhall Formation indicating a higher organic content and a harder rock type in the J-4 Unit.

The upper boundary between the Valhall and the Rødby Formations is also complicated by hiati. However, the gamma ray as well as the sonic velocity of the Rødby Formation are generally more irregular than those of the Valhall Formation.

Distribution: The Formation is widely distributed in the central North Sea, and it is also the most prominent part of the Lower Cretaceous in the Danish Central Graben (fig. 24). However, the Formation is generally thin or absent on structural highs, including salt domes, the Ringkøbing-Fyn High, and the Dogger High. In the northern part of the Danish Central Graben, the formation may also be thin or absent from areas with shale flow. However, on the basis of the available data it is not possible to conclude whether the Formation is present in W-1 and Q-1 - or not.

Geological age: In general the biostratigraphical datings indicate that both the upper and the lower boundaries of the Valhall Formation are diachronous (fig. 24).

Along the margin of the Ringkøbing-Fyn High, the Formation appears to be most completely developed and the Portlandian, Berriasian, Valanginian, Hauterivian, Barremian, and Lower Aptian stages appear to be represented. In the central part of the southern area, as well as in the northern part of the Danish sector (I-1), the Valhall Formation is more restricted in time, since the Portlandian, parts of the Berriasian and Barremian, as well as the Aptian are missing.

On the basis of the available data, it is impossible to conclude whether some of these hiati within the Early Cretaceous are of regional significance, or whether they are exclusively the result of syn-sedimentary halokinesis and faulting activity.

Depositional environment: Foraminiferal evidence suggests an open marine, neritic environment. Micropalaeontological, as well as palynological, evidence indicates predominantly aerobic bottom conditions, although thin strata with high preservation of sapropel may indicate occasional anaerobic conditions, at least in the sea bottom sediments.

Compared to the Late Jurassic formations the Valhall Formation is generally lighter in colour, indicating a larger terrigenous influx in relation to primary, marine production of organic material.

Several wells indicate that especially the Valhall-2 member is composed of numerous fining-upwards sequences with a thickness of the magnitude of 10-20'. This, together with the fact that the Valhall Formation contains a relatively large amount of terrigenous organic material, and microfossils reworked from older strata, may indicate that some parts of the Formation were formed by submarine fan accumulation, while other parts were formed by normal marine mud accumulation.

Source rock potential: The study of the organic matter of the Formation in a few wells indicates that it has no significant potential. In one well (V-1) the spore-coloration indicates that the organic matter is mature, which is unlikely to be the case in most of the other wells.

Reservoir potential: Generally poor. Intraformational porous zones belong to the LC-1 Unit or analogous yet undescribed formations.

Sealing potential: Good, due to the relatively thick and homogeneous mudstone series.

Rødby Formation Larsen 1966

The Rødby Formation was established by Larsen (1966) and named after the Rødby-1 well in south-eastern Denmark.

Type section: Danish Rødby-1 well, 459-469 m b.GL.

Reference sections: In the Danish Central Graben the Formation appears to be most completely developed in the following wells:

I-1 (9355-9508' b.KB, thickness 47 m) and
E-1 (8162-8297' b.KB, thickness 41 m).

Thickness: The Formation is generally thin, less than 50 m, typically 10-20 m, although local thickenings may occur as for instance in the I-1 and E-1 wells.

Lithology: The lithology of the Formation varies considerably from well to well, but the main characteristic feature is the occurrence of red to reddish-pink, yellowish brown, and occasionally also greenish marls, limestones or calcareous mudstones interbedded with grey clays and shales. In the I-1 well, greenish shales predominate in the lower 44 m of the Formation, while the upper 3 m consist of reddish limestone.

Log characteristics: The gamma ray readings are generally higher than in the overlying Chalk Group and lower than in the underlying Valhall Formation. The sonic velocity response varies greatly, although the sonic velocity generally is lower than in the Chalk Group and higher than in the Valhall Formation. These highly varying log responses reflect the heterogeneous nature of the Formation.

Boundaries: The upper boundary is usually marked by a slight break in the gamma ray and by the occurrence of reddish marls and shales below light grey limestones and marls.

The lower boundary is generally difficult to pinpoint on the basis of wireline logs alone, but it is defined by the occurrence of marls and limestones, or mudstones with reddish coloration above the boundary.

Distribution: The Formation is present in the Danish O-1, A-2, G-1, M-1, M-8, E-1, E-3, and I-1 wells. It is widely distributed in the central North Sea outside structural highs, in the southern part of the Danish-Norwegian Basin, and south of the Ringkøbing-Fyn High.

Geological age: On the basis of foraminiferal faunas, the Formation is invariably dated Albian and occasionally also referred to parts of the Aptian (? Late Aptian).

Depositional environment: Marine shelf.

Source rock potential: Poor. The content of organic material is too low to give any source rock potential.

Reservoir potential: Unknown.

Sealing potential: Fair, but this cannot yet be evaluated further.

3.6 Late Cretaceous and Danian limestone

By Kirsten Lieberkind, Inger Bang, Naja Mikkelsen & Erik Nygaard

At the termination of the Early Cretaceous period, the sea transgressed large earlier land areas. The transgression, the reduced relief of the continents, the generally diminished tectonic activity, the climatic change, and the enormous production of calcareous nannoplankton in the oceans profoundly changed the gross facies pattern in the North Sea region. The clastic sedimentation was replaced during Late Cre-

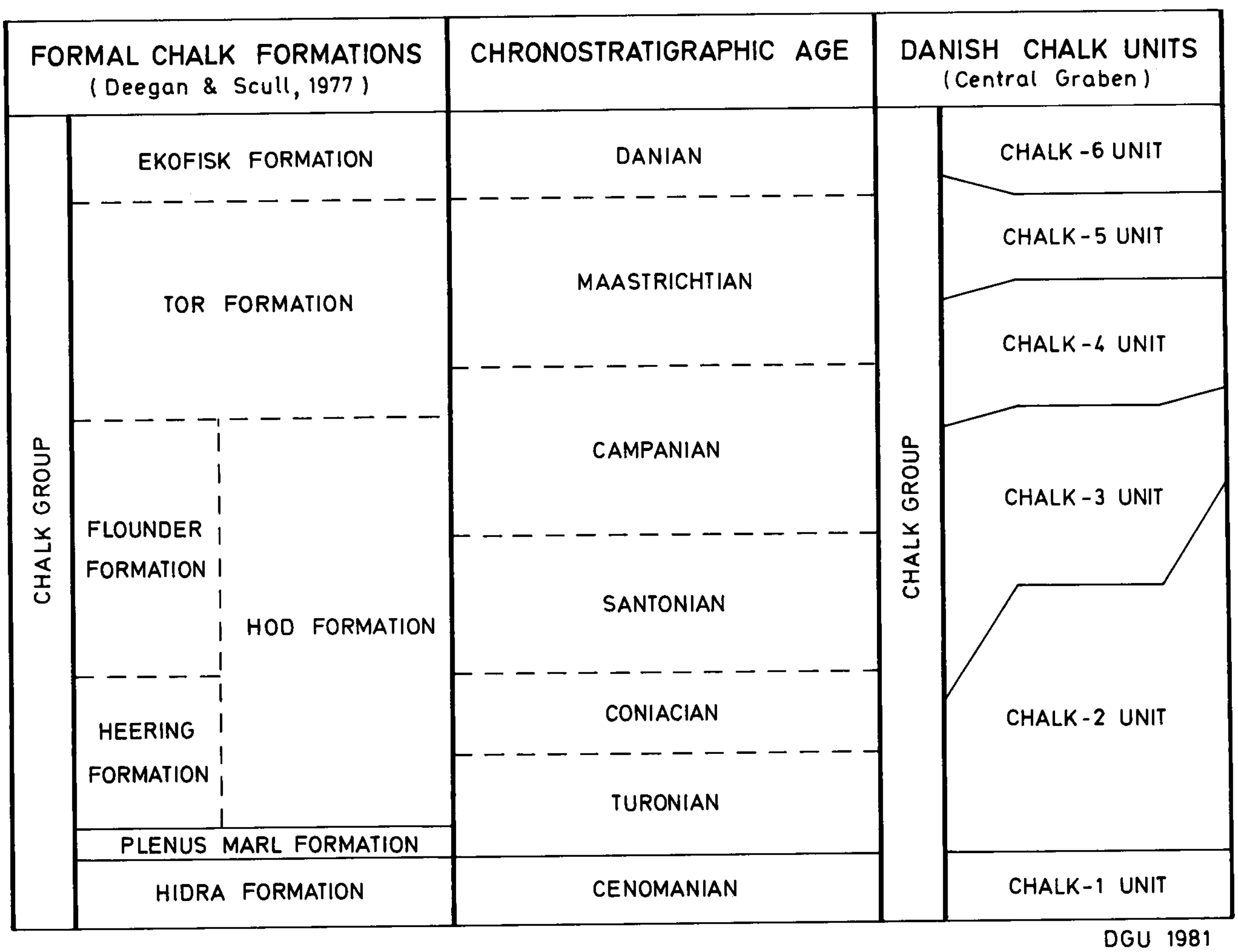


Fig. 25: A correlation between Chalk Units in the Danish Central Graben, the chronostratigraphic time table, and the formal Chalk Formations established by Deegan & Scull (1977) for the Northern and Central North Sea area.

taceous time by offshore relatively deep water carbonate sedimentation.

This resulted in the deposition of a chalk sequence reaching a thickness of 1-2 km in the Danish Subbasin and the North Sea area.

Chalk Group (Deegan & Scull 1977)

The chalk interval in the North Sea has been described as the Chalk Group by Deegan & Scull (1977).

Type section: The type area of the Chalk Group is the North Sea basin. A formal type section has not yet been established.

Reference sections: A thickness estimate based on a compilation of thicknesses of units from a number of wells in the type area suggests a thickness in the order of 1500 m.

A similar estimate for the Danish Central Graben is 1000 m, but the figures show a wide variety.

Lithology: The Chalk interval in the North Sea is represented by white limestone which shows wide variations in induration, colour, chert, clay, shale, and glauconite content. The term 'chalk' is used here as in Scholle (1977a).

Log characteristics: A number of formal chalk forma-

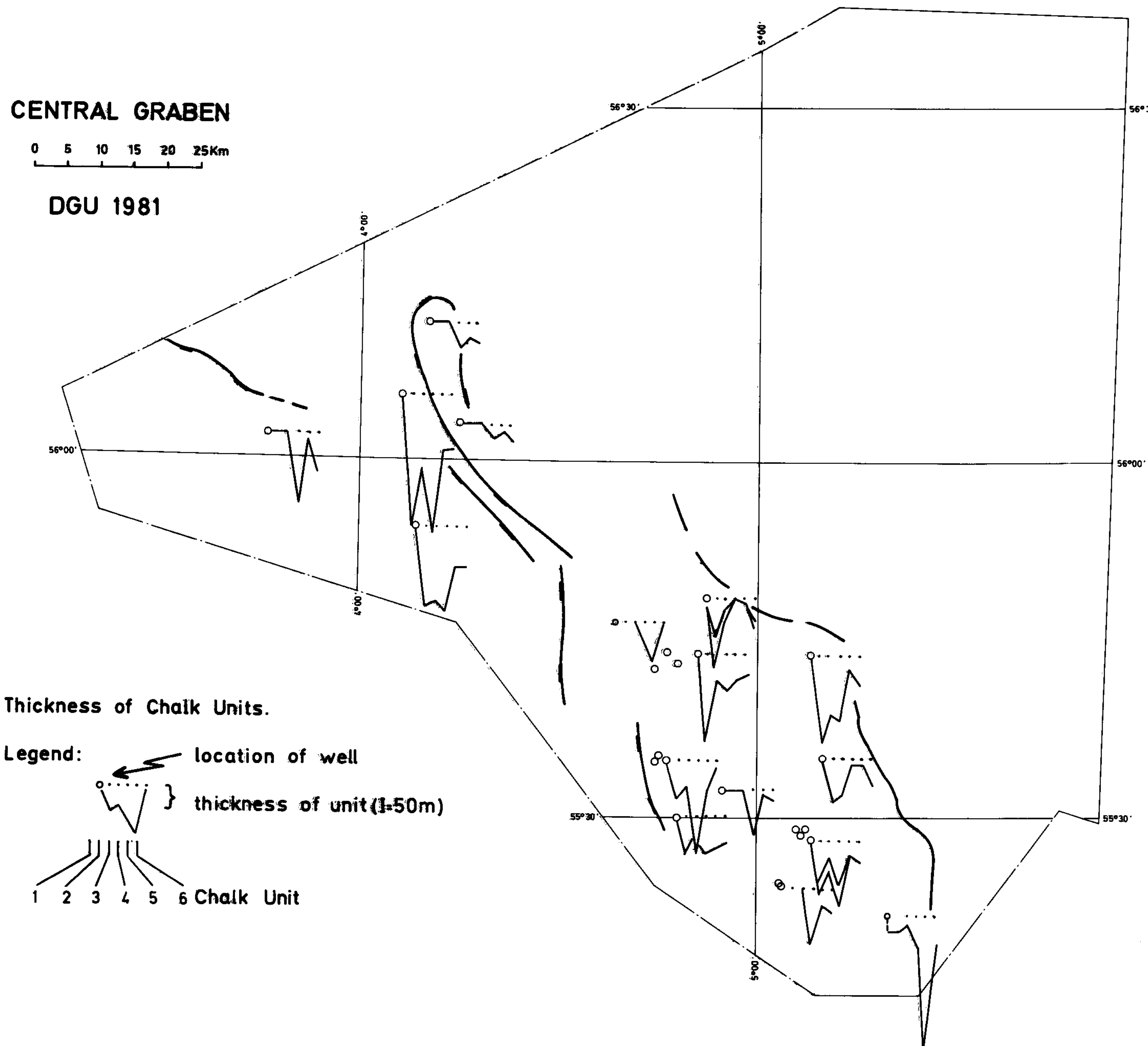


Fig. 26: a) Thicknesses of the six Chalk Units illustrating the development of the Chalk Group in relation to time and location in the Graben area.

tions have been established in the Norwegian sector by Deegan & Scull (1977).

In the Danish sector of the Central Graben, a total number of six log units have been established (see below). These units are mainly defined by gamma ray and sonic velocity responses. The units are labelled Chalk-1 Unit to Chalk-6 Unit, where the first represents the older sequence and the Chalk-6 Unit the younger.

The above mentioned units have not been given the rank of formal formations, as work remains before the definitions can be verified. The correlation between the formal chalk formations of Deegan & Scull (1977) and the proposed Danish chalk units (fig. 25) is therefore tentative.

Boundaries: The Chalk Group in the type area overlies the Early Cretaceous calcareous mudstone of the Cromer Knoll Group and, in the Danish sector, the Rødby Formation or older deposits. The boundary in both cases is only distinct if a hiatus is present.

The upper boundary to the overlying clastic sediments of the Tertiary may be sharp or gradual through the calcareous 'North Sea Marl' unit.

Distribution: The Group has a wide distribution in the central North Sea. It is present in the southern part of the Viking Graben, in southeast England, in the Dutch and German parts of the North Sea, and in the Danish onshore and offshore areas. At least a part of

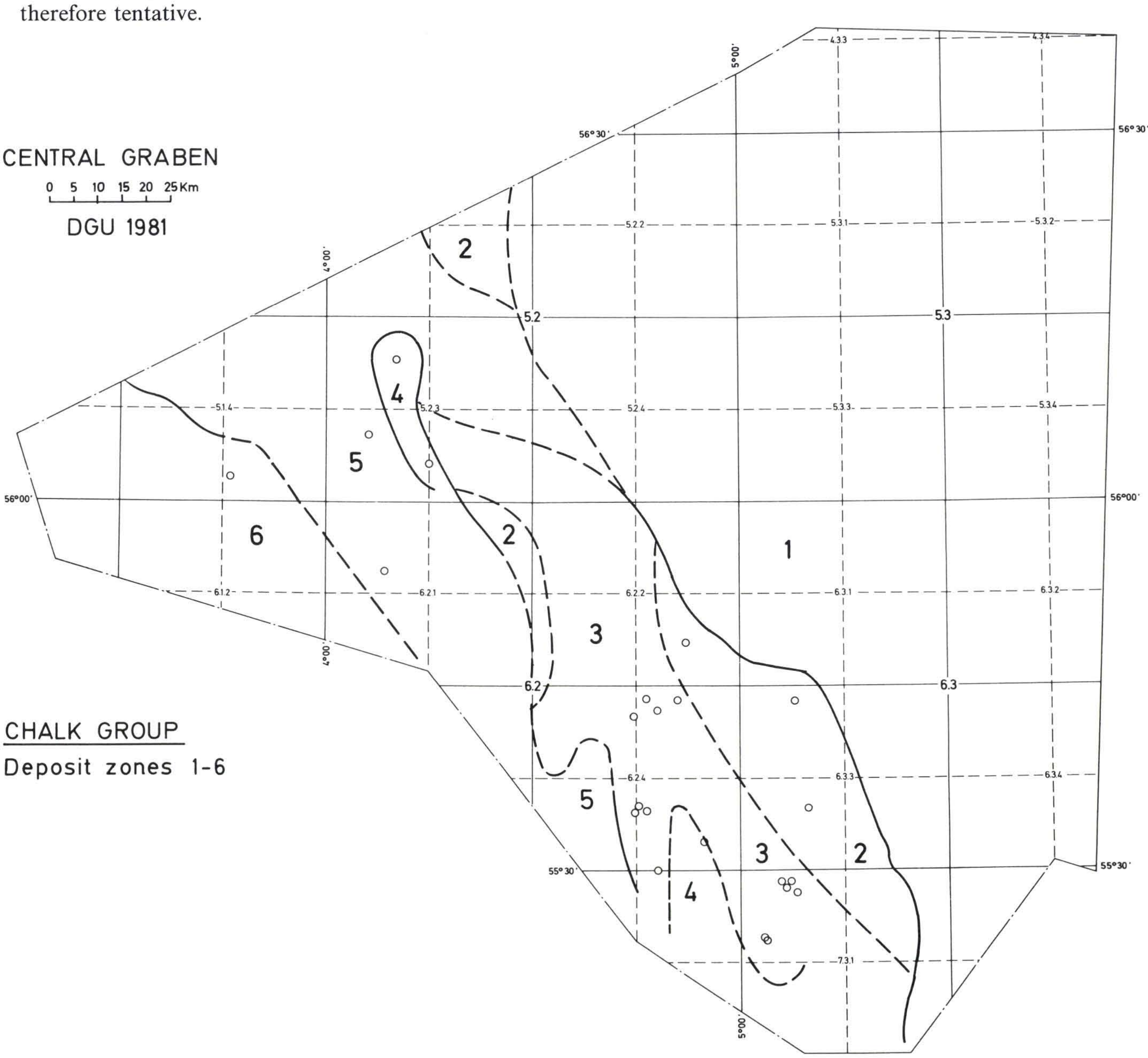


Fig. 26: b) Areal distribution of the chalk deposit zones 1 to 6 deduced from the chalk depositions.

the Chalk Group has been recognized in all wells from the Danish Central Graben. Based on the presence/ absence and thicknesses of the single chalk units (figs. 27 to 29), and the generalized isopach map (fig. 16) a set of six deposit zones is suggested (fig. 26). Wells situated within the same zone show a gross similarity in the chalk development (fig. 31).

Geological age: The dating of the Chalk Group in the North Sea is essentially based on micropalaeontological studies of foraminifera. The Chalk Group is referred to the stratigraphic interval from base Late Cretaceous to top Danian.

From palaeontological studies it is evident that Danian limestone is present in nearly all Central Graben wells. Chalk of Maastrichtian age is also recorded in all wells. Chalk of Campanian age is present in most wells, whereas the older chalk of Cenomanian to Santonian age has a rather scattered occurrence in the area.

Depositional environment: Open marine conditions dominated during the deposition of the Chalk Group. The general picture of the chalk sedimentation, however, seems to indicate rather disordered pre-Maastrichtian deposits in the Central Graben. The distribution pattern of these deposits is affected by folding, salt movements, and non-deposition or erosion, especially in the southern part. The Maastrichtian-Danian chalk deposits tend to be less affected by these processes, and they unconformably overlie the older chalk units on most piercement structures.

The chalk sequence is often bounded by two unconformities - a minor at the Cretaceous-Tertiary boundary and a major at the base of the chalk. The unconformity at the base of the chalk is diachronous. However, it clearly indicates a conspicuous change in the depositional environment between the chalk sequence and the older sediments. The unconformity is pronounced in the northern part of the Danish Central Graben and less striking in the middle and southern part. The most complete chalk sequences are recorded in deposit zones 2 and 3 (fig. 26) of the Central Graben. This area presumably subsided during the entire Late Cretaceous and Early Tertiary period. Indirect evaluations suggest a similar evolution in the western end of the Ringkøbing-Fyn High area. On the contrary, the older chalk sequence (from Cenomanian to Coniacian) is missing in deposit zones 4 to 6, creating the major hiati in these areas.

Source rock potential: The Chalk Group is in general considered to have a low source rock potential.

Reservoir rock potential: The primary porosity and fractures of the Chalk Group in general makes it a fair reservoir rock despite its low matrix permeability. Oil and gas have been located within the Chalk Group and production has been started in a few fields of the Danish part of the North Sea.

Sealing potential: Clay lamina, stylolites, and diagenetic horizons within the Chalk Group represent sealing possibilities. However, the Chalk Group in general is considered to have a poor sealing potential.

Chalk-1 Unit *(informal name)*

Type section: The Danish Adda-1 well (7420-7512' b.KB), thickness 28 m.

Reference section: The Danish O-1 well (7500-7580' b.KB), thickness 22 m.

In the Danish Central Graben, the Chalk-1 Unit is also present in the E-1 well, the data of which are given in chapter 8.

The Unit may furthermore be present in the A-2, B-1, and H-1 wells, where the sections are very condensed.

Tentative correlations: The Chalk-1 Unit may be correlated with the Hidra Formation.

Thickness: The Chalk-1 Unit is only recognized with certainty in three wells in the middle and southern part of Central Graben. The maximum thickness of the Unit is recorded in Adda-1 (28 m) (fig. 27).

Lithology: The Chalk-1 Unit is dominated by hard to moderately hard chalk. The colour is white to light grey and occasionally slightly pink. The chalk is often interbedded with greyish and light green marl and shale. Thin beds of calcisiltite may be present (O-1) and in places the chalk is slightly dolomitized (Adda-1).

Log characteristics: The Chalk-1 Unit is defined by the gamma ray and sonic velocity, which have constant low and high values respectively. In some wells the logs have an irregular curve pattern reflecting clayey and marly intercalations in the chalk.

Boundaries: The lower boundary between the Rødby Formation and the Chalk-1 Unit is often gradual. The boundary is defined where for the first time constant, low gamma ray and high sonic velocities are encoun-

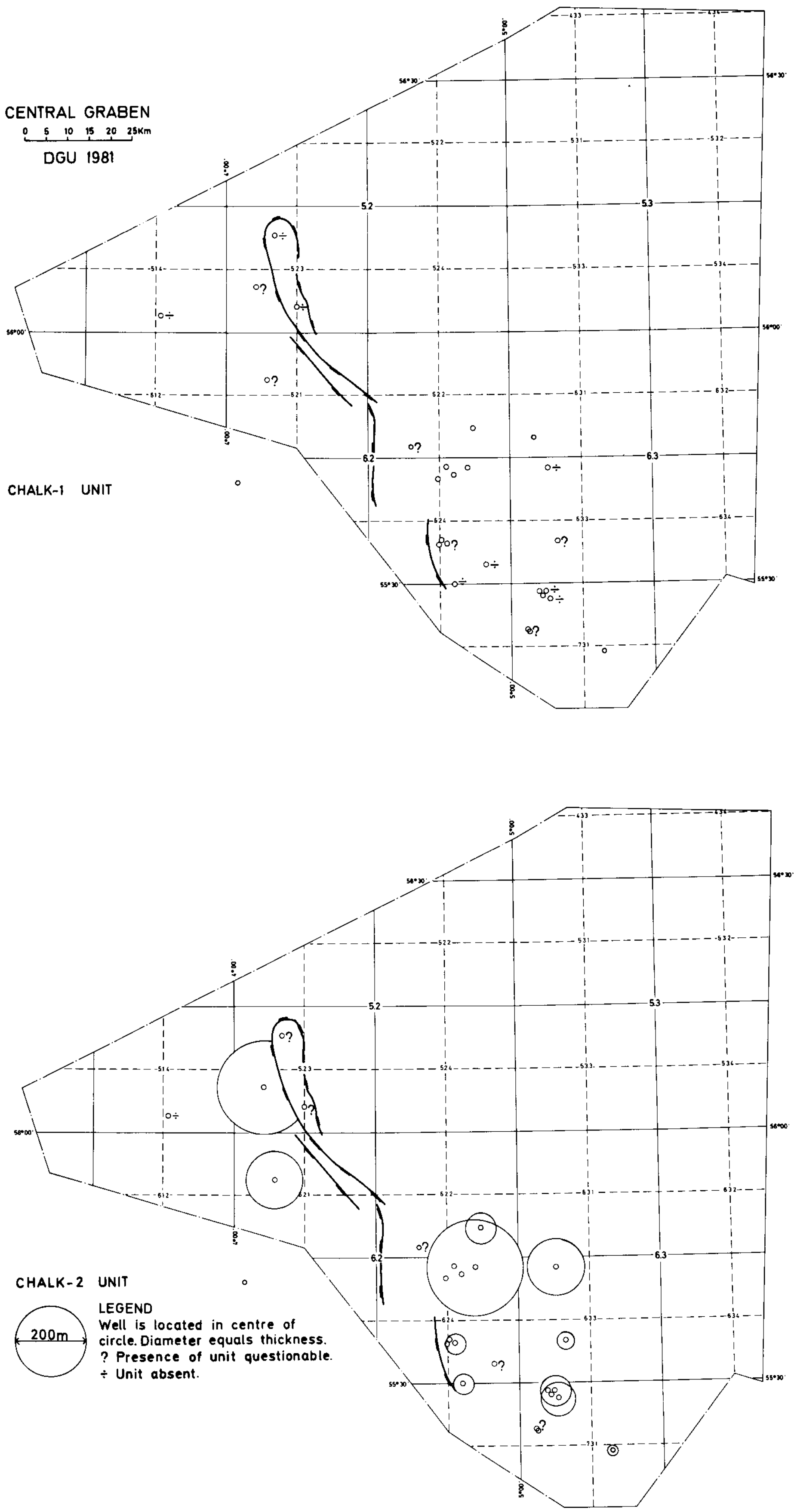


Fig. 27: Distribution and thickness of a) Chalk-1 Unit and b) Chalk-2 Unit.

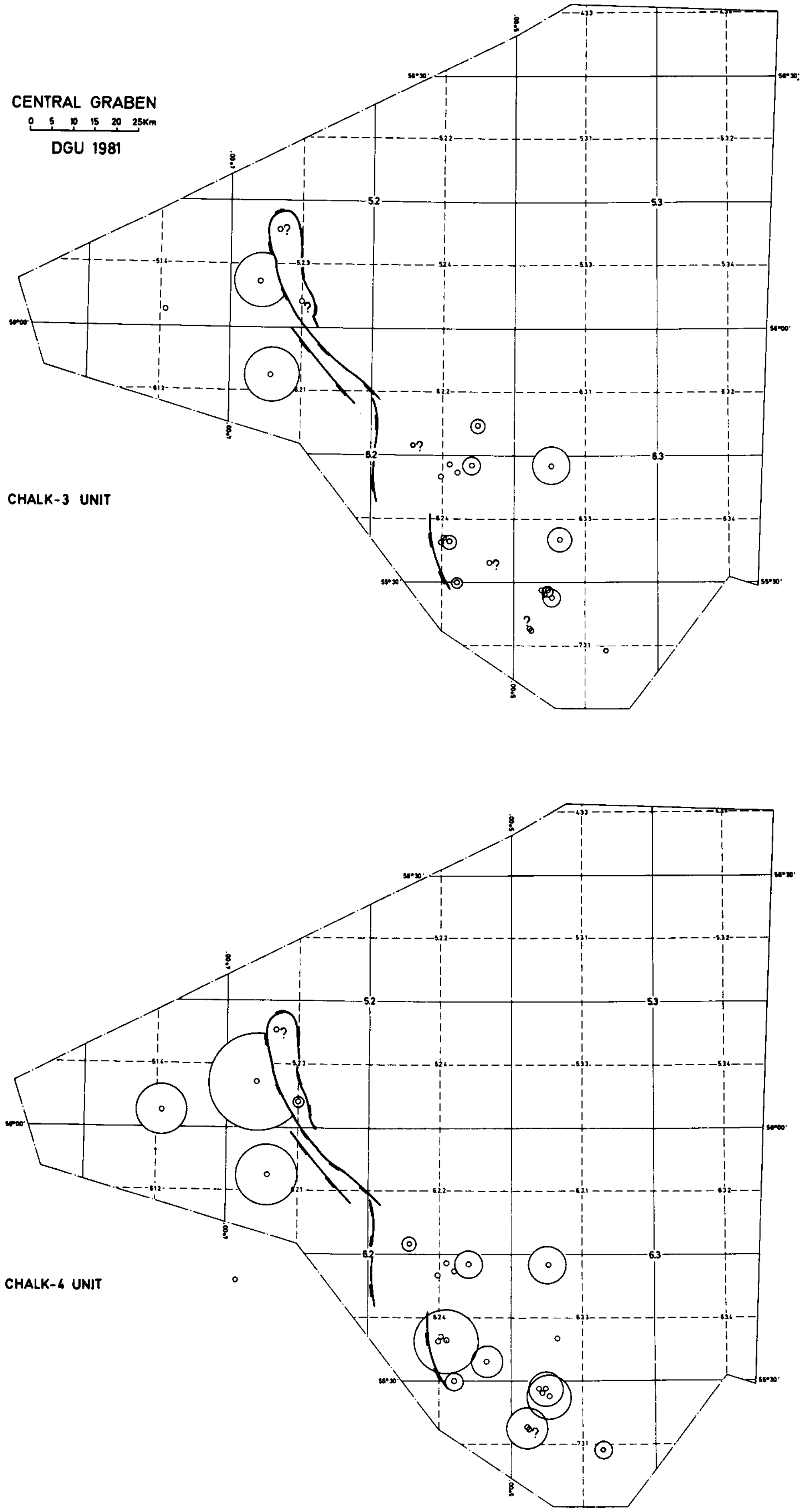


Fig. 28: Distribution and thickness of a) Chalk-3 Unit and b) Chalk-4 Unit. – For legend, see fig. 27.

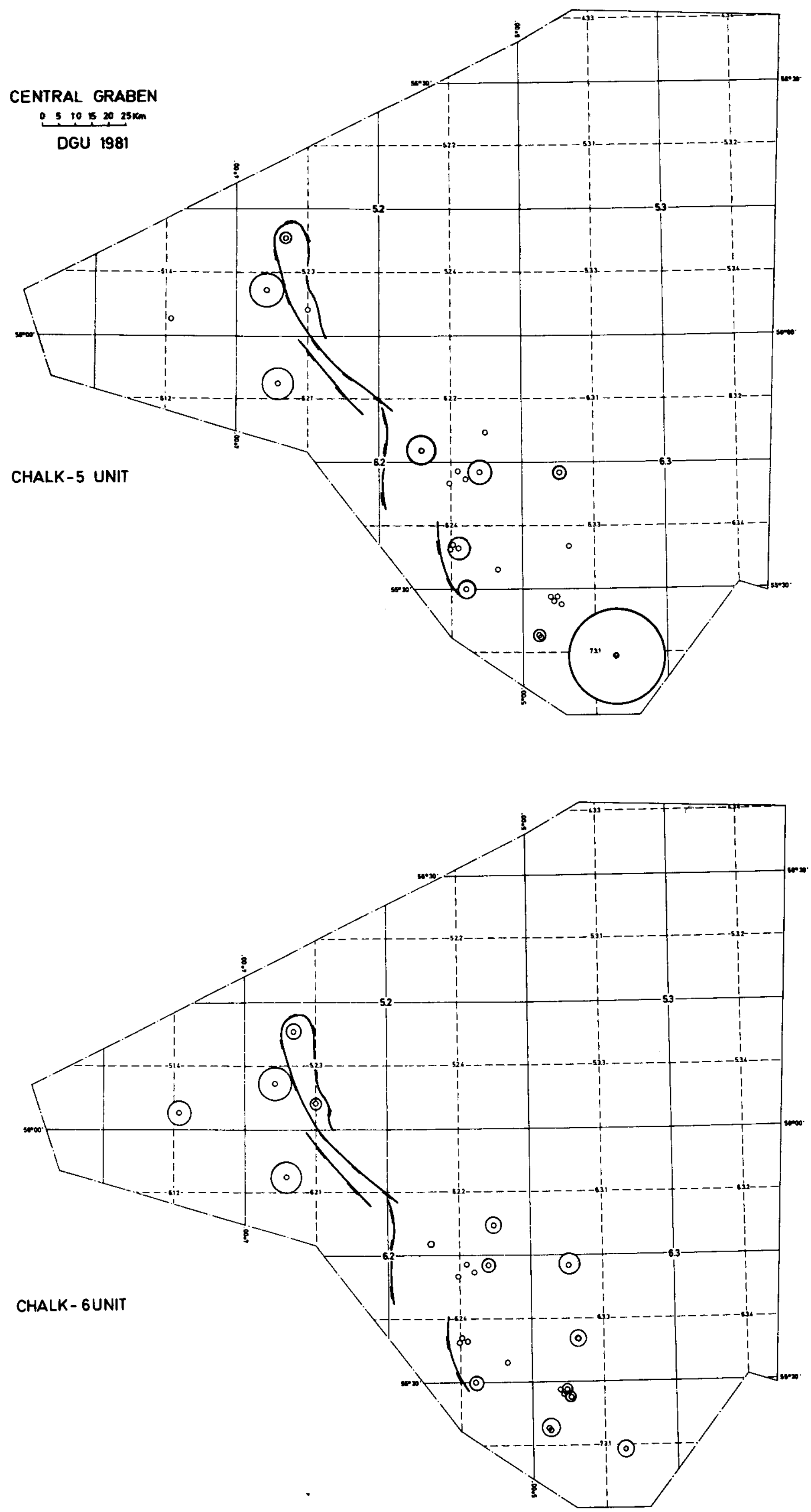


Fig. 29: Distribution and thickness of a) Chalk-5 Unit and b) Chalk-6 Unit. – For legend, see fig. 27.

tered. Where the Rødby Formation is missing the log pattern changes very abruptly.

The upper boundary to the Chalk-2 Unit can only be defined where the 'Turonian Shale' is present. In these cases the boundary is defined where the gamma ray and sonic velocity change abruptly to much higher and lower values respectively.

Distribution: The Chalk-1 Unit has been identified only in wells from the middle and southern part of the deposits zones 2 to 3 (fig. 26). The Unit is missing from wells in all zones of the northern part, and it has not been recorded in wells drilled on top of salt structures, which points to erosion during syn-sedimentary halokinesis.

The Hidra Formation is widely distributed in the southern and central parts of the North Sea. It is likely that the Danish equivalent, the Chalk-1 Unit, is present in the deposit zones 1 to 3 in the Danish Central Graben.

Geological age: All biostratigraphic datings of the Chalk-1 Unit point to a Cenomanian age. The Hidra Formation in the Norwegian sector is also of a Cenomanian age.

Depositional environment: The foraminiferal data indicate an open marine environment of deposition with neritic conditions. The shale and marl lamina within the chalk might indicate a stronger periodical influx of terrestrial materials.

Source rock potential: The Unit is not known as a source rock.

Reservoir potential: The Chalk-1 Unit is fairly tight (chapter 9) and it is probably not a good reservoir rock, unless fractured.

Sealing potential: Only the shale lamina within the Unit would have a good sealing potential. The shales, however, are only a minor constituent of the Unit. The Unit may therefore be characterized as having a poor sealing potential.

Chalk-2 Unit *(informal name)*

Type section: The Danish E-1 well 7500-8115' b.KB, thickness 188 m.

Reference section: The Danish V-1 well 8375-8940' b.KB. In the Danish sector of Central Graben the Chalk-2 Unit is present in the wells given in chapter 8.

Tentative correlations: The 'Turonian Shale' at the base of the Chalk-2 Unit in the Danish sector is probably equivalent to the lower part of the Plenus Marl Formation in the Norwegian sector (fig. 25).

The 'Turonian Shale' is, in this presentation, considered to be the base of the Chalk-2 Unit. However, it may be defined as a separate unit at a later stage, when more information on the shale is available.

The chalk sequence of the Unit seems to correlate with the lower part of the Hod Formation (fig. 25), or with the Heering and the lower part of the Flounder Formations which are homotaxial to the Hod Formation.

The 'Turonian Shale' and the rest of the Chalk-2 Unit have also been recognized in the Danish onshore area.

Thickness: The thicknesses listed in chapter 8 show a wide scatter which apparently is related to the depositional subdivision of the Graben area. The maximum thicknesses are found in the wells of the northern and middle parts of the Graben, i.e. deposit zones 2, 3 and 5, whereas the Unit is thin or absent above the salt structures of deposit zone 4 in the southern part (figs. 26 and 27). This pattern appears to be enhanced by syn-sedimentary growth of the salt piercement structures.

In the Danish type section the 'Turonian Shale' is approximately 2 m thick.

Lithology: The base of the Unit is represented by the distinct 'Turonian Shale', which is in general a black non-calcareous shale.

Above the basal shale there is a white to light grey chalk sequence which is hard with moderately hard intercalations. The chalk is often dominated by numerous stylolites seams, and sometimes horse-tail solution structures. Occasionally marly intervals or fine clay lamina are present in the chalk (e.g. the E-1 well).

Log characteristics: At the base of Unit-2 both gamma ray and sonic velocities show peaks, corresponding to the 'Turonian Shale'. Upwards in the rest of the Unit the gamma ray and the sonic velocity read constant low and high values respectively. The sonic velocity is generally lower than in Unit-1. However, the sonic velocity pattern is rather nervous, with high amplitudes. With greater depth of burial, this feature becomes less distinct, as seen in the Q-1 well.

Boundaries: The lower boundary is identical to the upper boundary of the Chalk-1 Unit. The upper boundary to the Chalk-3 Unit is defined where the gamma ray changes to a constant and slightly lower level, and the sonic velocity reads higher values.

Distribution: The Chalk-2 Unit is known from wells in deposit zones 2, 3, 5, and 6 in the Central Graben (fig. 27). The Unit is likely to be present in between the salt structures of the deposit zone 4.

Geological age: The age of the shale at the base of Unit-2 is unknown but it is assigned a Turonian age. The datings of the overlying chalk sequence indicate the nature of the Unit to be diachronous. In the middle part of deposit zones 2 to 3 of the Graben area, the Unit seems to be of Turonian-Coniacian age. In the southern part it is difficult to make log- and age-interpretations. However, the Chalk-2 Unit in the less structurally affected well 0-1 is of a Turonian-Coniacian age.

In deposit zone 6 and the mid- northern part of zone 2, the micropalaeontological dating of the Chalk-2 Unit points to an overall Santonian age. The change from a depositional environment influenced by terrestrial sources (as recognized in the lithology of the Chalk-2 Unit), to an environment with less terrestrial influence (as recognized in the lithology of the Chalk-3 Unit) thus occurred at a later stage in the northern than in the middle and southern part of the Danish Central Graben.

Depositional environment: Apart from the basal part the Unit is deposited in an open marine neritic environment. A number of hypotheses have been proposed for the depositional history of the 'Turonian Shale'. It has been suggested that the Unit represents weathered volcanic detritus since it has a high content of montmorillionite and a wide distribution despite its relative thinness.Another hypothesis proposes that deposition occurred during a regression period with anaerobic conditions. The Chalk-2 Unit is widely distributed in the Central Graben, and unconformably overlies older rocks of Early Cretaceous and Jurassic ages in the northern part of the area. In deposit zones 2 and 3, the shale conformably overlies the Chalk-1 Unit. In deposit zone 4 halokinetic movements have disturbed the depositional pattern. During the deposition of Unit-2, subsidence must have increased considerably since the younger part of the Unit is also found in deposit zone 5.

After the deposition of the Turonian Shale, pure chalk of a basinal character was deposited, and stable outer marine conditions seem to have prevailed.

Source rock potential: The Turonian Shale might be considered a possible source rock. It may have a fairly high organic content, but is presumably immature. The source rock potential of the remaining part of the Chalk-2 Unit must be characterized as poor, due to a rather low organic matter content.

Reservoir potential: The Unit normally displays a rather moderate porosity (chapter 9) which reduces the reservoir potential of the Unit, unless it is fractured. However, in the Adda-1 well, high porosity oil-bearing zones have been encountered within the Unit.

Sealing potential: The Turonian Shale at the base of the Unit might provide a seal. The upper part of the Unit has a low sealing potential due to the porosity of the chalk.

Chalk-3 Unit *(informal name)*

Type section: The Danish V-1 well, 8357-8737' b.KB, thickness 107 m.

Reference section: The Danish Q-1 well, 11,240-12,128' b.KB, thickness 149 m.

The Unit has furthermore been recognized in the Danish wells noted in chapter 8.

Tentative correlations: The Chalk-3 Unit is tentatively correlated to the middle part of the Hod Formation, and a part of the homotaxial Flounder Formation (fig. 25). The Chalk-3 Unit may also be recognized in the Danish offshore area northeast of the Central Graben, as well as in the Danish onshore area.

Thickness: The thicknesses listed in chapter 8 show a wide range, from 18 m in the O-1 well to 157 m in the W-1 well. The Unit is well developed in deposit zone 5 as well as in zones 2 and 3 along the western margin of the Ringkøbing-Fyn High (fig. 26). In deposit zone 4 of the southern salt dome province of the Central Graben, the thickness of the Unit is only about 25 m (fig. 28).

Lithology: The Chalk-3 Unit consists of a white to light grey crypto- to microcrystalline hard chalk with a very low clay content ($<2\%$).

Log characteristics: The gamma ray is characterized by constant low values. The sonic velocities are high, especially in the bottom and top parts, giving the general curve trend a concave shape. The sonic curve also has a somewhat serratic pattern with low amplitudes. In this Unit the sonic velocity shows often the highest values found in the entire Chalk Group.

Boundaries: The lower boundary is identical to the upper boundary of the Chalk-2 Unit. The upper boundary to Unit-4 is defined where the sonic velocities change abruptly to a constant lower level. Normally the boundary is indistinct on the gamma ray log. However, the gamma ray sometimes changes to slightly higher values in Unit-4.

Distribution: The Chalk-3 Unit is present in almost all wells drilled within the Danish Central Graben, except for deposit zone 6 and the southern part of zone 4 (figs. 26 and 28).

Geological age: The age datings based on foraminiferal analyses of the Chalk-3 Unit show ages ranging from Coniacian to Early Maastrichtian, but most datings of the Unit fall within the time interval of Early Campanian to Late Santonian. A time transgressive nature of the Unit may be illustrated by the apparent younger age of the Chalk-3 Unit in depositional zones 5 and 6 (Late Santonian-Campanian) than in zones 2 and 3 (Santonian-Coniacian).

Depositional environment: The palaeontological data point to an open marine type of deposition. The subsidence, which started during the deposition of the Chalk-2 Unit, seems to have continued but apparently at a reduced rate. The overall thickness of the Unit is thus reduced compared to the previous interval. The salt dome and piercement structures of deposit zone 4 were presumably active in the depositional period of the Chalk-3 Unit, since the Unit is thin or absent on these structures.

The apparent time transgressive nature of the Unit may illustrate regional changes in the history of deposition. The Unit thus covers a much longer time span in deposit zones 2 to 3 than elsewhere. This may indicate a slower rate of change in the depositional environment of deposit zones 2 to 3 than in the remaining areas. Compared to the depocentres of the Chalk-2 Unit, the depocentre of the Chalk-3 Unit has moved north within deposit zones 2 to 3 (figs. 27 and 28).

Source rock potential: The Unit in general has a very low content of organic material and is generally a poor source rock.

Reservoir potential: The porosity and permeability of the chalk is fairly low (chapter 9). The Unit may therefore be considered a poor reservoir rock in general. Fractures occur occasionally above salt structures and thereby provide some reservoir potentials for the Unit.

Sealing potential: The Unit may have a moderate sealing potential due to the fairly low porosity.

Chalk-4 Unit *(informal name)*

Type section: The Danish M-1 well, 6118-6471' b.KB, thickness 108 m.

Reference section: The Danish Q-1 well, 10,730-11,640' b.KB, thickness 227 m.

The Unit, which is known as the 'Maastrichtian Tight', has been recognized in the wells given in chapter 8.

Tentative correlation: The log pattern of the Chalk-4 Unit may allow a correlation to the uppermost part of the Flounder Formation and the lower part of the Tor Formation in the Norwegian sector of Central Graben (fig. 25).

As with the above described chalk units, a correlation is possible between the chalk section in the Danish Central Graben and the Danish onshore, as well as the Danish offshore area to the northeast.

Thickness: The thicknesses listed in chapter 8 show a wide range (fig. 28), which again reflects the structural development of the Graben area. The maximum thicknesses are found in deposit zone 5 along the eastern flank of the Dogger High, whereas the Unit is totally missing in the Adda-1 well. It is relatively thin above the salt structures in the northern part of deposit zone 4, and thin or absent in deposit zone 2.

Lithology: The formation consists of a white to light grey chalk. The upper part of the Unit is sometimes referred to as 'Calcisphere Chalk' as allochems of calcispheres make up 20-30% of the rock. The induration of the Chalk-4 Unit may vary, but it is generally less firm than the older units. Stylolites are common. Flint, chert beds, and clays are unevenly distributed.

Log characteristics: The gamma ray values are low and fairly constant throughout the Unit. The sonic curve pattern is either open or densely serratic, with a small amplitude. The sonic velocity values are generally high in the lower part of the Unit and decrease steadily upwards. In the middle of the Unit a distinct high velocity peak is seen. This is referred to as the 'Maastrichtian Hard Strike' which, when cored in the M-1 well, proved to be a flint bed with a thickness of one foot. When present, this peak is an excellent marker. The marker is developed in the middle part of the Central Graben.

Boundaries: The lower boundary is identical to the upper boundary of the Chalk-3 Unit. The upper boundary to Unit-5 is defined at an abrupt change in the sonic velocity from generally high to generally lower values. This point corresponds to a change from a steep to a low inclination of the general trend of the curve from Unit-4 to Unit-5 respectively.

Geological age: The palaeontological age datings point to a Late Campanian-Early Maastrichtian age for the Unit, and it seems to be less time transgressive than the previous units.

Depositional environment: The Chalk-4 Unit has been deposited under open marine conditions, whereas the Calcisphere content in the upper part of the Unit suggests a shallowing upwards situation. The primary productivity of the rock forming coccoliths has been high and the sediments show only minor terrestrial influence.

Except for deposit zone 2 and the northern part of zone 4, the rate of subsidence in the Graben area increased during the deposition of the Unit, and the depositional environment of the remaining deposit zones was equivalent to the older periods of the chalk deposition. The halokinetic movements were reduced, although the fact that the Unit is slightly condensed, or shows intraformational unconformities above salt structures, indicates that they did not entirely cease.

Source rock potential: The Unit contains very small amount of organic matter, and therefore it is considered to have only minor source rock potential.

Reservoir potential: The primary porosity is good and the permeability is fair (chapter 9) The Unit acts as a reservoir in several fields of the Central Graben.

Sealing potential: The high porosity of the Unit gives it in general a poor sealing potential.

Chalk-5 Unit *(informal name)*

Type section: The Danish M-1 well, 6032-6118' b.KB, thickness 26 m.

Reference section: The Danish 0-1 well, 6264-7187' b.KB, thickness 281 m.

In the Danish Central Graben this Unit, often referred as the 'Maastrichtian Porous', has been recorded in all wells (chapter 8).

Tentative correlations: The Unit seems to correlate to the upper part of the Tor Formation in the Norwegian sector (fig. 25). It can also be correlated to the Danish onshore, as well as the Danish offshore area to the northeast. The layer of clay which in some wells has been found at the boundary between the Chalk-5 and Chalk-6 Units has in all investigated wells proved to be younger than the 'Fish-clay' described from the cliff at Stevns in eastern Denmark.

Thickness: The thicknesses of the Unit show a wide range in the drilled sequences. The greatest thickness is found in the O-1 well with more than 200 metres of sediment.

The average thickness of the Unit seems to be around 20 to 80 m in the remaining part of the Graben area, except for the salt and upheaval structures and the Dogger High where the minimum thicknesses are recorded (fig. 29).

Lithology: Unit-5 is clean biogenic chalk, white to off-white or tan in color, rarely light grey. The chalk is moderately hard with soft intercalations. The clay content is low (2-8%). Clay lamina are rare except for a layer occasionally present at the top of the Unit. Flint and chert may occur, and stylolites are common.

Log characteristics: The gamma ray reads generally constant low values. The sonic velocity pattern is rather nervous with high amplitudes. The sonic values are highest at the base of the Unit and decrease gradually towards the top of the Unit. The upper part of the Unit noramlly yields the lowest sonic velocities encountered within the entire Chalk Group.

Boundaries: The lower boundary is identical to the upper boundary of the Chalk-4 Unit. The upper boundary to Unit-6 is often marked by a slight increase of gamma ray values. The sonic velocity defines the boundary by a distinct change from low to considerably higher values, creating a double velocity peak just above the boundary.

Distribution: The Chalk-5 Unit is widely distributed in the North Sea area. It has been recorded in all Danish offshore wells (fig. 29) and it has a considerable thickness in the Danish onshore area. In the

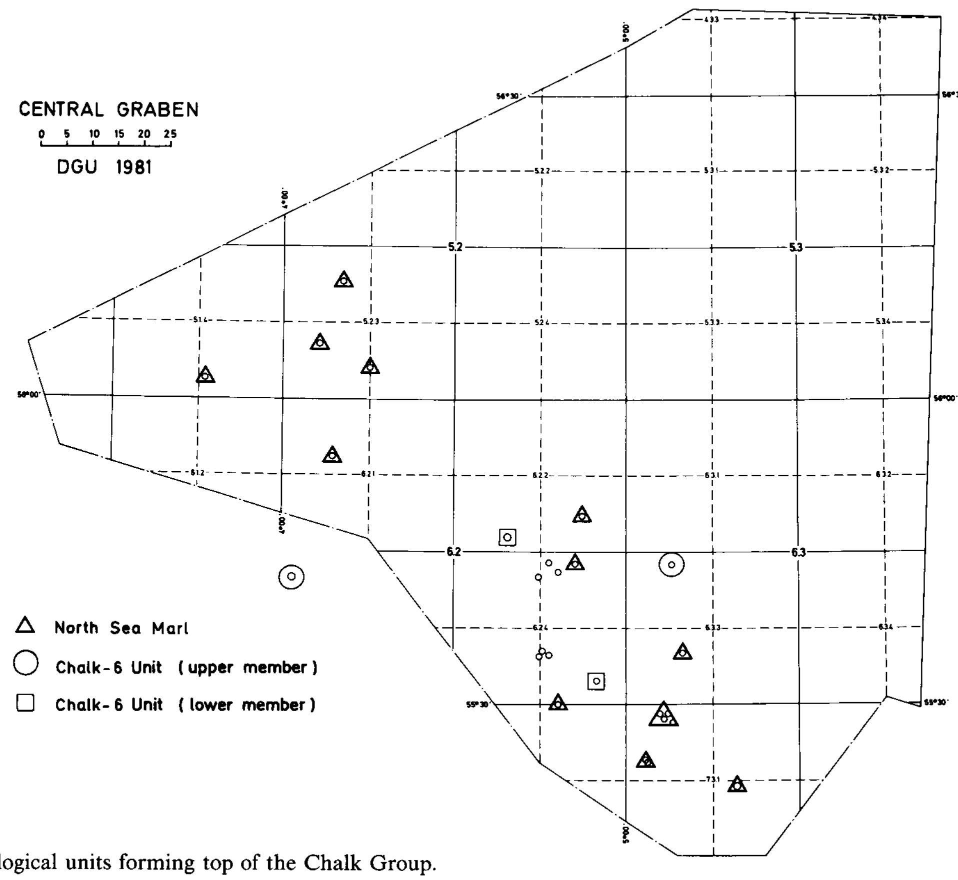


Fig. 30: Lithological units forming top of the Chalk Group.

Norwegian and British sectors, the equivalent formation is well developed in the central parts of the North Sea. To the north it passes into a sequence of interbedded pure limestones and shales in the Norwegian Viking Graben.

Geological age: The micropalaeontological dating of the Chalk-5 Unit points to a general Late Maastrichtian age. The upper boundary of the Unit in most cases is identical to the Maastrichtian-Danian boundary. Despite the fact that the upper boundary apparently straddles the Maastrichtian-Danian boundary in a few wells, the Unit seems to be rather contemporaneous in the North Sea area.

Depositional environment: The general pattern of sediment distribution which was initiated during the deposition of the Chalk-4 Unit presumably continued during the deposition of the Chalk-5 Unit. An exception is shown by the O-1 well which follows a separate pattern. The foraminiferal content of the Chalk-5 Unit points to an open marine depositional environment with outer shelf conditions. The increasing amount of benthonic foraminifera from the bottom to the top of the Unit might indicate a gradual shallowing of the water depth towards the top of the Maastrichtian Chalk-5 Unit. Halokinesis was active in Late Maastrichtian time, as illustrated by the reduced thickness of the Unit on top of salt structures. As indicated by the logs, it is often the uppermost highly

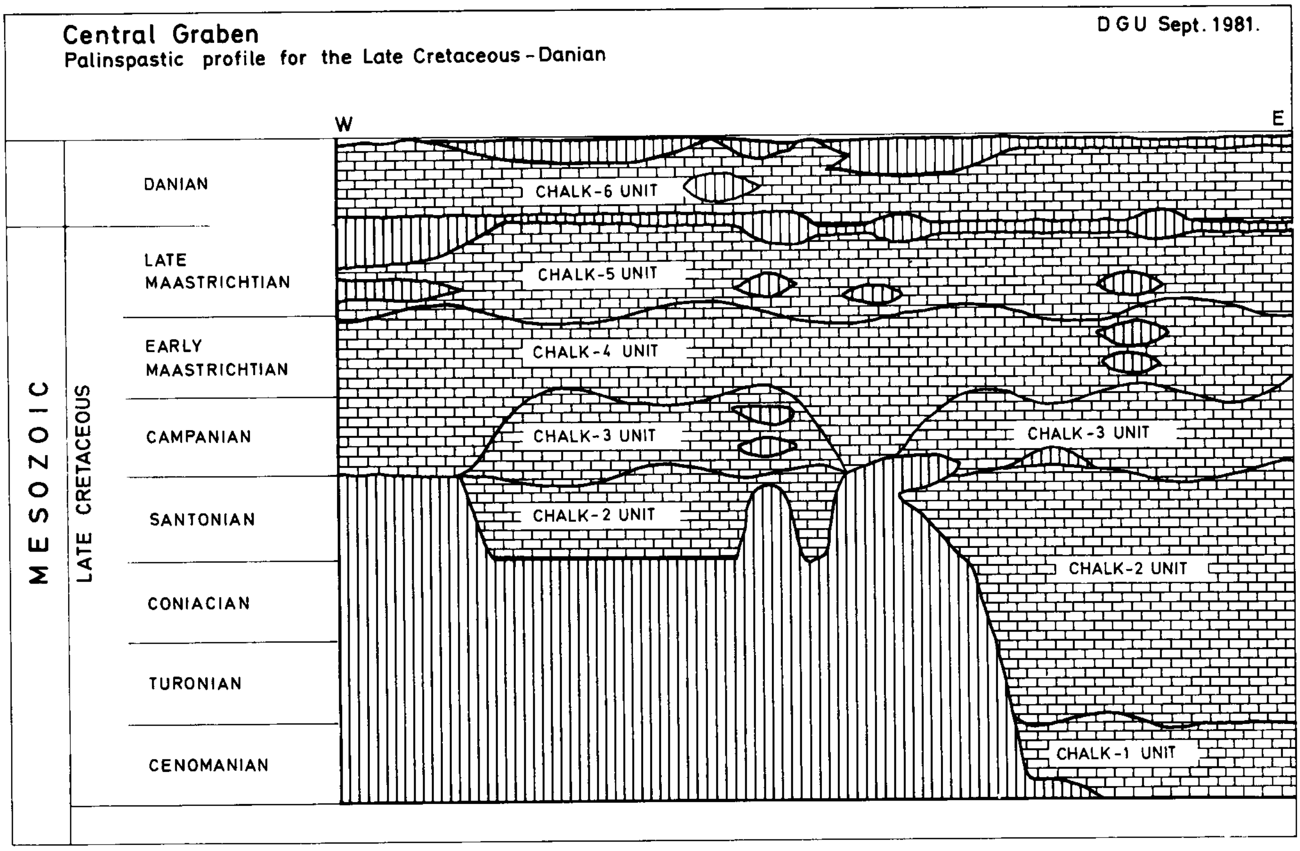


Fig. 31: Palinspastic profile of the Late Cretaceous-Danian deposits. – For legend, see fig. 3.

porous part of the Unit which is preserved on the salt structures whereas the lower part may be missing.

Source rock potential: The Unit is almost devoid of organic material and hence a poor source rock.

Reservoir potential: The primary porosity and permeability data (chapter 9) are generally good and point to fair reservoir characteritics for the Unit. A number of oil reservoirs have been proven within the Unit in both the Danish and Norwegian sectors.

Sealing potential: The high porosity of the Unit gives it a very poor sealing potential.

Chalk-6 Unit *(informal name)*

Type section: The Danish G-1 well, 6620-6790' b.KB, thickness 52 m.

The Unit is divided into a lower member, often referred to as 'Danian Tight' and an upper member, often referred to as 'Danian Porous'.

Reference section: The Danish W-1 well, 10135-10413' b.KB, thickness 25 m.

In the Danish Central Graben the Unit has further been recorded in the wells mentioned in chapter 8.

Tentative correlation: The Chalk-6 Unit may be correlated with at least a part of the Ekofisk Formation.

In the Danish onshore area, the Chalk-6 Unit is equivalent to the informal unit 'Danske Kalken'.

Thickness: On a regional scale the thickness of the Chalk-6 Unit is larger in the northern than in the southern part of the Central Graben (fig. 29). The maximum thickness is recorded in deposit zone 6 and in the mid-northern part of deposit zone 2. The thickness is rather uniform in the remaining area. The smallest thickness is found on an inversion structure in the H-1 well (10 m).

Lithology: The lower member is chalk, white to greyish or cream colour, moderately-hard to hard. The clay content is fairly high (15-20%), and thin clay lamina, flint beds, and chert are commonly found.

The upper member is a pure, white to cream and buff coloured chalk, which is soft to moderately hard and in which the occurrence of flint and chert is common. The clay content is generally lesser than in the lower member.

Log characteristics: The Chalk-6 Unit is divided into two distinct intervals: a lower member and an upper member.

The gamma ray generally reads slightly higher values in the lower member than in the upper one. The sonic curve shows numerous high velocity peaks, reflecting the numerous flint beds throughout the entire unit. In the lower member the sonic values are considerably higher than in the upper member, which normally reads values equally low as in the upper part of Unit-5.

Boundaries: The lower boundary is identical to the upper boundary of the Chalk-5 Unit.

The upper boundary to the 'North Sea Marl' is gradual, showing an increase from constantly low gamma ray values and a decrease in the sonic velocities. Where the 'North Sea Marl' is missing, the change is very abrupt. The boundary is defined at the point where the gamma ray and sonic values change to higher and lower values respectively.

Distribution: The Chalk-6 Unit has been recorded in all Danish wells (fig. 29) and, together with the equivalent Ekofisk Formation, this chalk sequence has a wide distribution, being recognized in the Dutch, German, English, Norwegian, and Danish sectors of the central North Sea.

Geological age: The Chalk-6 Unit has recently been dated by means of planktonic foraminifera. These datings point to a Danian age exclusively. Previous datings pointed to a slight time transgressive nature for the Unit.

Detailed studies of the Chalk-6 Unit show that the boundary between the upper and the lower member falls within the *G. daubjergensis* Zone. The upper member may be divided into three subzones, one of which is apparently related to a characteristic log marker. The age of the top of the Chalk-6 Unit varies due to erosion of the chalk (fig. 30).

Depositional environment: The planktonic foraminifera point to outer neritic marine conditions. The recorded thickness of the Chalk-6 Unit in the Central Graben points to a slightly higher rate of subsidence in the northern part (fig. 29). Local variations seem to be less pronounced than in previous periods and the effect of halokinesis has decreased, as verified by a relatively thick sequence of the Chalk-6 Unit on top of salt structures.

Source rock potential: The upper member contains only a small amount of organic matter and is immature. Although the lower member may contain relatively more organic matter, it has never reached a mature stage.

Reservoir potential: The lower member has a fair primary porosity and a fairly low permeability (chapter 9), but it is nevertheless a reservoir rock. The fairly high clay content causes poor production characteristics due to fairly low permeability, unless fractured. The upper member has a good reservoir potential, and high hydrocarbon saturations have often been encountered within this member.

Sealing potential: The presence of clay lamina and chert beds within the lower member may occasionally render the Unit a sealing potential.

3.7 Cenozoic excl. Danian limestone

By Finn Nyhuus Kristoffersen & Inger Bang

During the Quaternary and Tertiary a regional subsidence took place resulting in a large depositional basin, the axis of which coincides with the central part of the present North Sea. Thick Tertiary and Quaternary series were deposited, consisting mainly of clays with an increasing amount of sand upwards. The upper part of the series is particularly uninfluenced by deeply seated structures or by major tectonic activities (fig. 36).

North Sea Marl *(informal name)*

The North Sea Marl may be correlated to the unnamed marl unit in the Norwegian Central North Sea mentioned as an equivalent to the Maureen Formation of the Montrose Group (Deegan & Scull 1977), in the Norwegian Central North Sea.

Type section: The Danish E-1 well, 6725-6735' b.KB.

Reference sections: In the Danish Central Graben the following wells characterize the Unit: N-1 (6839-6897' b.KB), P-1 (9504-9580' b.KB), Q-1 (9971-10072' b.KB), Adda-1 (6841-6866' b.KB), and L-1 (6548-6732' b.KB) outside Central Graben.

Thickness: The thickness varies from 56 m in the L-1 well to less than one meter in the A-2 well, where the Unit mostly occurs as matrix between chalk nodules (fig. 32).

Parts of the Unit seem to be missing in some wells.

Lithology: Marl, greyish-green; calcareous clay, light to dark grey or greyish-green; and chalk, clayey, light grey to green, often with a high content of pyrite.

The type section shows a very condensed but apparently complete series, which has been cored. The lithology is from top: clay, greyish-green, calcareous, grading downwards into slightly shaly marl, and limestone, light greenish-grey, clayey.

Log characteristics: The gamma ray pattern shows diversity depending on the lithology (clay content).

Boundaries: The top of the Unit is defined by a maximum on the gamma ray readings below which generally lower values can be found, together with corresponding higher values on the sonic velocity. There often seems to be a gradual change to the underlying Chalk-6 Unit, and the boundary is then defined on the gamma ray at the transition to the more homogenous limestone of the Chalk-6 Unit.

Distribution: The Unit has been found in most wells and seems to be distributed over major parts of the Danish Central Graben apart from a few structures (fig. 32).

Geological age: The age is Late Danian-Early Selandian. The biostratigraphy is established on the basis of planktonic foraminifera and forms 3 successive assemblages in the *S. triloculionides* Zone.

The Unit may occasionally contain reworked foraminifera. They derive from different parts of the Chalk-6 Unit but never, as mentioned from the Norwegian North Sea sector, from the Cretaceous formations.

Depositional environment: The planktonic foraminifera indicate uniform oceanic conditions (high salinity, open marine) while the benthonic foraminifera seem to show a great variation, from near littoral on some structures to deeper water facies.

Source rock potential: Poor and immature for oil generation.

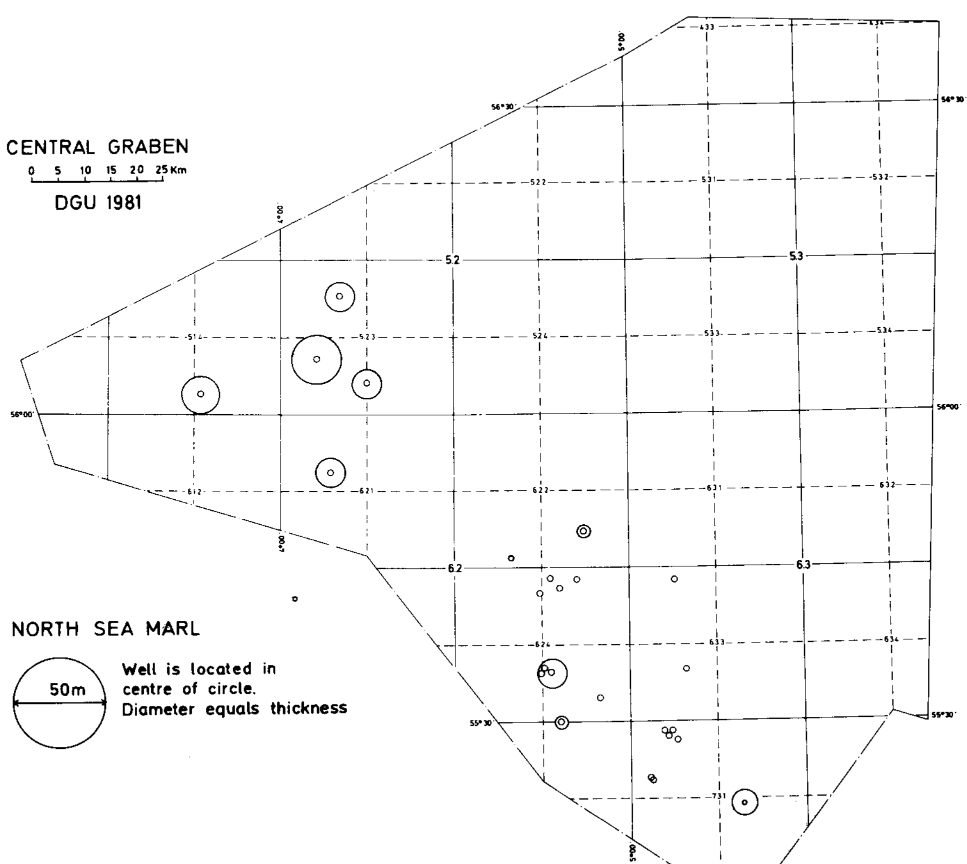


Fig. 32: Distribution and thickness of the North Sea Marl.

Reservoir potential: Hydrocarbon shows have been found within the Unit in: E-1, I-1, N-1, T-1, U-1, Adda-1, and B-1.

Sealing potential: Generally poor but some of the clay layers may act as sealing beds.

CEN-1 Unit *(informal name)*

The Unit includes Selandian non-calcareous clays. It may correspond to the Norwegian Lista Formation (Deegan & Scull 1977).

Type section: The Danish E-1 well, 6683-6725' b.KB.

Reference sections: In the Danish Central Graben the following wells characterize the Unit: A-2 (5898-5950' b.KB), P-1 (9282-9504' b.KB), and Q-1 (9790-9971' b.KB).

Thickness: The Unit has a varying thickness from 3 to 68 m (fig. 33).

Lithology: Clay and shale, non-calcareous, mostly red-brown, greenish-grey and grey, but other colours occur, with subordinate layers of silt or sandstone (in the P-1, Q-1, and W-1 wells). Beds of diagenetically formed limestone (? dolomite) have been found in a few wells.

In the type well, the cored section consists of shale, red-brown; with clay, greyish-green (6688-6703'); shale, brownish grey with red-brown and greenish parts (6703-6708'); there is no recovery from 6708-6727'.

Log characteristics: The gamma ray readings are higher in the top and bottom, and the Unit can best be characterized by its boundaries.

Boundaries: The upper boundary is well defined at the base of the beds with volcanic tuff corresponding to the base of the gamma ray peaks mentioned under the CEN-2 Unit. The lower boundary is defined at a maximum of the gamma ray readings below which a change to generally lower values occur.

Distribution: The Unit seems to cover most of the Danish Central Graben (fig 33).

Geological age: The age is Selandian (Paleocene). The top of the Unit contains diatoms (*Coscinodiscus* sp.) succeeded by a (mostly poor) fauna of arenaceous foraminifera with *Spiroplectammina spectabilis.* It is often interrupted by a zone dominated by radiolaria.

Depositional environment: The sediments and the fossil content indicate deposition below the calcite compensation depth: Marine, bathyal.

Source rock potential: Poor. Studies of a few well sections show an immature stage for oil generation.

Reservoir potential: Hydrocarbon shows have been seen within the Unit in the E-1, E-2, H-1, M-1, T-1, Adda-1, and Ruth-1 wells.

Sealing potential: Generally good, due to the relatively homogenous clay series.

CEN-2 Unit *(informal name)*

The Unit is a very important chronostratigraphic marker, since it contains a widely distributed volcanic tuff series. It is easily recognized on the gamma ray log and is easily mapped on the seismic sections in at least the Norwegian, Danish, and British Central Graben areas.

The CEN-2 Unit is equivalent to the Sele and Balder Formations to the north of the Danish sector (Degan & Scull 1977), but a subdivision into the two formations has not yet been possible in the Danish Central Graben area.

A possible correlation to the volcanic ash series of onshore Denmark has not yet been studied.

Type section: The Danish E-1 well, 6640-6683' b.KB.

Reference sections: The following Danish well sections characterize the Unit: A-2 (5823-5898' b.KB), H-1 (6620-6670' b.KB), and M-1 (5787-5832' b.KB).

Thickness: The thickness is 13 m in the type section. The general thickness is 20 m (fig. 33).

Lithology: In the type section the Unit comprises greenish-grey, dark grey, and greyish-black claystones with numerous interbedded volcanic ash layers. The greyish-black claystone occurs mainly as finely laminated claystones. Part of the ash series has been cored in two Danish Central Graben wells: E-1 and A-2. There seems, however, to be some discrepancies with respect to the stratigraphic position of the laminated claystone which, in the E-1 well is found in the top of the CEN-2 Unit, while in the A-2 well is described from the bottom. In a number of wells the ditch

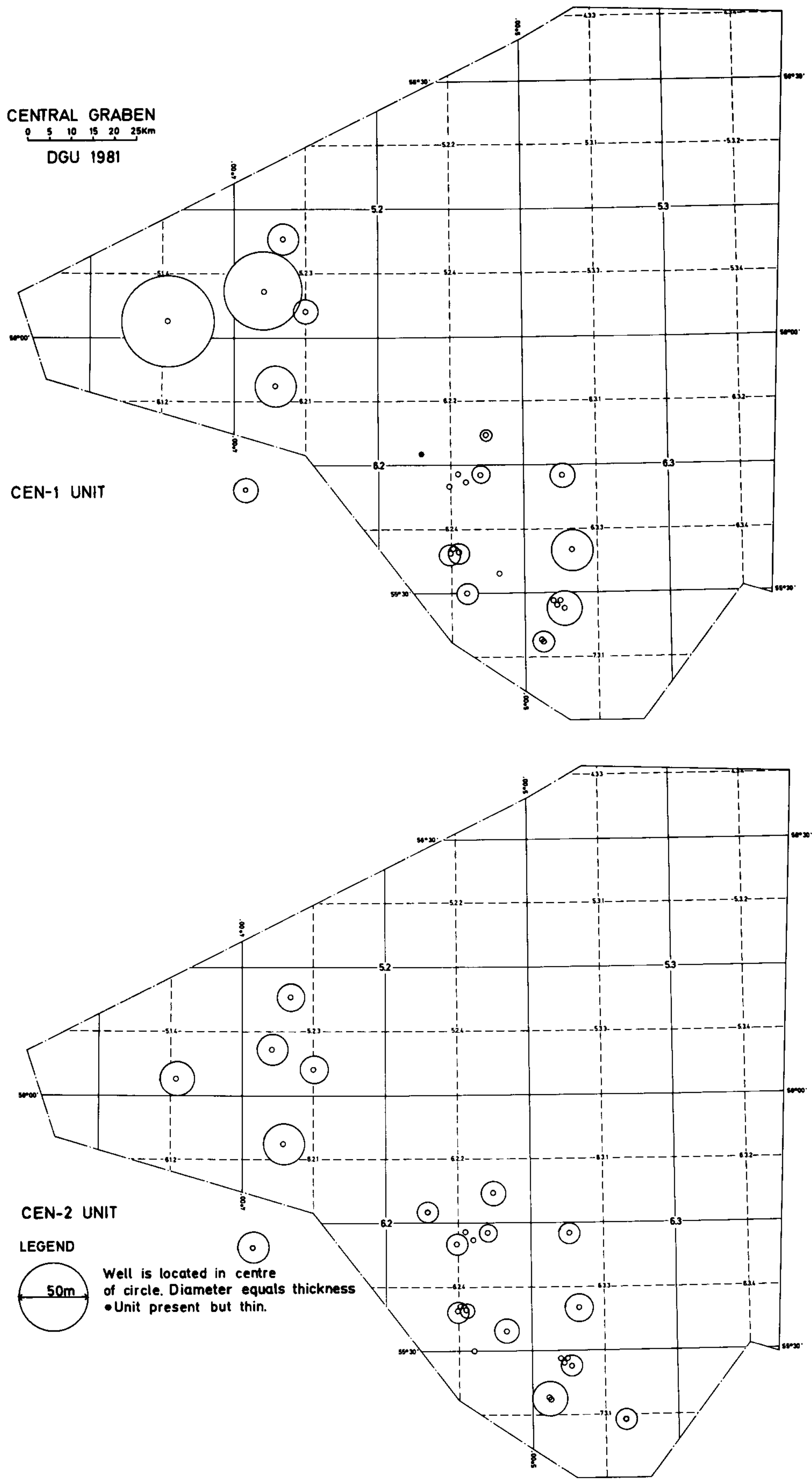


Fig. 33: Distribution and thickness of a) the CEN-1 Unit and b) the CEN-2 Unit.

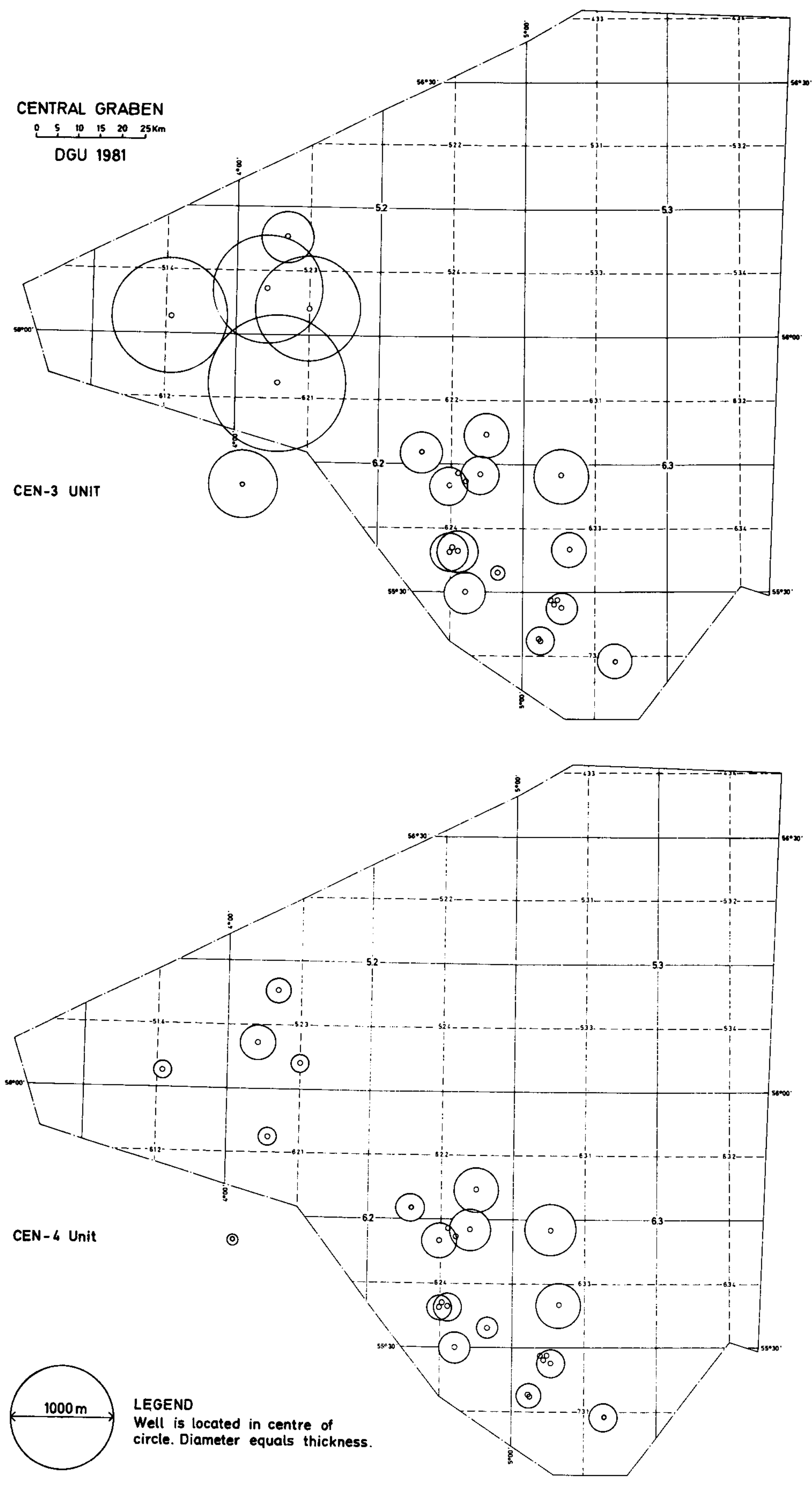


Fig. 34: Distribution and thickness of a) the CEN-3 Unit and b) the CEN-4 Unit.

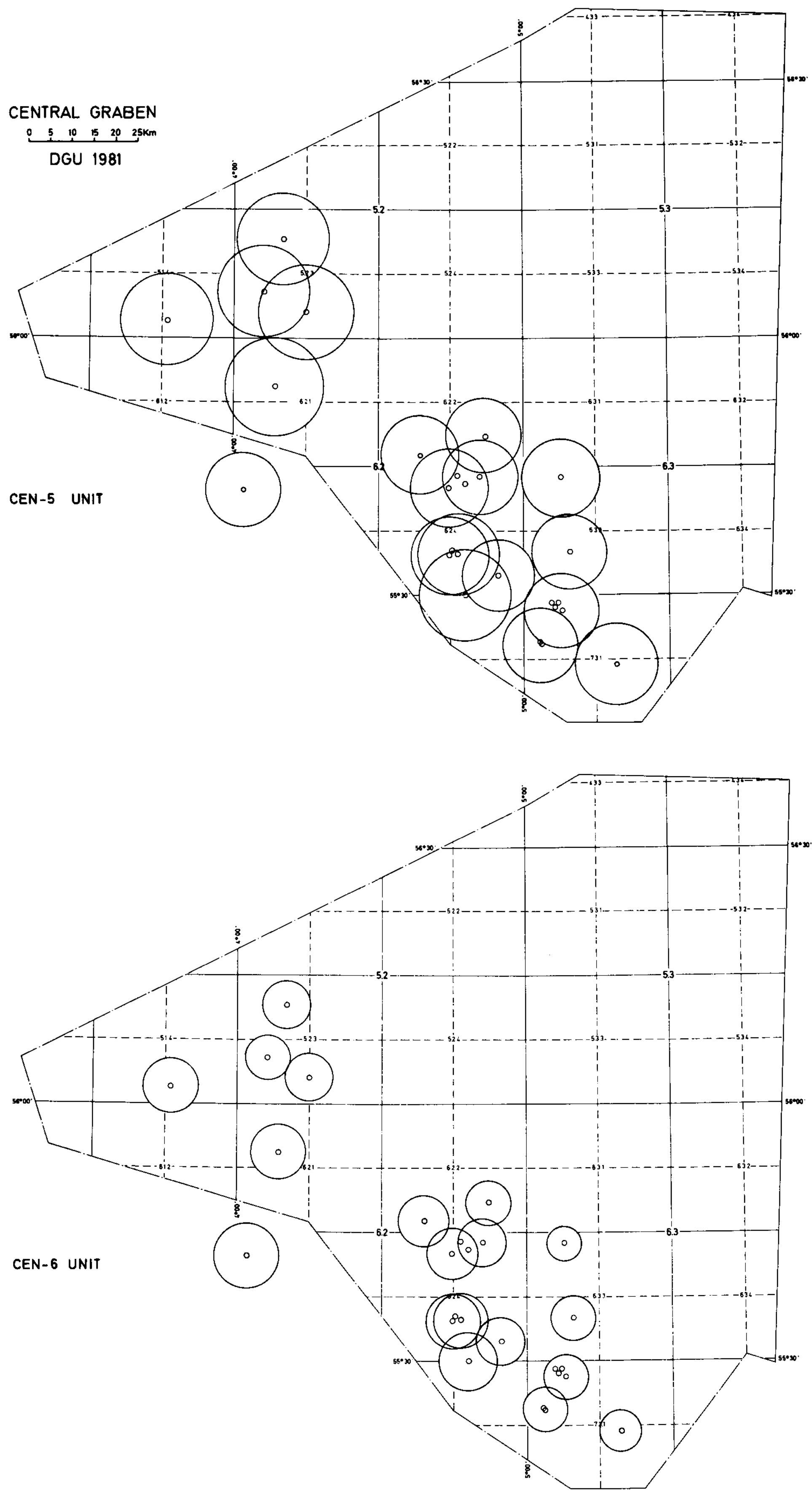


Fig. 35: Distribution and thickness of a) the CEN-5 Unit and b) the CEN-6 Unit. – For legend, see fig. 34.

sample descriptions indicate that the laminated claystone occurs below the ash layers, that is in the lower part of the CEN-2 Unit. Thin layers of sandstone occur frequently.

Log characteristics: The CEN-2 Unit is easily recognized from the gamma ray readings. It is typically a narrow section delimited upwards and downwards by distinct peaks with high gamma ray.

Boundaries: The lower boundary lies between the reddish-brown claystone of the CEN-1 Unit and the laminated claystone.

The upper boundary lies between the dark grey claystones of the CEN-2 Unit and the reddish-brown claystone which typically seems to make up the basal section of the CEN-3 Unit.

Distribution: The volcanic ash series is widely distributed within the North Sea Basin and is found in all Danish Central Graben wells (fig. 33).

Geological age: Foraminifera are very rare in this Unit and they are all long-range forms. Pyritized diatoms are frequent. Based on the presence of the ash series, the Unit is referred to a Late Paleocene - Early Eocene age.

Depositional environment: Possibly a marine, bathyal environment with contemporaneous volcanic activity.

Source rock potential: Poor. Studies of a few well sections show an immature stage for oil generation.

Reservoir potential: Poor. Diminutive hydrocarbon shows are referred to thin layers of siltstone and volcanic ash.

Sealing potential: Good, due to well-developed claystone series.

CEN-3 Unit *(informal name)*

The basal reddish-brown claystone of the CEN-3 Unit may correlate with the Early Eocene Røsnæs clay of onshore Denmark. The superjacent silty claystones are equivalent to the Lillebælt Formation, the Søvind Formation, the Viborg Formation, and possibly to the Late Oligocene Branden Clay.

Comparison with Norwegian units has not yet been attempted because lithologic subdivisions have not been carried out in the Norwegian Middle and Late Tertiary.

Type section: The Danish U-1 well, 5870-7195' b.KB.

Reference sections: The following Danish well sections are regarded as characteristic: E-1 (5460-6640' b.KB) and W-1 (5600-9850' b.KB).

Thickness: The thickness is 404 m in the type section; the general thickness is 3-400 m in the southern Central Graben and 11-1200 m in the northern (fig. 34).

Lithology: The sediments of this Unit are predominantly greenish-grey and grey, more or less silty claystones, which become slightly brownish in the uppermost part. The basal layers are typically reddish-brown claystones. Numerous thin limestone layers are present throughout the Unit, perhaps most frequently in the lower part.

Log characteristics: The gamma ray readings show generally gently upwards increasing values through the interval, with some significant increase uppermost in the Unit. This sharp change to higher gamma ray readings may possibly correspond to a lithologic change from greenish-grey to darker and more greyish claystone uppermost. Close to the base of the Unit, a narrow interval shows relatively high gamma ray values. This is a characteristic marker horizon, which at present cannot be referred to any specific lithological feature.

Boundaries: The lower boundary is at the change from the dark grey claystones with high gamma ray values in the CEN-2 Unit, to the basal reddish-brown claystone in the CEN-3 Unit. The upper boundary is defined at the top of a log motif with two rounded gamma ray peaks, which might be very difficult to identify in some wells. This feature is best demonstrated in the Danish W-1 well, whereas it is indistinct in the type section. The boundary is between greenish-grey and grey claystones below, and somewhat darker and slightly brownish claystones above, in the CEN-4 Unit.

Distribution: The Unit is widely distributed in the North Sea Basin, and is present in all Danish Central Graben wells (fig. 34).

Geological age: The rather abundant foraminiferal species are mainly long-ranging arenaceous forms. The very rare calcareous benthonic and planktonic species refer the Unit to an Early Eocene - Late Oligocene age.

Depositional environment: The foraminiferal fauna and the fine-grained sediment suggest a deposition in a marine bathyal environment. The depocentre is situated in the northern part of the Danish Central Graben area and in the adjacent Norwegian Central Graben area, where thicknesses exceed 1000 metres, more than three times the thicknesses in the southern part of the Danish Central Graben area.

Source rock potential: Poor. Studies from a few well sections show an immature stage for oil generation.

Reservoir potential: The numerous thin layers of limestone constitute a rather limited reservoir potential.

Sealing potential: Good, due to the thick claystone series.

CEN-4 Unit *(informal name)*

The CEN-4 Unit is equivalent to the micaceous clay and sand formations of Upper Oligocene and Lower to Middle Miocene age in Jylland, where these marine and non-marine formations interfinger. In particular, the Middle Miocene Hodde Formation seems in some respects comparable with the upper part of the CEN-4 Unit.

A comparison with Norwegian formations has not been possible because only the oldest part of the Norwegian Tertiary has been subdivided.

Type section: The Danish M-1 well, 4015-4900' b.KB.

Reference sections: The following Danish wells are regarded as characteristic sections: U-1 (4870-5870' b.KB), V-1 (3860-5553' b.KB), and W-1 (5050-5600' b.KB).

Thickness: The CEN-4 Unit has a thickness of 270 m in the type section, and the general thickness is 200-400 m (fig. 34).

Lithology: In the type section the Unit is a dark greyish-brown, non-calcareous and micaceous clay or claystone, which becomes more greyish towards the base. In the northern part of the Danish Central Graben area, these dark claystones seem to be replaced by light grey, rather sticky claystones. Thin layers of siltstone are frequent.

Log characteristics: Based on the gamma ray it seems possible to divide the Unit into two subunits. The gamma ray readings are generally on a slightly lower level in the upper part than in the lower part of the Unit. At present, however, this difference has not succesfully been related to lithological features.

Boundaries: There is an indistinct transition from the greenish claystones of CEN-3 to the brownish claystones of the present Unit. As already mentioned, the lower boundary has been very difficult to determine on the basis of wire line logs. However, it has been possible to identify two gently rounded peaks on the gamma ray curve in the top of the CEN-3 Unit. These peaks are best developed in W-1.

The upper boundary is at the base of a distinct gamma ray marker. This boundary coincides with the upper boundary of the zone with 'overpressured shales'.

Distribution: The CEN-4 Unit is widely distributed in the central North Sea area and is found in all Danish Central Graben wells (fig. 34).

Geological age: Based on the investigations of foraminiferal fauna, a Late Oligocene age is proposed for the lower part of the Unit. The fauna are very different from those known from the corresponding formations in Jylland, and only few forms have been recorded from both areas. One of these, *Plectofrondicularia seminuda*, seems to be characteristic for the younger Oligocene in the North Sea area.

While the lower part of the CEN-4 Unit shows an almost pure arenaceous foraminiferal fauna, the upper part contains a calcareous fauna with numerous planktonic species. Many of these are indicative of an Early to Middle Miocene age.

Depositional environment: The CEN-4 Unit has been deposited in an open marine and outer sublittoral environment.

Source rock potential: Poor. Studies of a few well sections show an immature stage for oil generation.

Reservoir potential: Poor. A number of diminutive hydrocarbon shows are recorded in thin siltstone layers.

Sealing potential: This homogenous claystone series probably has good sealing potentials.

CEN-5 Unit *(informal name)*

The CEN-5 Unit can be correlated with the Late Miocene Gram Formation and the micaceous clay and silt series of supposed Pliocene age in southwestern Jylland.

Comparisons with Norwegian formations has not been attempted since a lithological subdivision of the younger Tertiary and Quaternary series has not yet been carried out in the Norwegian central North Sea area.

Type section: The Danish N-1 well, 2028-4633' b.KB.

Reference section: The following Danish well sections are found to be characteristic: E-1 (1695-4200' b.KB) and M-1 (1585-4015' b.KB).

Thickness: The CEN-5 Unit has a thickness of 794 m in the type section, and the general thickness is 700-900 m (fig. 35).

Lithology: Grey, occasionally micaceous, silty clay predominates in the lower part of the Unit. Intercalations of micaceous sand and silt are frequent. Towards the top of the Unit, the amount of sand and silt increases. A rather thick gravelly sand bed forms the uppermost part.

Log characteristics: The gamma ray readings are generally on a medium level, but with an upwards increasing number of oscillations, reflecting the presence of graded beds towards the top.

Boundaries: The lower boundary is defined at the base of a distinct marker with high gamma ray values. This marker is typically composed of two gamma ray peaks.

The upper boundary is at the top of the thick gravelly sand bed characterized by low gamma ray values. It appears to be a sharp boundary towards the clayey bed above.

Distribution: The CEN-5 Unit is widely distributed in the Danish North Sea area and it is found in all Danish Central Graben wells (fig. 35).

Geological age: The Unit is referred to Upper Miocene and Pliocene. By means of foraminifera, the lower part is correlated with the Upper Miocene Gram Formation. Differences in the fauna are regarded as reflecting different depositional environments.

For the upper part, a Pliocene age is proposed, based on faunal correlation to Pliocene strata known from the Netherlands.

Depositional environment: The alternation between silty clay and sand beds, the numerous graded beds which appear from the gamma ray readings, and the open marine, sublittoral foraminiferal fauna, give the impression that the CEN-5 Unit was deposited in a delta front in the subsiding North Sea Basin.

Source rock potential: Probably poor. Studies in a few well sections point to an immature stage for oil generation.

Reservoir potential: The uppermost gravelly sand of Pliocene age has good reservoir potential. Gas accumulations are frequently met with in these beds and give rise to the 'bright spots' on the seismic sections.

Inferior hydrocarbon shows are related to thin layers of limestone or siltstone close to the lower boundary.

Sealing potential: The sealing potential is generally poor in the Pliocene sand, but good in the Miocene clay sequence.

CEN-6 Unit *(informal name)*

The Unit comprises mainly marine sediments. Glacial deposits known from onshore Denmark have not been recognized within the Unit.

Comparison with Norwegian units has not been attempted since a lithological subdivision of the younger Tertiary and Quaternary has not yet been carried out in the Norwegian central North Sea area.

Type section: The Danish E-1 well, 245-1695' b.KB.

Reference sections: The following Danish wells have characterizing sequences: A-2 (263-1675' b.KB) and H-1 (274-1942' b.KB).

Thickness: The Unit has a thickness of 442 m in the type section, and the general thickness is 400-500 m (fig. 35).

Lithology: Silt, sand, and gravel alternate with grey silty clays. Shell fragments and lignite occur frequently.

Log characteristics: The basal part is characterized by relatively high gamma ray readings reflecting a basal clay bed. The superjacent part shows strongly oscillating gamma ray readings corresponding to interbedded sand and clay layers.

Boundaries: The lower boundary is very distinct on the gamma ray, changing very abruptly from low values in the sand uppermost in the CEN-5 Unit, to high values in the basal clay bed of the CEN-6 Unit. The upper boundary is represented by the sea floor.

Distribution: The Unit is widely distributed within the Danish North Sea region and is found in all Danish Central Graben wells (fig. 35).

Geological age: Foraminifera occur abundantly in the lower part of the Unit, while they are rare or absent above. The restricted number of foraminiferal species recorded points unambiguously to a Pleistocene to recent age. The lower bed with abundant foraminifera is referred to the Early Pleistocene (Icenian).

Depositional environment: The alternating sand and silty clay layers, the frequency of lignite and megaspores, and the common accumulations of shells point to marine, littoral to inner sublittoral environments related to a delta front in the subsiding North Sea Basin.

Source rock potential: Poor. Studies in a few well sections indicate an immature stage for oil generation.

Reservoir potential: Good in unconsolidated porous sand layers.

Sealing potential: Poor in the intraformational parts. The lower clay layer may probably act as a seal for hydrocarbon accumulations in the unit below.

4.0 Formation temperatures

By Peter Klint Jensen

Borehole temperatures have been studied to evaluate the natural temperature field of the geological formations (fig. 37). Formation temperature and time are main factors affecting maturation of source rocks and should, therefore, be compared with maturation measurements. Furthermore, temperature gradients through sedimentary sequences provide information about relationships between their heat conductivities, and this can be used to extrapolate temperatures measured in wells to the surrounding rock masses.

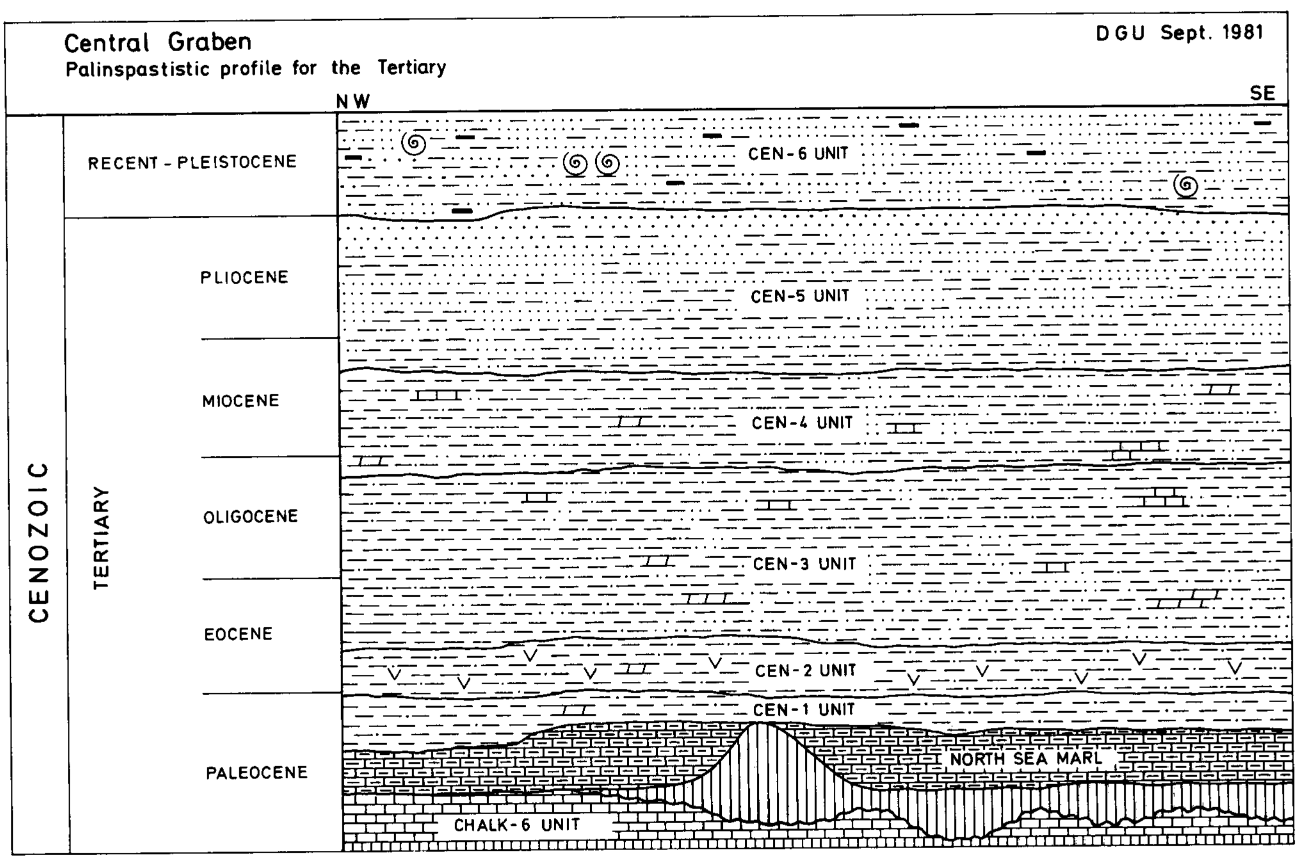


Fig. 36: Palinspastic profile of the Cenozoic deposits. For legend, see fig. 3.

Experience shows that mean gradients calculated from well measurements are related to the structural style of the area.

The temperature field in a sedimentary basin is controlled by the following factors:
1) Heat flow beneath the basin floor partly caused by radioactive elements in the crust.
2) Distribution of heat conductivities of the formations. This also implies focusing and de-focusing effects caused by the geometry of the formations.
3) Faulting or folding of rock masses contemporaneous with erosion and sedimentation, and other movements, e.g. those caused by halokinesis.
4) Circulation of formation water in thick porous and permeable sedimentary sequences, or in fracture systems penetrating deeply into the crust.
5) Intrusion of igneous rocks during tectonically active periods.
6) Change of surface temperature through time.

Geothermal gradients in North Sea wells have been computed by Evans & Coleman (1974) showing mean values from 18°C/km to 40°C/km, with high values found in the northern Central Graben. Mean values for the gradients between surface and bottom of wells in the Danish area have been mapped by Madsen (1975). The trend shows high gradients, about 32°C/km for the Central Graben, and low gradients, about 22-29°C/km for the Ringkøbing-Fyn High. Anomalous high gradients are to be expected above salt structures.

The area which has been re-investigated here is the deepest part of the Danish Central Graben around the Tyra field, and parts of the Tail End Graben. The wells selected are presumably uninfluenced by refraction of heat flow caused by salt structures. An exception could be the I-1 well.

The temperature calculations are based on downhole temperatures measured during tests with production of fluid, and measurements of bottom hole temperatures during wire line logging. The flow conditions during a test period seem to disturb the temperature, especially when producing gas. Therefore, measurements from gas-producing periods of the test are omitted. The temperature level is furthermore influenced by the drilling operation itself, including the circulation of the drilling fluid. The total effect is a cooling of the formation around the bottom of the borehole. If at least two measurements are obtained after cessation of the mud circulation, a correction formula can be used to find a true formation temperature. The following parameters must be known:
a) Bottom hole temperature.
b) Time of the measurements since cessation of circulation.
c) Time of cooling at the depth of measurement, which is assumed to be 30' above maximum depth. This means, that the drilling rate and the time of mud circulation after cessation of drilling must be known. The last parameter is taken to be from a half to one hour.

Changes in surface temperature during the past is reflected in the temperature profile of the subsurface formations. Heating after the end of the last glaciation is especially important. During the Quaternary glaciations, a mean surface temperature of approximately 0°C is normally accepted. During the last 10,000 years the mean surface temperature has increased to approximately 8°C. At a depth of 1 km, the temperature has increased to about 10% of the original surface formation temperature. Heating can be disregarded at depths greater than 1.5 km.

The results of temperature investigations in six wells are summarised in the table below. The final tempera-

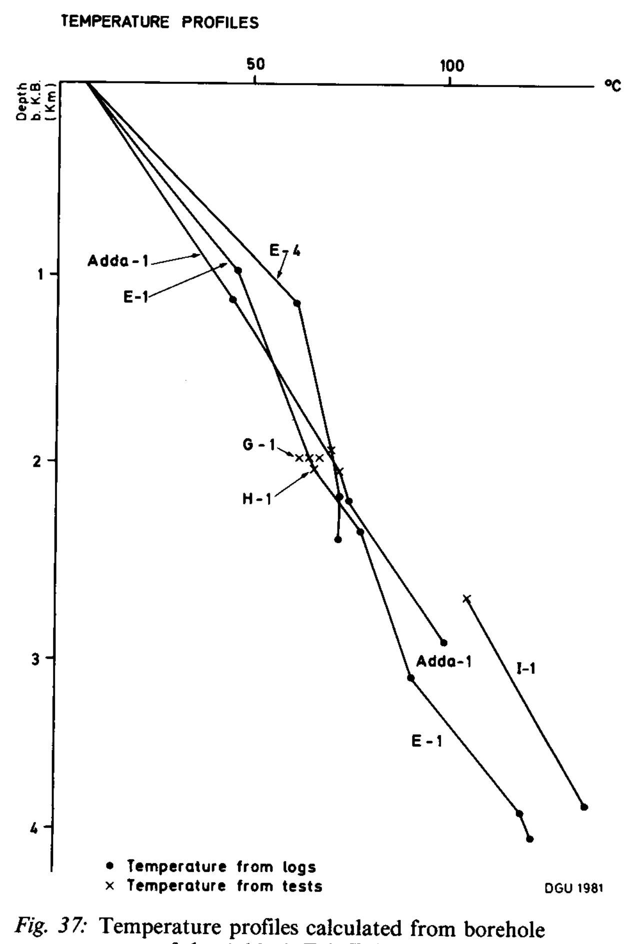


Fig. 37: Temperature profiles calculated from borehole measurements of the Adda-1, E-1, E-4, G-1, H-1, and I-1 wells.

ture measurement for a given depth (last °C) and the time since cessation of circulation are noted. If at least two measurements have been carried out after cessation of mud circulation, the true formation temperature is estimated by the above mentioned correction formula (corr. °C). The maximum correction factor was 10°C. The mean gradient between the surface and a given depth is computed (grad. °C/km). Mean values for sea floor temperatures as a function of depth can be found in Evans & Coleman (1974). To avoid the influence of local heating of the upper 1.5 km since the last glaciation, the true formation temperature has been corrected (ice corr. °C), accepting a value of 0°C as the mean surface value during the Quaternary. The corresponding mean gradients are listed (corr. grad. °C/km).

Table on temperatures and mean gradients

Well	Feet b.KB	Metres b.GL	Time since circ. hrs.	Last °C	Corr. °C	Ice corr. °C	Grad. °C/km	Corr. grad. °C/km	Type
Adda-1	3973	1139	4	40	45	41	34	36	logs
	7042	2074	-	74	-	74	32	36	tests
	7474	2206	18	72	76	76	31	34	logs
	10000	2976	18	94	101	101	31	34	logs
E-1	3526	1000	5.5	46	47	42	40	42	logs
	6798	1997	-	66	-	66	29	33	tests
	6900	2028	-	67	-	67	30	33	tests
	8088	2391	26	80	80	80	31	34	logs
	10650	3171	5.5	94	-	94	27	30	logs
	12926	3865	-	122	-	122	30	32	tests
	13406	4012	12.5	126	-	126	30	31	logs
E-4	4038	1162	4.5	62	67	60	51	52	logs
	6599	1942	-	71	-	71	33	37	tests
	7425	2195	7	73	-	73	30	33	logs
	7520	2233	27	72	73	73	30	33	logs
G-1	6822	1993	5.5	63	-	63	28	32	tests
H-1	6789	1986	-	67	-	67	30	34	tests
I-1	9195	2708	-	107	-	107	37	40	tests
	12848	3822	10	129	139	139	35	36	logs

The corrected formation temperatures (corr. °C) listed in the table are plotted on fig. 37 as a function of depth. The temperature around the Tyra field at 1 km depth is between 40 and 55 °C. The mean gradients to this depth (33-48 °C/km) indicate a surface layer of relatively low heat conductivity which corresponds approximately to the uncompacted Quaternary and Upper Tertiary sandy/silty formations. At a depth of 2 km, the temperature ranges from 63 to 72°C. The mean gradient through the consolidated Lower Tertiary and Upper Cretaceous formations is about 20°C/km. Computation of the temperature and the gradient in the Upper Jurassic formations is of interest since these are considered to be possible source rocks. The temperature for the Upper Jurassic varies from 82 to 88°C. The E-1 well indicates a gradient of 40°C/km in Jurassic shales. A temperature estimate of the Upper Jurassic boundary at I-1 yields 123°C and a gradient for the Lower Cretaceous and Jurassic formations of 30°C/km. The relatively high temperature is caused by greater depth of burial and a high mean gradient for the I-1 well.

The few examined temperature measurements indicate that the present temperature field can be explained by a purely conductive model. During previous geological periods, the higher tectonic activities might have contributed to a higher regional heat flow as well as local heating by intrusions or convective systems.

Presently, additional wells in the Central Graben are being investigated to discover the regional trend and to determine relative heat conductivity contrasts for all lithostratigraphical units.

5.0 Source rocks

By Holger Lindgreen, Erik Thomsen & Per Wrang

Little has been published on source rocks of Paleozoic and Mesozoic ages in the North Sea. Gas in many fields of the southern North Sea is known to originate from Late Carboniferous Coal Measures, (Eames 1975). In the East Midlands area of England, the oil in Carboniferous reservoirs is believed to originate from Carboniferous rocks (Bernard & Cooper 1981). Several papers published on the oil fields in the southern and northern North Sea suggest a Late Jurassic source rock (see review by Weismann 1979 and Bernard & Cooper 1981). Also Early and Middle Jurassic shales are suggested as possible source rocks in parts of the North Sea (Fuller 1975, Oudin 1976). Published data on source rock conditions in the Danish sector is limited to Weismann (1979).

5.1 Source rock definition

The term source rock is often used in an ambiguous way.

In the present report a source rock is defined as a rock containing a sufficient amount of organic matter of a proper type, and of sufficient maturity. A potential source rock is an immature source rock. The source rock parameters applied herein are 1) amount of organic matter, 2) type of organic matter, 3) maturity of the organic matter.

Results from the source rock analyses carried out by DGU are illustrated by selected wells located in the Central Graben area.

Methods
The source rock analyses have been performed by mineralogical organo-chemical, and coal petrographical methods. The amount of organic matter was determined as a total organic carbon percentage. The type of organic matter was determined by optical and chemical methods. Optically the organic matter was rated qualitatively in reflected light supplemented with blue-light induced fluorescence. Additional information is given by organochemical parameters (extractability, alifate/hydrocarbon ratio, prostane/phytane ratio, pyrolysis). The mineralogical analysis determines sediemntation and deagenesis parameters and contributes to the determination of the organic matter and type. The maturity of the organic matter was determined by vitrinite reflectance, by organochemical parameters (extractability, pristane/n-C17 ratio, CPI values, alifate/hydrocarbon ratio and composition of alifate fraction from gas chromatography) and by inorganic parameters (degree of diagenesis of carbonates, iron compounds and clay minerals, catalytic effect of clay minerals).

Total Carbon (TC) and Total Organic Carbon (TOC) were measured on a Leco carbon analysator. TOC was measured after pretreatment with hot, concentrated HCl. Soluble Organic Matter (SOM) was determined from the extract from a Soxhlet extraction of the chrushed sample with methylenchloride in 24 hours. The separation of SOM was performed by column-chromatography with hexane, methylenchloride and methanol as eluents. GLC (Gas Liquid Chromatography) of the alifate fraction was performed on an OV 1 capillary column. Rock-Eval analyses was performed on some selected samples.

Semiquantitative mineralogy and clay mineralogy were determined by X-ray diffraction on powdered bulk samples and on pretreated oriented clay samples. Qualitative and for carbonates and sulfides quantitative mineralogy was determined by differential thermal analysis on powdered bulk samples, with detection of CO_2, H_2O, and SO_2. The oxidation state and mineralogical positions of Fe was determined by Mossbauer spectroscopy on powdered bulk samples.

Viewing and measurements were made with a refelcted-light Zeiss Photomicroscope. Measuring principles were in accordance with the outlines in Stach et al. 1975. The organic matter was rated using three broad categories: vitrinite, liptinite and inertinite (for details see Tissot & Welte 1978). Approximate threshold values for the maturity levels corresponding to the onset of oil generation, expulsion of oil and the peak zone of oil generation, were used according to the suggestions by Hood et al. 1975, Dow 1977, and Tissot & Welte 1978.

5.2 Review of possible source rocks

Only Mesozoic rocks have up til now been analysed in the laboratory at DGU. However, based on the the geology of the Danish area and published information from the surrounding areas, the following tentative source rock possibilities are suggested.

Palaeozoic source rocks

A possible source rock of Early Palaeozoic age may be excluded due to an overprint of the area by the Caledonian metamorphism.

Devonian sediments have not yet been drilled in the study area, but they are known from the British and German sectors. However, no source rock of this age has been identified in these areas.

Lower Carboniferous (coals, sandstones, siltstones, and shales) was drilled in the P-1 well. The coal bearing Upper Carboniferous is probably limited to the basins south of the Mid-North Sea High and Ringkøbing-Fyn High, but may extend into the southern part of the study area. Upper Carboniferous coal measures are the sources for gas in the southern North Sea (Eames 1975) Carboniferous oil source rocks are less frequent, but oil shales in the Lower Carboniferous are believed to be the sources for the oil discoveries in the East-Midlands area of England.

Rotliegendes and Zechstein deposits have been drilled in the study area and are expected to cover main parts of the area. No source rock of Rotliegendes age is known. The volcanic rocks drilled on a few locations may possibly cover larger parts of the area, making the presence of source rocks of Rotliegendes and Carboniferous age speculative.

In the Zechstein, the possible source rocks are the Kupferschiefer and the Stinkschiefer and Stinkkalk (Taylor 1981). As these deposits are known both north and south of the Ringkøbing-Fyn High, they are presumably present in the Danish Central Graben.

Mesozoic source rocks

Triassic sediments have mainly been drilled in the southern part of the study area. Apart from the Winterton Formation, the known Triassic deposits consist of sandstones and evaporites in red bed facies with no source rock potential. The Jurassic sequence is comparable to that of the southern North Sea (Rhys 1974), the central and northern North Sea (Deegan & Scull 1977), and the Norwegian-Danish Basin (Michelsen 1975). The Jurassic Posidonomya Shale, which is regarded as the source rock for the oil elsewhere in Northwest Europe, has not yet been recorded from the Danish Central Graben. The Middle Jurassic is mainly represented by coal-bearing fluvio-deltaic deposits. These sediments are generally regarded as poor source rocks for oil due to the dominance of vitrinite and inertinite. However, sapropelic deposits are encountered in this depositional environment and represents possible sources for oil (Bernard & Cooper 1981). The Late Jurassic 'Kimmeridge Clay' is regarded as the main source rock for oil in the North Sea (see review by Bernard & Cooper 1981).

Upper Cretaceous and Tertiary deposits have been drilled in a large number of wells in the study area. According to Weismann (1979) these deposits have not generated hydrocarbons in any significant quantities.

5.3 Results from laboratory analyses

Winterton Formation

The Danish M-8 and O-1 wells have been investigated. The Winterton Formation is present in the Danish M-8, U-1, and O-1 wells. The mineralogy has been investigated in M-8 and O-1. The presence of medium to large amounts of anhydrite, salts, and mica points to sedimentation in alkaline environments in a dry climate unfavourable for the formation of potential source rocks. Few samples from the upper part of the formation in M-8 have been analyzed organo-chemically. They are rich in organic carbon. The material is unfavourable for oil generation, but may be a potential source rock for gas.

Fjerritslev Formation

The Danish M-8, A-2, and O-1 wells have been investigated.

M-8 well: The amount of organic matter is high and it is mainly represented by alginite and liptodetrinite, associated with vitrinite and inertinite. The samples are mature, but the extractabilities are generally too low to permit oil expulsion. This is probably due to weathering effects possibly associated with the Mid Cimmerian uplift, or to neutral to fresh water solutions migrating during early diagenesis (Millot 1970). This is supported by the high content of early diagenetic kaolinite of the side wall core at 10520' in well M-8 (fig. 41), and by the absence of pyrite. From mineralogical data of the O-1 well, it is indicated that weathering of the Fjerritslev Formation has not taken place in this well, but the diagenesis is low, indicating a low maturity of the organic matter.

The limited number of samples investigated so far permit only tentative conclusions concerning the hydrocarbon potential. However, it may be concluded that the formation will represent a good oil source rock where it is mature and not weathered.

J-2 Unit

The Danish M-8 well has been investigated.

M-8 well: The amount of organic matter is rich to extremely rich. The coal seams encountered in this formation are composed of humic coal and sapropelic coal. In the sapropelic coal and in carbagillites, the organic matter is dominated by sporinite, alginite, liptodetrinite and bituminite. Micrinite is frequently associated with desmocollinite. Expulsion of oil droplets is observed. The amount of extract is rich, and it is of algal origin. The pristane/phytane ratio indicates some oxidation of the material. The extractability, however, is only fair, which shows that only little migration has taken place. According to vitrinite reflectance, the formation is just within the zone of principal oil formation, and the Rock-Eval analysis shows a great residual potential for oil generation.

J-3 Unit

Only the M-8 well has been investigated. The amount of organic matter is high. The organic matter is dominated by vitrinite and inertinite associated with a varying amount of liptinite. With depth, the pristane/phytane ratio indicates an increasing influx of more oxidized material. The vitrinite reflectance (fig. 38) shows that the formation is just within the zone of oil generation. The amount of extract and the extractability is low. The degree of diagenesis of the carbonates and clay minerals is moderate (fig. 40). The clay

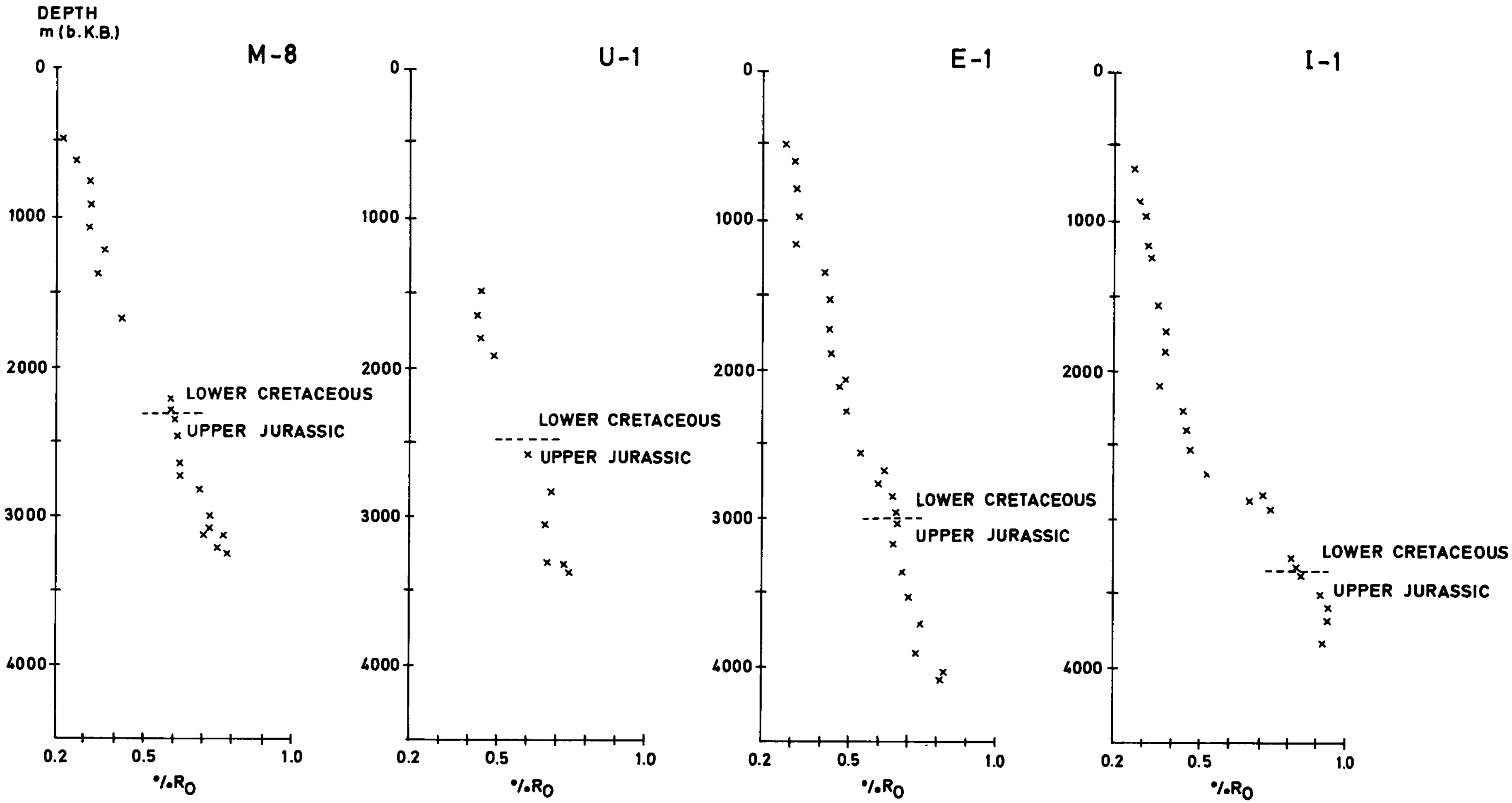


Fig. 38: Vitrinite reflection trends in the E-1, I-1, M-8, and U-1 wells. The Lower Cretaceous – Upper Jurassic boundary is marked.

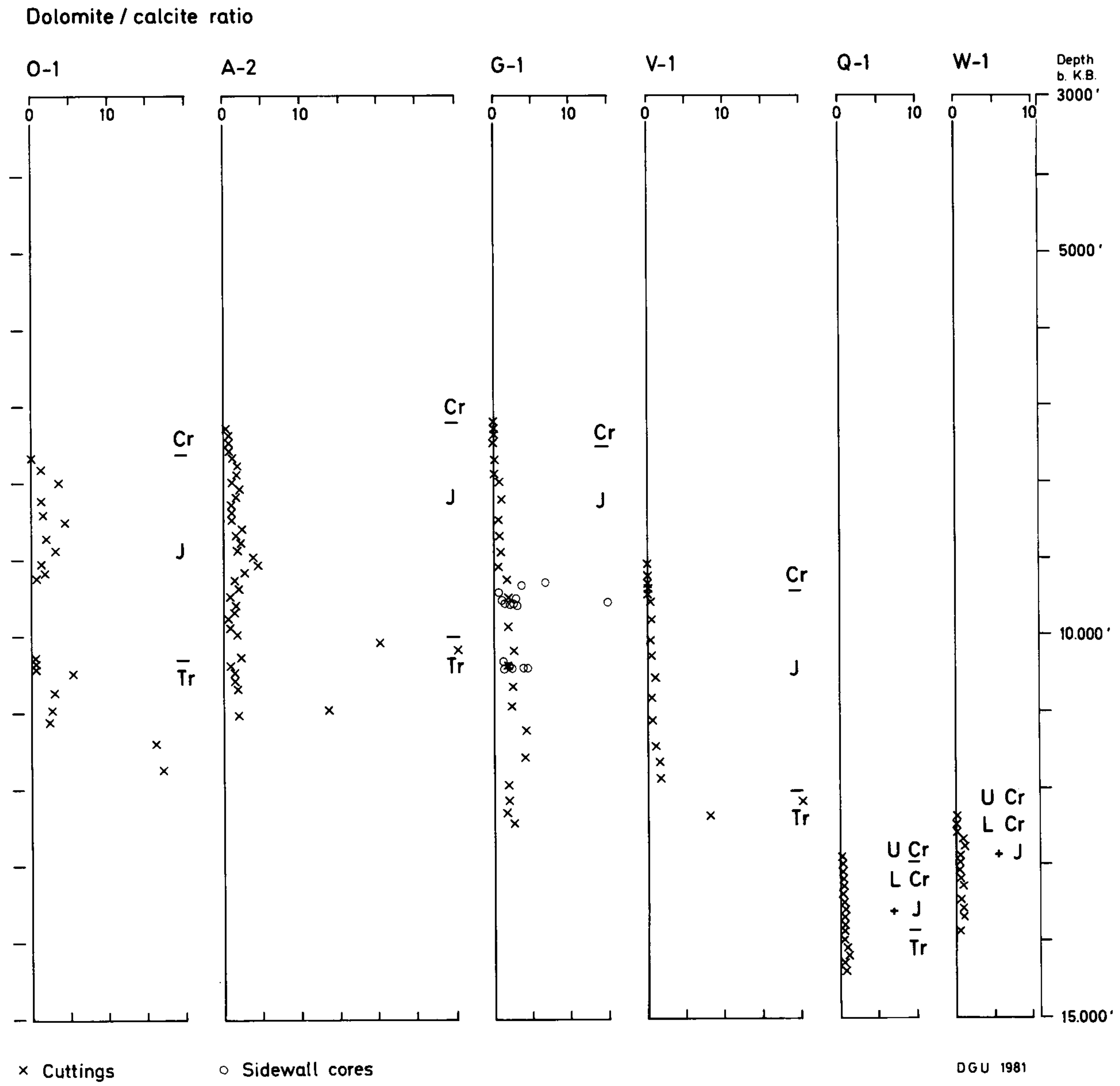


Fig. 39: Calcite/dolomite ratio in the O-1, A-2, G-1, V-1, Q-1, and W-1 wells. Cr = Createaceous, J = Jurassic, Tr = Triassic.

minerals contain a fair amount of smectite layers and provides the formation with good catalytic properties.

The Formation is not a promising source rock for oil, due to the unfavourable type of organic matter, but it might be a potential source rock for gas.

J-4 Unit

The M-8, E-1, and I-1 wells have been investigated. The amount of organic matter in the M-8 well is high. Microscopically the organic matter in the well is dominated by liptinite, mainly alginite, associated with varying contents of vitrinite and inertinite. Locally high contents of liptinite are observed. The extract is of algal origin. M-8 is just approaching the zone of oil formation as judged from vitrinite reflectance data (fig. 38). The amount of extract and the extractability shows that the formation has not yet generated sufficient amounts of oil to classify it as an actual source rock.

The amount of organic matter in the J-4 Unit of the well E-1 is good to rich. Microscopically the type of organic matter is analogous to the organic matter found in the M-8 well. However, the content of liptinite shows a significant increase upwards through the formation, and intervals very rich in liptinite, mainly alginite, also occur in the upper part of the formation. The same trend is seen in the organo-

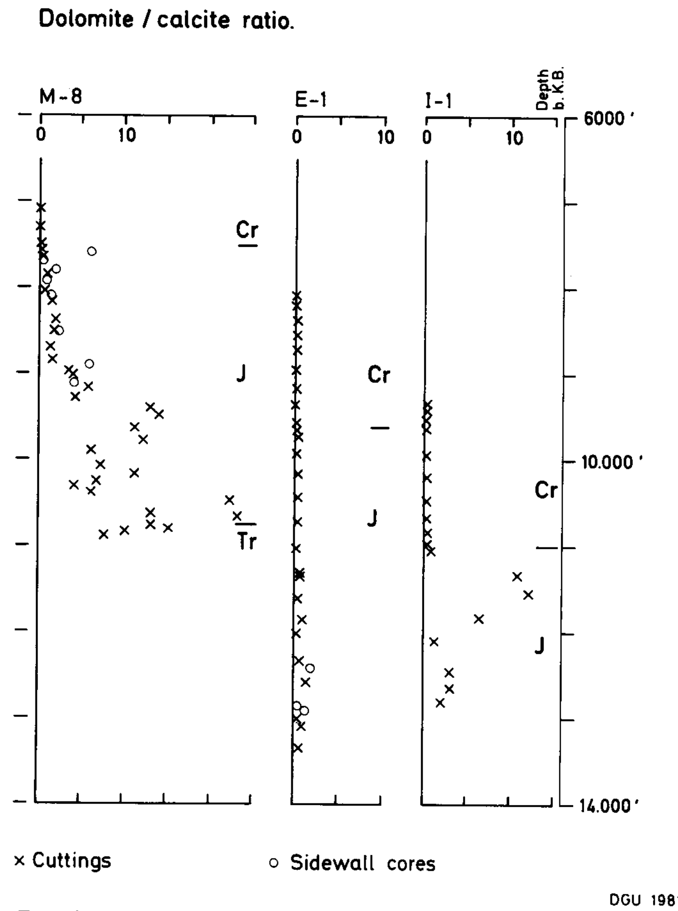


Fig. 40: Calcite/dolomite ratio in the M-8, E-1, and I-1 wells. Cr = Cretaceous, J = Jurassic, Tr = Triassic.

chemical data, but the diesel oil added to the drilling mud makes a proper evaluation difficult. Vitrinite reflectance (fig. 38) shows that the upper part of the formation is within the zone of oil generation, while the lowermost part has reached the zone of maximum oil generation (fig. 38). The extraction data indicate higher maturity than in the M-8 well. The mineralogical data show a very high amount of smectite in the interval 7530-7630' of M-8 and a high smectite content at 10400' in E-1 (fig. 41), which - indicated by a crystallographic analysis - was probably formed from volcanic ash weathered in a restricted basin with a high supply of nutrients from the ash. It has also a very high catalytic effect on the oil generation. The degree of inorganic diagenesis is the same at the maximum depth of the J-4 Unit in the E-1 and M-8 wells (fig. 40).

The amount of organic matter in the I-1 well is rich to extremely rich. The extract is of algal origin. The vitrinite reflectance (fig. 38) indicates that the J-4 Unit is well within the zone of maximum oil generation. The amount of extract is rich, and the extractability shows that the formation is releasing oil, which classifies the J-4 Unit as a rich source rock for oil in this area. The degree of inorganic diagenesis is much higher in the I-1 well than in the E-1 and M-8 wells (fig. 39).

The investigation shows that the J-4 Unit must be regarded as a much better oil source rock in the northern well I-1 than in the E-1 well in the central part of the study area or in the M-8 well in the southern part of the study area.

Valhall Formation

The E-1 and I-1 wells have been investigated. The amount of organic matter in E-1 is poor to fair. Microscopically, the organic matter is dominated by reworked vitrinite and inertinite, associated with a low content of liptinite. Vitrinite reflectance shows that the sequence is premature to mature. The degree of inorganic diagenesis is very low (fig. 39). The section in E-1 has a poor source rock potential.

The amount of organic matter in the I-1 well is poor to fair. The degree of inorganic diagenesis is very low (fig. 39). The extracts contain varying amounts of migrated oil, and this migrated oil dominates the extracts at a depth of 10630'. The vitrinite reflectance (fig. 38) shows that the formation is well within the zone of oil formation. The section is regarded as a poor to fair source rock.

Rødby Formation

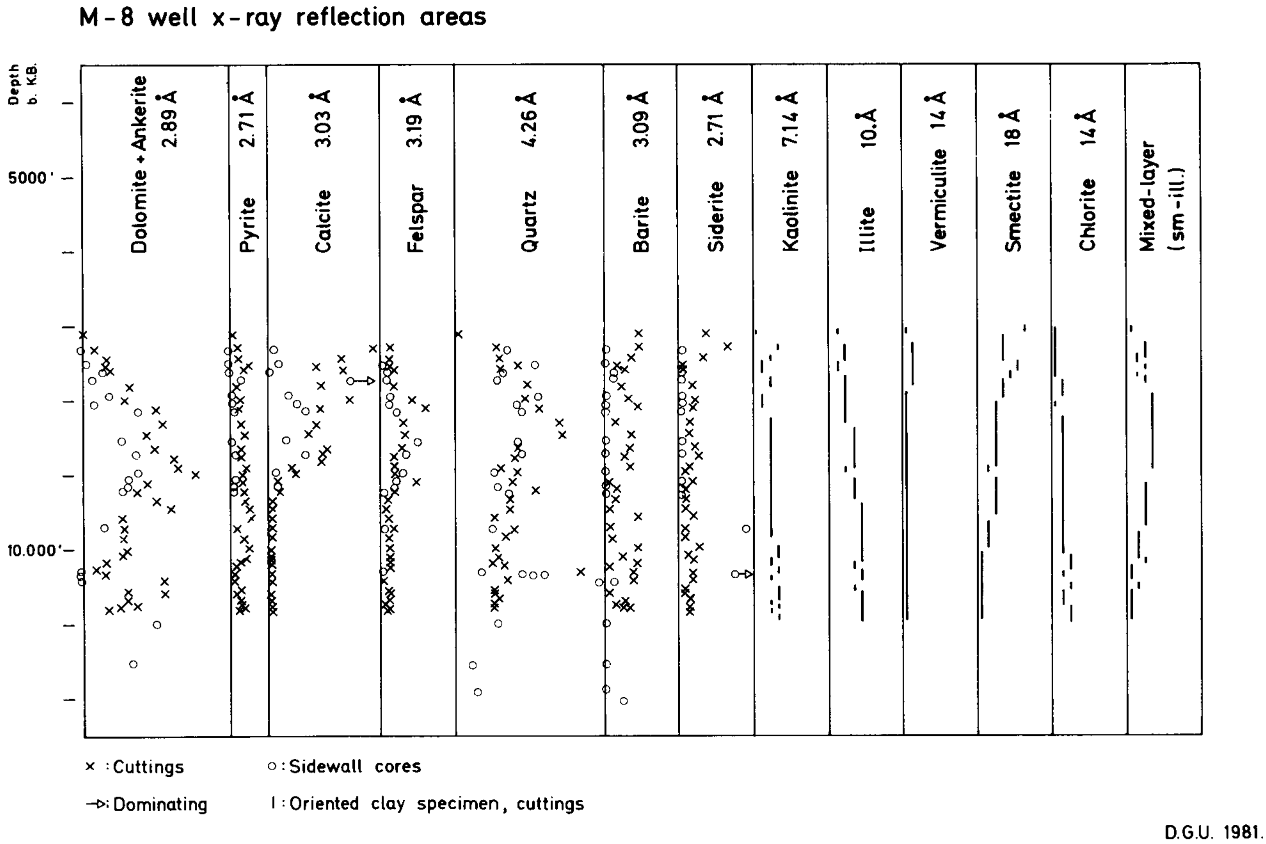
The E-1 and I-1 wells have been investigated. The amount of organic matter in I-1 is fair but locally rich. The vitrinite reflectance shows that the formation is within the zone of oil formation. The extraction data show a great content of migrated oil. The degree of inorganic diagenesis is very low. The formation is generally a poor source rock, but certain horizons may act as a source rock for oil and gas.

Chalk Group

The M-8, U-1, E-1, and I-1 wells have been investigated. The amount of organic matter is poor. The vitrinite reflectance shows that the formations are immature in the E-1 well (fig. 38). The Chalk Group has no potential for oil and gas generation in the examined wells due to the low content of organic matter.

Tertiary sequences

Vitrinite reflectance measurements have been carried



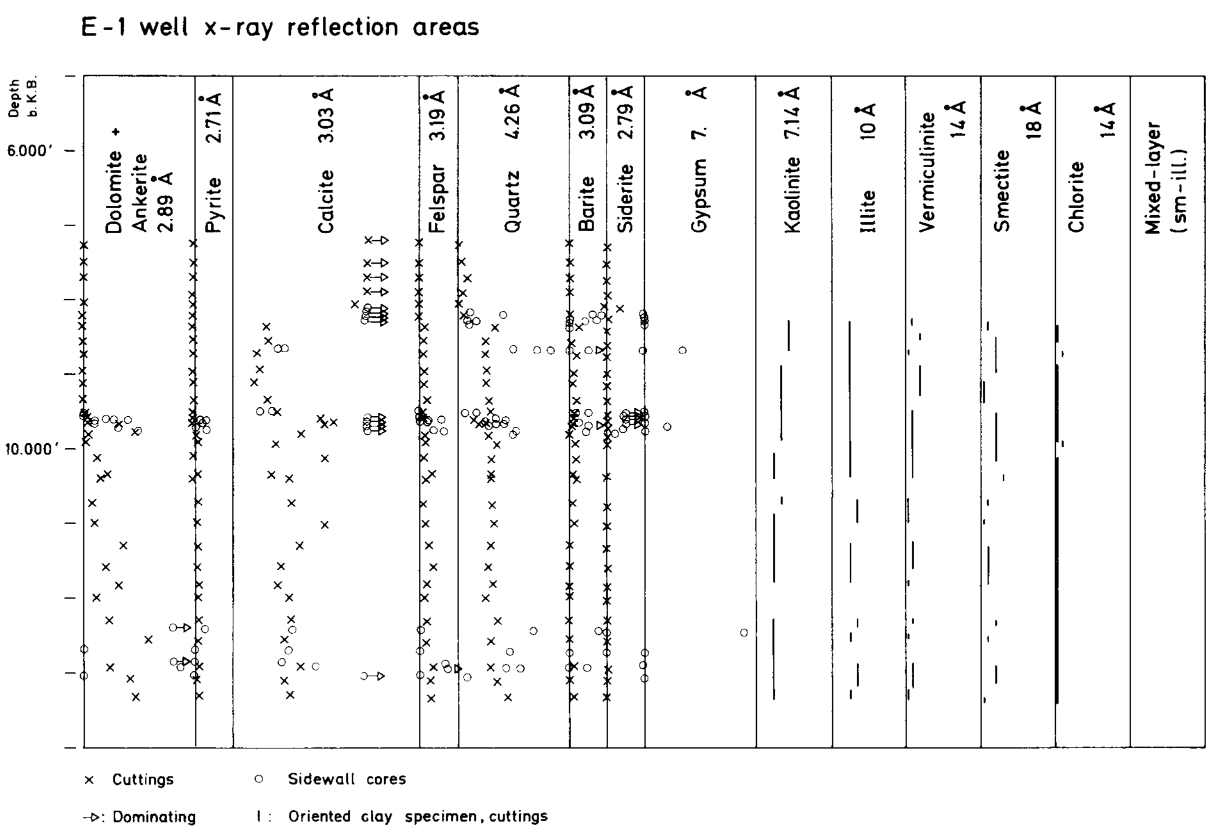


Fig. 41: X-ray reflection areas in the M-8 and E-1 wells.

out on samples from the M-8, U-1, E-1, and I-1 wells (fig. 38). The Tertiary sequences are immature in these wells.

5.4 Regional rank conditions

Fig. 38 shows vitrinite reflectance trends for a series of wells located on a north-south line through the Danish Central Graben with the I-1 well representing the northernmost location.

In the wells E-1, M-8, and I-1, the Cenozoic-Mesozoic sequence has been studied in detail. In the U-1 well only a preliminary study of this interval has been carried out.

The results show significant differences in the rank conditions. The highest rank is attained in Upper Jurassic sediments in the I-1 well. Compared with the southern wells M-8 and U-1, 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 gradients, i.e. the rank increase with depth, are lower in the E-1 and U-1 wells as compared to the I-1 well, whereas the M-8 well has an intermediate rank gradient. This is illustrated by a comparison between the E-1 and I-1 wells at comparable stratigraphic depths, i.e. Upper Jurassic sediments at a depth of approximately 3500 m (11500'). The E-1 well is just approaching the zone of actual oil expulsion (about 0.70 %RO), while the I-1 well is within the zone of maximum oil generation (0.80-0.90 %RO).

For sediments of approximately similar age and rank ranges, different rank gradients will 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 or 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 influence of which is reflected in the reflectance trend of this well. The E-1 and U-1 wells are located in areas 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.

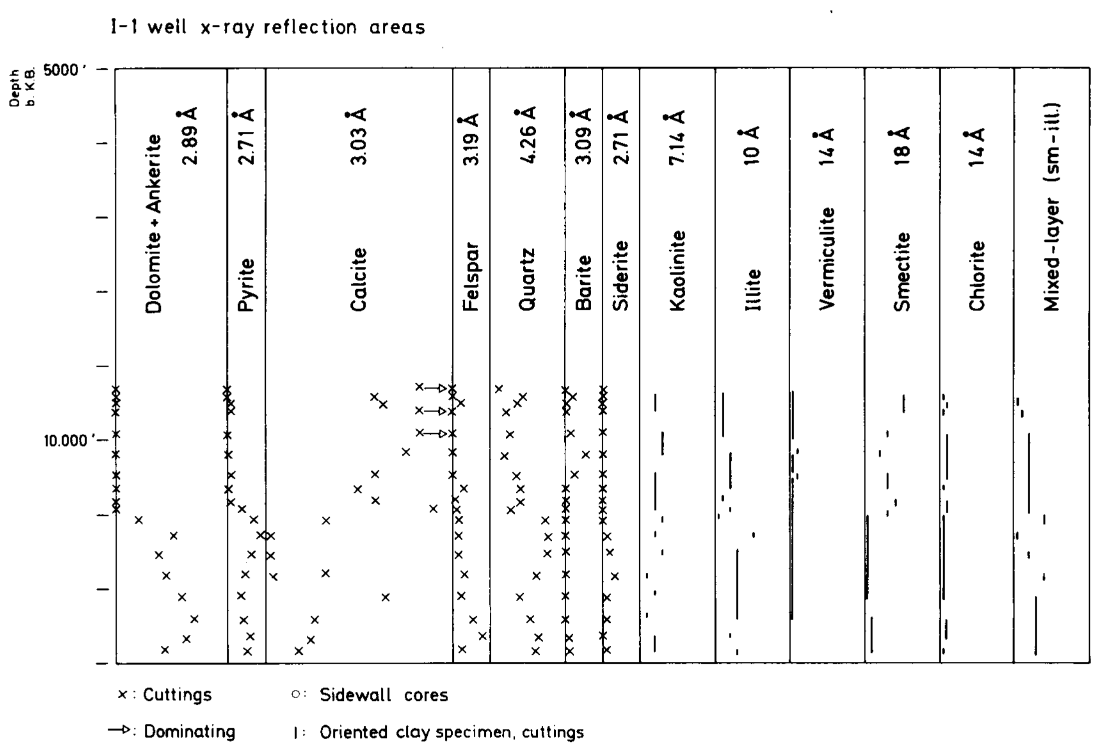


Fig. 42: X-ray reflection areas in the I-1 well.

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

5.5 Regional diagenesis

The mineralogy of the E-1, I-1, and M-8 wells is shown in figs. 41 and 42. Some minerals are detrital (quartz, some of the felspars, some clay minerals), some formed during sedimentation and early diagenesis (microcrystalline pyrite, some smectites, most of the calcite, and siderite), some are detrital minerals altered during diagenesis (mixed-layer clay minerals), and some were formed during late diagenesis (kaolinite, mica, well-crystalline pyrite, ankerite, dolomite, some of the felspars). Judging from the mineralogical investigations - by scanning electron microscopy, X-ray diffraction, Moessbauer spectroscopy, X-ray fluorescence, and differential thermal analysis (with gas detection and quantitative determination of evolved CO_2, H_2O, and SO_2) - kaolinite was probably formed during an early fresh water diagenesis, and mica (or at least a potassium fixation by expandable clays) was formed during a late brine diagenesis, in agreement with Millot (1970) and Hancock & Taylor (1978). In the investigated well sections, the formation of a well-crystalline pyrite, dolomite, ankerite, and of Na-feldspars, seems to have taken place during the same stage of diagenesis as the formation of mica or of potassium three layer clay minerals, i.e. during a late brine diagenesis.

The correlation between the rank of the vitrinite and the degree of late diagenesis (as measured from the dolomite+ankerite/calcite ratio) is fairly good for sediments older than the Cretaceous, whereas it is low for younger sediments (figs. 38, 39, 40). The late diagenesis is strongly influenced by the heat flow as well as by the brine chemistry, which partly explains the positive correlation. However, a certain heat threshold is presumably necessary for the late diagenesis to take place, whereas the rank of the vitrinite does not have such a precise threshold. This might explain the low correlation above the Jurassic-Cretaceous boundary.

As seen from the correlation between the rank data and the degree of late diagenesis, the Jurassic of the O-1 and A-2 wells are at the same level of maturity as that of M-8 (figs. 38, 39, 40). The well sections, G-1 and V-1, are furthermore at the same maturity level as E-1, although G-1 has undergone a little stronger diagenesis than E-1. On the contrary, the Jurassic deposits in the northerly located wells Q-1 and W-1 have undergone only weak diagenesis and seem to be only slightly mature despite the greater depth.

5.6 Source rock catalysis

Several publications refer to the importance of the presence of clay minerals for the catalytic processes during oil formation (Andeev et al. (1968), Sarkusyan (1970), Weaver (1960), and Hatch & Matar (1977)). In all studied wells, the Jurassic clays and Lower Cretaceous clays contain a fair to large amount of expandible, large-surface area clays, giving the rock fair to good catalytic properties.

5.7 Organo-chemical investigations

Figs. 43 to 46 show some selected results from the chemical investigation of the M-8, and I-1 wells.

M-8 well: Apart from 2 samples, the organic carbon content is below 2% to a depth of approximately 10100', where an irregular increase takes place (fig. 43).

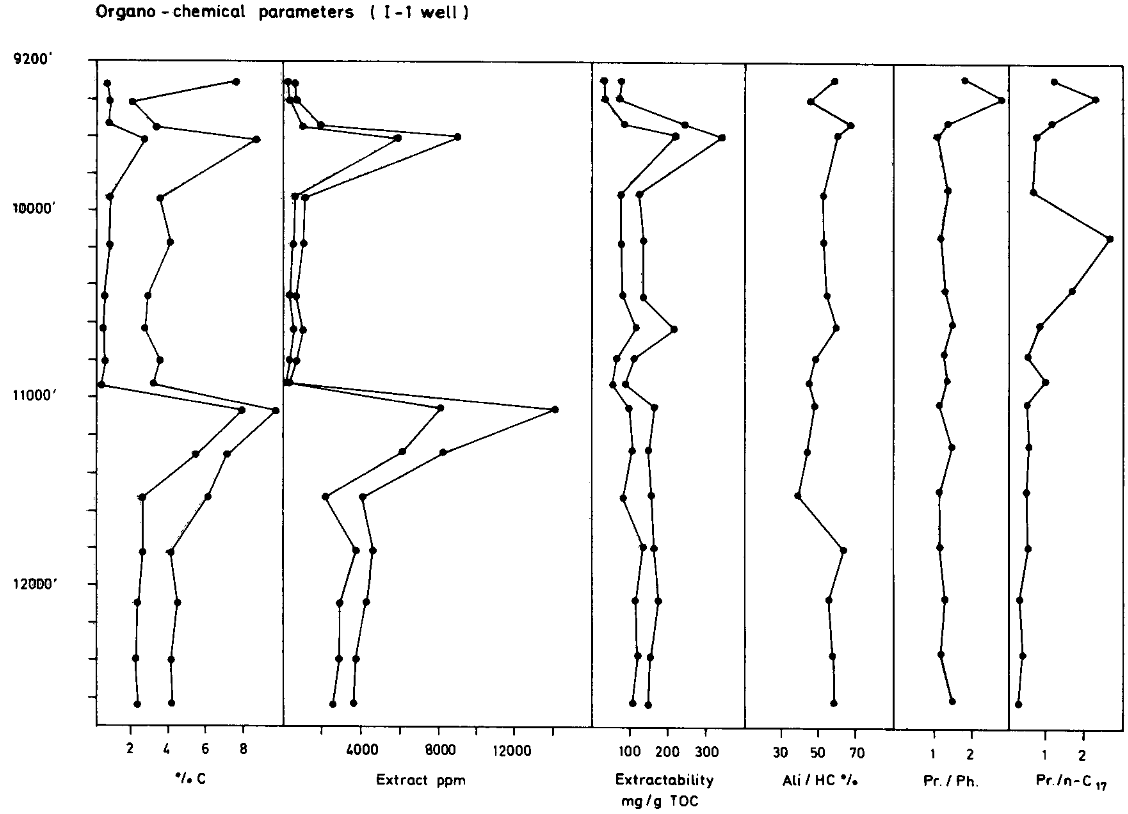
This is reflected in an increase in the amount of extract from the samples, but not in a significant increase in extractability. This means that although some levels (e.g. 10230') have produced large amounts of oil, significant migration will probably not take place.

The alifate/hydrocarbon ratio reflects increasing maturity and increasing influx from terrestrial material with depth.

The pristane/phytane ratio indicates increasing input of oxidized material (e.g. higher land plants) from 9000' to 10400'. Apart from a few levels with biodegradation, the pristane/n-C17 ratio reflects increasing maturity with depth. The value is rather high, indicating low maturity.

Fig. 44 shows the composition of the extract from M-8. The positions of the samples below 9930' are typical for marginally mature to mature extracts containing terrestrial material. Notice the position of the Dan field oil, which is typical for a migrated oil.

Fig. 45 shows the gas-chromatograms from the alifate fraction. The Dan Field oil shows the characteristic pattern for a partly bio-degraded oil. The horizons 7140', 7440', and 7530' show immature ex-



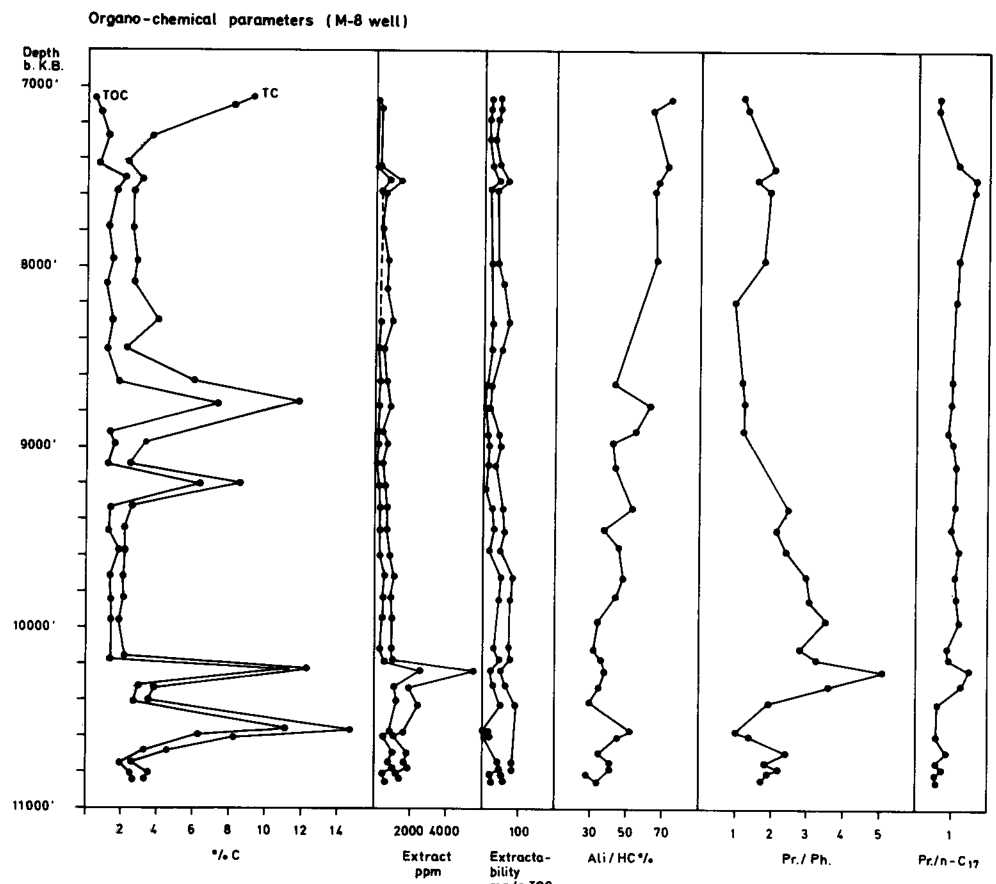


Fig. 43: Oroganо-chemical parameters for the I-1 and M-8 wells. TC = total carbon, TOC = total organic carbon, SOM = soluble organic matter, HC = hydrocarbons, Ali = slifate fraction, Pr = pristane, Ph = phytane.

tracts from algal material. Rock-Eval analyses indicate the horizon at 7530' as a potential source rock.

The J-3 Unit represented at 9720' shows a shift to a clearly different type of material (oxidized terrestrial). The horizon at 10230' indicates highly oxidized oil-prone material. The Rock-Eval analysis shows a great residual potential for oil. The horizons at 10410' and 10800' indicate more reduced material. The horizon at 10800' contains significant amounts of more waxy components from higher land plants.

I-1 well: Apart from the horizon at 9610', the organic carbon content is below 1% down to 11000' (fig. 43). Below 11000' the carbon content is very high. The amount of extract reflects organic carbon content and is much higher than in M-8. Below 11000' the extractability is nearly constant with values near the maximum value for a well-mature source rock for oil.

The two high levels in extractability at 9610' and 10630' indicate migration. This is confirmed by the high alifate/hydrocarbon ratio. More than 2/3 of the extract at 9610' is presumably migrated oil. A corrected value for the organic carbon indicates a source rock potential of the level.

The alifate/hydrocarbon ratio is rather constant around 50%, and the pristane/phytane ratio below 9500' is likewise constant with values around 1.3 indicating non-oxidized mature material of algal origin.

The high value of pristane/n-C 17 ratio at the levels 9410' and 10170' reflects bio-degradation presumably due to meteoric water. The low value below 11000' shows much higher maturity than in the M-8 well.

Fig. 44 shows the composition of the extracts. The positions for all extracts from levels below 11000' are within the limits for well mature oil source rocks.

Fig. 46 shows the gas-chromatograms from the I-1 well. Apart from the horizon at 9610', which contains more heavy paraffins, the extract is dominated by light components. At 9410' and 10170' bio-degradation has taken place. At 11050' and 12640' mature material from algal origin dominates the extract.

The formations below 11000' are regarded as the best source rocks in the examined wells. The deepest level still has the characteristics of a rich source rock.

5.8 Regional variations

The limited number of wells investigated makes a general source rock evaluation for the entire Central Graben area impossible. There are, however, indications for some trends which should be noticed.

The low content of organic matter found in most Cretaceous samples indicates poor source rock potential.

The J-4 Unit contains generally high amounts of oil prone material and it is probably the most important source rock in the area. The amount of material in this formation tends to be more than twice as high in the northern I-1 well as compared to the southern wells. Similarly the amount of generated oil is much higher in the I-1 well than in the M-8 well, but due to the possibility of heatflow anomalies this interpretation should be taken with reservations.

The results from the M-8 well indicate the same variation in the J-3 Unit as in the J-4 Unit, but the type

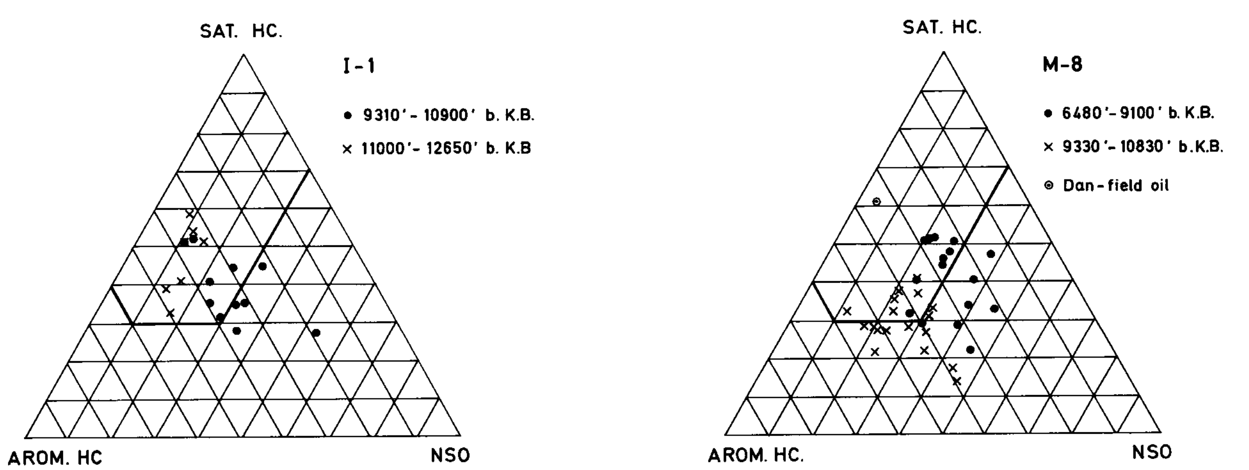


Fig. 44: Composition of extracts of the I-1 and M-8 wells. – SAT. HC. = saturated hydrocarbons, AROM. HC. = aromatic hydrocarbons, NSO = hetero-compounds.

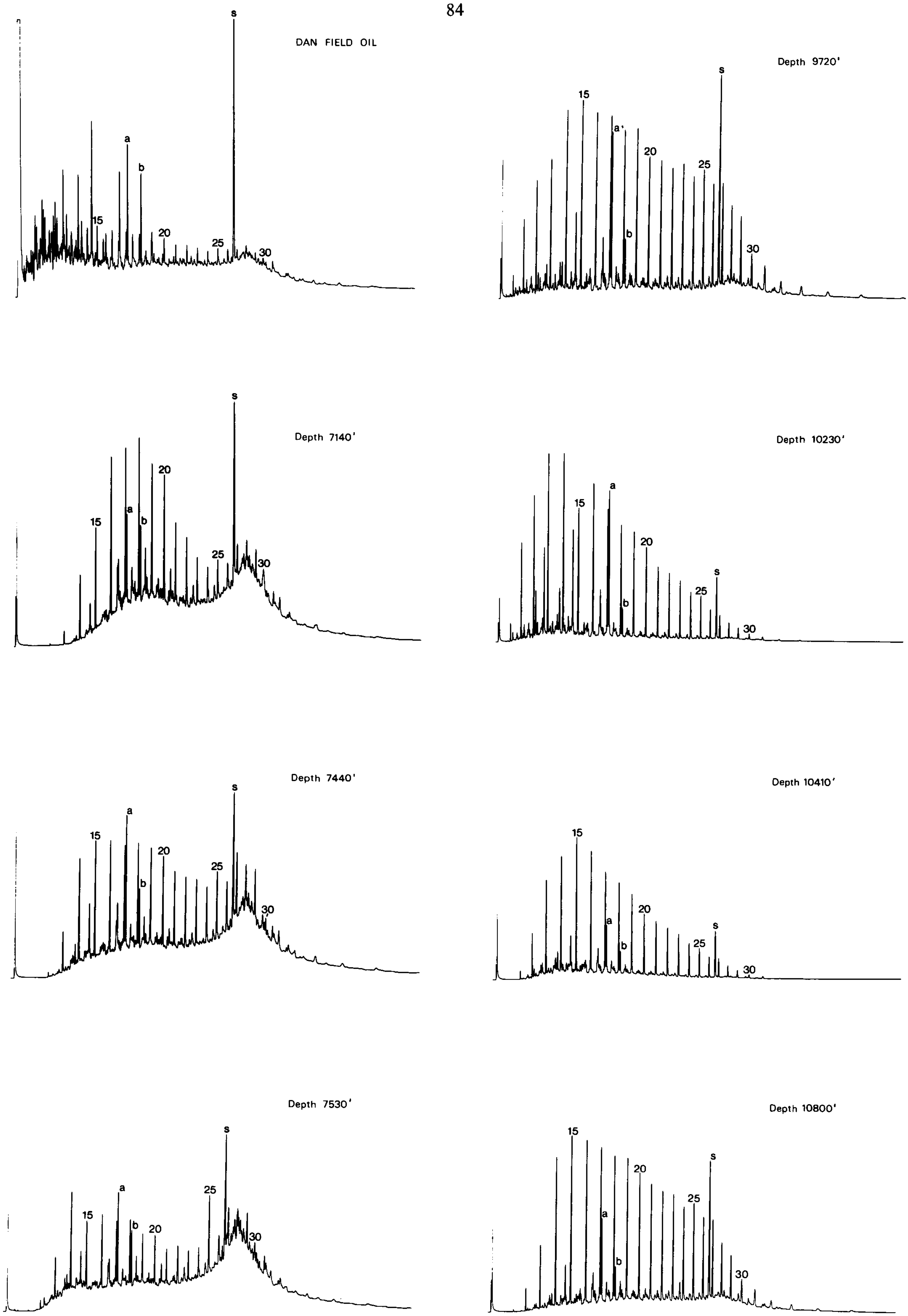


Fig. 45: Gas-chromatograms for the M-8 well. a = pristane, b = phytane, s = squalane (internal standard).

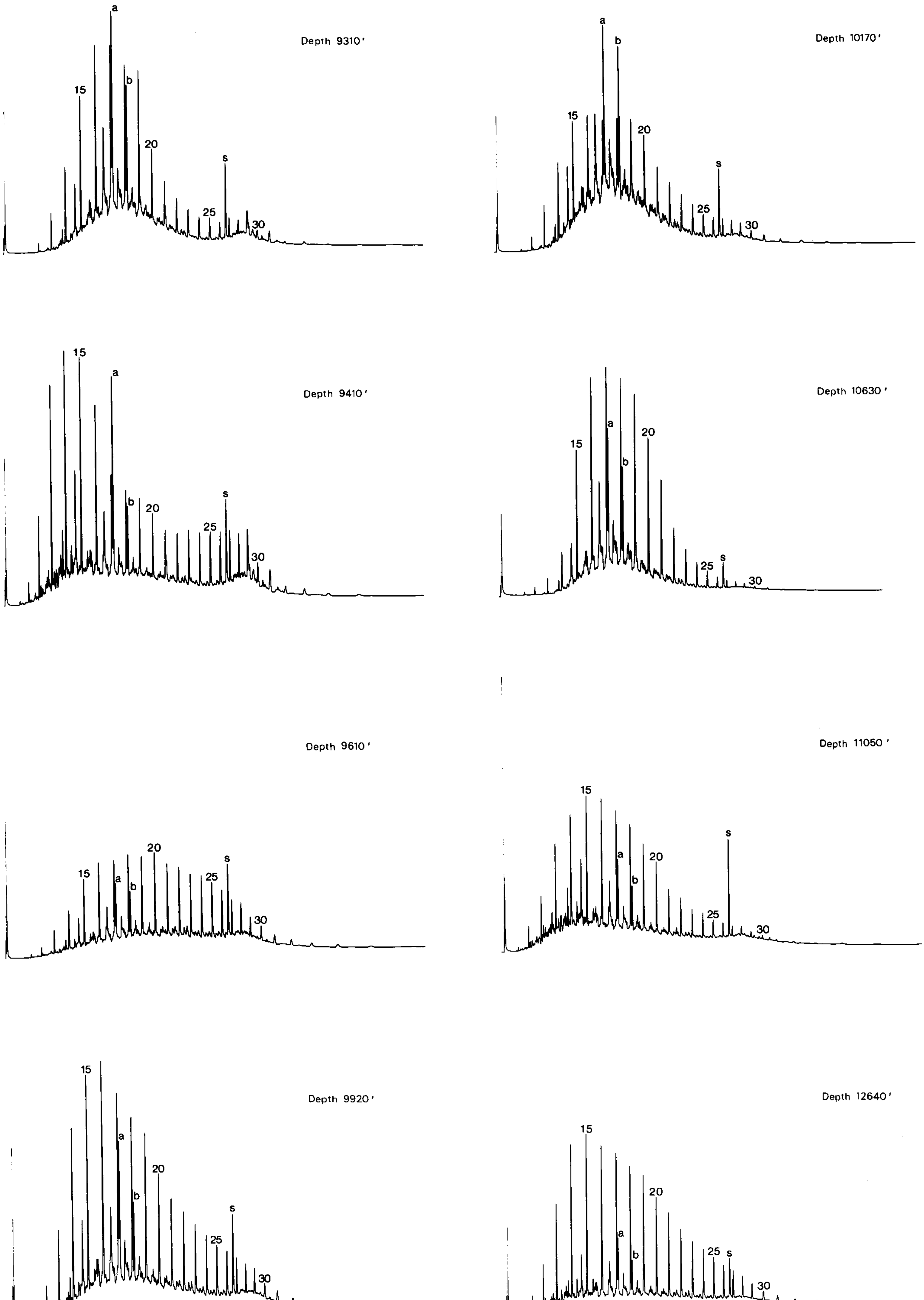


Fig. 46: Gas-chromatograms for the I-1 well. a = pristane, b = phytane, s = squalane (internal standard).

of material in the J-3 Unit is not as favourable as in the J-4 Unit.

The maturity parameters correlate to the rank gradients, with the same limitations.

5.9 Conclusions

The J-4 Unit is regarded as the principal source rock for oil in the study area. It is of a considerable thickness and the amount and type of organic matter is favourable. Data from the northern well (I-1), the central well (E-1) and the southern well (M-8) 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 southern wells. 3) In the northern well the entire J-4 Unit 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. The formation therefore must be regarded as a better oil source rock in the northern well. However, assuming sufficient burial, as seen in the M-8 well, the formation is still a good source rock in the southern area.

The conclusions are severely hampered by the limited number of wells drilled, especially in the northern area. The investigations show that the study area is very complex with respect to the amount of organic matter as well as the maturity conditions. Therefore, a detailed mapping of the source rock potential of the study area is strongly needed.

6.0 Potential hydrocarbon traps

By Jens Ole Koch

The formation of hydrocarbon traps is the result of local depositional and deformational history. The trap formation is governed by three main parameters: the geometry of the reservoir body, the sedimentary sealing history and the tectonic history. In the present chapter is discussed the distribution of potential hydrocarbon traps in different areas, each characterized by a structural style (figs. 47, 48). After a short definition of basic trap types, various areas of the Danish Central Graben, each of which is characterized by a certain structural style, are listed and described with emphasis on the distribution of potential hydrocarbon traps.

6.1 Definition of basic trap types

A hydrocarbon trap is a closed structure with a reservoir rock overlain by impermeable strata. The seal/reservoir interface may conform with the boundary of the two formations, but it is often a complex of unconformities and fault contacts between the reservoir body and various seals. Two basic types of potential traps exist, namely stratigraphic traps and structural traps (fig. 48).

Stratigraphic traps

A stratigraphic trap is a laterally limited reservoir body, sealed by impermeable strata. Inter alia, the reservoir may be alluvial or submarine fans fringing a sub-aerially exposed 'high' area, carbonate reefs, fluvial channel sands, and diagenetic formed high porosity zones. The seal may either be comformably deposited upon the reservoir body, or the reservoir body can be truncated and unconformably overlain by the seal. Consequently, there are two sub-types: Primary and secondary stratigraphic traps (fig. 48).

In primary stratigraphic traps, the reservoir is conformably overlain by the seal. The geometry and size of the trap is delineated by the original upper depositional surface of the reservoir body and possibly also by syn-sedimentary faults.

In secondary stratigraphic traps, the reservoir body is truncated and unconformably overlain by the seal. The geometry and size of the trap is defined by the topography of the erosional surface of the reservoir body.

Stratigraphic traps may retain hydrocarbons in completely undeformed areas, but they may also be deformed, which either improves or reduces their hydrocarbon trapping capability.

Structural traps

A structural trap is a laterally limited or unlimited reservoir body, which is overlain by an impermeable seal. It has been deformed into an upwhelming closed structure capable of trapping hydrocarbons.

Among a number of factors the deformation can be caused by extension, compression, density contrasts, differential loading, wrenching, or uplift. Two basic sub-types of structural traps can be distinguished:

Fault traps are situated in tilted fault blocks. The

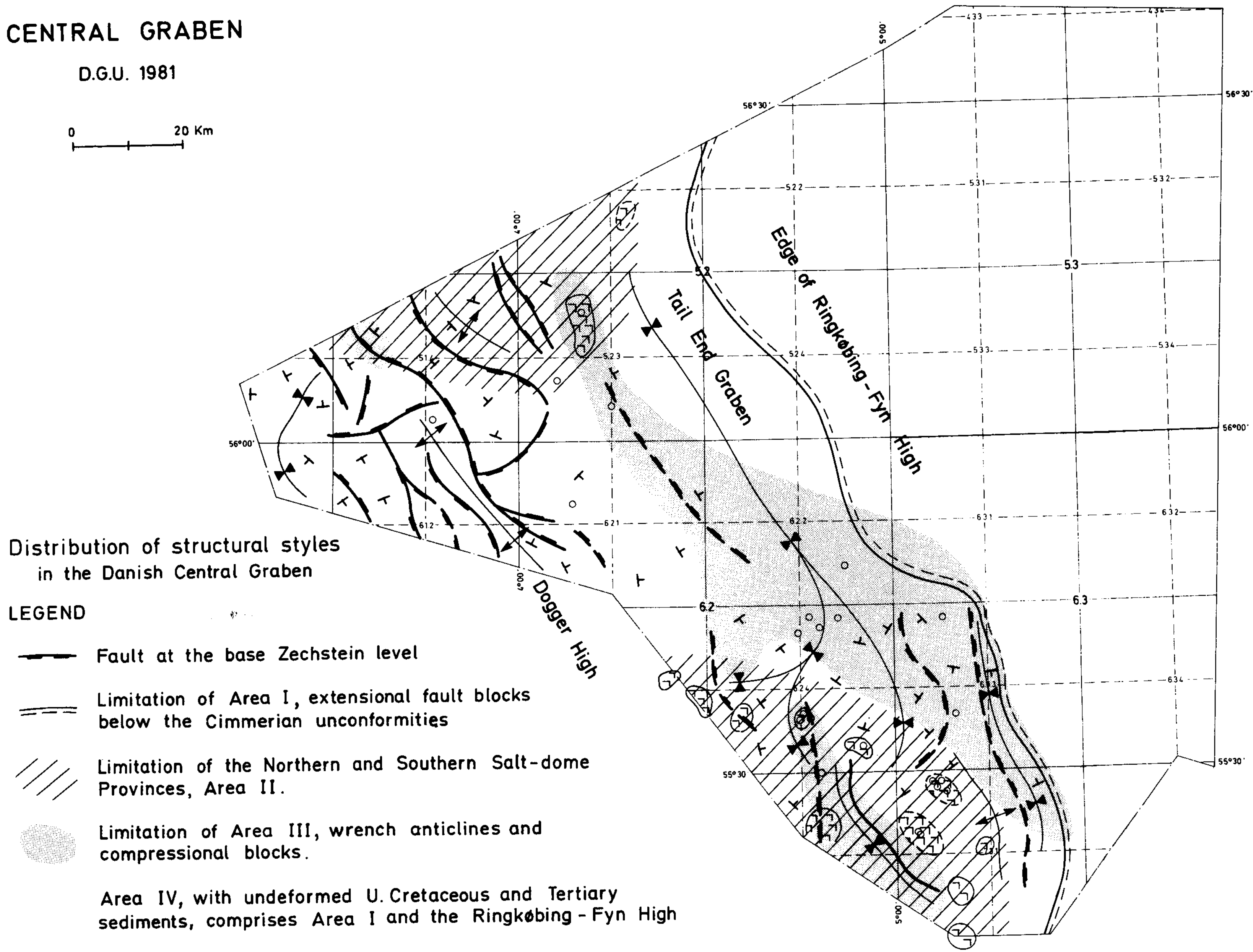


Fig. 47: Regional subdivision of the Central Graben area based on structural styles.

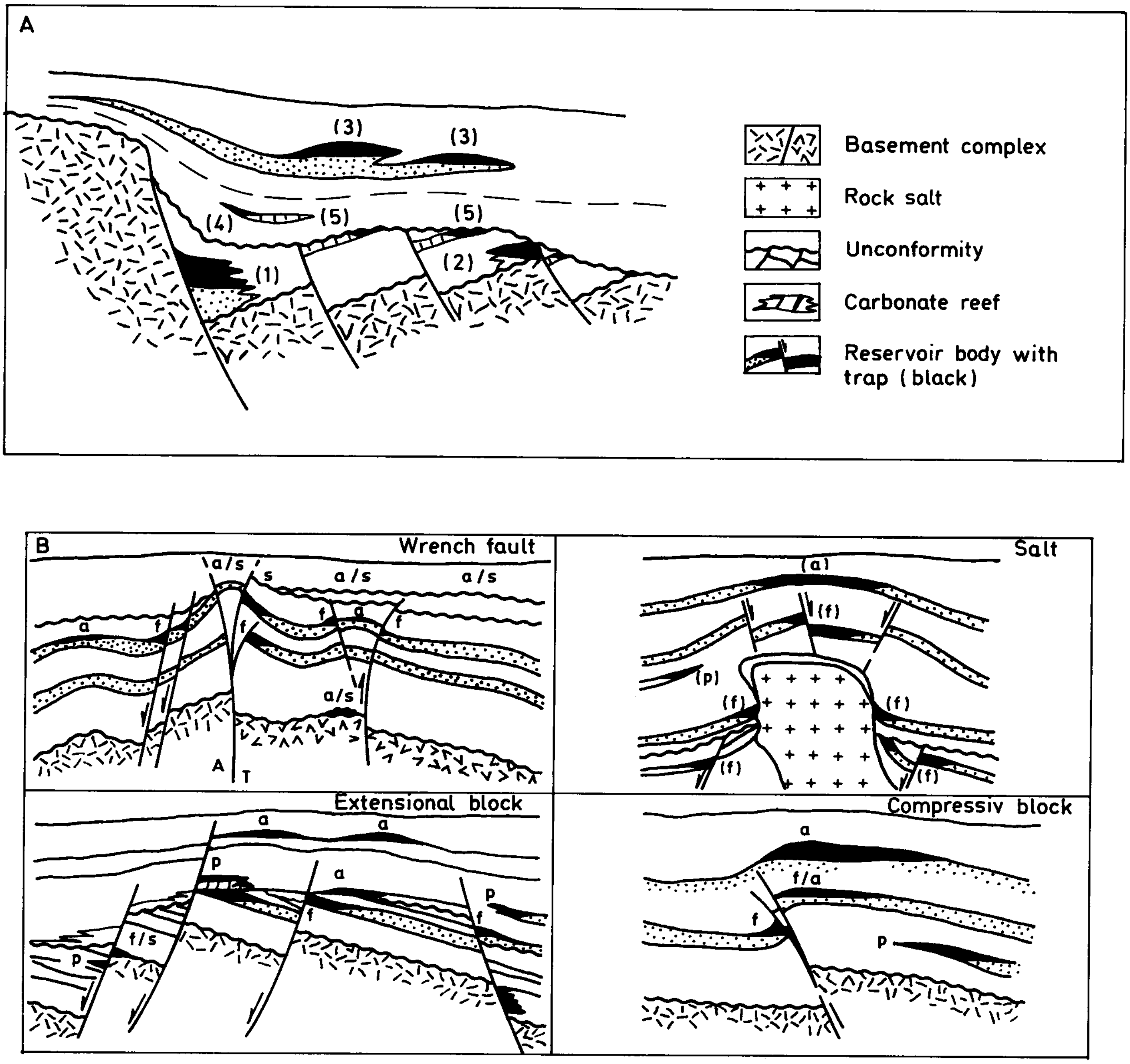
traps are delineated by fault planes, often on several sides, and by the overlying impermeable stratum.

Arch traps are upwhelming domes or arch structures with or without faults. The trap is delineated by the geometry of the domal surface of the reservoir rock.

Various structural traps often co-exist and a structural trap might be composite, e.g. composed by a fault trap on one side and an arch trap on the other (fig. 48).

6.2 Distribution of potential hydrocarbon traps

The formation of hydrocarbon traps is the result of the local depositional and structural history. This is, however, to a large degree governed by plate interactions or plate tectonic settings (Dickinson 1974). Harding & Lowell (1979) recognized eight different assemblages of geological structures, which they



DGU 1981

Fig. 48: Schematic diagrams of hydrocarbon traps. a) Stratigraphic trap in mainly undeformed sedimentary strata. (1)–(4) Primary stratigraphic traps: (1) alluvial fan, (2) carbonate reef, (3) submarine fan, (4) high porosity zone, (5) secondary stratigraphic trap. b) Distribution of traps related to wrench faults, salt diapirs, extensional blocks and compressive blocks. a = structural arch trap, f = structural fault trap, p = primary stratigraphic trap, s = secondary stratigraphic trap. T = displacement towards viewer, A = displacement away from viewer. Modified from Harding and Lowell (1979).

termed structural styles, and discussed their plate tectonic habitats and the distribution pattern of hydrocarbon traps. Blair (1975) and Ziegler (1977) reviewed the structural styles encountered in the North Sea in general.

The Late Palaeozoic to Mesozoic North Sea Grabens evolved in an intra-plate setting as interlinked rift systems which were dominated by extensional faulting. Thus, extensional fault blocks are recognized as the first structural style in the Danish Central Graben. The rifts failed to evolve further in Early Tertiary time, when active spreading and ocean floor formation took place elsewhere in the incipient Norwegian-Greenland Sea (Whiteman et al. 1975, Ziegler 1975, 1981). Thus, deep-seated NW-SE directed dextral strike-slip movements, probably related to the establishment of the new spreading center and the Laramide orogeny (Ziegler 1981), caused compressional and wrench deformation in certain areas of the Danish Central Graben. Consequently, wrench anticlines and compressional blocks are recognized as the second structural style.

The third structural style is found around salt pillows and salt piercement domes. This structural style is not derived from the large scale tectonic episodes but arises from halokinetic movements.

Undeformed or weakly deformed sediments and late movement structures are recognized as the fourth structural style in the Danish Central Graben.

Each of these four structural styles is distributed in certain areas which, however, to a great extent overlap each other. The distribution within the Danish Central Graben may be summerized as follows (fig. 47):

Area I: The Dogger High area and large parts of the Danish Central Graben floor was affected by extensional normal faulting and, as a result, extensional fault blocks can be found below the Cimmerian unconformities in this area.

Area II: The salt domes are located in a Southern and a Northern Salt-dome Province, which overlap area I. As a consequence, both deep-seated extensional fault blocks and salt structures are present in this area.

Area III: Late Cretaceous-Early Tertiary wrench anticlines and compressional blocks are concentrated in three zones. In these zones, pre-existing normal faults were re-activated, and strike-slip faulting created a complex pattern of anticlines and deformed salt domes.

Area IV: Above the Ringkøbing-Fyn and the Dogger Highs, and in the parts of the Danish Central Graben, which were neither affected by the three wrench zones nor by pronounced halokinesis, the Cretaceous and Tertiary deposits are undeformed.

In the following the four above mentioned structural styles encountered in the Danish Central Graben are described and discussed with respect to their geographical setting, history of development, and capability of forming hydrocarbon traps.

AREA I - Extensional fault blocks

Geographical setting: Extensional fault blocks are generally found in the Dogger High area and in the Central Graben floor outside the wrench zones (area I in fig. 47).

Geological description: In the North Sea Basin, normal faulting of the basement was the main tectonic agent in the formation of the Late Palaeozoic-Mesozoic rift systems. Sedimentation and basin formation was strongly controlled by normal faulting, which acted synsedimentarily along the structural highs. The basin floor was faulted and divided into several rotated fault blocks during the tectonic episodes in Permian, Triassic and Jurassic time.

The NW-SE faults in the Central Graben, outlined on the Base Zechstein structural map (fig. 5), define a system of tilted NW-SE trending elongate fault blocks parallel to the basin axis. The faults are generally normal faults which cut the pre-Permian basement and most of the Mesozoic sequence (fig. 13). These tilted and elongated extensional fault blocks are unconformably overlain by the Cretaceous and Tertiary formations. The fault blocks may be divided into the following three categories depending on their geological setting: The Dogger High horsts, the down-faulted blocks along the margins of the Dogger High and the Ringkøbing-Fyn High, and the extensional fault blocks in the basin floor.

Distribution of potential hydrocarbon traps: Structural fault traps are generally located on the upthrown edge of tilted fault blocks. Closures face the fault plane and conformably overlie impermeable strata (figs. 11, 13). If the crest of the tilted fault block has been truncated by erosion and unconformably overlain by a seal, the trap turns into a secondary stratigraphic trap type. In this type, the geometry of the trap is determined by the shape of the erosional surface. However, these elements are often combined so that a trap is outlined by the unconformity, as well as by fault planes which originated from later reactivations of the extensional faults.

Extensional fault block structures have not so far been drilled in the Danish sector, but the structural style is well exemplified e.g. by the Brent (Bowen 1975), Argyll and Brae (Harms et al. 1981) fields from the U.K. sector.

The Dogger High horsts: In the Dogger High horsts Palaeozoic reservoirs could be present in structural high positions and in lateral contact with Jurassic source rocks. Potential structural traps are present in the up-thrown edges of the horsts, where the old reservoirs might be sealed by the Late Cimmerian unconformity.

The down-faulted marginal blocks: Along the margins of the Dogger and the Ringkøbing-Fyn Highs, stratigraphic traps are probably located in the down-faulted marginal blocks (fig. 11). The reservoirs might for example be alluvial fans, nearshore sands (like the W-1 Unit) or deltas which fringed the highs in Jurassic and Cretaceous time (fig. 12).

The basin floor blocks: The extensional blocks in the basin floor generally trend NW-SE, and tilt towards the basin axis (fig. 47). Thus, potential structural fault traps are located in the upthrown edge of the blocks. The reservoirs might be conformly sealed, or the crest of the tilted fault blocks might be truncated and unconformly sealed. Undulations along the fault plane could create local closures in structural high positions.

AREA II - Salt pillows and salt piercement domes

Geographical setting: Two separate areas of this structural style are encountered in the Danish Central Graben. 1) The Southern Salt-dome Province occupying the southwesternmost part of the Danish sector and 2) the Northern Salt-dome Province occupying the northwestern, central part of the Danish sector (fig. 47).

Geological description: The density of rock salt is lower than the density of most other rocks. Furthermore, rock salt differs from most other rocks in its deformability by viscous flow. Consequently, deeply buried rock salt has a capacity for vertical mobility independent of external tectonic forces. However, deeply buried rock salt generally has been mobilized by an external tectonic event, which has initiated the onset of halokinesis. Structures of this origin are considered here as modifications of the particular structural assemblage with which they have developed.

In the Danish Central Graben, thick strata of rock salt, probably of Zechstein age, are buried below several kilometres of Mesozoic and Cenozoic sediments. The overburden, and the density contrast between overburden and salt, has caused the salt to move upwards by buoyancy. The salt domes have undergone a complex evolution through an initially much broader pillow into the piercement stage, where the salt may have pierced through most of the Mesozoic formations into the Upper Cretaceous Chalk Group. In contrast to the initial pillow stage, the piercement domes are narrower with diameters generally less than half the diameters of the pillows.

The evolution of salt domes has been influenced by accumulation rate, progradation rate, differential loading, regional dip of the base of the salt, density of overburden and salt, original thickness of the salt formations, and by the competance of the salt as well as that of the overburden. As a consequence, the assemblage of salt domes can be divided into two basic types: 1) Salt pillows and 2) salt piercement domes. Among these the salt pillows can be divided into two types, the morphology of which is not well understood at the present stage of investigation: A) Salt pillows formed by active salt flow, and B) salt pillows formed as residual structures, where the surrounding salt masses have flown away into neighbouring salt domes.

Distribution of potential hydrocarbon traps: Salt pillows: In salt pillows the deposits overlying the pillows form gentle arching domes. The crests of the domes are often dissected by normal faults. Hydrocarbons are found in structural arches and fault traps at the top of domes, and might be trapped in several reservoirs at different stratigraphic levels. In the Anne structure and the Dan Field, the oil and gas is trapped in the Maastrichtian-Danian reservoirs, but additional accumulations of oil are present in the Middle Jurassic J-2 Unit.

Piercement domes: In piercement domes located in the Danish Central Graben, the Zechstein salt has pierced through or into younger sediments. Typically the level of piercement is within the Chalk Group (fig. 12).

Structural fault and arch traps are located above the crests of the domes in positions similar to those above salt pillows. However, the flanks of piercement domes are steeper, and the top traps are often closed against a circular fault system.

Structural fault traps may occur on the flanks with fault closure against the nearly vertical flanks of the piercement domes. As of the present date, such traps have not been drilled in the Danish Central Graben, although their hydrocarbon potential is well established in other countries.

A third possible trap position is found around the domes, where secondary stratigraphic traps may have been formed below the Early Cimmerian unconformity by truncation of the Triassic during the broader initial salt pillow stage (fig. 12). Such traps are uncomformably sealed by the Lower Jurassic Fjerritslev Formation. Similar secondary stratigraphic traps may also be present at higher stratigraphic levels, e.g. in the J-2 Unit, depending on the age of the pillow stage (fig. 12).

Piercement of salt into overlying formations may create a secondary fracture permeability in the reservoirs. The degree of fracturing is apparently high in structures with large scale piercement and low in structures with little or no piercement (see chapter 7).

AREA III - Wrench anticlines and compressional blocks

Geographic setting: Anticlines and compressional blocks are found in a broad NW-SE trending rhomboid area from the North Arne through the Bo, Adda, Tyra, and Igor structures into the Ringkøbing-Fyn High at an oblique angle. Furthermore, one small anticline is located north of the Dogger High, and one area extends southwards from the Gorm Field through the Lola Structure (fig. 47).

Geological description: The zones are composed by a system of en echelon of alligned anticlines trending NW-SE.

In Late Cretaceous time, five narrow anticlines probably existed inside the wrench areas. These anticlines are outlined as a Late Cretaceous inversion axis. They were presumably formed as a response to deep-seated NW-SE directed dextral strike-slip movements between the Ringkøbing-Fyn High and the NNW-SSE trending fault zone west of the North Arne and Bo structures.

Early Tertiary strike-slip movements continued the deformation and created the recent configuration of anticlines.

The Upper Cretaceous Chalk Group is generally less than 500 metres on the crest of the anticlines.

Distribution of potential hydrocarbon traps: The large rhomboid wrench area, and the smaller area south of the Gorm Field, may apparently be differentiated into three sub-areas, each characterized by a different type of anticline structures:

1) Along the eastern limitation, the very rigid Ringkøbing-Fyn High has been opposed to the less competent sediments of the Central Graben. Compressional strike-slip movements have created characteristic structures where the anticlines meet the High. These structures show good closures in potential structural fault and arch traps along the main fault zone bordering the Ringkøbing-Fyn High. Secondary stratigraphic traps may additionally be present where the Lower Cretaceous sequence pinches out in the marginal areas.

2) At the opposite side of the rhomboidal area, severe deformation has taken place in the fault zones stretching from North Arne southwards to the Bo structure, and southwards from the Gorm Field through the Lola structure. In these zones, older extensional faults were reactivated and locally reversed, and the Mesozoic sequence was folded into the NNW-SSE trending anticlines seen today.

The anticline is fault bounded around the North Arne structure, in which salt has pierced into the Upper Cretaceous Chalk Group. Structural arch traps are located over this structure, and structural fault traps possibly exist along the flanks. The flank faults die out towards the south, through the South Arne structure to the Bo structure, where the anticline has no faults on the flanks. A similar pattern is found in the southern wrench area, in the fault zone south of the Gorm Field through the Lola structure. The Gorm Field apparently occupies a position similar to that of the North Arne structure in the northern fault zone.

Potential structural arch traps are located in local culminations of the anticlines, but potential flank traps disappear with flank faults.

In parts of the NNW-SSE trending anticlines, faults are only present on one flank, as in the Lola structure and part of the South Arne structure. Due to the reverse compressional faults, good closures might be present both in the top of the anticlines and on the faulted flanks. Furthermore, secondary stratigraphic traps may be present on the flanks, where the Lower Cretaceous sequence pinches out against the anticline.

3) In the intermediate area between the Ringkøbing-Fyn High and the North Arne to Bo fault zone, the trend is a system of parallel-alligned gentle anticlines through the Tyra Field and the Igor and Per structures. In these anticlines, structural arch traps are located in local culminations, probably at several stratigraphic levels within the anticlines.

AREA IV - Undeformed sediments and late movement structures

Geographical setting: Weakly or non-deformed Cretaceous and Tertiary sediments cover the entire Danish sector outside the wrench zones (figs. 10, 13, 47).

Geological description: In Permian, Triassic and Jurassic times, the individual fault blocks of the Central Graben subsided differentially along normal faults. In Cretaceous and Tertiary times, however, this pattern changed into a more general non-fault controlled subsidence of the entire North Sea area. Therefore non- or weakly deformed Upper Cretaceous and Tertiary sediments cover large parts of the Danish North Sea. In these sediments, stratigraphic traps are expected to be present.

In some areas, however, late movements along old deep-seated faults resulted in uplift, which in some cases has created gentle structural arch traps. This mechanism is also termed 'drape' (Blair 1975).

Distribution of potential hydrocarbon traps: In non-deformed sediments, hydrocarbons may be trapped in primary stratigraphic traps. These are often expected to be located along structural highs, but e.g. Paleocene submarine fans cover most of the northern Viking Graben. Stratigraphic traps might be improved by differential compaction. This mechanism is based on the assumption that there is less lithostatic pressure on the crest of the reservoir body than on the flanks. As a result sediments on the flanks undergo greater compaction, and the vertical closure of the stratigaphical trap is improved.

Unlimited reservoirs and stratigraphic traps may in addition be weakly deformed by drape into gentle structural arch traps or late movement structures. Simple drape, as defined by Blair (1975), is caused by re-juvenation of deep-seated old faults, resulting in uplift and creating a gentle dome structure.

An example of this type of late movement structure is the Inge structure which is located over the crest of the Dogger High. This structure is characterized by a rather large areal closure and a relatively small vertical closure, which were probably induced by late movements along the Dogger High faults.

7.0 Reservoir rocks

By Finn Jacoben, Kirsten Lieberkind & Erik Nygaard

The present chapter contains a review of the potential reservoir rocks drilled in the Danish Central Graben. The source data for this descriptive summary originates primarily from wells drilled to explore chalk reservoirs. The main part of possible chalk reservoirs has been evaluated only by using wire line logs, since few cores have been cut and very few tests performed. Therefore, further investigations are necessary to evaluate and describe these possible reservoir rocks properly.

In this chapter, each zone in which shows have been recorded, and each porosity zone, is described. This is done with reference to the formations/log-units given earlier in the paper. The characteristics relevant to reservoir evaluation, such as the extension, thickness, depth, porosity, and permeability, are described. The characterizing terms (good, fair, etc.) used for reservoir parameters in sandstone reservoirs cannot be applied automatically to chalk reservoirs. The descriptions are accompanied by maps showing the known occurrences.

7.1 CA-1 Unit (Early Carboniferous)

Lithologic characteristics: Sandstone, siltstone, carbonaceous shales and sporadic coal seams.

Extension, thickness, and depth: According to Ziegler (1977), Carboniferous deposits are present in the major part of the Central Graben, but due to lack of data a delineation of the extension in the Danish sector is not possible. The thickness recorded in the P-1 well is 67 m, but the regional thickness may well be 100 to 200 m. Away from the highs, the deposits are mostly very deeply seated.

Reservoir parameters (fig. 49): Only the sandstones may be considered as potential reservoirs (net reservoir rock 13.5 m). The sandstones vary from fine to medium-grained, occassionally silty. The porosity varies from 5 to 15% (average 11%). Calcite cement has been found and may reduce the porosity.

Remarks: The section is stratigraphically below the known potential sources. Therefore the CA-1 Unit may represent a possible reservoir in faulted areas only.

7.2 Rotliegendes Group

Lithological characteristics: The lower section comprises volcanic tuff. The upper section consists of soft, and occasionally silty marl, interbedded with shale, and at the base sandstone.

Extension, thickness, and depth: The thickness of the Rotliegendes is, in the P-1 well, more than 200 m, but may be more than 1000 m in the central part of the basin. Away from the highs the series is very deeply seated.

Reservoir parameters (fig. 49): Only the sandstones may be considered to have reservoir properties. They are coarse to fine grained and occassionally silty or shaly. Calcite cement is found in the lower beds. The total known thickness of the group is 213 m, with a maximum net reservoir zone of 20.5 m. The porosity is rather low (2-10%, average 5%) due to cement and a varying content of clay and silt. The permeability is not known.

Remarks: No shows are found in the Rotliegendes in the Central Graben area, but gas finds are known from the southern North Sea, northern Holland, Germany, and Poland. The probable lack of source rocks below the Rotliegendes Group suggests that it may be a hydrocarbon-bearing reservoir rock in faulted areas, where it may be sourced from younger beds only.

7.3 Zechstein Group

Lithologic characteristics: This section is characterized by evaporites.

Extension, thickness, and depth: In the Central Graben, Zechstein deposits are mostly drilled on domal structures. Therefore the stratigraphy, lithology, thicknesses of the units, extension etc. cannot be clarified. In the basin between the structures the series is very deeply seated.

Reservoir parameters (fig. 50): Dolomitic intervals are the only possible primary reservoirs. From onshore wells the dolomite beds are known in some instances to have fairly high porosities and permeabilities. Often the pores in the dolomites are filled with anhydrite, which reduces the porosity to near zero.

Some cap rock anhydrites in Central Graben are fractured. Overlying oil may have migrated into these fractures, but permeability remains very low.

7.4 Bacton Group (Early Triassic)

Lithologic characteristics: Dominated by claystone which in some places can be silty, anhydritic, or calcareous. There are minor silt and sandstone beds.

Extension, thickness, and depth: The formation has been encountered in 3 wells only (B-1, Q-1, and U-1), but it is probably present in the entire area.

Seismic evaluation is possible only in the southern part, where the top Triassic varies in depth from 3000 to 4500 m. To the north, the group grades into the Smith Bank Formation (Q-1).

The thickness is fairly constant and greatest near topographic highs. The thicker parts seem to consist of relatively coarse-grained sediments derived from the highs. The net sand thickness therefore seems to be a result of local geological processes.

Reservoir parameters (fig. 50): Gas shows are recorded in the Q-1 well, but the available data allow no statements regarding the reservoir conditions.

In the study area there is fair data only from the U-1 well. Here the porosities of the sand beds are 10 and 17%, for the Bunter Sandstone and Bunter Shale respectively. The higher porosity in the intercalated Bunter Shale Formation sand beds may be due to a higher clay content, which would reduce the permeability. No data to clarify this question are available.

7.5 J-2 Unit (Middle Jurassic)

Lithologic characteristics: Interbedded pure sandstones, claystones and heterolithic sand-siltstones with coal seams.

Extension, thickness, and depth: The Unit may cover most of the Central Graben area, but it is until now known only in the A-2, M-8, O-1, and U-1 wells. Most of these wells are situated on domal structures. The influence of halokinesis on the thickness of the formation has not yet been clarified. In large parts of the

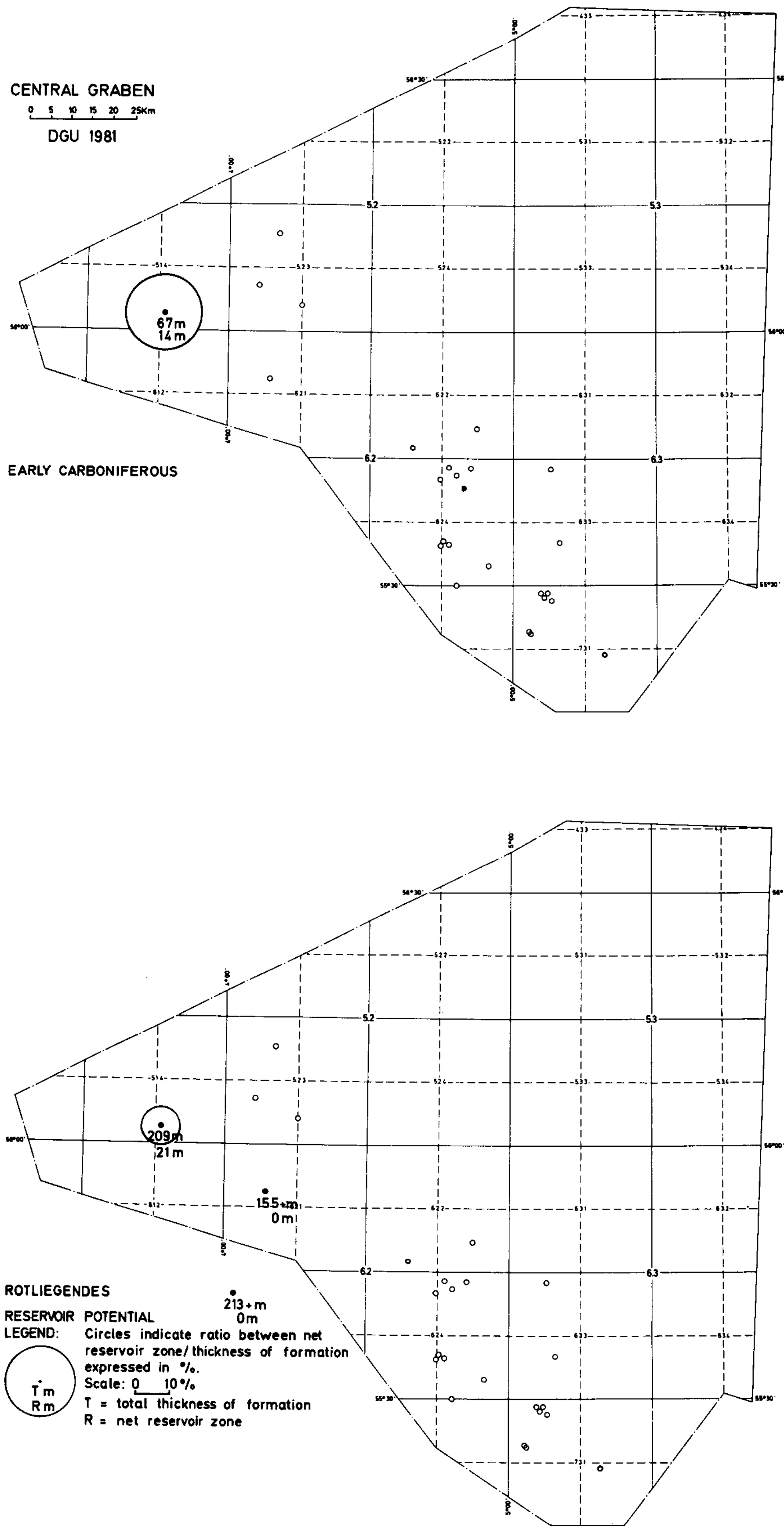
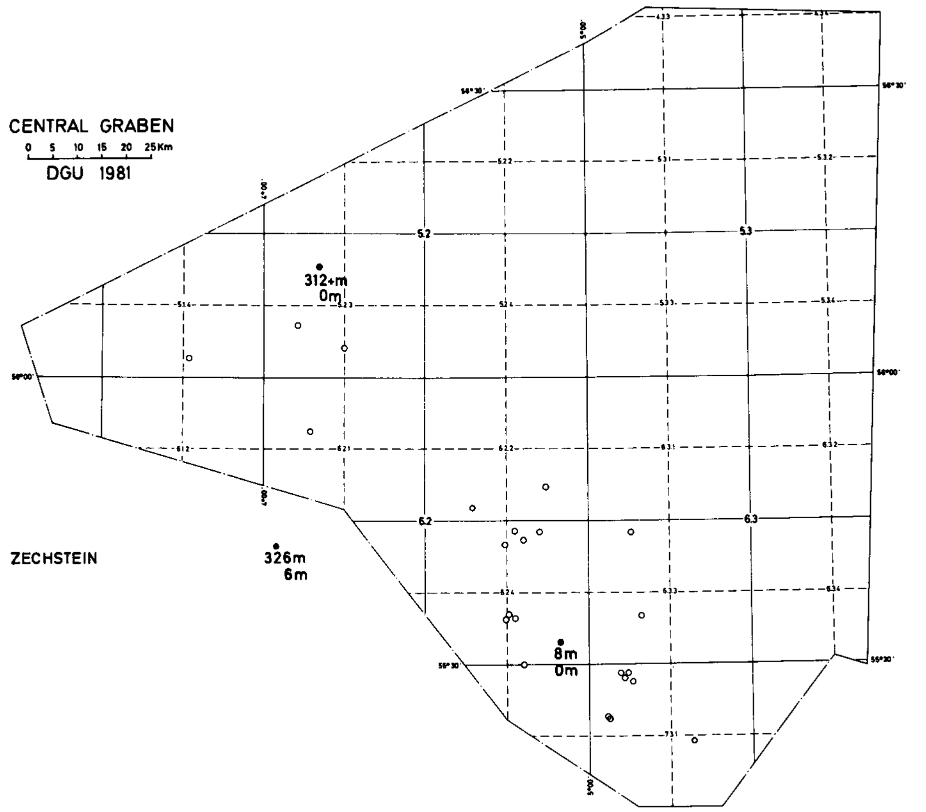


Fig. 49: The reservoir potential of a) Early Carboniferous and b) Rotliegendes section in the Central Graben area.



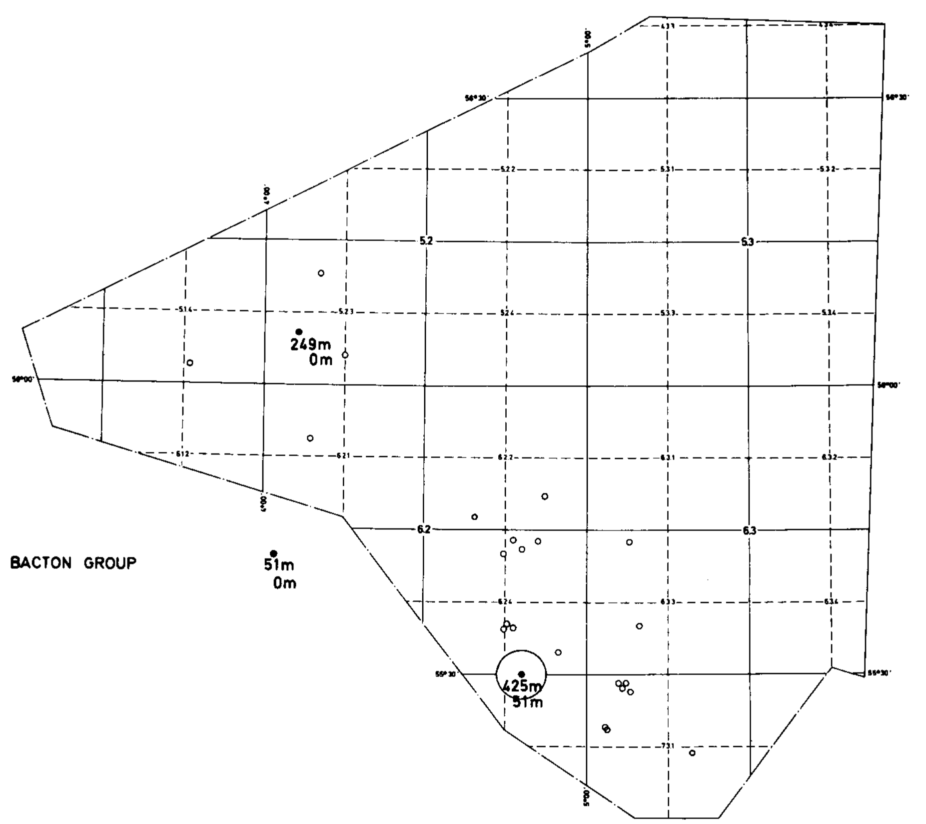
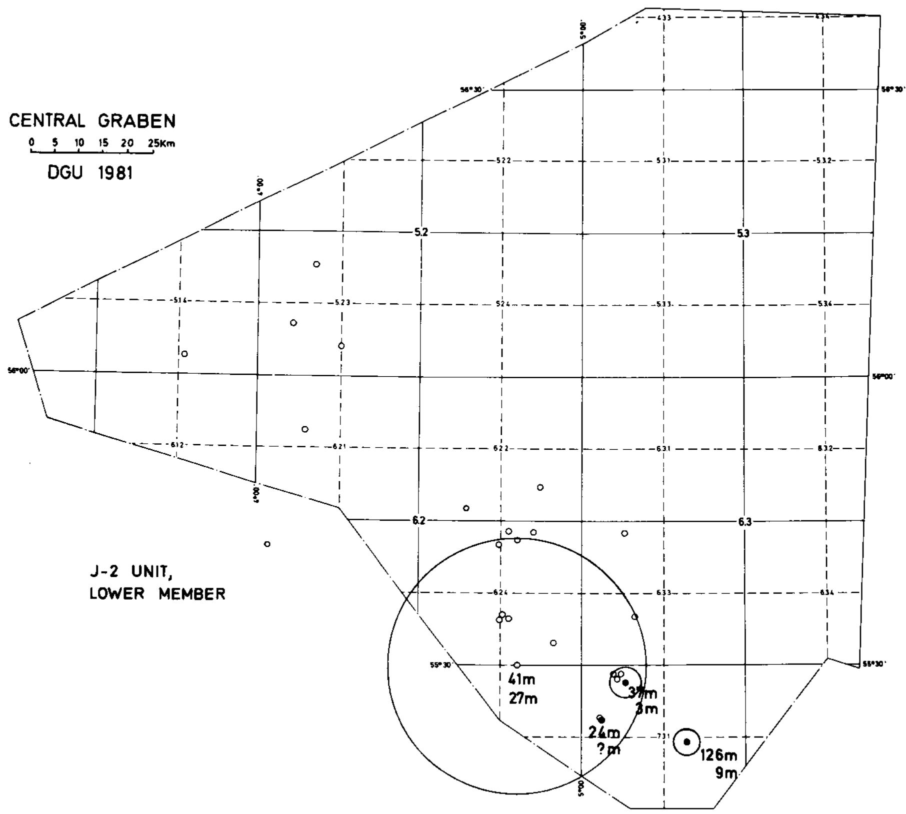


Fig. 50: The reservoir potential of a)Zechstein and b) the Bacton Group. – For legend, see fig. 49.



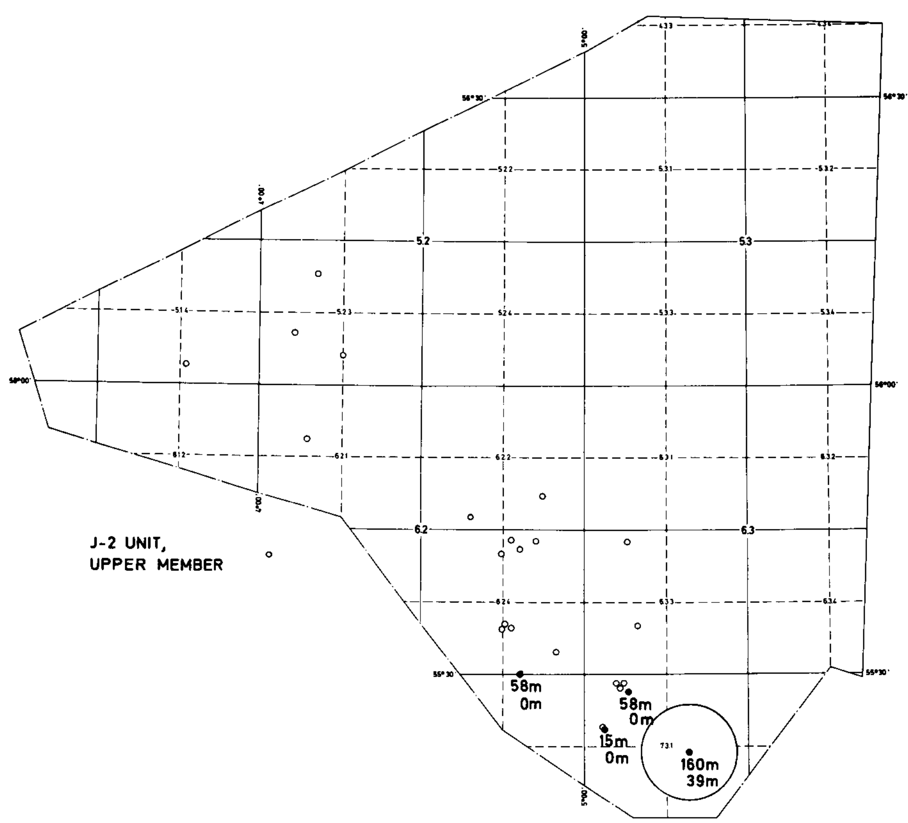


Fig. 51: The reservoir potential of a) the J-2 Unit, Lower Member and b) the J-2 Unit, Upper Member. For legend, see fig. 49.

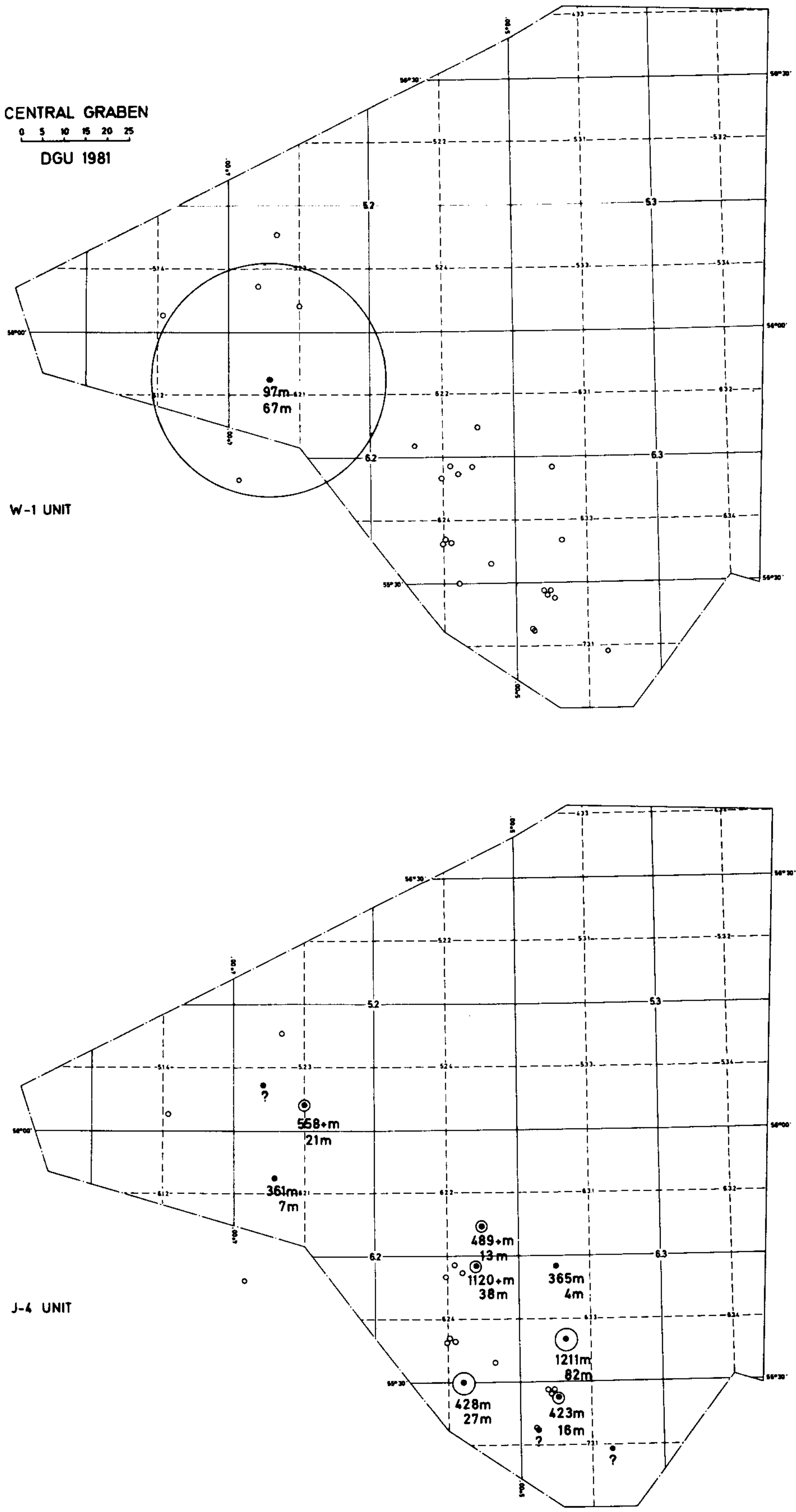
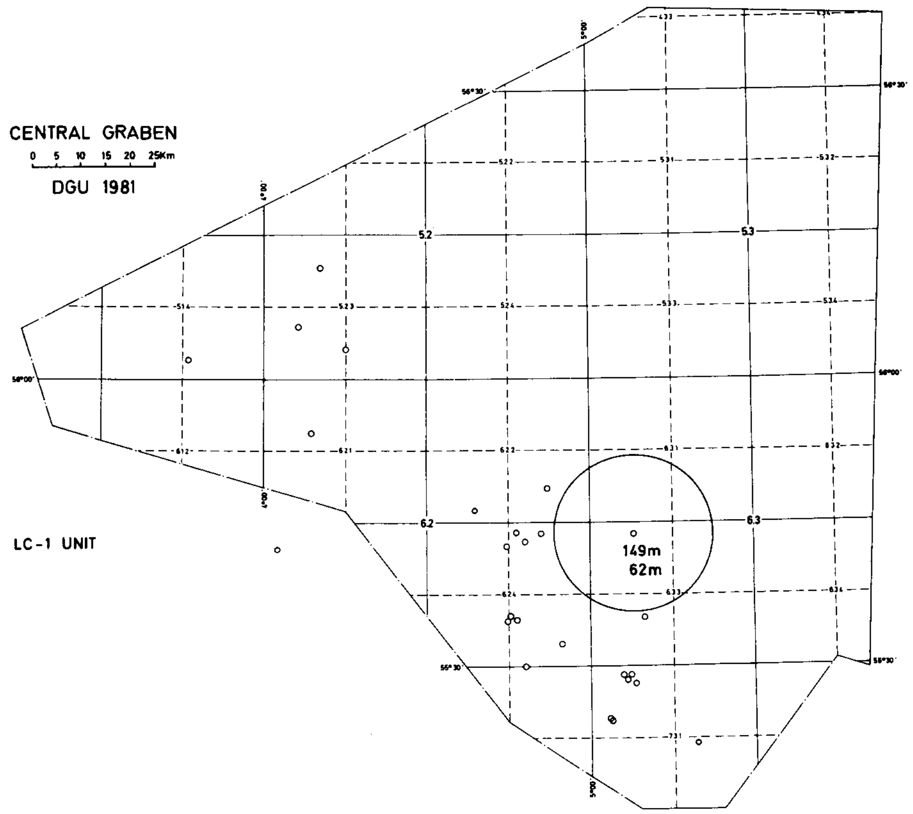


Fig. 52: The reservoir potential of a) W-1 Unit and b) the J-4 Unit. – For legend, see fig. 49.



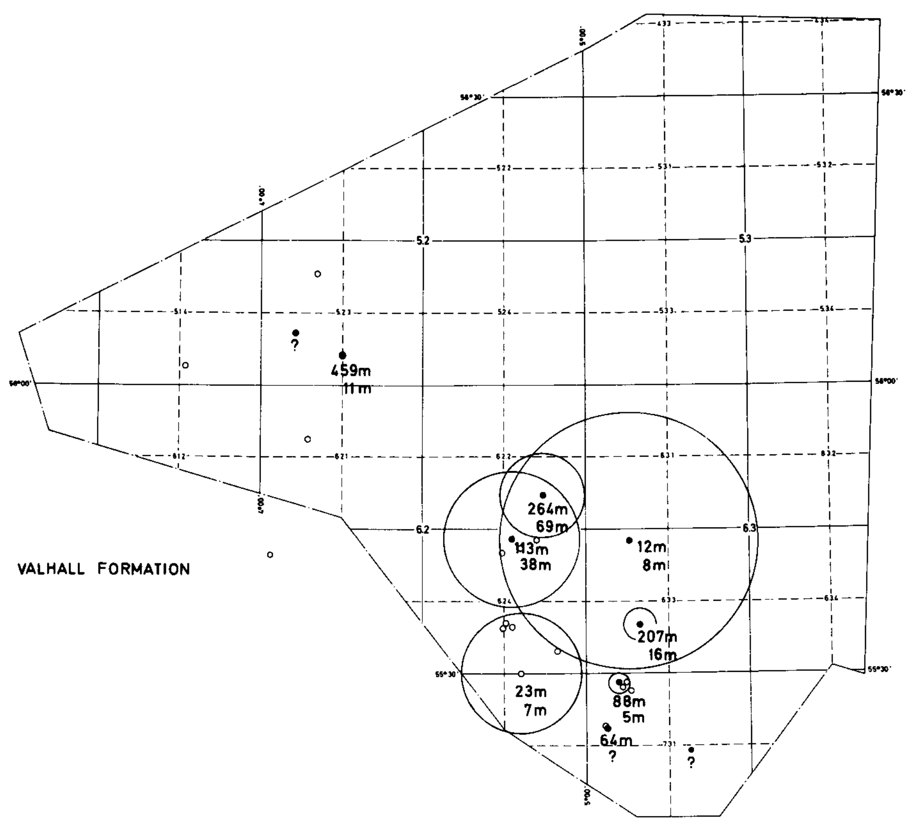


Fig. 53: The reservoir potential of a) the LC-1 Unit and b) the Valhall Formation. – For legend, see fig. 49.

Central Graben (between the structures) the depth may be 4000-5000 m.

Reservoir parameters (fig. 51): The Unit is divided into a lower member consisting of interbedded thick sandstones, claystones, and heteroliths and a less sandy upper member with coal seams.

In most wells there is a quantitatively upward decreasing occurrence of sandstone beds. This corresponds to the distribution of gas shows, which dominate in the lower member.

The following two facies may have reservoir properties: 1) the pure sandstone, which is hard to friable, fine to medium-grained, slightly calcareous with fair visible porosity, and 2) the heterolithic sand- and siltstones.

Only the sandstone beds are evaluated here. The average porosity is 20%, varying from 15-30%. Some sandy intervals are calcite cemented, which has reduced both porosity and permeability.

7.6 W-1 Unit (Late Jurassic)

Lithologic characteristics: The Unit consists of sandstones, minor siltstones, and conglomerates with interbedded, dark grey claystone and heterolithic silt- and claystones.

Reservoir parameters (fig. 52): All sections except the interbedded claystone seem to be potential reservoirs, with the conglomerates being the best reservoir rock. The conglomerates comprise rounded granular clasts of chalcedony and quartz, some dolomitic and granitic clasts and minor ammounts of siltstone clasts, all set in a medium-grained sand matrix.

The sandstones are fine-grained and firm, in part friable, depending on the degree of calcite-cementation. Loose medium-grained sand beds of vitreous and milky quartz have been found.

Three major sandstone intervals occur in the W-1 Unit, giving a net sand thickness of 67 m with a porosity varying from 6 to 14%. The average value of porosity is 11% based on bulk density log. The neutron porosity seems to be higher due to the clay content.

Two Formation Interval Tests (FIT) were performed in the W-1 Unit but no conclusive calculations of the permeability can be made. The moderate sorting and the presence of clay in the sandstone will lower the permeability.

7.7 J-3 Unit (Late Jurassic)

Lithologic characteristics: Claystone, often slightly silty, slightly calcareous; and subordinate occurrences of siltstone, medium to coarse-grained; and marlstone.

Reservoir parameters: Oil traces are reported from silty and calcareous layers in the A-2 and G-1 wells. Therefore silty layers may have reservoir properties, whereas the dominating clayey intervals have none. The irregular occurrence of the silty and calcareous beds may indicate restricted possibilities for commercial finds. These beds may be found along domal structures, on the top of which the J-3 Unit is absent or exists only as rims around the highs.

No cores have been cut and no tests performed in this Unit.

7.8 J-4 Unit (Late Jurassic)

Lithologic characteristics: Claystone, shaly, laminated, slightly silty and calcareous, with mica. Interbeds of thin lime- and dolostones are numerous.

Reservoir parameters (fig. 52): Several hydrocarbon shows have been reported from the lime- and dolostone stringers and the more silty intervals. The stringers may be of diagenetic origin and contain secondary porosity, contributing to the creation of reservoir conditions. The thickness of the stringers is approximately 2'. The log porosity in the stringers varies from 3-36%, averaging 10-12%. The total number of stringers varies from well to well.

The Unit is tested only in one well (E-1). The test indicated no significant amount of oil or gas. The permeability cannot be evaluated due to poor quality of test data.

The porous stringers may be sourced by the Unit itself.

7.9 LC-1 Unit (Late Jurassic - Early Cretaceous)

Lithologic characteristics: Sand and siltstone, silty sandstone, and sandy siltstones, with thin subordinate beds of calcareous shale and clay.

Extension, thickness, and depth: The Unit has been found in the V-1 well only, which is situated close to the margin of the Ringkøbing-Fyn High. Here the thickness is 61.5 m and depth 2702-2851 m. The Unit may be found as a fringe around other, similar structures.

Reservoir potential (fig. 53): The entire Unit seems to be a potential reservoir rock. This is confirmed by traces of oil and gas in the uppermost silty and sandy interval.

The porosity varies between 3 and 36% (log) with an average of 22%. No cores have been cut and no tests have been performed in the Unit.

7.10 Valhall Formation (Early Cretaceous)

Lithologic characteristics: Soft, grey to dark grey calcareous mudstone and shale with abundant limestone, marl, and siltstone beds.

In the lower part, the Formation has a relatively high terrigeneous content and may in parts be submarine fans. Dolomitic stringers (diagenetic) similar to those of the J-4 Unit are found in this lower part. The upper part of the Formation consists of lime and marlstone.

Extension, thickness, and depth: The Formation is the most prominent part of the Lower Cretaceous in the Danish Central Graben. The thickness of the Formation appears to show local maxima to more than 600 m, depending on the setting in relation to halokinetic structures. The Formation is generally thin or absent on structural highs.

Reservoir parameters (fig. 53): Due to the location of the Danish wells on salt domes, very little data are available on deep seated parts in the study area. However, in the V-1 well the sand- and siltstones interbedded with claystones might indicate good reservoir conditions. The porosity varies from 19 to 24% (log), averaging 22%.

The lime- and marlstones in the upper part of the formation may also have good reservoir properties, and shows are found in more wells.

The few tests from this Formation (the Adda-1 and E-1 wells) indicate relatively poor reservoir conditions.

7.11 Rødby Formation (Early Cretaceous)

Lithologic characteristics: The lithology varies considerably from well to well, but the main characteristic features of the Formation are marls, limestones or calcareous mudstones interbedded with clays and shales. Sandy intervals also occur.

Extension, thickness, and depth: The Formation is widely distributed in the Central Graben outside structural highs. The Formation is generally thin, typically 10-20 m, although local thicknesses up to 50 m may occur (the E-1 and I-1 wells). This greater thickness may be a result of sand deposition as indicated in the E-1 well.

Reservoir parameters: Apparently this Formation has limited reservoir potential. However, shows in sandy intervals in E-1 may indicate a small reservoir potential.

The porosity varies from 1% to 40%(log).

A drill stem test in the E-1 well gave no flow, indicating a very low permeability.

7.12 Chalk Group (Late Cretaceous - Early Cenozoic)

Exploration for oil and gas in chalk reservoirs, has been accelerated within the last ten years by discoveries of successful hydrocarbon reservoirs in the chalk in both the USA and the North Sea. Although chalk is a fairly poor reservoir rock, high production rates can be achieved if fracturing and a high oil column are present. The production can be enlarged by mechanical fracturing and/or acidizing of the rock, and the Chalk Group in general can be considered a reservoir rock (Scholle 1977b). More than 90% of the chalk is normally composed of calcareous nannoplankton (coccoliths) and foraminifera. Other biogenic- or terrestrial constituents such as bryozoans, clay-minerals, and clastic sand-grains are present in minor amounts.

The sediment is very fine-grained, as the sizes of the coccolith platelets range from 5-30 microns, and disintegrated platelets are even smaller. The foraminifera are found in the silt and sand fractions. The chalk provides a good primary porosity, but the narrow pore throats result in a low matrix permeability.

The coccolith- and foraminiferal skeletal calcium-carbonate has a low magnesium content, which makes the chalk somewhat resistant to the diagenetic alterations that cause loss or gain of porosity. Nevertheless, several factors affect the porosity.

Compaction and diagenesis: Chalk, upon initial deposition, has approximately 70% porosity. The initial porosity decreases with depth of burial resulting in a porosity value of 5% at a depth of 2500 m, following a 'normal compaction' trend (fig. 54). Several other factors affect the magnitude of porosity loss during the burial: Primary composition, tectonic stress, pore fluid pressure, the presence of hydrocarbons, pore water chemistry, and redeposition.

Primary composition: Variations in grain size, faunal composition, and clay content, result in differentiated diagenetic alterations, which cause variations in porosity and permeability.

The lower member of the Chalk-6 Unit, often has a clay content of 10-15%, which seems to prevent stylolitization and micro-fracturing. The clay occupies part of the pore space and blocks the pore throats. This causes a low porosity and permeability. The primary content of silicious skeletons, which during diagenesis is dissolved and reprecipitated as chert, also reduces porosity and permeability. In some places chert layers may even be permeability barriers, as seen at the Dan field.

A high content of calcispheres, as often found in the Chalk-4 Unit seems to cause a slight reduction in porosity and permeability.

The coccolith-foraminiferal chalk of the Chalk-5 Unit and the upper member of the Chalk-6 Unit, which seem to be the diagenetically most stable, has resisted porosity reduction at shallower depth. At greater depths of burial these units show abundant pressure solution (stylolites) as well as some reduction in porosity and permeability.

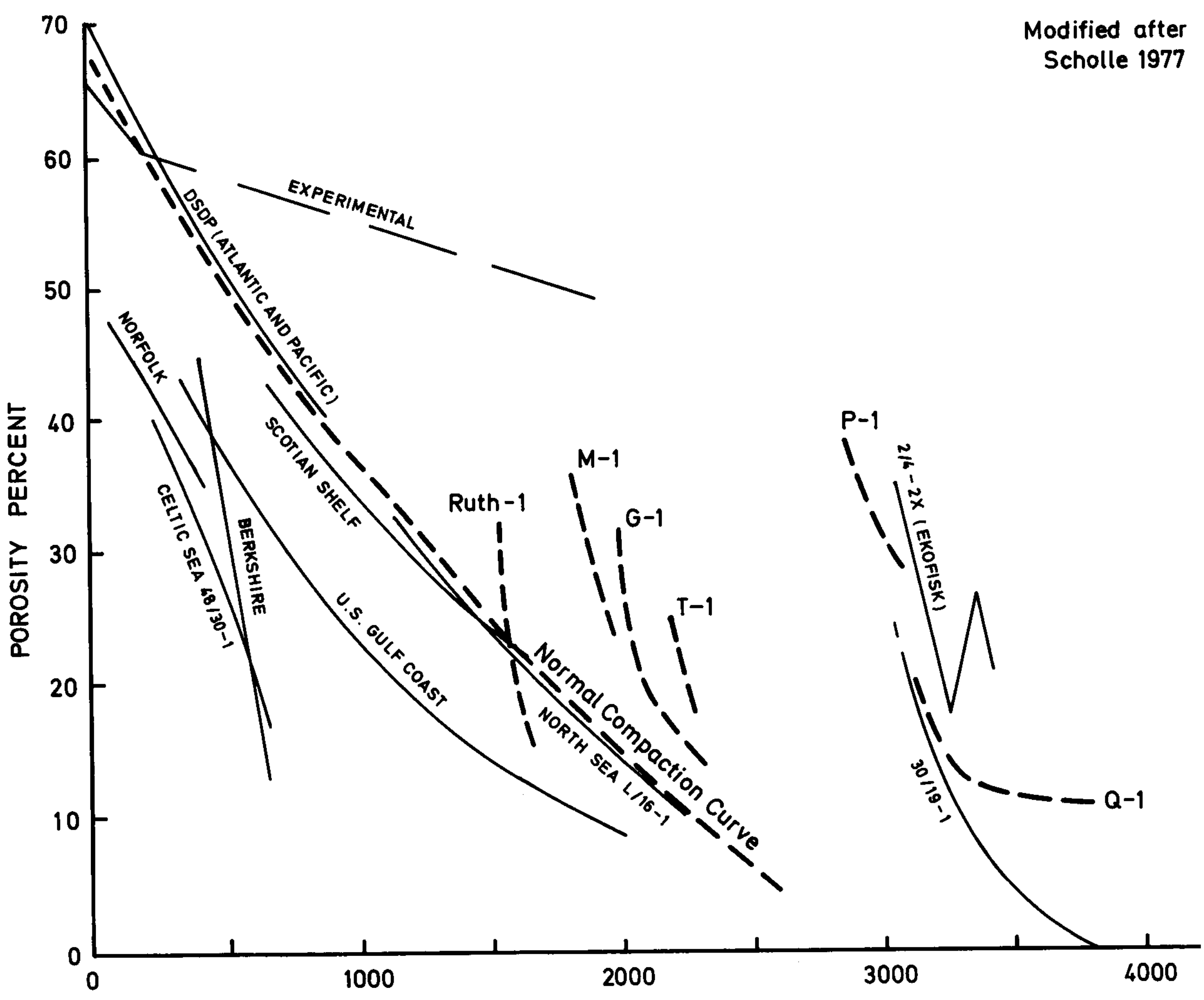


Fig. 54: Porosity v.s. depth of the Chalk Group in the G-1, M-1, P-1, Q-1, and Ruth-1 wells and a normal compaction curve plotted for comparison on a diagram from Scholle (1977b).

Tectonic stress: In heavily faulted or folded areas, stresses may be introduced causing reduction in porosity and permeability, similar to that of overburden. The tectonic stress may, however, also cause fracturing. Although the porosity increases only by a few per cent by fracturing, the permeability increases by a factor of 100 or even 1000. This is exemplified in the Ruth-1 well, drilled on top of a salt structure.

Pore fluid pressure: Mechanical and chemical compaction is dependent on expulsion of pore fluids. If the expulsion is obstructed, the pore fluid pressure will become higher than the hydrostatic pressure, grain to grain contact will be reduced and pressure solution will cease. In this way primary porosity and permeability can be preserved at much greater depths than those expected from 'normal compaction' curves. This is exemplified in the Dan field, where the fluid pressure is about 500 psi higher than the normal hydrostatic pressure, and the porosity is two times higher than that expected from the depth of burial (fig. 54). In the Danish Central Graben area, the Chalk Group is generally overpressured. The overpressuring is met at a depth of approximately 1200 m, close to top Middle Miocene. The overpressured interval seems to include the Chalk Group and part of the underlying shales.

Presence of hydrocarbons: Early migration of hydrocarbons into the chalk reservoirs reduces loss of porosity during further burial, by decreasing the water content and thereby slowing down its reaction with the rock. This effect cannot be fully evaluated for the Chalk Group in the Central Graben area, as it might be masked by the effects of pore fluid pressure. Oil- and water-wet chalk reservoirs are very similar in their porosity-depth distribution.

Pore water chemistry: The influx of fresh water into chalk tends to accelerate the loss of porosity and permeability. However, this has not been encountered so far in the Danish Central Graben area. The formation water hitherto found has either a normal marine salinity, or a higher chloride concentration. Moreover, salt-saturated brines have been found in wells situated on top of salt piercement structures. Alteration of chalk to dolomite, and associated porosity loss or gain, has been observed only in a few cases.

Redeposition: Allochtonous deposits may vary considerably in thickness and may be difficult to recognize in uncored intervals. In redeposited intervals higher porosities are often encountered, as compared to in situ chalk (R.F.P. Hardmann, pers. comm. 1981). Until now, slumped intervals have been recognized in only few wells in the Danish Central Graben; they may, however, be more common. Provided that the possible distribution areas of the slumped sediments and their nature are better known, there may be a chance of finding prospective reservoirs in allochtonous chalk.

Porosity distribution: In general porosity decreases with depth of burial (fig. 55). The average trend shows a decrease from 40% porosity at 1800 m, to 5% porosity at 3650 m. However, the total range for all wells is from 46% to 3% porosity.

The porosity versus depth distribution has a hourglass shape (fig. 56). The depth interval from 1768-2072 m is a high porosity zone with a porosity range from 14-46%. Another high-porosity interval is found from 2713-3109 m, where the porosity ranges from 2 to 38%. In between the two high porosity intervals, from 2347-2499 m, a rather narrow scatter of porosity values from 18-26% is encountered. From 3109 m, where the porosity range is 10-19%, the porosity gradually decreases downwards to much lower values. This indicates that chalk buried deeper than 3100 m is probably a poor reservoir rock. Chalk at depths shallower than 3100 m is considered a fairly good to good reservoir rock, since it has preserved much of its original primary porosity. In contrast to the small general decrease of porosity downwards, there is a considerable porosity reduction downwards in all individual wells (fig. 55).

Average porosities of the Chalk Units generally decrease with depth of burial. This reduction, however, is relatively small in the upper member of the Chalk-6 and Chalk-5 Units. Therefore these units are considered to be the best resevoirs within the Chalk Group from a matrix porosity point of view.

In fig. 57 the porosity ranges within the deposit zones are plotted against depth of burial. Going from deposit zones 2 to 3, both the structural elevation and the porosity increase. This can be explained as a depth-dependant porosity distribution. In deposit zone 4, the Chalk Group spans depths from above as well as below the values encountered in deposit zones 2 and 3. The porosity range in deposit zone 4, however, is smaller. As most of the reservoirs in deposit zone 4 are situated upon salt piercement structures, tectonic stress may have caused the reduction of up to 15% in porosity in this chalk, which is located equally or even structurally higher than deposit zone 3.

Deposit zone 5 encounters the deepest situated chalk reservoirs and the lowest porosities. The upper

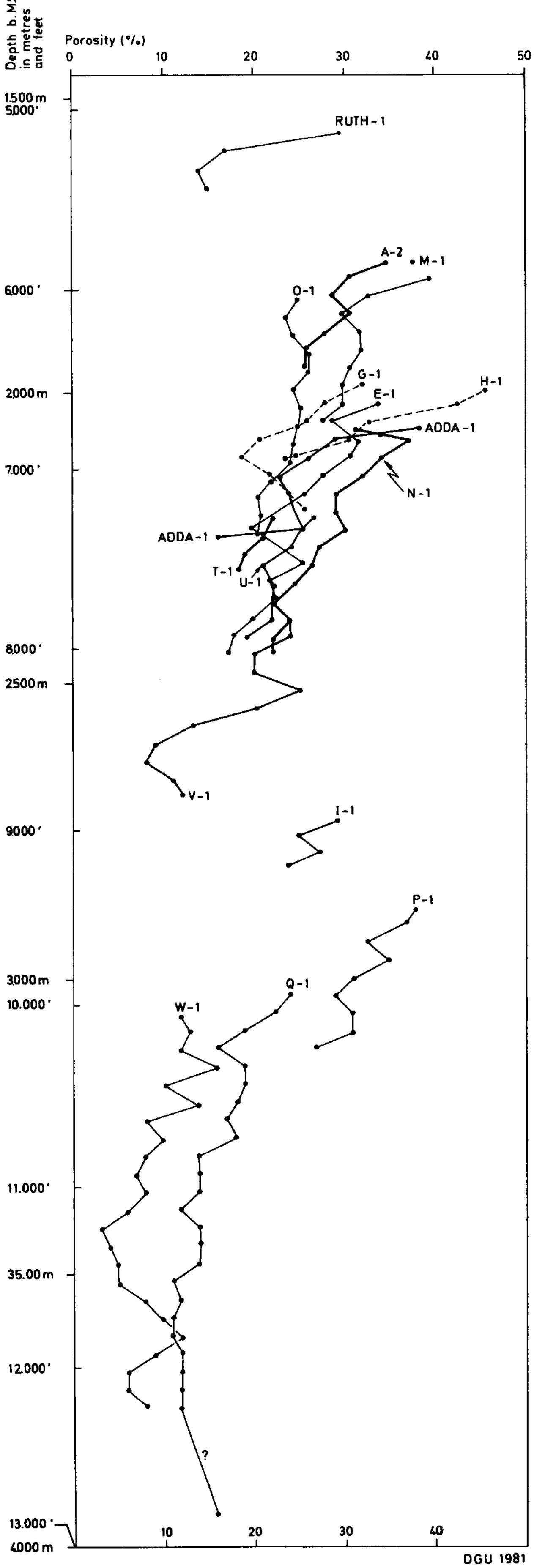


Fig. 55: Porosity v.s. depth plot of the Chalk Group in selected Central Graben wells.

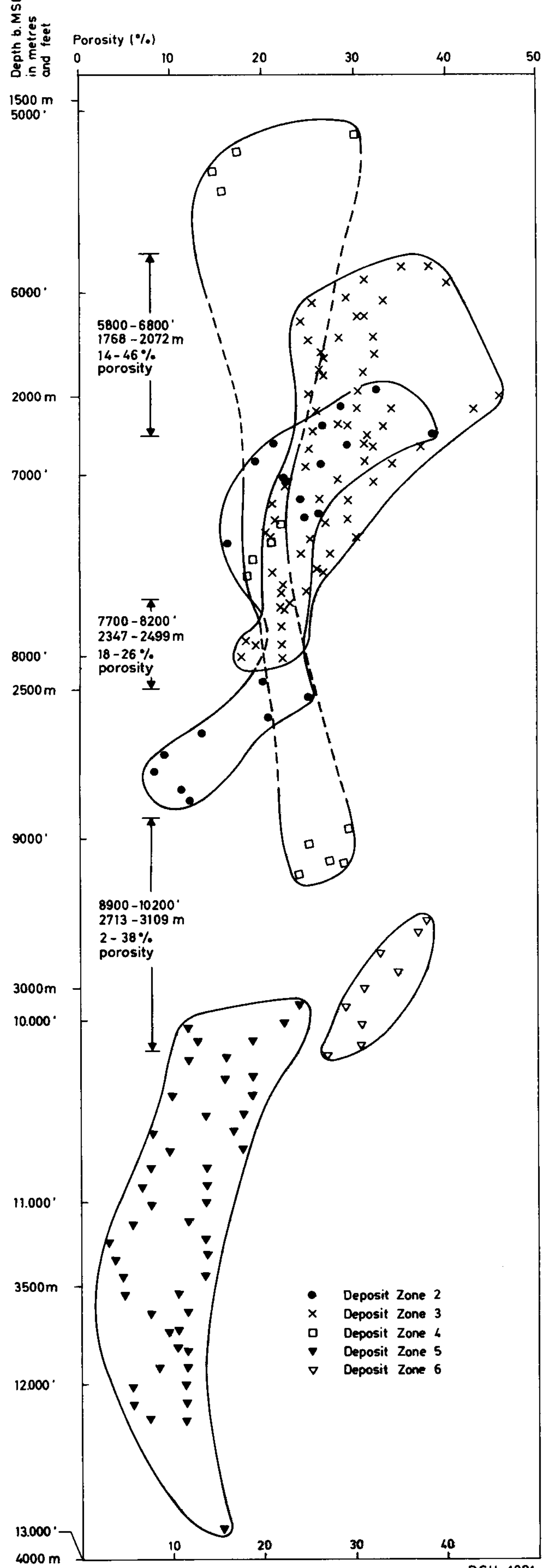


Fig. 56: Porosity v.s. depth plot of the Chalk Group. Data points are grouped and related to the Chalk deposit zones in Central Graben (see fig. 26).

parts of these reservoirs, however, still have fair porosities, similar to the lower values of deposit zones 2, 3, and 4.

Chalk in deposit zone 6 is found in a narrow depth interval. These reservoirs are deeper seated than in deposit zones 2, 3, and 4, but equal to the upper part of deposit zone 5. Despite the deep situation the porosities are as high as the higher values of deposit zones 2, 3, and 4, and they may be explained by formation water overpressure.

Permeability: As explained above, the primary permeabilities of chalks are low. Measured primary core permeabilities (air flow) generally range from 0.01 to 20 mD.

The permeability values vary greatly and show no clear relation to depth within the Chalk Units, (fig. 58). It is seen that the permeabilities in the two members of the Chalk-6 Unit cover the same range. Permeability values from the Chalk-3 and 4 Units have a very narrow range despite depth, but still within the range of the Chalk-6 Unit. This distribution, however, is based on much sparser data than those of the overlying units. The Chalk-5 Unit has the highest permeabilities encountered, and they fall allmost entirely outside the field of the other units.

Judged from the matrix permeability distributions described above, the Chalk-5 Unit holds the best reservoir conditions within the Chalk Group.

Porosity versus permeability (fig. 59): Matrix permeability sometimes correlates with matrix porosity as a function of depth. This is seen as a straight-line relationship on a semilog plot. In several cases, however, this relationship cannot be confirmed. This other relationship is probably caused by microfracturing of the chalk.

The existence of fractures has been indicated through comparisons between core permeabilities and permeabilities calculated from tests.

Until now, the presence of fractures has been confirmed by production tests performed in the following wells:

Strongly fractured: Ruth-1
Moderately fractured: T-1, N-1, Adda-1, H-1, I-1
Not fractured: G-1, E-1

The remaining wells in the Danish Central Graben area either have not been tested or permeabilities have not yet been calculated.

Fracture distribution: The fracture distribution seems to be correlatable with the degree of structural elevation. Strong fracturing is found on the high Ruth saltpiercement structure. Moderately fractured chalk reservoirs are generally found on low salt piercement- or shale flow structures, which are mainly found in deposit zones 2, 3, and the northern part of 4.

Exceptions from this general tendency, are the T-1 and Adda-1 wells. The T-1 well is situated on a salt piercement structure, but the fracture permeability is found to be very low. It is possible that this situation simply reflects the fact that only the lowermost part of the chalk section, where open fractures are less likely to exist than in the upper part, has yet been tested.

Tests suggest that the chalk section in the Adda-1 well is fractured. Unfortunately, no core-data are available for comparison. Adda-1 is drilled on a flat-top chalk closure, below which base chalk has a pronounced structural elevation. The oil zones in the Adda-1 well are close to the base of the Chalk Group, suggesting fracturing due to tectonic activity.

Chalk reservoirs where no fracturing is encountered seem to be correlatable to gentle structural mounds, with low structural elevation. This type of chalk reservoir seems to be restricted to deposit zones 2, 3, and 5. We have, however, only evaluated tests performed on the G-1 and E-1 wells in this type of structures.

Flat-top chalk closures have been encountered in deposit zones 2 and 3. These reservoirs should be

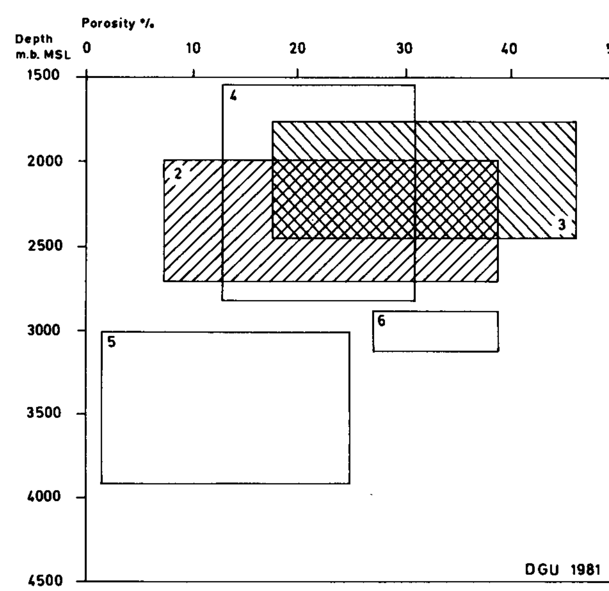


Fig. 57: Schematic presentation of porosity ranges in the Chalk Group related to Chalk deposit zones in the Central Graben. Numbers in squares refer to the individual Chalk deposit zones (cf. fig. 26).

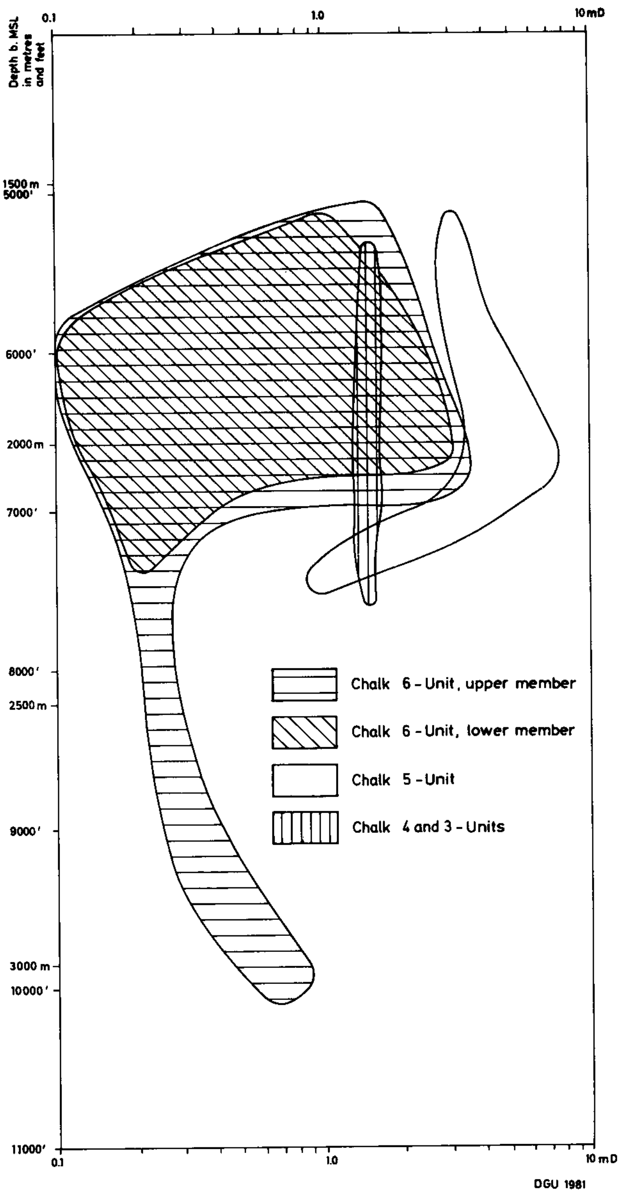


Fig. 58: Permeability distribution of Chalk Units.

expected to have a low fracture potential, provided that they follow the general pattern. It is known, as described above, that the Adda-1 well does not follow this pattern. Core descriptions from the H-1 well indicate fractures, but it is not known whether they contribute to permeability.

In the fracture system it is necessary to distinguish between fractures created by tension and by compression. Fractures and faults created by compression can have sealing properties, as demonstrated in the Gorm and Dan fields. Tension fractures, which are more likely to be open, may, however, later be sealed off by the precipitation of calcite cement.

Summary: Out of 16 released exploration wells in the Chalk Group, only the O-1 well proved (though questionably) to be without hydrocarbon shows. Two of the wells found the production fields - Dan and Gorm - and production has been planned on three other fields - Tyra, Skjold, and Roar.

The Chalk Group in general can be considered as a reservoir at least down to a depth of 3100 m. Within the Chalk Group, the upper member of the Chalk-6 Unit and certainly the Chalk-5 Unit can be considered to have good reservoir properties. This is based on the high primary porosity and fair permeability within these units. When naturally fractured they provide good production rates as exemplified by the Gorm field. The Chalk-6 and Chalk-5 Units are thickest in deposit zones 3 and 4. Through Chalk Units 4 to 1, the primary porosity and permeability generally decreases. If naturally fractured, however, and highly oil saturated, these units have proven to produce oil at fairly high rates as seen in Adda-1 and Ruth-1. The lower member of the Chalk-6 Unit might have the poorest reservoir properties. This is caused by rather low primary porosity and permeability and also by the relatively high clay content found in this unit. When the Formation is highly naturally fractured, however, high production rates can be achieved.

Classification of chalk reservoirs: Chalk reservoirs found in the Central Graben area can be divided into three groups as follows:

1) High primary porosity and fair primary permeability. Good reservoirs of this type have thick oil zones and hydrocarbon saturation up to 95% Sh.
2) Low primary porosity and permeability. These are reasonably good reservoirs even with hydrocarbon saturation as low as 50% Sh, provided a thick oil column is present.
3) High primary porosity and fair primary permeability together with secondary fracture porosity and permeability. These are potentially the best reservoirs.

7.13 North Sea Marl and CEN-1 to CEN-6 Unit (Cenozoic)

Lithologic characteristics: The units consist mainly of clastic material (clays and minor sands). The lowermost unit is dominated by a marl, upwards grading into a non-calcareous claystone or shale with subordinate layers of silt and sandstone. Above this the

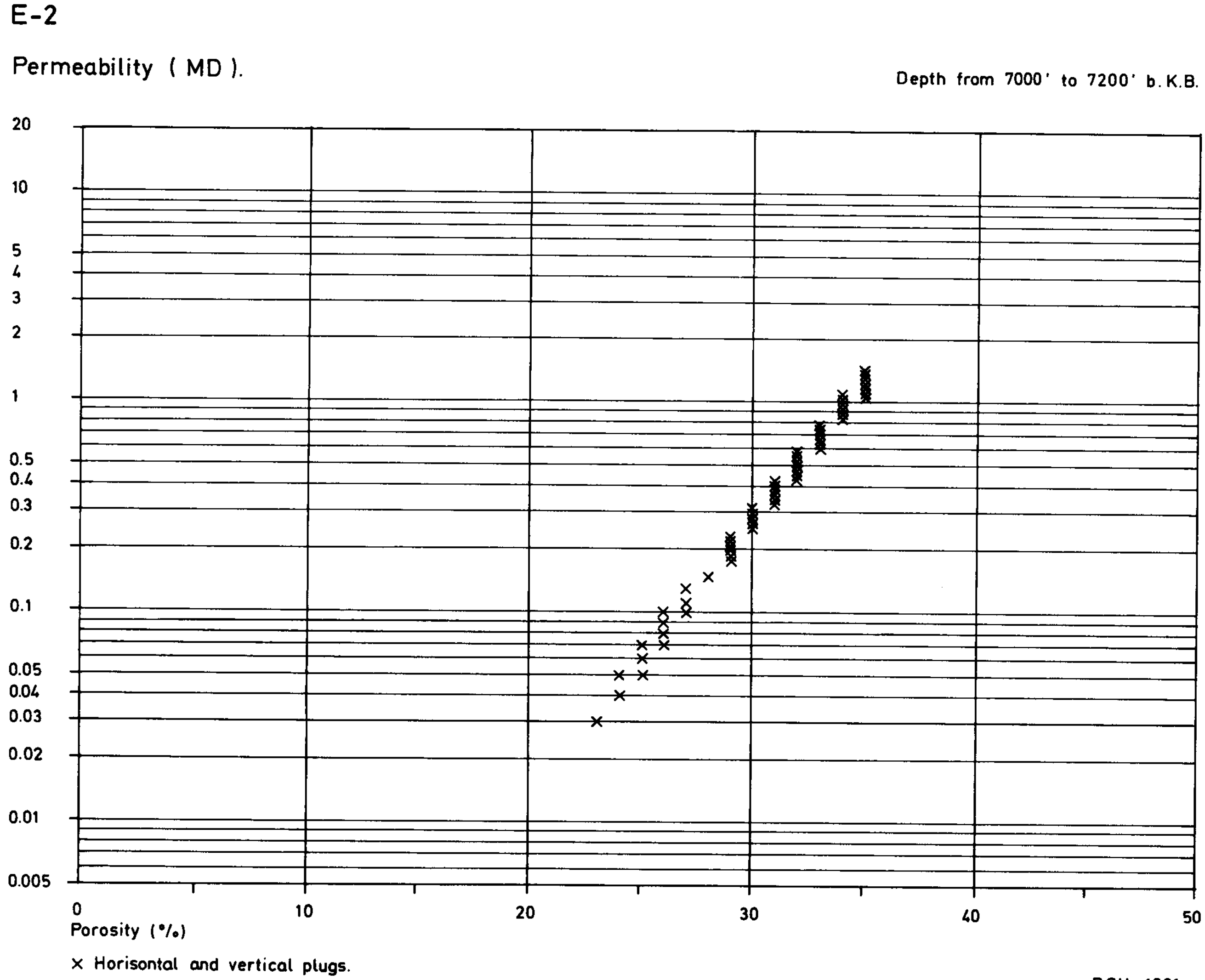


Fig. 59: Core porosity v.s. permeability plot (semi-log) from the E-2 and Ruth-1 wells. a) E-2 well. Non fractured chalk with a linear correlation. b) Ruth-1 well. Probably fractured chalk with a non-linear correlation.

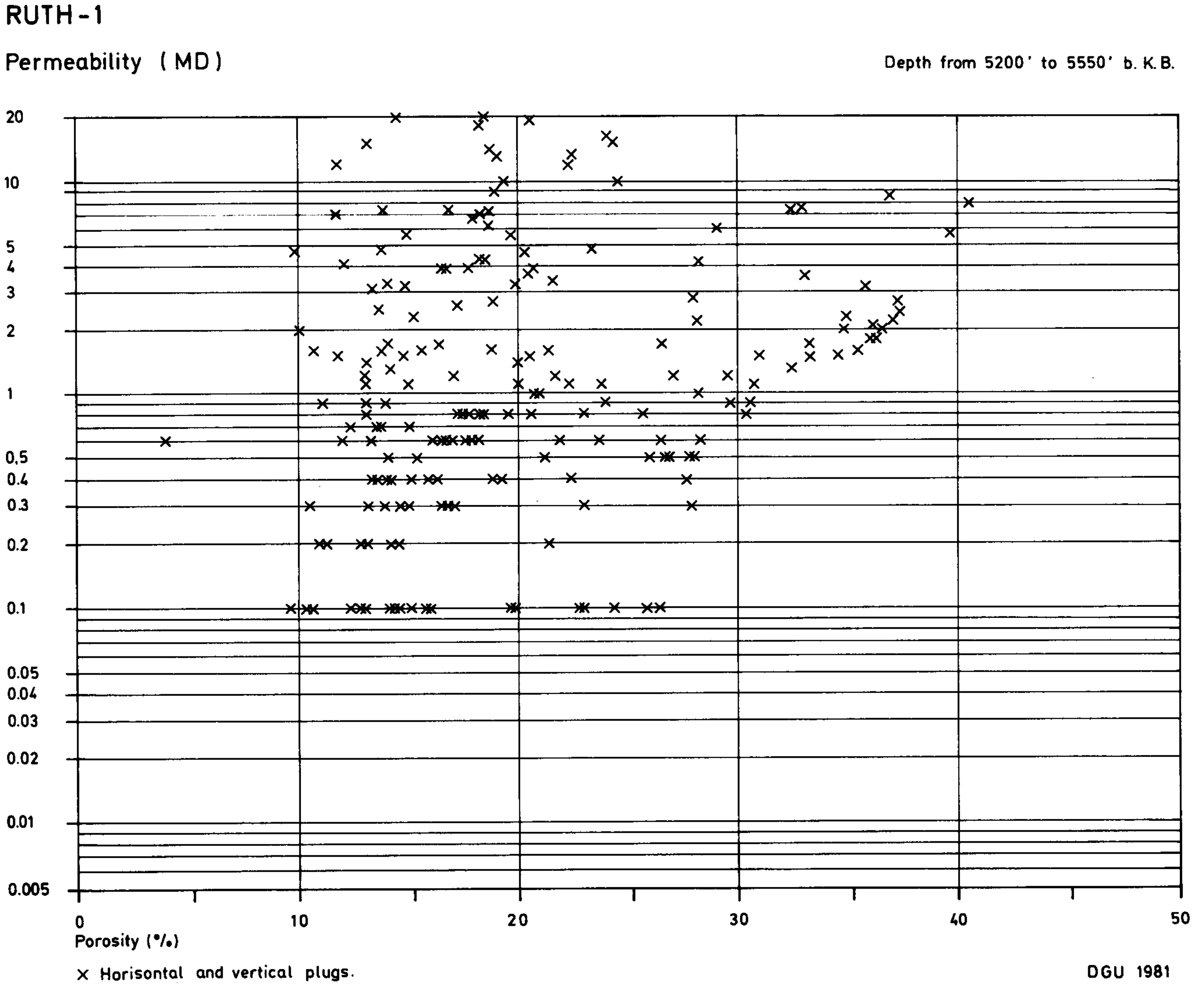
sequence contains layers of volcanic tuff, which succeed into more silty claystones with subordinate interbedded limestone. Sandy intervals become more common upwards, and the uppermost part of the CEN-5 Unit is a thick gravel-containing sandstone bed. The uppermost unit consists of clay, silt- , and sandstone interbedded with lignite and shell-rich beds.

Extension, thickness, and depth: Within the Danish Central Graben the entire sequence is 1700-3100 m thick. The sequence thins towards the northeast and east.

Reservoir parameters: Insignificant hydrocarbon shows are found in the lower units (CEN-3, 2, 1, and North Sea Marl) where they superpose hydrocarbon reservoirs in the chalk. The hydrocarbon accumulations are thought to be formed by leakage from the chalk reservoirs.

Information is restricted to little more than a small amount of core and wire line log data. The only porosity calculation made on the North Sea Marl found an average of 30% porosity in the Adda-1 well.

Porosity and permeability in the tuff/siltstone of the CEN-2 Unit are known from the E-1 and N-1 wells.



The porosity varies from 31-42% and 18-37.5% respectively. The permeability is 10 mD.

Nine limestone stringers in the CEN-3 Unit in the H-1 well, making up 22m net zone, are evaluated to have a porosity from 1 to 17%, whereas the permeability is not known.

The upper part of the Cenozoic sequence becomes more sandy, and the widespread gravelly sandstone in the uppermost part of the CEN-5 Unit is correllatable from one well to another. The porosity of the sandstones ranges from 20% to 45%, averaging 35%.

8.0 Tables on the formation depth and thickness

Legend

Log	Wire line logs used for identification of the boundary
SP	Spontaneous potential
Res	Resistivity
ITT	Interval transit time
GR	Gamma ray
FDC	Compensated formation density
CNL	Compensated neutron log
Cal	Caliper
/	Upper / lower boundary
DLL	Dual laterolog
TD	Total depth of the well
MSL	Mean sea level
KB	Kelly bushing
'	Minimum thickness

CA-1 Unit

Well	Depth b.KB (feet)	Log (characterizing)	Depth b.MSL (m)	Thickness (m)
A-1	not drilled			
A-2	not drilled			
Adda-1	not drilled			
B-1	not drilled			
E-1	not drilled			
E-2	not drilled			
E-3	not drilled			
G-1	not drilled			
H-1	not drilled			
I-1	not drilled			
M-1	not drilled			
M-2	not drilled			
M-8	not drilled			
N-1	not drilled			
N-2	not drilled			
O-1	not drilled			
P-1	11038-11259	ITT-GR/ITT-GR	3327-3394	67
Q-1	not drilled			
Ruth-1	not drilled			
T-1	not drilled			
U-1	not drilled			
V-1	not drilled			
W-1	not drilled			

Rotliegendes volcanics *(with sediments)*

Well	Depth b.KB (feet)	Log (characterizing)	Depth b.MSL (m)	Thickness (m)
A-1	not drilled			
A-2	not drilled			
Adda-1	not drilled			
B-1	11841-11985	Mudlog/TD	3574-3618	44'
E-1	not drilled			
E-2	not drilled			
E-3	not drilled			
G-1	not drilled			
H-1	not drilled			
I-1	not drilled			
M-1	not drilled			
M-2	not drilled			
M-8	not drilled			
N-1	not drilled			
N-2	not drilled			
O-1	not drilled			
P-1	10541-11038*	ITT-GR/ITT-GR	3175-3327	152
Q-1	14515-14745	Mudlog/TD	4386-4457	71'
Ruth-1	not drilled			
T-1	not drilled			
U-1	not drilled			
V-1	not drilled			
W-1	13888-14375	ITT-GR/TD	4199-4347	148'

* base of volcanics and sediments of Rotliegendes

Upper Rotliegendes sediments

Well	Depth b.KB (feet)	Log (characterizing)	Depth b.MSL (m)	Thickness (m)
A-1	not drilled			
A-2	not drilled			
Adda-1	not drilled			
B-1	11283-11841	Mudlog/Mudlog	3404-3574	170
E-1	not drilled			
E-2	not drilled			
E-3	not drilled			
G-1	not drilled			
H-1	not drilled			
I-1	not drilled			
M-1	not drilled			
M-2	not drilled			
M-8	not drilled			
N-1	not drilled			
N-2	not drilled			
O-1	not drilled			
P-1	10353-10541	ITT-GR/ITT-GR	3118-3175	58
Q-1	absent			
Ruth-1	not drilled			
T-1	not drilled			
U-1	not drilled			
V-1	not drilled			
W-1	absent			

Zechstein Group

Well	Depth b.KB (feet)	Log (characterizing)	Depth b.MSL (m)	Thickness (m)
A-1	not drilled			
A-2	not drilled			
Adda-1	not drilled			
B-1	10282-11283	Well data summary sheets	3068-3403	335
E-1	not drilled			
E-2	not drilled			
E-3	not drilled			
G-1	not drilled			
H-1	not drilled			
I-1	not drilled			
M-1	not drilled			
M-2	not drilled			
M-8	not drilled			
N-1	not drilled			
N-2	not drilled			
O-1	not drilled			
P-1	absent			
Q-1	?14385-?14515		4347-4386	39
Ruth-1	5590-5618	Mudlog/TD	1662-1677	8‘
T-1	7686-8713	Well data summary sheets/TD	2318-2631	312‘
U-1	not drilled			
V-1	not drilled			
W-1	?13860-?12888		4190-4199	9

Bacton Group (Bunter Sandstone and Shale Formations)

Well	Depth b.KB (feet)	Log (characterizing)	Depth b.MSL (m)	Thickness (m)
A-1	not drilled			
A-2	not drilled			
Adda-1	not drilled			
B-1	9990-10190	CNL-GR/CNL-GR	3009-3060	51
E-1	not drilled			
E-2	not drilled			
E-3	not drilled			
G-1	not drilled			
H-1	not drilled			
I-1	not drilled			
M-1	not drilled			
M-2	not drilled			
M-8	not drilled			
N-1	not drilled			
N-2	not drilled			
O-1	not drilled			
P-1	absent			
Q-1	13910-14385	ITT-GR/ITT-GR	4203-4348	145
Ruth-1	not drilled			
T-1	not drilled			
U-1	14651-16045	ITT-GR/TD	4437-4962	425‘
V-1	not drilled			
W-1	absent			

Dowsing Dolomitic Formation

Well	Depth b.KB (feet)	Log (characterizing)	Depth b.MSL (m)	Thickness (m)
A-1	not drilled			
A-2	10050-11143	Mudlog/TD	3027-3360	333
Adda-1	not drilled			
B-1	absent			
E-1	not drilled			
E-2	not drilled			
E-3	not drilled			
G-1	not drilled			
H-1	not drilled			
I-1	not drilled			
M-1	not drilled			
M-2	not drilled			
M-8	not drilled			
N-1	not drilled			
N-2	not drilled			
O-1	not drilled			
P-1	absent			
Q-1	absent			
Ruth-1	not drilled			
T-1	not drilled			
U-1	13074-14651	ITT-GR/ITT-GR	3957-4437	480
V-1	12080-12654	ITT-GR/TD	3648-3823	175‘
W-1	absent			

Dudgeon Saliferous Formation

Well	Depth b.KB (feet)	Log (characterizing)	Depth b.MSL (m)	Thickness (m)
A-1	not drilled			
A-2	absent			
Adda-1	not drilled			
B-1	absent			
E-1	not drilled			
E-2	not drilled			
E-3	not drilled			
G-1	not drilled			
H-1	not drilled			
I-1	not drilled			
M-1	not drilled			
M-2	not drilled			
M-8	11559-12007	ITT-GR/TD	3494-3647	153‘
N-1	not drilled			
N-2	not drilled			
O-1	11193-11740	ITT-GR/TD	3384-3550	166‘
P-1	absent			
Q-1	absent			
Ruth-1	not drilled			
T-1	not drilled			
U-1	12159-13074	ITT-GR/ITT-GR	3678-3957	279
V-1	absent			
W-1	absent			

Triton Anhydritic Formation

Well	Depth b.KB (feet)	Log (characterizing)	Depth b.MSL (m)	Thickness (m)
A-1	not drilled			
A-2	absent			
Adda-1	not drilled			
B-1	absent			
E-1	not drilled			
E-2	not drilled			
E-3	not drilled			
G-1	not drilled			
H-1	not drilled			
I-1	not drilled			
M-1	not drilled			
M-2	not drilled			
M-8	10793-11559	ITT-GR/ITT-GR	3260-3494	234
N-1	not drilled			
N-2	not drilled			
O-1	10401-11193	ITT-GR/ITT-GR	3142-3384	242
P-1	absent			
Q-1	absent			
Ruth-1	not drilled			
T-1	not drilled			
U-1	11250-12159	ITT-GR/ITT-GR	3401-3678	277
V-1	absent			
W-1	absent			

Winterton Formation

Well	Depth b.KB (feet)	Log (characterizing)	Depth b.MSL (m)	Thickness (m)
A-1	not drilled			
A-2	absent			
Adda-1	not drilled			
B-1	absent			
E-1	not drilled			
E-2	not drilled			
E-3	not drilled			
G-1	not drilled			
H-1	not drilled			
I-1	not drilled			
M-1	not drilled			
M-2	not drilled			
M-8	10771-10793	ITT-GR/ITT-GR	3253-3260	7
N-1	not drilled			
N-2	not drilled			
O-1	10347-10401	ITT-GR/ITT-GR	3126-3142	16
P-1	absent			
Q-1	absent			
Ruth-1	not drilled			
T-1	not drilled			
U-1	11209-11250	ITT-GR/ITT-GR	3389-3401	12
V-1	absent			
W-1	absent			

Fjerritslev Formation

Well	Depth b.KB (feet)	Log (characterizing)	Depth b.MSL (m)	Thickness (m)
A-1	not drilled			
A-2	absent			
Adda-1	not drilled			
B-1	no evaluation			
E-1	not drilled			
E-2	not drilled			
E-3	not drilled			
G-1	not drilled			
H-1	not drilled			
I-1	not drilled			
M-1	not drilled			
M-2	not drilled			
M-8	10467-10771	ITT-GR/ITT-GR	3161-3154	93
N-1	not drilled			
N-2	not drilled			
O-1	9838-10347	ITT-GR/ITT-GR	2971-3126	155
P-1	absent			
Q-1	13608-13910	ITT-GR/ITT-GR	4111-4203	92
Ruth-1	not drilled			
T-1	not drilled			
U-1	11048-11209	ITT-GR/ITT-GR	3340-3389	49
V-1	absent			
W-1	absent			

J-2 Unit, all members

Well	Depth b.KB (feet)	Log (characterizing)	Depth b.MSL (m)	Thickness (m)
A-1	not drilled			
A-2	9920-10050	Mud log	2988-3027	39
Adda-1	not drilled			
B-1	no evaluation			
E-1	not drilled			
E-2	not drilled			
E-3	not drilled			
G-1	not drilled			
H-1	not drilled			
I-1	not drilled			
M-1	not drilled			
M-2	not drilled			
M-8	10143-10467	ITT-GR/ITT-GR	3062-3161	99
N-1	not drilled			
N-2	not drilled			
O-1	8901- 9840	ITT-GR/ITT	2685-2971	286
P-1	absent			
Q-1	13429-13608	ITT-GR/ITT-GR	4063-4111	48
Ruth-1	not drilled			
T-1	not drilled			
U-1	10665-11048	ITT-GR/CNL-FDC	3222-3339	117
V-1	absent			
W-1	absent			

J-2 Unit, upper member

Well	Depth b.KB (feet)	Log (characterizing)	Depth b.MSL (m)	Thickness (m)
A-1	not drilled			
A-2	9920- 9970	Mud Log	2988-3003	15
Adda-1	not drilled			
B-1	no evaluation			
E-1	not drilled			
E-2	not drilled			
E-3	not drilled			
G-1	not drilled			
H-1	not drilled			
I-1	not drilled			
M-1	not drilled			
M-2	not drilled			
M-8	10143-10260	ITT/GR-ITT	3062-3098	36
N-1	not drilled			
N-2	not drilled			
O-1	8901- 9425	ITT-GR/ITT-GR	2685-2845	160
P-1	absent			
Q-1*	? - ?	? - ?	?	
Ruth-1	not drilled			
T-1	not drilled			
U-1	10665-10853	ITT-GR/ITT-GR	3222-3280	58
V-1	absent			
W-1	absent			

* no evaluation

J-2 Unit, lower member

Well	Depth b.KB (feet)	Log (characterizing)	Depth b.MSL (m)	Thickness (m)
A-1	not drilled			
A-2	9970-10050	Mud Log	3003-3027	24
Adda-1	not drilled			
B-1	no evaluation			
E-1	not drilled			
E-2	not drilled			
E-3	not drilled			
G-1	not drilled			
H-1	not drilled			
I-1	not drilled			
M-1	not drilled			
M-2	not drilled			
M-8	10260-10467	ITT-GR/ITT-GR	3098-3161	37
N-1	not drilled			
N-2	not drilled			
O-1	9425- 9838	ITT-GR/ITT	2845-2971	126
P-1	absent			
Q-1*	? - ?		? - ?	?
Ruth-1	not drilled			
T-1	not drilled			
U-1	10853-11048	ITT-GR/FDC-CNL	3280-3339	41
V-1	absent			
W-1	absent			

* no evaluation

W-1 Unit

Well	Depth b.KB (feet)	Log (characterizing)	Depth b.MSL (m)	Thickness (m)
A-1	not drilled			
A-2	absent			
Adda-1	not drilled			
B-1	no evaluation			
E-1	not drilled			
E-2	not drilled			
E-3	not drilled			
G-1	absent			
H-1	not drilled			
I-1	not drilled			
M-1	not drilled			
M-2	not drilled			
M-8	absent			
N-1	not drilled			
N-2	not drilled			
O-1	absent			
P-1	absent			
Q-1	absent			
Ruth-1	not drilled			
T-1	not drilled			
U-1	absent			
V-1	absent			
W-1	13521-13860	ITT-GR/ITT	4087-4184	97

J-3 Unit

Well	Depth b.KB (feet)	Log (characterizing)	Depth b.MSL (m)	Thickness (m)
A-1	not drilled			
A-2	? - 9920	Mudlog	?-2988	?
Adda-1	not drilled			
B-1	no evaluation			
E-1	not drilled			
E-2	not drilled			
E-3	not drilled			
G-1	12037-12517	ITT-GR/TD	3632-3778	146‘
H-1	not drilled			
I-1	not drilled			
M-1	not drilled			
M-2	not drilled			
M-8	8940-10143	ITT-GR/ITT-GR	2695-3062	367
N-1	not drilled			
N-2	not drilled			
O-1	? - 8901	/ITT-GR	?-2685	?
P-1	absent			
Q-1	not drilled			
Ruth-1	not drilled			
T-1	not drilled			
U-1	9595-10665	ITT-GR/ITT-GR	2896-3222	326
V-1	?10601-12080	ITT-GR/ITT-GR	?3198-3648	?450
W-1	absent			

J-4 Unit

Well	Depth b.KB (feet)	Log (characterizing)	Depth b.MSL (m)	Thickness (m)
A-1	not drilled			
A-2	7470- ?	Mudlog	2241- ?	?
Adda-1	8400- 10005	ITT-GR/TD log	2526- 3015	489'
B-1*	? - ?		? - ?	?
E-1	9727- 13403	ITT-GR/TD log	2928- 4048	1120'
E-2	not drilled			
E-3	not drilled			
G-1	8088- 12037	ITT-GR/ITT-GR	2429- 3632	1204
H-1	not drilled			
I-1	11018- 12848	ITT-GR/TD log	3321- 3879	558'
M-1	7190- 7374	ITT-GR/TD log	2158- 2475	117'
M-2	not drilled			
M-8	7517- 8940	ITT-GR/ITT-GR	2262- 2695	433
N-1	not drilled			
N-2	not drilled			
O-1*	? - ?		? - ?	?
P-1	absent			
Q-1*	? - ?		? - ?	?
Ruth-1	not drilled			
T-1	not drilled			
U-1	8190- 9595	ITT-GR/ITT-GR	2468- 2896	428
V-1	9462-?10601	ITT-GR/ITT-GR	2833-?3198	?347
W-1	12333-13521	ITT-GR/ITT-GR	3725- 4087	362

* no evaluation

LC-1 Unit

Well	Depth b.KB (feet)	Log (characterizing)	Depth b.MSL (m)	Thickness (m)
A-1	not drilled			
A-2	absent			
Adda-1	absent			
B-1	no evaluation			
E-1	absent			
E-2	not drilled			
E-3	not drilled			
G-1	absent			
H-1	not drilled			
I-1	absent			
M-1	absent			
M-2	not drilled			
M-8	absent			
N-1	not drilled			
N-2	not drilled			
O-1	absent			
P-1	absent			
Per-1	absent			
Q-1	absent			
Ruth-1	absent			
T-1	no evaluation			
U-1	absent			
V-1	8972-9462	GR,FDC,CNL,ITT/ GR,FDC,CNL,ITT	2702-2851	149
W-1	absent			

Valhall Formation

Well	Depth b.KB (feet)	Log (characterizing)	Depth b.MSL (m)	Thickness (m)
A-1	not drilled			
A-2	7260- 7470	Mudlog/Mudlog	2177-2241	64
Adda-1	7530- 8400	ITT-GR/ITT-GR	2262-2526	264
B-1	no evaluation			
E-1	8297- 9727	ITT-GR/ITT-GR	2492-2928	236
E-2	not drilled			
E-3	8350- 8722	GR/GR	2515-2628	113‘
G-1	7410- 8088	ITT-GR/ITT-GR	2222-2429	207
H-1	no evaluation			
I-1	9508-11018	ITT-GR/ITT-GR	2862-3321	459
M-1	6902- 7190	ITT-GR/ITT-GR	2071-2159	88
M-2	not drilled			
M-7	8934- 9070	Mudlog/Mudlog	2691-2733	42‘
M-8	7280- 7517	ITT-GR/ITT-GR	2190-2262	72
N-1	not drilled			
N-2	not drilled			
O-1	7580- ?	CNL-GR/ ?	2283- ?	
P-1	absent			
Per-1	absent			
Q-1 ?				
Ruth-1	absent			
T-1	no evaluation			
U-1	8112-8190	ITT-GR/ITT-GR	2445-2468	23
V-1	8937-8972	GR-ITT/ GR,GDC,CNL,ITT	2691-2702	12
W-1	?			

Rødby Formation

Well	Depth b.KB (feet)	Log (characterizing)	Depth b.MSL (m)	Thickness (m)
A-1	not drilled			
A-2	7240-7260	Mudlog/Mudlog	2171-2177	6
Adda-1	7512-7530	ITT-GR/ITT-GR	2256-2262	6
B-1	no evaluation			
E-1	8162-8297	ITT-GR/ITT-GR	2451-2492	41
E-2	not drilled			
E-3	8305-8350	ITT-GR/GR	2502-2515	13
G-1	absent			
H-1	not drilled			
I-1	9355-9508	ITT-GR/ITT-GR	2815-2862	47
M-1	6858-6902	ITT-GR/ITT-GR	2057-2071	14
M-2	not drilled			
M-8	7212-7280	ITT-GR/ITT-GR	2169-2190	21
N-1	not drilled			
N-2	not drilled			
O-1	7570-7580	CNL-GR/CNL-GR	2280-2283	3
P-1	absent			
Per-1	absent			
Q-1	no evaluation			
Ruth-1	absent			
T-1	no evaluation			
U-1	absent			
V-1	absent			
W-1	absent			

Chalk-1 Unit

Well	Depth b.KB (feet)	Log (characterizing)	Depth b.MSL (m)	Thickness (m)
A-1	no logs			
A-2	no logs			
Adda-1	7420-7512	ITT-GR/ITT-GR	2227-2256	28
B-1	absent			
E-1	8115-8162	ITT-GR/ITT-GR	2436-2451	14
E-2	absent			
E-3	absent			
G-1	no logs			
H-1	absent			
I-1	absent			
M-1	absent			
M-2	no evaluation			
M-8	absent			
N-1	not drilled			
N-2	no evaluation			
O-1	7500-7580	ITT-GR/ITT-GR	2258-2282	24
P-1	absent			
Q-1	?no logs*			
Ruth-1	absent			
T-1	absent			
U-1	absent			
V-1	absent			
W-1	absent			

*No logs from 12270-12950'

Chalk-2 Unit

Well	Depth b.KB (feet)	Log (characterizing)	Depth b.MSL (m)	Thickness (m)
A-1	no logs			
A-2	no logs			
Adda-1	7138- 7420	ITT-GR/ITT-GR	2142-2227	85
B-1	7520- 7595	ITT-GR/ITT-GR	2256-2279	23
E-1	7500- 8115	ITT-GR/ITT-GR	2249-2436	187
E-2	no evaluation			
E-3	no evaluation			
G-1	7120- 7410	ITT-GR/ITT-GR	2133-2222	89
H-1	absent			
I-1	absent			
M-1	6590- 6858	ITT-GR/ITT-GR	1975-2057	82?
M-2	no evaluation			
M-8	6880- 7212	ITT-GR/ITT-GR	2067-2169	102
N-1	7904-TD 8155	ITT-GR/ITT-GR	2377-2453	76'
N-2	no evaluation			
O-1	7408- 7500	ITT-GR/ITT-GR	2230-2258	28
P-1	absent			
Q-1	12128-13000	ITT-GR/ITT-GR	3659-3925	266
Ruth-1	absent			
T-1	absent			
U-1	7898- 8109	ITT-GR/ITT-GR	2379-2443	64
V-1	8375- 8937	ITT-GR/ITT-GR	2519-2690	171
W-1	11782-12333	ITT-GR/ITT-GR	3557-3725	168

Chalk-3 Unit

Well	Depth b.KB (feet)	Log (characterizing)	Depth b.MSL (m)	Thickness (m)
A-1	no logs			
A-2	no logs			
Adda-1	7063- 7138	ITT-GR/ITT-GR	2119-2142	23
B-1	7447- 7520	ITT-GR/ITT-GR	2234-2256	22
E-1	7325- 7500	ITT-GR/ITT-GR	2195-2249	54
E-2	no evaluation			
E-3	no evaluation			
G-1	6875- 7120	ITT-GR/ITT-GR	2067-2142	75
H-1	absent			
I-1	absent			
M-1	6471- 6590	ITT-GR/ITT-GR	1939-1975	?36
M-2	no evaluation			
M-8	6681- 6880	ITT-GR/ITT-GR	2007-2067	60
N-1	7745- 7904	ITT-GR/ITT-GR	2328-2377	49
N-2	no evaluation			
O-1	7349- 7408	ITT-GR/ITT-GR	2212-2230	?18
P-1	absent			
Q-1	11640-12128	ITT-GR/ITT-GR	3510-3659	149
Ruth-1	absent			
T-1	absent			
U-1	7800- 7898	ITT-GR/ITT-GR	2339-2369	30
V-1	8025- 8375	ITT-GR/ITT-GR	2412-2519	107
W-1	11267-11782		3400-3557	157

Chalk-4 Unit

Well	Depth b.KB (feet)	Log (characterizing)	Depth b.MSL (m)	Thickness (m)
A-1				
A-2	6262-(6650)*	ITT-GR/ITT-GR	1873-1991	118‘
Adda-1	absent			
B-1	7402- 7447	ITT-GR/ITT-GR	2220-2234	14
E-1	7072- 7325	ITT-GR/ITT-GR	2118-2195	77
E-2	no evaluation			
E-3	no evaluation			
G-1	6830- 6875	ITT-GR/ITT-GR	2045-2058	13
H-1	6981-TD 7100	ITT-GR/ITT-GR	2091-2127	36‘
I-1	9241- 9355	ITT-GR/ITT-GR	2779-2814	35
M-1	6118- 6471	ITT-GR/ITT-GR	1831-1935	108
M-2	no evaluation			
M-8	6256- 6681	ITT-GR/ITT-GR	1877-2007	130
N-1	7147- 7745	ITT-GR/ITT-GR	2146-2328	182
N-2	no evaluation			
O-1	7187- 7349	ITT-GR/ITT-GR	2163-2212	49
P-1	9865-10350	ITT-GR/ITT-GR	2969-3117	148
Q-1	10730-11640	ITT-GR/ITT-GR	3233-3510	277
Ruth-1	5290- 5586	ITT-GR/ITT-GR	1577-1668	91
T-1	7519- 7685	ITT-GR/ITT-GR	2267-2317	50
U-1	7594- 7800	ITT-GR/ITT-GR	2286-2349	63
V-1	7639- 8025	ITT-GR/ITT-GR	2295-2412	117
W-1	10695-11267	ITT-GR/ITT-GR	3226-3400	174

* (6650') base log.

Chalk-5 Unit

Well	Depth b.KB (feet)	Log (characterizing)	Depth b.MSL (m)	Thickness (m)
A-1				
A-2	6125- 6262	ITT-GR/ITT-GR	1831-1873	42
Adda-1	7040- 7063	ITT-GR/ITT-GR	2112-2119	7
B-1	absent	ITT-GR/ITT-GR		
E-1	6880- 7072	ITT-GR/ITT-GR	2060-2118	58
E-2	no evaluation			
E-3	no evaluation			
G-1	6790- 6830	ITT-GR/ITT-GR	2032-2045	13
H-1	6713- 6981	ITT-GR/ITT-GR	2009-2091	82
I-1	9182- 9241	ITT-GR/ITT-GR	2761-2779	18
M-1	6032- 6118	ITT-GR/ITT-GR	1805-1831	26
M-2	no evaluation			
M-8	6152- 6256	ITT-GR/ITT-GR	1846-1877	31
N-1	6937- 7147	ITT-GR/ITT-GR	2082-2146	64
N-2	no evaluation			
O-1	6254- 7187	ITT-GR/ITT-GR	1878-2163	285
P-1	9818- 9865	ITT-GR/ITT-GR	2955-2969	14
Q-1	10378-10730	ITT-GR/ITT-GR	3125-3233	108
Ruth-1	5266- 5290	ITT-GR/ITT-GR	1570-1577	7
T-1	7419- 7519	ITT-GR/ITT-GR	2236-2267	31
U-1	7430- 7594	ITT-GR/ITT-GR	2236-2286	50
V-1	7550- 7639	ITT-GR/ITT-GR	2268-2295	27
W-1	10413-10695	ITT-GR/ITT-GR	3140-3226	86

Chalk-6 Unit

Well	Depth b.KB (feet)	Log (characterizing)	Depth b.MSL (m)	Thickness (m)
A-1				
A-2	5950- 6125	ITT-GR/ITT-GR	1778-1831	52
Adda-1	6866- 7040	ITT-GR/ITT-GR	2059-2112	53
B-1	7373- 7402	ITT-GR/ITT-GR	2212-2220	8
E-1	6735- 6880	ITT-GR/ITT-GR	2016-2060	44
E-2	no evaluation			
E-3	no evaluation			
G-1	6610- 6790	ITT-GR/ITT-GR	1978-2032	54
H-1	6680- 6713	ITT-GR/ITT-GR	1999-2009	10
I-1	9070- 9182	ITT-GR/ITT-GR	2727-2761	34
M-1	5902- 6032	ITT-GR/ITT-GR	1765-1805	40
M-2	no evaluation			
M-8	6013- 6152	ITT-GR/ITT-GR	1803-1846	43
N-1	6897- 6937	ITT-GR/ITT-GR	2070-2082	12
N-2	no evaluation			
O-1	6097- 6254	ITT-GR/ITT-GR	1830-1878	48
P-1	9580- 9818	ITT-GR/ITT-GR	2882-2955	73
Q-1	10058-10378	ITT-GR/ITT-GR	3028-3125	97
Ruth-1	5205- 5266	ITT-GR/ITT-GR	1551-1570	19
T-1	7283- 7419	ITT-GR/ITT-GR	2195-2236	41
U-1	7300- 7434	ITT-GR/ITT-GR	2197-2238	41
V-1	7356- 7550	ITT-GR/ITT-GR	2208-2268	60
W-1	10135-10413	ITT-GR/ITT-GR	3055-3140	85

North Sea Marl

Well	Depth b.KB (feet)	Log (characterizing)	Depth b.MSL (m)	Thickness (m)
A-1	absent			
A-2	5950- 5952	ITT-GR/GR	1778-1778	
Adda-1	6841- 6866	ITT-GR/GR	2051-2059	8
B-1	absent			
E-1	6725- 6735	ITT-GR/GR	2013-2016	3
E-2	absent			
E-3	absent			
G-1	absent			
H-1	absent			
I-1	9011- 9070	ITT-GR/GR	2709-2727	18
M-1	absent			
M-2	absent			
M-8	absent			
N-1	6839- 6897	ITT-GR/GR	2052-2070	18
N-2	absent			
O-1	6043- 6097	ITT-GR/GR	1814-1830	16
P-1	9504- 9580	ITT-GR/GR	2859-2882	23
Q-1	9971-10072	ITT-GR/GR	3001-3032	17
Ruth-1	absent			
T-1	7228- 7283	ITT-GR/GR	2178-2195	17
U-1	7279- 7300	ITT-GR/GR	2190-2197	7
V-1	absent			
W-1	10040-10094	ITT-GR/GR	3026-3043	17

CEN-1 Unit

Well	Depth b.KB (feet)	Log (characterizing)	Depth b.MSL (m)	Thickness (m)
A-1	no evaluation			
A-2	5898 - 5950	ITT-GR/ITT-GR	1762-1778	16
Adda-1	6819 - 6841	ITT-GR/ITT-GR	2044-2051	7
B-1	7305 - 7372	ITT-GR/ITT-GR	2191-2211	20
E-1	6683 - 6725	ITT-GR/ITT-GR	2000-2013	13
E-2	6530 - 6547	ITT-GR/ITT-GR	1953-1958	5
E-3	no evaluation			
G-1	6512 - 6610	ITT-GR/ITT-GR	1948-1977	29
H-1	6670 - 6680	ITT-GR/ITT-GR	1969-1999	3
I-1	8942 - 9011	ITT-GR/ITT-GR	2688-2709	21
M-1	5832 - 5910	ITT-GR/ITT-GR	1744-1768	24
M-2	no evaluation			
M-8	no evaluation			
N-1	6800 - 6839	ITT-GR/ITT-GR	2040-2052	12
N-2	6545 - 6590	ITT-GR/ITT-GR	1964-1977	13
O-1	6035 - 6043	ITT-GR/ITT-GR	1811-1814	3
P-1	9892 - 9504	ITT-GR/ITT-GR	2791-2859	68
Q-1	9790 - 9971	ITT-GR/ITT-GR	2946-3001	55
Ruth-1	5188 - 5205	ITT-GR/ITT-GR	1546-1551	5
T-1	7157 - 7228	ITT-GR/ITT-GR	2156-2178	22
U-1	7233 - 7279	ITT-GR/ITT-GR	2176-2190	14
V-1	7300 - 7356	ITT-GR/ITT-GR	2192-2209	17
W-1	9945 -10040	ITT-GR/ITT-GR	2997-3029	29

CEN-2 Unit

Well	Depth b.KB (feet)	Log (characterizing)	Depth b.MSL (m)	Thickness (m)
A-1	5727-5810	ITT-GR/ITT-GR	1736-1761	25
A-2	5823-5898	ITT-GR/ITT-GR	1739-1762	23
Adda-1	6760-6819	ITT-GR/ITT-GR	2026-2044	18
B-1	7230-7305	ITT-GR/ITT-GR	2168-2191	23
E-1	6640-6683	ITT-GR/ITT-GR	1987-2000	13
E-2	6485-6530	ITT-GR/ITT-GR	1939-1953	14
E-3	no evaluation			
G-1	6450-6512	ITT-GR/ITT-GR	1929-1948	19
H-1	6620-6670	ITT-GR/ITT-GR	1981-1996	15
I-1	8880-8942	ITT-GR/ITT-GR	2669-2688	19
M-1	5787-5832	ITT-GR/ITT-GR	1730-1744	14
M-2	5985-6030	ITT-GR/ITT-GR	1793-1807	14
M-8	5900-5950	ITT-GR/ITT-GR	1769-1784	15
N-1	6765-6800	ITT-GR/ITT-GR	2030-2040	10
N-2	6495-6545	ITT-GR/ITT-GR	1948-1964	16
O-1	5983-6035	ITT-GR/ITT-GR	1796-1811	15
P-1	9200-9282	ITT-GR/ITT-GR	2766-2791	25
Q-1	9717-9790	ITT-GR/ITT-GR	2924-2946	22
Ruth-1	5132-5188	ITT-GR/ITT-GR	1529-1546	17
T-1	7090-7157	ITT-GR/ITT-GR	2136-2156	20
U-1	7195-7233	ITT-GR/ITT-GR	2165-2176	11
V-1	7256-7300	ITT-GR/ITT-GR	2178-2192	14
W-1	9850-9945	ITT-GR/ITT-GR	2968-2997	29

CEN-3 Unit

Well	Depth b.KB (feet)	Log (characterizing)	Depth b.MSL (m)	Thickness (m)
A-1	4800-5727	ITT-GR/ITT-GR	1454-1736	282
A-2	4925-5823	ITT-GR/ITT-GR	1465-1739	274
Adda-1	5344-6760	ITT-GR/ITT-GR	1595-2026	431
B-1	5035-7230	ITT-GR/ITT-GR	1499-2168	669
E-1	5460-6640	ITT-GR/ITT-GR	1627-1987	360
E-2	5270-6485	ITT-GR/ITT-GR	1569-1939	370
E-3	no evaluation			
G-1	5330-6450	ITT-GR/ITT-GR	1587-1929	342
H-1	5255-6620	ITT-GR/ITT-GR	1565-1981	416
I-1	5515-8880	ITT-GR/ITT-GR	1644-2669	1025
M-1	4900-5787	ITT-GR/ITT-GR	1460-1730	270
M-2	4980-5985	ITT-GR/ITT-GR	1487-1793	306
M-8	4940-5900	ITT-GR/ITT-GR	1476-1769	293
N-1	5480-6765	ITT-GR/ITT-GR	1638-2030	392
N-2	5340-6495	ITT-GR/ITT-GR	1596-1948	352
O-1	4945-5983	ITT-GR/ITT-GR	1479-1796	317
P-1	5490-9200	ITT-GR/ITT-GR	1636-2766	1130
Q-1	6140-9717	ITT-GR/ITT-GR	1834-2924	1090
Ruth-1	4658-5132	ITT-GR/ITT-GR	1385-1529	144
T-1	5397-7090	ITT-GR/ITT-GR	1620-2136	516
U-1	5870-7195	ITT-GR/ITT-GR	1761-2165	404
V-1	5553-7256	ITT-GR/ITT-GR	1659-2178	519
W-1	5600-9850	ITT-GR/ITT-GR	1673-2968	1295

CEN-4 Unit

Well	Depth b.KB (feet)	Log (characterizing)	Depth b.MSL (m)	Thickness (m)
A-1	4040-4800	ITT-GR/ITT-GR	1222-1454	232
A-2	4134-4925	ITT-GR/ITT-GR	1224-1465	241
Adda-1	3893-5344	ITT-GR/ITT-GR	1152-1595	443
B-1	4745-5035	ITT-GR/ITT-GR	1411-1499	88
E-1	4200-5460	ITT-GR/ITT-GR	1243-1627	384
E-2	4210-5270	ITT-GR/ITT-GR	1246-1569	323
E-3	no evaluation			
G-1	3885-5330	ITT-GR/ITT-GR	1147-1587	440
H-1	4364-5255	ITT-GR/ITT-GR	1293-1565	272
I-1	4928-5515	ITT-GR/ITT-GR	1465-1644	179
M-1	4015-4900	ITT-GR/ITT-GR	1190-1460	270
M-2	4070-4980	ITT-GR/ITT-GR	1209-1487	278
M-8	4028-4940	ITT-GR/ITT-GR	1198-1476	278
N-1	4633-5480	ITT-GR/ITT-GR	1380-1638	258
N-2	4570-5340	ITT-GR/ITT-GR	1362-1596	234
O-1	4087-4945	ITT-GR/ITT-GR	1218-1479	261
P-1	4895-5490	ITT-GR/ITT-GR	1454-1636	182
Q-1	4997-6140	ITT-GR/ITT-GR	1485-1834	349
Ruth-1	3978-4658	ITT-GR/ITT-GR	1177-1385	208
T-1	4660-5397	ITT-GR/ITT-GR	1395-1620	225
U-1	4870-5870	ITT-GR/ITT-GR	1456-1761	305
V-1	3860-5553	ITT-GR/ITT-GR	1143-1659	516
W-1	5050-5600	ITT-GR/ITT-GR	1505-1673	168

CEN-5 Unit

Well	Depth b.KB (feet)	Log (characterizing)	Depth b.MSL (m)	Thickness (m)
A-1	1600-4040	ITT-GR/ITT-GR	478-1222	744
A-2	1675-4134	ITT-GR/ITT-GR	475-1224	749
Adda-1	1580-3893	ITT-GR/ITT-GR	447-1152	705
B-1	?2430-4745	ITT-GR/ITT-GR	?705-1411	706
E-1	1695-4200	ITT-GR/ITT-GR	479-1243	764
E-2	1820-4210	ITT-GR/ITT-GR	518-1246	728
E-3	no evaluation			
G-1	1480-3885	ITT-GR/ITT-GR	414-1147	733
H-1	1942-4364	ITT-GR/ITT-GR	555-1293	738
I-1	1901-4928	ITT-GR/ITT-GR	542-1465	923
M-1	1585-4015	ITT-GR/ITT-GR	450-1190	740
M-2	1630-4070	ITT-GR/ITT-GR	466-1209	743
M-8	1598-4028	ITT-GR/ITT-GR	458-1198	740
N-1	2028-4633	ITT-GR/ITT-GR	586-1380	794
N-2	2095-4570	ITT-GR/ITT-GR	607-1362	755
O-1	1453-4087	ITT-GR/ITT-GR	415-1218	803
P-1	2093-4895	ITT-GR/ITT-GR	600-1454	854
Q-1	2075-4997	ITT-GR/ITT-GR	595-1485	890
Ruth-1	1750-3978	ITT-GR/ITT-GR	498-1177	679
T-1	1720-4660	ITT-GR/ITT-GR	499-1395	896
U-1	2073-4870	ITT-GR/ITT-GR	604-1456	852
V-1	1340-3860	ITT-GR/ITT-GR	375-1143	768
W-1	1944-5050	ITT-GR/ITT-GR	558-1505	947

CEN-6 Unit

Well	Depth b.KB (feet)	Log (characterizing)	Depth b.MSL (m)	Thickness (m)
A-1	177 - 1600	ITT-GR/ITT-GR	45 - 478	433
A-2	263 - 1675	ITT-GR/ITT-GR	44 - 475	431
Adda-1	237 - 1580	ITT-GR/ITT-GR	38 - 447	409
B-1	252 -?2430	ITT-GR/ITT-GR	41 -?705	664
E-1	245 - 1695	ITT-GR/ITT-GR	37 - 479	442
E-2	256 - 1820	ITT-GR/ITT-GR	41 - 518	477
E-3	no evaluation			
G-1	282 - 1480	ITT-GR/ITT-GR	49 - 414	365
H-1	274 - 1942	ITT-GR/ITT-GR	46 - 555	509
I-1	310 - 1901	ITT-GR/ITT-GR	57 - 542	485
M-1	250 - 1585	ITT-GR/ITT-GR	43 - 450	407
M-2	236 - 1630	ITT-GR/ITT-GR	41 - 466	425
M-8	237 - 1598	ITT-GR/ITT-GR	43 - 458	415
N-1	234 - 2028	ITT-GR/ITT-GR	39 - 586	547
N-2	223 - 2095	ITT-GR/ITT-GR	37 - 607	570
O-1	233 - 1453	ITT-GR/ITT-GR	43 - 415	372
P-1	339 - 2093	ITT-GR/ITT-GR	66 - 600	534
Q-1	321 - 2075	ITT-GR/ITT-GR	60 - 595	535
Ruth-1	243 - 1750	ITT-GR/ITT-GR	39 - 498	459
T-1	298 - 1720	ITT-GR/ITT-GR	66 - 499	433
U-1	235 - 2073	ITT-GR/ITT-GR	43 - 604	561
V-1	271 - 1340	ITT-GR/ITT-GR	49 - 375	326
W-1	285 - 1944	ITT-GR/ITT-GR	53 - 558	555

9.0 Tables on reservoir parameters

Recorded and calculated values of the reservoir properties.

Reservoir Parameters for: CA-1 Unit (Early Carboniferous)

Well Name	Depth b. KB (FT)	Depth b. MSL (M)	Thickn. (M)	Unit no.	Shows	Net.res. zone (M)	Log type	Porosity %						Permeability MD				Test Type
								log			core			core			test	
								Ømax	Ømin	$\bar{Ø}$	Ømax	Ømin	$\bar{Ø}$	Kmax	Kmin	$\bar{K}$	K	
P-1	11038-11259	3327-3394	67			14		15	5	11								

Reservoir Parameters for: Rotliegendes Group

Well Name	Depth b. KB (FT)	Depth b. MSL (M)	Thickn. (M)	Unit no.	Shows	Net.res. zone (M)	Log type	Porosity %						Permeability MD				Test Type
								log			core			core			test	
								Ømax	Ømin	$\bar{Ø}$	Ømax	Ømin	$\bar{Ø}$	Kmax	Kmin	$\bar{K}$	K	
B-1	11283-TD11985	3404-3618	214+			0												
P-1	10350-11038	3119-3327	208			20.5	FDC/CNL	10	2	5								
W-1	13888-TD14375	4196-4345	149+			0												

Reservoir parameters for: Zechstein Group

Well Name	Depth b. KB (FT)	Depth b. MSL (M)	Thickn. (M)	Unit no.	Shows	Net.res. zone (M)	Log type	Porosity %						Permeability MD				Test Type
								log			core			core			test	
								Ømax	Ømin	$\bar{Ø}$	Ømax	Ømin	$\bar{Ø}$	Kmax	Kmin	$\bar{K}$	K	
B-1	10190-11283	3009-3404	395			6		10	4	5								
Ruth-1	5586-TD5618	1668-1678	10+			0												
T-1	7690-TD8713	2319-2631	312+			0					4a	0.3a	1a	1a	0a	0a		

a) Non res. zone

Reservoir parametres for: Bacton Group

Well Name	Depth b. KB (FT)	Depth b. MSL (M)	Thickn. (M)	Unit no.	Shows	Net.res. zone (M)	Log type	Porosity %						Permeability MD				Test Type
								log			core			core			test	
								Ømax	Ømin	$\bar{Ø}$	Ømax	Ømin	$\bar{Ø}$	Kmax	Kmin	$\bar{K}$	K	
B-1	9990-10190	3009-3060	51			0												
Q-1	13910-14620	4203-4420	217		+	a												
U-1	14651-TD16045	4437-4862	425+			43b	FDC/CNL	11	8	10								
						8c		21	14	17								

a) Very thin. Very poor data
b) Bunter Sandstone Formation
c) Bunter Shale Formation

Reservoir parameters for: J-2 Unit

Well Name	Depth b. KB (FT)	Depth b. MSL (M)	Thickn. (M)	Unit no.	Shows	Net.res. zone (M)	Log type	Porosity % log $\varnothing_{max}$	log $\varnothing_{min}$	log $\bar{\varnothing}$	core $\varnothing_{max}$	core $\varnothing_{min}$	core $\bar{\varnothing}$	Permeability MD core K_{max}	core K_{min}	core $\bar{K}$	test K	Test Type
Upper Member																		
A-2	9920-9970	2988-3003	15			?												
M-8	10143-10260	3062-3098	36			0												
O-1	8901-9425	2685-2845	160			39	FDC/CNL	27	15	25								
U-1	10665-10853	3222-3280	58			0												
Lower Member																		
A-2	9970-10050	3003-3027	24		+	?												
M-8	10260-10467	3098-3161	37		+	3	FDC/CNL	21	18	19							?	FT
O-1	9425-9838	2845-2971	126			9	FDC/CNL	25	18	20								
U-1	10853-11048	3280-3339	41		+	27	FDC/CNL	30	15	20							3	FT

Reservoir parameters for: W-1 Unit

Well Name	Depth b. KB (FT)	Depth b. MSL (M)	Thickn. (M)	Unit no.	Shows	Net.res. zone (M)	Log type	Porosity % log $\varnothing_{max}$	log $\varnothing_{min}$	log $\bar{\varnothing}$	core $\varnothing_{max}$	core $\varnothing_{min}$	core $\bar{\varnothing}$	Permeability MD core K_{max}	core K_{min}	core $\bar{K}$	test K	Test Type
W-1	13521-13839	4087-4184	97			67	FDC	14	6	11							?	FIT

Reservoir parameters for: J-3 Unit

Well Name	Depth b. KB (FT)	Depth b. MSL (M)	Thickn. (M)	Unit no.	Shows	Net.res. zone (M)	Log type	Porosity % log $\varnothing_{max}$	log $\varnothing_{min}$	log $\bar{\varnothing}$	core $\varnothing_{max}$	core $\varnothing_{min}$	core $\bar{\varnothing}$	Permeability MD core K_{max}	core K_{min}	core $\bar{K}$	test K	Test Type
A-2	- 9920				+	?												
G-1	12037-TD12517	3632-3778	146+		+	?												
M-8	8940-10143	2695-3062	367			0?												
O-1	- 8901	-2685				?												
U-1	9595-10665	2896-3222	326			0	FDC/CNL			19								
V-1	?10601-12080	?3198-3648	?450			?												

Reservoir Parameters for: J-4 Unit

Well Name	Depth b. KB (FT)	Depth b. MSL (M)	Thickn. (M)	Unit no.	Shows	Net.res. zone (M)	Log type	Porosity % log $\varnothing_{max}$	log $\varnothing_{min}$	log $\bar{\varnothing}$	core $\varnothing_{max}$	core $\varnothing_{min}$	core $\bar{\varnothing}$	Permeability MD core K_{max}	core K_{min}	core $\bar{K}$	test K	Test Type
A-2	7470-?				+	? a)												
Adda-1	8400-TD10005	2526-3015	489+		+	13 22	FDC/CNL	20	14	18								
E-1	9727-TD13403	2928-4048	1120+		+	38 62											0	DST
G-1	8088-12037	2429-3632	1204		+	89 134	ITT	18	4	11								
I-1	11018-TD12848	3321-3879	558+			21 35	ITT	13	3	7								
M-1	7190-TD7574	2158-2275	117+			?												
M-8	7517- 8940	2262-2695	433			16 26												
O-1	?					?												
Q-1	?					?												
U-1	8190- 9595	2468-2896	428		+	27 44	FDC/CNL	19	13	18								
V-1	9462-10601?	2851-3198?	?347			4 7												
W-1	12333-13521	3725-4087	362		+	7 11	FDC/CNL	8	4	5								

a) Numbers of dolostone stringers

Reservoir parameters for: LC-1 Unit

Well Name	Depth b. KB FT	Depth b. MSL M	Thickn. M	Unit no.	Shows	Net.res. zone M	Log type	Porosity % log Ømax	log Ømin	log $\bar{Ø}$	core Ømax	core Ømin	core $\bar{Ø}$	Permeability MD core Kmax	core Kmin	core $\bar{K}$	test K	Test Type
V-1	8972-9462	2702-2851	149		+	62	CNL	36	3	22								

Reservoir parameters for: Valhall Formation

Well Name	Depth b. KB FT	Depth b. MSL M	Thickn. M	Unit no.	Shows	Net.res. zone M	Log type	Porosity % log Ømax	log Ømin	log $\bar{Ø}$	core Ømax	core Ømin	core $\bar{Ø}$	Permeability MD core Kmax	core Kmin	core $\bar{K}$	test K	Test Type
A-2	7260- 7470	2177-2241	64			?												
Adda-1	7530- 8400	2262-2526	264		+	22	FDC/CNL	36	24	28							8.55 87a mDft	PT
E-1	8297- 9727	2492-2928	436		+	7	FDC	24	7	19							0	DST FT
E-3	8350-TD8722	2515-2628	113+			38	FDC/CNL	34	19	25	28	17	24					
G-1	7410- 8088	2222-2429	207			16	ITT			17								
I-1	9508-11018	2862-3321	459		+	11	?			27								
M-1	6902- 7190	2071-2159	88			5	ITT	31	13	26								
M-7	8934-TD9070	2691-3733	42+			0				?								
M-8	7280- 7517	2190-2262	72			0				?								
O-1	7580-?	2283-?				?												
Q-1	?																	
U-1	8112- 8190	2445-2468	23		+	7	FDC/CNL	30	13	23								
V-1	8937- 8972	2691-2702	12			9	FDC/CNL	25	9	20								

a) Prod. test 5, test after acid

Reservoir parameters for: Rødby Formation

Well Name	Depth b. KB FT	Depth b. MSL M	Thickn. M	Unit no.	Shows	Net.res. zone M	Log type	Porosity % log Ømax	log Ømin	log $\bar{Ø}$	core Ømax	core Ømin	core $\bar{Ø}$	Permeability MD core Kmax	core Kmin	core $\bar{K}$	test K	Test Type
A-2	7240-7260	2171-2177	6			?												
Adda-1	7512-7530	2256-2262	6			?	FDC/CNL	38	21	29								
E-1	8162-8297	2451-2492	41		+	?	FDC	36	15	23							none flow	DST
E-3	8305-8350	2502-2515	13			?	FDC/CNL	35	20	26			18					
I-1	9355-9508	2815-2862	47			?	FDC	27	13	20								
M-1	6858-6902	2057-2071	14			?	FDC	21	11	16								
M-8	7212-7280	2169-2190	21			?	FDC/CNL	40	13	27								
O-1	7570-7580	2280-2283	3			?	ITT											
Q-1	?																	
W-1	?																	

Reservoir parameters for: Chalk Group

Well Name	Depth b. KB FT	Depth b. MSL M	Thickn. M	Unit no.	Shows	Net.res. zone M	Log type	Porosity % log Ømax	Ømin	Ø̄	core Ømax	Ømin	Ø̄	Permeability MD core Kmax	Kmin	K̄	test K	Test Type
A-2	5952-6015	1778-1797	19	6 U	+	19	ITTa	38	27	35	38	12	28	4	0	0.1	66-166	DST
A-2	6015-6125	1797-1831	34	6 L	+	34	ITTa	35	22	31	35	12	22	5	0	0	2-28	DST
A-2	6125-6262	1831-1873	42	5	+	42	ITTa	33	29	30							3	DST
A-2	6262-6650	1873-1991	118	4	+	118	ITTa	30	23	27								
Adda-1	6866-6959	2059-2087	28	6 U	+	28	FDC/CNL/ ITT	40	28	37								
Adda-1	6959-7040	2087-2112	25	6 L		25	”	34	22	28								
Adda-1	7040-7063	2112-2119	7	5	+	7	”	35	26	29							1	FT
Adda-1	7063-7138	2119-2142	23	3	+	23	”	27	16	22								
Adda-1	7138-7420	2142-2227	85	2	+	85	”	35	18	24							103, 51	SF, FT
Adda-1	7240-7512	2227-2556	28	1	+	28	”	28	16	21								
E-1	6735-6810	2016-2039	23	6 U	+	23	ITT	36	32	34	39	16	36	5	0.2	2		DST, FT
E-1	6810-6880	2039-2060	21	6 L	+	21	ITT	32	22	29	37	12	30	2	0.03	1		DST, FT
E-1	6880-7072	2060-2118	58	5	+	58	ITT	37	27	31	33	25	30	5	2	3		DST
E-1	7072-7325	2118-2195	77	4	+	77	ITT	31	21	27								
E-1	7325-7500	2195-2249	54	3	+	54	ITT	24	16	20								
E-1	7500-8115	2249-2436	187	2	+	187	ITT	28	17	22								
E1	8115-8162	2436-2451	14	1	+	14	ITT	18	16	18								DST
G-1	6610-6675	1978-1997	19	6 U	+	19	ITT/GR	37	33	36	38	25	36	2	0.13	1	0.45	DST
G-1	6675-6790	1997-2032	35	6 L	+	35	ITT/GR	34	20	29	39	20	30	2	0.03	0.3	0.07	DST
G-1	6790-6830	2032-2045	13	5	+	13	ITT/GR	32	23	29								DST
G-1	6830- 6875	2045-2058	13	4	+	13	ITT/GR	25	20	23								
G-1	6875- 7120	2058-2133	75	3	+	75	ITT/GR	22	19	21								
G-1	7120- 7410	2133-2222	89	2	+	89	ITT/GR	27	23	25								
H-1	6680- 6713	1999-2009	10	6 b	+	10	FDC	49	42	46	46	40	43	12	1	3		DST
H-1	6713- 6981	2009-2091	82	5	+	82	FDC	49	22	36	46	32	39	17	3	7		DST
H-1	6981-TD7100	2091-2127	36+	4	+	36	FDC	29	18	24								
I-1	9070- 9138	2727-2748	21	6 U	+	21	ITT	33	26	30	32	15	29	1	0.05	0.3		DST
I-1	9138- 9182	2748-2761	13	6 L	+	13	ITT	28	9	24	28	5	17	0.23	0.01	0.05		DST
I-1	9182- 9241	2761-2779	18	5	+	18	ITT	32	21	28	24	18	20	1	0.01	0.1	30	DST
I-1	9241- 9355	2779-2814	35	4	+	35	ITT	28	18	25								
M-1	5902- 5962	1765-1784	19	6 U	+	19	ITT	42	36	39	42	23	35	6	0.02	2		
M-1	5962- 6032	1784-1805	21	6 L	+	21	ITT	42	31	34	37	17	27	3	0.01	0.2		
M-1	6032- 6118	1805-1831	26	5	+	26	ITT	42	35	40	45	25	35	10	2	5		
M-1	6118- 6471	1831-1939	108	4	+	108	ITT	34	31	32	33	20	27	9	0.3	2		FT
M-1	6471- 6590	1939-1975	36	3	+	36	ITT	33	31	31	27	21	24	4	1	2		FT
M-1	6590- 6858	1975-2057	82	2		82	ITT	31	29	30								
N-1	6897- 6918	2070-2076	6	6 U	+	6	ITT/GR	35	31	34	37	18	28	6	0.16	3		FT
N-1	6918- 6937	2076-2082	6	6 L	+	6	ITT/GR	33	25	30	?	?	27	0.35	0.18	0.26		FT
N-1	6937- 7147	2082-2146	64	5	+	64	ITT/GR	37	32	26	34	33	34	4	3	3		FT
N-1	7147- 7745	2146-2328	182	4	+	182	ITT/GR	32	25	28								
N-1	7745- 7904	2328-2377	49	3		49	ITT/GR	24	22	23								
N-1	7904-TD8155	2377-2453	76+	2		76	ITT/GR	24	22	23								
O-1	6097- 6180	1830-1856	26	6 U		26	CNL			27	32	19	25	2	0.01	0.05		
O-1	6180- 6254	1856-1878	22	6 L		22	CNL			25								
O-1	6254- 7187	1878-2163	285	5		285	CNL	28	25	26								
O-1	7187- 7349	2163-2212	49	4		49	CNL	23	21	22								
O-1	7349- 7408	2212-2230	18	3		18	CNL	22	21	21								
O-1	7408- 7500	2230-2258	28	2		28	CNL			21								
O-1	7500- 7580	2258-2282	24	1		24	CNL			21								
P-1	9580- 9745	2882-2932	50	6 U	+	50	ITT	39	33	37								
P-1	9745- 9818	2932-2955	23	6 L	+	23	ITT	35	33	33								
P-1	9818- 9865	2955-2969	14	5	+	14	ITT			35								
P-1	9865-10350	2969-3117	148	4	+	148	ITT	31	27	30								
Q-1	10058-10195	3028-3097	69	6 U	+	69	ITT	25	23	24	17	3	13	0.29	0.01	1		
Q-1	10195-10378	3097-3125	28	6 L	+	28	ITT	20	16	18								
Q-1	10378-10730	3125-3233	108	5		108	ITT	20	16	19								
Q-1	10730-11640	3233-3510	277	4		277	ITT	19	12	14								
Q-1	11640-12128	3510-3659	149	3		149	ITT	13	11	12								

Q-1	10378-10730	3125-3233	108	5		108	ITT	20	16	19								
Q-1	10730-11640	3233-3510	277	4		277	ITT	19	12	14								
Q-1	11640-12128	3510-3659	149	3		149	ITT	13	11	12								
Q-1	12128-13000	3659-3925	265	2		265	ITT	16	13	15								
T-1	7283- 7355	2195-2217	22	6 U	+	22	FDC/CNL	30	19	23	32	12	27	8	0.007	0.2		
T-1	7355- 7419	2217-2236	19	6 L	+	19	ITT	26	18	21	38	8	21	10	0.006	0.07		
T-1	7419- 7519	2236-2267	31	5	+	31	ITT	28	14	20	31	12	23	20	0.007	1		
T-1	7519- 7685	2267-2317	50	4	+	50	ITT	27	14	18	28	2	18	19	0.005	2	5	DST
U-1	7300- 7360	2197-2215	18	6 U	+	18	FDC/CNL	30	23	26								
U-1	7360- 7434	2215-2238	23	6 L	+	23	FDC/CNL	27	21	25								
U-1	7434- 7594	2238-2286	48	5	+	48	FDC/CNL	25	24	24								
U-1	7594- 7800	2286-2349	63	4	+	63	FDC/CNL	24	20	22								
U-1	7800- 7898	2349-2379	30	3	+	30	FDC/CNL	24	20	22								
U-1	7898- 8109	2379-2444	65	2	+	65	FDC/CNL	26	17	21								
V-1	7355- 7470	2208-2243	39	6 U	+	35	FDC/CNL	25	23	25								
V-1	7470- 7550	2243-2268	35	6 L	+	35	FDC/CNL	25	23	24								
V-1	7550- 7639	2268-2295	27	5	+	27	FDC/CNL	24	22	23								
V-1	7639- 8025	2295-2412	117	4	+	117	FDC/CNL	24	22	23								
V-1	8025- 8375	2412-2519	107	3	+	107	FDC/CNL	24	20	22								
V-1	8375- 8937	2519-2690	171	2	+	171	FDC/CNL	24	8	14								
W-1	10135-10249	3055-3090	35	6 U	+	35	FDC/CNL	13	12	12								
W-1	10249-10413	3090-3140	50	6 L	+	50	FDC/CNL	13	12	13								
W-1	10413-10695	3140-3226	86	5	+	86	FDC/CNL	17	11	13								
W-1	10695-11267	3226-3400	174	4	+	174	FDC/CNL	10	6	8								
W-1	11267-11782	3400-3557	157	3	+	157	FDC/CNL	8	4	5								
W-1	11782-12333	3557-3725	168	2	+	168	FDC/CNL	12	6	9								

a) No logs below 6650’. Base chalk at 7230’ b. KB
b) Unit 6 cannot be subdivided

10.0 References

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List of figures

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