MESOZOIC STRUCTURAL AND SEDIMENTARY DEVELOPMENT OF THE DANISH CENTRAL GRABEN[1]

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ABSTRACT

Michelsen, O. & C. Andersen 1983 Mesozoic structural and sedimentary development of the Danish Central Graben. In: J. P. H. Kaasschieter & T. J. A. Reijers (eds.): Petroleum geology of the southeastern North Sea and the adjacent onshore areas (The Hague, 1982) – Geol. Mijnbouw 62: 093-102.

The structural framework of the Central Graben, probably created in Late Palaeozoic times, controlled the sedimentary conditions during major parts of the Mesozoic.

The Danish Central Graben is subdivided into a number of sub-areas each characterized by specific structural styles, the most important being the Northern and Southern Salt-dome Provinces, the Tail End Graben and the Dogger High.

During the Triassic subsidence a sedimentary sequence not surpassing 2000 m was deposited. The Early Kimmerian tectonic phase caused erosion into the top of the Triassic sequence on anticlinal structures. The Jurassic and Early Cretaceous periods were dominated by strong subsidence and more than 4000 m of sediments were accumulated in the Tail End Graben. Both the Mid and Late Kimmerian tectonic phases affected the Central Graben. During the Late Cretaceous the change from a rifting phase into one of gradual subsidence was accompanied by inversion tectonics.

INTRODUCTION

In the present paper the authors have compiled data and interpretative results reached by the staff of the Danish Geological Survey. A major part of this work is presented in detail in MICHELSEN (1982).

REGIONAL SETTING

The Danish Central Graben is a part of the rifting system stretching north-south through the North Sea (Fig. 1). This graben system 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 of the Danish sector it separates the Anglo-Dutch Basin from the Northwest German Basin; to the north the Forth Approaches Basin from the Norwegian-Danish Basin. Within the Danish sector the graben system separates the Mid North Sea High from the Ringkøbing-Fyn High. Both sides of the Graben are clearly defined by normal rotational faults that were intermittently active from Triassic to Early Cretaceous.

A comprehensive and detailed description of the geological and structural development in the North Sea region is found in ZIEGLER (1981).

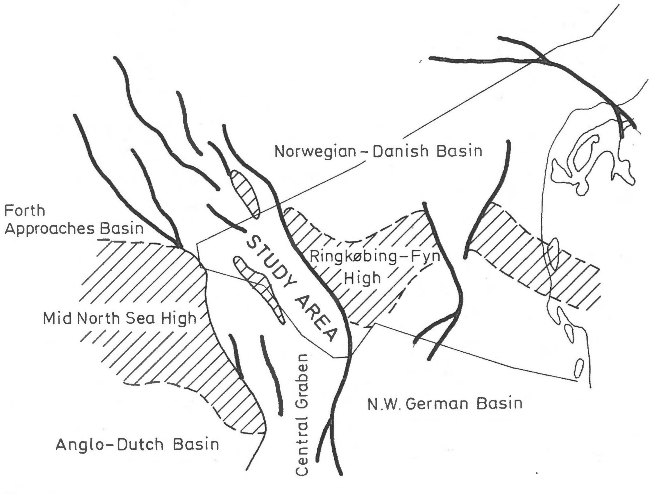

Fig. 1
Location map.

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STRUCTURAL OUTLINE

The Danish Central Graben is subdivided into the following units, which are defined by ANDERSEN ET AL. (1982) and which are referred to in the following text (see also Fig. 2).

To the north and the south are the Northern and Southern Salt-dome Provinces, which are believed to belong to the Northern and Southern Zechstein Basins, respectively. Halokinesis of the Zechstein evaporites during the Mesozoic is a characteristic feature.

The deepest part of the Central Graben is named the Tail End Graben, which forms a half graben-like axial depression adjacent to the boundary fault system of the Ringkøbing-Fyn High. The depth to the top Palaeozoic is locally about 10 to 11 km. In contrast, depths of about 3 km are found on the bordering part of the Ringkøbing-Fyn High.

The western margin of the Tail End Graben is characterized by a major fault zone which, at Late Cretaceous and Early Tertiary levels, has been interpreted as having reverse components, probably caused by compressional strike-slip movements. The Dogger High, which extends northwestwards from the German North Sea into the Danish sector, is a rather complex horst structure on which Mesozoic sediments older than Late Cretaceous limestones are missing. The area west, north and east of the Dogger High are the least known due to lack of available data. The area is generally characterized by intermediate depths to top Palaeozoic. The Mid North Sea High may extend into the Danish Sector.

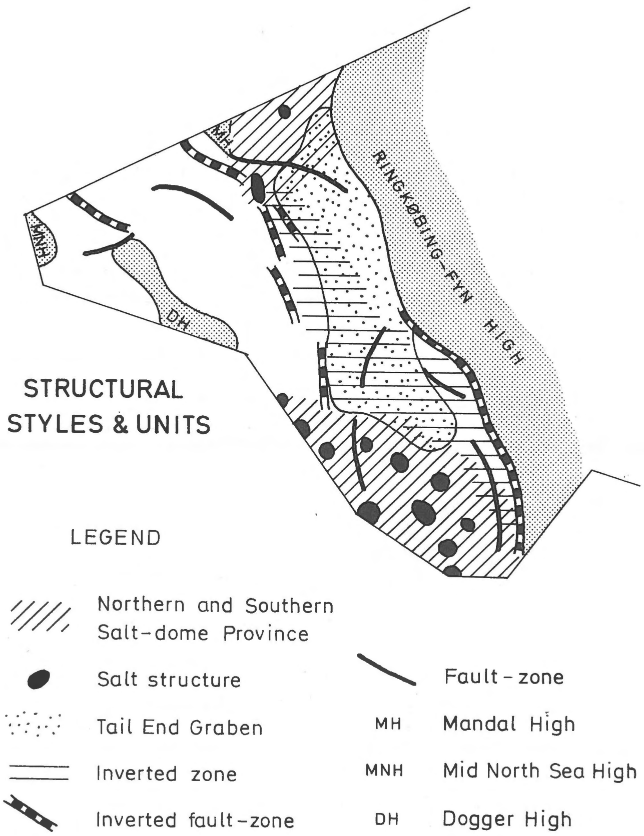


Fig. 2
Structural styles and Units.

LITHOSTRATIGRAPHY

The lithostratigraphic units referred to below are listed in Table I. A more comprehensive description is found in MICHELSEN (1982).

SEDIMENTARY AND STRUCTURAL DEVELOPMENT

Underlying the Mesozoic sequence extensive Zechstein evaporites occur to the north and south, and in the centre of the Danish Central Graben thin halites or shallow marine sediments are believed to be present. Below the base Zechstein level, well data have proven a Rotliegendes sequence consisting of an upper sedimentary series of redbeds and a lower volcanic series. Certain parts of the series in the P-1 and W-1 wells have been interpreted as lava flows (JACOBSEN & LARSEN, 1982). Carboniferous sediments and Caledonian greenschists are found in the P-1 well (BERTELSEN, 1978).

The Triassic sequence has been drilled in few wells which, except for Q-1, are located in the southern part of the region. The Triassic sediments in the North Sea region are generally subdivided into two parts. A northern suite dominated by continental sediments and a southern suite with continental and marine interbeds. It is suggested that the Danish Central Graben is located in a transitional zone between these two regions. In the Danish Q-1 well to the north (Fig. 3), series of coarse clastic sediments are found which are referred to the Smith Bank Formation, as defined by DEEGAN & SCULL (1977). Due to limited well control the stratigraphic and regional distribution presented by JACOBSEN (1982, Fig. 20) is considered a model only. From seismic records as compiled in profile 3 (Fig. 5), the Triassic sequence is roughly calculated to 1000 m thickness. This is primarily the case in the Tail End Graben, as the sequence is thinning and locally truncated by Jurassic sequences to the west.

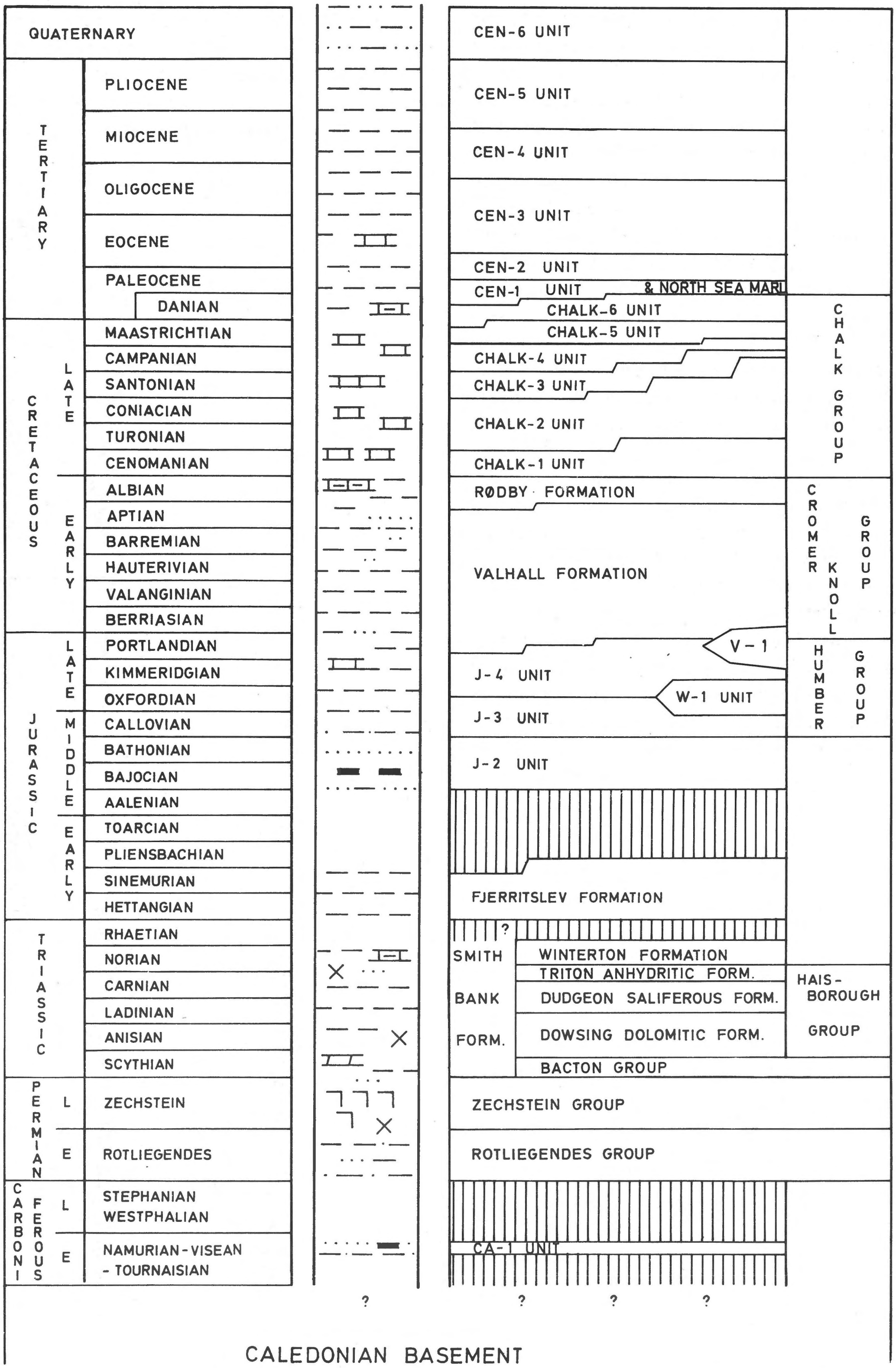
To the south the Triassic sequence is known from the A-2, M-8, O-1, and U-1 wells. Biostratigraphic indications are scarce, but the sedimentary succession can be closely related in a lithostratigraphic sense to that of the Southern North Sea (cf. RHYS, 1974; BERTELSEN, 1980; JACOBSEN, 1982). Covering the Zechstein evaporites supratidal and alluvial sediments of the Bacton Group are found in a clay dominated facies (see the U-1 well, Fig. 3). The low sand content is explained by the distal position of this area in relation to the source area. Upon the Bacton Group follows the Dowsing Dolomitic Formation which represents the first transgression from the south. The Formation comprises evaporites which probably correspond to the Röt transgression. The overlying Dudgeon Saliferous

Table I

DANISH CENTRAL GRABEN

STANDARD STRATIGRAPHIC SUBDIVISION

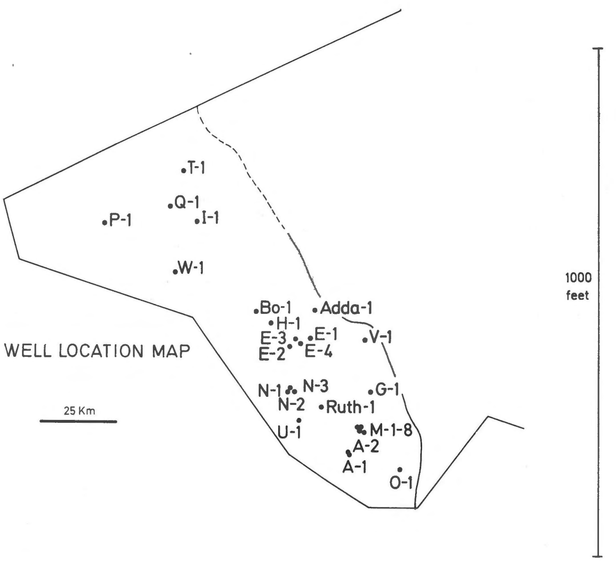
DGU 1982



and Triton Anhydritic Formations represent a regressive phase with deposition of interbedded marlstones and anhydrite-bearing claystones. These are interpreted as belonging to a continental sabkha environment interrupted by distal flood plain settings. The evaporite series was probably precipitated during periodic flooding of the area. Recent interpretation of seismic data and well logs suggests that the sequence in the U-1 well is intersected by a reverse fault, causing repetition of the two formations (Fig. 3). The youngest drilled Triassic unit comprises brackish and shallow marine claystones which are referred to as the Winterton Formation. Interpretation of seismic data, as compiled in profiles 1 and 2 (Fig. 5), indicates a general thickness of 1500 to 2000 m in the Southern Saltdome Province. However, rather considerable variations in thickness caused by Early Kimmerian erosion occur. This tectonic event may also explain, why Rhaetian sandstones have not been drilled as yet. The Base Jurassic seismic reflection is often developed as a distinct unconformity surface, showing erosion on anticlinal structures, where the wells are located.

The sedimentary development in the Danish Central Graben during Jurassic times is closely correlatable with that known from other parts of the North Sea region. A succession of Early Jurassic shallow shelf and Middle Jurassic near-coastal environments is followed by increasing depth conditions during the Late Jurassic. The Jurassic sequence has been drilled in a few wells. The U-1, E-1, and I-1 wells are presented in figure 4b. The U-1 well section is the most complete with regard to all Jurassic units. The E-1 section is regarded as typical for the youngest part, and the I-1 section is representative for the northern region with features resembling 'hot shales'.

The lowermost Jurassic sequence consists of clay deposited in a shallow shelf environment. Based mainly on log-patterns, it is referred to the Fjerritslev Formation, known from the Norwegian-Danish Subbasin. The sonic log-motif is characteristic for the F-1a and F-1b Members (MICHELSEN, 1978a). Biostratigraphic datings refer the series to Hettangian and Sinemurian (MICHELSEN, 1978b). The overlying series, the J-2 Unit, is referred to the Middle Jurassic (Bajocian and Batho-



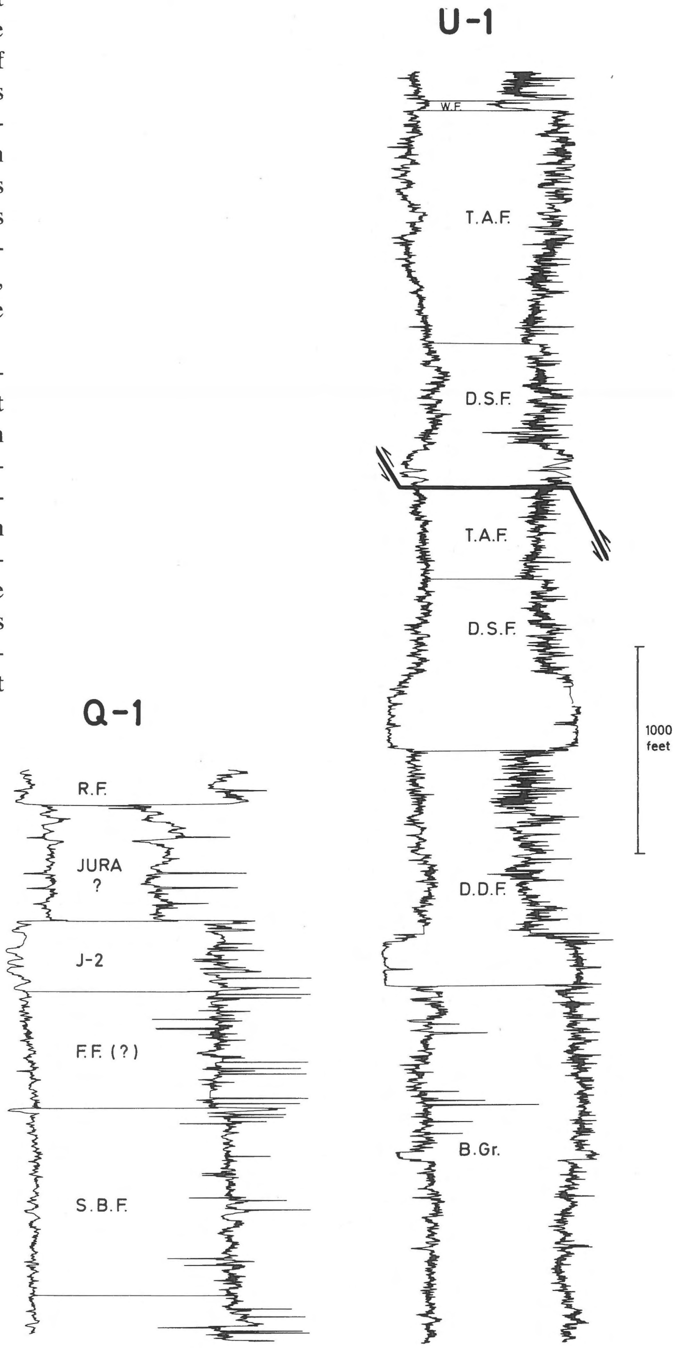


Fig. 3
Gamma Ray and Sonic log-motifs of selected Triassic well sections. *Legend:* W. F. = Winterton Formation, T. A. F. = Triton Anhydritic Formation, D.S.F. = Dudgeon Saliferous Formation, D.D.F. = Dowsing Dolomitic Formation, B.Gr. = Bacton Group, R.F. = Rødby Formation, J-2 = J-2 Unit, F.F. = Fjerritslev Formation, S.B.F. = Smith Bank Formation.

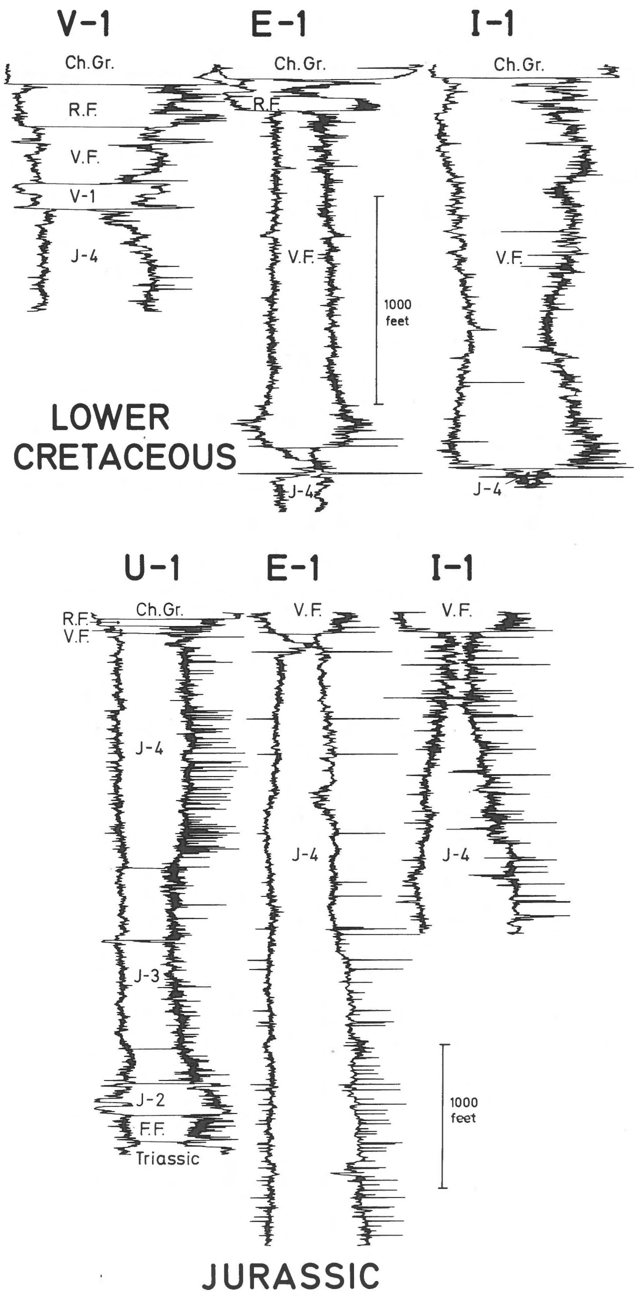


Fig. 4a-b
Gamma Ray and Sonic log-motifs of selected Jurassic and Lower Cretaceous well sections. *Legend:* Ch.Gr. = Chalk Group, R.F. = Rødby Formation, V.F. = Valhall Formation, V-1 = V-1 Sand, J-4 = J-4 Unit, J-3 = J-3 Unit, J-2 = J-2 Unit, F.F. = Fjerritslev Formation. For location see figure 3.

nian) on the basis of palynology. There is, therefore, a hiatus comprising the main part of the Early Jurassic which is interpreted as a result of the Mid Kimmerian uplift and subsequent erosion. The J-2 Unit consists of interbedded sandstones, claystones and heterolithic sandstones with coal seams. It is subdivided into two members: a lower member, dominated by sand and clay, and an upper one, characterized by coal seams. The depositional environment is not yet established, however, it seems reasonable to apply a model of fluvial and deltaic environments (cf. KOCH, 1983). The distribution of these Early and Middle Jurassic sediments is only sparsely documented by drilling. To the north, however, the Q-1 well section is tentatively correlated as the Fjerritslev Formation and the J-2 Unit (Fig. 3).

The overlying claystone sequence is subdivided into the J-3 and J-4 Units (see Fig. 4b). The J-3 Unit, consisting of silty claystone, is biostratigraphically dated to Oxfordian and (probably) Callovian. The silt content and the dominance of terrestrial plant remains suggest a shallow shelf depositional environment. The J-4 Unit, dated as Late Oxfordian to Kimmeridgian and locally as Tithonian, consists of claystones. The content of marine plant remains suggests that deposition was on the deeper shelf. The characteristic sonic log patterns indicate the occurrence of numerous dolomitic stringers (see Fig. 4b). High gamma ray readings in the I-1 well indicate an equivalence to the 'hot shale' of the northern North Sea. The three well sections illustrate the great variation in thickness, which may be due to their location on local structures, but which may also be caused by variations in the regional subsidence pattern. Marginal sand bodies have been proven in two wells. In the W-1 well, east of the Dogger High, a sandstone series underlying the J-4 Unit is found and is tentatively referred to late Middle Jurassic and early Late Jurassic. The sequence has a mixed lithology and contains granitic clasts and shell fragments. It was probably deposited in a shallow marine coastal environment. In the V-1 well, close to the border fault of the Ringkøbing-Fyn High, a sand series is found above the J-4 Unit. Biostratigraphic dating suggests a Late Jurassic age. It is a sand/siltstone series, probably deposited under shallow marine conditions. Both types of sand deposits are expected to occur along the fault zones bordering the Danish Central Graben (see KOCH, 1983).

A second major hiatus is found at top of the J-4 Unit. It is interpreted as a result of the Late Kimmerian tectonic event, which has affected the entire North Sea region. Preliminary studies have placed the hiatus uppermost in the Late Jurassic.

The correlation of the Jurassic sequence with that of the remaining part of the Danish area is briefly reviewed. The sequences known from the Danish Subbasin show a similar sedimentary development as those of the Graben. However, the Rhaetian shallow marine sand is preserved in the Subbasin. The Mid Kimmerian unconformity is found both in the Subbasin and in the Graben. Late Jurassic sedimentation in the Subbasin took place under relatively shallow marine conditions, with the shallow shelf represented by the Børglum Member and the near-coastal area by the Frederikshavn Member. A hiatus or erosion caused by the Late Kimmerian event is only proven in the Central Graben.

The structural development during Jurassic time is elucidated in more detail by studies of seismic data. On the profiles in figure 5 the Late Kimmerian unconformity is illustrated, but examples of internal Jurassic unconformities, probably

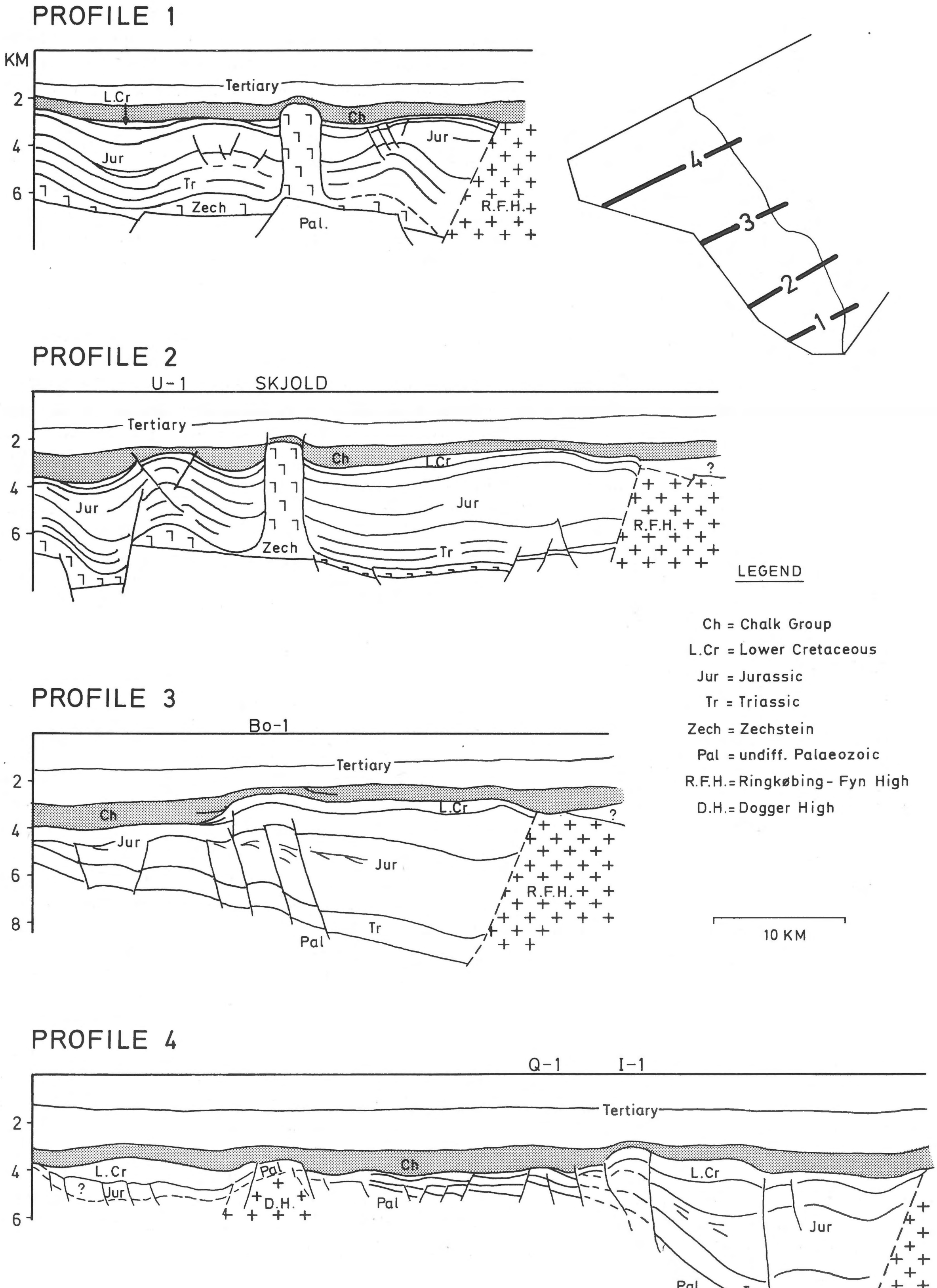


Fig. 5
Seismic profiles showing various structural styles and sedimentary sequences.

within the J-4 Unit, are also indicated.

The thickness of the Jurassic sequence (see Fig. 6), of which the major part consists of Late Jurassic claystones, exceeds 4000 m in the Tail End Graben. West of this, the sequence is reduced in thickness and it is totally absent on the crest of the Dogger High. The structural development, especially the marked subsidence of the Tail End Graben, is evident from the Base and Top Jurassic maps (Fig. 7). The maximum depth of the Base Jurassic is here approximately 8000 m, whereas it is about 4000 m in the shallower parts. The depth to the Top Jurassic varies from 2500 to 4500 m.

The Late Jurassic is the main subsiding period for the Danish Central Graben. The great variation in thickness is primarily due to the subsidence of, and deposition on, individual rotational fault blocks. It is tentatively suggested that the major part of the Tail End Graben subsided as one large rotational fault block with the boundary fault zone of the Ringkøbing-Fyn High acting as one major synthetic fault zone. In the Southern Salt-dome Province, the thickness is generally between 1000 and 2000 m, it being thickest in the rim-synclines.

The Late Kimmerian tectonic phase led to a framework of differentially subsiding rotational fault blocks, which were only slightly changed during the Early Cretaceous. The rate of subsidence slowed down, however. Sedimentation of shallow shelf claystones prevailed. They are referred to the Valhall Formation (defined by DEEGAN & SCULL, 1977). Onlap features on seismic records are common above the Late Kimmerian unconformity.

The log-motif illustrated by the E-1 well section (Fig. 4a) is taken as typical for the Danish region where the Valhall Formation is most completely developed. The lower 'onion-shaped' part is indicative of a more coarse-clastic development, and the overlying clay series does not have dolomitic layers as does the underlying J-4 Unit. Biostratigraphic studies indicate a Tithonian to Early Aptian age of the Valhall Formation in the Danish Central Graben.

Reddish marlstones of the Rødby Formation, known from large parts of the North Sea region, are found at the top of the Valhall Formation. The Formation is mainly referred to the Albian, and it is regarded to represent the onset of the

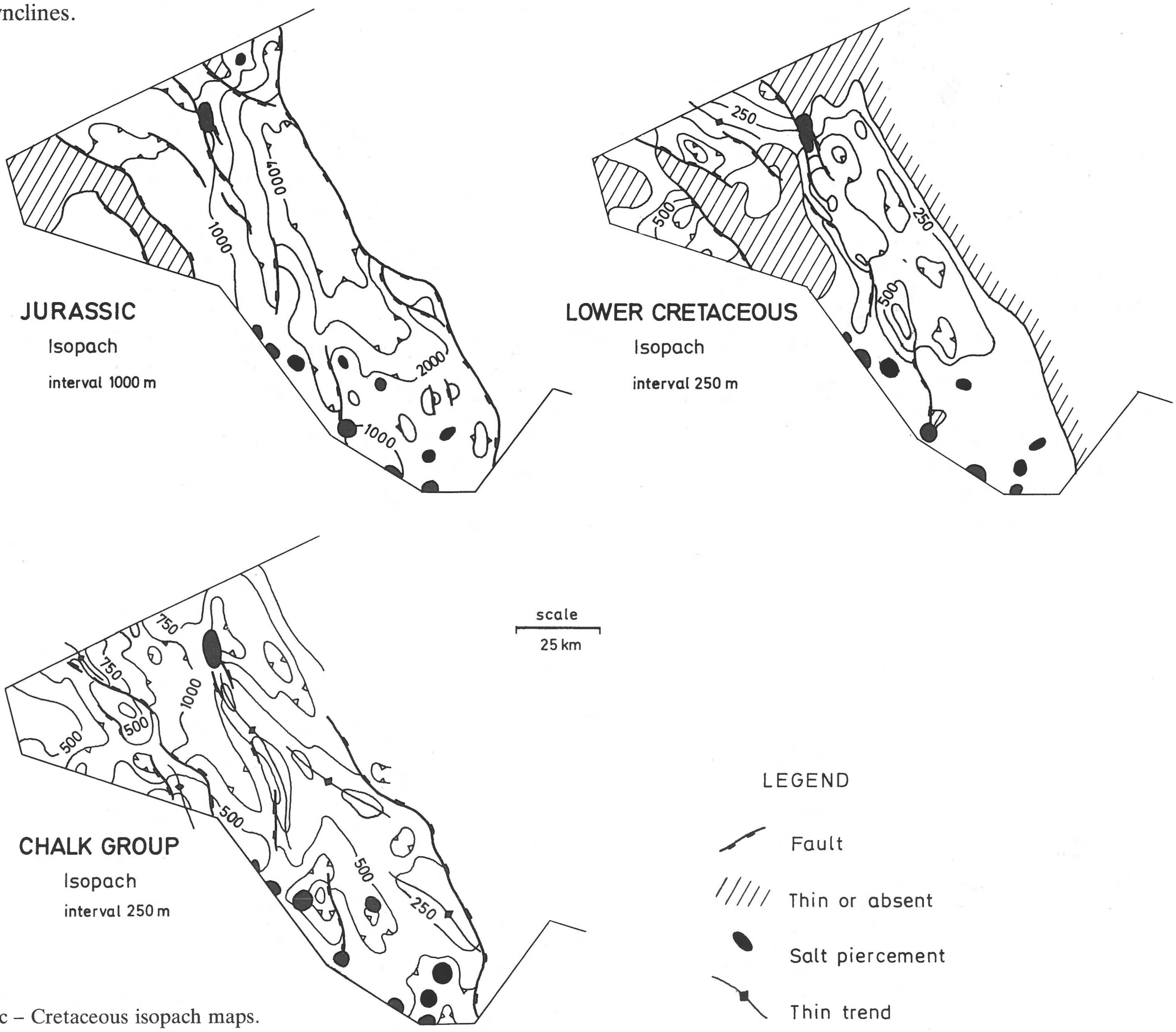


Fig. 6
Jurassic – Cretaceous isopach maps.

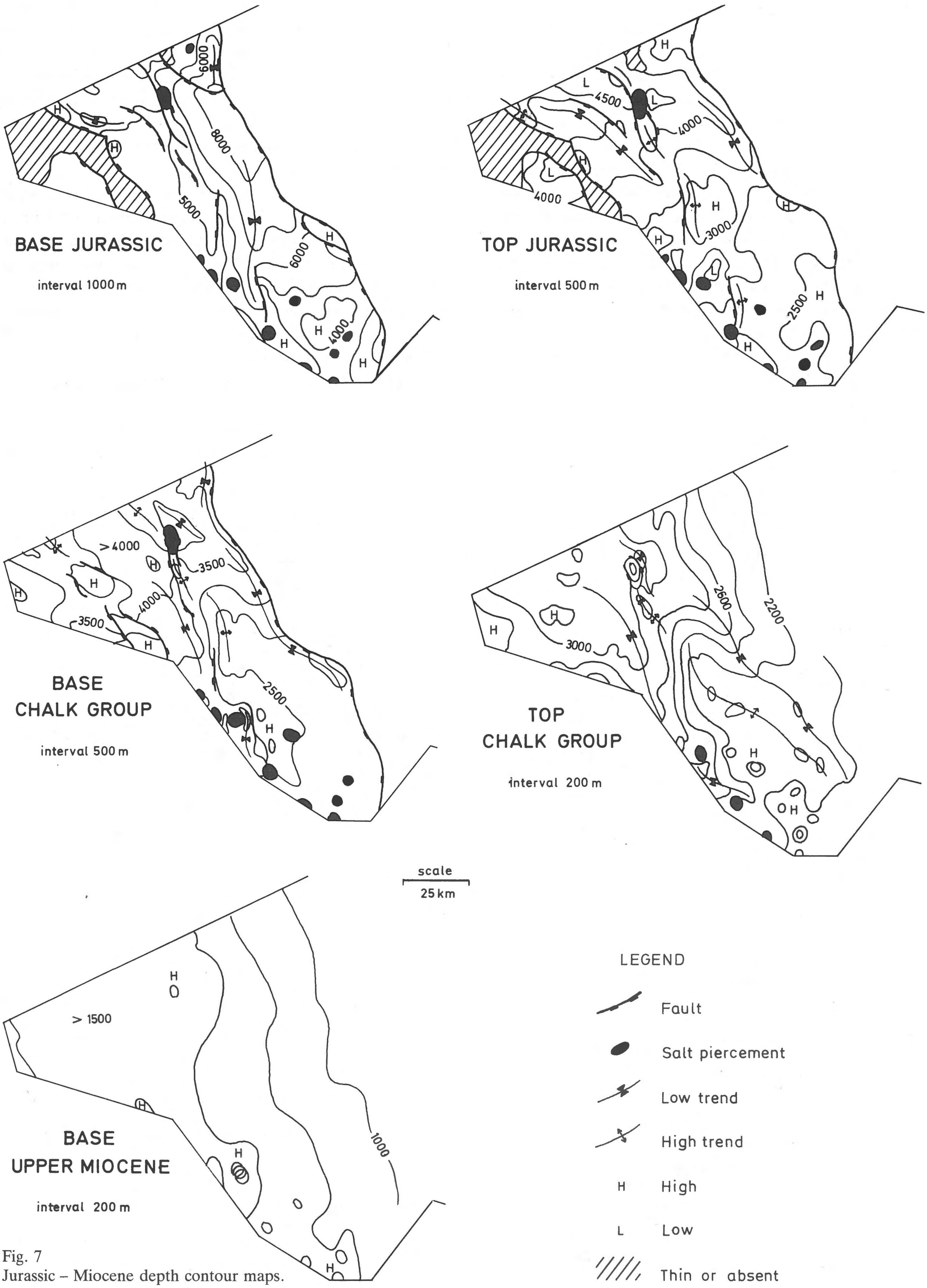


Fig. 7
Jurassic – Miocene depth contour maps.

Cretaceous transgression which culminated in the Maastrichtian. However, marly or strongly calcareous layers older than the Rødby Formation have been drilled. Thus more sedimentologic and biostratigraphic work has to be carried out to clarify the sedimentary development during late Early Cretaceous.

The overlying Chalk Group (defined by DEEGAN & SCULL, 1977), which is of Late Cretaceous to Danian age, is only reviewed briefly here, as it is treated in detail by NYGAARD ET AL. (1983). In the Danish Central Graben, the Chalk Group has been subdivided into six lithostratigraphic units. Biostratigraphic studies, which have not yet been carried out to a satisfactory level, indicate the diachronous nature of some of the lower units. The boundary between Units 5 and 6 coincides with the Maastrichtian/Danian boundary except for local hiati. The presence and absence of the individual units, and the relative thicknesses, are probably dependent upon syn-sedimentary tectonic movements.

The thickness of the Lower Cretaceous (Fig. 6) is less than 250 m in the Southern Salt-dome Province, exceeds 500 m in the Tail End Graben and is locally more than 900 m. The Lower Cretaceous sequence is thin or absent over the crest of the Dogger High (profile 4, Fig. 5). The areas just east of the High were uplifted and eroded prior to the deposition of the Chalk Group. The contour patterns of Top Jurassic and Base Chalk Group (Fig. 7) are similar. The thickness of the Chalk Group (Fig. 6) outside the halokinetic structures varies considerably, from less than 250 m in the south to more than 1250 m in the northern part close to the regional depocentre in the Norwegian sector. It is noteworthy that the Chalk Group often is thicker on the edge of the Ringkøbing-Fyn High than in the adjacent part of the Graben.

Comparison of the isopach map of the Lower Cretaceous sequence with that of the Chalk Group (Fig. 6) shows that a thick Lower Cretaceous sequence often is overlain by a thin Chalk Group. This phenomenon is associated with a system of antiformal and synformal gentle flexures arranged in an en echelon pattern. This structural pattern is illustrated by profiles 3 and 4 in figure 5. It is believed to be the effect of Late Cretaceous and Early Tertiary inversion tectonics caused by a compressional strike-slip stress regime. Profiles 1-3 also demonstrate the thickening of the Chalk Group on the edge of the Ringkøbing-Fyn High.

The change from rifting, which dominated in Jurassic times, to a phase of gradual subsidence was thus accompanied by inversion tectonics whereby the previous tensional basins were deformed by compressional and wrench forces. The contour patterns on the Base and Top Chalk Group maps are similar. Both maps show the results of the regional subsidence. The N-S and NW-SE directions of the contour lines flank the main areas of inversion and compression caused by N-S strike-slip movements.

In addition, the general subsidence features of the basin are illustrated by the map of the Base Upper Miocene. The maximum depth of more than 1500 m is found in the previously mentioned area to the north, close to the depocentre in the Norwegian sector. The smooth topography is only disturbed by few halokinetic features.

CONCLUSIONS

The basinal development of the Danish Central Graben during the Mesozoic is described, and a subdivision of the Graben into structural units is presented.

The Northern and Southern Salt-dome Provinces, probably belong to the Northern and Southern Zechstein Basins, respectively. Halokinesis of the Zechstein evaporites appears to have started in the Late Triassic and, in some cases, to have continued into the Quaternary. It is noteworthy that few salt domes actually pierced the Chalk Group. Development of rim-synclines became important during the Late Jurassic. A few salt pillows, for example below the Dan Field, are caused by flow of Triassic salt.

The Tail End Graben is a half-graben structure which primarily was active in Jurassic times. More than 4000 m of Jurassic sediments were deposited in the central part of the Graben. The structural style is characterized by differential subsidence controlled by rotational fault blocks in the pre-Late Cretaceous. The major fault zone west of the Tail End Graben had a reverse component during Late Cretaceous and Early Tertiary times, and may even appear overfolded locally. Overpressured shales appear to be an important element in this zone. Corresponding tectonic features are known from the southern part of the border-zone along the Ringkøbing-Fyn High. Inversion tectonism has overprinted the older structural patterns in parts of the Tail End Graben as indicated on the map (Fig. 2). This northwest-southeast trending rhomboid area is situated in an oblique position to the Ringkøbing-Fyn High. Another anticline is found north of the Dogger High and is part of the Lindesness Ridge (see SKJERVEN ET AL., 1983).

The Dogger High has probably been an elevated structure during the pre-Late Cretaceous Mesozoic time. At least, it seems to have been a sedimentary source area in the Late Jurassic. Even chalk thicknesses are reduced on this horst.

The subsidence pattern changed from Triassic time, when rather uniform conditions prevailed within the entire Graben, to Jurassic time when the main depocentre was found in the Tail End Graben. This pattern changed gradually, and during the Late Cretaceous the depocentre was found to the northwest, close to the regional depocentre within the Norwegian sector.

The maximum rate of subsidence in Mesozoic times occurred during the Late Jurassic (HOLM, 1983). However, the most rapid and widespread subsidence occurred during the Late Miocene to Quaternary as a result of the general Tertiary subsidence of the North Sea basin.

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