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A contribution to EFP-83 project: Jurassic-Lower Crectaceous stratigraphy and basin development of the Danish North Sea sector

Key-words:
North Sea, Denmark, Jurassic, Structural elements

with 4 maps

Vignette:
East-West section through the Tail End Graben

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Preface

The present paper is one of several reports issued as the result of a research project carried out by the Geological Survey of Denmark in cooperation with the Geological Institute at the University of Copenhagen. The project has been financed by special contributions given by the Ministry of Energy for the period 1st of August 1983 to 31st of December 1985.

The project was entitled "Jurassic – Lower Cretaceous stratigraphy and basin development of the Danish North Sea sector". It has been decided to limit the study area to the Danish Central Trough, and furthermore the effort has been concentrated on the Midd Jurassic, the Upper Jurassic, and the Lower Cretaceous.

The scope of the project was to coordinate analyses of the stratigraphy, facies development and burial history in order to create a basis for predicting possible occurrences of reservoir rocks. The following reports (including the present one) will be printed in the series published by the Geological Survey of Denmark and issued in 1986 and 1987:

Frandsen,.N.: Middle Jurassic deltaic and coastal deposits in the Lulu-1 well of the Danish Central Trough.

Heilmann-Clausen, C.: Lower Cretaceous dinoflagellate biostratigraphy in the Danish Central Trough.

Hoelstad, T.: Palynology and palynofacies analyses of the Middle Jurassic to Lower Cretaceous in the Danish Central Trough.

Hoelstad, T.: Palynology of the Middle Jurassic Lower Graben Sand Formation of the U-1 well, Danish Central Trough.

Jensen, T.F., Holm, L., Frandsen, N. & Michelsen, O.: Jurassic – Lower Cretaceous lithostratigraphic nomen-clature for the Danish Central Trough.

Møller, J.J.: Seismic structural mapping of the Middle and Upper Jurassic in the Danish Central Trough. Danm.

Vejbæk, O.V.: Seismic stratigraphy and tectonic evolution of the Lower Cretaceous in the Danish Central Trough.

Poulsen, N.: Callovian (Jurassic) to Ryazanian (Cretaceous) dinoflagellate biostratigraphy of the Danish Central Trough.

Thomsen, E. 1986: Lower Cretaceous nannofossil biostrati-graphy in the Danish Central trough.

Michelsen, O., Frandsen, N., Holm, L., Jensen, T.F., Møller, J.J. & Vejbæk, O.V.: Jurassic – Lower Cretaceous of the Danish Central Trough; – depositional environments, tectonism, and reservoirs.

DGU, 30th December 1985.

Olaf Michelsen

Contents

Abstract

The Middle and Upper Jurassic of the Danish Central Trough have been studied by the use of seismic structural mapping. The area studied is divided into the following structural elements which are the Ringkøbing-Fyn High, the Mid North Sea High, the Mads High (new name), the Inge High (new name), the Mandal High, the Tail End Graben, the Arne-Elin Graben (new name), the Feda Graben, the Gertrud Graben (new name), the Salt Dome Province, the Søgne Basin, the Poul Plateau (new name), the Heno Plateau (new name), the Outer Rough Basin, the Grensen Nose, and the Gert Ridge (new name). These structural elements are described individually.

The structural framework is demonstrated to be dominated by north-south trending normal faults and northwest-southeast trending right-lateral strike-slip faults. The most active rifting phases in the Mesozoic period took place during the Middle and Late Jurassic. The tectonic activity ceased during the Late Jurassic in the southern part of the Danish Central Trough, while in the northern part the activity continued into the Early Cretaceous. During the Late Cretaceous and Early Tertiary the faults were reactivated by inversion caused by transpression related to the formation of the Alpine Fold Belt.

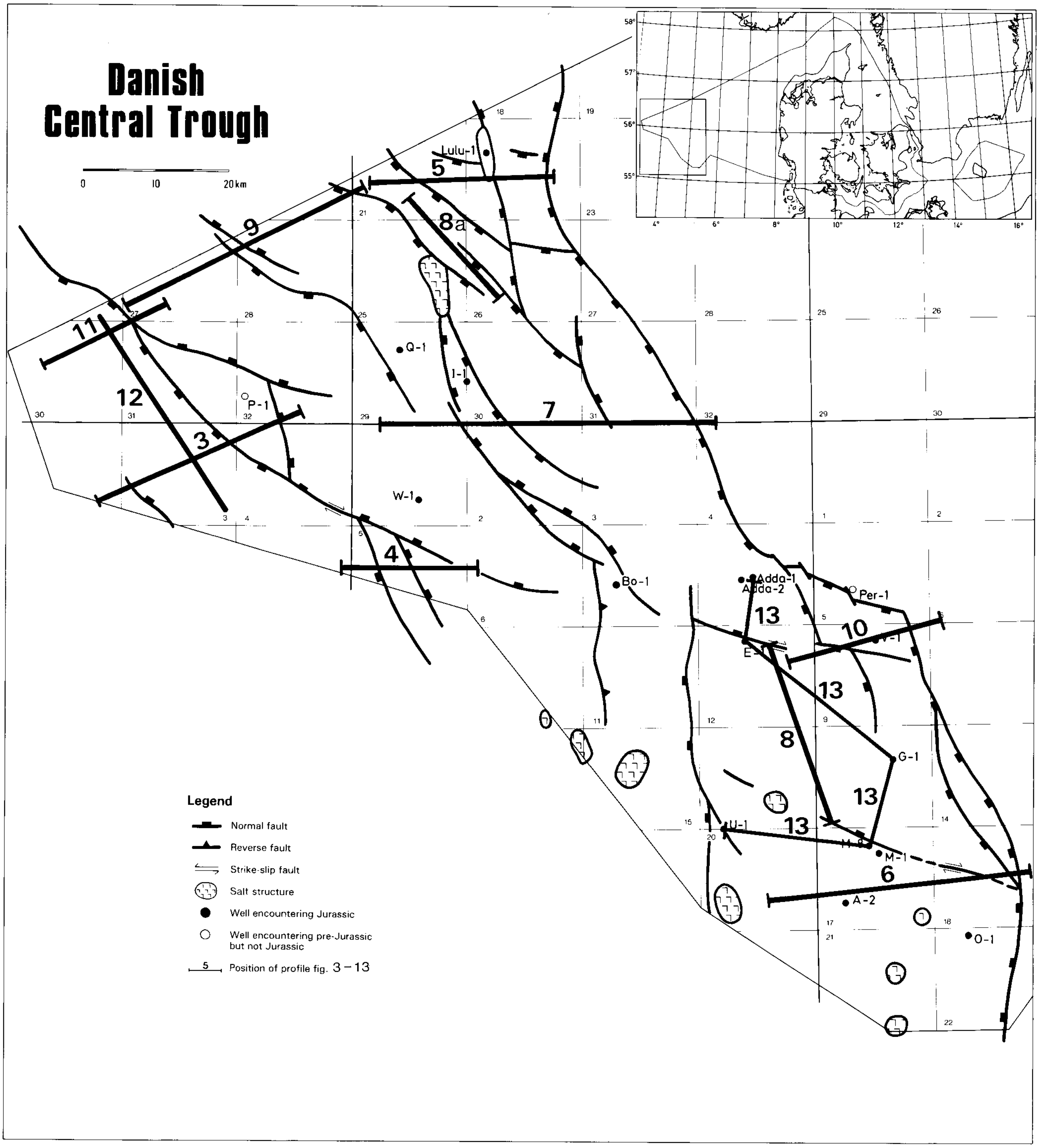


Fig. 1. Jurassic structural outline of the Danish Central Trough, including location of wells penetrating Jurassic or older sequences, and the location of profiles in figs. 3–13.

Introduction

The Middle and Upper Jurassic in the Danish Central Trough has previously been treated seismically by Andersen et al. (1982), who gave the first structural description covering the whole area. Later Gowers and Sæbøe (1985) described the structural evolution of the Norwegian and Danish Central Trough, and it is the most recent description of the structural elements in the area.

In the present study seismic structural mapping has been carried out for the Middle and Upper Jurassic in the Danish Central Trough on seismic data acquired in the period from 1979 to 1982. The area investigated comprises the Danish part of the Central Trough (fig. 1) with emphasis on the eastern and southern parts, where well ties are available. The investigation was carried out on a regional scale in order to elucidate the tectonic evolution. Local phenomena like truncations around salt structures will only be discussed briefly.

A number of reflectors which represents sequence boundaries in the Middle and Upper Jurassic have been selected. They have been tied into the wells shown in fig. 1. The ages of the different sequence boundaries have been estimated from biostratigraphic investigations in some of the wells (Poulsen 1986). The structural development during the Jurassic will be discussed on the basis of selected geosections.

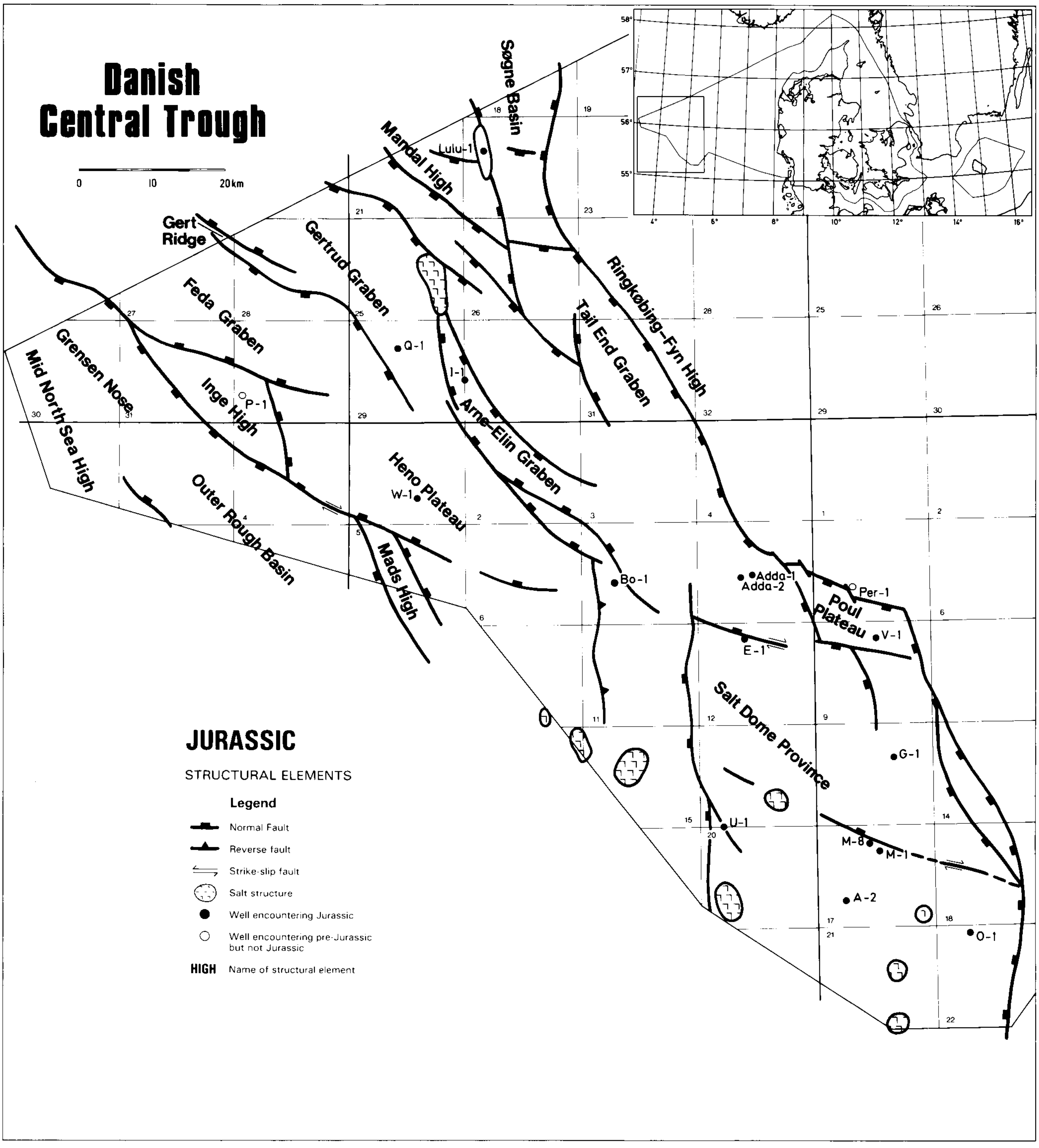


Fig. 2. Jurassic structural outline of the Danish Central Trough, including names of structures and location of wells penetrating Jurassic or older sequences.

Geological setting

During the Middle and Late Jurassic the area was exposed to subsidence and the structural framework is dominated by a number of north-south to northwest-southeast trending basement attached faults. The north-south trending faults have been intermittently active throughout the Mesozoic whereas the northwest-southeast trending faults seem to have formed in the Jurassic times. To the south the Jurassic sedimentation pattern is influenced by the development of the Zechstein and Triassic salt structures also.

The main tectonic features and a subdivision of the Central Trough are shown in fig. 2. The structural nomenclature follows the proposals of Gowers and Sæbøe (1985) with minor modifications. The structural elements can be divided into three groups:

1) Highs, where the Precambrian or Caledonian basement is relatively elevated and the Jurassic sequence is thin or absent. They include the Ringkøbing-Fyn High, the Mid North Sea High, the Mads High, the Inge High, and the Mandal High.
2) Grabens and basins, characterized by a relatively high rate of subsidence and sedimentation during the Jurassic. They include the Salt Dome Province, the Tail End Graben, the Søgne Basin, the Feda Graben, the Gertrud Graben, and the Arne-Elin Graben.
3) Areas of intermediate or poorly defined subsidence. They include the Heno Plateau, the Poul Plateau, the Outer Rough Basin, the Grensen Nose, and the Gert Ridge.

The highs

The Danish part of the Central Trough is bounded to the east and west by two major highs, viz. the Ringkøbing-Fyn High and the Mid North Sea High. In the trough three minor highs occur, viz. the Mads High, the Inge High and the Mandal High.

The Ringkøbing-Fyn High

The Ringkøbing-Fyn High forms the boundary of the Central Trough to the east. It forms a part of the east-west trending central North Sea highs which were formed during Late Carboniferous-Early Permian times (Ziegler 1982).

In the Per-1 well (fig. 2) Precambrian basement was encountered directly below the Upper Cretaceous chalk. In places there are seismic indications of the

SEISMIC SEQUENCE CORRESPONDING TO

A CHALK GROUP
B LOWER CRETACEOUS
C FARSUND FORMATION UPPER PART
D FARSUND FORMATION LOWER PART
E MIDDLE JURASSIC and LOLA FORMATION
F MIDDLE JURASSIC
G MIDDLE JURASSIC and UPPER JURASSIC
H TRIASSIC and LOWER JURRASSIC
I ZECHSTEIN SALT
J PRE-ZECHSTEIN
K MESOZOIC

The sequence code is used in figs. 4–12.

presence of sediments between the basement and the chalk. The boundary to the Central Trough is characterized by normal faults, downthrown to the west.

The bounding structural elements are from south to north the Salt Dome Province, the Poul Plateau, the Tail End Graben, and the Søgne Basin (fig. 2).

The Mid North Sea High

The Mid North Sea High forms the boundary of the Danish part of the Central Trough to the west. Like the Ringkøbing-Fyn High it is a part of the east-west trending central highs. Only relatively thin sediments are encountered between the Zechstein and the Upper Cretaceous sequences in British sector. The boundary to the Central Trough is characterized by a gently dipping unconformity surface (fig. 3). The bounding structural elements are to the southeast the Outer Rough Basin, to the east the Inge High and to the northeast the Grensen Nose.

The Mads High

The Mads High is a northnorthwest-southsoutheast striking high, being the southern part of the Dogger High as described by Andersen et al. (1982). It continues to the south into the German part of the Central Trough. There is no well information from the high, but seismic data strongly indicate that Jurassic and Lower Cretaceous sediments are absent. The boundary to the east is a gently dipping unconformity surface with minor normal faults. To the west it was probably bounded by the same types of faults, but this faulting is completely masked by the Late Cretaceous inversion (fig. 4). To the north it is bounded by a relatively steep fault which has a significant right-lateral strike-slip compo-

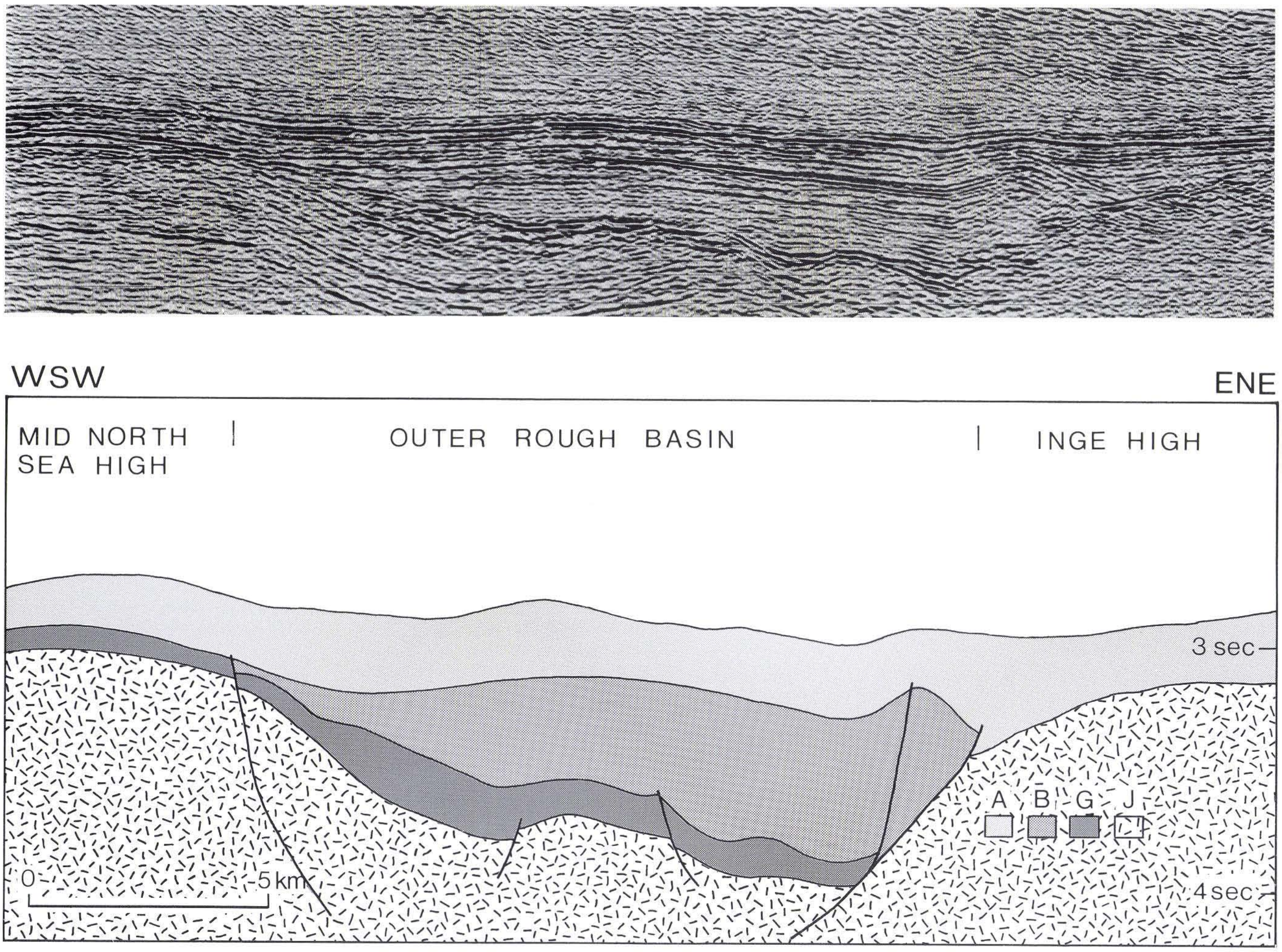


Fig. 3. WSW-ENE profile through the Mid North Sea High, the Outer Rough Basin and the Inge High. For location see fig. 1.

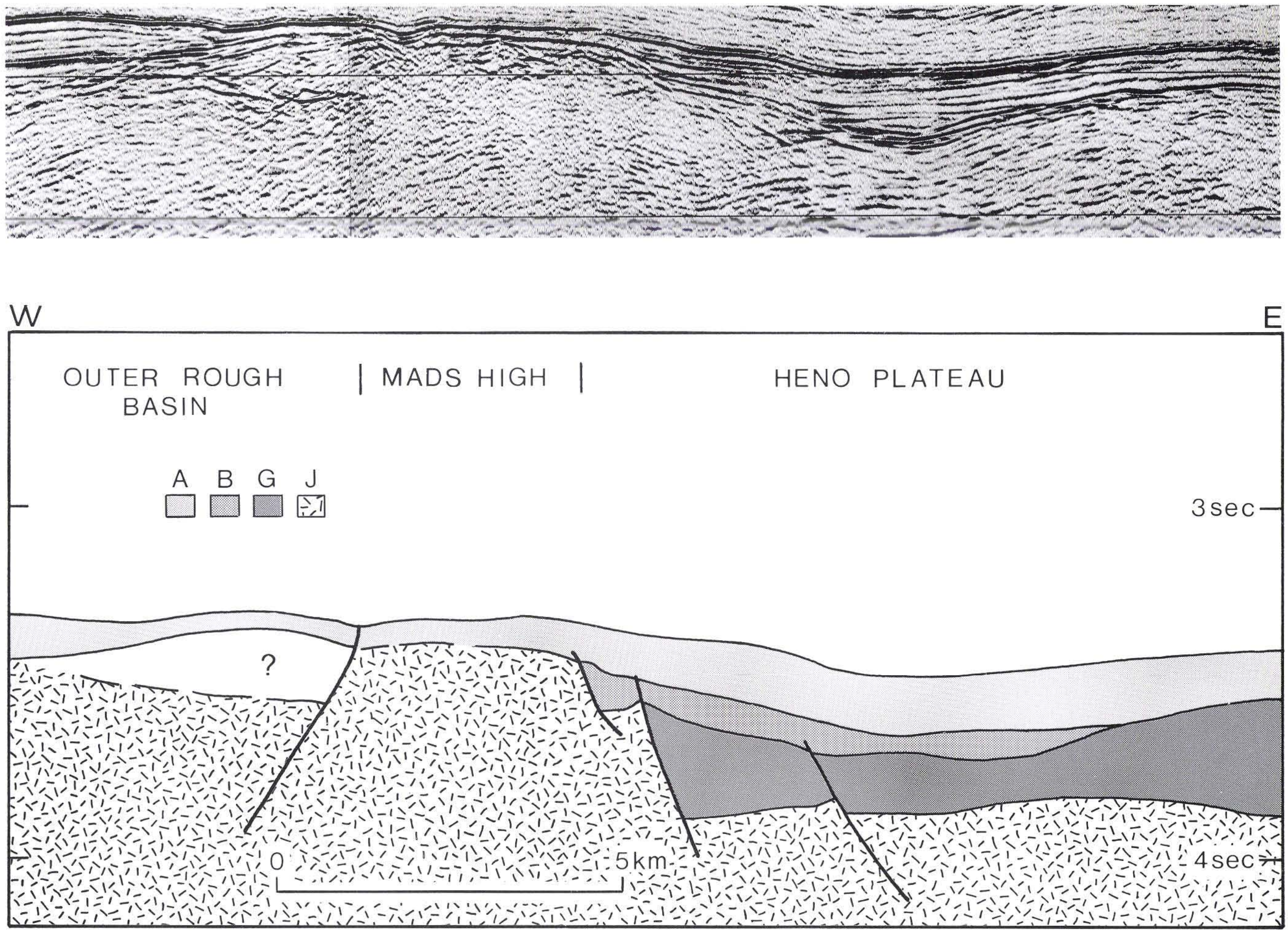


Fig. 4. W-E profile across the Mads High. For location see fig. 1.

nent of Jurassic age. The Jurassic tectonic pattern is disturbed by Cretaceous inversion of the same faults.

The Inge High

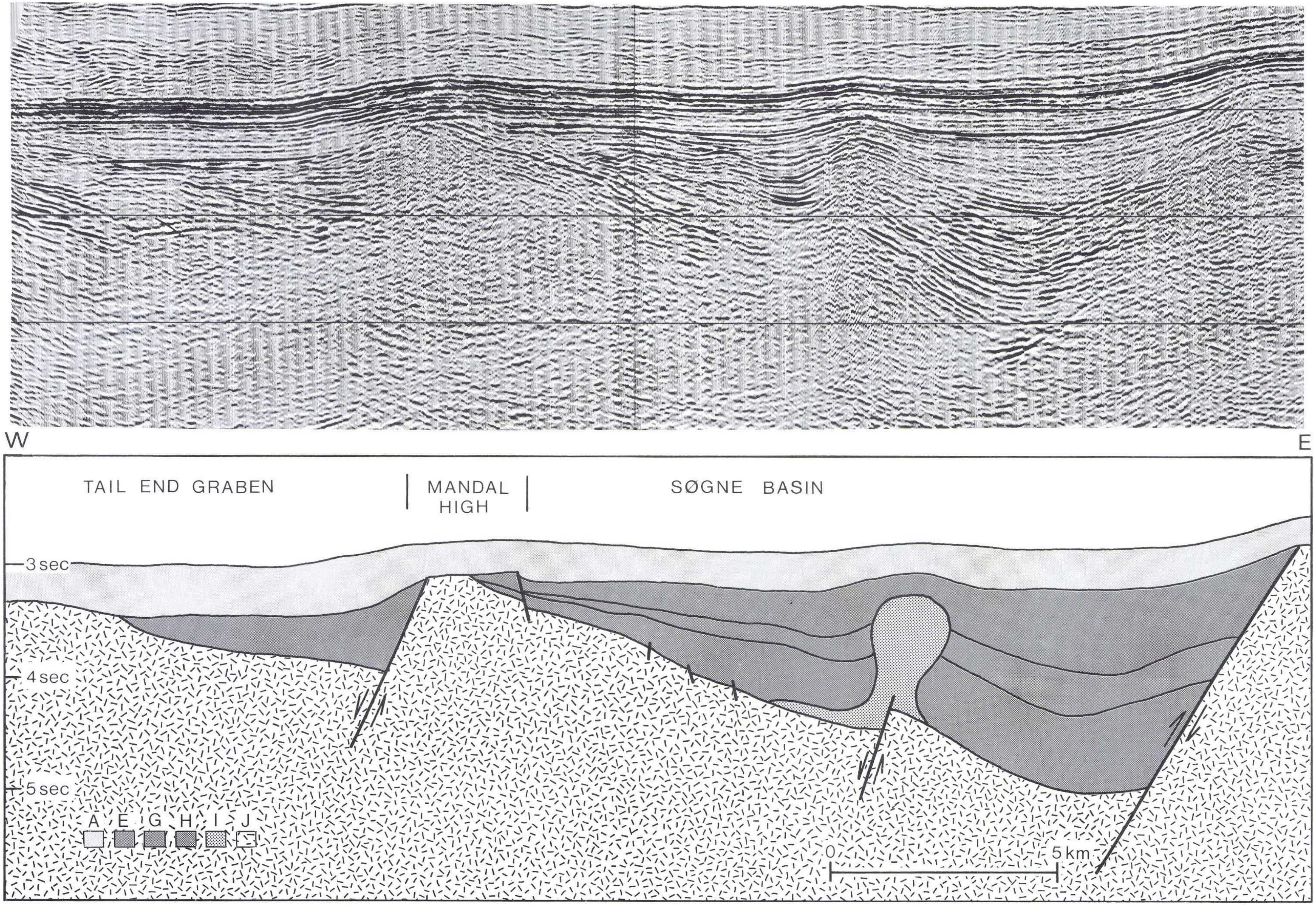
The Inge High is the northern part of the Dogger High. This structural feature is separated from the Mads High by a northwest-southeast trending fault zone which had a Late Jurassic right-lateral strike-slip component. It is not possible to make any seismic tie across this fault zone below the Upper Cretaceous chalk sequence. The P-1 well is located on the Inge High (fig. 2). This well encountered 340 m of Palaeozoic rocks between the Caledonian basement and the Upper Cretaceous chalk (Larsen and Michelsen 1982).

The Mandal High

The Mandal High extends from Norwegian waters into the Danish part of the Central Trough. It was first described by Rønnevik et al. (1975). Gowers and Sæbøe (1985) suggest that the name Mandal High should be restricted to the most elevated of several northnorthwest-southsoutheast trending fault blocks. Here i n the 3/7–1 well, situated a few kilometres north of the Danish-Norwegian border, crystalline basement was encountered directly below Upper Cretaceous chalk. In the Danish area the Mandal High forms the western edges of the Søgne Basin (fig. 5).

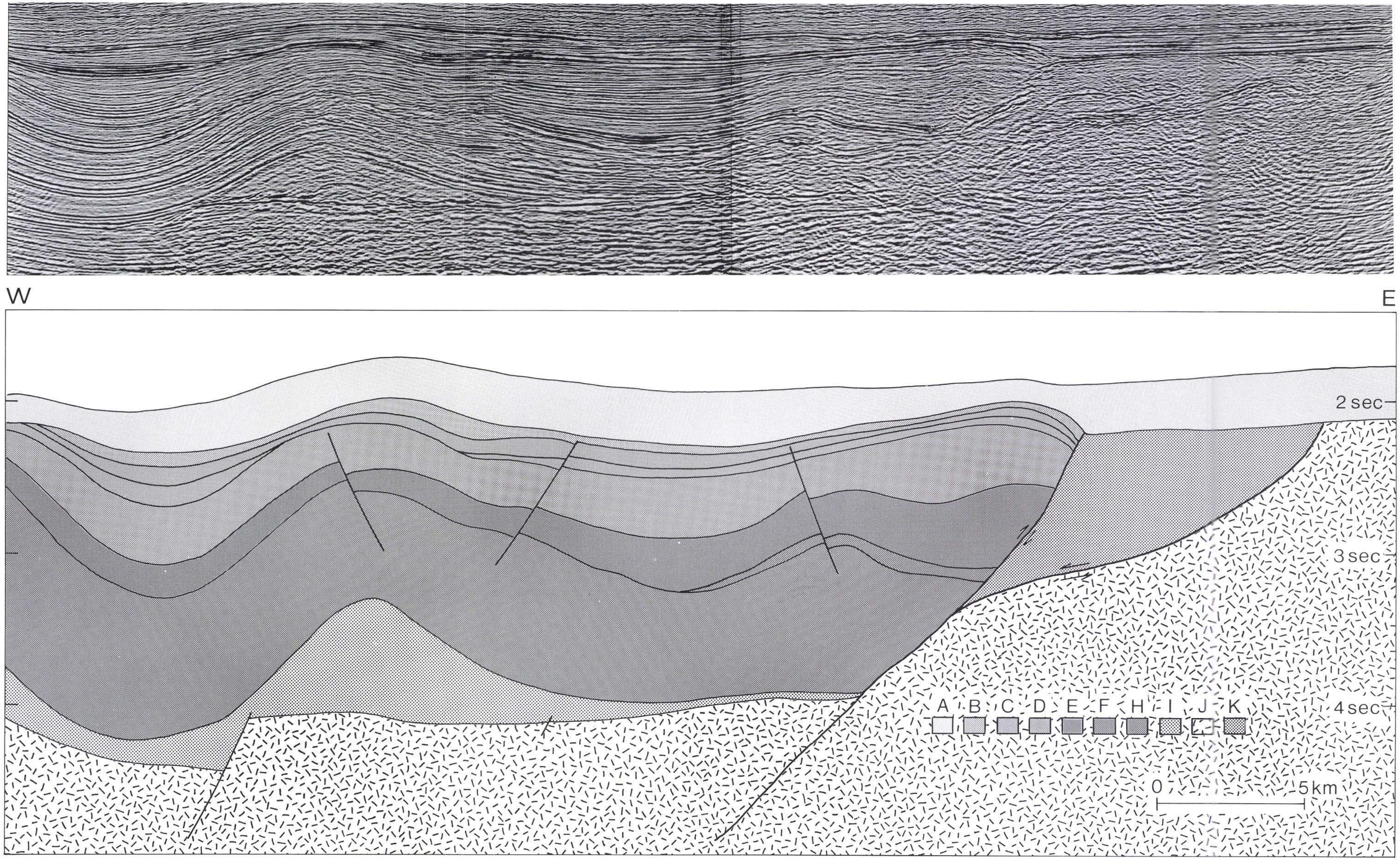
The grabens and basins

The major subsidence areas are interpreted as having had a similar tectonic evolution in the Middle and early Late Jurassic. In the late Late Jurassic the Tail End Graben and the Feda Graben have been exposed to increased subsidence compared to the other grabens. In the lack of well ties and direct seismic ties to the north western part of the Danish Central Trough the tectonic interpretation of the Feda Graben and the Gertrud Graben is highly tentative.


W
E
TAIL END GRABEN
MANDAL HIGH
SØGNE BASIN
3 sec
4 sec
5 sec
A E G H I J
0
5 km

▲ *Fig. 5. W-E profile across the Mandal High and the Søgne Basin. For location see fig. 1.*

Fig. 6. W-E profile across the Salt Dome Province. For location see fig. 1. ▼



The Salt Dome Province

The Salt Dome Province is located in the southern part of the Danish Central Trough and extends southwards into the German part. The eastern boundary to the Ringkøbing-Fyn High is formed by a basement attached normal fault zone. In this province there are several north-south trending faults which during the Jurassic were normal faults downthrown to the west. The fault activity decreased during the Late Jurassic, and the faults were reactivated during the Late Cretaceous. No significant thickness variation of the Middle and Upper Jurassic sediments can be seen in an east-west section across the Salt Dome Province (fig. 6). The thickness is, however, increasing from the south towards the north, and especially the late Late Jurassic sediments become thicker to the north.

The Tail End Graben

The Tail End Graben is a half graben with the depocentre situated to the east along the Ringkøbing-Fyn High, where the Middle and Upper Jurassic sequences are more than 4 km thick (fig. 7). The main subsidence took place in late Late Jurassic Volgian time. There is a gradual transition to the Salt Dome Province (fig. 8). The main differences between the two structural elements are the great subsidence in the Tail End Graben during the late Late Jurassic and the lack of salt movements. The inverted fault west of the Bo-1 well (fig. 2) is of Cretaceous age and was hardly active during the Jurassic. In the Jurassic the area west of this fault formed a part of the Tail End Graben. Further north the Tail End Graben is bounded to the Arne-Elin Graben in the west by a normal fault. To the north between the Gertrud Graben in the west and the Mandal High- Søgne Basin in the east the Tail End Graben is narrowing and the Jurassic sequence is thinning out (fig. 8a). The lowermost of the sequence boundaries are onlapping towards the north. This northern part of the Tail End Graben is not separated as an individual structural element although the cross section (fig. 5) does not look like the Tail End Graben further south. Further north it becomes a part of the Vigeland Ridges described by Gowers and Sæbøe (1985).

The Søgne Basin

The Søgne Basin is the northeastern part of the Danish Central Trough. Its evolution is similar to the Salt Dome Province with relatively thick Triassic to lower Upper Jurassic sequences and relatively thin upper Upper Jurassic sequences. It forms a halfgraben with depocentre along the Ringkøbing-Fyn High (fig. 5). To the south and southwest it is bounded by the Tail End Graben, and the Mandal High forms the westernmost part of the Søgne Basin. The Lulu-1 well is located on a salt structure in the basin. This well encountered both Middle and Upper Jurassic sediments (Frandsen 1986).

The Feda Graben

The Feda Graben is an asymmetric, northwest-southeast elongated trough with a complex Jurassic depocentre geometry. In the southern part of the graben the depocentre was situated to the west along the bounding Inge High. Following the depocentre further north it gradually moved to the centre of the graben. The graben continues to the north into the Norwegian and British parts of the Central Trough (Gowers and Sæbøe 1985).

The Gertrud Graben

Like the Feda Graben, the Gertrud Graben is an asymmetric, northwest-southeast elongated trough with the depocentre situated to the northeast along the boundary to the Tail End Graben. The graben is restricted to the Danish part of the Central Trough. To the north it becomes part of the Vigeland Ridge as introduced by Gowers and Sæbøe (1985). The graben has a gradual transition to the Heno Plateau in the south.

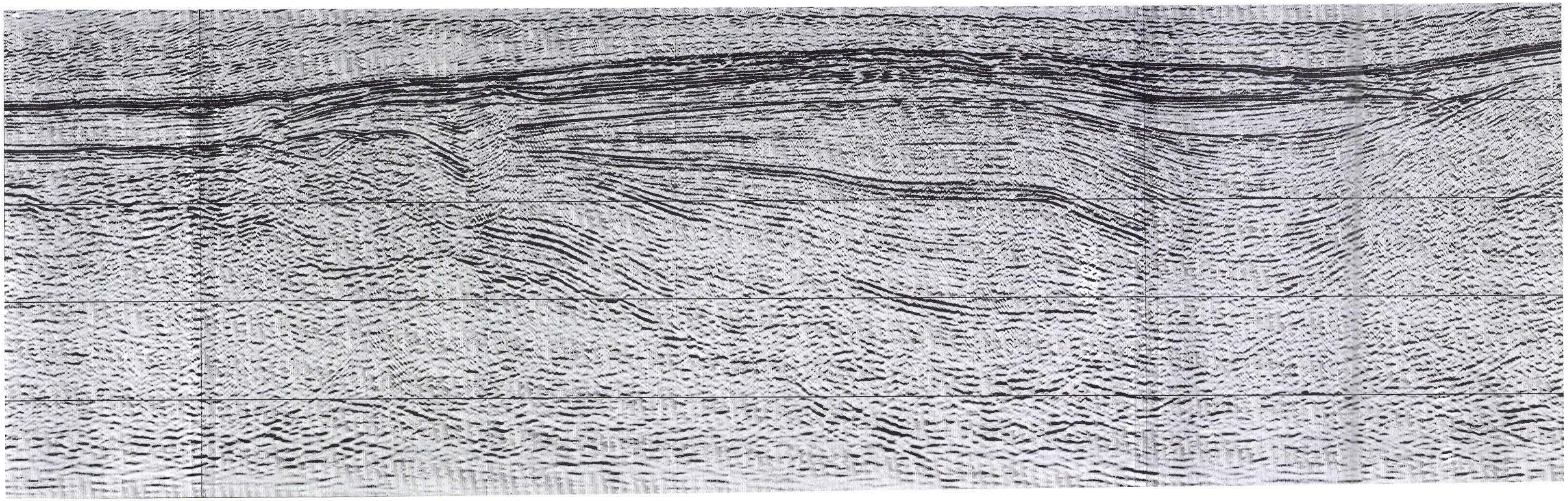
The Feda and Gertrud Grabens are separated by a northwest-southeast trending ridge, the Gert Ridge. They are more or less symmetric around this ridge (fig. 9). The lack of well information makes it difficult to define the base of the Jurassic sequence. However, the two grabens seem to have been connected for long periods in the Jurassic.

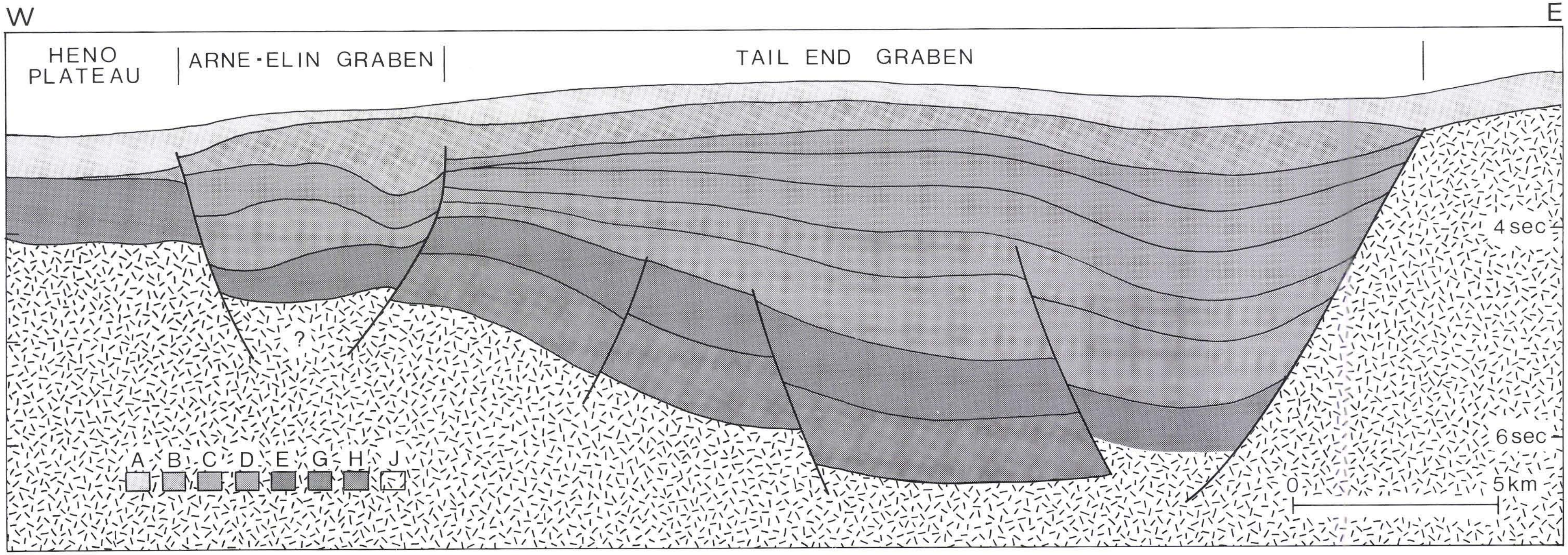
The Arne-Elin Graben

The Arne-Elin Graben is a narrow northnorthwest-southsoutheast trending graben developed during the late Late Jurassic, simultaneously with the main subsidence in the Tail End Graben (fig. 7). The bounding faults were both inverted during the Cretaceous. The seismic resolution in the Jurassic sequence is poor. To the north the graben terminates in the North Arne salt structure. To the south it gradually extends into the Tail End Graben. The opening of the graben is believed linked to movements along the northwest-southeast trending fault system which had a strike-slip component.

▶

Fig. 7. W-E profile across the Arne-Elin Graben and the Tail End Graben. For location see fig. 1.





W
E
HENO PLATEAU
ARNE-ELIN GRABEN
TAIL END GRABEN
?
4 sec
6 sec
0
5km
A B C D E G H J

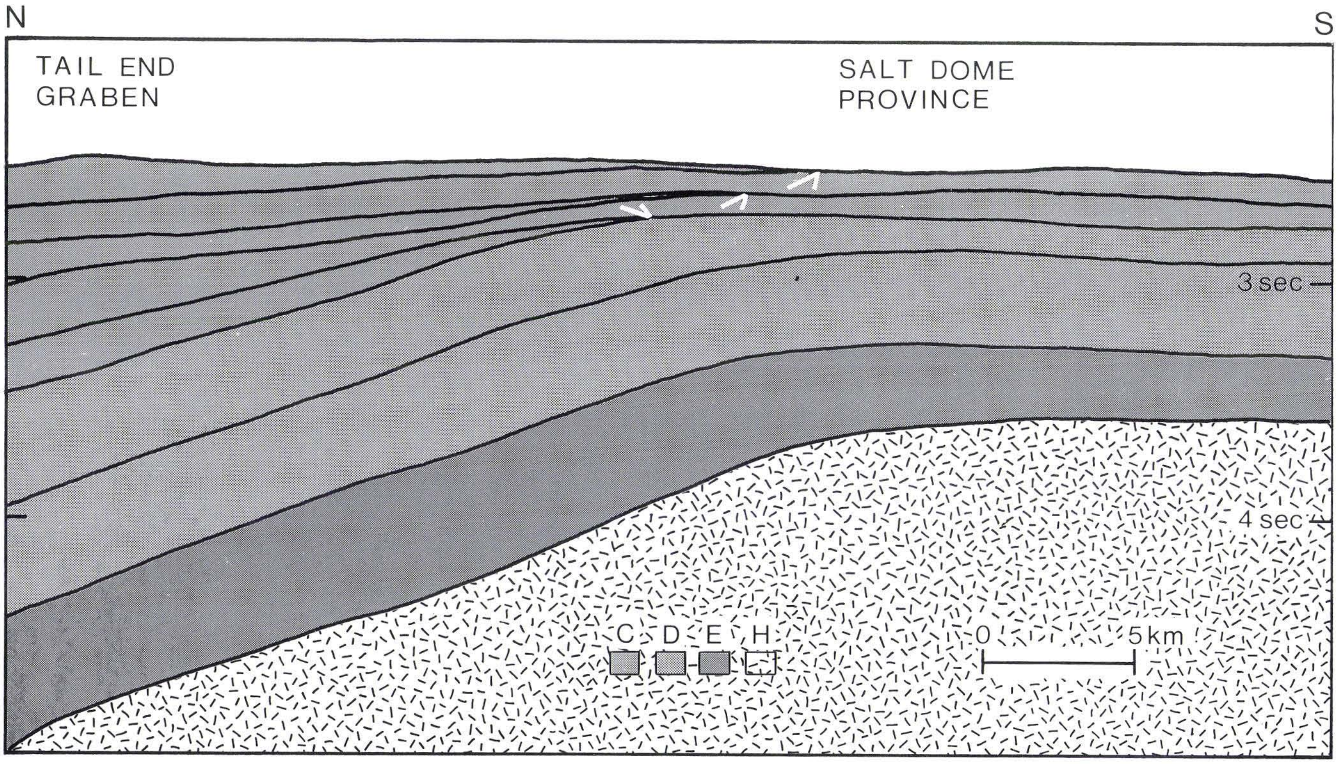


Fig. 8. N-S profile across the boundary between the Tail End Graben and the Salt Dome Province. For location see fig. 1.

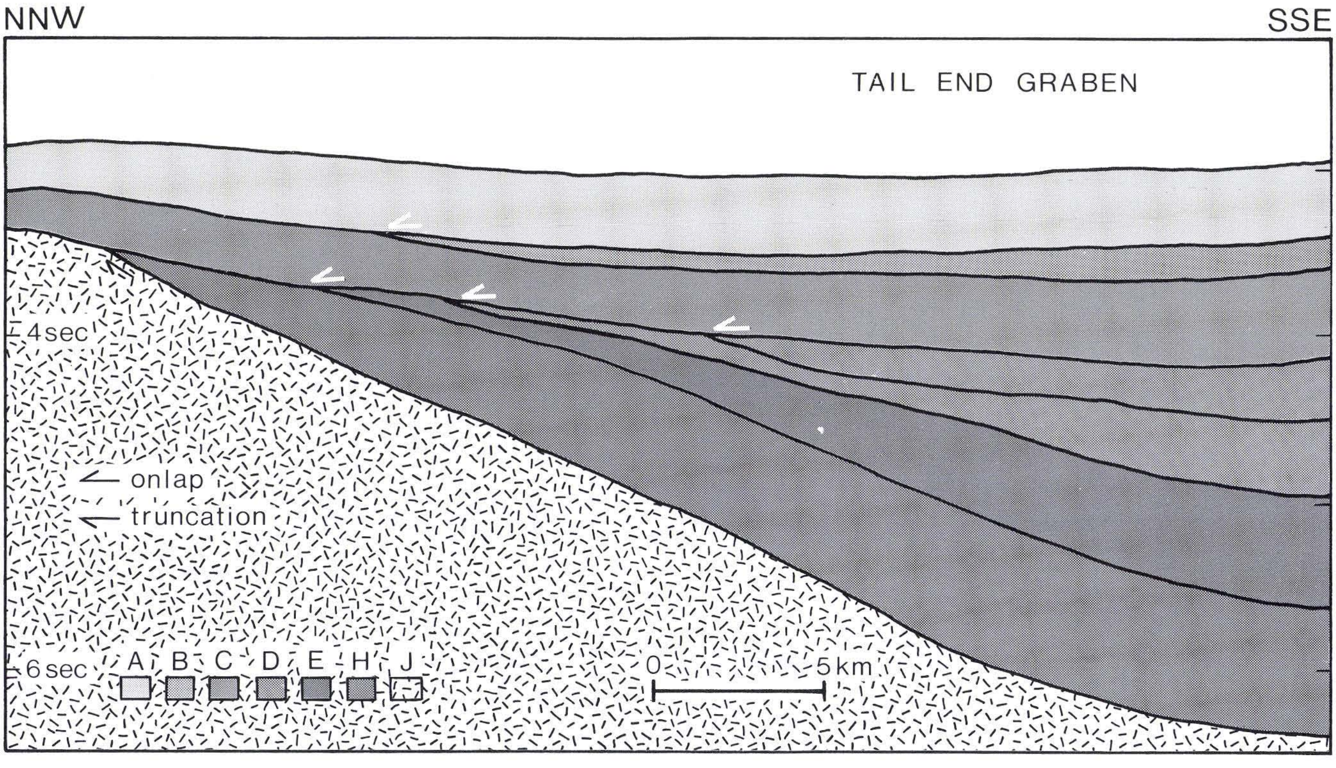


Fig. 8a. NW-SE profile from the northern part of the Tail End Graben. For location see fig. 1.

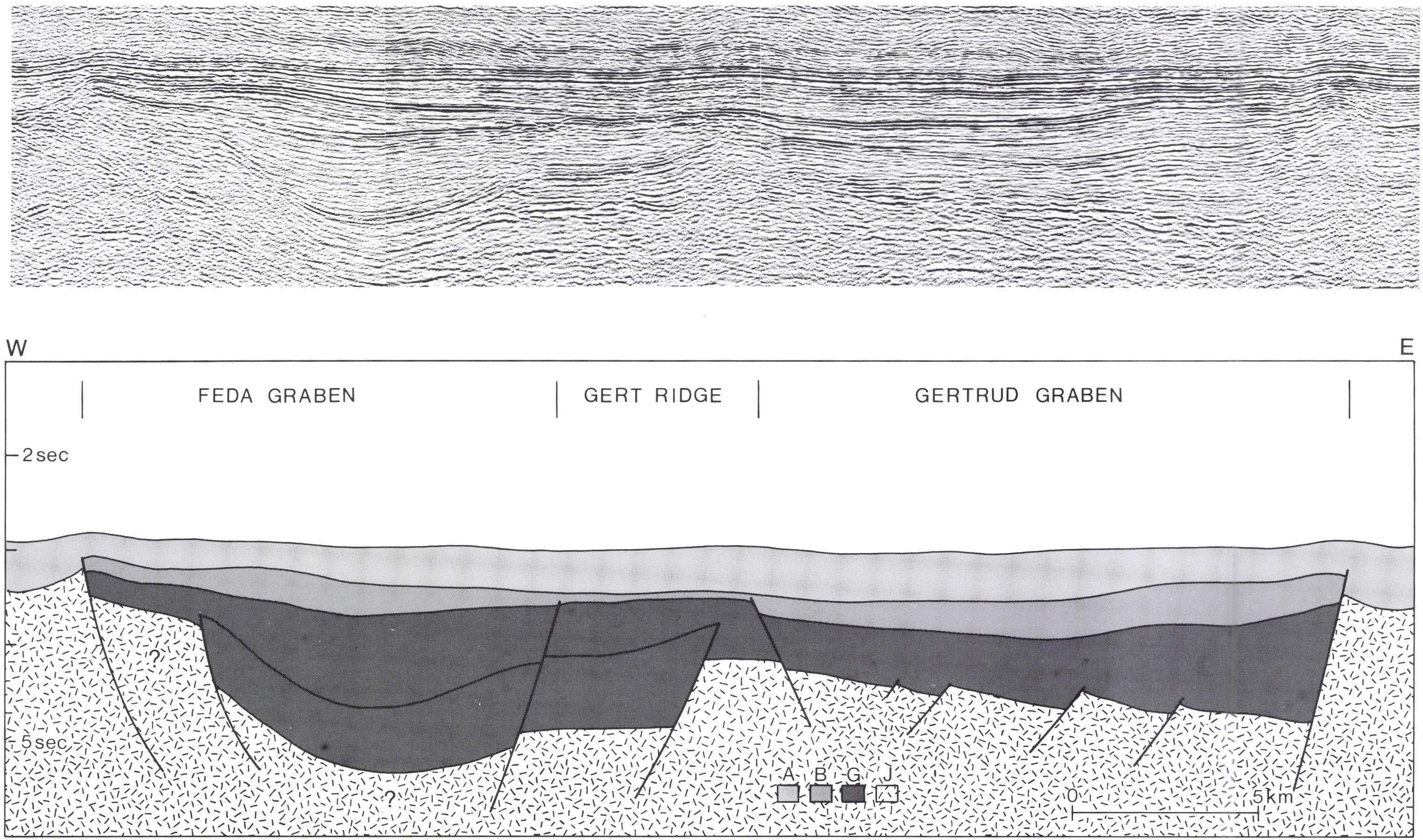
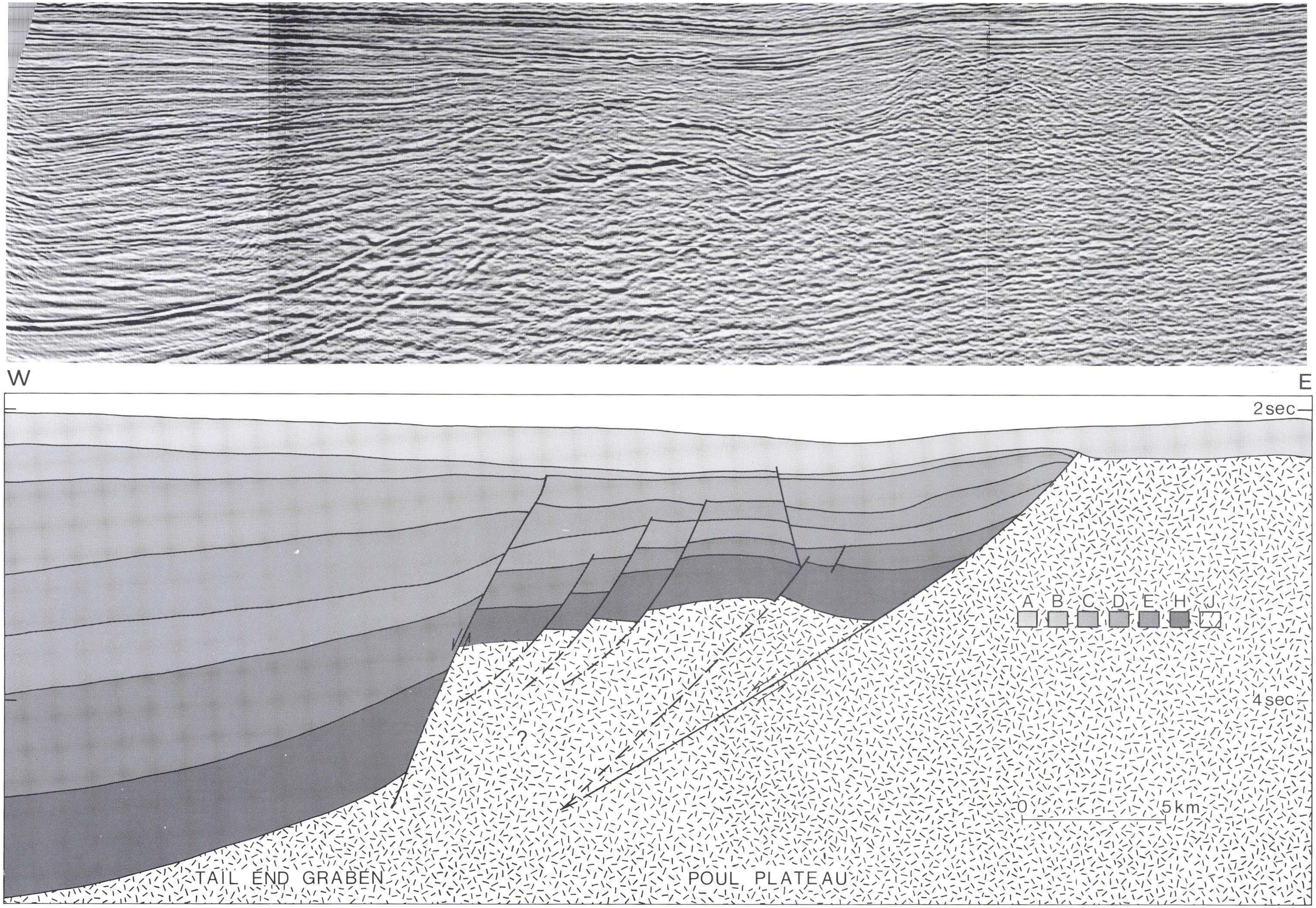


Fig. 9. W-E profile across the Feda Graben, the Gert Ridge and the Gertrud Graben. For location see fig. 1.


W
E
2 sec
4 sec
A B C D E H J
?
0
5 km
TAIL END GRABEN
POUL PLATEAU

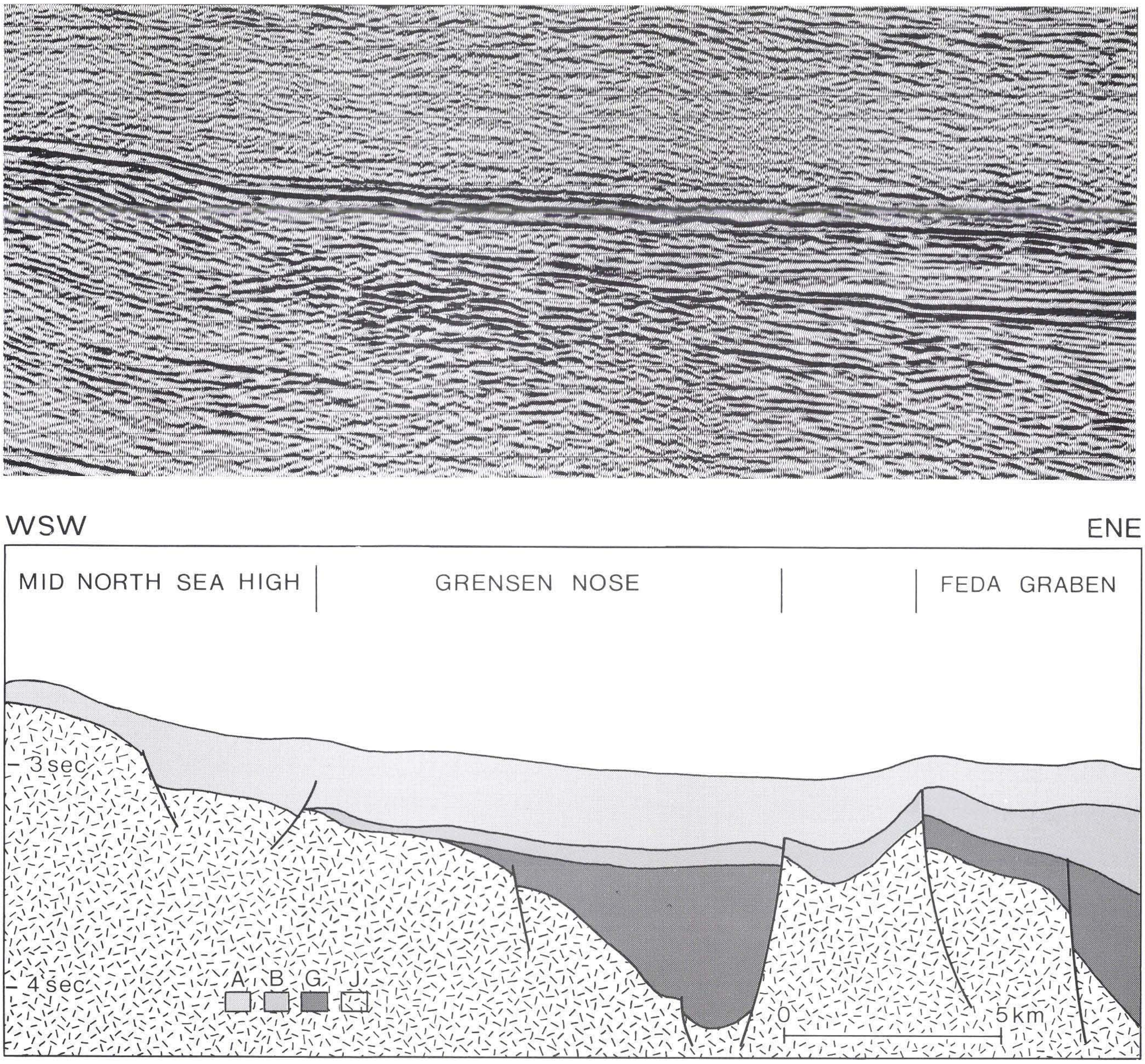


Fig. 11. E-W profile across the Grensen Nose. For location see fig. 1.

Areas of intermediate or poorly defined subsidence

The remaining structural elements do not necessarily have anything in common. They are elements, which cannot be clearly described as either highs, grabens or basins.

The Heno Plateau

The Heno Plateau is a fault-bounded area of poorly defined nature situated between the Arne-Elin Graben and the Mads-Inge Highs. The boundaries to the Feda Graben and the Gertrud Graben in the north and the Tail End Graben in the south are transitional and poorly defined. The thickness of the Jurassic sequence is less than 1000 m. The W-1 well (fig. 2) is situated on this plateau, and in this well sediments of Middle and early Late Jurassic age are absent (Jensen et al. 1986). The area is probably not a single tectonic element, but a more complex feature.

◄
Fig. 10. W-E profile across the Poul Plateau. For location see fig. 1.

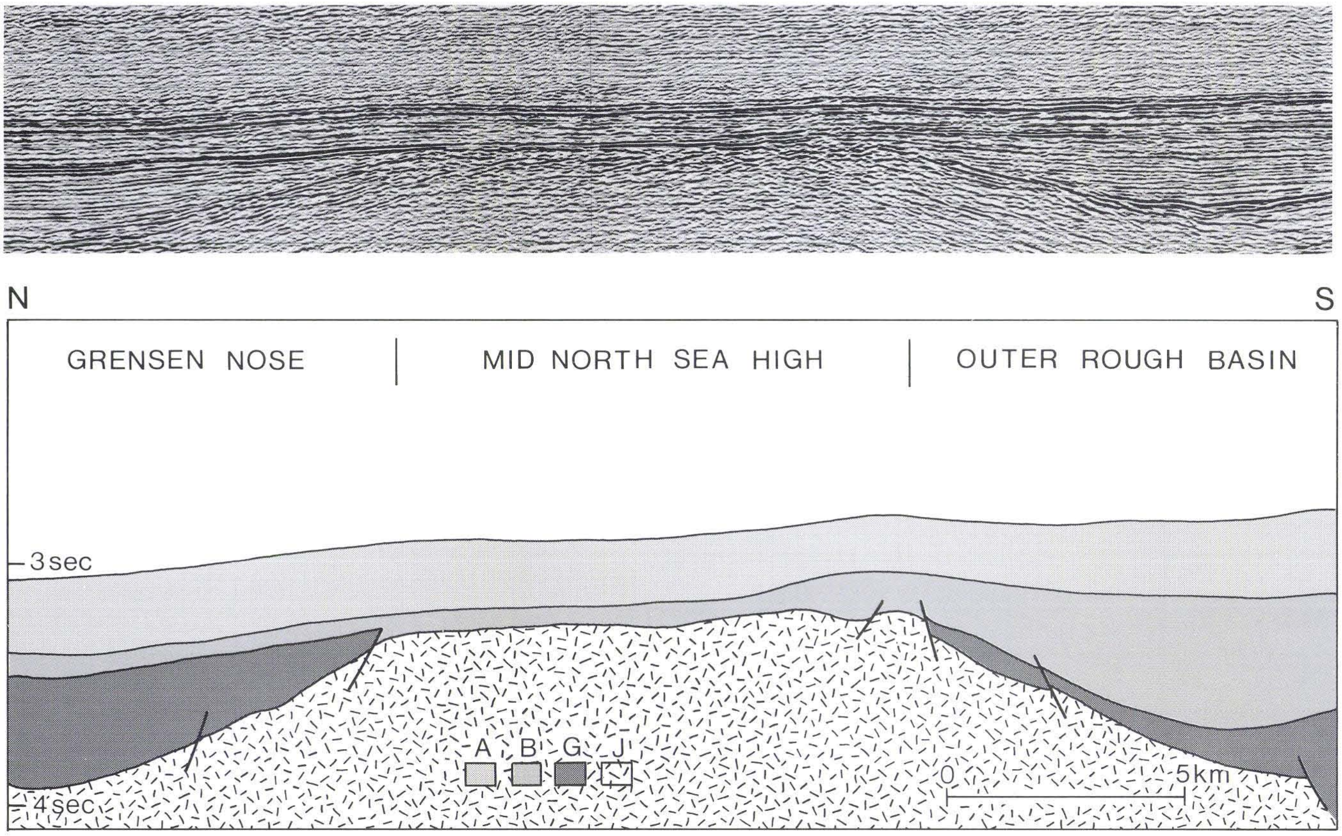


Fig. 12. N-S profile across the Grensen Nose, the Mid North Sea High and the Outer Rough Basin. For location see fig. 1.

The Poul Plateau

The Poul Plateau is situated along the Ringkøbing-Fyn High. It is one of several fault blocks formed during the Jurassic (fig. 10). A possible mechanism for the formation of the fault blocks is as riders (Gibbs 1984) formed by backstepping of the active fault into the Ringkøbing-Fyn High. The V-1 well (fig. 2) is situated on the plateau and it encountered 623 m of the Farsund Formation and 245 m of the Lola Formation before it drilled into the Triassic (Jensen et al. 1986). This indicates that the fault block was formed between the Triassic and the early Late Jurassic, and that the surrounding part of the Ringkøbing-Fyn High originally was covered with Triassic sediments.

The Outer Rough Basin and the Grensen Nose

Along the boundary of the Mid North Sea High two areas of intermediate subsidence can be defined, the Outer Rough Basin to the south and the Grensen Nose to the north. The two structural elements are separated by the easternmost part af the Mid North Sea High. They were probably parts of this high until the Late Jurassic (Gowers and Sæbøe 1985), and they developed mainly during the Cretaceous (figs. 3, 11 and 12). There is no well data from the Danish part of the Mid North Sea High, the Outer Rough Basin and the Grensen Nose, and a direct seismic tie from wells further east is not possible. Therefore the postulated Jurassic sequence has been established by comparing the seismic patterns, and other interpretations are possible.

The Gert Ridge

The Gert Ridge separates the Feda Graben from the Gertrud Graben. It was probably not active until the late Late Jurassic and remained a structural feature during the Cretaceous (fig. 9).

Sequence boundaries

Nine Middle and Upper Jurassic sequence boundaries have been followed over a large part of the area studied. They have been tied to the wells located in the area (fig. 2).

In fig. 13 some of the wells are shown with the seismic ties. In table 1 all the wells are listed with a seismic tie line, two way times (TWT's) and depths to the reflectors. Some of the wells are situated on salt structures, and the absence of some of the seismic sequences in these wells is caused by local erosion or non-deposition, and is thus not of regional significance. All the sequence boundaries are penetrated by either the U-1 or the E-1 wells.

The lowermost sequence boundary mapped corresponds to the Mid Cimmerian Unconformity (MCU) and marks the base of the Bryne Formation in the north and the Central Graben Group in the south (Jensen et al. 1986). The corresponding ages are assumed to be Bathonian in the north and Callovian in the south (Hoelstad 1986a,b, Poulsen 1986).

The uppermost sequence boundary (LCU) is equivalent to the top of the Farsund Formation or the base of the Valhall Formation corresponding to the Late Cimmerian Unconformity (Rawson and Riley 1982). The age of the sequence boundary is Late Ryazanian to Early Valanginian (Heilmann-Clausen 1986).

The seven sequence boundaries between the MCU and the LCU are named as follows starting from below: UJ-1, UJ-2 etc. up to UJ-7. The seismic tie into the two wells U-1 and E-1 have shown that these boundaries correspond to ages from the Late Oxfordian to the Middle Volgian (Poulsen 1986).

In the U-l well, the ages of the sequence boundaries are:

- UJ-1: Oxfordian-Kimmeridgian boundary
- UJ-2: Early to Late Kimmeridgian
- UJ-3: Late Kimmeridgian

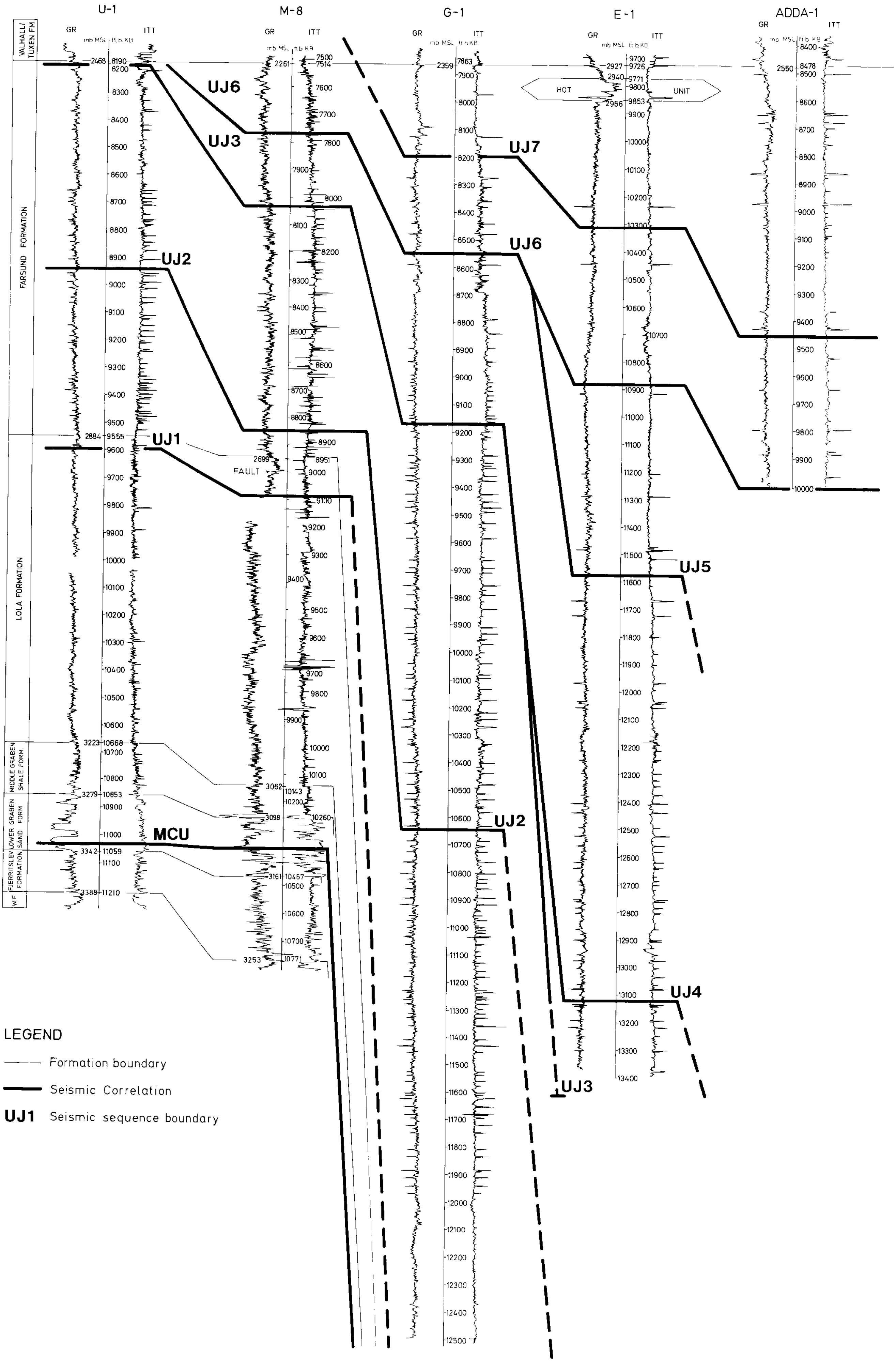
Continuing in the E-1 well:

- UJ-4: Early Volgian
- UJ-5: Middle Volgian
- UJ-6: Middle Volgian
- UJ-7: Middle Volgian

The ages of the sequence boundaries have been confirmed by analyses from other wells, listed in table 1.

Table 1.

Reflector / Well	LCU depth feet	LCU TWT m/sec	UJ7 depth feet	UJ7 TWT m/sec	UJ6 depth feet	UJ6 TWT m/sec	UJ5 depth feet	UJ5 TWT m/sec	UJ4 depth feet	UJ4 TWT m/sec	UJ3 depth feet	UJ3 TWT m/sec	UJ2 depth feet	UJ2 TWT m/sec	UJ1 depth feet	UJ1 TWT m/sec	MCU depth feet	MCU TWT m/sec	Seismic line	Comments
O-1	?	2100			?	2125									8530	2225	9470	2540	DK-79-28	gap in log
A-2	?	2025											?	2150	?	2325	?	2550	CGT-81-13	no log inf.
M-8	?	2075									8030	2300	8860	2375	9040	2425	10350	2675	0507 (1971)	
U-1	8170	2275									8190	2280	8940	2450	9600	2600	11025	2930	RTD-81-31	
G-1	7760	2110	8200	2300	8560	2370					9180	2500	10650	2800					RTD-81-44	
E-1	9730	2570	10310	2710	10850	2850	11580	3025	13120	3325									CGT-81-01	
ADDA-1	8400	2390	9460	2670	10005	2800													SP-82-32	
ADDA-2	8950	2500																	SP-82-32	
V-1	8090	2425			8350	2500					8790	2600	9200	2725	9780	2875			RTD-81-30	
BO-1	8350	2375	8780	2500															RTD-81-27	
W-1	13330	3250																	DMK-5554	
Q-1	13140	3425																	DKI-5606	


U-1
M-8
G-1
E-1
ADDA-1
GR
ITT
VALHALL/ TUXEN FM.
FARSUND FORMATION
LOLA FORMATION
MIDDLE GRABEN SHALE FORM.
LOWER GRABEN SAND FORM.
FJERRITSLEV FORMATION
WF
HOT
UNIT
FAULT
UJ7
UJ6
UJ5
UJ4
UJ3
UJ2
UJ1
MCU
LEGEND
Formation boundary
Seismic Correlation
UJ1 Seismic sequence boundary

The maps

The time structure maps

A total of four time structure maps have been prepared:

Map name	Reflector	
1. Near base Middle Jurassic/ Top pre-Jurassic	(MCU)	Encl. 1
2. Oxfordian-Kimmeridgian Boundary	(UJ-1)	Encl. 2
3. Late Kimmeridgian Marker	(UJ-3)	Encl. 3
4. Near top Jurassic/Base Cretaceous	(LCU)	Encl. 4

MCU. Near base Middle Jurassic

This sequence boundary is generally a high amplitude positive reflector with high lateral continuity. It is characterized by reflector truncations below and a parallel seismic reflection configuration above. The reflector can be correlated to four wells: A-2, M-8, O-1, U-1 (fig. 2), the well mentioned first being without acoustic log information. The well ties show that the seismic sequence boundary correlates with either the base or the top of the Central Graben Group (Jensen et al. 1986). In the O-1 well there is a seismically detectable separation of the top and the base of this lithostratigraphic unit. It is suggested that the reflector correlates to the base of Central Graben Group, and furthermore this is supported by the sonic log readings.

The wells mentioned above are all situated on salt pillows in the Salt Dome Province. The sequence boundary can fairly easily be traced into the eastern part of the Tail End Graben. In the central part of this graben the sequence boundary is below 4.5 sec (fig. 14), and consequently the seismic resolution becomes poor. At this depth it is not possible to distinguish whether the reflector represents an unconformity or not.

It is not possible to make any direct seismic tie to the western part of the Tail End Graben, but it is possible to recognize a seismic pattern similar to that of the graben. This pattern is chosen as the continuation of the sequence boundary.

The sequence boundary is a truncation in the area between the western part of the Tail End Graben and the Heno Plateau (fig. 14). The seismic resolution is low in this area and the position of the reflector-termination is highly uncertain. The Q-1 and W-1 wells represent the only well tie possibilities in the area. The Middle Jurassic sequence is absent in these wells. Therefore the map, which is extended onto the plateau represents the base of the Jurassic – equivalent to the lower limit of the Upper Jurassic.

Along the Ringkøbing-Fyn High rotational normal faulting has produced a number of plateaus. The V-1 well (fig. 10) is located on one of these the Poul Plateau. In this well a hiatus between the Triassic to the Upper Jurassic has been recorded. The termination of the MCU in this area (fig. 14) is partly controlled by faults and partly by onlapping.

The inversion of the north-south trending fault west of the U-1 well is mainly a Cretaceous feature, but the fault was also active as a normal fault, downthrown to the west, during Middle and early Late Jurassic times.

The inverted north-south trending fault west of the Bo-1 well divides the Tail End Graben into two parts, but most likely it was not active during Middle Jurassic times.

◄
Fig. 13. Profile showing the seismic ties to five wells in the Salt Dome Province and the Tail End Graben. For location see fig. 1.

UJ-1. Oxfordian-Kimmeridgian boundary

This sequence boundary corresponds to a low-amplitude, positive reflector which is conformable with the underlying reflection configuration. Above the boundary the reflectors are onlapping towards structural highs.

It is tied to the same wells as the MCU sequence boundary: A-2, M-8, O-1, U-l (fig. 2).

The sequence boundary correlates well with the boundary between the Lola Formation and Farsund Formation. The age of the boundary is Late Oxfordian close to the Oxfordian-Kimmeridgian boundary (Poulsen 1986).

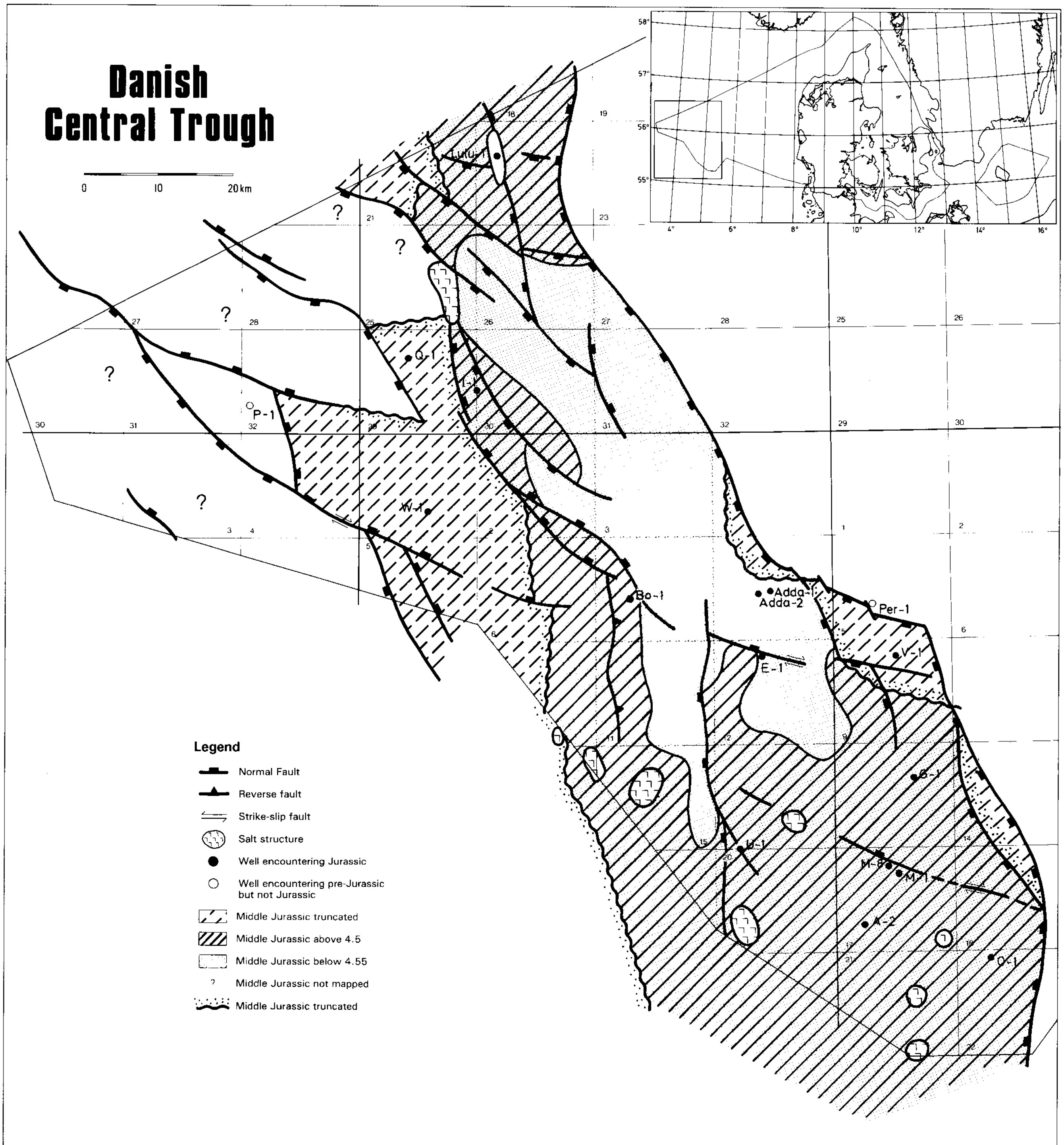


Fig. 14. Map showing seismic termination of the MCU reflector and areas where the reflector goes below 4.5 sec TWT corresponding to 5500 m.

The sequence boundary can be traced northwards through the eastern part of the Tail End Graben, but as it is represented by a low-amplitude reflector, it is not possible to recognize the seismic pattern in the western part of the Tail End Graben and on the Heno Plateau. This area is therefore not mapped.

The structural pattern seen on the UJ-1 map (Encl. 2) is similar to that of the Middle Jurassic MCU map (Encl. 1). The north-south trending basement attached faults have been intermittently active in the period between Middle Jurassic and Late Oxfordian times.

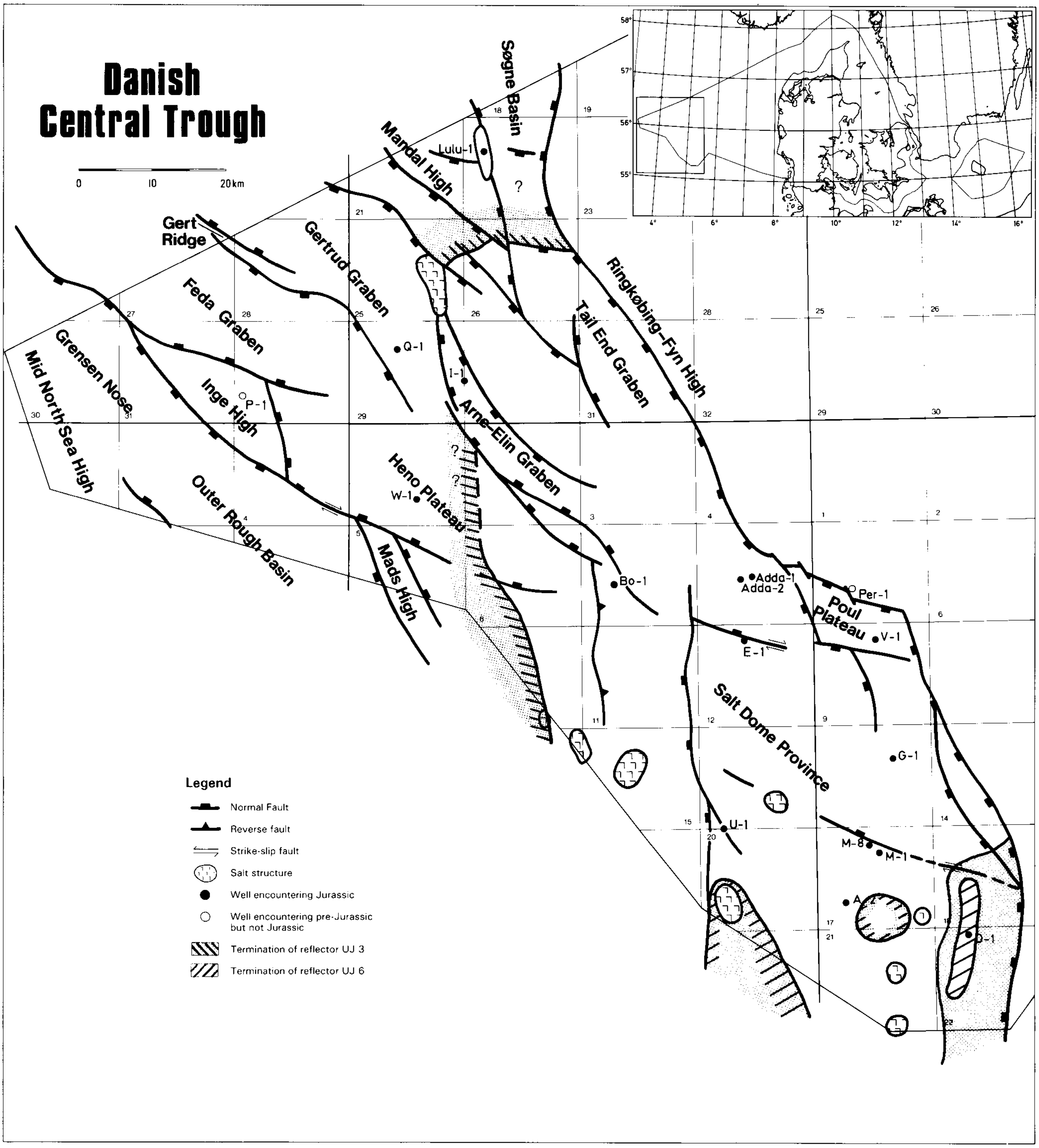


Fig. 15. Map showing seismic termination of the UJ-3 reflector.

UJ-3. Late Kimmeridgian marker

This sequence boundary is defined by a generally high amplitude, positive reflector, which is the lowermost of two high amplitude reflectors of a high lateral continuity. The reflectors below and above are parallel. The seismic sequence boundary can be tied to the following wells: A-2, G-1, M-8, U-1 (fig. 2). The age of the sequence boundary is Late Kimmeridgian (Poulsen 1986).

To the south in the Salt Dome Province the reflector looses amplitude and the sequence boundary becomes less prominent. It appears to extend southwards into German waters. It is seismically truncated in some areas (fig. 15), probably due to halokinesis. The sediments on either side of the reflector may, however, be present in most places, but in a condensed form. Where the sequence boundary is terminated by truncation the overlying UJ-6 reflector has been mapped. To the north, where the Tail End Graben is bounded to the Gertrud Graben and the Mandal High – Søgne basin, the UJ-3 is terminated by onlap (fig. 8a).

LCU. Near top Jurassic

This sequence boundary is represented by a high-amplitude reflector of a high lateral continuity located below a strong negative reflector. It is tied to the wells mentioned in table 1. The age of the sequence boundary is Late Ryazanian to Early Valanginian.

The sequence boundary is correlated to the Late Cimmerian Unconformity (Rawson and Riley 1982). In the Danish part of the Central Trough it is not normally developed as an unconformity. This is discussed in detail by Vejbæk (1986).

The isopach maps

A total of 5 isopach maps are prepared. viz:

1) Middle and Upper Jurassic	fig. 16
2) Middle Jurassic and Lola Formation	fig. 17
3) Farsund Formation	fig. 18
4) Farsund Formation, lower part	fig. 19
5) Farsund Formation, upper part	fig. 20

The maps are constructed on the basis of isocore maps by using a constant sonic velocity of 3000 m/s. This velocity will generally lead to an overestimation of thicknesses, especially the Upper Jurassic is thick compared to the Middle and lower Upper Jurassic.

The Middle and Upper Jurassic sequence

The mapped sequence corresponds to the Middle and Upper Jurassic in the Danish part of the Central Trough (fig. 16). It is bounded above by the LCU reflector, and below by the MCU reflector in the Salt Dome Province and the Tail End Graben. At the Heno Plateau the lower boundary corresponds to the boundary between Upper Jurassic and pre-Jurassic sequences. Further north in the Feda and Gertrud Graben it is bounded below by a sequence boundary without well ties which is believed to be close to the base of the Middle Jurassic. Although the interpretation is ambiguous the same structural trend would appear, if another reflector was chosen.

Three major subsidence areas can be recognized within the Danish Central Trough and they are: the Tail End Graben plus the Salt Dome Province, the Gertrud Graben and the Feda Graben, the Tail End Graben having the largest subsidence, with more than 4 km of sediments.

The major subsidence occurred probably in the Late Jurassic in all three areas. In the Tail End Graben and the Salt Dome Province this assumption is confirmed by well data, and in this area the Middle and Upper Jurassic sequence has been subdivided into three sequences, which will be described below.

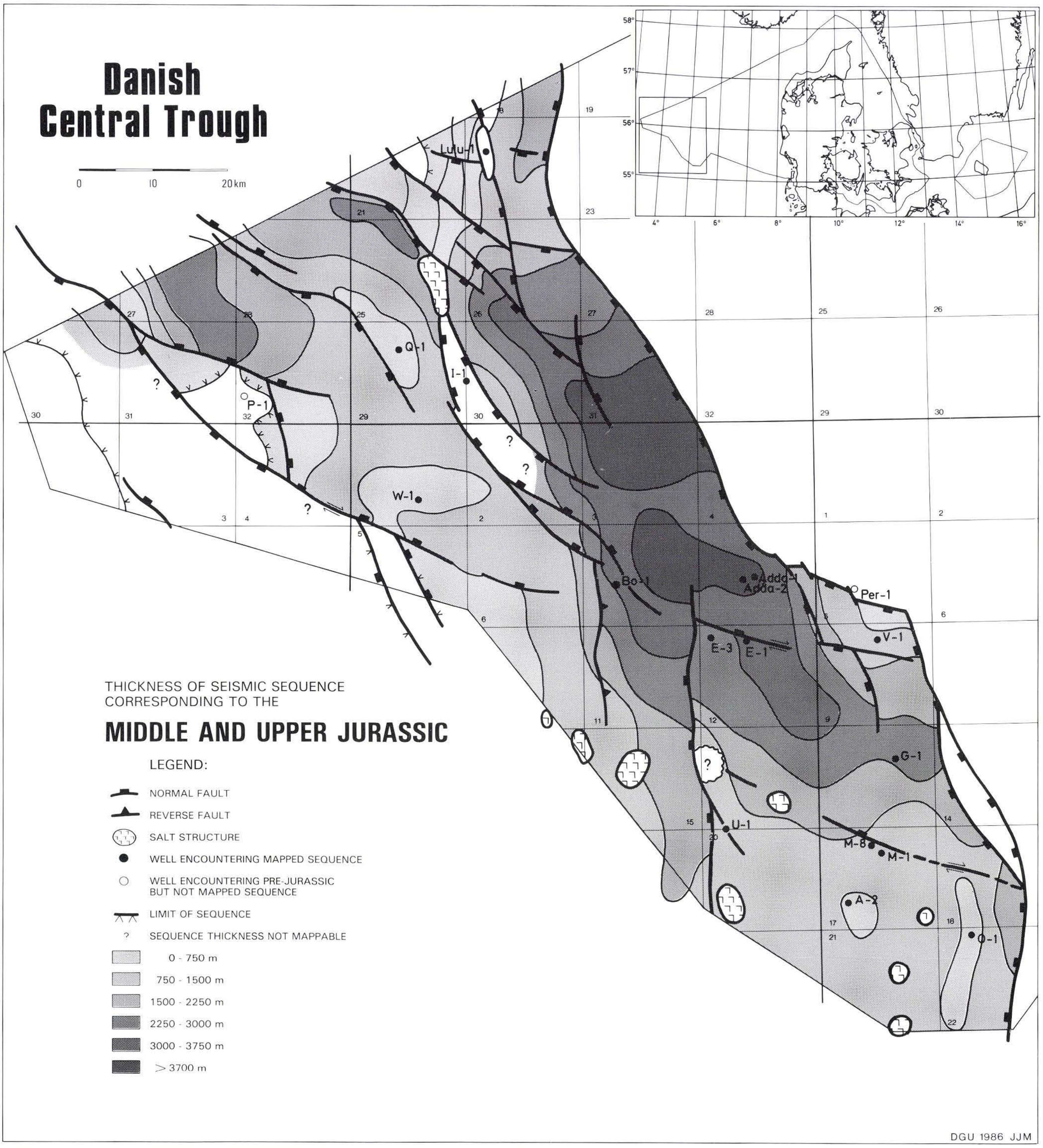


Fig. 16. Thickness and distribution of the seismic sequence corresponding to the Middle and Upper Jurassic formations.

The Middle Jurassic and the Lola Formations

This map shows the lowermost part of the Middle and Upper Jurassic sequence mapped (fig. 17). It is bounded below by the MCU reflector and above by the UJ-1 reflector. It corresponds to the Middle Jurassic and the Lola Formation (Jensen et al. 1986). Regionally the sequence is characterized by a depocentre in the southern part of the Tail End Graben and it thins towards the south and north.

Local depocentres have been formed on the western sides of the north-south trending basement faults. During the Middle and Late Jurassic the subsidence rate along the fault west of the U-1 well was of the same magnitude as along the bounding fault to the Ringkøbing-Fyn High. Right-lateral strike-slip movement along the northwest-southeast trending fault system probably took place in this period, with local depocentres situated south of the proposed faults.

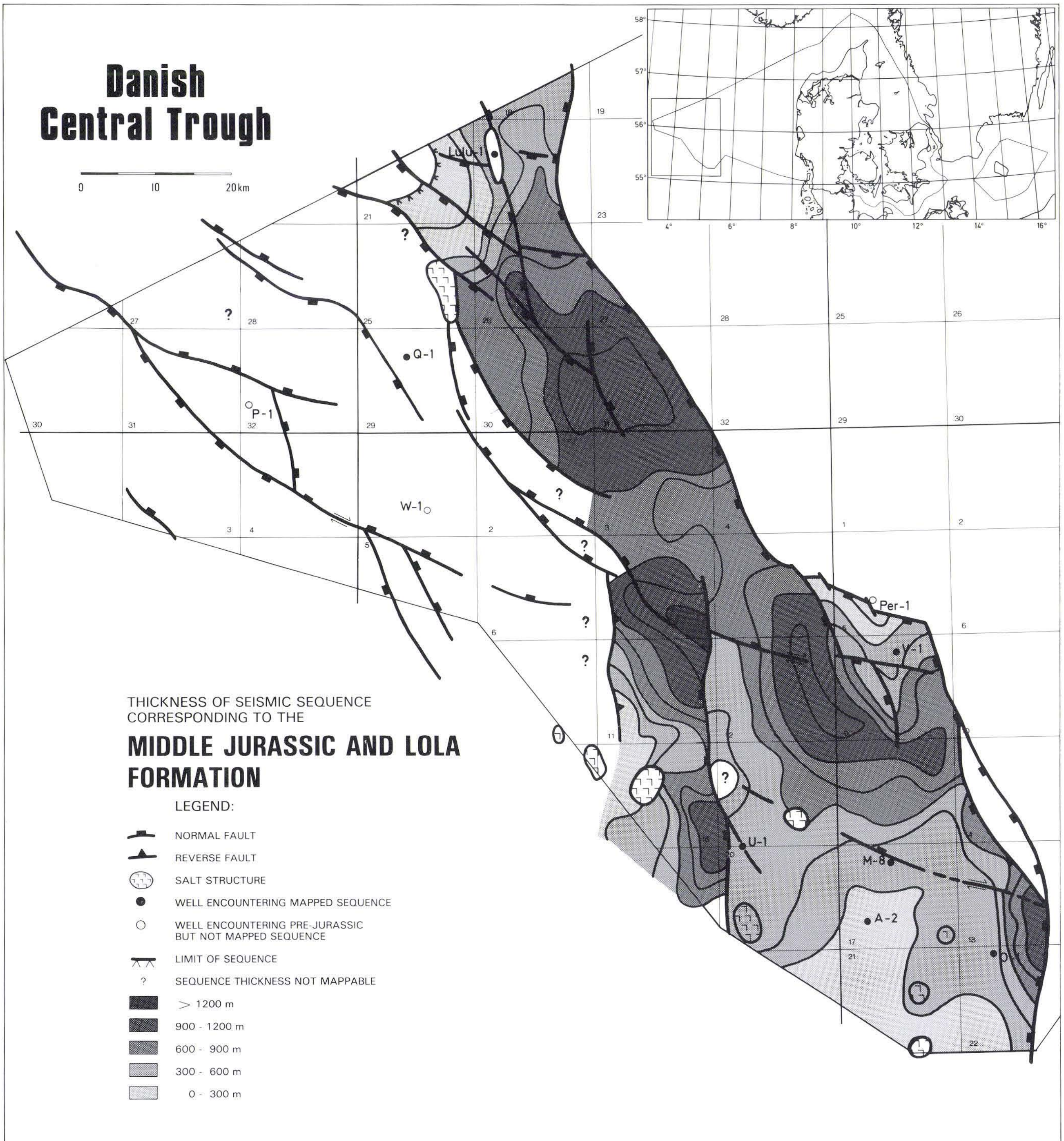


Fig. 17. Thickness and distribution of the seismic sequence corresponding to the Middle Jurassic and Lola Formations in the Salt Dome Province and the Tail End Graben.

The Farsund Formation

The mapped sequence is bounded below by the UJ-1 reflector and above by the LCU reflector, and corresponds to the Farsund Formation (Jensen et al. 1986). The regional subsidence pattern for this formation (fig. 18) is the same as for the total Middle and Upper Jurassic (fig. 16). However the depocentre in the southern part of the Tail End Graben is better defined and the subsidence along the fault west of the U-1 well decreased. This sequence is divided into a lower and an upper sequence which are depicted separately on the following two maps.

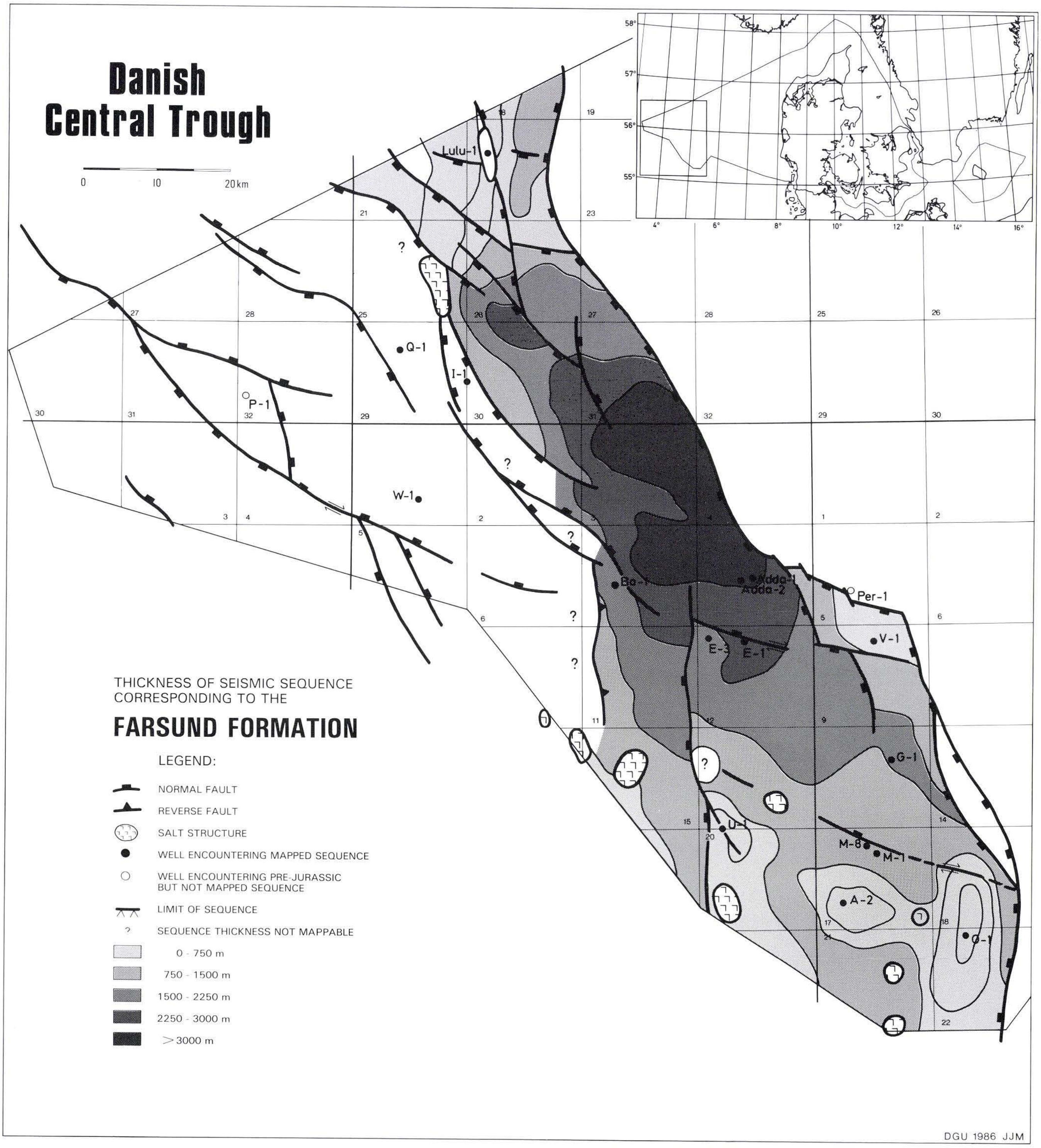


Fig. 18. Thickness and distribution of the seismic sequence corresponding to the Farsund Formation in the Salt Dome Province and the Tail End Graben.

The Farsund Formation (lower part)

The mapped sequence is bounded below by the UJ-1 reflector and above by the UJ-3 reflector (fig. 19). It corresponds to the lower part of the Farsund Formation.

The regional subsidence pattern is the same as for the underlying sequence (fig. 17), except that in this sequence the depocentre is more clearly located in the southern part of the Tail End Graben.

During this period no local depocentre developed east of the O-1 well, whereas the other local depocentres (fig. 17) continued, with small lateral displacements to the south. In the area north of the Bo-1 well and around the Adda-1 well two new depocentres developed north of the proposed right-lateral strike-slip fault.

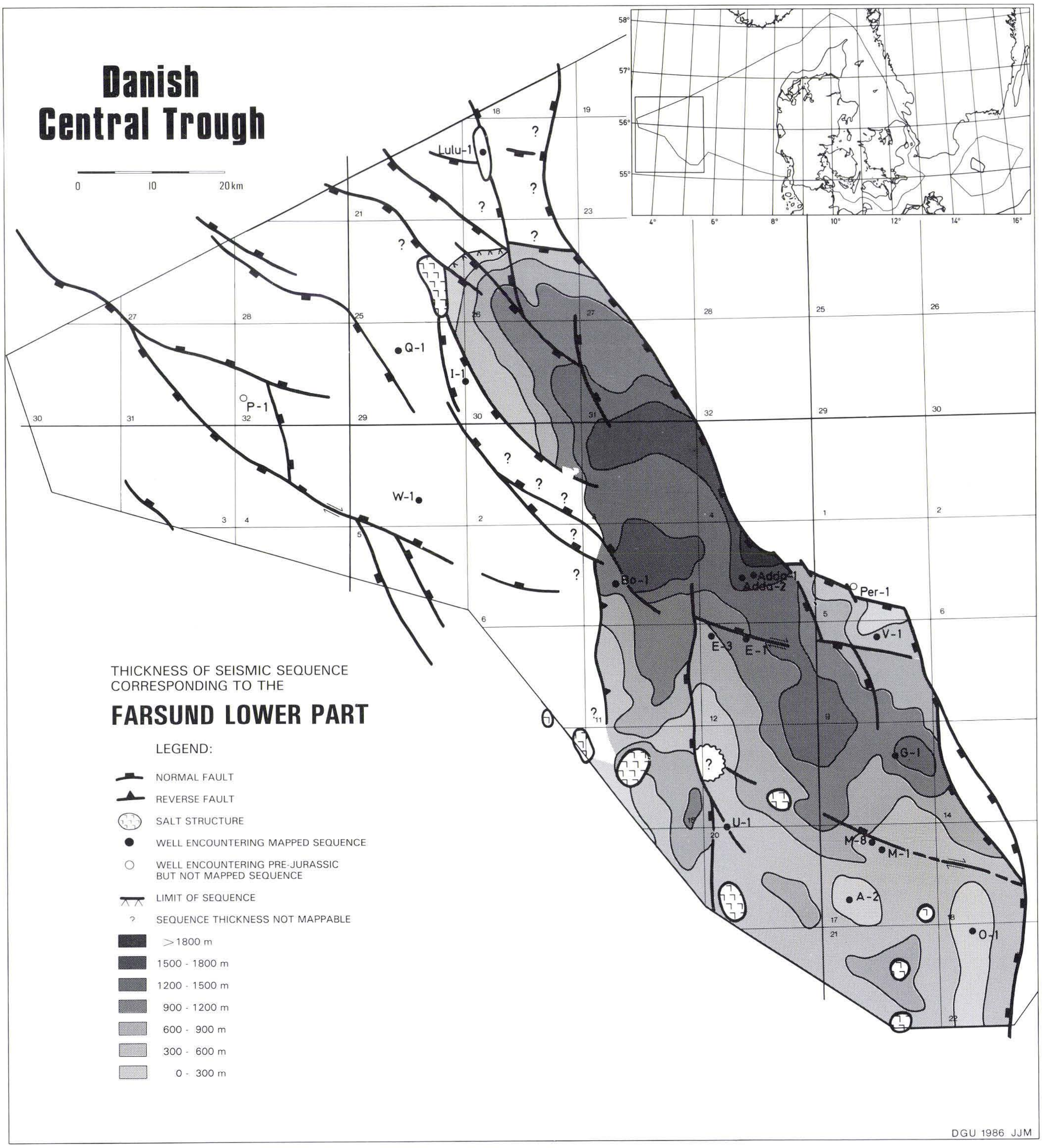


Fig. 19. Thickness and distribution of the seismic sequence corresponding to the Farsund Formation, lower part in the Salt Dome Province and the Tail End Graben.

The Farsund Formation (upper part)

The mapped sequence is bounded below by the UJ-3 reflector and above by the LCU reflector (fig. 20). It corresponds to the upper part of the Farsund Formation, and does thus contain the hot unit also (Jensen et al. 1986).

The regional subsidence pattern from the sequences below continued with one major depocentre in the southern part of the Tail End Graben.

The local depocentre in the Salt Dome Province, seen in the sequences below, was not active during the deposition of this sequence, and the area was without any significant tectonic activity except for the bounding fault to the Ringkøbing-Fyn High.

The depocentre in the Tail End Graben developed north of the right-lateral strike-slip fault just as the depocentre in the underlying sequence.

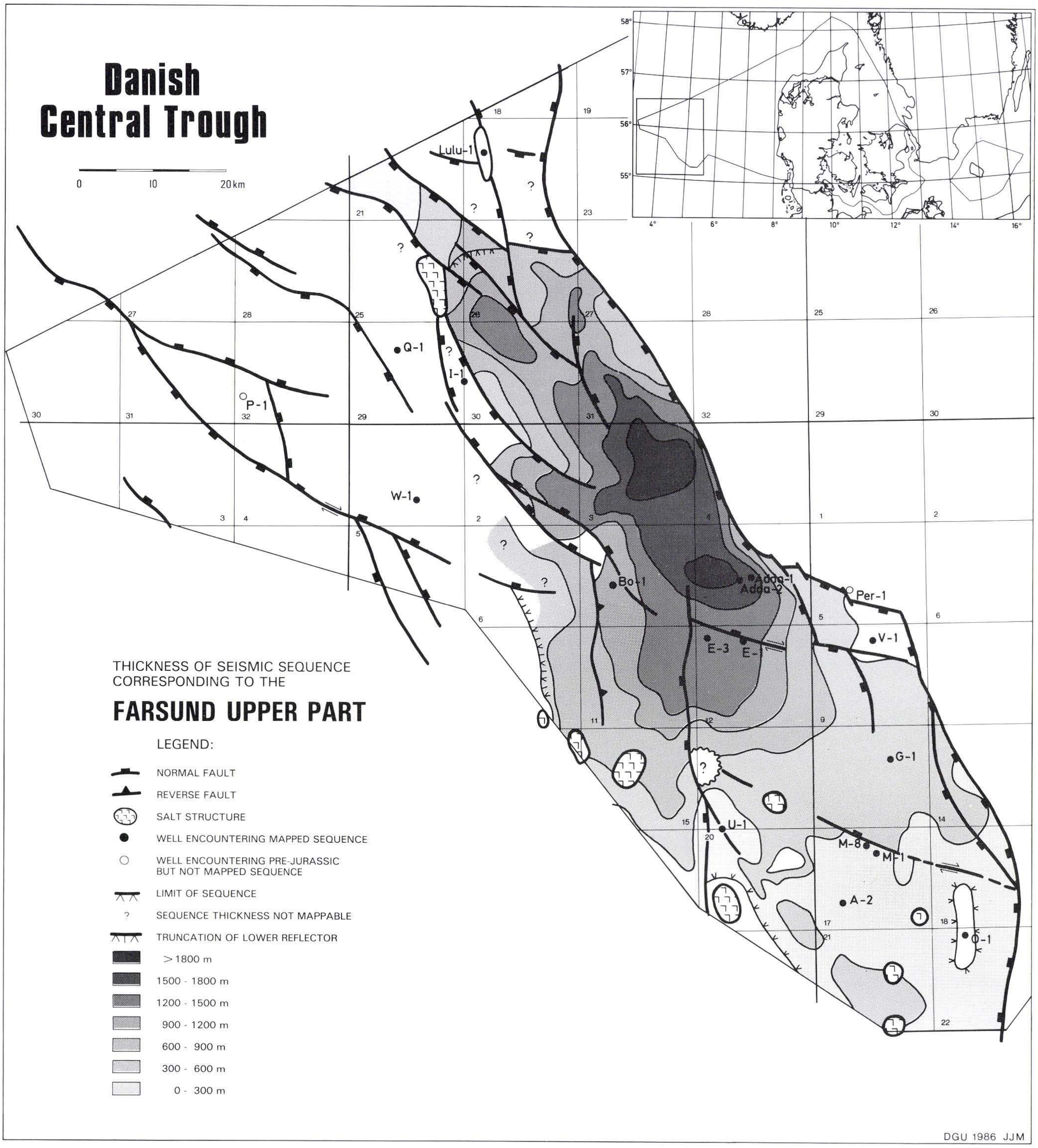


Fig. 20. Thickness and distribution of the seismic sequences corresponding to the Farsund Formation, upper part in the Salt Dome Province and the Tail End Graben.

Tectonic evolution of the Middle and Late Jurassic

The tectonism of the Middle and Late Jurassic was to some extent a continuation of the Early Mesozoic tectonic pattern (Whiteman et al. 1975). During the Triassic and the Jurassic the Danish Central Trough was part of a north-south trending rifting system, where faulting caused subsidence in the major grabens and basins along north-south trending faults.

In addition to this fault direction there was a northwest-southeast fault direction with a strong component of right-lateral strike-slip according to Gowers and Sæbøe (1985). The activity of the latter fault system is believed to be of the same age as that of the north-south trending faults.

The introduction of a few right-lateral strike-slip fault zones is probably a simplification and several more were probably present, especially in the northern part, where the southwest bounding fault along the Mandal High may be regarded in the same way.

If this interpretation of the northwest-southeast trending faults is correct some of the faults must extend into the Ringkøbing-Fyn High, but they are not seen on the seismic data. This does not exclude the existence of such faults. If the postulated right-lateral movement did take place, the offset between the Salt Dome Province and the Tail End Graben was greater than now. This is in agreement with a difference in nature of the Middle Jurassic sediments in the two areas (Jensen et al. 1986). The lateral displacement along the faults has not been detected.

A result of this right-lateral strike-slip movement is that the more stable structural units between two active faults could have rotated clockwise (fig. 21) with the result that thrusting could occur in an area dominated by transtensional faulting. At the moment there is no seismic or well data, which clearly support the presence of thrusting developed in the Danish Central Trough during the Jurassic.

After an initial inspection of the structural map (fig. 2), a comparison of the displacement of the Inge High relative to the Mads High and the displacement of the Ringkøbing-Fyn High north of the V-1 well might lead to an idea of a left-lateral strike-slip movement. However, this idea requires stress directions which are incompatible with the observed north-south striking Late Jurassic normal faults.

The various strike-slip faults (fig. 2) have not necessarily been active at the same time. The fault north of the M-8 well was active in pre-Middle Jurassic time, and decreased in activity in the Late Jurassic. The fault south of the Poul Plateau was active in pre-Middle Jurassic time, but increased in activity during the Late Jurassic. The right-lateral movement along this fault system is believed to have been responsible for the relatively high subsidence rates in the Tail End Graben compared to that in the Salt Dome Province during the Late Jurassic, and for the initiation of the Arne-Elin Graben. Further west at the Inge High the activity along this fault ceased and was taken over by a fault further north by right stepping (Gowers and Sæbøe 1985). This fault caused the subsidence of the Feda Graben.

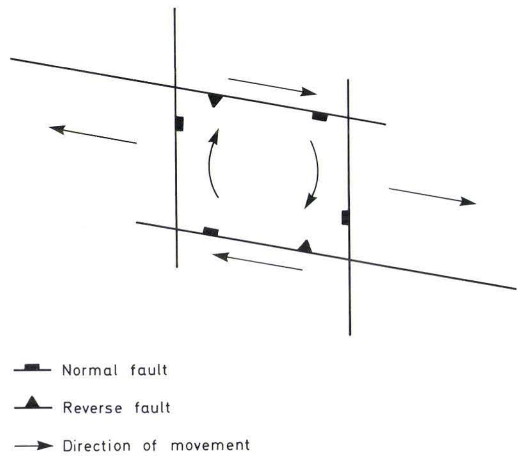


Fig. 21. Schematic clockwise rotation of a structural unit between two active strike-slip faults.

The lack of well ties in the northwestern part of the Danish Central Trough make the seismic interpretation tentative in this area, and the postulated tectonic movements, which were responsible for the subsidence of the Feda Graben and the Gertrud Graben are based on a time equivalence to the Tail End Graben.

The tectonic evolution of the Heno Plateau, the Inge High, the Outer Rough Basin, and the Grensen Nose is not fully understood at the moment, but it is believed that the whole area was relatively elevated and exposed to erosion until late Late Jurassic time, and that the Inge High remained as a high also during the latest part of the Late Jurassic.

Summary

The Middle and Late Jurassic of the Danish Central Trough can be regarded as the most active part of a rifting period, that persisted through the Mesozoic until Late Cretaceous times.

The tectonic framework was dominated by north-south trending normal faults and northwest-southeast trending right-lateral strike-slip faults, and a number of structural elements developed during the Middle and Late Jurassic. The structural elements are divided into three groups:

1) Highs, where the Precambrian or Caledonian basement is relatively elevated and the Jurassic sequence is thin or absent. They include the Ringkøbing-Fyn High, the Mid North Sea High, the Mads High, the Inge High, and the Mandal High.
2) Grabens and basins, characterized by a relatively high rate of subsidence and sedimentation during the Jurassic. They include the Salt Dome Province, the Tail End Graben, the Søgne Basin, the Feda Graben, the Gertrud Graben, and the Arne-Elin Graben.
3) Areas of intermediate or poorly defined subsidence. They include the Heno Plateau, the Poul Plateau, the Outer Rough Basin, the Grensen Nose, and the Gert Ridge.

During the Middle and early Late Jurassic the subsidence areas developed identically with several local depocentres situated on the western side of the north-south trending faults. During the Late Jurassic the major subsidence occured in the Tail End Graben and the Feda Graben. The thickness of the Middle and Upper Jurassic sequences is more than 4 km in the Tail End Graben.

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Data base

The seismic data used in this study are from the period 1979–1982. They are all processed to at least 5 sec, which equals depths of at least 6 km. They include two types of seismic surveys:

1) Proprietary data shot by DUC.
2) Speculative data, which were shot by different seismic contractors.

The seismic surveys are covered by a five year confidentiality clause, and cannot be published until this period is expired. That means that a number of the surveys used in the investigation will be confidential at the expected time of publication of the present paper. They have, however, been released for this purpose.

In table 2 the various surveys and their owners are listed, and in fig. 22 the density of the seismic grid are shown.

A rather dense grid of seismic data, vintage 1964–1977, exists in the area. This data-set has not been used, as the resolution below the Chalk Group is poor. Furthermore the data have not been migrated.

Table 2. The various seismic surveys used in the interpretation.

Survey	Contractor Company	Type	Vintage
CGT	Nopec	Speculative	1981
RTD	Nopec	Speculative	1981
MERLIN	Merlin	Speculative	1982
DK1	GSI	Speculative	1982
DMK	GSI	Speculative	1982
GSI 79	DUC	Proprietary	1979
GSI 80	DUC	Proprietary	1980
GSI 81	DUC	Proprietary	1981

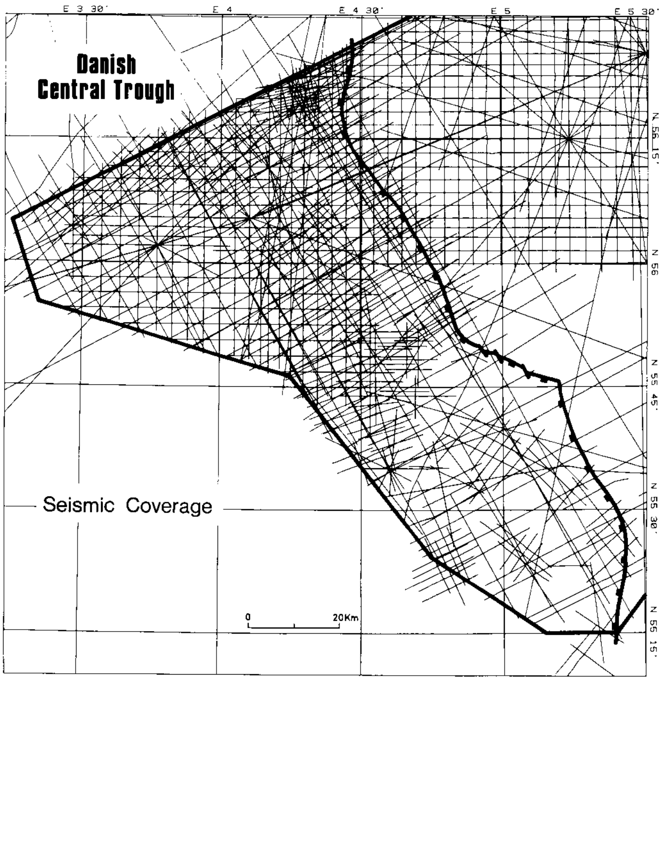


Fig. 22. The density of the seismic grid used in this investigation.

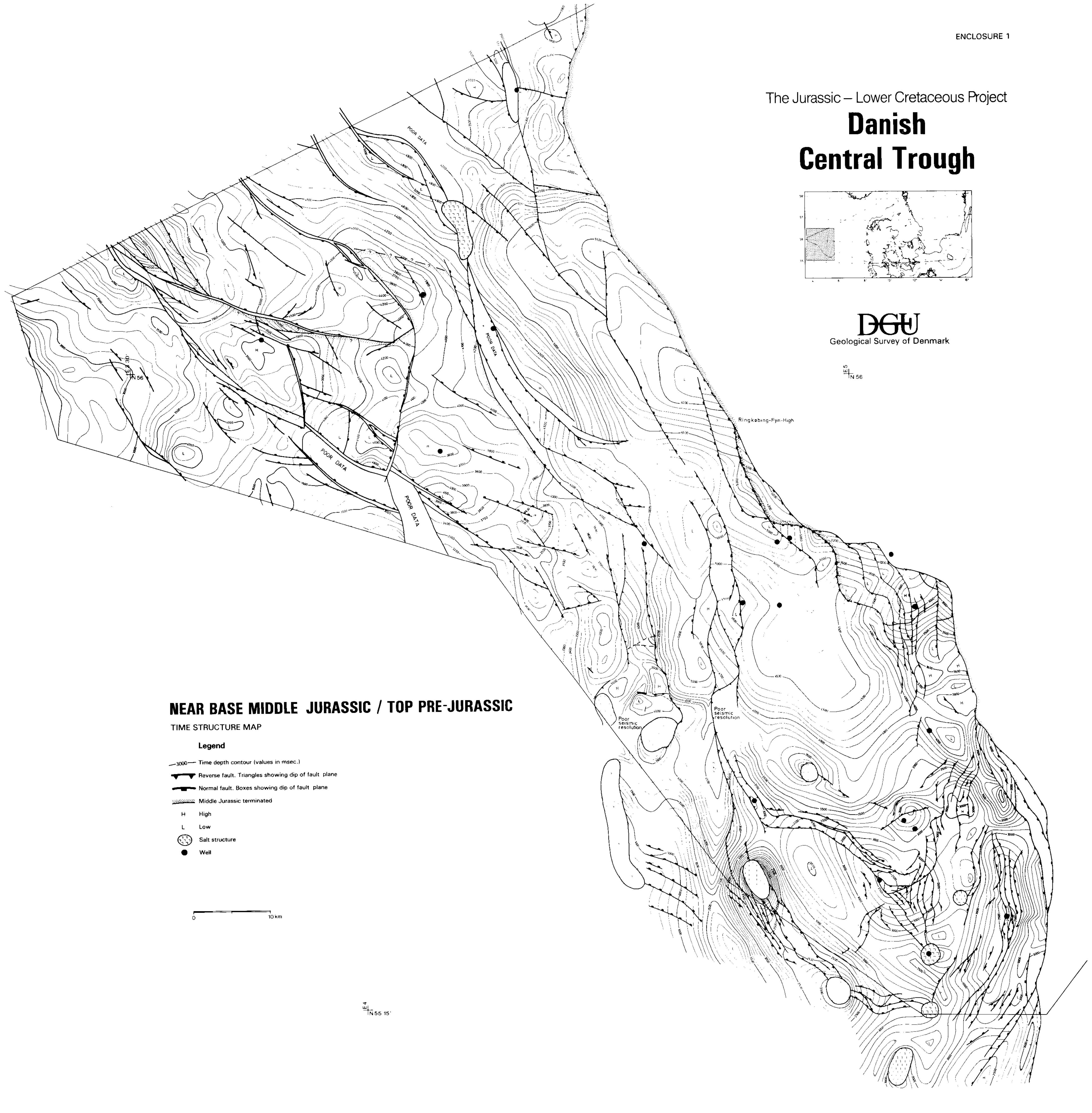
Enclosures 1–4

List of enclosures

The Jurassic – Lower Cretaceous Project

Danish Central Trough

DGU
Geological Survey of Denmark



NEAR BASE MIDDLE JURASSIC / TOP PRE-JURASSIC

TIME STRUCTURE MAP

Legend

- 3000 — Time depth contour (values in msec.)
- Reverse fault. Triangles showing dip of fault plane
- Normal fault. Boxes showing dip of fault plane
- Middle Jurassic terminated
- H High
- L Low
- Salt structure
- Well

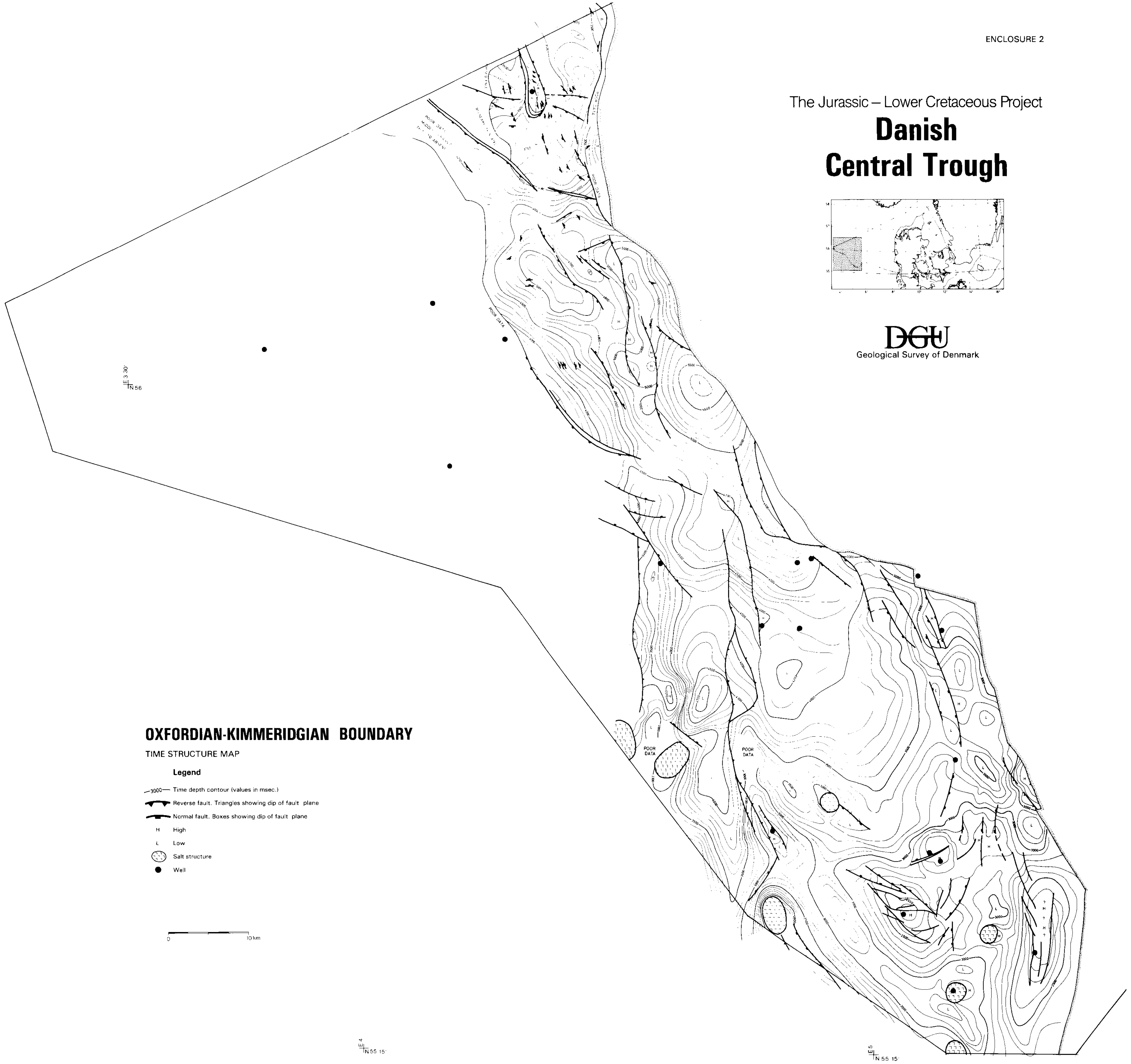
0 — 10 km

ENCLOSURE 2

The Jurassic – Lower Cretaceous Project

Danish Central Trough

DGU
Geological Survey of Denmark



OXFORDIAN-KIMMERIDGIAN BOUNDARY

TIME STRUCTURE MAP

Legend

- 3000 — Time depth contour (values in msec.)
- Reverse fault. Triangles showing dip of fault plane
- Normal fault. Boxes showing dip of fault plane
- H High
- L Low
- Salt structure
- Well

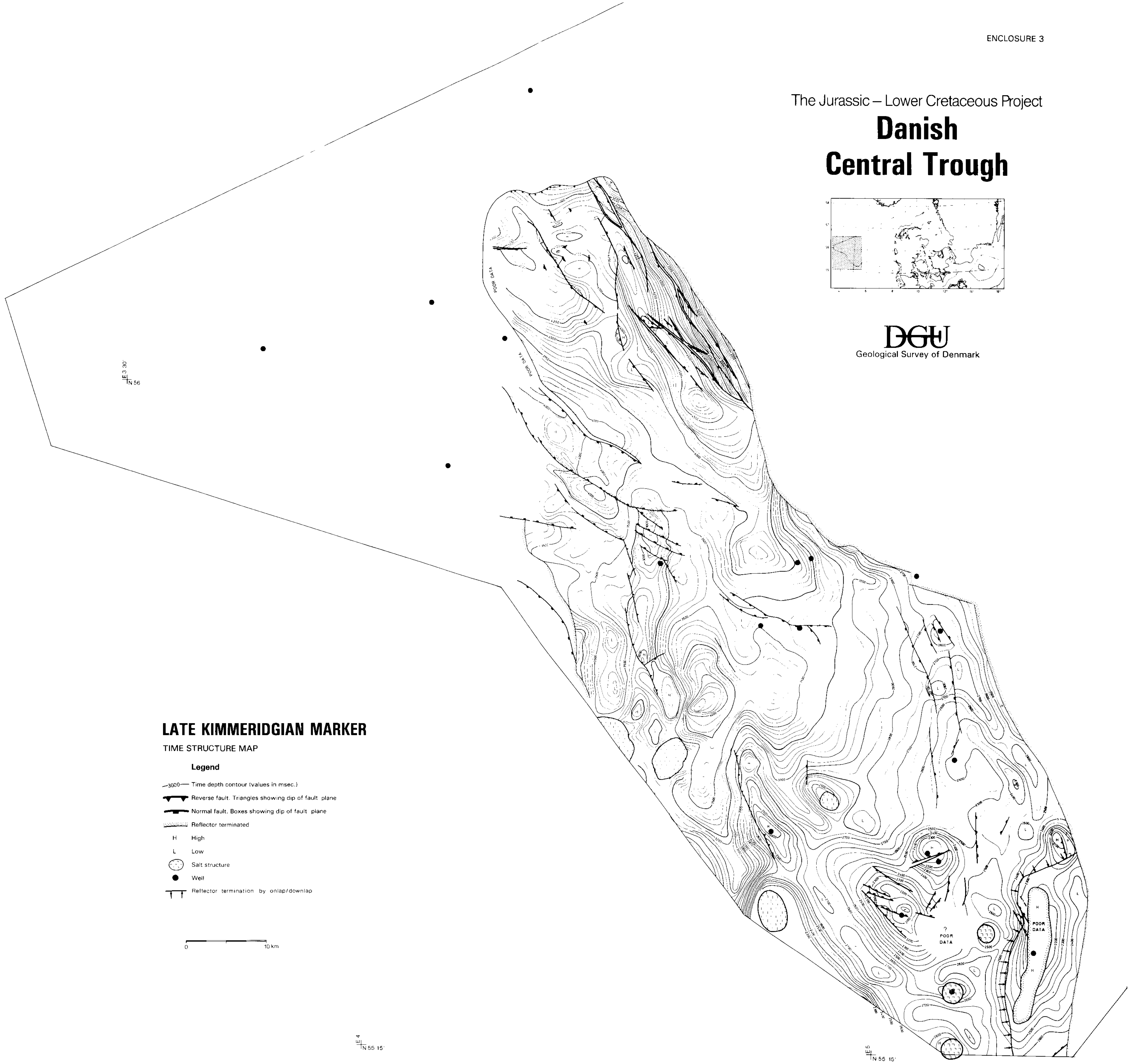
0 — 10 km

ENCLOSURE 3

The Jurassic – Lower Cretaceous Project

Danish Central Trough

DGU
Geological Survey of Denmark



LATE KIMMERIDGIAN MARKER

TIME STRUCTURE MAP

Legend

- 3000 — Time depth contour (values in msec.)
- Reverse fault. Triangles showing dip of fault plane
- Normal fault. Boxes showing dip of fault plane
- Reflector terminated
- H — High
- L — Low
- Salt structure
- Well
- Reflector termination by onlap/downlap

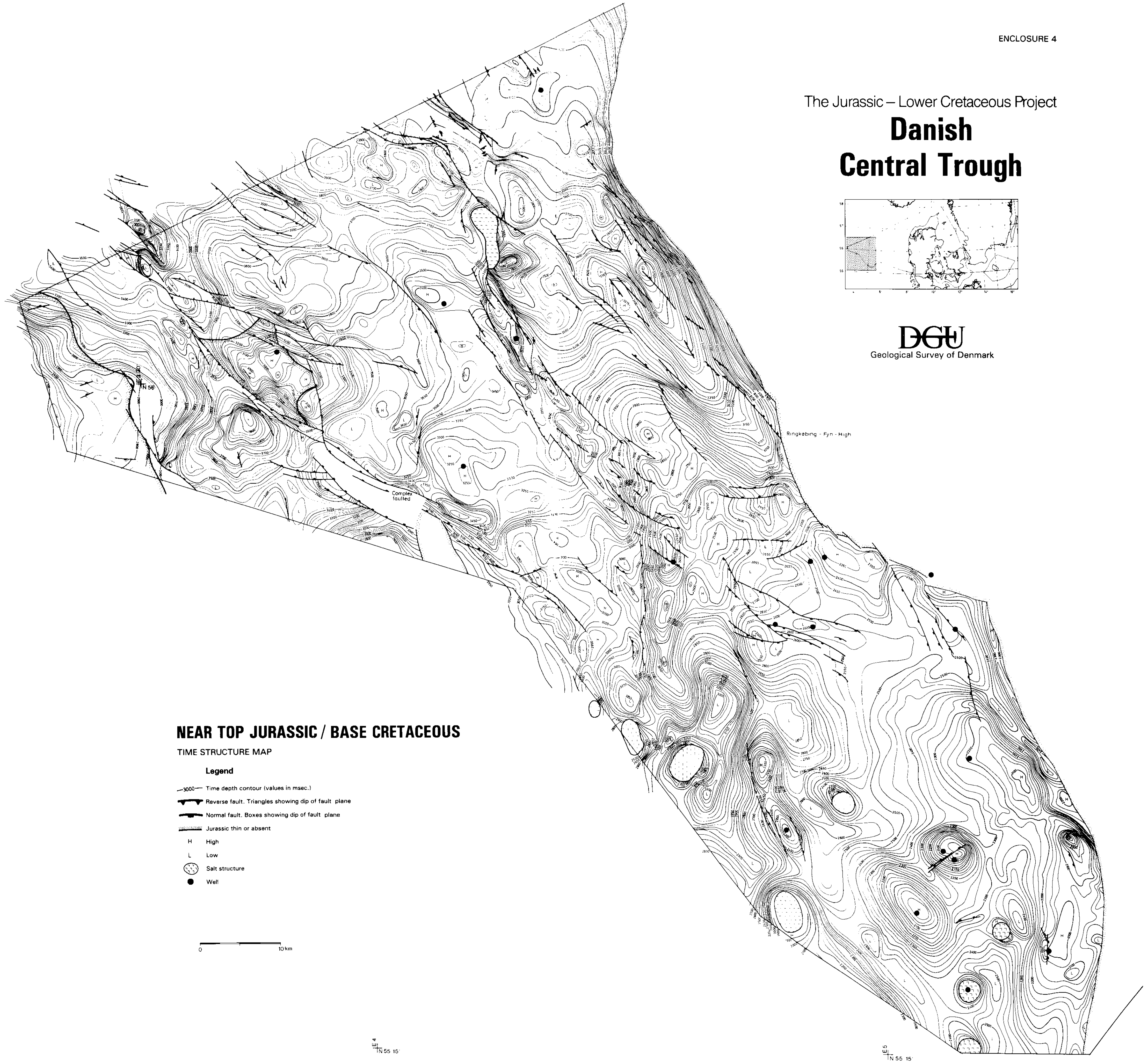
0 — 10 km

ENCLOSURE 4

The Jurassic – Lower Cretaceous Project

Danish Central Trough

DGU
Geological Survey of Denmark



NEAR TOP JURASSIC / BASE CRETACEOUS

TIME STRUCTURE MAP

Legend

- 3000 — Time depth contour (values in msec.)
- Reverse fault. Triangles showing dip of fault plane
- Normal fault. Boxes showing dip of fault plane
- Jurassic thin or absent
- H High
- L Low
- Salt structure
- Well

0 10 km

A dense number of seismic lines have made it possible for the author to present in this paper a detailed study of the structural development during the Middle and Upper Jurassic in the Danish Central Trough.

A number of seismic maps complete the study.

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