

## LATE PALAEOZOIC TO EARLY CENOZOIC STRUCTURAL DEVELOPMENT OF THE SOUTH-SOUTHEASTERN NORWEGIAN NORTH SEA<sup>1</sup>

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### ABSTRACT

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The Late Palaeozoic to Cenozoic structural development of the southern and southeastern Norwegian offshore sector is described, based on detailed maps of Top Chalk, Base Valanginian and Base Zechstein levels.

The history of the main structural elements confirms that block faulting has occurred through the Permian, Triassic and Jurassic along NW-SE, N-S and E-W trending fault systems. Shear movements occurred in the Late Jurassic and in the Late Cretaceous/Early Tertiary, mainly along the N-S and E-W trends.

### INTRODUCTION

The main structural features of the southern part of the Norwegian North Sea are known from several publications: RØNNEVIK ET AL. (1975), P. ZIEGLER (1981, 1982) and HAMAR ET AL. (1980).

The present review is based mainly on seismic interpretations carried out in the NPD. In total, 7 reflectors have been mapped in the study area. The structural development is illustrated by maps at three different levels (Figs. 2-4) and by several cross-sections (Fig. 5). The aim has been to give a fairly detailed picture of the development of the major structural features. The nomenclature used is mainly based on RØNNEVIK ET AL. (1975), but some modifications and amendments are introduced. In some areas, however, especially towards the Fennoscandian Border Zone, the interpretation of the complicated structures is difficult because of sparse data.

### MAIN STRUCTURAL ELEMENTS

Within the southern part of the Norwegian North Sea sector several major structural elements are defined. Established already in Permian times, but reactivated later, these struc-

tures largely controlled North Sea sedimentation throughout Mesozoic and Cenozoic times. Figure 1 shows the main tectonic elements of the area.

#### *Central Graben*

The Central Graben is a major NW-SE trending graben system which was active during Mesozoic rifting and subsidence. Its early history is difficult to unravel. The Graben is bounded by normal en echelon rotational faults which are clearly defined along its northeastern margin. Within the Graben are narrow discontinuous structural highs and lows. These elements, probably of Mesozoic to Cenozoic age, are characteristic for the Norwegian and UK parts of the Central Graben.

#### *Vestland Arch*

The Vestland Arch is a high trend running east of the Central and Viking Graben. It parallels the Graben axis and comprises a series of eastward rotated fault blocks, separating the Norwegian-Danish Basin from the Central Graben. The Utsira High and Jæren High belong to this complex, as well as the Hydra fault blocks which are located in the transition zone towards the Central Graben. The Vestland Arch complex is bounded to the southwest by large normal faults and is dipping gently northeastward into the Egersund Sub-Basin area. In the southeast it merges with the Ringkøbing-Fyn High.

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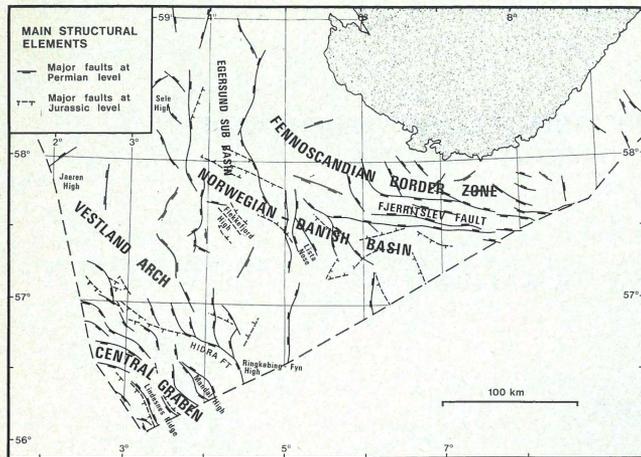


Fig. 1  
Main structural elements.

### *Norwegian-Danish Basin*

The Norwegian-Danish Basin is a WNW-ESE trending basin limited by the Ringkøbing-Fyn High to the SSW. This Basin started developing in Permian time. It is characterized by thick sediments of Permian and Triassic age. To the east and northeast, the Basin is bounded by basement faults of the Fennoscandian Shield. Sub-basins have developed in the north of this basin, mainly during the Kimmerian movements and are separated by structural highs and major faults. These sub-basins contain thick Mesozoic sedimentary sequences, which are best developed in the Egersund Sub-Basin. The Norwegian-Danish Basin is partly subdivided into a north-western and a southeastern part by the Lista Nose, a SSEward plunging structural high.

### *Fennoscandian Border Zone*

The Fennoscandian Border Zone is a complex fault zone separating the Norwegian-Danish Basin from the Fennoscandian Shield. The oldest age of this tectonic element is unknown, but the Zone was activated during Kimmerian and Laramide movements. An important feature, in connection to the Fennoscandian Border Zone, is the Fjerritslev Fault. This WNW-ESE trending fault system, initiated in Permian times, is clearly defined in the eastern Norwegian North Sea region. The fault movements were down to the north, but inversion and wrench characteristics along the fault zone have been observed in the Mesozoic section.

## GEOLOGICAL DEVELOPMENT

### *Pre-Permian*

The Caledonian orogeny, as indicated by wells, has affected the whole area to the west of 4° E (FROST ET AL., 1981). The Caledonian trend is best developed in the north, where NE-

SW striking fault systems are responsible for separating basement highs like the Utsira High and the Sele High (Fig. 1). Also a NE-SW trending fault zone, northeast of the Egersund Sub-Basin, follows this alignment.

Devonian and Carboniferous deposits are not well known in the study area. Deposits possibly of this age have been penetrated on the western flank of the Central Graben. In addition the seismic data show strong reflections that partly subcrop beneath the Rotliegendes to the north of the Ringkøbing-Fyn High and in the Egersund Sub-Basin area. These subcrops may represent Devonian or Carboniferous sediments. It is not obvious that the southern Norwegian North Sea region was a non-depositional area as indicated in p. ZIEGLER's (1982) maps.

### *Permian*

The Hercynian tectonic phase, which had its culmination in Late Carboniferous to Early Permian times, mainly led to deformation south of the central North Sea (ZIEGLER, 1981). Nevertheless, these structural movements influenced the palaeogeography and sedimentation of the region – under discussion and initiated the formation of major tectonic elements. These include E-W and NW-SE striking rift structures. The most prominent structural features reflecting these directions in the central North Sea are the Ringkøbing-Fyn High and the Mid-North Sea High. The late Hercynian Stephanian-Autunian orogenic movements mark the onset of a period dominated by extension tectonics. This is demonstrated by the development of N-S trending fracture systems and grabens. The strongly magmatic Oslo Graben was formed in Permo-Carboniferous times, and igneous activity along an approximately NNE-SSW fracture system occurred at the present coast of southwestern Norway (FAERSETH ET AL., 1975).

The Norwegian-Danish Basin, which was formed in Permian times, is considered to be an epirogenic subsiding basin, without synsedimentary faults of Permian age. It was a part of the northern Permian Basin.

The characteristic clastic deposits of Rotliegendes are related to continental deposition dominated by arid and semi-arid climatic conditions. Aeolian deposits are encountered on the north flank of the Ringkøbing-Fyn High, whereas coarser clastics have been penetrated further north in the Norwegian-Danish Basin.

Subsidence of the Permian basins in the North Sea accelerated during the Late Permian, when cyclic carbonates and evaporites of the Zechstein were deposited during episodes of transgressions and regressions. These deposits are thought to have had locally original thicknesses of more than 1000 m. Later extensive halokinetic movements produced numerous structures, which today represent the main exploration targets (Fig. 3). The eastern limit of the Zechstein Group is shown in figure 2. East of this limit the mapped seismic horizon is correlated with the Base Zechstein/Top Rotliegendes boundary to the west.

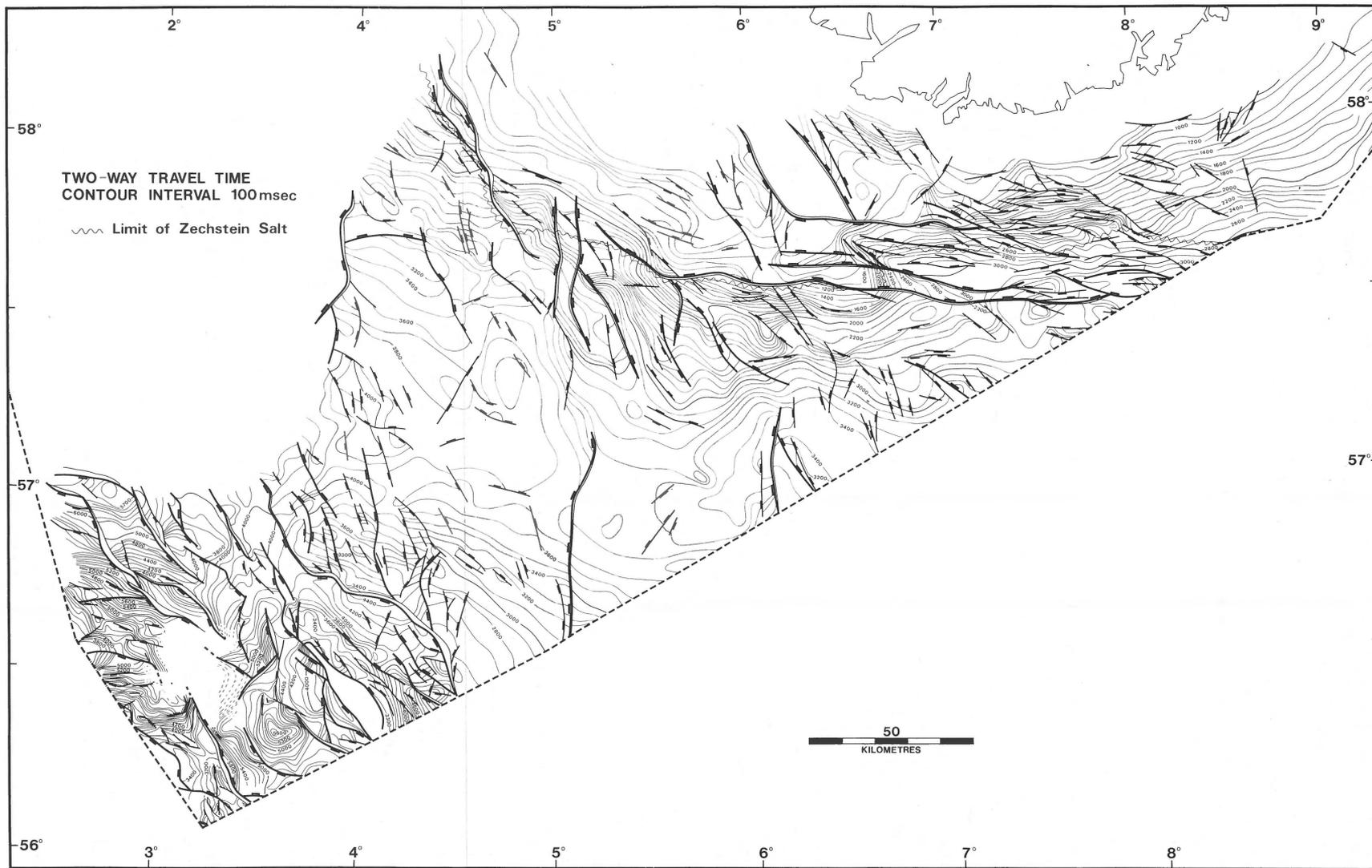


Fig. 2  
 Isochron map Base Zechstein.

Well information from the margins of the Central Graben indicates igneous activity during Rotliegendes, which may have been associated with post-orogenic rifting. From seismic sections crossing the Graben between the Mid-North Sea High and the Ringkøbing-Fyn High, it is evident that relatively thick Zechstein deposits accumulated. However, based on observations from the Norwegian area, it is difficult to determine whether the Central Graben initiated at this time, as proposed by W. ZIEGLER (1975).

### *Triassic*

The connection between the North-West European Permian basins and the Arctic seas was interrupted in Late Permian times, leading to the re-establishment of a continental depositional regime at the onset of the Triassic.

Within the southern Norwegian North Sea, both extensional rifting and subsidence of different depositional basins occurred during the Triassic. These tectonic movements reflect the initial rifting in the North Atlantic. The main structural trends were roughly north-south, including extensional rifting of the Central Graben and the establishment of new basins in the Norwegian-Danish Basin. Uplift and erosion led to accumulation of thick clastic sequences, the coarsest material being deposited in basins near the Norwegian mainland (Fig. 5b).

The structural evolution during the Triassic is well illustrated in the Egersund Sub-Basin area. Major faults bounding N-S trending basins seem to have had their main activity in Triassic times. This is evident for the fault limiting the Egersund Sub-Basin to the west, which shows strong growth fault characteristics. The tectonically controlled sedimentation gave rise to more than 1000 m of Triassic clastic deposits in the sub-basins. There are no indications of marine Triassic in the area. The prevalent coarse clastic supply indicates proximity to the source area. This suggests some tectonic activity throughout the period, which is also supported by contemporaneous igneous dike intrusions in the coastal area of West Norway (FAERSETH ET AL., 1975). The Hardegsen tectonic pulse, found to be of regional significance in the southern North Sea, may also have influenced the structural and sedimentological picture in the Norwegian-Danish Basin.

Both in the Norwegian-Danish Basin and in the Central Graben Triassic overburden and tectonic activity initiated salt movements which continued into Cenozoic times.

In the Central Graben, the thickness and facies distribution of the Triassic is not well documented. This is due to lack of deep wells in the Graben area as well as to rigorous halokinetic disturbances of Mesozoic sediments. However, seismic mapping indicates Triassic rocks extending into the area, and well data in the transition zone between the Graben and the Vestland Arch show hundreds of meters of Triassic rocks (Fig. 5d).

Concerning the formation of the Graben, the lack of data allows for different interpretations. One possibility is that the

Central Graben was developing in Permo-Triassic times along the NW-trending faults. The other possibility is that the Triassic north-south trend extended south into the Central Graben area and initiated the first transection of the Ringkøbing-Fyn High. In this case the NW-SE block faulting must be of Kimmerian age.

Tectonic activity is reflected in a marked intra-Triassic unconformity. Seismically, its areal extent is restricted to the north/northeastern flank of the Graben. This event, which most likely corresponds to the Hardegsen pulse, has locally affected considerably the topography.

### *Jurassic*

Within the study area, Lower Jurassic has been encountered southwest of the Vestland Arch and in the Egersund Sub-Basin. Most of the area was probably inundated in Early Jurassic times but it was subjected to later erosion. Although there is no clear evidence for particular rifting pulses, various unconformities occur in the Lower Jurassic.

An intensive tectonic activity seems to have accentuated the relief at the onset of Middle Jurassic. This Mid-Kimmerian phase, comprising several tectonic pulses, led to a massive uplift of the central North Sea region. The triple junction between the Central Graben, Viking Graben and Moray Firth became a major volcanic centre (P. ZIEGLER, 1981). Subsidiary igneous activity occurred in the Egersund Sub-Basin and on the coast of SW Norway. Tectonically, this led to an uplift and eastward tilting of the Vestland Arch. Its sediments were eroded and redeposited in the basins. However, the main source area for the deltaic and fluvial sequences, which accumulated in the subsiding basins, is supposed to have been the Fennoscandian Shield. These deposits are overlain by a shallow marine sand, which probably marks the onset of a major transgressive cycle at the transition into the Late Jurassic. In the south, seismic information indicates Middle Jurassic fault activity along the eastern flank of the Central Graben (Fig. 5e).

Throughout the rest of the Jurassic period, tectonic activity in the area seems to have been increasing. An interplay between transgressions and structural movements produced a series of unconformities in the west and has strongly influenced the sediment distribution.

*Norwegian-Danish Basin* – The development of the Egersund Sub-Basin into a significant depocentre is evident (Fig. 5b). The differential subsidence of this area indicates a reactivation of N-S trending basement faults along the Fennoscandian Border Zone. In addition, faults trending NW-SE have controlled the basin formation (Figs. 1 and 3). The direction of these faults corresponds to the trend of the Fjerritslev Fault. A wide range of complicated structural features is observed. These are strongly influenced by salt tectonics, but it is possible that strike-slip movements have contributed to the formation of the described fault systems. However, it is

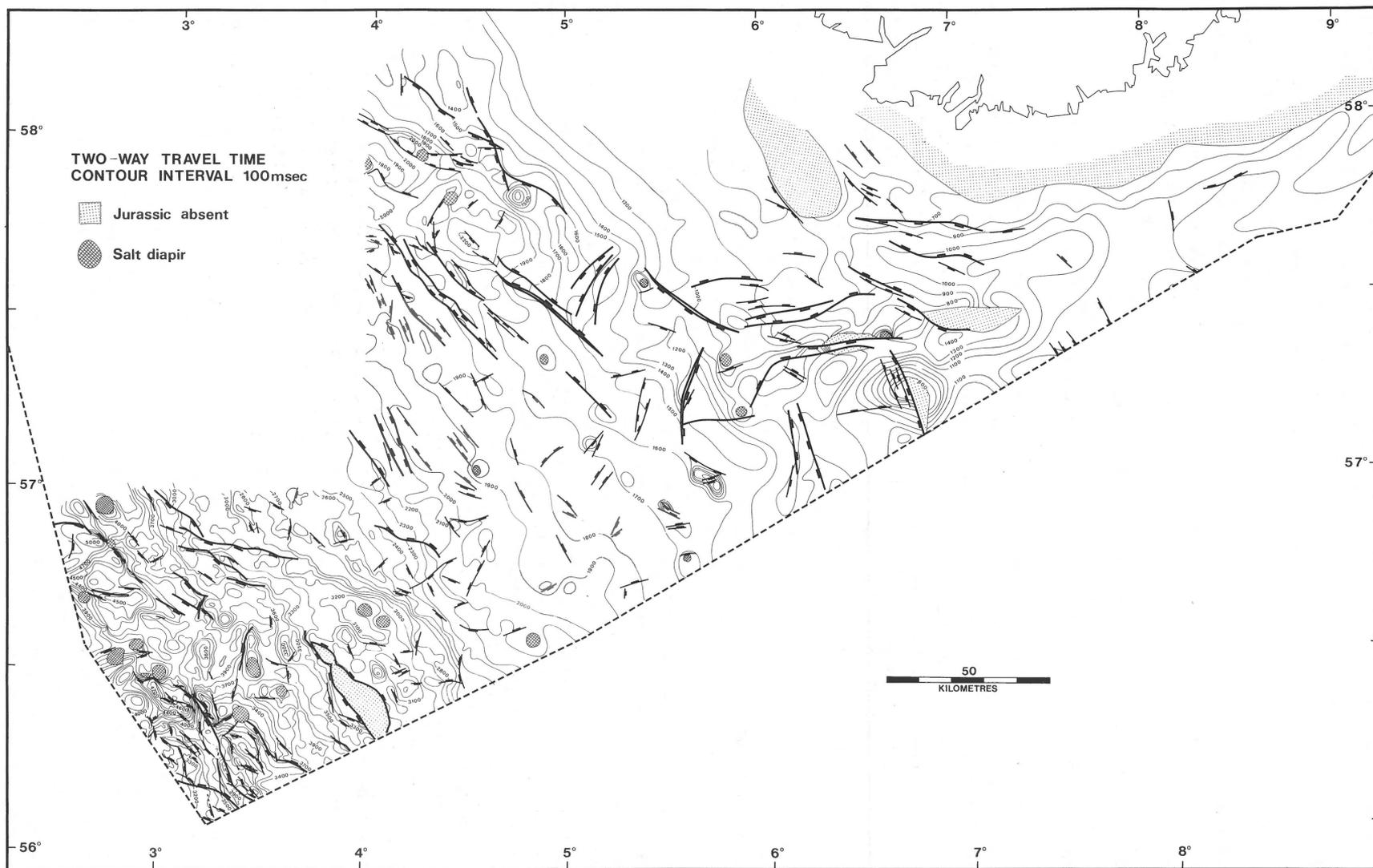


Fig. 3  
Isochron map Base Valanginian.

difficult to map the strength and character of these possible movements.

A continuous subsidence of the Egersund Sub-Basin area prevailed into Early Cretaceous times. Seismic data indicate sediment transport being mainly from the north and east.

The area north of the Fjerritslev Fault system developed into a WNW-ESE trending fault-bounded basin during Mesozoic times. Accelerated subsidence occurred during the Late Jurassic, whereafter no significant basin formation is observed (Fig. 5c).

The formation of these late Jurassic basins, adjacent to the Fennoscandian Border Zone, is related to post Mid-Jurassic tectonic activity along the Fjerritslev Fault Zone.

*Central Graben* – In the Central Graben, rifting and subsidence dominated throughout the Late Jurassic. Development of growth faults, indicating syn-sedimentary structural processes, occurred along the northeastern margin of the Graben. This is illustrated by thick sedimentary sequences on the downthrown side of step-like rotational fault-blocks, like the Hidra Fault Zone (Figs. 3 and 5d). The shallow marine sand/silt deposits were probably eroded from the uplifted pro-vent areas to the east. Further transgressions and subsidence led to the establishment of increasingly deep-water conditions in the Central Graben.

The Central Graben, south of 56° 30'N, will be discussed in some detail (Fig. 6). The general structure in the Central Graben is dominated by NW-SE trending fault blocks facing to the west. In the southern part this trend is broken by a more or less N-S trending set of faults (Figs. 2 and 5e), and along this crossing trend inversion movements have taken place in Late Jurassic and Late Cretaceous times.

The timing of the activity of the large NW-SE trending faults is uncertain because of lack of deep well data. However, well information and seismic mapping in the southern part of the Graben indicate the existence of a large Late Jurassic basin (Figs. 6 and 7). Upper Jurassic shales and sandstones reach up to 1000 m or more. This suggests important fault activity during the late Jurassic.

Inversion of parts of this basin was initiated in the Late Jurassic, partly along pre-existing faults. In the southwest, these inversion movements continued in the Late Cretaceous, and the result was the ridge shown in figures 3 and 4. It is proposed to call this inversion ridge the Lindesnes Ridge to distinguish it from the Dogger High, which is a basement high. As shown in figures 2 and 7, the basement high in the Norwegian sector is situated to the west of the Lindesnes Ridge.

Figures 3 and 6 show the structure of the Lindesnes Ridge as a combination of highs and lows arranged in a setting indicative for an overall dextral motion for the fault zone. A few wells along the ridge have bottomed in salt, suggesting that the structure was enhanced by salt movement. However, the salt is too deep-seated to justify an explanation of the Lindesnes Ridge as a simple salt-induced structure. A lateral fault

system with a dextral sense of shear may also be supported by the regional geological setting (Fig. 3). The Late Jurassic and Early Cretaceous basins within the Lindesnes Ridge may be matched with the basins west of its northern end.

The structure to the northeast of the Lindesnes Ridge (Fig. 6) is far less pronounced at the level of Top Jurassic, but it exhibits comparable inversion features, partly enhanced by salt movement. The timing of these features is similar, and this structure can be interpreted as a result of dextral strike-slip movements occurring at the same periods as in the Lindesnes Ridge.

### *Cretaceous*

A widespread major unconformity, giving rise to a distinct seismic reflector, is recognizable within large areas of the central North Sea (Fig. 3). Tectonic movements, referred to as the Late Kimmerian phase, accompanied with an eustatic fall in sea level, resulted in this prominent stratigraphic and lithologic boundary. From seismic data it is evident that rapid subsidence occurred along fault patterns, mainly established during preceding Jurassic movements.

Particularly in the west, in the Central Graben area, the Early Cretaceous sediment distribution reflects the presence of a significant ridge-basin framework existing throughout the period. This gave rise to thicknesses of more than 1000 m of clastic sediments in the subsiding areas, whereas the uplifted basin margins only show thin deposits (Fig. 5f). Minor sand accumulations related to the basin margins and the intra-basinal highs have been encountered.

In the Norwegian-Danish Basin and particularly in the Egersund Sub-Basin, the late Kimmerian movements did not produce any good seismic marker. In this area, thick clastic deposits indicate continuous sedimentation from Late Jurassic into Early Cretaceous. West of the Egersund Sub-Basin, a considerable thickness of clastic deposits was accumulated in the Sele High area indicating inversion during Cretaceous.

In general, the Late Cretaceous was a quiet period in the North Sea with accumulation of thick Chalk deposits (Fig. 4). However, within the study area, a number of Late Cretaceous unconformities have been recognized. From seismic data and well information, it is evident that inversion tectonics occurred in the Central Graben and along the Fennoscandian Border Zone.

Along the basement fault zone separating the Fennoscandian Shield from the Egersund Sub-Basin, a characteristic domal feature is observed (Figs. 5b and 8). It is partly faulted, showing an asymmetrical form and upthrusting away from the basin. Most likely the movement was a reverse rejuvenation of the old basement fault. Seismic and well information indicate that active inversion occurred during the Late Cretaceous. This has given rise to the thinning of the Chalk sequence, together with several hiatuses. The inversion tectonics seems to have come to an end in Early Tertiary times. These pulses correspond to the Laramide movements. The

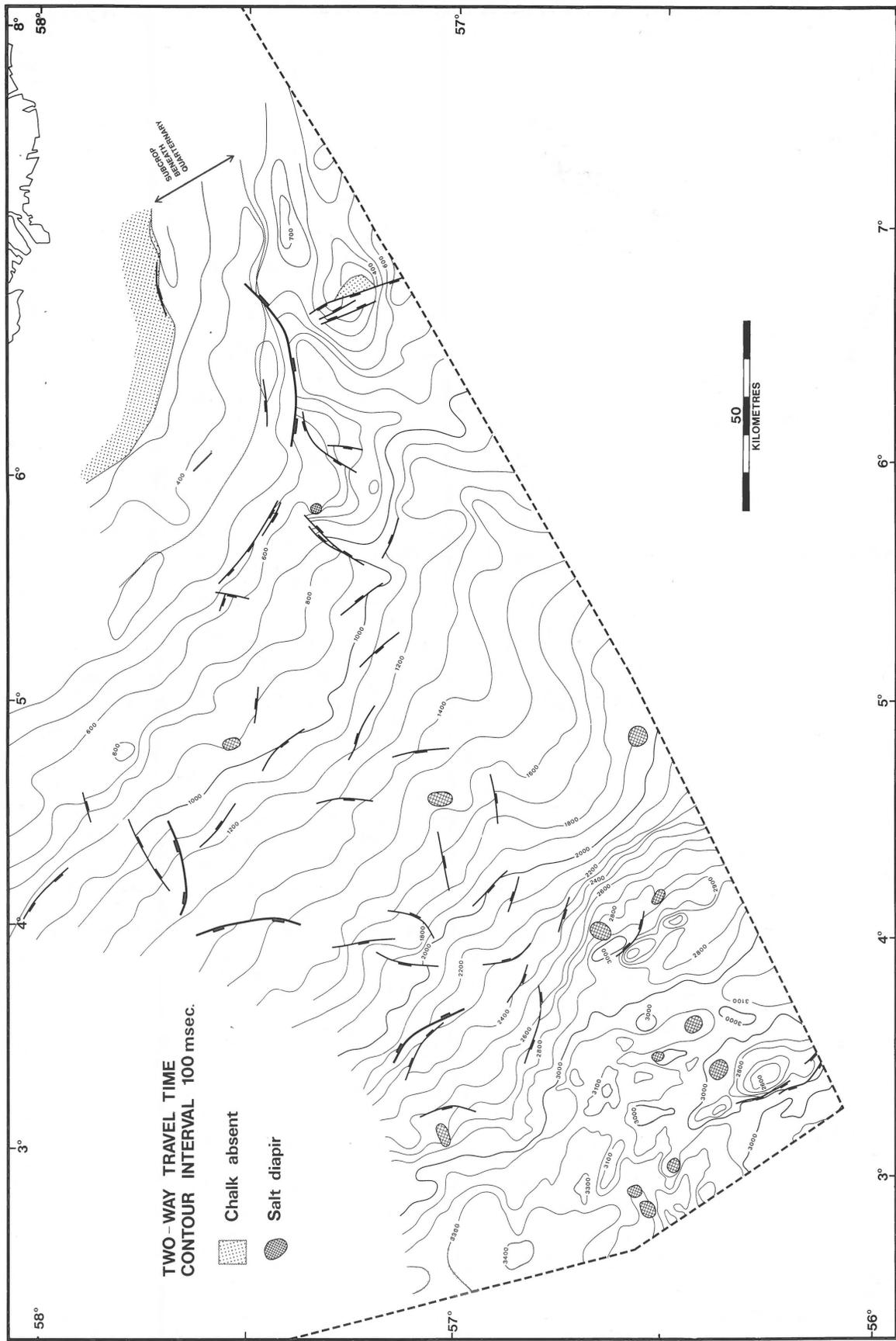
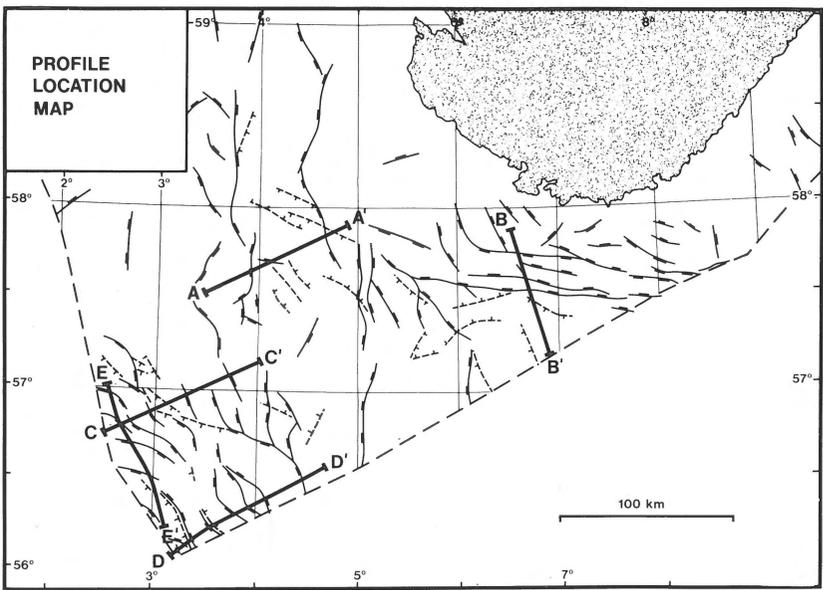


Fig. 4  
Isochron map Top Chalk.



- REFLECTORS:**
- ① MID MIOCENE
  - ② T. PALEOCENE
  - ③ T. CHALK
  - ④ B. CHALK
  - ⑤ B. VALANGINIAN
  - ⑥ INTRA JURASSIC
  - ⑦ T. TRIASSIC
  - ⑧ T. ZECHSTEIN
  - ⑨ B. ZECHSTEIN

Fig. 5a  
Profiles in south and southeastern Norwegian North Sea.

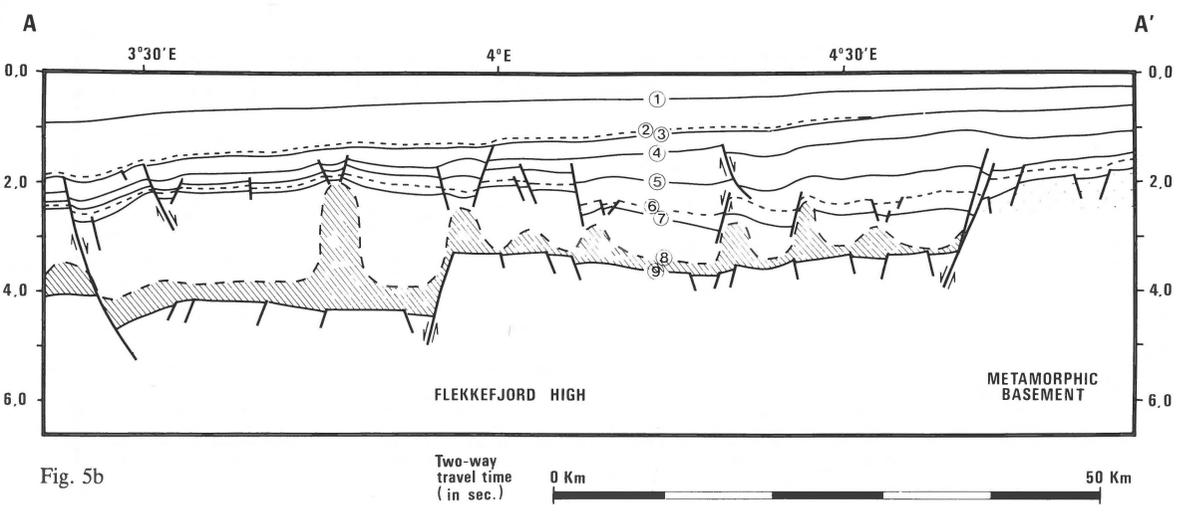


Fig. 5b

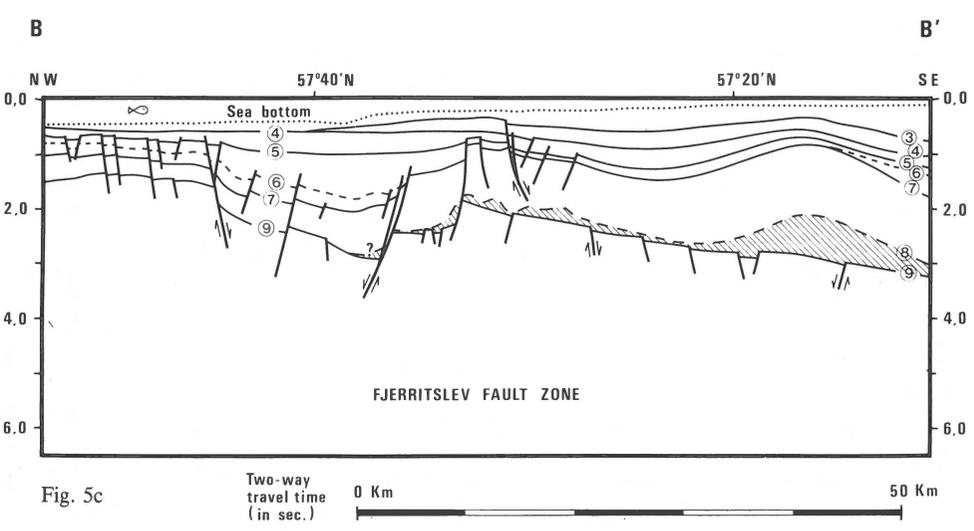
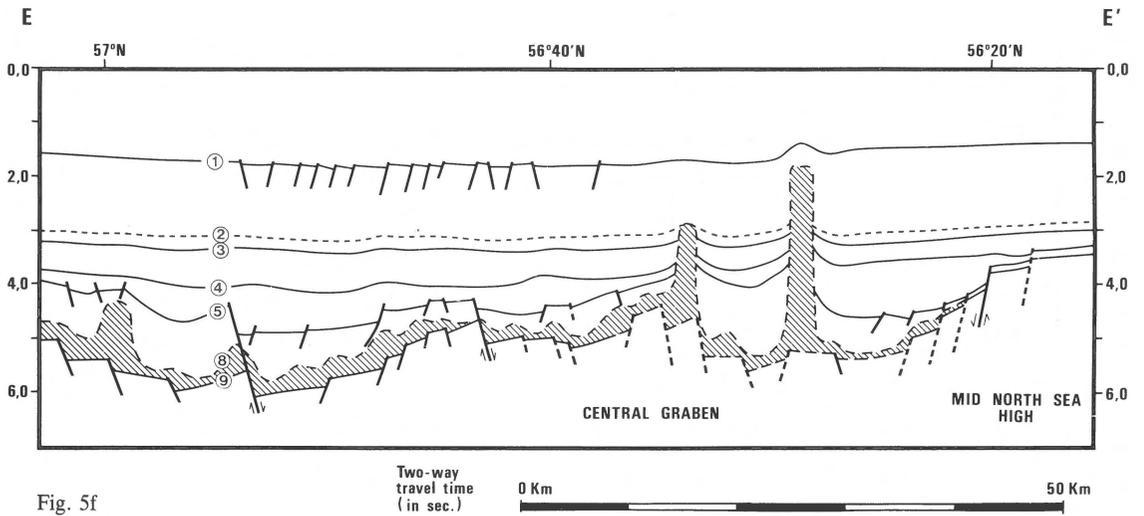
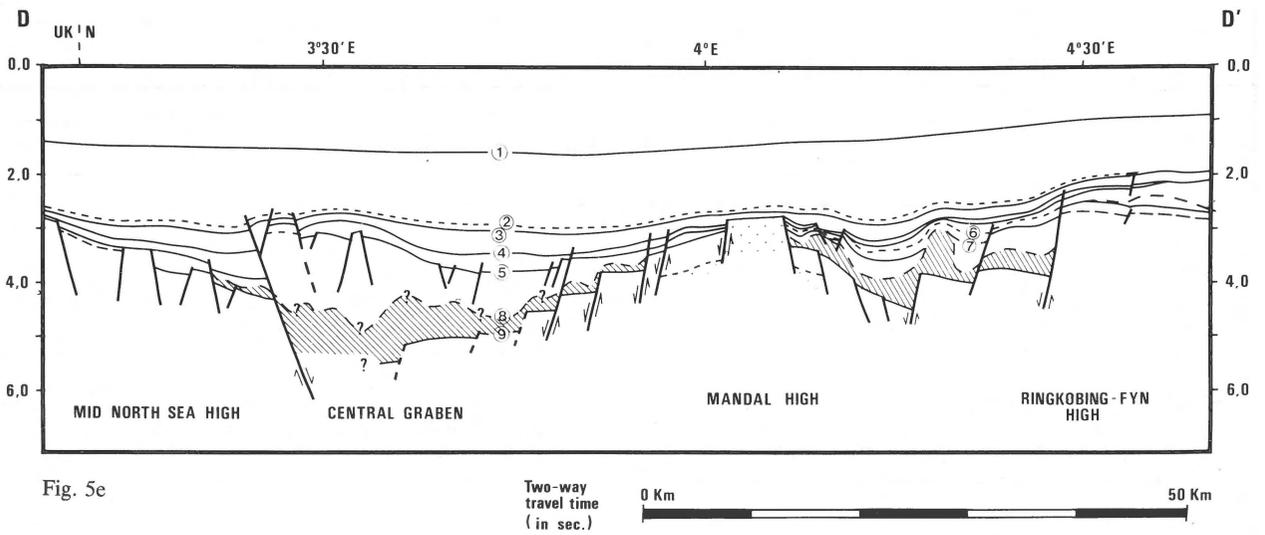
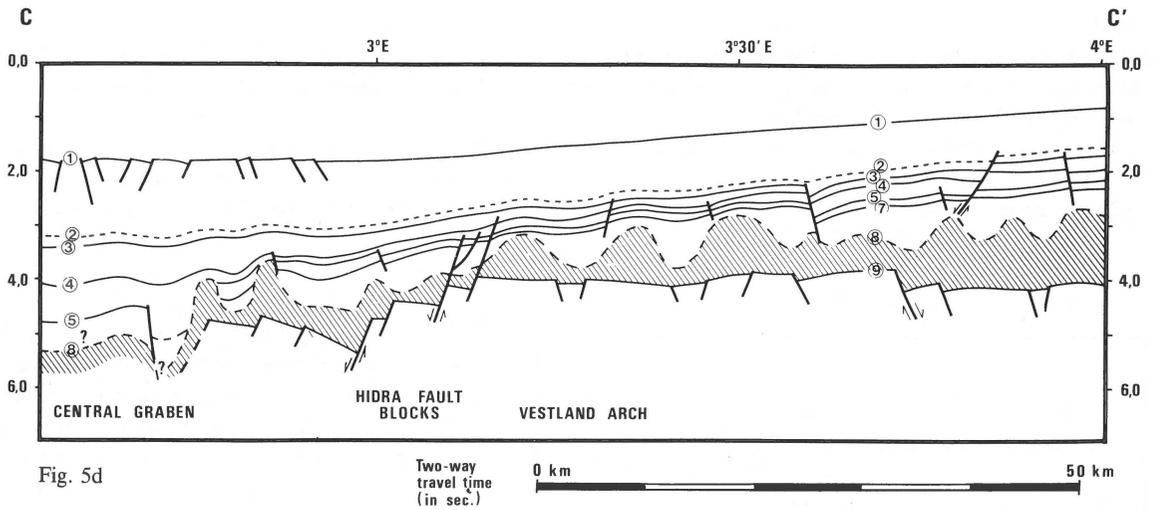


Fig. 5c



observed features may also indicate that strike-slip movements have contributed to the structural evolution. The seismic interpretation indicates that inversion characteristics are related to the Fjerritslev Fault system and to the region north-west of the Egersund Sub-Basin. Here, uplift of basement blocks accompanied by extensive erosion of the Chalk Group indicates active tectonic movements.

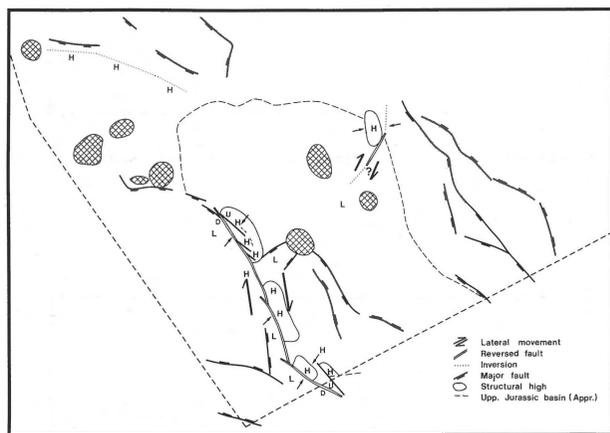


Fig. 6  
Central Graben – Tectonic sketch map.

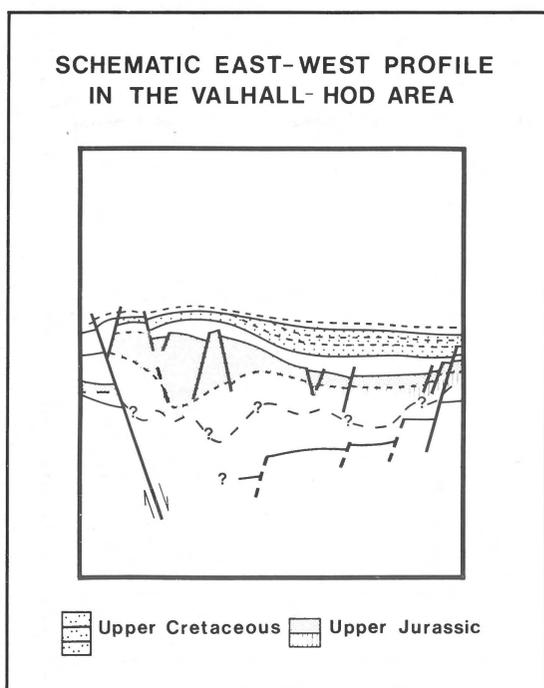


Fig. 7  
Schematic east-west profile in the Valhall-Hod area.

In the Central Graben, inversion tectonics continued in pulses along some of the faults during the late Cretaceous (Fig. 6). Especially along the Lindesnes Ridge, this uplift caused considerable erosion (Fig. 7). Abundant well data and seismic mapping indicate that the main pulses took place in Coniacian and Maastrichtian times. This corresponds to the 'Intra-Senonian' phase of P. ZIEGLER (1981).

### Tertiary

The Chalk deposition persisted into the earliest Tertiary. Paleocene rifting pulses led to accelerated subsidence of the Central Graben. This was accompanied by uplift of the Graben flanks, and subsequent erosion and redeposition of older sediments. It was followed by a return to a clastic depositional regime including progradational deep-water sand/shale sequences. Lower Tertiary sand deposits have also been mapped in the Egersund Sub-Basin area. A widespread tuffaceous interval in the study area reflects the opening of the Atlantic Ocean.

The rest of the Tertiary was characterized by a continuous subsidence and accumulation of thick clastic sequences, in excess of 3000 m in the Central Graben.

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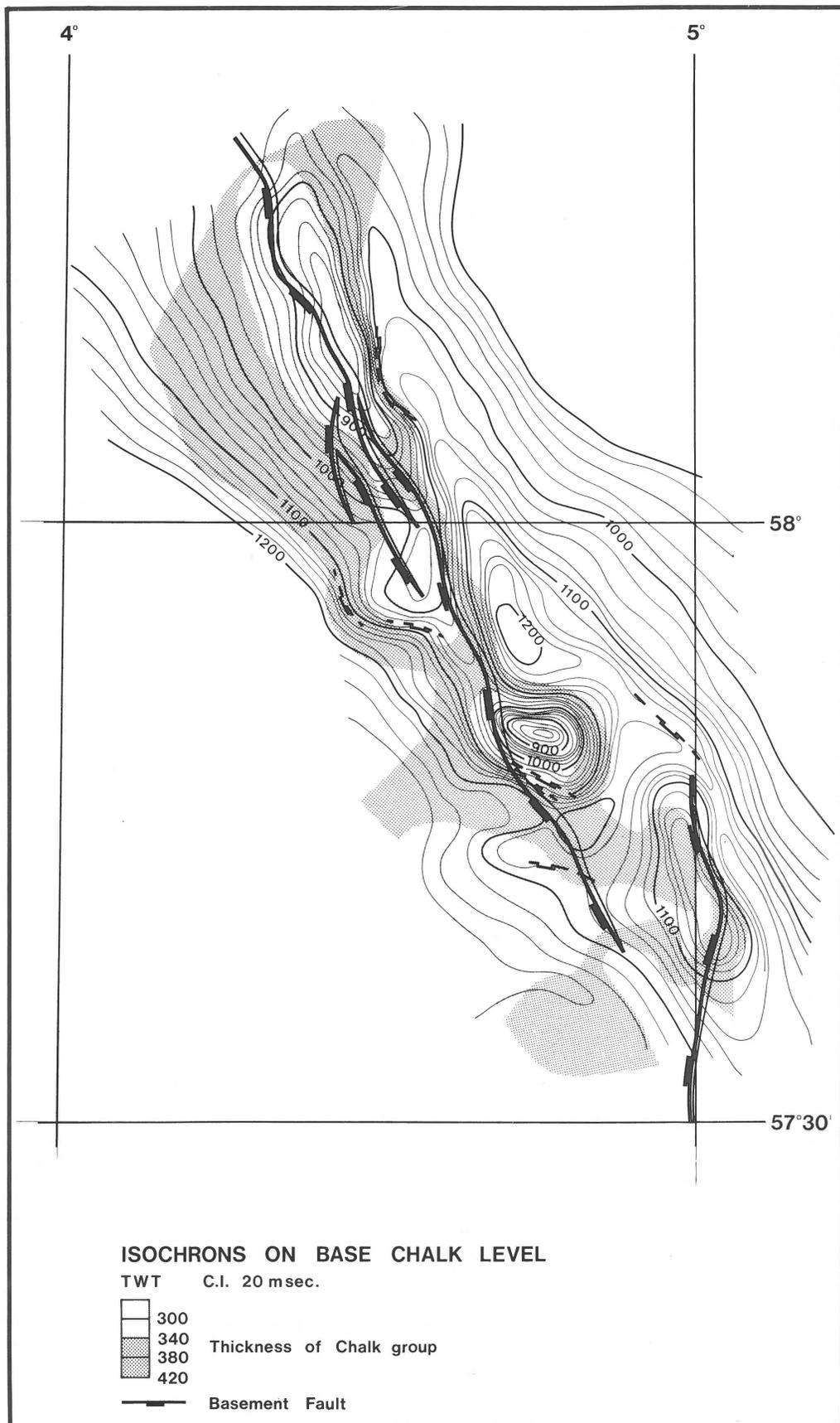


Fig. 8  
Inversion tectonics along the  
Fennoscandian Border zone.