Regional Cenozoic uplift and subsidence events in the southeastern North Sea

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Abstract

The Paleocene topography of the Fennoscandian Shield is indicated by outbuilding towards the Central Trough and the Ringkøbing-Fyn High. From Eocene until Pliocene time three events of relative vertical movements are indicated by changes in outbuilding directions and reflection termination patterns in the central North Sea. The first event of uplift was in the Eocene and resulted in relative uplift of the Mid North Sea High and contemporary subsidence east of it, indicated by a change in outbuilding from north to west. A second event of uplift is indicated to the north of the study area at the Eocene-Oligocene boundary by renewed southward outbuilding in the Norwegian-Danish Basin. In Miocene until Early Pliocene time a relatively stationary, almost east-west striking, basin margin was probably located to the north along the Tornquist Zone as indicated by the continued outbuilding towards the Ringkøbing Fyn High . A third event of relative uplift is indicated east of the study area by changes in the Pliocene outbuilding pattern. After the first event of uplift it appears that the deepest parts of the Eocene North Sea Basin was located more easterly than the deepest parts are today. Apparantly the two latest uplift events north and east of the study area were related to movements of, or along the Tornquist Zone or to regional uplift of the Fennoscandian Shield finally resulting in the present-day configuration of the North Sea.

Introduction

This study focus on Tertiary outbuilding directions and subsidence/uplift patterns in the Danish North Sea and adjacent areas. The results are based on seismic interpretation carried out during the Cenos Project[1] (Michelsen et al., in prep). The database comprises more than 20000 km of multichannel reflection profiles (Fig. 1). The results of the seismic interpretation is documented in Jordt (in prep.).
Several structural elements within the study area (Fig. 1) are of importance for the Tertiary outbuilding. Among these are: the Norwegian-Danish Basin, the Central Trough, the Mid North Sea High and the Ringkøbing-Fyn High.
Sequences are defined relative to a full cycle of relative change of onlap, and internally by a backstepping and a forestepping system. Progradation is used to indicate outbuilding directions. Seismic reflection termination maps are used to indicate the palaeo-geometry of the basin and events of vertical movements.

Sequence stratigraphic method

The sequence definition is related to a full cycle of the controlling parameter (Surlyk et al., 1993). This sequence definition focus on observations in the seismic sections and is therefore, of greater relevance than sequence definitions based on different types of hiatal surfaces. The controlling parameters are reflection terminations against the sequence boundaries and internal reflection geometry. Thus, a sequence is present if onlap on the lower sequence boundary can be followed from the basin towards the margins and fol-

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[1]Cenozoic North Sea Study, Aarhus University, Denmark

lowed back to the basin again along the upper sequence boundary. Often such a sequence is comprised of a backstepping and a forestepping system, characterized by the internal reflection geometry (Fig. 2).

In the Norwegian-Danish Basin, we have mapped a lowermost Oligocene sequence that can be subdivided into a backstepping and a forestepping system separated by a maximum flooding surface (Fig. 2). The lower sequence boundary is characterised by parallel reflections with onlap indicated farther northward. The upper sequence boundary is characterised by truncation below and by onlap above. Also a topographic low, comparable to the erosional valley cf. Vail (1987), is seen at the top of the sequence. A full cycle of relative change of onlap, defining this sequence, is indicated by internal reflection geometry and by reflection terminations against lower and upper sequence boundary.

A more typical North Sea sequence from the lowermost Miocene is shown in Fig. 3. It is charaterized by onlap against the upper and lower sequence boundaries and by subtle toplap. The progradation of the sequence appears as basinward migration of subunits outlined by internal reflections. In this case the sequence definiton is based on the recognition of a full cycle of relative change of onlap. Although different, both sequences are adequately defined by the sequence definition proposed by Surlyk et al., (1993)

Near the limit of the seismic resolution it may be impossible to distinguish between interference patterns that look like reflection terminations and geologically significant reflection terminations. To overcome this problem, reflection terminations against the lower sequence boundaries are mapped regionally to find a consistent pattern. In this way we found for all boundaries regionally coherent areas characterized by either onlap, downlap or reflections parallel to the boundary. In all cases outbuilding was from the onlap area towards the downlap area.

The sediment supply may have been perpendicular or parallel to the coast during deposition. Sediment supply in a fluvial dominated delta is mainly perpendicular to the coast, whereas, coast parallel sediment transport is the dominant process between deltas. In both cases, if the supply of sediment along the coast is greater than the erosion rate, then the coastline will move seaward (Bjørlykke, 1989). Thus outbuilding observed on seismic data does not directly indicate source or provenance areas.

Downlap and onlap reflect the palaeo-topography of the basin floor during deposition (Mitchum et al., 1977). On a regional scale, it is suggested that coherent regions with onlap are located landwards and updip relative to downlap areas. Therefore, it is assumed that the boundary separating these areas shows the approximate strike direction of the basin margin from which outbuildning of the overlying sequence took place. This means that reflection-termination maps combined with outbuilding directions can be used to indicate the palaeo-geometry of the basin.

The coherent areas with onlap or downlap are generally defined in the entire study area for the mapped sequences. It is therefore suggested, that the observed regional changes in the reflection termination configuration and the suggested strike of the basin margin were caused by regional changes in the geometry of the basin, and probably indicate variations in the pattern of relative vertical movements.

Outbuilding patterns

Isopach and seismic reflection termination maps for seven sequences representing the time from Late Paleocene to the Quarternary are used to indicate outbuilding patterns. The dating of the sequences (Fig. 4) are from Michelsen et al., (in prep).

The Cenozoic sediment distribution in the eastern North Sea appears related to older structural elements (Fig. 1). It is shown below that events of vertical movements influenced the Norwegian-Danish Basin to the north and the Ringkøbing-Fyn High to the east. The Tornquist Zone (Pegrum, 1984) separates these structural elements from Fennoscandia To the west the Mid North Sea High was also affected by uplift. The Northwest German Basin to the south appears to be continuously subsiding in the entire Cenozoic era. The Central Trough to the west influenced the sediment dispersal for several sequences.

In the Late Paleocene and Early Eocene outbuilding took place in the Norwegian-Danish Basin mainly towards the south and southwest (Fig.5). In the later part of this period, sediments probably also built out from the Mid North Sea High as Late Paleocene uplift and eastward tilting of the Shetland Platform resulted in development of an eastward-directed drainage pattern (Ziegler, 1982). The seismic facies map shows that the areas to the north and northeast and later also the areas to the west comprised topographic highs relative to the Central Trough and the Ringkøbing-Fyn High.

From Middle Eocene times outbuilding from the west dominated (Fig. 6A). The Lower Eocene outbuilding in the Norwegian-Danish Basin is followed by starved sedimentation indicated by pinch out of overlying sequence. This marked change in reflection stacking pattern and outbuilding direction may indicate uplift to the west and relative subsidence of the Norwegian-Danish Basin and probably also the Ringkøbing-Fyn High.

A major shift in the outbuilding directions again took place at the Eocene-Oligocene transition (Fig. 6B). The two Lower Oligocene sequences shows outbuilding from north. Onlap against the lower sequence boundary shows that the Oligocene sediments were deposited on a southward inclined surface indicating that subsidence in the Norwegian-Danish Basin was succeeded by uplift. It is suggested that the pronounced progradation of the Lower Rupelian sequence may indicate that the sediments was deposited near a prograding shoreline possibly established by uplift along the Tornquist Zone. The two overlying Chattian sequences show weak progradation from northeast.

In the latest Oligocene and Early Miocene outbuilding was from the Norwegian-Danish Basin towards the Central Trough and the Ringkøbing-Fyn High (Fig. 7). The location of the depocenter is highly influenced by the underlying Oligocene deposits. The northeast- and eastward thinning and pinchout of the two Lower Miocene sequences in the Norwegian-Danish Basin is probably due to sediment starvation or bypass.

The seismic facies map indicates that the Middle Miocene - Quarternary sequence progrades towards the Central Trough and towards south across the Ringkøbing-Fyn High (Fig. 8). This reflection termination pattern shows south- and southeast-ward inclination of the basin margin north of the study area, and indicates the presence of an uplifted Fennoscandian Shield. In the German and Dutch areas only westward progradation is observed. The integrated study of sequence 7.0 shows that the two Middle -Upper Miocene and Lower Pleistocene sequences (i.e. sequence 7.1 & 7.2) prograde to the south, while the overlying sequences show westward progradation (Michelsen et al., in prep.). This change from southward to westward outbuilding probably took place in Early Pliocene times. It is suggested that this shift in outbuilding directions from south to west was caused by a change in the basin geometry to the east as a result of uplift. Possibly the Ringkøbing-Fyn High was affected by this uplift event, as indicated by the direction of Late Pliocene and Quarternary progradation.

History of relative vertical motion.

Three main events of relative vertical motion during Eocene until Pliocene time is indicated by outbuilding directions and reflection termination patterns (Fig. 9). These events probably resulted in marked changes in the basin geometry.
- A topographically high area was present north of the study area in Late Paleocene - Early Eocene and in Oligocene - Late Miocene times.
- The Mid North Sea High was uplifted contemporary with relative subsidence of the areas to the east in Middle - Late Eocene times. This probably resulted in an eastward movement of the deepest parts of the basin relative to the present-day situation. It appears also that the North Sea Basin was extended to the northeast, as no marginal facies of these sequences has been found to the North and East
- A marked shift in the pattern of vertical motions took place at the Eocene-Oligocene transition due to uplift north and northeast of the study area. Possibly this event resulted a basin-margin striking parallel to the Tornquist Zone
- A new episode of uplift probably took place east of the study area in the Late Miocene - Early Pliocene, resulting in change from southward to westward progradation across the Ringkøbing-Fyn High. It appears that this event may have resulted in a basin configuration very similar to the present-day North Sea.

The Tornquist Zone and the Mid North Sea High may have been among the most important structural elements during the Cenozoic era in relation to the history of vetical motions in the study area. The western margin of the North Sea Basin was probably located along the Central Trough in Middle - Late Eocene, and possibly the Mid North Sea High constituted a prominant high even in Pliocene times. To the north and east the location of the basin-margin may have been controlled by movements along the Tornquist Zone as indicated by the reflection terminations. Possibly the two latest uplift events were focused along the Tornquist Zone (Fig. 9), as it is a fundamental structural lineation representing the southwestern margin of the Fennoscandian Precambrian basement platform, and characterised by complex, often rejuvenated faulting and frequently by tectonic inversion (Pegrum, 1984).

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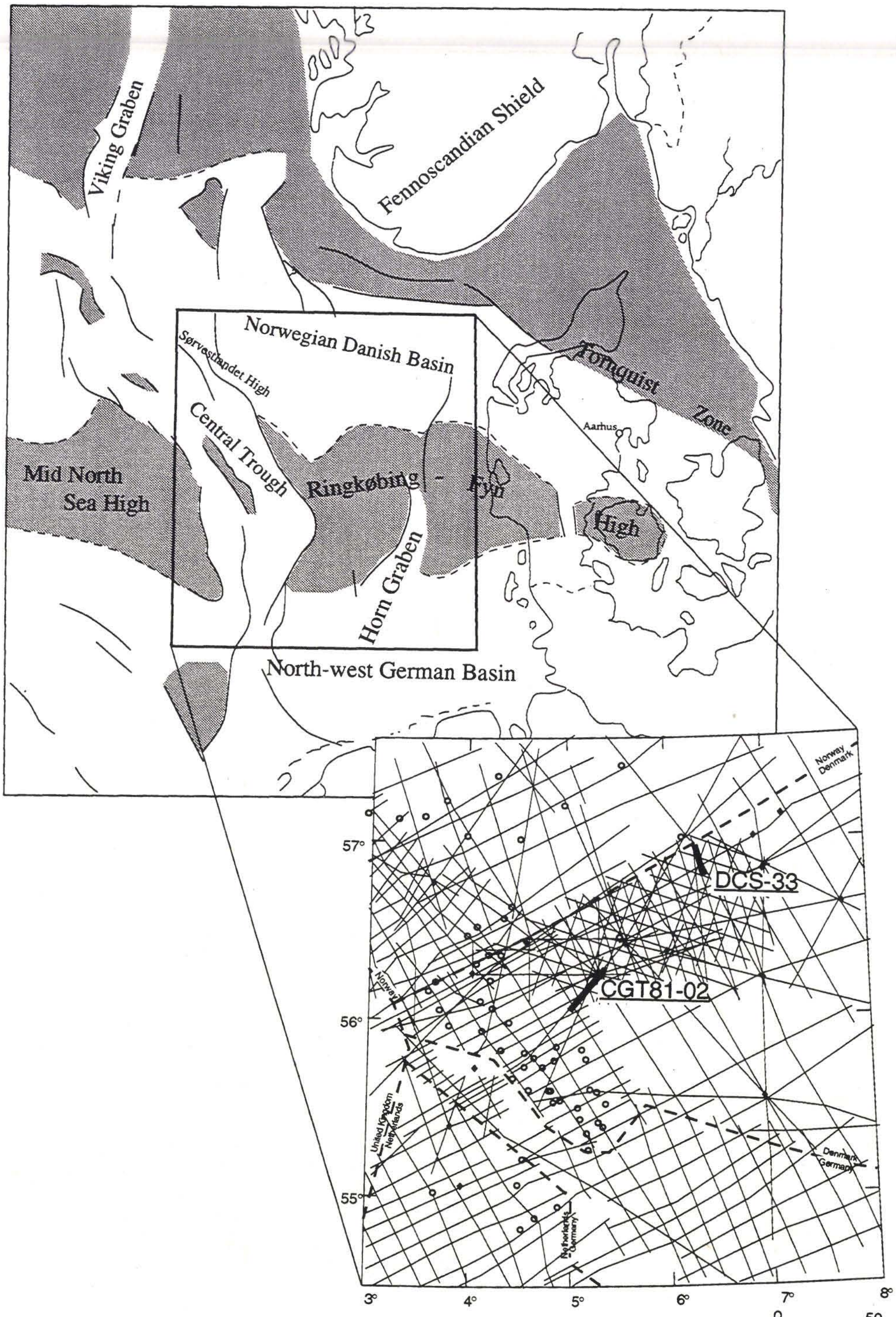

Fig. 1 Regional map showing the main pre-Cenozoic strutural elements in the North Sea and the location of the study area. Platform areas and highs are shaded. The location map shows the seismic database and the wells used in the Cenos study. Bold lines indicate locations of the seismic examples in Figs 2 and 3.

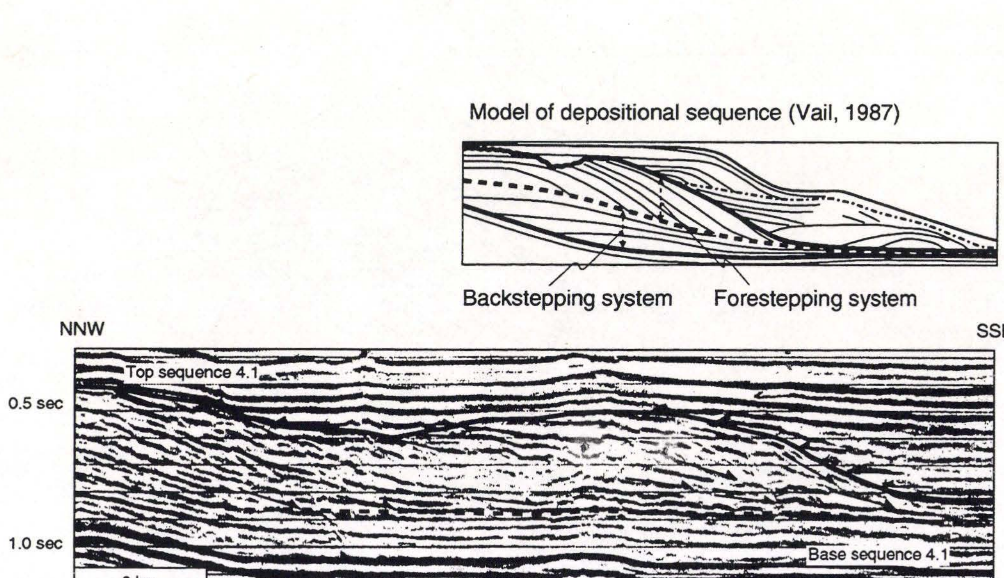

Fig. 2 Sequence 4.1, Lower Rupelian, shown on the seismic section DCS-33. The location of the profile is indicated in Fig. 1.

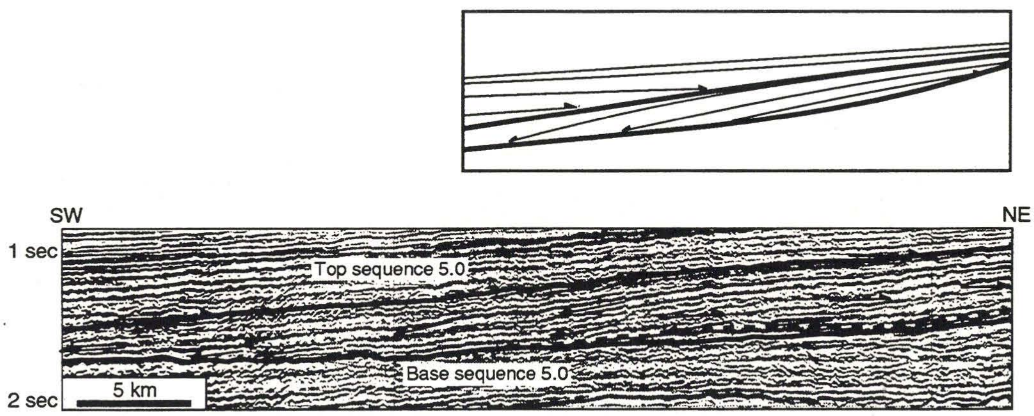

Fig. 3 Sequence 5.0, uppermost Oligocene- Lower Miocene, shown on the seismic section CGT81-02. The location of the profile is indicated in Fig. 1.

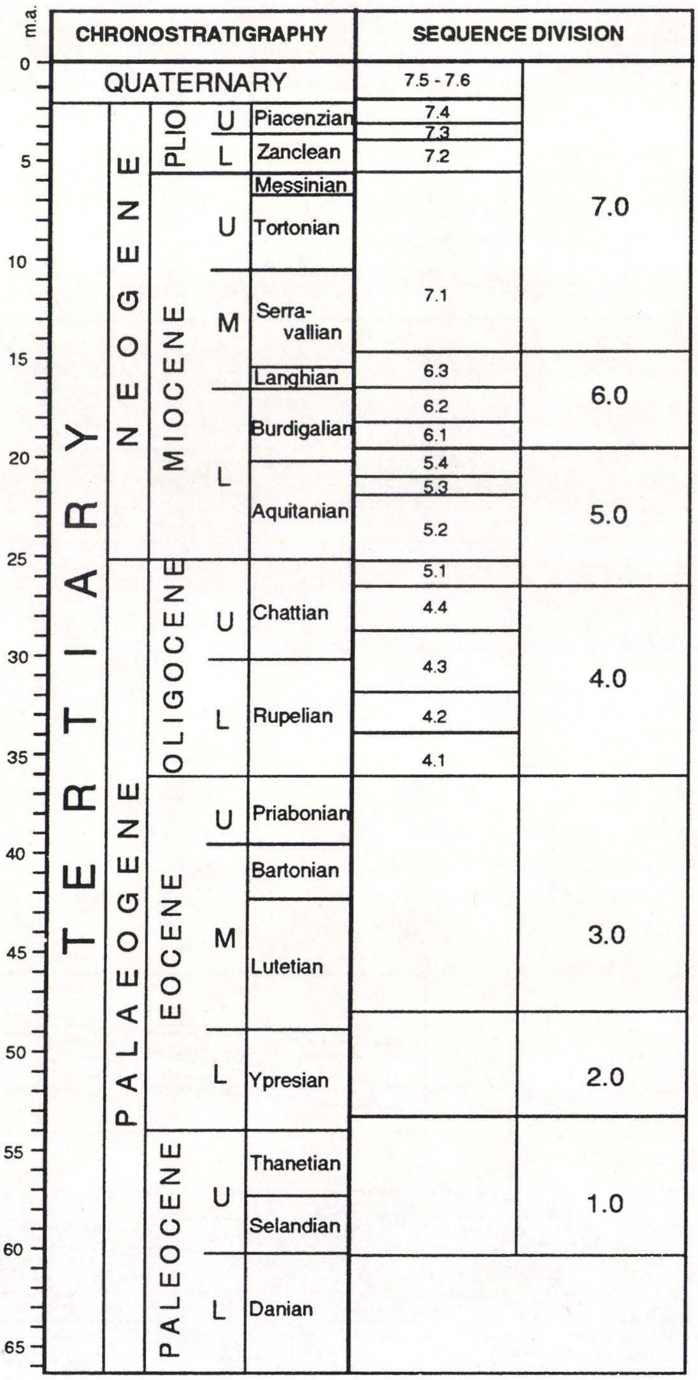

Fig. 4 Chronostratigraphic correlation of all the sequences mapped in the Cenos study. Isopach and reflection termination maps are shown for the sequences 1.0 - 7.0 in Figs 5-8.

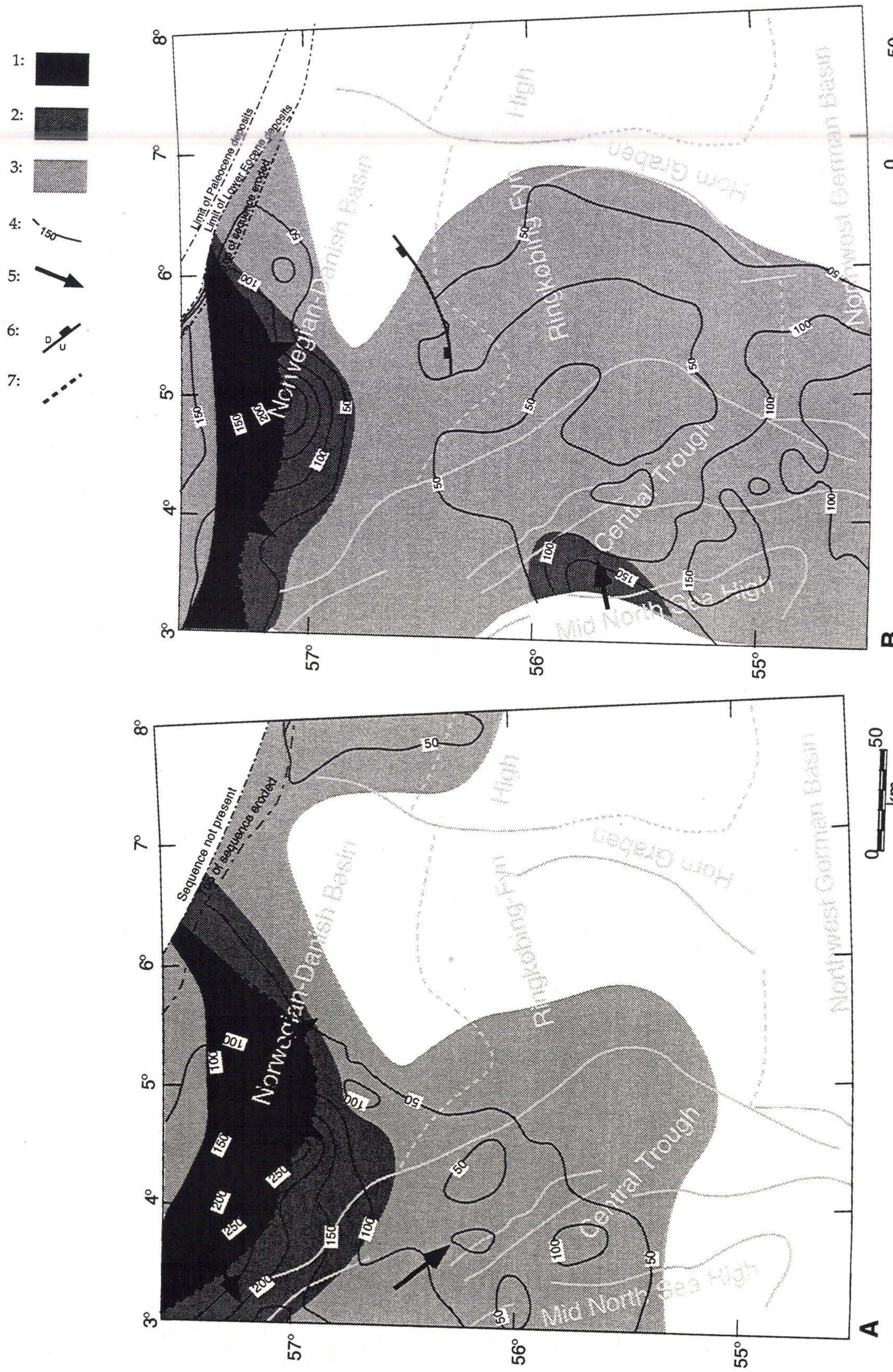

Fig. 5 Isopach and reflection termination maps of (A) Sequence 1.0, Upper Paleocene, and (B) Sequence 2.0, Lower Eocene. 1: area with observed onlap; 2: area with observed downlap; 3: area with reflections parallel to lower sequence boundary; 4: contour line in ms, contour interval 50 ms; 5: direction of progradation; 6: fault trace at lower boundary; 7: observed boundary between areas of onlap and downlap.

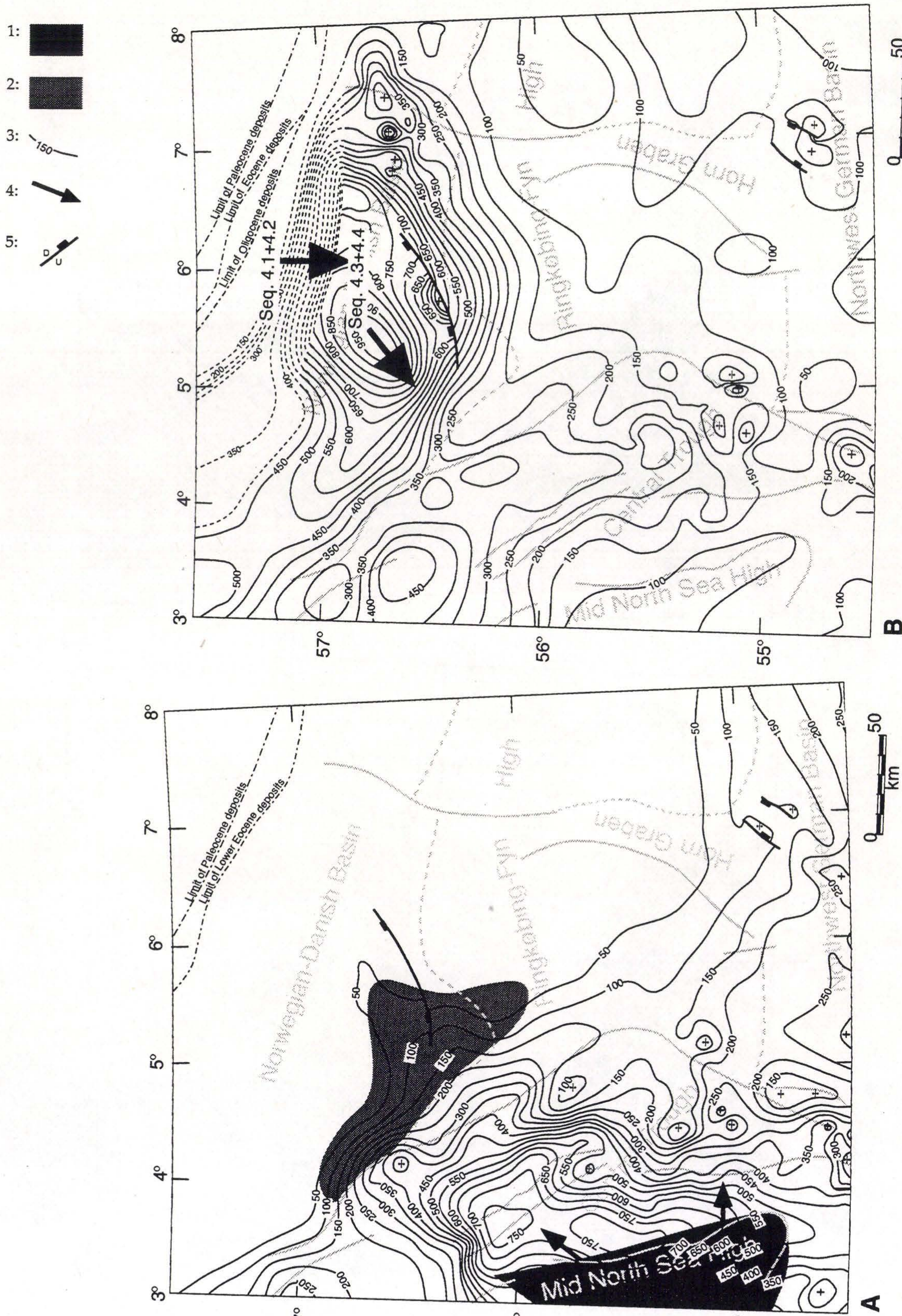

Fig. 6 Isopach and reflection termination maps of (A) Sequence 3.0, Middle-Upper Eocene, and (B) Sequence 4.0, Oligocene. 1: area with observed onlap; 2: area with observed downlap; 3: contour line in ms, contour interval 50 ms; 4: direction of progradation; 5: fault trace at lower boundary.

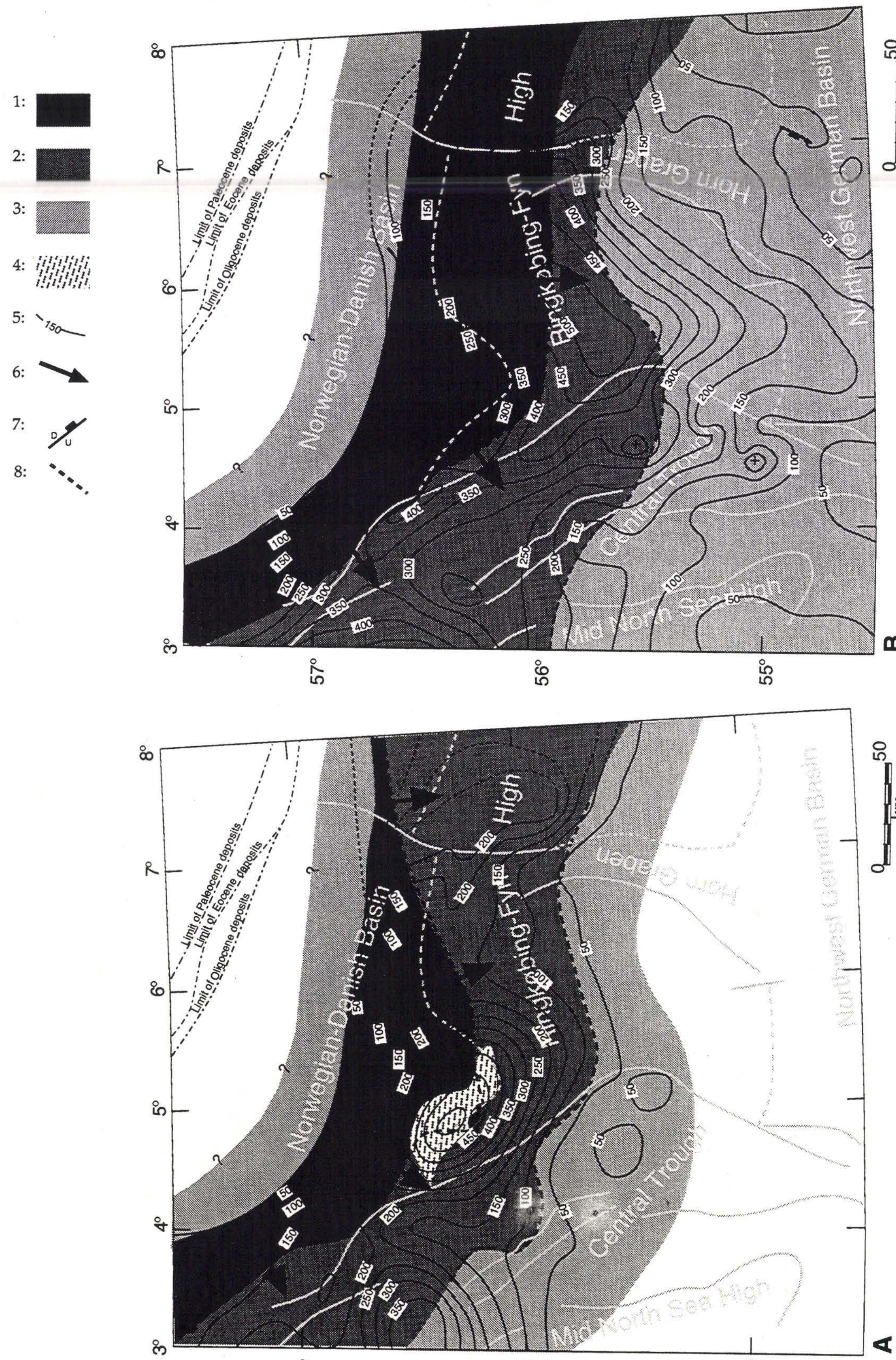

Fig. 7 Isopach and reflection termination maps of (A) Sequence 5.0, Lower-Middle Miocene and (B) Sequence 6.0, upper Lower- lower Middle Miocene. 1: area with observed onlap; 2: area with observed downlap; 3: area with reflections parallel to lower sequence boundary; 4: mounded seimic unit; 5: contour line in ms, contour interval 50 ms; 6: direction of progradation; 7: fault trace at lower boundary; 8: observed boundary between areas of onlap, downlap and parallel reflections.

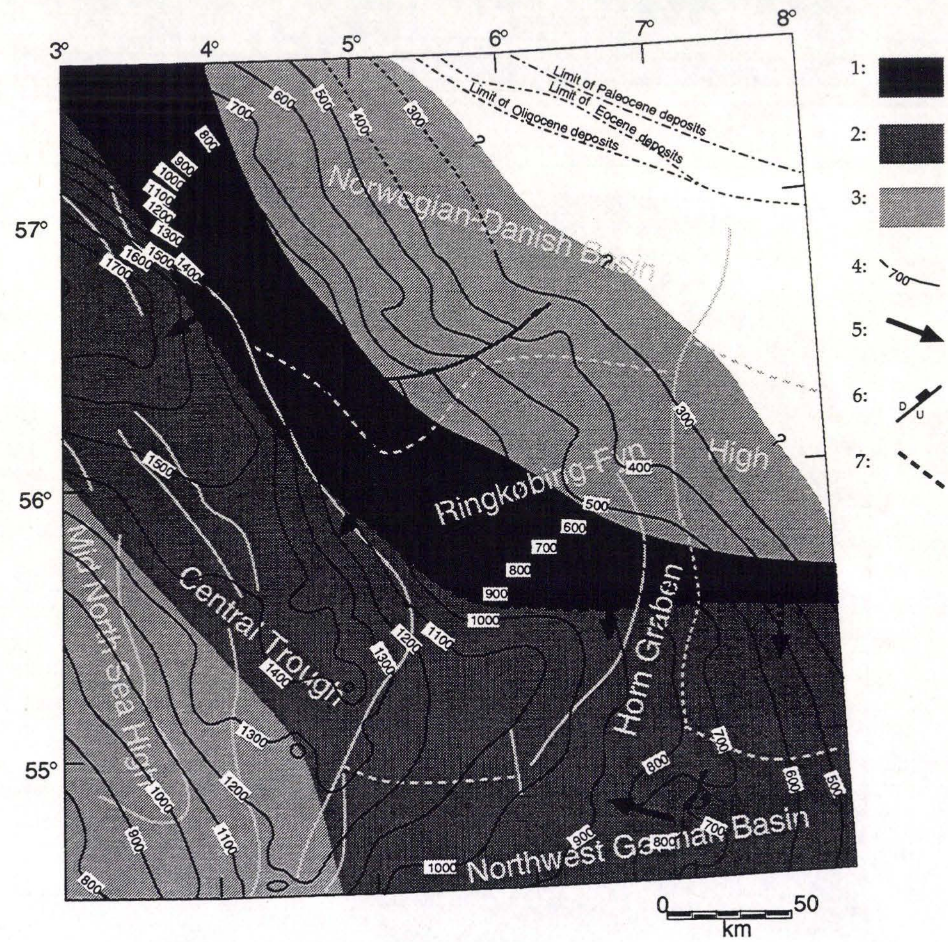

Fig. 8 Isopach and reflection termination map of Sequence 7.0, upper Middle Miocene - Quarternay. 1: area with observed onlap; 2: area with observed downlap; 3: area with reflections parallel to lower sequence boundary; 4: contour line in ms, contour interval 100 ms; 5: direction of progradation; 6: fault trace at lower boundary; 7: observed boundary between areas of onlap, downlap and parallel reflections.

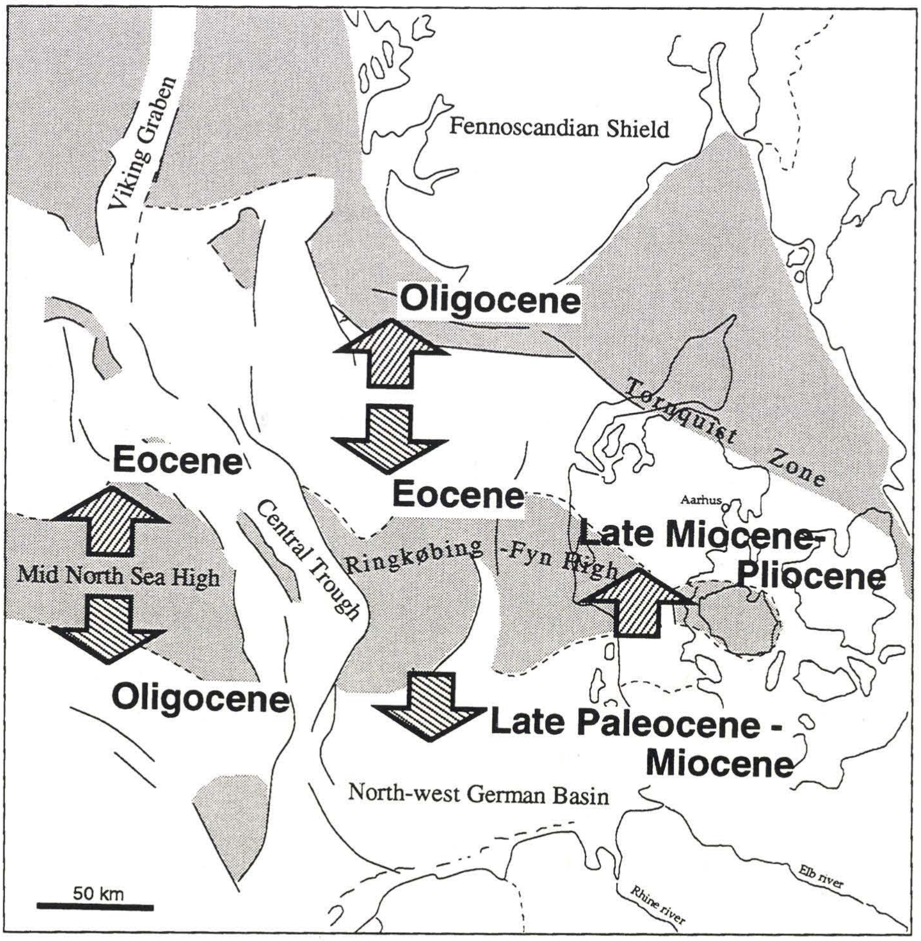

Fig. 9 Regional map indicating timing and location of uplift/subsidence during the Tertiary. Arrows indicate direction of relative vertical movement.