Origin of a deep buried valley system in Pleistocene deposits of the eastern central North Sea

Inger Salomonsen

Abstract

In the North Sea, the sedimentary development of the late Tertiary and early Quaternary was dominated by deltaic sedimentation in a fast subsiding basin. During the Pleistocene, pronounced climatic changes affected the sedimentation of the area and progradation of the delta systems ceased. The Middle and Upper Pleistocene sedimentary successions consists of alternations of marine and fluvial deposits, partly reworked during glacial periods. Seismic records from the Danish sector of the North Sea reveal numerous deep incisions cut down from various levels of the Middle and Upper Pleistocene successions. These incisions are concluded to form a pattern of buried valleys. Detailed seismic stratigraphic analysis shows the occurrence of various internal unconformities within these buried valleys. It is concluded that the valleys originate from a river system developed in periods of repeated sea-level changes. Fluvial erosion during glacial sea-level lowstand and glacial meltwater action is proposed to have been responsible for the origin of the valley system. Thus, in Middle and Upper Pleistocene glacial periods drainage and associated sediment transport occurred from Northwest and Central European land areas via a presently buried river system in the southeastern North Sea towards a depositional basin north and northwest of the Danish North Sea sector.

Introduction

During the Miocene, Pliocene and the Early Pleistocene, deltas from northwest European rivers prograded towards the west and northwest from present-day North European land areas towards the North Sea. Here they formed one large delta system. The drainage from the North German and the Baltic areas took place through a Baltic river system. In connection to these rivers a well developed delta was build (Kay, 1993). During the upper Miocene the depocentre moved northwards from the Dutch land area to the southern North Sea area. Sediments transported by the Palaeo-Rhine were deposited in another delta, south of the Baltic river delta. During the Pliocene the depocentre for this delta moved northwestwards following the axis of the Central Trough (Cameron et al., 1987; Zagwijn, 1989; Kay, 1993).

In the eastern North Sea area, the supply of sediment came mainly by the Baltic rivers (Gibbard, 1988). In the beginning of the Early Pleistocene, in the Praetiglian, the delta developed in front of these rivers prograded further westwards. Sedimentation in shallow marine environment was prevalent at that time in the easternmost area.

Deposits from the Baltic rivers can be traced in the North Sea up to the Tiglian stage by virtue of their mineralogical composition (Gibbard et al., 1991). In the same period, a Proto-Baltic basin developed, causing drainage of the southeastern part of the Scandinavian and Baltic areas into this basin in stead of into the North Sea basin. From then on the North German and Central European rivers were the major agents of sediment transport to the North Sea (Gibbard, 1988).

During the Quaternary, significant changes occurred in the southern North Sea. The depocentre which in Pliocene moved towards the North to the Central Trough area, continued northward to the present-day position. The sedimentation rate increased during the Quaternary to ten times the rates of the Early Tertiary, yielding a Quaternary sedimentary sequence with a thickness of more than 900 m in the centre part of the North Sea (Zagwijn & Doppert, 1978; Zagwijn, 1989).

Climatic changes with extreme fluctuations in temperature characterized the Quaternary period. During glacial periods northwest Europe was north of the tree limit and the area was affected by severe permafrost. Under these conditions erosion of the hinterland occurred and the supply of sediment to the basin increased. In the warm periods, trees and other vegetation covered the area again. This pattern of changing cold and warm periods started at 2.3 m.a. with the first cold stage, the Praetiglian, and persisted during the entire Quaternary (Gibbard et al., 1991).

Study area

The area in which the occurrence of buried valleys has been studied covers almost the entire Danish North Sea sector (Fig. 1).
The latitude of 56°45'N defines the northern boundary for this investigation. South of this boundary, the available seismic lines form a relatively dense grid. The quality of the data, permits to resolve details in the seismic profiles, required for the interpretation of the valley structures. North of 56°45' N, only a relatively thin cover of Quaternary deposits are preserved and the late Tertiary and Quaternary deposits are intensively disturbed by halokinesis and associated fault structures.
Detailed interpretation has been carried out in the area west of 4°45'E. The valley described here is situated in this westernmost part of the Danish area. In this area the Cenozoic sedimentary succession is among the most complete seen in the basin, and data of very high quality is available.

Data and Methods

For the seismic interpretation, the regional mapping and the analyses of the valley systems, both conventional and high-resolution seismic data have been used.
The conventional seismic profiles are multichannel airgun seismic data from regional 2-D seismic surveys, made for the exploration of oil and gas. In the western and southeastern part of the study area, a high density seismic grid is available, while a more open grid is found in the rest of the study area. The interpretation was mainly performed at 10-cm migrated profiles. For some few surveys only 5-cm profiles were available. The unmigrated (filtered) profiles were used when no migrated version existed. For this type of study the character of most profiles, with the lack of resolution in the very top part, enables a interpretation of the profiles only for the section below 200 msec TWT and deeper.
Additional multichannel sleeve-gun seismic data have been used. These data were collected particularly in order to obtain information on the Quaternary succession. At this type of profiles interpretation is possible between 50 and 900 msec TWT. One survey has been made especially to investigate the buried valley further described here.
Shallow seismic and high-resolution multichannel sleeve-gun profiles permit to trace regional unconformities representing the erosive subsurfaces from which the valleys are incised (Salomonsen & Jensen, unpublished data).
Several unconformable surfaces can be detected in the uppermost part of the seismic sections. On the seismic records the outline of the valleys appears from reflector terminations seen as erosional truncations. The valleys intersected by two ore more seismic profiles have been marked, and dimensions as depth and width have been measured. The basal erosion surface of the deep incisions is very well defined on the seismic profiles, though it may be masked by multiples. The surface expresses the deepest position of the erosional level in combination with later subsidence and tectonic movements in the area.

In the study area, several geotechnical boreholes are drilled in the Holocene and Pleistocene sedimentary succession in connection to the deep oil wells. Additional, two stratigraphical boreholes are available from a multidisciplinary study of the Quaternary in the Southern North Sea. Foraminiferal analyses from some of these boreholes have established the stratigraphy of the area (Knudsen, 1985; Salomonsen & Jensen, unpublished data).

Case study of a buried valley

The valley located in the western part of the Danish North Sea sector, is the most prominent seen in the area (Fig. 2). The valley has been studied in detail by including conventional profiles from other surveys to the regional seismic data base, resulting in a grid of profiles with intervals of approximately 500-1000 m perpendicular to the structure and approximately 1750 m parallel to its strike direction. In addition, two high-resolution profiles, one cross-section and one parallel section were used.

The SSE-NNW orientated valley is seen as part of a group of valleys of similar orientation recognized in the central part of the North Sea basin. The valley is an elongated structure, 2-4 km wide. The structure is mapped from the seismic sections over a distance of 35 km. The depth to the lowermost unconformity is in general 400-500 msec TWT corresponding to 360-450 m below present sea level. Maximum depths at 550 msec TWT (500 m) are found locally in the centre and northern part of the valley. The bottom of the valley gradually deepens towards the north. Towards SE, minor valleys observed in the southern part of the area join the main valley. In the northern part of the area, the main valley branches out in several small valleys. The acoustic character of these valleys is below the seismic resolution level. It is therefore not possible to follow the continuation of the valleys north of the area mapped in this study on the conventional seismic records.

In conventional seismic profiles cross sections of the valley show at least two, occasionally three, unconformable internal reflections, indicating several generations of incision within the main valley structure. When using the high-resolution seismic profiles, it is evident that more internal unconformities are present. At least five erosional surfaces are seen, and it is obvious that the valley has been generated during repetitive cycles of erosion and deposition (Fig. 3). With only one cross-section of high-resolution quality available, the regional mapping is based on the conventional profiles. Downlaps in the lower part of the infill of the valley have been observed on a record from near the main axis of the valley. The unconformity of the first generation of incision is only seen in the northern part of the valley, the second generation unconformity is observed in part of the valley, whereas the third generation unconformity is seen in the entire valley.

Interpretation

The mapped structure is interpreted to be part of a fluvial system, which is responsible for repeated erosion in the area. Each of the unconformities showing the shape of a valley represents a river flowing through the area. The unconformities may be separated by a body of sediment deposited as infill of the valley in periods between the erosive phases. The orientation of the downlaps in the lower part of the valley indicate directional deposition by water running from the drainage area SE of the structure towards NW to a depositional basin. Signs of the first generation of erosion in the area which is only preserved in a small area in the northern part of the valley, indicate an initial northward inclination of the thalweg. The minor valleys in the southern part of the area are thus tribu-

taries to the main river, which basinwards changes into a braided river system in a deltaic environment.
The composite valley detected from conventional and high-resolution seismic profiles is shown in Fig. 4. In the southern part of the valley only one 'second-generation' inlet to the river is preserved. The unconformity of the second generation is not preserved from this inlet until a position more to the northwest. Along the northern part of the main valley this generation is preserved.
Two inlets from the third erosional generation are seen. During this third phase the erosion in the southern part of the valley may have been more intensive than previously, as the infill and outline of the older valley is not preserved. Towards the northwest the discharge current forces decreased. The two erosional levels, indicating the bottom of the respective valleys, split and are preserved here as separate unconformities. In the northernmost part a transition into a braided river system occur. The causes of braiding may be found in specific climatic conditions, affecting the discharge, water flow speed and sediment load.
The unconformable boundaries are interpreted as 'Type-1-sequence boundaries' characterized by stream rejuvenation and fluvial incision. The shelf was an area of sedimentary bypass and an abrupt basinward shift of facies and coastal onlap occurred. A eustatic fall of sea-level and low rates of subsidence may characterize the shelf margin (Vail & Todd, 1981).

Regional pattern of buried valleys

A network of deep buried valleys recognized in the entire study area has been mapped and the outline of the valley pattern is shown in Fig. 5. The dimensions of the mapped valleys vary from 0.5 to 5 km in cross-section width and 5 to 40 km in length. The depth of the valley floor is usual between 150 and 400 m, but in the northwestern part of the area, the bottom of valleys are detected below 540 m b.s.l. (600 msec TWT). This represents the deepest level of erosion seen in connection to valley formation. The distance between the valleys varies, a high number of valleys is seen in the western part of the area, while a more open pattern is observed in the eastern area. However, it should be noted, that the seismic grid in the latter part of the area is less dense.
The orientation of the valleys is in the eastern part of the area dominated by a E-W and NE-SW orientation, while a SSE-NNW to SE-NW orientation is prevalent in the area close to the British North Sea sector.
The distribution of the valleys in the area may reflect the older structural elements affecting the subsidence and thereby the Pleistocene surfaces. High density of valleys are seen in the areas of the Central Trough and Horn Graben, while no valleys are seen in the area of the Ringkøbing-Fyn High. The latter area may have been a highland during most of the Pleistocene.

Geological model

Seismic studies at the eastern North Sea basin have demonstrated that progradation of a delta complex took place during the Miocene, Pliocene and Early Pleistocene (Kay, 1993; Salomonsen, in press). Delta top and fluvio-deltaic sediments were deposited during the Pliocene to Middle Pleistocene in the eastern part of the basin, while the deposition was delayed until Early Middle Pleistocene in the western part of the basin. The sedimentary succession of this delta complex has been described in terms of a shallowing upwards basin fill.
A drainage system in the southern and central North Sea as indicated by river valleys points to a drainage basin in the area of the present Denmark, the Baltic area and the North German area. Discharge from these regions caused fluviatile sediment transport through the present southern North Sea. The rivers followed the gradient of the palaeo-surface towards a depositional basin situated north or northwest of the Danish area, pre-

ferably in the central North Sea. Several generations of valley incision may be related to glacial periods. It has been possible to date some of the younger erosive surfaces to the Saalian and Weichselian glacial epochs by foraminiferal stratigraphy (Salomonsen & Jensen, unpublished data).

Thus, during sea-level fall and lowstand in relation to Pleistocene glacial periods, incised valleys were cut in the shelf as extensions of existing river valleys. The valleys seen on-shore in present-day Jutland are part of this drainage system.

In the beginning of a cooling period the landscape was exposed and periglacial conditions occurred. The erosion of land areas increased and sediment was transported by rivers towards the depositional basin, where sedimentation rates increased. When the source areas were covered by ice, a decrease of sedimentation occurred. During the cooling phase and establishing of the ice sheet a lowstand situation was developed. The sea-level was lowered in an order of 100-130 m below present sea-level during the Weichselian glacial stades (Jelgersma, 1979). The weight of the ice cap oppressed the underlying part of the shelf, causing the development of a peripheral bulge in front of the ice covered area. Some sediment must have been transported from the ice covered area towards the depositional basin by subglacial streams as indicated by glaciomarine sedimentation in the Central North Sea.

Networks of braided river systems developed at an alluvial plain, the alluvial fans had their apex at the front of the glacier. Locally the valleys and incisions may have been eroded further by the ice itself, by 'jökulhlaups' or other ice front related processes, and thus indicate the extension of the ice cap (Ehlers & Linke, 1989; Ehlers & Wingfield, 1991; Wingfield, 1989; 1990).

The change to warmer climatic conditions in the interglacial periods caused melting of ice. At initial ice cap melting, these incisions and river valleys were further deepened by excessive meltwater discharge. Contemporary to an isostatic uplift of the continent, the sea-level also rose due to ice melting. Further erosion was possible in the elevated area and increased sediment supply to the basin occurred. With rising sea-level, the coastline moved landward and a highstand situation developed. The valleys were filled during the late lowstand period by fluvial sediments and by marine sediments during the succeeding transgressive phase. A different character of the infill of the valleys is evident on seismic amplitude studies indicating different lithologies of the fill deposits. Some of the valleys were not filled totally before covered by the Holocene sediments and thus cause depressions at the sea floor.

Thus, lateral movement of the environments on the shelf during the climatic changes, resulted in a stacked pattern of sediments and erosional valleys. More generations of valleys in the same main trace represents the development of the same environment several times in the area during the Late Quaternary.

Conclusions

The regional pattern of deep buried valleys seen in the North Sea is interpreted to be the result of intermittent fluvial erosion in relation to glacial periods as part of the drainage system in Northwest Europe. Discharge took place through rivers through the present North Sea area, following the gradient of the palaeosurface towards a depositional basin. This basin was situated north or northwest of the Danish North Sea area, preferably in the central and northern North Sea. The valleys seen on-shore in present-day western Jutland are part of this system.

The two mappable generations of valleys are results of changes in the hydrographical regime in the area. Erosion of the river floor are expressed as reflectors defined by

erosional truncations at the seismic profiles. These are separated by a body of sediments representing intermediate periods of deposition.
The valleys were filled during the lowstand period, when accommodation space in the coastal area decreased. During the following transgressive phase, the valleys were buried and a very low relief surface was formed.
The erosive valleys observed in seismic records from the Danish North Sea area are thus indicative of a larger system of river valleys. The distal part of the rivers, at the transition to the depositional basin, are not visible on the seismic profiles due to low resolution. The valleys have not been generated as local incisions due to subglacial erosion solely.
The few high-resolution data available in the Danish area has confirmed the interpretation based upon the conventional seismic data. The study has evidently shown that high-resolution seismic data are a prerequisite for a detailed reconstruction of the Quaternary environment of the North Sea area.

Acknowledgements

This study was carried out at the Geological Survey of Denmark and University of Copenhagen during a Ph.D. study supported by the Carlsberg Foundation. The acquisition of the regional high-resolution seismic data and drilling of stratigraphic boreholes were made during the Southern North Sea Project funded by the CEC-Science programme. Collaboration with the University of Aarhus and the Oceanographic Institute in Kaliningrad made it possible to acquire additional high-resolution seismic lines. Antoon Kuijpers is thanked for reviewing the manuscript.

References

Cameron, T.D.J., M.S. Stoker & D. Long, 1987: The history of Quaternary sedimentation in the UK sector of the North Sea Basin. Journal of the Geological Society, London, vol. 144, 43-58.

Ehlers, J. & G. Linke, 1989: The origin of deep buried channels of Elsterian age in Northwest Germany. Journal of Quaternary Science, 4 (3), 255-265.

Ehlers, J. & R. Wingfield, 1991: The extension of the Late Weichselian/Late Devensian ice sheets in the North Sea Basin. Journal of Quaternary Science, vol. 6 (4), 313-326.

Gibbard, P.L., 1988: The history of the great northwest European rivers during the past three million years. Phil. Trans. R. Soc. London, B 318, 559-602.

Gibbard, P.L., R.G. West, W.H. Zagwijn, P.S. Balson, A.W. Burger, B.M. Funnel, D.H. Jeffery, J. de Jong, T. van Kolfschoten, A.M. Lister, T. Meijer, P.E.P. Norton, R.C. Preece, J. Rose, A.J. Stuart, C.A. Whiteman & J.A. Zalasiewicz, 1991: Early and early Middle Pleistocene correlations in the southern North Sea Basin - Quaternary Science Reviews 10: 23-52.

Jelgersma, S., 1979: Sea-level changes in the North Sea basin. In: E. Oele, R.T.E. Schüttenhelm & A.J. Wiggers (eds.): The Quaternary History of the North Sea, 233-248. Acta Univ. Ups. Symp. Univ. Ups. Annum Quingentesimum Celebrantis : 2, Uppsala.

Kay, C., 1993: A regional depositional model for the southern North Sea during the Late Tertiary and Quaternary. Abstract Supplement No. 1 Terra nova 5: 605.

Knudsen, K.L., 1985: Foraminiferal stratigraphy of Quaternary deposits in the Roar, Skjold and Dan fields, central North Sea. Boreas 14, 311-324.

Salomonsen, I, in press: A seismic stratigrahic analysis of Lower Pleistocene deposits in the western Danish sector of the North Sea. Geologie en Mijnbouw.

Salomonsen, I. & K.A. Jensen, in prep.: Quaternary erosional surfaces in the Danish North Sea. Submitted to Boreas.

Vail, P.R. & R.G. Todd, 1981: North Sea Jurassic unconformities, chronostratigraphy and sea-level changes from siesmic stratigraphy. Petroleum Geology of the Continental Shelf of Northwest Europe, Proceedings, 216-235.

Wingfield, R.T.R., 1989: Glacial incisions indicating Middle and Upper Pleistocene ice limits off Britain. Terra Nova 1, 538-548.

Wingfield, R.T.R., 1990: The origin of Major Incisions Within the Pleistocene Deposits of the North Sea. Marine Geology, 91, 31-52.

Zagwijn, W.H. & J.W.C. Doppert, 1978: Upper Cenozoic ofthe Southern North Sea Basin: Palaeoclimatic and Palaeogeographic evolution. Geologie en Mijnbouw, vol. 57, 577-588.

Zagwijn, W.H., 1989: The Netherlands during the Tertiary and the Quaternary: A case history of Coastal Lowland evolution. Geologie en Mijnbouw, vol. 68, 107-120.

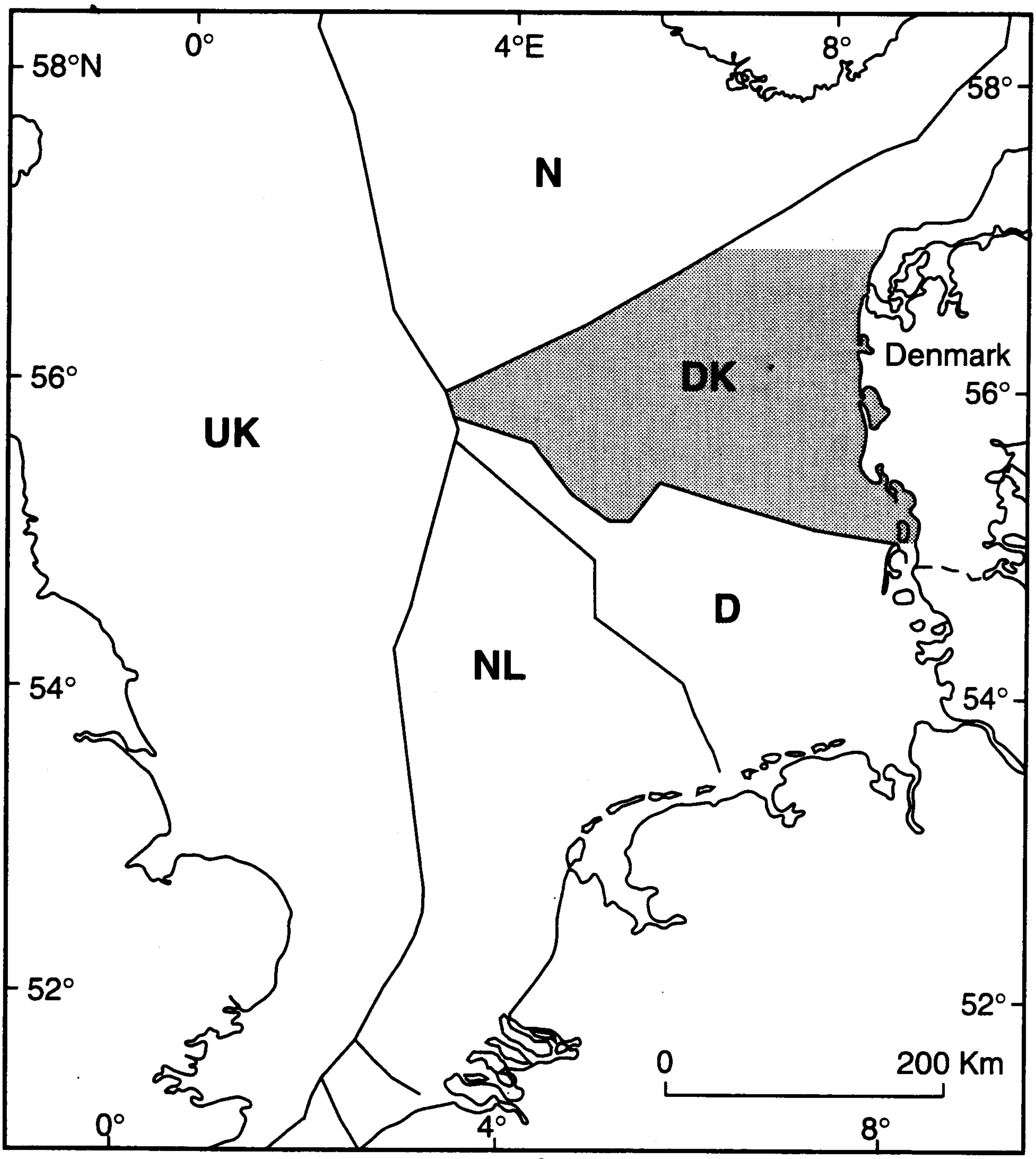
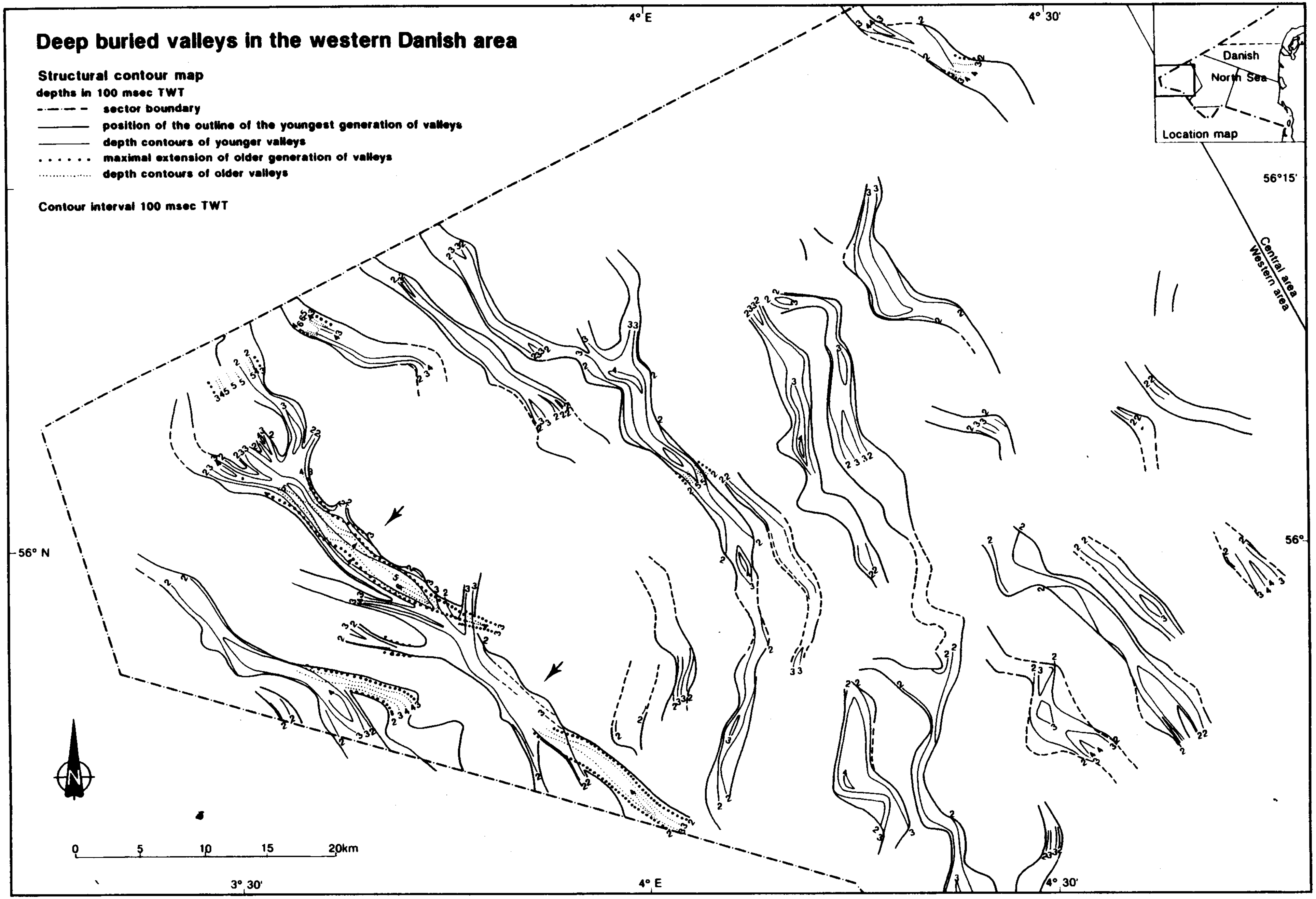


Fig. 1 Position of the study area in the North Sea region.


Deep buried valleys in the western Danish area
Structural contour map
depths in 100 msec TWT
sector boundary
position of the outline of the youngest generation of valleys
depth contours of younger valleys
maximal extension of older generation of valleys
depth contours of older valleys
Contour interval 100 msec TWT
Danish
North Sea
Location map
Central area
Western area
4° E
4° 30'
56°15'
56° N
56°
3° 30'
0
5
10
15
20km
N

◀ Fig. 2 Structural contour map (msec TWT) showing the outline and depths to the deepest erosional surfaces indicating the buried valleys in the western part of the study area. The valley analyzed in detail is marked by arrows.

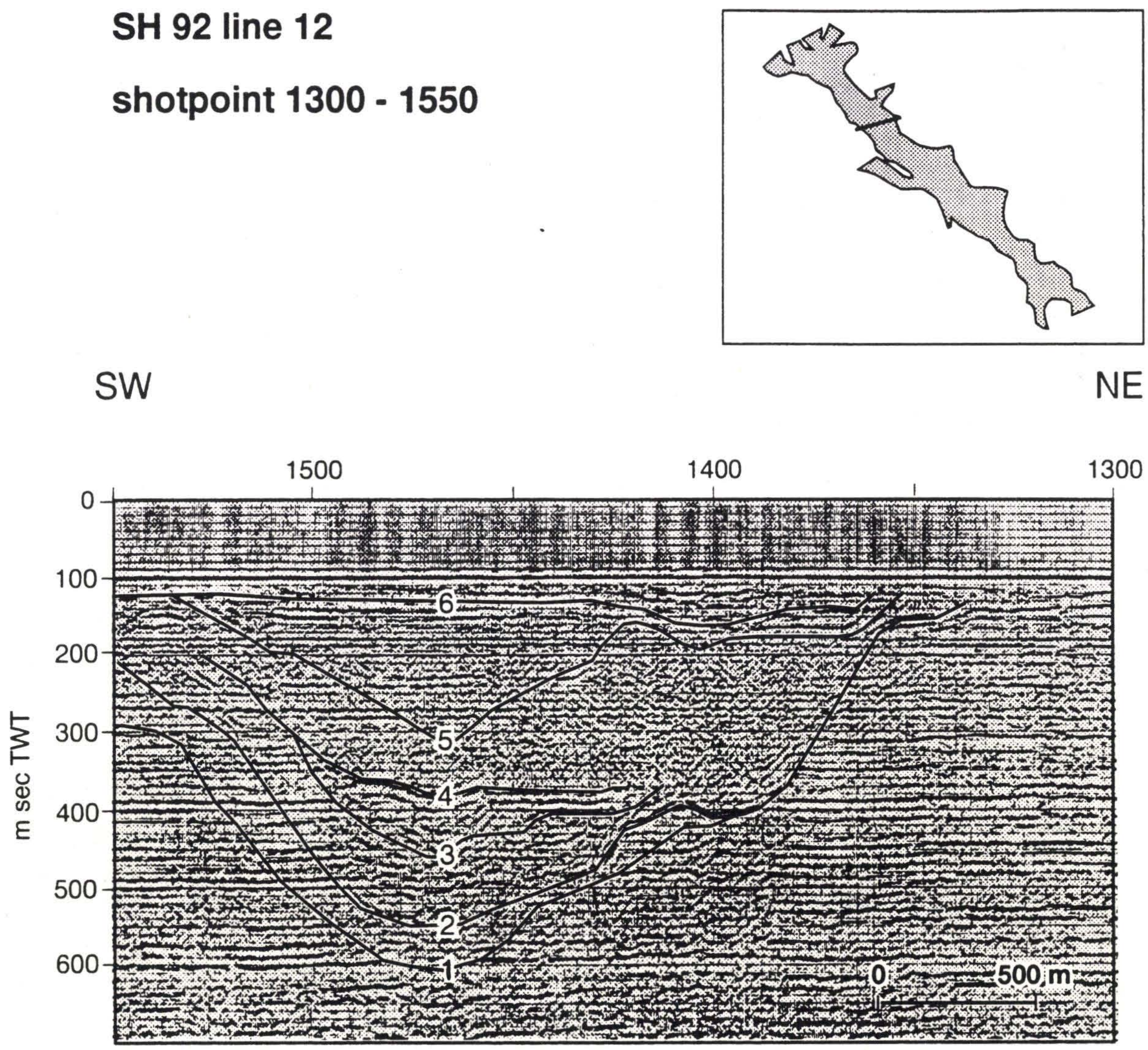


Fig. 3 High-resolution seismic section showing a cross-section through the valley. The five unconformable surfaces in the valley are indicated.

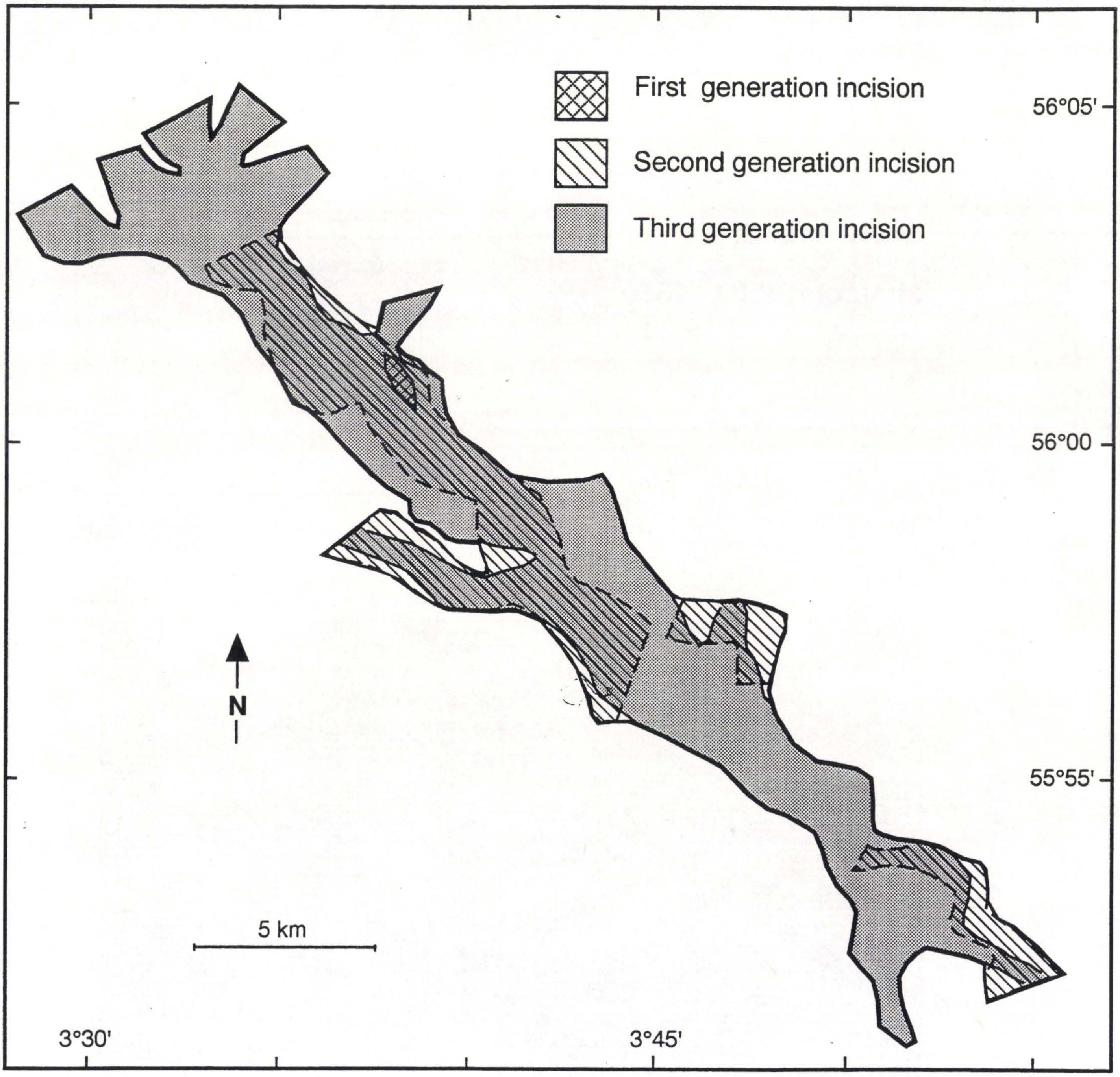


Fig. 4 The extension of the various unconformities representing three phases of incision, based on both conventional and high-resolution seismic data.

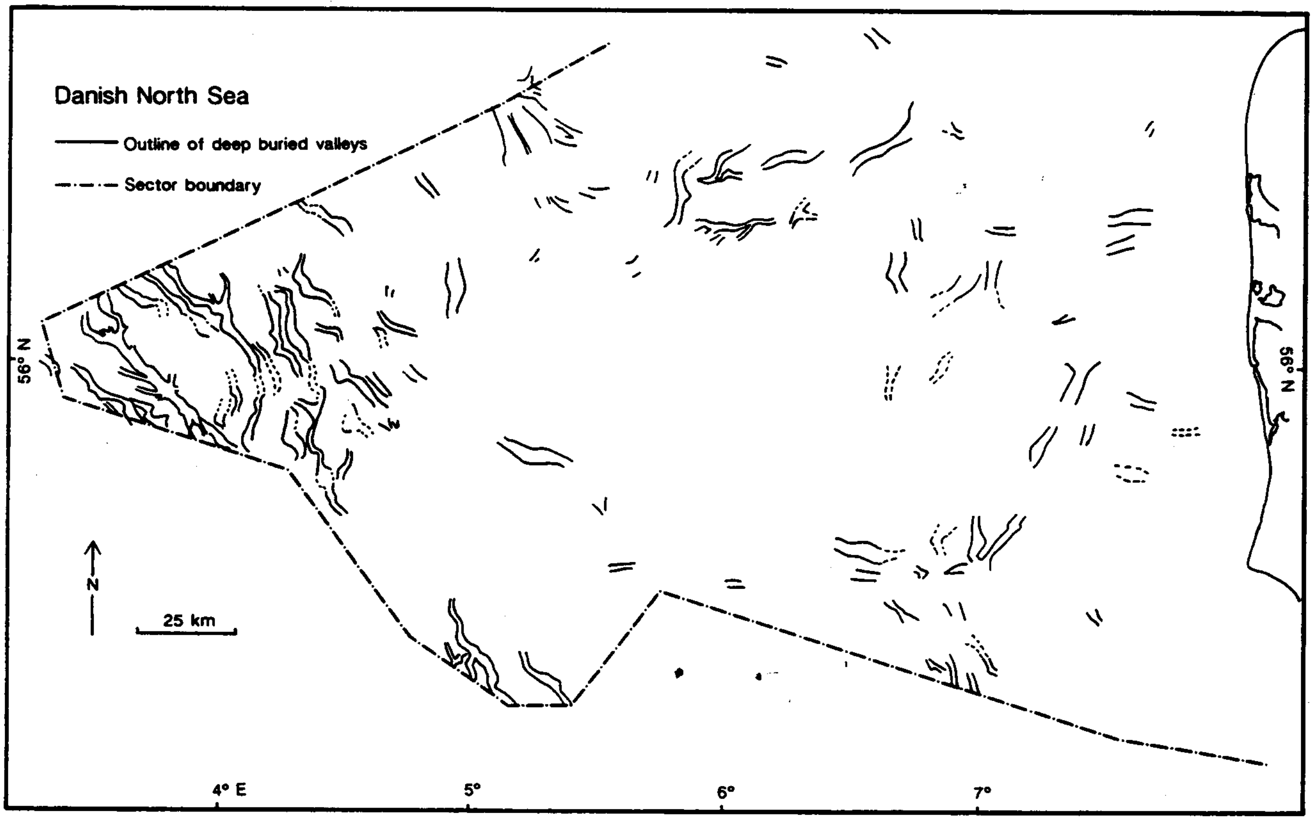


Fig. 5 The regional pattern of deep buried valleys in the eastern North Sea basin.