Geologie en Mijnbouw **75:** 317–340, 1997.

The Cenozoic fill of the North Sea Basin (UK sector 56–62° N), a seismic stratigraphic study with emphasis on Paleogene massflow deposits

Paul C. H. Veeken
Ecole Nationale Supérieure de Géologie, 94 avenue de Lattre de Tassigny, B.P. 452, 54001 Nancy, France

Received 2 October 1995; accepted in revised form 28 May 1996

Key words: basin evolution, depositional sequence, lithofacies, submarine fan, seismic facies, turbidite

Abstract

Seismic stratigraphic study techniques allow to recognise several Cenozoic sedimentary cycles in the central and northern part of the North Sea area (UK sector), and to deduce their depositional history. Large-scale sedimentation patterns are illustrated with emphasis on Paleogene massflow deposits, forming important hydrocarbon-bearing reservoirs.

Five regional unconformities form the bases of five depositional sequences (DS). These sequences can be subdivided into systems tracts in which seismic lithofacies units are outlined, calibrated by 76 wells. The base of DS-1 (Paleocene–Early Eocene) reflects the change from predominantly pelagic carbonates to clastic deposition. Within DS-1, prograding slope systems are present. Fan-delta systems supplied clastics to the shelf, whilst in the coastal area prograding deltas, swampy lakes and barrier complexes existed. Base-of-slope sand-prone sediments were laid down as slope-front fills, in submarine fan mounds and in parallel-bedded basinfloor deposits. Massflow sedimentation is dominant in the deeper parts of the basin. Axial basinfloor transport is indicated by the mound geometry and abnormal tichkness of the bottom sets. A volcanic pulse is expressed by a volcano-clastic seismic marker.

In DS-2 (Eocene–Early Oligocene) a slope system fringed the western margin of the basin. Massflow sedimentation continued; sources and depocentres are correlatable to those active in the Paleocene. Subordinate input sources existed in the Norwegian sector.

The base of DS-3 (Late Oligocene–Middle Miocene) is onlapped by fine-grained marine deposits. Sediment thickness increases basinwards. Rapid sedimentary loading of underlying shales prevented proper dewatering, causing plastic deformation and under-compaction.

In DS-4 (Late Miocene–Early Pleistocene) sediment input from the east increased. DS-5 (Quaternary) shows that sediment supply from the south-southwest became more significant.

Introduction

Cenozoic deposits of the northern and central North Sea (UK 56–62° N latitude, Figure 1) have been studied using seismic stratigraphic interpretation techniques. Special emphasis is put on the deeper-marine Paleogene clastics, which form important hydrocarbon reservoirs in the North Sea area (e.g. the Forties, Nelson, Montrose, Gannet, Frigg, Forth, Alba and Everest fields). The purpose of the study is to present a methodology to identify gross lithological sedimentary units directly from a heterogeneous 2D seismic dataset and to reconstruct the Cenozoic geological development of the area. Non-conventional seismic stratigraphic study techniques are applied in order to obtain a consistent interpretation of the subsurface. These techniques comprise recognition of depositional sequence boundaries and systems tracts, identification of seismic facies units closely around the wells, and establishment of the corresponding lithofacies units. These units are outlined over the complete seismic sections, and an iterative step guarantees the consistency of the interpretation in all calibration points. Subsequently, a prediction on the distribution of sedimentological bod-

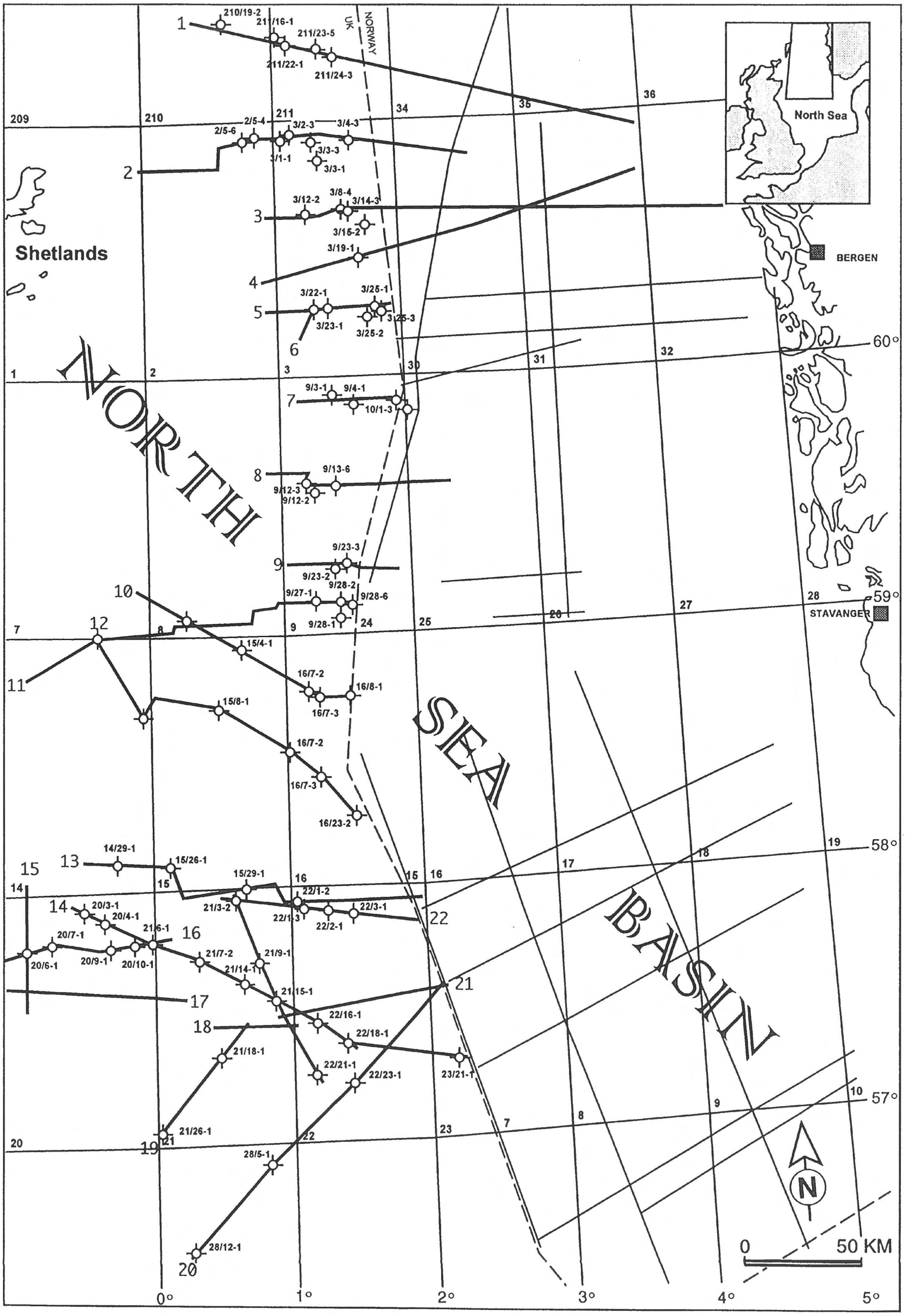


Figure 1. Location map showing the seismic grid (Lines 1–22) and the 76 calibration wells used in the study. The lines in the Norwegian waters have been used to back-up the observations made in the UK sector.

ies within the basinfill is given and the depositional history is deduced.

In the current study, 22 representative regional seismic sections were selected from a larger data set. Norwegian lines were only used in a general manner. The lines are stemming from several seismic vintages (1972 to 1983), which poses serious compatibility problems. It hampers unambiguous recognition of seismic and/or lithofacies units, but nevertheless allows delineation of gross lithological units. A total of 76 wells was used to calibrate the seismic observations (Figure 1).

Below, first the general geological setting is described and then non-conventional seismic stratigraphic interpretation techniques are presented. The individual depositional sequences and aspects of the hydrocarbon habitat are discussed. Finally a synopsis of the Cenozoic paleogeographic evolution of the area is given.

Geological setting

Two important orogenic events affected the area:

- the Caledonian diastrophism with collision of the Laurentian–Greenland and the Fenno-Scandian blocks, thus forming the Laurasia continent,
- the Variscan orogeny with suturing of Laurentia with the Gondwana continent in the south and creation of the Pangean mega-continent (Ziegler 1975, Ziegler 1978, 1982a).

In Permian times two intra-cratonic basins developed in which continental Rotliegend clastics accumulated. During the Late Permian regional transgression, thick Zechstein evaporites were deposited in the central parts of these basins, with contemporaneous carbonate deposition along the bordering highs (e.g. Auk field, Brennand & Van Veen 1975). These Zechstein salt deposits were subject to later plastic deformation (cf. Jenyon 1986).

A regression in the Triassic restored continental sedimentation. A new N–S trending fault system was initiated. This tectonic grain would become an even more prominent structural element in Jurassic and Cretaceous times, when the North Sea graben system fully developed (Figure 2). In Triassic times, halokinesis of Zechstein salt started; locally it continued until the sub-Recent.

The Mesozoic rifting was accompanied by a short-lived Jurassic volcanic pulse (Figure 3). A Rhaetic–Liassic transgression came in from the northern Atlantic as well as from the Tethys (Ziegler 1987). Several phases of subsidence are recorded in the Jurassic and Cretaceous (cf. Vail et al. 1977b, Vail & Todd 1981, Wood & Barton 1983). Erosion along the flanks of the graben system provided clastics which were dumped into the marine rift (e.g. the Brae-Miller area, Harms et al. 1981, Stow et al. 1982).

An important unconformity marks the Jurassic–Cretaceous boundary (Rawson & Riley 1982, Ziegler 1990). During Early Cretaceous times, deep-marine conditions prevailed in the deepest part of the graben, while on the highs submarine erosion and/or sediment bypass took place. Subaerial exposure is not indicated by diagenesis studies. A rise in sealevel is expressed by the Late Cretaceous transgression (Vail et al. 1977a, b, Pitman 1978, Haq et al. 1988). The Cretaceous deposits form the main infill of the Mesozoic block-faulted basinfloor topography.

During the Late Cretaceous, pelagic carbonate deposition (coccolith chalk), with intercalated submarine gravitational slides, occurred in the south (Kennedy 1987). In the north these chalks are replaced by deeper-marine marls and clays. Coeval inversion tectonics in the south reflects the northern extent of plate tectonic adjustments in the Alpine hinterland (Ziegler 1982b, Kooi & Cloetingh 1989).

A major break in basin evolution coincides with the Early Paleocene sealevel lowstand (Mudge 1979, Ziegler 1990). From the uplifted and tilted East Shetland Platform, clastics were shed into the North Sea Basin. Delta systems were connected to basinfloor submarine fan complexes (Parker 1975, Deegan & Scull 1977, Sutter 1980, Knox et al. 1981, Ziegler 1982b, Lovell 1984, Stewart 1987).

A pulse of volcanic activity is evidenced by a Lower Eocene volcano-clastic horizon (Evans et al. 1973, Jacque & Thouvenin 1975, Knox & Morton 1983, 1988, Hitchen & Ritchie 1987, Mussett et al. 1988, White 1988, Ziegler 1990, Lewis et al. 1992). In the central North Sea, massflow deposition continued well into the Eocene (Harding et al. 1990). In the north only sporadic influx of sands is observed. During the Late Eocene and Early Oligocene the basinfloor topography was infilled by onlapping and draping fine-grained deposits.

The Mid-Oligocene and Mid-Miocene sealevel lowstands (Vail et al. 1977a) are reflected by truncational and onlap surfaces. Several low-angle slope systems are present in the Upper Tertiary deposits. During the Neogene the main source areas were located in the east-southeast.

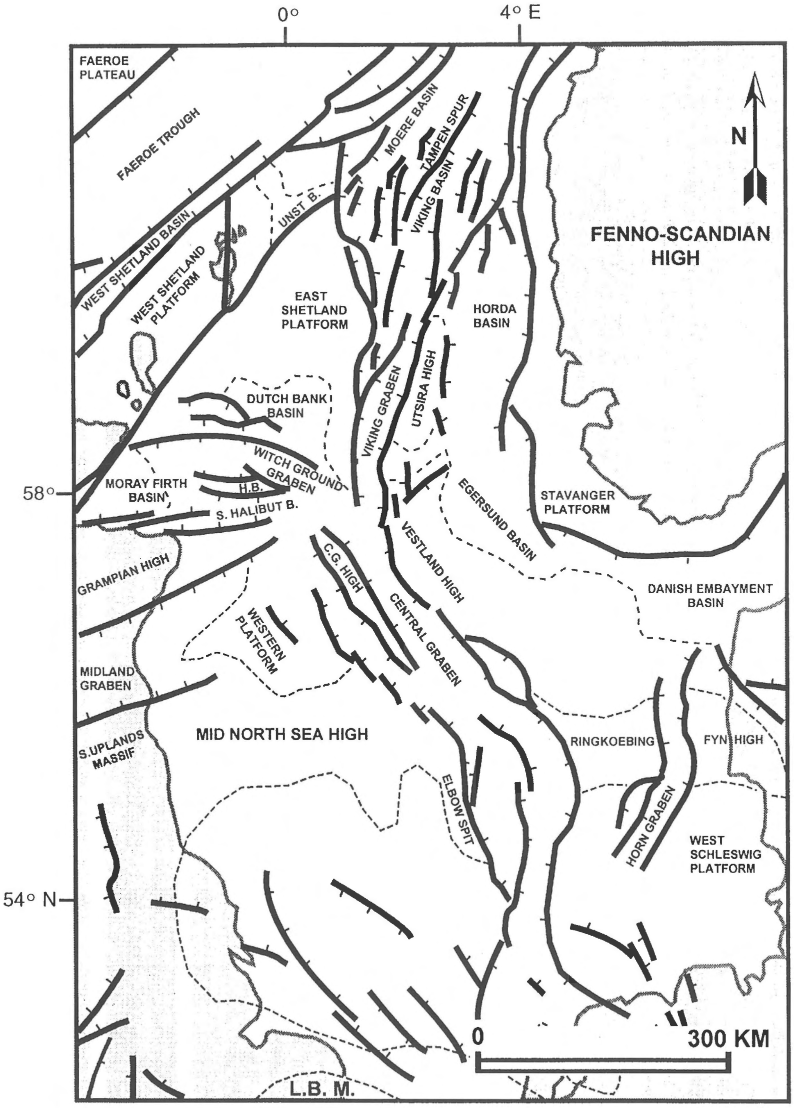


Figure 2. The main tectonic elements in the North Sea area. C.G. High = Central Graben High, H.B. = Halibut Horst, L.B.M. = London-Brabant Massif.

The glacially induced Mid-Pleistocene sealevel lowstand (Vail et al. 1977a, Haq et al. 1988) is represented by a regional unconformity. From this time onwards the western borders of the shallow-marine basin become once again important contributors to the sediment-supply.

Non-conventional application of seismic stratigraphic study techniques

The Cenozoic basin fill is subdivided into depositional sequences based on seismic reflection termination mapping (Payton 1977, Rochow 1981, Stewart 1987, Den Hartog Jager et al. 1993, Jones & Milton 1994). A total of five regional unconformities are recognised, bounding five major depositional sequences (Figure 4). These unconformities are surfaces defined by reflection terminations and extended into their correlative con-

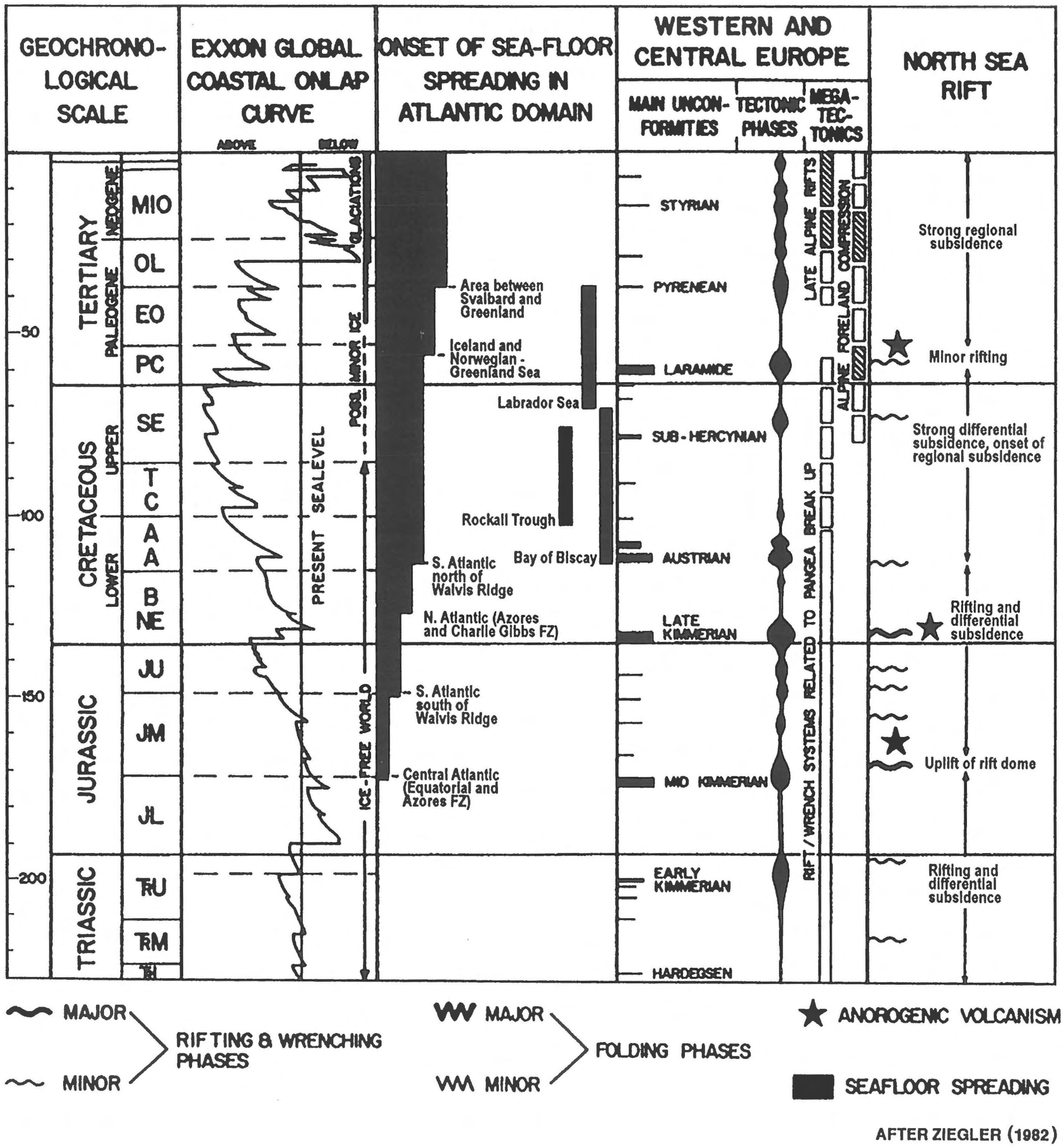


Figure 3. Mesozoic–Tertiary tectonic evolution of the North Sea area shown in relation to seafloor spreading events in the Atlantic domain (after Ziegler 1982b).

formities. The depositional sequences can be split into systems tracts (cf. Van Wagoner et al. 1987), based on the occurrence of local unconformities. A second step in the seismic stratigraphic analysis is the delineation of seismic facies units using the reflection configuration, continuity, amplitude and frequency.

The heterogeneous nature of the data (i.e. different acquisition, processing and display parameters) does not allow proper three-dimensional correlation of these seismic facies units over the grid of seismic lines. This phenomenon calls for an unconventional approach in the identification of the lithofacies units. The same lithofacies unit can display varying seismic attribute characteristics. For example the amplitude of a reflection is determined by the gain function applied, and the latter can vary from survey to survey. As a consequence the internal reflection configurations and external geometries are the most diagnostic attributes

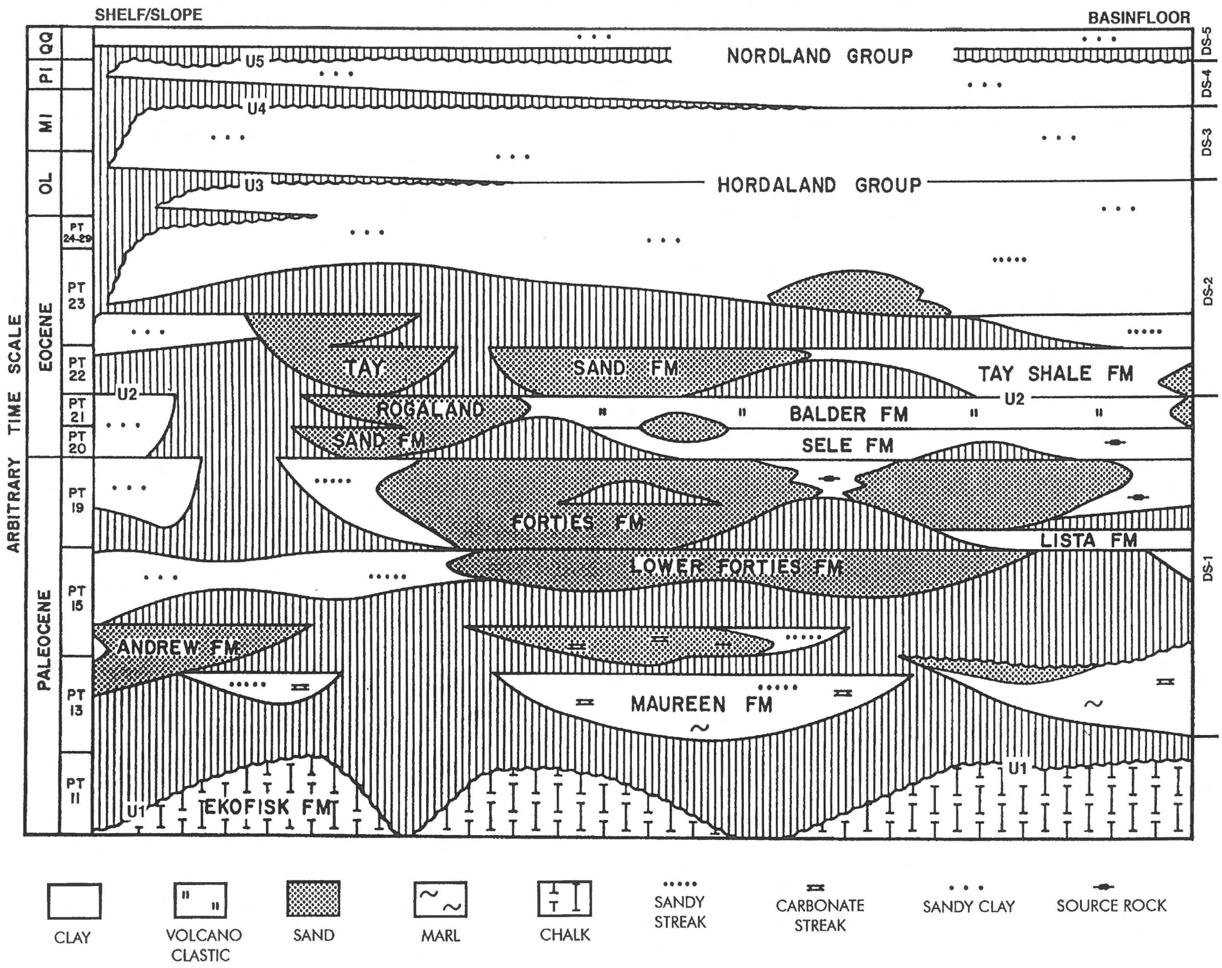


Figure 4. Chronostratigraphic chart for the Cenozoic in the central North Sea area. The palynological PT-zonation (Schroeder 1992) allows detailed timestratigraphic correlations. The depositional sequences (DS-1 to DS-5) are subdivided into systems tracts based on the presence of local unconformities. These systems tracts coincide largely with the stratigraphic units distinguished by other workers (Deegan & Scull 1977) but in addition they honour the seismic correlations between wells and are therefore not strictly lithostratigraphic units. The Lower Paleocene chalk deposits of the Ekofisk Formation are not included in the current study. Vertical hatching signifies non-deposition and/or erosion.

to determine lithofacies units. These aspects are less variable from survey to survey. In the adopted non-conventional approach the depositional sequences are divided into distinct lithofacies units at the well locations. These lithofacies units are related to the specific seismic expression directly around the well. The seismic facies character on the various intersecting seismic lines will be slightly different. Dip-depending variations can be verified and accounted for. These distinct seismic facies expressions and their direct link with the well calibration are used to interpret the seismic line. It is emphasised that the internal reflection configuration and the geometry of the subsurface seismic units are the most diagnostic features to predict the distribution of gross lithofacies. These characteristics are most useful to interpolate and extrapolate into areas beyond well control (Figure 5). Differential compaction effects are important to establish the nature of lithofacies units (e.g. a sand-prone channel fill in a shaly sequence can show up with a convex upward top boundary).

The delineation of the seismic facies units is an iterative process. The whole data set has to be examined and the consistency of the interpretation should be checked to increase the confidence in the distribution of seismic facies and lithofacies units. The procedure implies that the interpreter goes back to the original

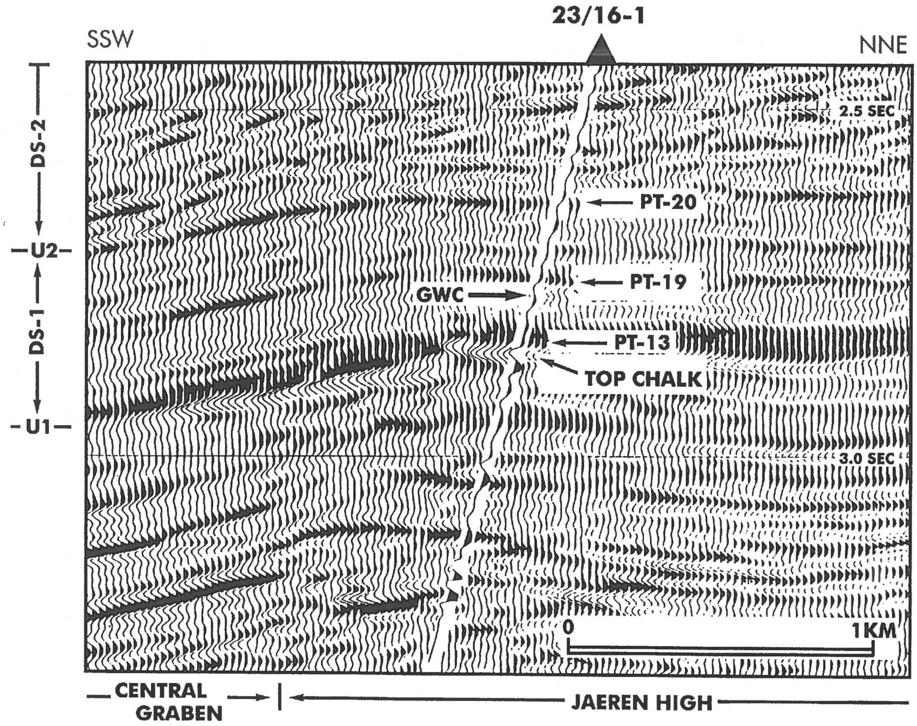


Figure 5. Example of a Paleogene well-to-seismic tie for the deviated well 23/16-1 on the Jaeren High bordering the Central Graben. The palynological PT-zonation is after Schroeder (1992). The gas–water contact (GWC) occurs in PT-19 reservoir sands. The hydrocarbon charge is derived from Jurassic source rocks that are mature in the graben area. The migration path is envisaged along the fractured flanks of a Zechstein saltdome and also along the graben boundary faultzone.

observations at the well and follows the interpretation to other well locations, verifying that the lithofacies corresponds to that actually present in the calibration points. It might prove necessary to make a more general seismic facies grouping in order to make sure that a coherent subsurface model is obtained. Examples of various seismic facies units are given below in the section concerning the characteristics of the DS-1 submarine fan deposits.

With the aid of seismic stratigraphic (reflection planes are considered as 'timelines' in a broader sense) and biostratigraphic criteria, ages are assigned to the depositional sequences and ultimately the Cenozoic basin evolution can be reconstructed. Palynological datings (PT-zonation) provide a useful chronostratigraphic frame for the Paleogene deposits (Figure 4; Schroeder 1992, Kulpecs & Van Geuns 1990). The diversity in oil companies, analysing the biostratigraphic data, introduces certain inconsistencies and shows the importance of the iterative method applied.

Depositional Sequence 1 (Paleocene–lowermost Eocene)

DS-1 forms a basinward thinning unit in which prograding shelf-slope systems can be recognised. The basal unconformity (U-1) is mainly the result of submarine erosion. Subaerial exposure of the shelf area cannot be excluded, but typical incising features are absent on the seismics. Moreover, in well studies no indications for karstification surfaces have been reported upon. U-1 forms the top of the Chalk Group, which includes coccolith oozes of Danian age (Ekofisk Formation). These Lower Tertiary chalk deposits are not incorporated in the current study.

The top boundary U-2 is defined by truncations and onlap. U-2 tends to be undulating in basinal areas due to the existence of submarine fans. The presence of the latter is deduced from the general setting together with numerous well and reservoir studies. The unconformity coincides largely with a wide-spread seismic marker of volcano-clastic origin. It results from volcanic activity in the nearby Thulean province (western Scotland)

and along the Rockall–Faroe rift (Hitchen & Ritchie 1987, Knox & Morton 1988, Mussett et al. 1988, Lewis et al. 1992). Unconformities of local significance allow to outline systems tracts within this DS-1 (Figure 4). These systems tracts reflect the various submarine fan complexes and correspond basically to the gross lithostratigraphic units as distinguished by earlier workers like Deegan & Scull (1977). These systems tracts are thought to represent changes in baselevel profile in the hinterland, due to tectonics and/or relative sealevel changes. Natural switching of depocentre locations in fan systems occurs frequently, especially when the basinfloor topography is rather smooth. As these submarine fans contain prolific hydrocarbon reservoirs, it is useful to summarise briefly the main depositional units in an ideal fan system.

General remarks on the facies distribution and geometries of submarine fan systems

This section gives a simplified overview on the main depositional features of an ideal submarine fan. The model is certainly not exhaustive, but it puts the sedimentology of the main Tertiary hydrocarbon reservoirs into an interpretational frame. For more details on submarine fan models the reader is referred to Reading & Richards (1994). Figure 6 shows the outline of lithofacies associations and geometry on an ideal submarine fan system with one input source. Three areas are distinguished:

a) *Large leveed fan valley(s) of the upper fan region*, containing wide (1–5 km) valley-floor deposits which are the coarsest on the fan and that are laid down in meandering and/or braided shallow channels within the confines of the fan valley (e.g. Amazon deep-sea fan, Damuth et al. 1988). These coarse sediments grade laterally into finer-grained, more regularly bedded deposits building the levees of the fan valley.

b) *Suprafan or depositional lobes of the mid fan*, located at the termination of the leveed fan valley. On a radial profile this suprafan shows up as a convex-upward bulge. In the proximal suprafan numerous non-leveed channels and also isolated depressions are found. The width of the channels is usually less than 1 km and they are filled with thinning- and fining-upward sequences. At the mouths of the distributary channels most of the sediment load is deposited. These radial sheet-like sediments at the terminus of the channel system normally show a high sand/shale ratio.

c) *Flat and smooth topography of the lower fan*, which generally lacks channel features and merges into the basinplain. It is characterised by continuous sheet-like deposits with a lower sand/shale ratio. If the fan is outbuilding, then coarsening- and thickening-upward sequences are most common.

The upper fan essentially forms an area of sediment-bypass, while the mid fan represents a zone of active deposition (cf. Mutti & Ricci Lucchi 1978). In freely out- and upbuilding submarine fan systems the regular shift of the depocentre position in space and time is common (Normark 1970, Figure 7).

The overall geometry of submarine fan complexes depends on a number of factors like for example the quantity of input sources, amount and nature of clastic supply, the depositional gradient and the basinfloor topography.

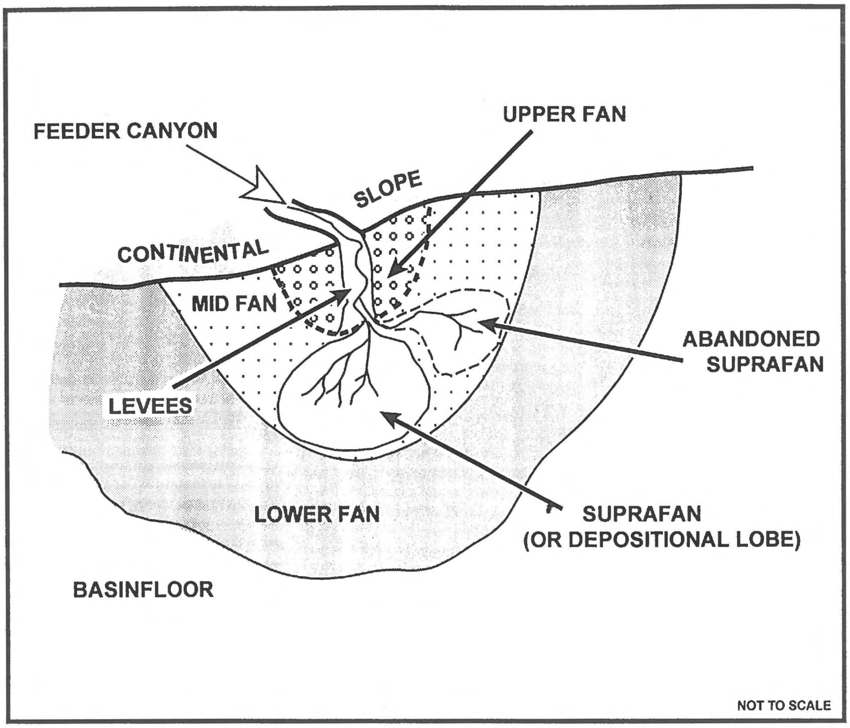
For the interpretation of ancient fan deposits one should bear in mind that the original depositional geometries are overprinted by burial effects. As a result of differential compaction, the stacked sand-rich channel fills may coincide in the subsurface with a convex-upward bulge relative to the finer-grained laterally equivalent overbank deposits, which originally constituted the elevated levees of these channels.

Characteristics of the DS-1 shelf and slope deposits

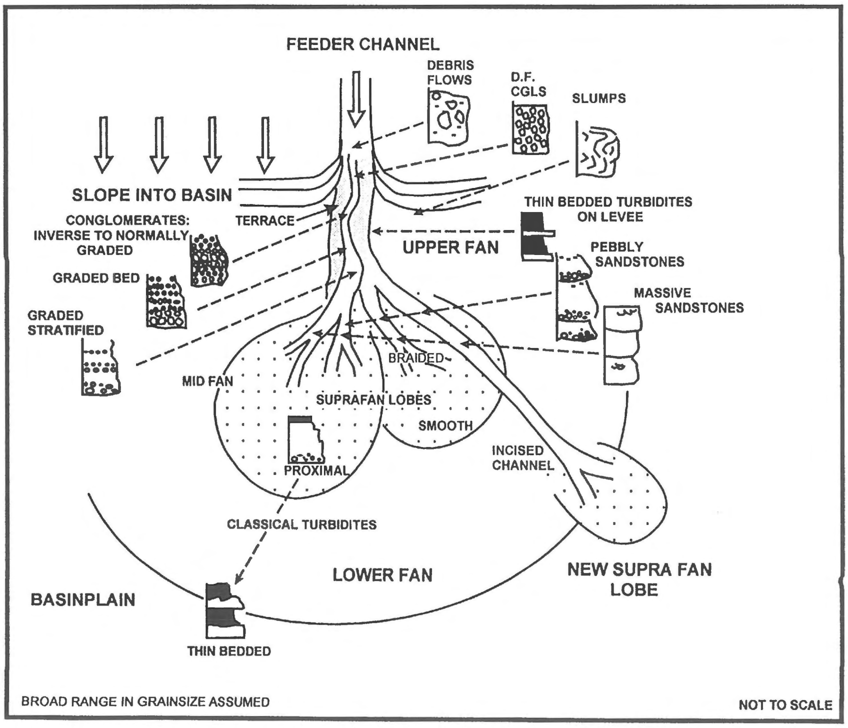
The position of the lithofacies units in DS-1 is illustrated in Figure 8 for deposits belonging to the PT-19, PT-20 and PT-21 bio-zones. Sand-prone deltaic progradation on the shelf (shingled reflections) passes eastward into a shale-prone outer-shelf (sub-parallel reflections). Subsequently it merges into a shale-prone slope (low-angle foresetting) and a shale-prone basinfloor (sub-parallel reflections). In case of massflow sedimentation the basinfloor can also be sand-prone. The term massflow is here used to describe subaquatic sediment transport down a depositional slope induced by gravitational forces and/or density-thermal contrasts. It comprises several different modes of transport, like for example rock fall, sliding, debrisflow and turbulent flow.

The Paleocene slope along the East Shetland Platform is in part fairly sand-rich (e.g. area around Line 12, Figures 1 and 8).

In front of the slope, an onlapping slopefront-fill is often present, containing sand-prone sediments. At two localities, however, such a clear shelf-slope system is absent and here fan-deltas are assumed to be



a) RECENT SUBMARINE FAN MORFOLOGICAL FEATURES (AFTER NORMARK 1978).



b) SUBMARINE FAN FACIES ASSOCIATIONS (AFTER WALKER 1978).

Figure 6. Comparison of the ideal physiographic submarine fan model according to Normark (1978) with the lithofacies association distribution as proposed by Walker (1978).

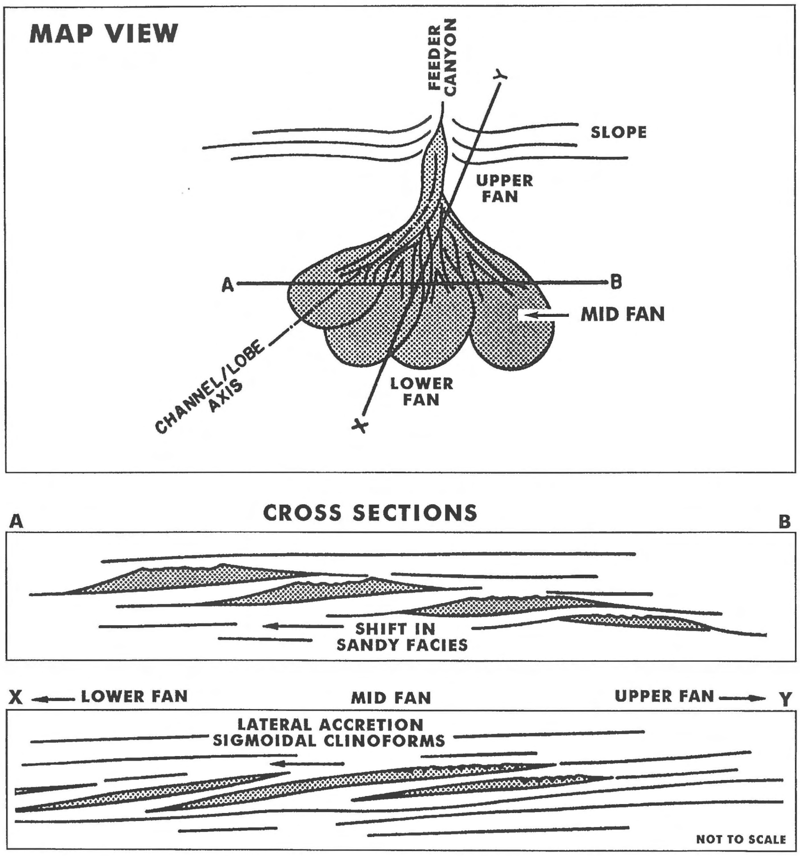


Figure 7. Model for upbuilding submarine fan deposits. Note the lateral shift in depocentre position in time. This shift is triggered by natural causes like discharge fluctuations, bedload upbuilding and/or channel wall instability.

present (Figure 8). Line 2 shows a slopefront prism in front of the East Shetland Platform (Figure 9). Erosion on the platform (subaerial?) resulted in removal of Early Paleocene deposits (pollen zones PT-11 to PT-13). On this line the DS-1 slope deposits, west of well 2/5-6, might either represent a fully marine or a proximal alluvial fan and/or fan-delta complex. The latter interpretation is supported by wells 3/2-3 and 3/3-3, where lignite and dolomite layers have been penetrated and also by the uni-directional character of the foresetting in the 3/3 and 3/4 blocks. Depositional lobe switching in a submarine fan complex would generate more diverse foreset directions (e.g. Tabernas Fan, Kleverlaan 1989). The Paleocene foresetting around the 3/4-4 well hence reflects normal marine shelf-edge progradation (cf. Rochow 1981). A minimum estimate for the waterdepth can be calculated at 700 m by simply measuring the foreset height. An approximate angle of deposition amounts to 0.78°, a normal angle of repose for deep-marine sediments. No compaction effects have been taken into account in these calculations. Differential compaction over a deeper-seated Mesozoic faultblock can play a major role in creating an apparent Paleocene slope on the western part of the section.

Line 15 shows a Paleogene foresetted sediment wedge with the clinoform direction oriented opposite to the regional dip of the underlying Paleozoic–Mesozoic deposits (Figure 10). The Halibut Horst, just north of this line, is separated from the Grampian High by the South Halibut Basin. Geometries suggest that the faultzone, bounding the Halibut Horst, has been active during Paleogene times. This tectonic activity increased the supply of clastics to the South Halibut Basin and resulted in an overall wedge-shaped sediment pile. A decrease of supply in a southerly direction is illustrated by the low-angle downlap onto U-1. The relative importance of U-5 on this line shows that even

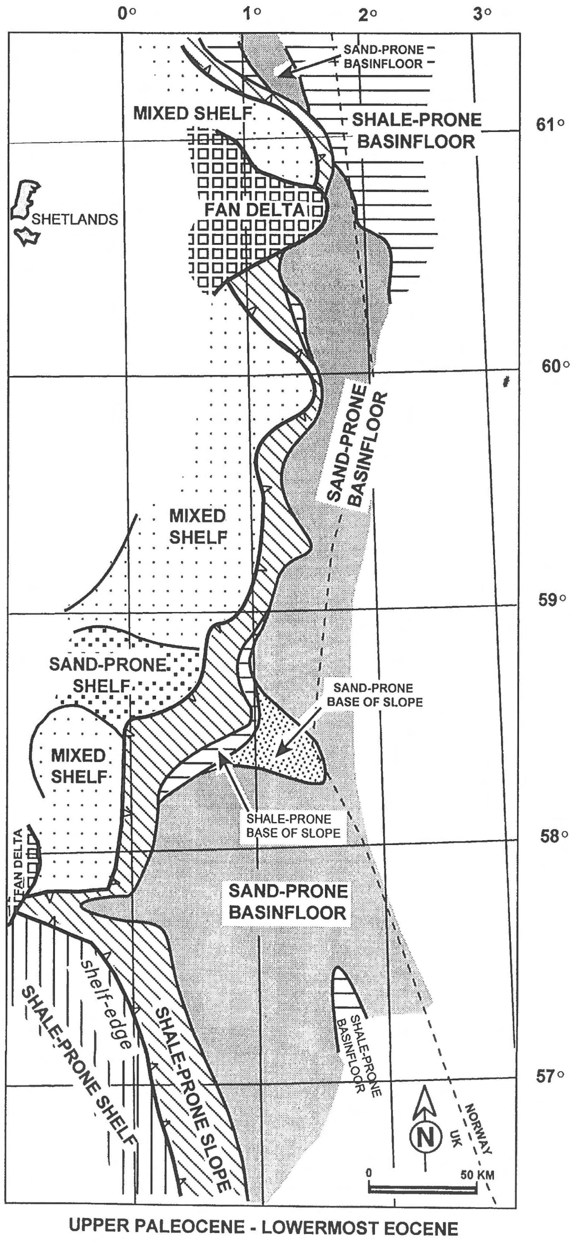


Figure 8. Lithofacies map for the Upper Paleocene to lowermost Eocene sediments (DS-1: PT-19, PT-20 and PT-21 bio-zones), based on the seismic facies distribution. Note the two fan-delta complexes on the shelf sourced from the British hinterland and the presence of a shale-prone shelf in the extreme southwest. The indented shelf-edge just south of latitude 58° N is one of the conduits for massflows derived from the Halibut Horst region and deposited on the adjacent smooth basinfloor. Areas without control are left blank.

in Late Tertiary times differential subsidence occurred. If one assumes that the basinfloor geometry at the end of the Cretaceous was more or less sub-horizontal, than a flattening operation on the top Cretaceous reflection gives an idea of the Early Tertiary depositional topography. It also illustrates that the South Halibut Basin subsided and experienced a rotational tilt in respect to the Grampian area. The low-angle downlaps are thus steepened. The adjacent Halibut Horst, constituted an important positive topographic feature and sediments were laid down directly in front of the Halibut fault scarp in an up- and out-building fan-delta system. Correlation with other seismic lines shows that the toe of this fan system merges distally into sub-parallel topset shelf deposits.

On the shelf various shale-prone and sand-prone lithofacies units can be outlined (Figure 8), based mainly on geometrical appearances: parallel bedding, shingling, hummocky bedding and mounding.

In the Norwegian sector (Line 1, Figure 1) a westward prograding slope system fringes the Scandinavian block. At the base of the slope a slumped and/or redeposited sediment body is present. Time-correlatable shelf sediments are here absent due to later Pleistocene erosion and/or the fact that the shelf area was extremely narrow.

Characteristics of the DS-1 submarine fan deposits

Paleogene mound-shaped sediment bodies occur in the base-of-slope and basinfloor region, and are mainly restricted to the UK side of the North Sea basin. These mounds are interpreted as submarine fan complexes (Fowler 1975, Walmsley 1975, Heritier et al. 1979, Morton 1979, 1982, Sutter 1980, Carman & Young 1981, Ziegler 1990). Locally erosional channels formed conduits for clastics. Several lithofacies units can be distinguished on the basinfloor, each with its characteristic seismic expressions. Figure 11 summarises the characteristics of submarine deposits and gives some examples of seismic units than can be distinguished:

1) *Sand-prone I* (high sand/shale ratio): shingled, parallel, low amplitude.
2) *Sand-prone II* (low sand/shale ratio): parallel, medium amplitude.
3) *Sand-prone III*: parallel, low amplitude.
4) *Mixed sand- and shale-prone*: hummocky, chaotic.
5) *Shale-prone*: parallel, low-medium amplitude.

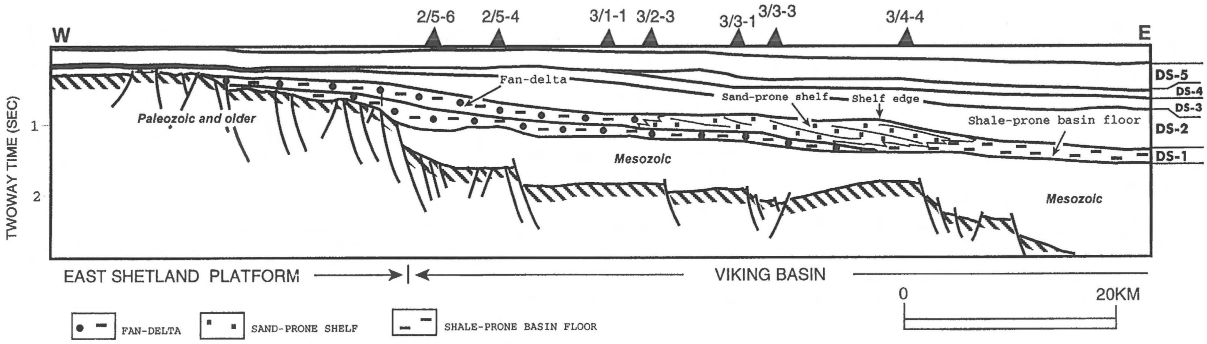


Figure 9. The large-scale sedimentary geometries in the northern North Sea area as recognised on Line 2 (for location see Figure 1). The lignite deposits encountered in the 3/3-3 well support a paleo shelf-edge position in blocks 3/3 and 3/4. A fan-delta system is present on the extreme western part of the section providing clastics to the shelf and the basinal areas.

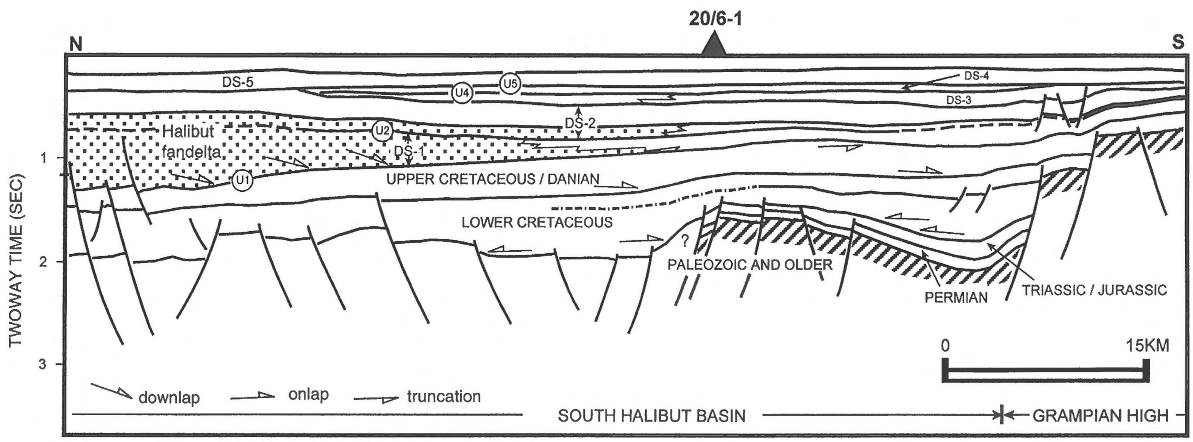


Figure 10. Line 15 depicting the Lower Tertiary Halibut fan-delta (stippled) which was active during tectonic uplift of the adjacent Halibut Horst in the north. For the location of the line see Figure 1. The thickness variation and the degree of tilt shown by the Upper Cretaceous to Lower Tertiary deposits illustrate the tectonic instability of the Halibut Horst region.

Based on external seismic geometries the following types of massflow deposit associations can be distinguished:

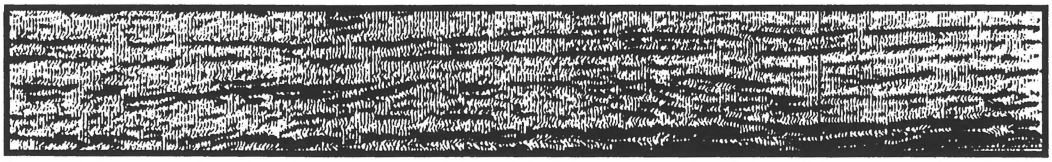
1) *Slope-front fills* accumulating in front of a paleohigh, indicative for bypass of the upper part of the slope and/or axial sediment transport in the basin.
2) *Mound-shaped sediment bodies* reflecting sedimentation in the upper and mid fan regions.
3) *Sheet-like continuous deposits* interpreted as lower mid fan to lower fan sediments laid down in a wider area with uniform sedimentation conditions.

In the upper fan region, slope canyons funnel material downslope to basinal areas. The slope itself is normally shale-prone, but in some areas it can also be sand-rich (around Line 12, Figures 1, 8). A chaotic seismic facies unit reflects the cut-and-fill nature of these slope areas. Numerous stacked erosional events point to the up- and outbuilding nature of these slope deposits.

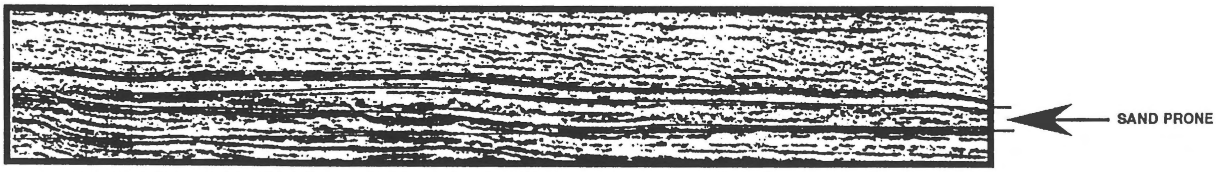
As said already, base-of-slope and basinfloor mounding is observed. It indicates dumping of material (oblique transport component) and/or is the result of differential compaction over sand- and shale-prone deposits. Locally erosive and also non-erosive (on a seismic scale) channel fills with a chaotic seismic facies expression within these mounds are laterally replaced by parallel and/or converging depositional lobe sands; an assembly reflecting a mid fan setting. The distributary channel fills can be either sand-prone (convex upward top) or shale-prone (concave upward top surface). In sections across the distal part of a depositional lobe normally no channeling is observed, but bi-directional low-angle downlap is typically present.

CHARACTERISTICS OF SUBMARINE FAN DEPOSITS

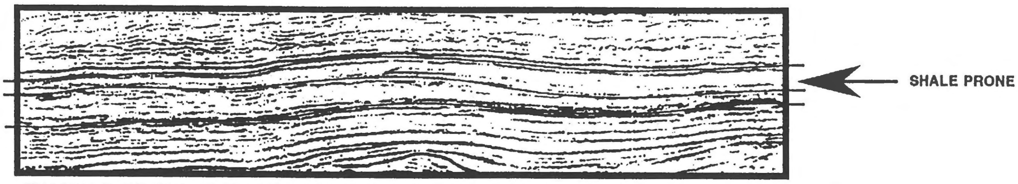
Depositional features	Upper fan	Mid fan	Lower fan
Channel type	Erosional tributary	Erosional / non-erosional distributaries	Not applicable
Levees	Yes	No	
Relative sedimentation rate	Low (bypass)	High	Low
Transportation mode	Traction and suspension	Traction and suspension	Suspension
Seismic facies			
Geometry	Chaotic Low angle foresetting	Hummocky : Mounded Shingled / Parallel Bi-directional shingling	Parallel Low angle converging
Continuity	Low	Medium	High
Reservoir parameters			
Net to gross ratio	Variable	High	Low
Sorting	Poor	Good	Variable
Vertical interconnection	Variable	Good	Poor
Lateral continuity	Low	Variable	High
Geometry	Elongated stringers	Lobate (small area)	Lobate (large area)



EXAMPLE OF BI-DIRECTIONAL DOWNLAP IN A MID FAN POSITION;
CENTRAL PART OF DEPOSITIONAL LOBE MOUND SHOWS A LOW AMPLITUDE AND DISCONTINUOUS SEISMIC FACIES, INTERPRETED AS CHANNELISED DEPOSITS.



EXAMPLE OF LOW-ANGLE FORESETTING IN A MID FAN POSITION;
INTERPRETED AS SAND-PRONE DEPOSITIONAL LOBE OR SUPRA-FAN DEPOSITS.



EXAMPLE OF ONLAP OF SUB-PARALLEL BASINFLOOR DEPOSITS;
INTERPRETED AS SHALE-PRONE DEEP MARINE SEDIMENTS. NOTE ALSO THE PINCH-OUT OF THE LOWER FAN UNIT.

Figure 11. Reservoir and seismic attribute characteristics of depositional units that can be distinguished within submarine fans.

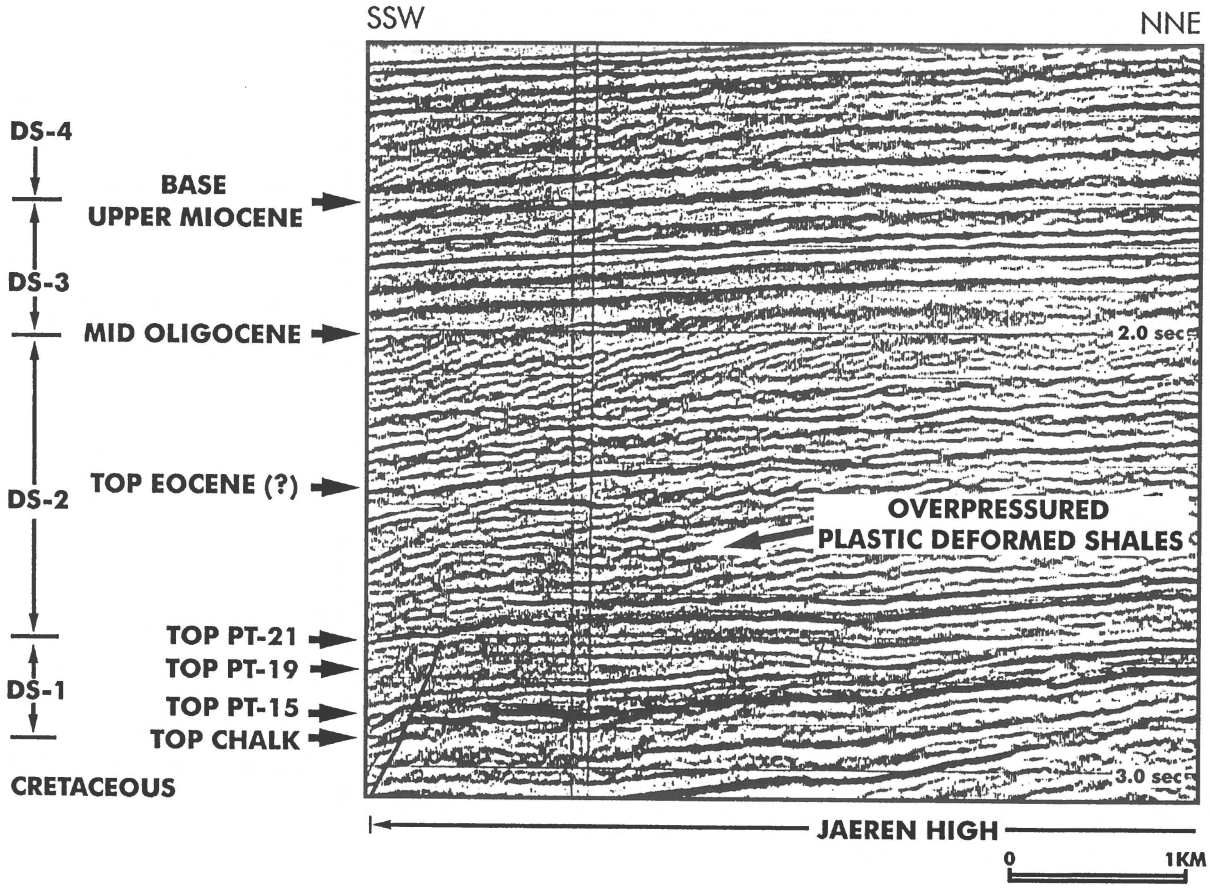


Figure 12. Example of the distal pinch-out of Upper Paleocene PT-19 depositional lobe sands. The late uplift of the Jaeren High created the trap in these reservoirs. The low-reflective PT-19 package is downlapping (apparent onlap) the top PT-15 marker and wedges out towards the east.

An example of the distal pinch-out of Upper Paleocene (PT-19) depositional lobe sands is depicted in Figure 12. Late uplift of the pinch-out results in an apparent onlap relationship.

The DS-1 in the central North Sea area provides good examples of widespread sheet-like massflow deposits on a rather smooth basinfloor. These sheet sands are the product of high-energy massflow currents spreading out rapidly over vast areas. The sands are derived from the uplifted Scottish highlands and are related to tectonic instability along the shelf-edges fringing the Halibut Horst, Witch Ground Graben and Fladen Ground Spur regions. The non-confinement of the massflows points to the lack of shale-prone levees. This can imply that the supply is only coarser grained. Another possibility is that there existed important paleo-bottom currents removing the fine-grained components (cf. Enjolras et al. 1986). In this case it is rather difficult to pinpoint the exact site where the eroded sediments can now be found.

Depositional Sequence 2 (Eocene– Lower Oligocene)

DS-2 infills and drapes the topography of U-2. The depocentre is located basinwards of the former DS-1 shelf-edge. The lithofacies distribution map for the lowermost part of DS-2 (Lower–Middle Eocene, PT-22 and lower PT-23) is shown in Figure 13. The low-angle upbuilding slope geometry shows relatively thick bottomsets. In the south the exact position of the U-2 unconformity is questionable due to the limited data set. In the deeper parts of the basin massflow sedimentation continued. The source areas are largely coinciding with those already existing in the Paleocene. Important internal features are the hydrocarbon-bearing Tay,

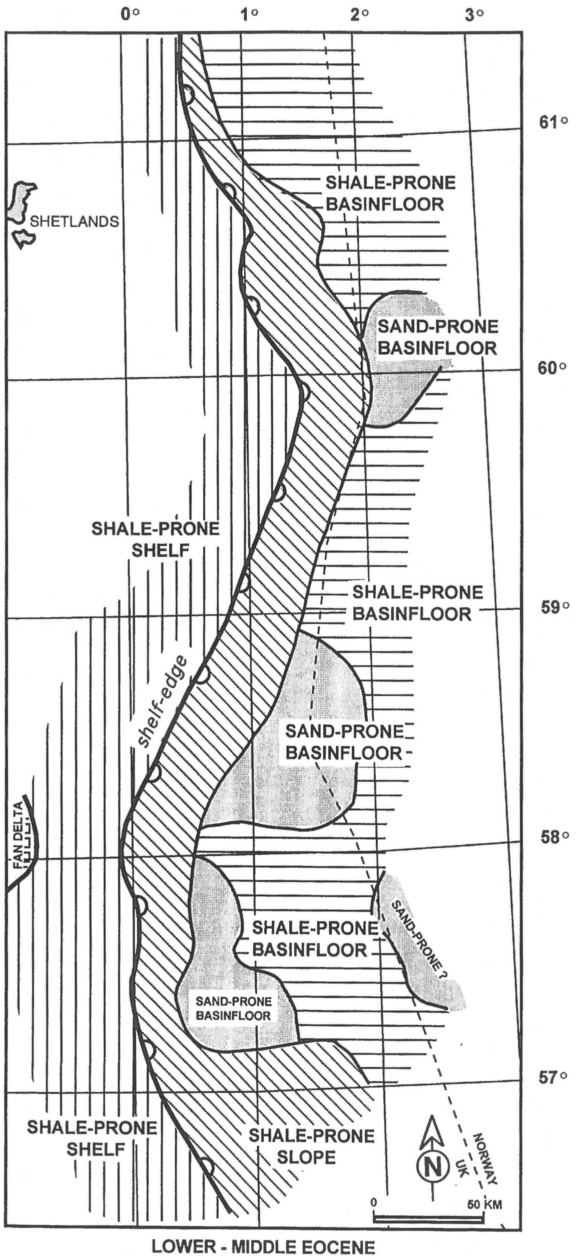


Figure 13. Lithofacies map for the Lower to Middle Eocene (DS-2: PT-22 and lower PT-23 bio-zones) based on seismic facies distribution. Note the shale-prone shelf and the isolated coarser-grained submarine fan complexes on the basinfloor. One of the fans in the south is sourced from the east.

Frigg and Alba fan systems, which can be subdivided into individual systems tracts based on reflection configuration and biostratigraphy.

A shallow-marine barrier complex with shingled foresetting in a topset position, passes into a slope system to the east overlying a Mesozoic fault system (Figure 14). The Paleogene sand-prone barrier complex (shingled unit) is the product of longshore currents. It protected an inner-shelf area where mainly silt and clay accumulated. Lignite layers penetrated in an adjacent well 8/27a-1 point to the existence of swampy coastal lakes landward of the inner shelf. In some cases a strong lignite reflection coincides with the Paleocene–Eocene boundary and can be mistaken for the Thulean tuff marker (also a high-continuity and high-amplitude reflection).

On seismic line 15 (Figure 10) the top boundary U-3 is defined by truncation of DS-2 deposits and onlap of DS-3. Here a local unconformity, separating two systems tracts and resulting from submarine erosion, can be traced. This unconformity coincides more or less with the Eocene–Oligocene boundary (Figure 4).

A typical seismic facies unit is distinguished showing a discontinuous and chaotic seismic character. This facies corresponds to overpressured and under-compacted shales, slumps and/or re-worked submarine fan deposits (Figure 15). Indications for low-angle foresetting can be observed locally.

Depositional Sequence 3 (Upper Oligocene–Middle Miocene)

This sequence largely infills the depositional topography of DS-2. Unconformity U-3 truncates DS-2 and is onlapped by DS-3. This onlap is mainly responsible for the thinning of DS-3 towards the west. The top-boundary U-4 is defined by truncation and by onlap of DS-4.

In DS-3 a low-angle upbuilding slope system is recognised with rather thick bottomsets, pointing to axial transport in the basin. Both sand-prone and shale-prone topsets can be delineated. In the north, sand-prone clastics, derived from the East Shetland Platform as well as the Norwegian region in the east, were laid down in a deeper marine environment. The loading effect and inefficient de-watering of shales caused plastic deformation (sticky shales in wells). In the south, only shale-prone deposits are encountered.

A relatively thick prograding clastic slope wedge is present on lines in the Norwegian sector. On some lines a high-amplitude erosional unconformity is interpreted to represent the base of the Miocene.

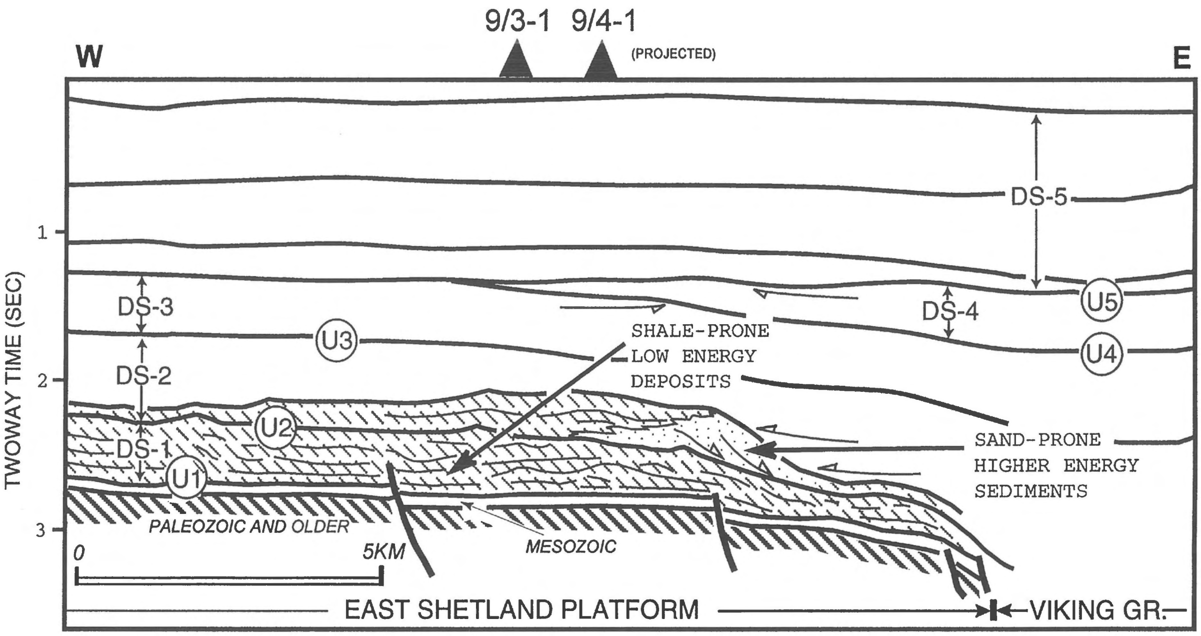


Figure 14. Line 7 shows a shallow-marine barrier complex within DS-2, characterised by a shingled seismic facies, that protected a low-energy shale-prone inner shelf. For the location of the line see Figure 1. The higher-energy low-angle slope system of DS-2 is transitional to basinfloor deposits that accumulated eastward of the graben boundary fault. For reflection termination symbols see Figure 10.

Depositional Sequence 4 (Upper Miocene–Lower Pleistocene)

This sequence varies considerably in thickness and thins towards the west. The basal unconformity U-4 is defined by truncations of the underlying unit. The overlying deposits show downlap and also onlap relationships.

Again a low-angle slope system is recognised. A prograding slope system along the eastern margin of the Viking Graben indicates high sediment input from the Scandinavian hinterland, while relatively smaller amounts of clastics were derived from the East Shetland Platform and Moray Firth areas. South of latitude 58° N the slope system is essentially upbuilding and contains only fine-grained sediments.

In the southern area, local erosional features within this sequence are confined to slope areas. These features show a rather stable position in time (Figure 16). They can be interpreted as a stationary distributary system (meandering), funnelling clastics downslope. The main progradation direction is from the south-southeast with a thinning towards the west. The associated pull-up effect observed on the deeper underlying reflector might point to a higher-velocity infill of these features. It is also possible that the phenomenon is not erosional in nature, but is related to plastic deformation of an underlying shale layer. A pull-down effect may indicate therefore the presence of overpressured shales. The localised character of these features could possibly support such an origin.

Depositional Sequence 5 (Upper Pleistocene–Recent)

DS-5 thickens and becomes somewhat more shale-prone towards the south and the centre of the basin. The basal unconformity U-5 is defined by truncations and onlap. The erosional contact reflects the glacially induced Pleistocene sealevel lowstand.

The sequence is mainly built by sub-parallel reflections with variable continuity and amplitude. Only in the northern part of the Viking Graben, prograding slope sediments are present. Low-angle foresets are oriented towards the northeast and material is derived from the East Shetland Platform. The bulk of the DS-5 clastics is derived from the south. Several local unconformities separate individual systems tracts. Pronounced canyon and channel geometries

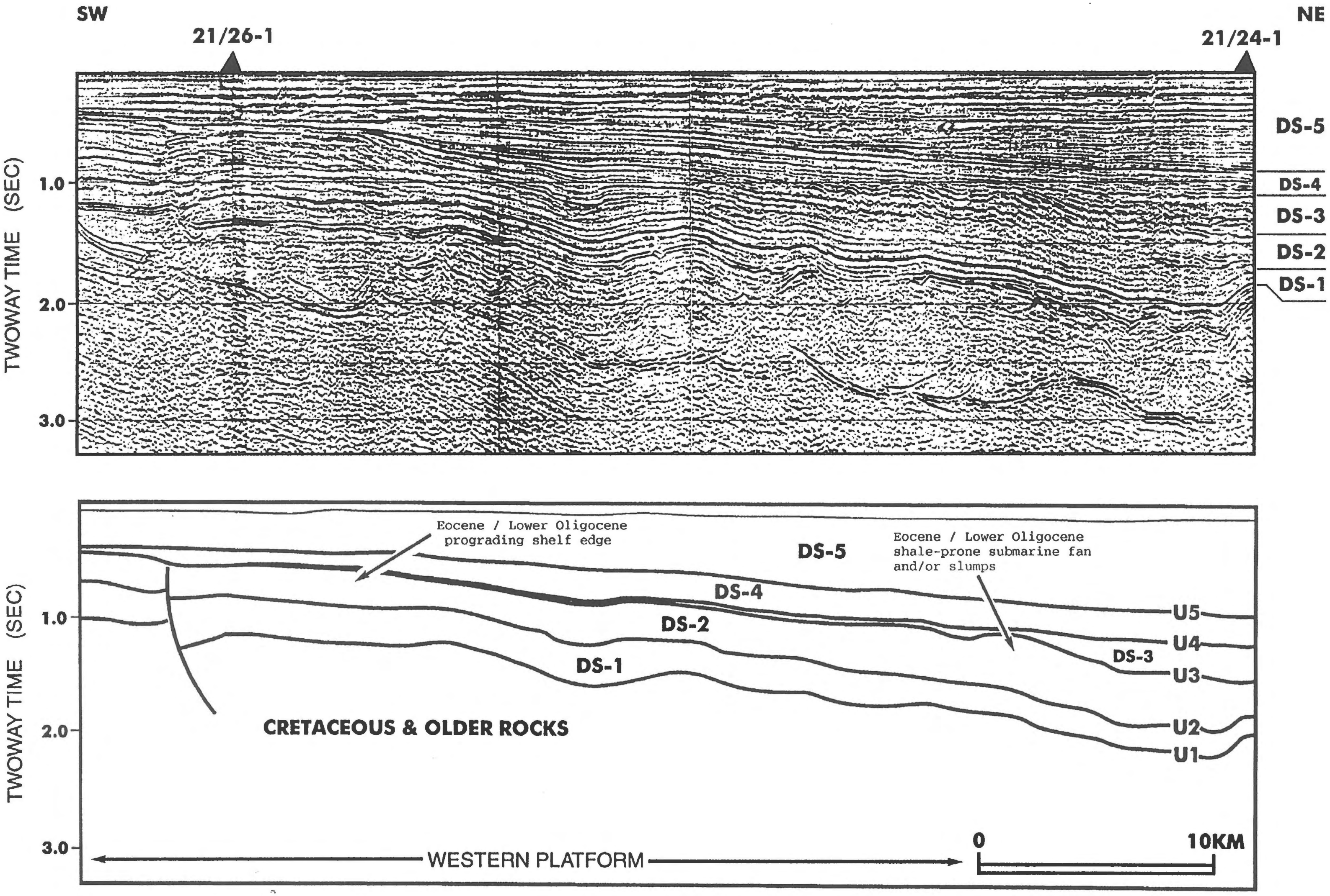


Figure 15. Example of seismic geometries as encountered on the Western Platform. The Tertiary sediments are affected by Zechstein salt diapirism and a listric growth-fault exists west of well 21/26-1. An Eocene to Lower Oligocene prograding and upbuilding shelf-edge is indicative for rising baselevel conditions. At the base of the slope, mounded geometries at the U-3 level represent reworked submarine fan deposits, slumped material, and/or plastically deformed overpressured shales.

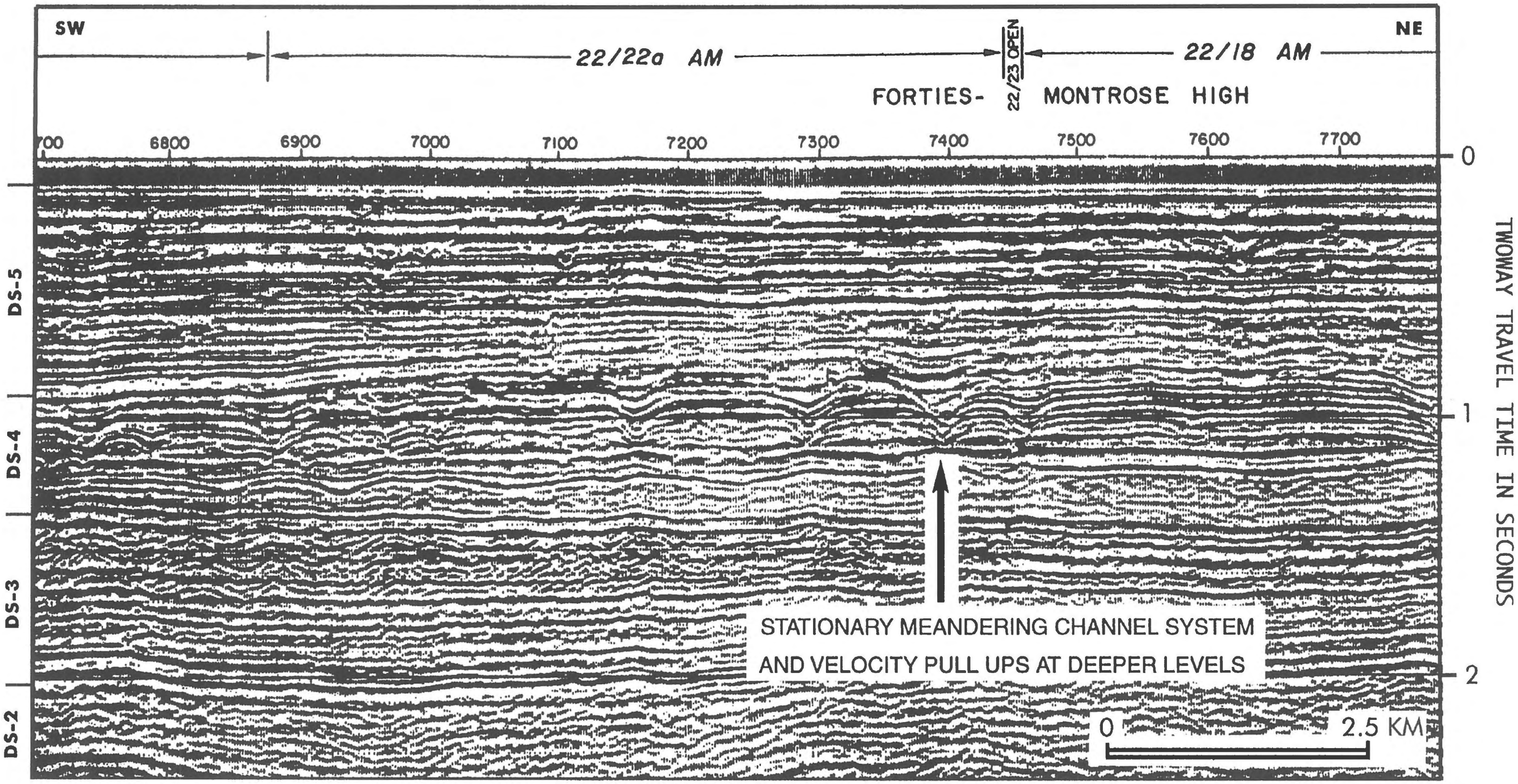


Figure 16. Aggrading distributary channel system in the Upper Tertiary sequence DS-4 of the central North Sea Basin. Only minor lateral shifts in channel axis position are observed. The geometry, shown by this low-angle foresetted prodelta sequence, suggests that subsidence and sedimentation rates were both rather high and more or less in equilibrium. Such conditions are necessary to preserve the sediments. Note also that the different interval velocities for the channel infills result in a pull-up effect on deeper horizons. The geometry may also be due to an early plastic deformation of the directly underlying shale sequence. The velocity deformation of the deeper reflectors would then represent a pull-down effect where the shales are thickest. A short lateral extent of these features would be in line with the latter deformational model.

relate to glacially induced sealevel lowstands. Precise dating of these unconformities is difficult because of the intersecting nature of the events and the lack in biostratigraphic datings.

Hydrocarbon habitat and occurrence

The Tertiary massflow deposits (DS-1, DS-2 and DS-3) form prolific hydrocarbon reservoirs in the North Sea Basin; e.g. the Forties (Carman & Young 1981, Wills & Peattie 1988), Nelson (Whyatt et al. 1991), Montrose (Fowler 1975), Gannet (Armstrong et al. 1987), Frigg (Heritier et al. 1979), Forth (Alexander et al. 1991), Alba (Winter et al. 1989) and Everest (Thompson & Butcher 1990) fields. In general the reservoir characteristics are excellent with porosities of up to 35% and permeabilities in the order of 1500 milli-Darcy.

Structuration is provided by the depositional morphology overprinted by differential compaction effects, reactivation of older fault trends and also ongoing salt tectonics.

Charge for the Tertiary traps is mainly derived from mature Jurassic source rocks in the regional kitchen situated in the deeper graben and platform areas (cf. Goff 1983). Connections are envisaged via vertical faults and along the flanks of Zechstein salt piercements (cf. Chiarelli & Issard 1990). Relatively long migration distances have to be assumed, in some cases up to 60 km, to fill individual structures. Additional source rock intervals have been encountered in the Cretaceous (e.g. 22/9-1 well) and also within the Lower Tertiary (PT-19 and PT-20 shales; e.g. 23/16-1 well). The latter interval can be marginally to fully mature in deeper parts of the North Sea Basin. The lower part of the Paleocene is relatively wood-prone while the lowermost Eocene is rich in amorphous organic matter, reflecting a dysoxic to anoxic environment in the centre of the basin (Goodall et al. 1991). Contributions from Tertiary source rocks are considered however too insignificant to explain the presently known accumulations. The oils discovered in the Paleogene range in API gravity between 12 to 42°. The low gravity can be explained by bacterial degradation of the hydrocarbons in the reservoir. Biogenic gas has been encountered in the Upper Tertiary sequence.

Some of the accumulations show on seismic 'Direct Hydrocarbon Indicators' like amplitude anomalies, flat spots and also gas chimneys, e.g. Gannet (Armstrong et al. 1987) and Frigg (Heritier et al. 1979). The generation of a proper fluid-contact reflection (mostly a flat event) is depth-dependent and in many cases it is obscured by tuning effects around thin beds (Figure 5).

Most of the Tertiary traps are drilled on structural and depositional dipclosures. Only a limited number of stratigraphic traps have been penetrated (e.g. Gannet, Alba). Detailed seismic stratigraphic mapping is needed to support the definition of subtle stratigraphic traps within the stacked Paleogene submarine fan complexes.

Also Plio-Pleistocene deposits should be given attention as proven depositional structuration provides the required trap potential. Connection to a kitchen is envisaged along graben boundary faults, flanks of salt domes, and the faults in their collapsed crestal areas. The shallow burial and limited pressures do not favour large accumulations. Attention should focus on large structures with little elevation that are difficult to map. Examples of such structures are the Alba field, the PT-22 and PT-23 pinch-out in UK block 21/17, or the Paleogene stratigraphic trap in the Norwegian block 16/4 (Fagerland 1984). Disappointingly the latter two traps have been proven dry due to lack in charge and/or retention problems. The weak seismic response, caused by a limited acoustic impedance contrast between hydrocarbon-filled sands and the overlying shales at shallow depth, and also the depth-conversion problems do not facilitate the identification of such traps.

Cenozoic depositional evolution of the northern and central part of the North Sea area

The Cenozoic North Sea Basin forms basically a wide sagged depocentre over a complex Paleozoic-Mesozoic graben system. It developed in response to the gradual lithospheric cooling of an underlying Mesozoic rift dome (Ziegler 1983). The main graben features were infilled by the end of the Cretaceous. Some graben boundary faults have been active up to Miocene times. The general tilt of the deposits on the platform areas (i.e. rift shoulders) and the fault activity point to differential subsidence in the Tertiary. Accelerated basin subsidence during the Paleocene, with respect to a normal lithospheric cooling model, is proposed by Joy (1993). It is probably related to the opening of the Atlantic Ocean between Norway and Greenland. It equally coincides with the change in hotspot position from the Faeroe Ridge to Iceland.

The Cenozoic sediments show in general only evidence for minor faulting due to compaction and slope instability. Local salt tectonics is however an important deforming factor for the Tertiary sediments (e.g. saltdomes in blocks 29/3, 29/8 and 23/16) and may affect the entire Mesozoic to Quaternary sequence. Recent dissolution of these saltdomes along aquifer interfaces cannot be excluded, with possibly some salt flow still going on internally.

A major break in sedimentation is caused by an Early Paleocene tectonic pulse, responsible for the uplift and eastward tilt of the East Shetland Platform (Ziegler 1982b). Pelagic carbonate deposition ceased and clastic sedimentation took over. From the basin margins, clastics were shed into the largely infilled Mesozoic graben system. Sands are mainly derived from the Scottish highlands and the Moray Firth area. Heavy mineral assemblages suggest Lower Jurassic sands and metamorphic basement rocks to be the main sources (Morton 1979). Fission track studies indicate an uplift of at least 1 km of these source areas during Tertiary times (Den Hartog Jager et al. 1993). Several depositional episodes are recognisable in the DS-1 sedimentary cycle. The significance of these episodes is especially evident in the stacked submarine fans at the basinfloor, which now form important hydrocarbon reservoirs.

Thick piles of clastics accumulated in a coalescing slope-front prism in front of the East Shetland Platform fault scarp. A relative sealevel rise is indicated by the upbuilding nature of the topset shelf deposits. Sand-prone and mixed shale- and sand-prone areas existed on the shelf. Two different fan-delta systems formed important input sources (Figure 8). The submarine fan complex can be classified as a multiple-source submarine fan with a mud- and sand-rich development (cf. Reading & Richards 1994).

The northern part of the East Shetland Platform was subject to subaerial erosion in Early Paleocene (PT-11 and PT-13) times. The shelf-edge position was controlled by the fault zone bounding the East Shetland Platform to the east. In the south the basin slope is underlain by tilted Mesozoic fault blocks. DS-1 equivalent sediments (PT-20 and PT-21 ?) exhibit a depositional slope system prograding and sourced from the Scandinavian side. Its contribution to the study area is however very limited and is restricted to shale-prone sediments on the basinfloor.

Indications for important tectonic movements, apart from a degree of general tilting during the Paleocene, are found in Quadrants 9, 16 and 20.

South of 58° N latitude the Paleocene shelf-edge position is not coinciding with the Early Eocene shelf margin. The Paleocene shelf-edge of DS-1 is more serrate and located further to the west (Figure 8). An embayment existed between the Halibut Horst and the Grampian High. High-energy massflow currents, derived from the fan-delta system fringing the Halibut Horst, spread out over the adjacent shelf and into this embayment. These little-confined massflow sheet-sands show a rather high sand/shale ratio. They were deposited on a rather smooth basinfloor (estimated water-depth 400 to 800 m) and demonstrate a gradual thinning in a northerly and easterly direction. With time these massflows tend to show more confined geometries, and mounded structures become more evident. These mounds are indicative for an axial transport component oriented towards an easterly to south-southeastly direction.

During Early Eocene times (PT-20 and PT-21), massflow deposition continued. Anoxic sedimentation conditions occurred in the deepest parts of the basin (cf. Goodall et al. 1991), where organic material was preserved from oxidation. Windblown and reworked volcanic ashes, derived from the Thulean Province and the Erlend complex north of the Shetlands (Gatliff et al. 1984), were additional sources for sediment supply. More or less starved sedimentation conditions, due to a relative rise in sealevel, favoured the enrichment in both volcano-clastic material and organic matter. On the basinfloor there is a tendency to develop from now on more isolated fan systems. The sand-prone massflow sediments belonging to DS-2 are more confined to isolated depocentres (cf. Den Hartog Jager et al. 1993). A relative increase in shale contents of the deposits cannot be ruled out. The clastics were mainly supplied from the west with only minor input from the Vestland–Utsira High. The coalescent character and the different geometries displayed by the various Paleogene submarine fan complexes are illustrated in Figure 17.

The gradual decrease in sand supply from the west in Eocene times can be related to subsidence of the Rockall–Faeroe rift dome (cf. Ziegler 1978). Deformation of Eocene sediments suggests syn-sedimentary tectonics in Quadrant 9. Onlap of deeper-marine shales in the north points to a relative rise in sealevel. A subtle low-angle shelf and slope system can be recognised. Another slope system is located along the border of the Scandinavian block further to the east.

Local submarine erosion accentuates the base Oligocene unconformity in the Central North Sea and the southern part of the Viking Graben, without reflecting a major change in the mode of deposition.

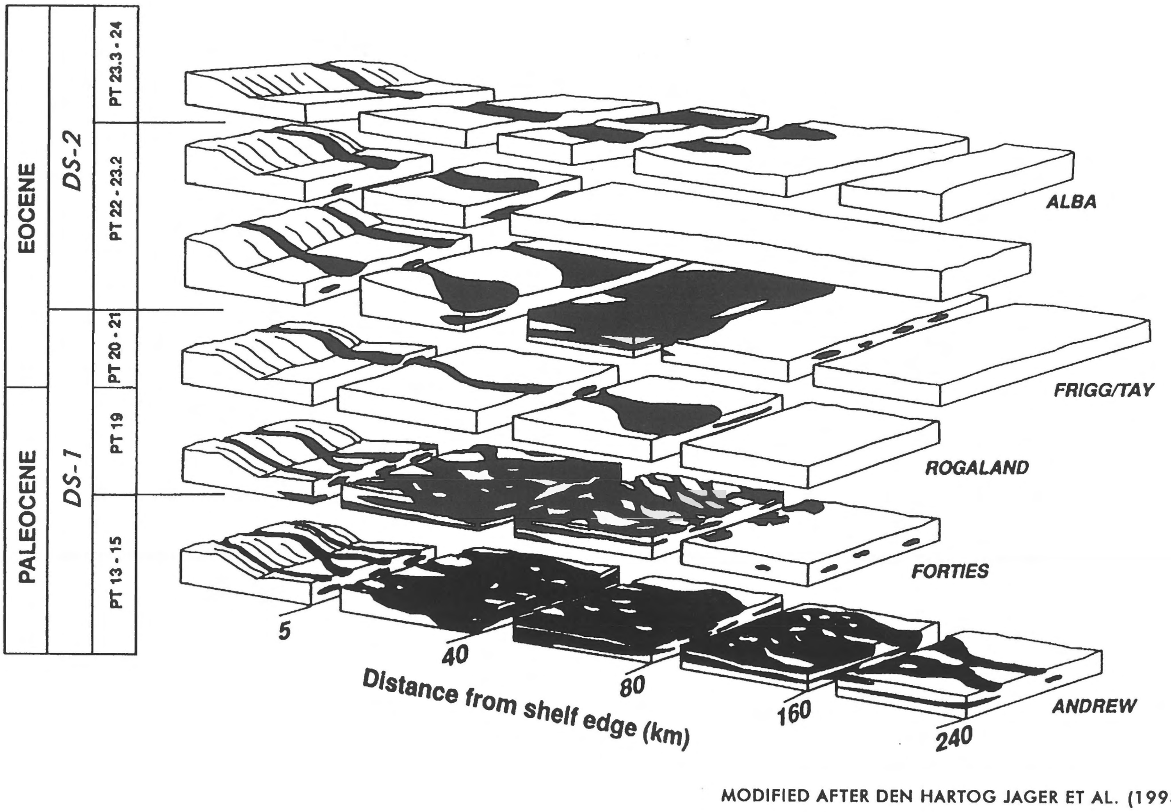


Figure 17. Geometries displayed by Paleogene submarine complexes in the UK North Sea region (after Den Hartog Jager et al. 1993). Sand-prone submarine fan sediment bodies are shown in black. Note the change from non-confined sheet-like deposits in DS-1 (PT-13 and PT-15; Andrew Fm) towards the more isolated fan units of the younger DS-2 (PT-23 and PT-24; Alba Fm) deposits.

A minor drop in relative sealevel, leading to truncation of the Eocene–Lower Oligocene sequence (DS-2), was followed by a renewed rise that resulted in onlap of DS-3 deposits. In Late Oligocene to Middle Miocene times, low-angle slope systems existed along the East Shetland Platform and the Scandinavian shield. In a southerly direction, where the main depocentre was located, the shale-prone sediments represent a low-energy protected shallow-marine environment. Thinning of the sequence to the west is the result of onlap and erosion on the shelf during the glacially induced Mid-Pleistocene sealevel lowstand.

During the Mid-Miocene eustatic sealevel lowstand, submarine erosion occurred in basinal areas, while on the previous shelf area subaerial erosion took place. Intra-plate stresses, correlated to plate tectonic adjustments in the Alpine hinterland, resulted in differential movements within the North Sea area. Low-angle slope systems existed along the East Shetland Platform (DS-4). The shelf break along the Scandinavian block is even more prominent. The bulk of the clastics consists of shaly deposits, but in the north also coarser material accumulated. The rapid loading of the underlying DS-3 shales during burial caused overpressuring due to inefficient dewatering and resulted in plastic deformation. Two discrete low-angle foresetted shale-prone systems indicate the Vestland–Utsira High and the East Shetland–Moray Firth regions as two discrete source areas. A stationary distributary channel system on the upbuilding slopes funnelled material to the basinfloor (Figure 16). The upbuilding character reflects a relative rise in sealevel correlatable to a Middle Miocene global event that was reported upon by Vail et al. (1977a) and Haq et al. (1988).

During the Mid-Pleistocene sealevel lowstand, older sequences were truncated and a renewed rise in baselevel resulted in onlap geometries of DS-5 sediments. Three regional glaciations have affected the area in Quaternary times: the Elsterian, Saalian and Weichselian events (Cameron et al. 1987). During these episodes major erosional canyons and/or valleys (up to 10 km wide and more than 400 m deep) were cut into the basin fill. The stacked nature of the unconformities makes it difficult to trace individual events over the whole seismic grid. Their exact dating is hampered by lack in biostratigraphic analysis. Channels are orientated mainly in a N–S direction. In recent times deeper marine sedimentation conditions only prevail in the extreme north-northeast, where also the recent shelf-edge is located. The main depocentre for the Upper Pleistocene to Recent is situated in the south; it is infilled with predominantly shale-prone sediments. On the shelf frequent channelling is observed. In contrast to the underlying Oligocene to Lower Pleistocene series the bulk of the sediment input was derived from the eastern margin of the basin, where uplift of the Scandinavian block is still occurring today.

Conclusions

Seismic stratigraphic study techniques allow to unravel the Cenozoic depositional history of the northern and central parts of the North Sea area, despite the miscellaneous nature and limited size of the available dataset. Five regional depositional sequences are recognised in the Cenozoic basinfill. A further breakdown into individual systems tracts can be implemented by using local unconformities. These systems tracts are thought to be related to baselevel changes (tectonics and relative sealevel position), variations in the sediment supply and/or natural switching of depocentre location in fan systems due to fluctuations in discharge.

The iterative seismic stratigraphic approach is a powerful tool to delineate the lithofacies distribution, especially for studies concerned with heterogeneous datasets. Seismic stratigraphic investigation techniques provide a consistent frame for dating sediments by considering reflections as a sort of ‘time line’. In the North Sea area the biostratigraphic method is hampered by reworking, caving, poorly developed faunas and also by the diversity in oil-companies involved carrying out the analyses. A denser seismic grid and more well control are needed to increase the accuracy of the paleo-geographical maps and the gross lithological predictions.

The presence of two Paleogene fan-deltas along the margin of the deeper basin is documented. They form important input sources for clastics derived from the East Shetland Platform and the Halibut Horst areas.

Lower Tertiary massflow deposits in the North Sea Basin constitute prolific hydrocarbon reservoirs. Charge is provided by mature Jurassic source rocks with the kitchen located in the deeper graben and platform areas. A connection is envisaged via permeable rocks, vertical faults and along Zechstein salt domes. In some cases relatively long migration distances of over 60 km have to be assumed. Contribution from Cretaceous and marginally mature Tertiary source rocks is conjectural.

Most of the Tertiary traps are drilled on structural and depositional dip-closures, where the quality of the base seal has little importance. Few wells are drilled on stratigraphic traps (e.g. Gannet, Alba). Detailed seismic stratigraphic mapping is needed to support definition of stratigraphic traps within the stacked Paleogene submarine fan complexes. The overlying Neogene sequence should also be given attention as the occurrence of more isolated sand stringers (e.g. the Alba feeder-lobe complex) cannot be ruled out beforehand. In the Neogene the acoustic impedance contrast between sands and shales can be rather low and therefore the delineation of prospects is depending on subtle seismic variations that are difficult to trace.

Acknowledgements

The author expresses his gratitude to the Shell UK Exploration & Production and PGS NOPEC UK Ltd companies for granting permission to publish their data. Various colleagues are thanked for their enthusiasm and constructive comments. The suggestions, made by N.J. Milton (BP Norge), W.J.E. Van de Graaff (SIPM) and the reviewers, have been highly appreciated and resulted in an improved manuscript. The INPL (Institut National Polytechnique de Lorraine), the ENSG (Ecole Nationale Supérieure de Géologie) and the LSTS (Laboratoire des Structures et Transferts en milieu Sédimentaire) are thanked for their support and financial assistance in the final preparation of this publication.

References

Alexander, R.W.S., K. Schofield & M. Williams 1991 Understanding the Forth field reservoir, Block 9/23B: myths of deep sea sands exploded. In: EAPG. 3D Conference, Florence Italy, Technical Programme and Abstracts, E44 – Eur. Ass. Petroleum Geol., Zeist: 48, 49

Armstrong, L., T. Ten Have & H.D. Johnson 1987 The geology of the Gannet fields, Central North Sea, U.K. sector. In: J. Brooks & K.W. Glennie (eds) Petroleum Geology of North West Europe – Graham & Trotman, London: 533–548

Brennand, T.P. & F.R. van Veen 1975 The Auk oil-field. In: A.W. Woodland (ed) Petroleum and the continental shelf of NW Europe, Vol. 1 – Applied Science, Barking: 275–283

Cameron, T.D.J., M.S. Stoker & D. Long 1987 The history of Quaternary sedimentation in the UK sector of the North Sea Basin – J. Geol. Soc. London 144: 43–58

Carman, G.J. & R. Young 1981 Reservoir geology of the Forties oilfield. In: L.V. Illing & G.D. Hobson (eds) Petroleum geology of the continental shelf of northwest Europe – Heyden, London: 371–379

Chiarelli, A. & F. Issard 1990 Central Graben (Norway): Hydrocarbon distribution related to source rock maturation, Abstract – Amer. Ass. Petroleum Geol. Bull. 74: 627

Damuth, J.E., R.D. Flood, R.O. Kowsmann, R.H. Belderson & M.A. Gorini 1988 Anatomy and growth pattern of Amazon deep-sea fan as revealed by Long-Range Side-Scan Sonar (GLORIA) and high-resolution seismic studies – Amer. Ass. Petroleum Geol. Bull. 72: 885–911

Deegan, J.C. & B.J. Scull 1977 A proposed standard lithostratigraphic nomenclature for the Central and Northern North Sea – Report Inst. Geol. Sciences 77/25, Bull. Norw. Petroleum Direct. 1, 36 pp

Den Hartog Jager, D., M.R. Giles & G.R. Griffiths 1993 Evolution of Paleogene submarine fans of the North Sea in space and time. In: J.R. Parker (ed) Petroleum Geology of North Western Europe. Proc. 4th Conf. – Geol. Soc. London: 59–71

Enjolras, J.M., J. Gouadain, E. Mutti & J. Pizon 1986 New turbiditic model for the lower Tertiary sands in the South Viking Graben. In: A.M. Spencer et al. (eds) Habitat of Hydrocarbons on the Norwegian Continental Shelf – Norw. Petroleum Soc., Graham & Trotman, London: 171–178

Evans, A.L., F.J. Fitch & J.A. Miller 1973 Potassium-argon age determinations on some British Tertiary igneous rocks – J. Geol. Soc. London 129: 419–443

Fagerland, N. 1984 A rift related stratigraphic trap – J. Petroleum Geol. 7/2: 227–236

Fowler, C. 1975 The geology of the Montrose Field. In: A.W. Woodland (ed) Petroleum and the continental shelf of NW Europe, Vol. 1 – Applied Science, Barking: 467–477

Gatliff, R.W., K. Hitchen, J.D. Ritchie & D.K. Smythe 1984 Internal structure of the Erlend Tertiary volcanic complex, north of Shetland, revealed by seismic reflection – J. Geol. Soc. London 141: 555–562

Goff, J.C. 1983 Hydrocarbon generation and migration from Jurassic source rocks in the East Shetland basin and Viking graben of the Northern North Sea – J. Geol. Soc. London 140: 445–474

Goodall, J., S. Wood & R. Tyson 1991 North Sea Paleogene palynofacies, Abstract – Palynology 15: 243

Haq, B.U., J. Hardenbol & P. Vail 1988 Mesozoic and Cenozoic chronostratigraphy and cycles of sealevel change. In: C.K. Wilgus et al. (eds) Sealevel changes: An integrated approach – Soc. Econ. Paleontol. Mineral., Spec. Publ. 42: 71–108

Harding, A.W., T.J. Humphrey, A. Latham, M.K. Lunsford & M.H. Strider 1990 Controls on Eocene submarine fan deposition in the Witch Ground Graben. In: R.F.P. Hardman & J. Brooks (eds) Tectonic Events Responsible for Britain's Oil and Gas Reserves – Geol. Soc. London, Spec. Publ. 55: 353–367

Harms, J.C., P. Tackenberg, E. Pickles & R.E. Pollock 1981 The Brae oil field area. In: L.V. Illing & G.D. Hobson (eds) Petroleum geology of the continental shelf of northwest Europe – Heyden, London: 352–357

Heritier, F., E. Lossel & E. Wathne 1979 Frigg field: Large submarine fan trap in Lower Eocene rocks of the North Sea Viking Graben – Amer. Ass. Petroleum Geol. Bull. 63: 1999–2020

Hitchen, K. & J.D. Ritchie 1987 Geological review of the West Shetland area. In: J. Brooks & K.W. Glennie (eds) Petroleum Geology of North West Europe – Graham & Trotham, London: 737–750

Jacque, M. & J. Thouvenin 1975 Lower Tertiary tuffs and volcanic activity in the North Sea. In: A.W. Woodland (ed) Petroleum and the continental shelf of NW Europe, Vol. 1 – Applied Science, Barking: 455–465

Jenyon, M.K. 1986 Some consequences of faulting in the presence of a salt rock interval – J. Petroleum Geol. 9/1: 29–52

Jones, R.W. & N.J. Milton 1994 Sequence development during uplift: Palaeogene stratigraphy and relative sea-level history of the Outer Moray Firth, UK North Sea – Marine and Petroleum Geol. 11/2: 157–165

Joy, A.M. 1993 Comments on the pattern of post-rift subsidence in the Central and Northern North Sea Basin. In: G.D. Williams & A. Dobb (eds) Tectonics and seismic sequence stratigraphy – Geol. Soc. London, Spec. Publ. 71: 123–140

Kennedy, W.J. 1987 Late Cretaceous and Early Paleocene Chalk Group sedimentation in the Greater Ekofisk area, North Sea Central Graben – Bull. Centr. Rech. Explor.-Production Elf-Aquitaine 11: 91–126

Kleverlaan, K. 1989 Three distinctive feeder-lobe systems within one time slice of the Tortonian Tabernas fan, SE Spain – Sedimentology 36: 25–45

Knox, R.W.O.B. & A.C. Morton 1983 Stratigraphical distribution of Early Paleocene pyroclastic deposits in the North Sea Basin – Proc. Yorkshire Geol. Soc. 44: 355–363

Knox, R.W.O.B. & A.C. Morton 1988 The record of Early Tertiary N. Atlantic volcanism in sediments of the North Sea Basin. In: A.C. Morton & L.M. Parson (eds) Early Tertiary Volcanism and the Opening of the NE Atlantic – Geol. Soc. London, Spec. Publ. 39: 407–419

Knox, R.W.O.B., A.C. Morton & R. Harland 1981 Stratigraphic relationships of Paleocene sands in the UK sector of the Central North Sea. In: L.V. Illing & G.D. Hobson (eds) Petroleum geology of the continental shelf of northwest Europe – Heyden, London: 267–281

Kooi, H. & S.A.P.L. Cloetingh 1989 Intraplate stresses and the tectono-stratigraphic evolution of the central North Sea – Amer. Ass. Petroleum Geol. Mem. 46: 541–558

Kulpecs, A.A. & L.C. Van Geuns 1990 Geological Modelling of a Turbidite Reservoir, Forties Field, North Sea. In: J.H. Barwis, J.G. McPherson & R.J. Studlick (eds) Sandstone Petroleum Reservoirs – Springer Verlag, New York: 489–508

Lewis, C.L.E., A. Carter & A.J. Hurford 1992 Low-temperature effects of the Skye Tertiary intrusions on Mesozoic sediments in the Sea of Hebrides Basin. In: J. Parnell (ed) Basins on the Atlantic Seaboard: Petroleum Geology, Sedimentology and Basin Evolution – Geol. Soc. London, Spec. Publ. 62: 175–188

Lovell, J.P.B. 1984 Cenozoic. In: K.W. Glennie (ed) Introduction to the petroleum geology of the North Sea – Blackwell Scientific Publ., Oxford: 151–169

Morton, A.C. 1979 The provenance and distribution of the Paleocene sands of the Central North Sea – J. Petroleum Geol. 2/1: 11–21

Morton, A.C. 1982 Lower Tertiary sand development in the Viking Graben, North Sea – Amer. Ass. Petroleum Geol. Bull. 66: 1542–1559

Mudge, D.C. 1979 The Cretaceous/Tertiary boundary in the Northern North Sea. In: W.K. Christensen & T. Birkeland (eds) Proc. Symposium on Cretaceous-Tertiary boundary events – Univ. Copenhagen, Copenhagen: 95–102

Mussett, A.E., R. Dagley & R. Skellhorn 1988 Time and duration of activity in the British Tertiary Igneous Province. In: A.C. Morton & L.M. Parson (eds) Early Tertiary Volcanism and the Opening of the NE Atlantic – Geol. Soc. London, Spec. Publ. 39: 337–348

Mutti, E. & F. Ricci Lucchi 1978 Turbidites of the Northern Appennines: Introduction to facies analysis – Int. Geol. Rev. 20: 125–166

Nelson, C.H. & L.D. Kulm 1973 Submarine fans and deep-sea channels. In: G.V. Middleton & A.H. Bouma (eds) Turbidites and deep-water sedimentation – Soc. Econ. Paleont. Mineral. Pacific Section, Short Course, Anaheim: 39–78

Normark, W.R. 1970 Growth patterns of deep-sea fans – Amer. Ass. Petroleum Geol. Bull. 54: 2170–2195

Normark, W.R. 1978 Fan valleys, channels and depositional lobes on modern submarine fans: characteristics for recognition of sandy turbidite environments – Amer. Ass. Petroleum Geol. Bull. 62: 912–931

Normark, W.R., D.W. Piper & G.R. Hess 1979 Distributary channels, sand lobes and mesotopography of Navy submarine fan, California Borderland, with application to ancient fan sediment – Sedimentology 26, 749–774

Parker, J.R. 1975 Lower Tertiary sand development in the Central North Sea. In: A.W. Woodland (ed) Petroleum and the continental shelf of NW Europe, Vol. 1 – Heyden London: 447–452

Payton, C.E. (ed) 1977 Seismic stratigraphy: application to hydrocarbon exploration. Amer. Ass. Petroleum Geol. Mem. 26: 516 pp

Pitman, W.C. 1978 Relationship between eustacy and stratigraphic sequences on passive margins – Geol. Soc. Amer. Bull. 89: 1389–1403

Rawson, P.F. & L.A. Riley 1982 Latest Jurassic– Early Cretaceous events and the late Cimmerian unconformity in the North Sea area – Amer. Ass. Petroleum Geol. Bull. 66: 2628–2648

Reading, H.G. & M. Richards 1994 Turbidite systems in deep-water basin margins classified by grain size and feeder system – Amer. Ass. Petroleum Geol. Bull. 78: 792–822

Rochow, K.A. 1981 Seismic stratigraphy of the North Sea Paleocene deposits. In: L.V. Illing & G.D. Hobson (eds) Petroleum geology of the continental shelf of northwest Europe – Heyden, London: 255–266

Schroeder, T. 1992 A palynological zonation for the Paleocene of the North Sea Basin – J. Micropalaeont. 11: 113–126

Stewart, I.J. 1987 A revised stratigraphic interpretation of the Early Paleogene of the Central North Sea. In: J. Brooks & K.W. Glennie (eds) Petroleum Geology of North West Europe – Graham & Trotman, London: 557–576

Stow, D.A.V. 1986 Deep Clastic Seas. In: H.G. Reading (ed) Sedimentary Environments and Facies, 2nd ed. – Blackwell Scientific Publ., Oxford: 399–444

Stow, D.A.V., C.D. Bishop & S.J. Mills 1982 Sedimentology of the Brae oil field, North Sea: fan models and controls – Petroleum Geol. 5: 129–148

Sutter, A.A. 1980 Paleogene sediments from the United Kingdom sector of the Central North Sea. Thesis Aberdeen University, Aberdeen, 389 pp

Thompson, P.J. & P.D. Butcher 1990 The geology and geophysics of the Everest complex: Abstract – Amer. Ass. Petroleum Geol. Bull. 74: 778

Vail, P.R. & R.G. Todd 1981 Northern North Sea Jurassic unconformities, chronostratigraphy and sealevel changes from seismic stratigraphy. In: L.V. Illing & G.D. Hobson (eds) Petroleum geology of the continental shelf of northwest Europe. Heyden, London, 216–235

Vail, P.R., R.M. Mitchum, R.G. Todd, J.M. Widmier, S. Thompson, J.B. Sangree, J.N. Bubb & W.G. Hatlelid 1977a Seismic stratigraphy and global changes in sea level. In: C.E. Payton (ed) Seismic stratigraphy: application to hydrocarbon exploration – Amer. Ass. Petroleum Geol. Mem. 26: 49–212

Vail, P.R., R.M. Mitchum & R.G. Todd 1977b Eustatic model for the North Sea during the Mesozoic. In: Norw. Petroleum Soc., Proc. Mesozoic Northern North Sea Symposium MNNSS/12: 1–35

Van Wagoner, J.C., R.M. Mitchum, H.W. Posamentier & P.R. Vail 1987 Seismic stratigraphy interpretation using sequence stratigraphy, part II: Key definitions of sequence stratigraphy. In: A.W. Bally (ed) Atlas of Seismic Stratigraphy – Amer. Ass. Petroleum Geol., Studies in Geology 27: 1–10

Walker, R.G. 1978 Deep-water sandstone facies and ancient submarine fans: models for exploration for stratigraphic traps – Amer. Ass. Petroleum Geol. Bull. 62: 932–966

Walmsley, P.J. 1975 The Forties field. In: A.W. Woodland (ed) Petroleum and the continental shelf of NW Europe, Vol. 1 – Applied Science, Barking: 477–484

White, R.S. 1988 A hot-spot model for Early Tertiary volcanism in the North Atlantic. In: A.C. Morton & L.M. Parson (eds) Early Tertiary Volcanism and the Opening of the NE Atlantic – Geol. Soc. London, Spec. Publ. 39: 3–13

Whyatt, M., J.M. Bowen & D.N. Rhodes 1991 Nelson: successful application of a development-geoseismic model exploration – First Break 9: 265–280

Wills, J.M. & O.K. Peattie 1988 The Forties Field and the evolution of a reservoir management strategy. In: A.T. Buller, E. Berg, O. Hjelmeland, J. Kleppe, O. Torsaeter & J.O. Aasen (eds) North Sea Oil and Gas Reservoirs - II – Graham & Trotman, London: 1–23

Winter, S.R., H.H. Bretthauer & G.A. Mattingly 1989 Alba field: Middle Eocene deep-water channel in U.K. North Sea: Abstract – Amer. Ass. Petroleum Geol. Bull. 73: 426

Wood, R. & P. Barton 1983 Crustal thinning and subsidence in the North Sea – Nature 302– 134–136

Ziegler, P.A. 1978 Northwestern Europe: tectonics and basin development – Geol. Mijnbouw 59: 589–626

Ziegler, P.A. 1982a Faulting and graben formation in Western and Central Europe. In: P. Kent et al. (eds) The evolution of sedimentary basins – Phil. Trans. Roy. Soc., ser. A305, London: 113–143

Ziegler, P.A. 1982b Geological atlas of Western and Central Europe – Shell Int. Petroleum Mij., The Hague: 130 pp

Ziegler, P.A. 1983 Crustal thinning and subsidence in the North Sea – Nature 304: 561

Ziegler, P.A. 1987 Evolution of the Arctic-North Atlantic borderlands. In: J. Brooks & K.W. Glennie (eds) Petroleum geology of northwest Europe – Graham & Trotman, London: 1201–1204

Ziegler, P.A. 1990 Geological Atlas of Western and Central Europe (2nd edn.) – Geol. Soc. Publ., Bath, 239 pp

Ziegler, W.H. 1975 Outline of the geological history of the North Sea. In: A.W. Woodland (ed) Petroleum and the continental shelf of NW Europe, Vol. 1. Heyden, London, 165–187