Upper Cenozoic stratigraphy on the Mid-Norwegian continental shelf

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A regional stratigraphy is established between 64°N and 65°N dividing the upper Pliocene and Quaternary sediments overlying IKU Bedrock Units IX and X into 11 informal units (L, K, I, H, G, F, E, D, B, A and U) separated by regional reflectors. The database consisted of about 5000 km of seismic profiles (site surveys, multichannel seismic tie lines between wells, selected conventional deep seismic lines, IKU's regional analog sparker grid), lithological and geophysical well information. 'Base Unit IX' represents the oldest event mapped and forms the basis for IKU Bedrock Units IX and X in the east and for the Plio/Pleistocene sediment wedge increasing to more than 1500 m thickness westwards at the shelf edge. The delta-like coastal Unit IX (of supposed Oligocene age) is very characteristic on seismic profiles. It has been mapped from Møre to Lofoten and probably consists mainly of sand. Most of the overlying sediments (Units X to E) seem to have been deposited by glacial processes, which explains the high sedimentation rates compared to the older units. The undulating reflector forming the base of Unit D (earlier assumed to be base Quaternary) is now interpreted as a result of the Saalian glaciation. The overlying layered sediments in Unit D consist of glaciomarine and marine (Eemain) sediments. The three topmost units (B, A and U) are dominated by unsorted material representing Weichselian tills.

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Introduction

The Mid-Norwegian continental shelf has long been investigated by biologists, hydrographers and geologists (Holtedahl 1993). The last decades of oil exploration have, however, greatly increased the geological database. The wells drilled give good coverage of the uppermost Triassic though Tertiary sediments. Less information exists for the older parts of the sedimentary succession as well as for the upper Cenozoic sediments (Dalland et al. 1988).

The purpose of this article is to increase the regional knowledge about the upper Cenozoic sediments on the Mid-Norwegian continental shelf, by establishing a regional seismostratigraphy linked to well information for the upper 1000–1500 m of sediments. It is based on the results from a study of the upper Cenozoic sediments between 64°N and 65°N (Figs. 1 and 2) conducted by IKU Petroleum Research for Norsk Hydro, Saga and Statoil (Rise & Rokoengen 1991).

The study area

The 'Haltenbanken South' area is situated on the central part of the Mid-Norwegian continental shelf (Fig. 2). The shelf is approximately 250 km wide north of Haltenbanken, decreasing to about 100 km south of Frøyabanken. The two banks have minimum water depths of about 90 m and 160 m respectively and are connected by the bathymetric ridge Frøyryggen running

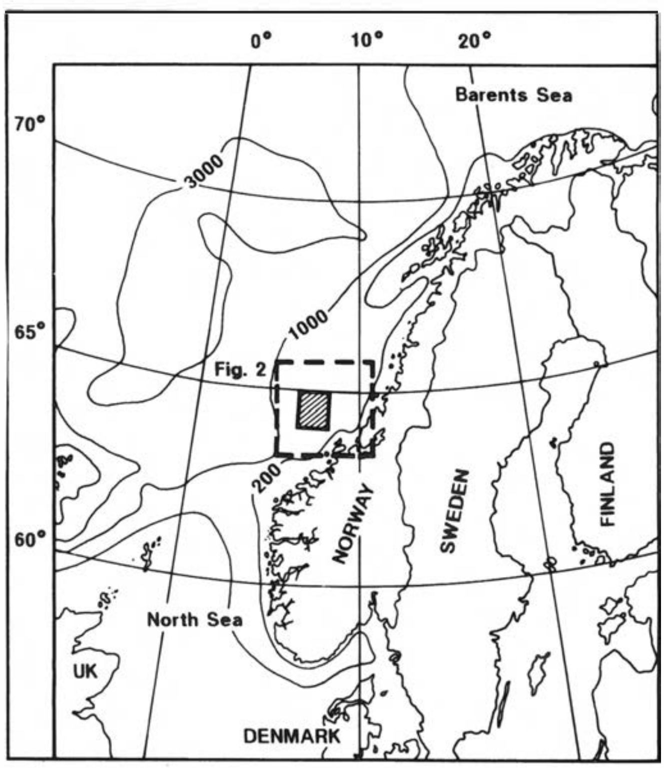

Fig. 1. Location map indicating the main bathymetry (water depths in metres) and location of the study area (shaded).

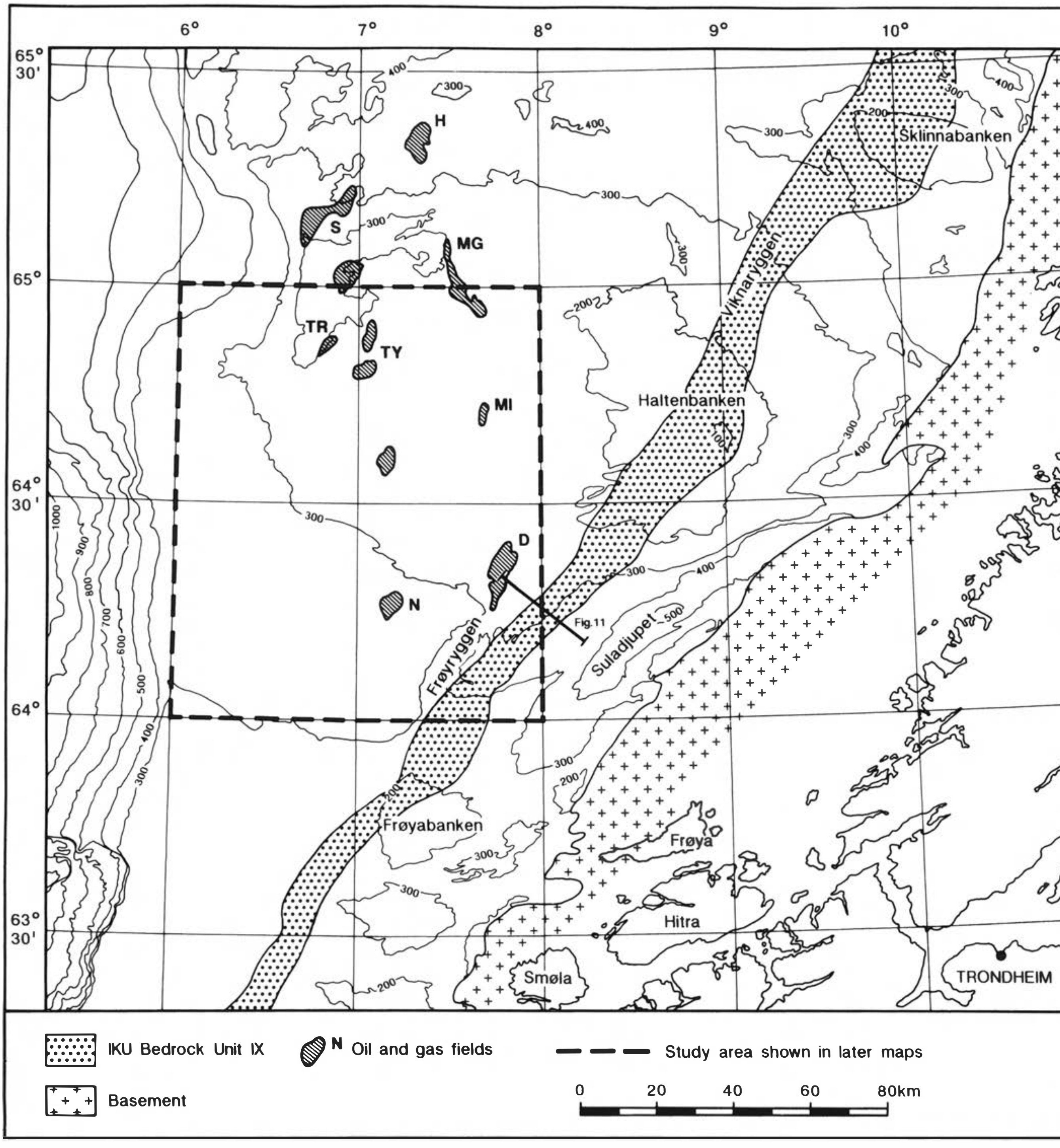

Fig. 2. Bathymetry of the study area and surrounding parts of the Mid-Norwegian continental shelf. Water depths in metres based on soundings by the Hydrographic Office of Norway (after Bugge et al. 1987). Border between basement and sedimentary rocks and IKU Bedrock Unit IX after Rokoengen et al. (1988). H – Heidrun, S – Smørbukk, MG – Midgard, TR – Trestakk, TY – Tyrihans, MI – Mikkel, N – Njord, D – Draugen.

SW–NE. Landwards from Frøyryggen the Quaternary thickness is small, and the bathymetry reveals the different resistance to erosion of the Mesozoic and Tertiary bedrock units.

Frøyryggen (Fig. 2) is a part of the Bedrock Unit IX mapped by IKU, and Suladjupet is a trough with water depths of more than 500 m formed by glacial erosion in the dark, Upper Jurassic/Lower Cretaceous claystone (The Spekk Formation, Dalland et al. 1988; IKU Bedrock Unit IV, Bugge et al. 1976, 1978, 1984; Rokoengen et al. 1988). The irregular topography along the coast is caused by crystalline basement rocks of Caledonian and Precambrian age.

The shelf edge is found a little west of 6°E at a water depth of about 400 m. Westwards from both Frøyabanken and Haltenbanken fairly shallow areas continue to the shelf edge. The former represents the southern limit of the study area while the latter forms the northern half of it. Between the two shallower areas there is a water depth of more than 300 m extending from Frøyryggen to the shelf edge (Fig. 2).

The general topography of the continental shelf is very regular and smooth compared to the skerry coastal zone (Nansen 1904; Holtedahl 1940; Andersen 1975). Locally, however, the topography may be quite irregular as a result of ploughing by icebergs during the last deglaciation (Belderson & Wilson 1973; Rokoengen & Bugge 1976; Lien 1983). Just north of the study area the seabed is very irregular as a result of inferred glaciotectonic processes (Sættem et al. 1993).

The existence of large sedimentary basins offshore Mid-Norway was shown by geophysical studies (Eldholm 1970; Åm 1970; Grønlie & Ramberg 1970; Talwani & Eldholm 1972) at the same time as the first hydrocarbon discoveries were made in the Norwegian sector of the North Sea. These early studies gave a crude picture of sediment thicknesses and seismic velocities.

Further investigations in the 1970s included seismic tie lines to wells in the North Sea area (Rønnevik & Navrestad 1977; Jørgensen & Navrestad 1979) and the regional geological mapping by IKU with shallow seismic profiling and seabed sampling (Bugge et al. 1976; Bugge 1980; Gunleiksrud & Rokoengen 1980). Samples were obtained from Mesozoic and Tertiary sediments outcropping at or near the seabed (Bugge et al. 1975, 1984; Rokoengen et al. 1988; Rokoengen & Rise 1989).

Exploration drilling offshore Mid-Norway started in 1980 (well 6507/12-1 northeast of Midgard, Fig. 2). Later, considerable number of wells have been drilled and several important discoveries of hydrocarbons made (e.g. Spencer et al. 1984, 1986; Dalland et al. 1988).

Database and interpretation

The database for the present article included about 5000 km of seismic data (Figs. 3 and 4) in addition to more detailed information from site surveys. Three types of seismic lines were used:

- High resolution multichannel airgun lines at the various wells and tie lines between wells (2.5 sec. two-way travel time (twt) recording).
- Conventional deep seismic lines (upper part, 0–2.5 sec. twt).
- IKU regional sparker lines (mainly 0.5 sec. twt).

The high resolution multichannel tie lines (heavy lines in Fig. 3) have been the key lines for the regional interpretation below the characteristic base Unit D reflector. These lines are of medium to good quality (Fig. 5). As no regular grid of high resolution multichannel lines exists in the area, it has been necessary in addition to use conventional seismic and regional analog sparker lines in order to obtain a confident regional interpretation of the various units.

The conventional seismic lines were chosen from several

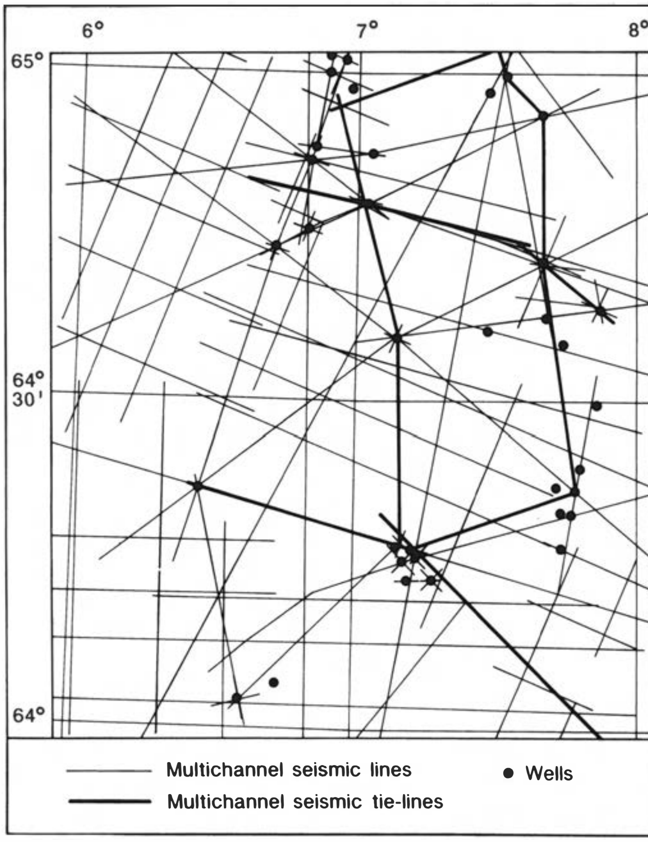

Fig. 3. Multichannel seismic data used in the study. High resolution tie lines are marked with heavy lines and interpretation shown in Figs. 6 and 7. The multichannel seismic database includes both high resolution and conventional deep seismic lines.

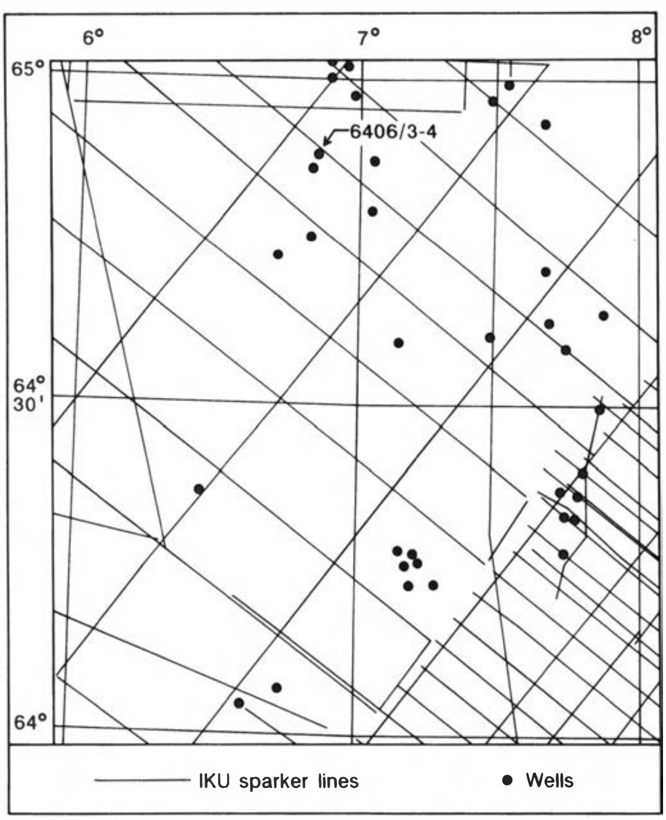

Fig. 4. Profile grid for IKU's analog sparker grid in the study area (after Rise 1988). The locations of wells drilled in the study area are also marked.

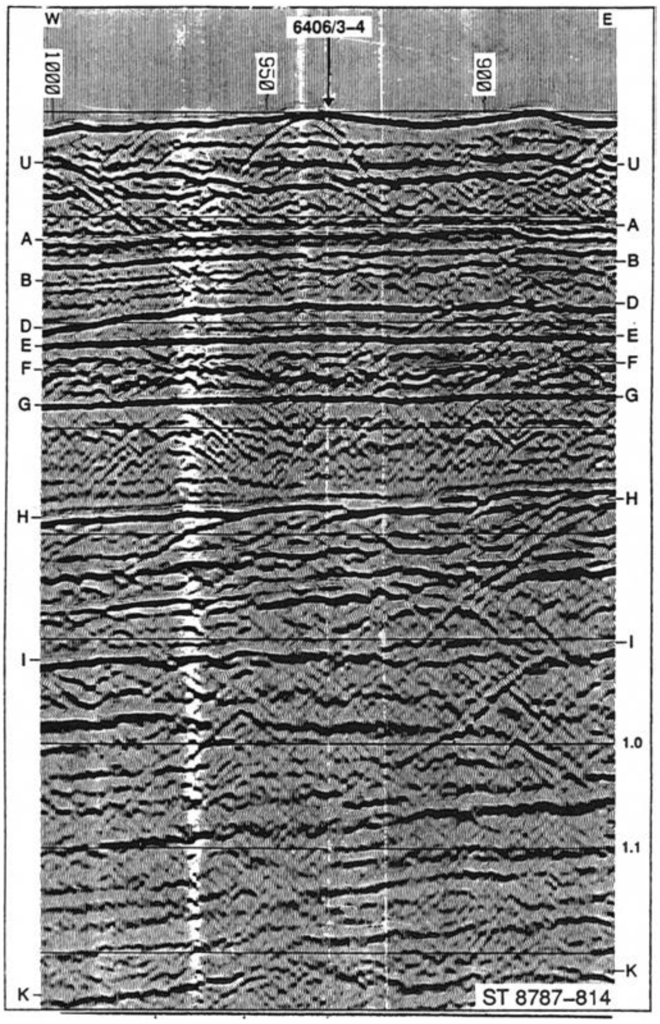

Fig. 5. Interpretation of regional reflectors (base of units) down to base Unit K on a multichannel seismic profile section near the Trestakk Field (Fig. 2). Scale lines show a 100 millisecond interval of two-way travel time (twt) and the shot point interval is 12.5 m. Location shown in Fig. 4.

surveys in order to obtain regional coverage within the area (Fig. 3). Most of the deep seismic lines used were cut at 2.5 sec. and the data quality in the upper 0.5–1 sec. is variable. On some of the good quality lines a complete interpretation of the Upper Cenozoic seismic stratigraphy has been carried out. In general, however, the conventional seismic lines have been used to interpret the deepest reflectors (base Units L, K, I) and to trace several of the overlying reflectors in the westernmost part of the study area.

A regular analog sparker grid of 10–15 km spacing in a NW–SE direction and approximately 25 km spacing in a NE–SW direction has been run by IKU between 64°N and 65°N (Fig. 4). Most records have a vertical scale of 0.5 sec. and are delayed to 'close to sea floor'. The penetration varies, but normally it is restricted by the first multiple (Rise 1988). In general, the quality is medium in the upper part and poor in the lower part of the records, but some long lines are of good quality and very illustrative of the geological development, particularly in the upper units. The tie to high resolution multichannel seismic tie lines and conventional deep seismic lines has made it possible to interpret the analog sparker data in a more confident way. In addition, multichannel and analog airgun data from several site surveys have been used in more detailed mapping near the well locations.

Completion logs and mud logs down to the base of the Naust Formation (Dalland et al. 1988) from most of the exploration wells in the area (Figs. 3 and 4) have been used to link lithological and geophysical well information to the interpreted seismic stratigraphy. The sonic logs have been used for time/depth conversion. Although there are few check shots in the studied interval, a fairly confident correlation has been obtained between most of the regional reflectors and the log responses, and there is a good fit between seismic character and log patterns (Rise & Rokoengen 1991).

Based on the tie lines, six detailed geoseismic profiles have been constructed and are shown in Figs. 6 and 7. A total of 11 informal seismostratigrpahic units have been mapped (L, K, I, H, G, F, E, D, B, A and U) in addition to IKU Bedrock Units IX and X (Bugge et al. 1984; Rokoengen et al. 1988). The three most striking unconformities are found at the base of Units IX, I and D.

The pinchout of the different units mapped (Figs. 8 and 9) and the schematic section (Fig. 10) illustrate the complexity of the area. In a broad sense, however, the map and sections show that the most complete stratigraphy is preserved in the northwest. Towards the southeast the units are eroded at different unconformities, and in the southeastern corner of the study area only Unit U is present above the bedrock. Furthermore, within each unit the depositional environments and corresponding geotechnical and geological properties will vary.

The regional reflectors are also presented in site survey reports. However, the nomenclature used on the same regional reflector varies from site to site. At some locations a more detailed seismostratigraphy is defined, but this is mainly because local reflectors are included (Rise & Rokoengen 1991).

Description of the stratigraphic units

In IKU's regional mapping off Mid-Norway during the 1970s and early 1980s the bedrock surface was divided into 11 units more or less parallel to the coast, and informally named I to XI. Lithostratigraphic information was obtained from a number of the units (Bugge et al. 1984; Rokoengen et al. 1988). The ages of the units sampled ranged from Triassic to Pliocene. Especially in the youngest part (Units VIII to XI) the datings were very uncertain as most effort was put into the sampling of the pre-Tertiary rocks. The bedrock investigations were located along the margin of the basins on the Mid-Norwegian continental shelf and will therefore partly have lithologies that are different from the central parts of the basins.

The Units IX, X and XI of supposed Oligocene, Miocene and Pliocene age respectively are included in the present study in addition to the Quaternary sediments as

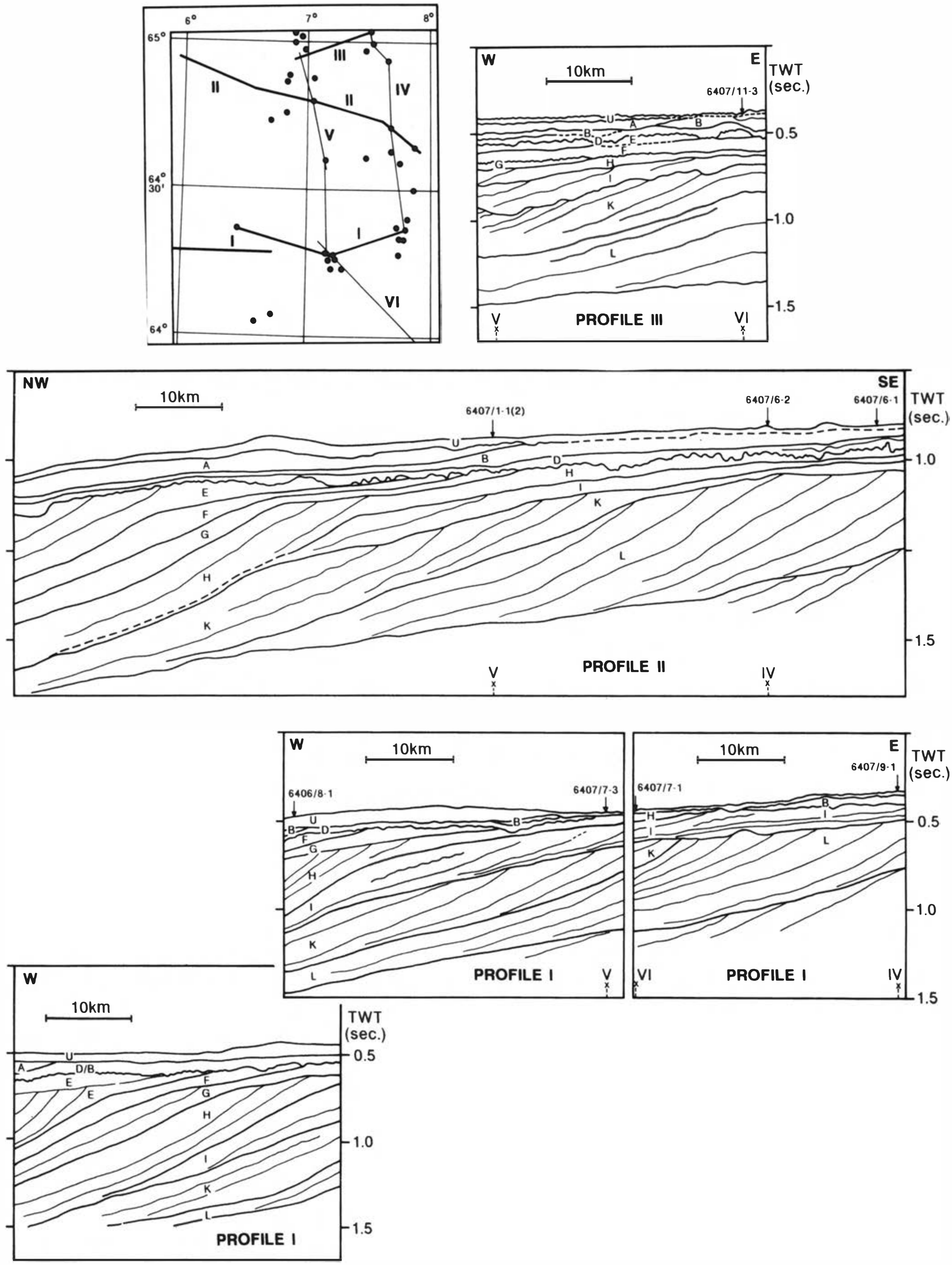

Fig. 6. Geoseismic profiles I, II and III showing the upper Cenozoic stratigraphic units in the Haltenbanken area.

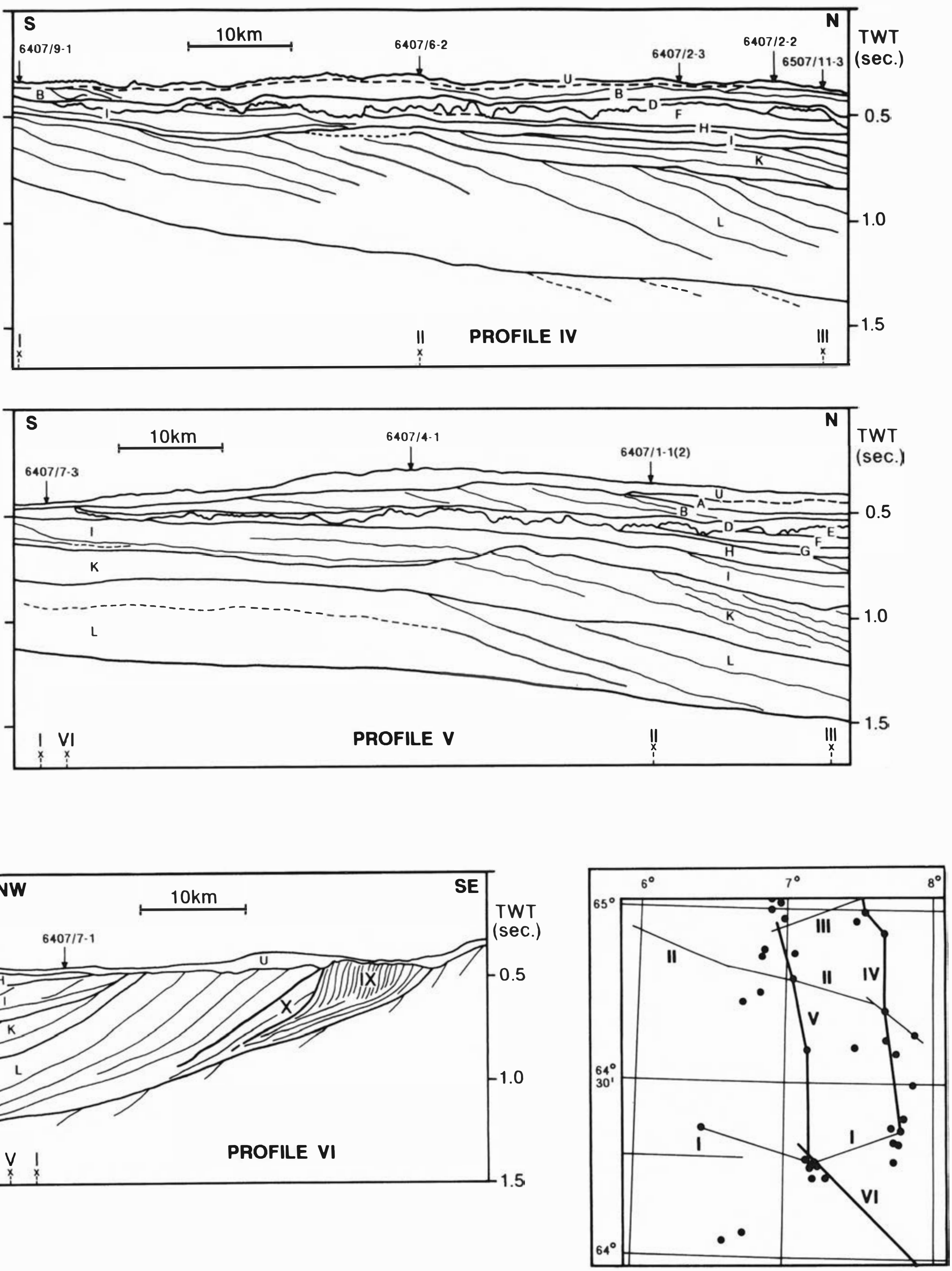

Fig. 7. Geoseismic profiles IV, V and VI showing the upper Cenozoic stratigraphic units in the Haltenbanken area.

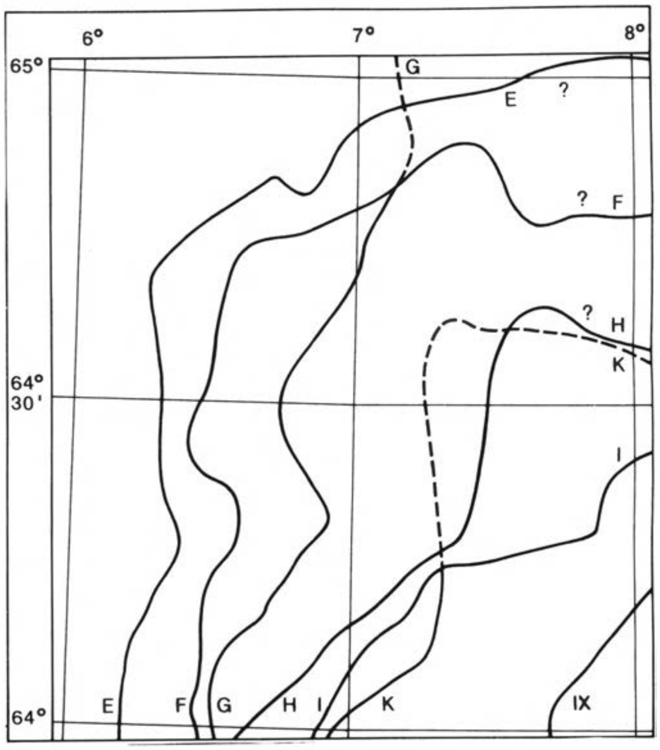

Fig. 8. Pinchout of Units IX, K, I, H, G, F and E in the study area. Pinchout at base Unit D (or younger units) is shown as an unbroken line and older units below as a broken line.

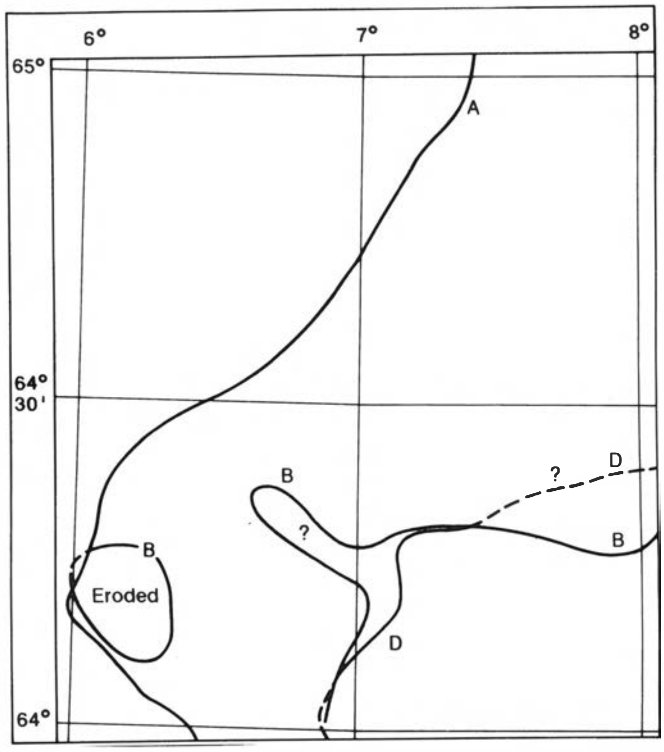

Fig. 9. Pinchout of Units D, B and A. Pinchout at base Unit U is shown as an unbroken line and older units below as a broken line. Unit U covers the whole area with Quaternary sediments present.

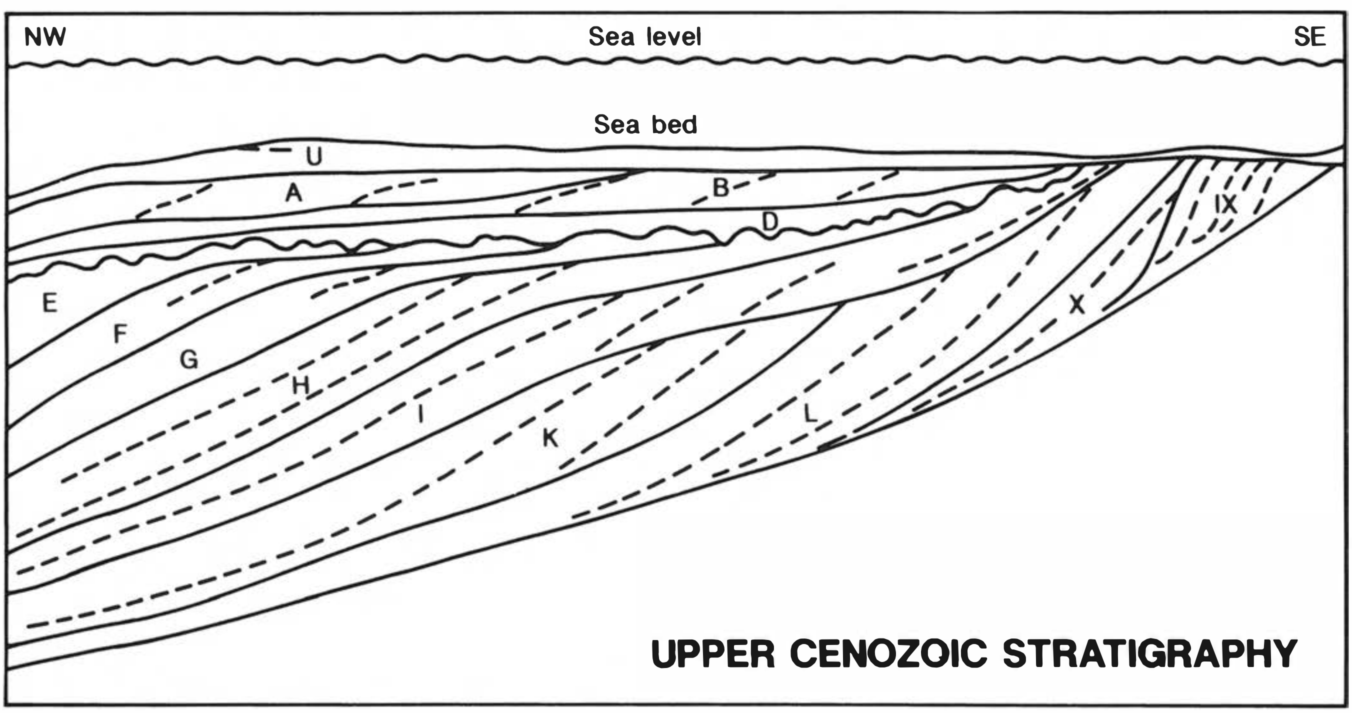

Fig. 10. Schematic section showing the upper Cenozoic stratigraphy in the Haltenbanken area.

previously defined (Bugge 1980; Bugge et al. 1984; Bugge & Wøien 1984; Maisey & Wøien 1984; Wøien et al. 1984; Rise et al. 1988; Vorren et al. 1992).

The deepest reflector mapped in the present study represents the 'base of IKU Bedrock Unit IX' and is very marked. The overlying IKU Bedrock Units IX and X have been used as before, while IKU Bedrock Unit XI has been subdivided into seven different units (L, K, I, H, G, F and E). The previously assumed base Quaternary is a very marked unconformity mapped as base Unit D in the present study. The overlying sediments are subdivided into four units (D, B, A and U).

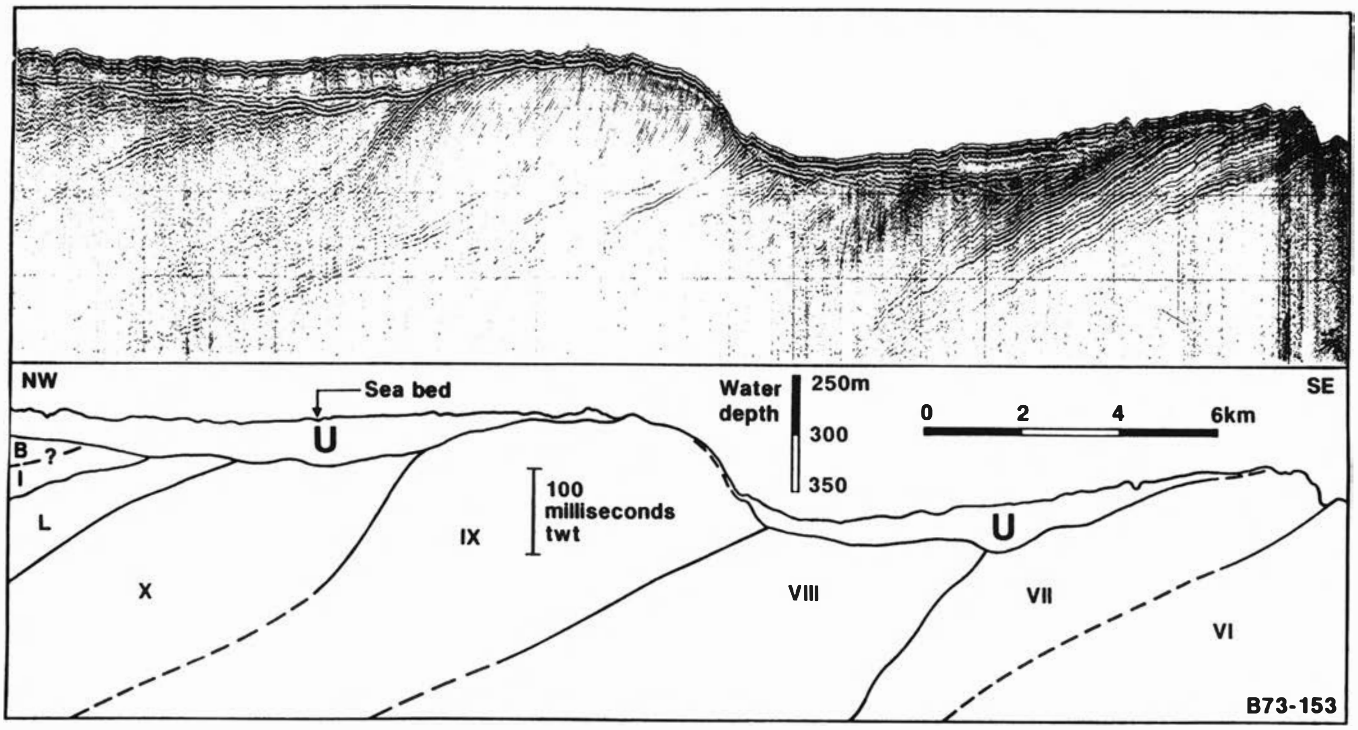

Fig. 11. Sparker section showing IKU Bedrock Unit IX and adjoining units. For location, see Fig. 2.

IKU Bedrock Unit IX

The IKU Bedrock Unit IX (Figs. 2 and 11) is very characteristic on the sparker profiles. The proximal part, believed to be dominated by sand, has shown greater resistance to later glacial erosion than the assumed more clayey sediments below and above (e.g. Frøyryggen, Fig. 2). The lateral continuity from Møre to Lofoten suggests a very large and uniform sediment supply (Bugge et al. 1984; Rokoengen et al. 1988; Sigmond 1992).

The depositional environment and age of Bedrock Unit IX is important as it marks the transition between two quite different types of sediments on the Mid-Norwegian continental shelf. The internal reflectors have quite steep dips (mainly 10–15°) and the unit consists mainly of sand in the upper part (Knarud et al. 1982; Skarbø et al. 1983). The samples obtained are, however, all quite short and partly disturbed by later glaciotectonic activity. Westwards, Bedrock Unit IX thins very rapidly to less than the seismic resolution (Profile VI, Fig. 7).

The interpreted depositional environment for the Bedrock Unit IX is coastal/deltaic (Fig. 12). The position of the unit compared with the conditions prevailing in the area today suggests that it was formed in a wave-dominated environment with extensive longshore drift.

Base IKU Bedrock Unit IX (Fig. 11) is mainly defined from conventional deep seismic data as a prominent seismic marker representing an angular unconformity with downlapping clinoforms above (see Figs. 6, 7 and 10). The reflectors in the units below are truncated at a small angle, and therefore on some lines it is difficult to follow the base Unit IX reflector westwards.

The base of IKU Bedrock IX is poorly defined on the high resolution 2.5 sec. lines, but can on several of them be traced as a somewhat higher amplitude event. The continuity of the reflector is, however, variable on these lines due to limited penetration. The reflector is seen as an angular unconformity on the high resolution seismic lines only in the southeastern part of the study area (Profiles I, II, Fig. 6 and Profile VI, Fig. 7). On most of the petrophysical logs the sound velocity and resistivity show a marked upward increase at the boundary, and the gamma readings often decrease.

A contour map showing the depth to the reflector in millisec. twt is shown in Fig. 12. The surface is steepest in the southeastern part of the study area where the unit pinches out near the seabed. The reflector is 1600–1700 millisec. below sea level near the present shelf break in the west.

The reflector shows a quite regular northwesterly dip. The outer part (the shelf edge at the time of formation) is probably depositional, while the inner part is clearly erosional. A critical question is whether the erosion was marine or glacial. The regular forms of the reflector over such a large area, with no observed overdeepenings or other typical glacial forms, favours a formation caused by a relative drop in sea level creating marine erosion. The sea level drop may, however, have been a result of growing glaciers on land.

IKU Bedrock Unit X and Unit L

The IKU Bedrock Unit X consists of low-angle clinoforms onlapping Unit IX in the east and downlapping on the base Unit IX reflector westwards (Profile VI, Fig. 7).

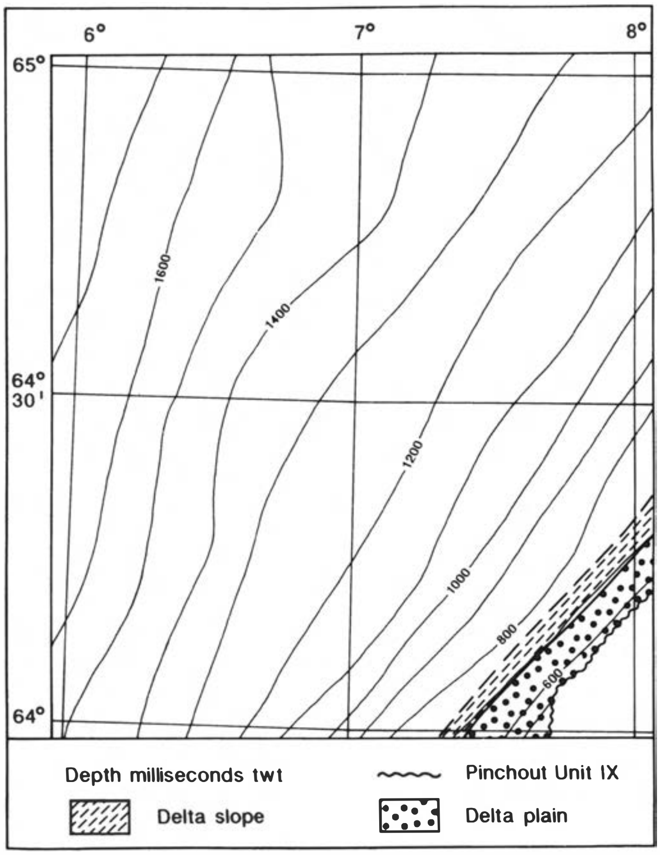

Fig. 12. Contour map showing the depth to base IKU Bedrock Unit IX in milliseconds twt. Note the pinchout of the formation in the southeast map corner and the interpreted depositional environment for the unit.

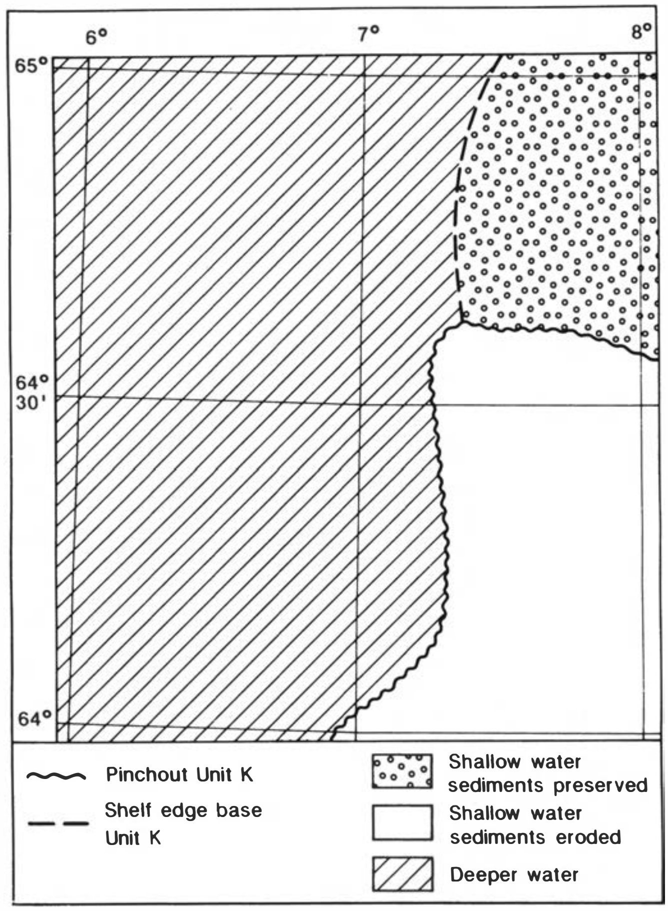

Fig. 13. Depositional environment of Unit K.

Large-scale clinoforms (Unit L) prograde further northwestwards and downlap on the base Unit IX reflector (Figs. 6 and 7). The inferred very high sedimentation rate compared to the older Tertiary sediments indicates glacial influence in both transport and deposition.

Glacial influence is supported by a sidewall core containing scattered sharp-edged gravel in a muddy matrix 815 m below the seabed in well 6407/2-2 (Carlsen et al. 1985). The gamma logs indicate only small lithological variations, and Unit L probably consists mainly of a mixture of clay, silt and sand. In general, only a few thin sand layers are detected on the logs.

Unit K

The base of Unit K indicates a former shelf edge in the northern part of the study area (Profile II, Fig. 6 and Fig. 13). In the eastern areas the reflector is clearly erosional and we believe that considerable amounts of older sediments were removed by the erosion creating the base of Unit K (Figs. 6 and 7).

The top of Unit K is truncated by another important regional reflector. As indicated on Figs. 6, 7, and 13, this erosion in the south has removed the top of the Unit K shelf sediments, whereas they are preserved in the north. They have there contained shallow gas at several locations, e.g. well 6407/6-2, where the shallow gas blowout that destroyed the West Vanguard Platform occurred (Luk-kien 1982; NOU 1986; Haugane et al. 1986).

Units I to E

The contour map of base Unit I shows that the main trend is a northwesterly dip (Fig. 14). A relatively high east–west trending ridge on the I level is, however, found in the middle of the study area. One possible explanation could be glacial erosion caused by two different ice streams. The large-scale morphological forms seen in the northern part could also indicate glacial erosion.

The overlying succession (such as Units L and K) gradually outbuilds the shelf edge, as shown on the profiles in Figs. 6 and 7. In general, the units are sheet-like with erosional boundaries in the inner more horizontal part and they thicken above descending palaeoslopes. The formation would normally imply overconsolidation in the inner erosional part, while the outer part probably is more normally consolidated.

The seismostratigraphical features observed in Units I to E resemble those described in the Trænabanken area (Bugge et al. 1984; King et al. 1987; Rokoengen et al. 1988; Poole & Vorren 1993), from the mouth of the Norwegian Trench (Sellevoll & Sundvor 1974; Rokoengen &

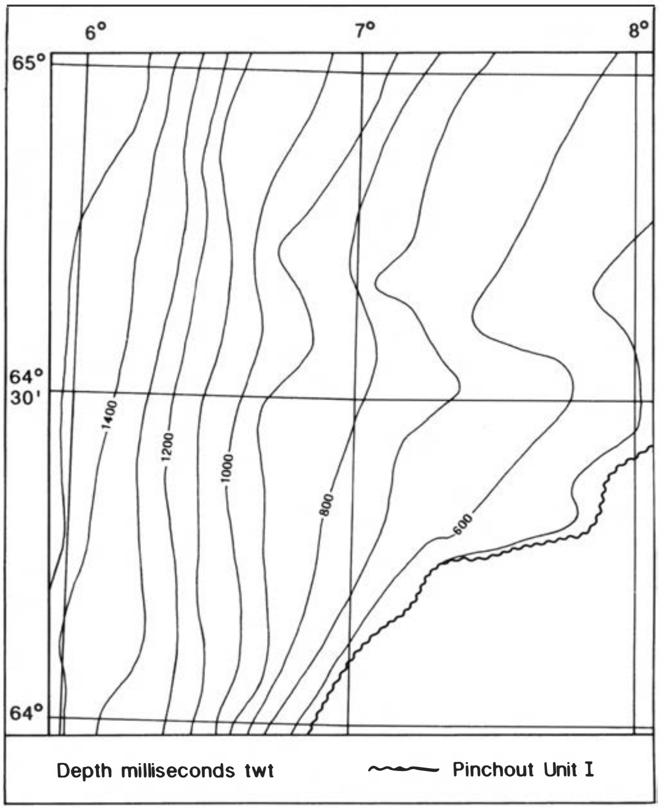

Fig. 14. Contour map showing the depth to base Unit I in milliseconds twt.

Rønningsland 1983), in the Barents Sea (Sættem et al. 1992, 1994) and in Antarctica (Alley et al. 1989; Larter & Barker 1989). The models explaining these features differe somewhat, but there seems to be rather general agreement about a formation with contemporaneous glacial erosion on the inner part of the shelf, transportation on the middle part and deposition near the grounding zone on the outer part of the shelf.

Compared to the other area studied, 'Haltenbanken South' has very good data coverage including a number of drilled and logged wells. We consider the I to E succession to be dominated by tills interbedded with glaciomarine sediments and grading into mainly glaciomarine clays, westwards. Many of the internal reflectors gradually terminate within the massive incoherent units and are interpreted as till tongue roots (King et al. 1987). Features interpreted as till tongues with tips and grading into glaciomarine sediments have been found in several of the units.

Thus an important result from the present interpretation is that the glacial deposition seems to have started much earlier than assumed from the previous regional mapping off Mid-Norway, and that sediments from many glaciations are preserved.

Unit I has been sampled in shallow boreholes at Draugen (Fig. 2), indicating that it comprises both till and glaciomarine sediments (Haflidason et al. 1991). An undrained shear strength of up to 1000 kPa was measured, indicating a marked glacial overconsolidation.

Several of the reflectors also have features that suggest glacial erosion. The most prominent small-scale irregular surface in the study area (base Unit F) has been studied in detail by Statoil, showing elongated troughs in various directions resembling iceberg ploughmarks on the present seabed (Amaliksen et al. 1989; Gallagher & Braaten 1990).

The regional reflectors dividing the units may, particularly in the inner part of the shelf, just represent a change of acoustic impedance between tills. The reflectors may also represent thin layers of sediments that can be either clay or sand, depending on the depositional environment and energy level. Depth/time conversion of shallow gas anomalies in exploration wells indicated that 'high level readings' often correlated to regional reflectors (Rise & Rokoengen 1991). They will represent the intervals where sand deposits are believed to be concentrated, and therefore also accumulations of shallow gas.

Unit D

The typically undulating surface forming the base of Unit D is very marked on the seismic profiles. The level is also a prominent angular unconformity in most of the studied area, and many of the older units pinch out (or are partly eroded) at this boundary. The reflector also marks the boundary to more flat-lying units above (Figs. 6–10). On shallow seismic data it is the deepest level that can be followed regionally, and it has been interpreted as base Quaternary in several of the earlier studies in the area (Bugge et al. 1978, 1984; King et al. 1987; Amaliksen et al. 1989; Vorren et al. 1992).

Our present interpretation is that the surface was glacially formed. Similar undulating features are found on today's surface between about 8°E and the shelf edge just north of the study area (Fig. 2). They were interpreted by King et al. (1987) to have been formed by ice and were called 'hummocky moraine'. Sættem et al. (1993) described the conditions in the Smørbukk area (Fig. 2) in more detail and interpreted the features as a result of large-scale glaciotectonics. These topographic forms are believed to have low potential for preservation during the erosion of later glaciations, and similar morphology has not been recognized at any other levels in the study area.

Unit D shows consistenly sound velocity readings of about 1700 m/sec. The seismic records reveal layered sediments typically infilling the uneven topography. The stratification becomes less defined where the unit thins, and above palaeo-highs where the unit has a more structureless seismic appearance. The unit is interpreted to comprise glaciomarine and marine sediments preserved from later erosion. A period with smaller glaciations and/or increase in relative sea level could explain why it has not been eroded.

Units B and A

These units are mostly mapped from the IKU sparker profiles (Fig. 4). The boundary between the two units is

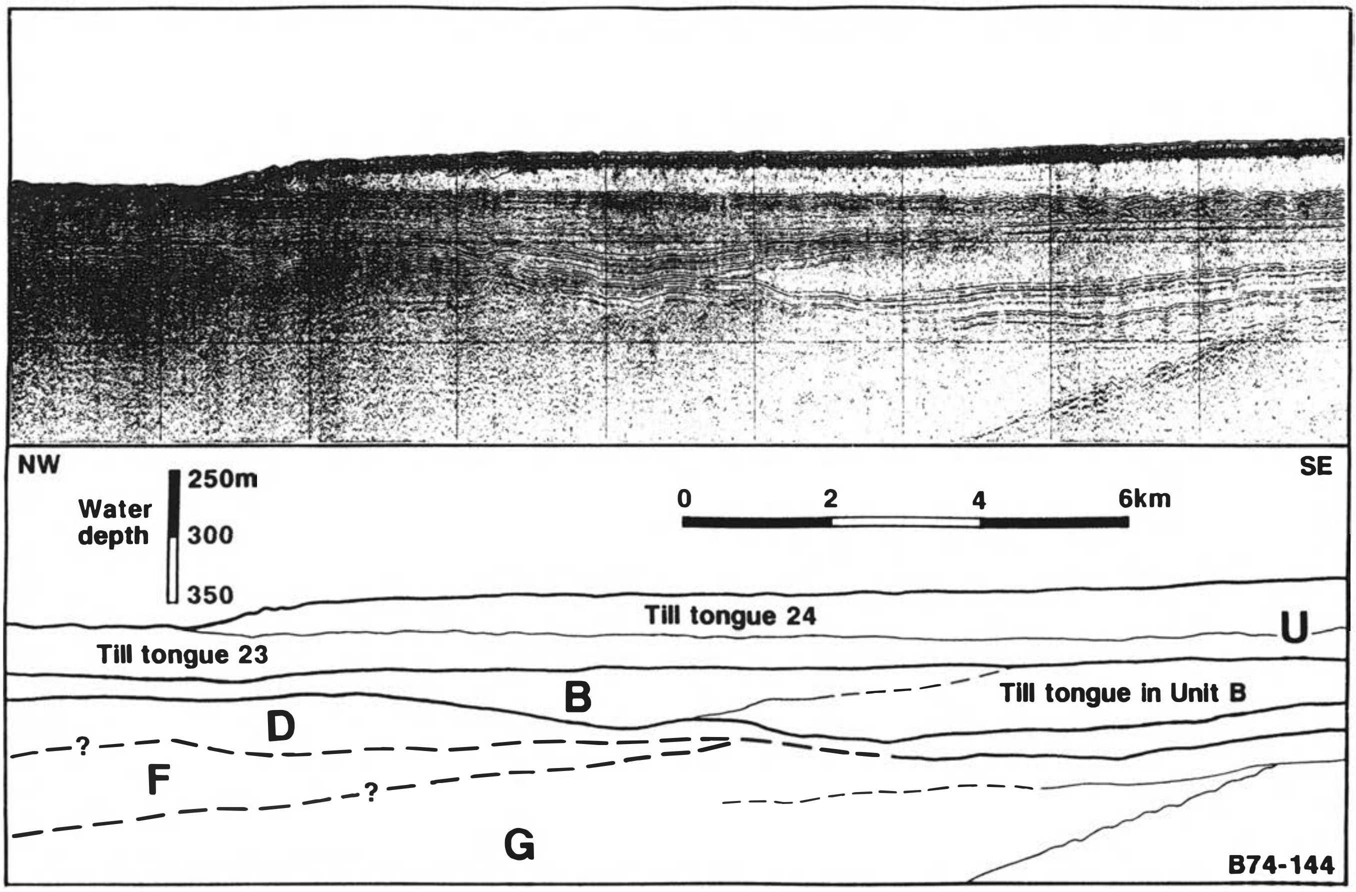

Fig. 15. Sparker profile section with interpretation sketch showing the stratigraphy in the southern part of the area (for location see Figs. 16 and 17). The buried till tongue is believed to belong to Unit B while the till tongue forming the surface is a part of Unit U (correlated to till tongues 23 and 24, King et al. 1987).

in some areas difficult to define, but the well-developed till tongue geometry is striking and the section as a whole can, in our opinion, be explained by the till tongue model (King et al. 1987). An example of a till tongue with glaciomarine sediments at the tip is given in Fig. 15.

The section in Fig. 15 also illustrates the difficult interpretation in the southern part of the study area with extensive erosion between the units. Till tongues in Unit B are best developed in the northeastern part of the study area, but there also they are typically cut by erosion of Unit U. The outermost till tongue is marked on the palaeofacies sketch for Unit B in Fig. 16. In the northwest the unit consists of glaciomarine sediments.

Unit A is mainly found in the northwestern part of the study area (Profile II, Fig. 6 and Fig. 9). It represents a large glacial event extending beyond the shelf edge, and the end of the outermost till tongues are found west of the study area. In the southern part of the study area Unit A is almost totally eroded by Unit U, and mostly found only along the shelf edge (Profile I, Figs. 6 and 9). We believe, however, that it reappears just south of the study area in the shallower areas west of Frøyabanken (Fig. 2).

The geotechnical investigations at the Smørbukk and Heidrun Fields (Fig. 2) have shown that Unit A consists of different tills with a high content of stones and boulders, and that the till matrix may vary from being moderately to heavily overconsolidated (Mogensen & Rise 1988).

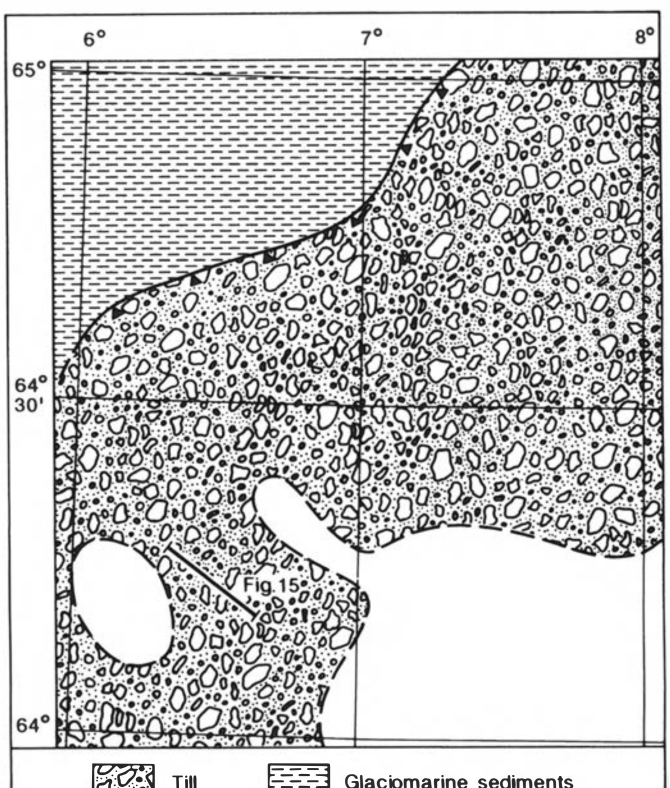

Fig. 16. Distribution and depositional facies of Unit B.

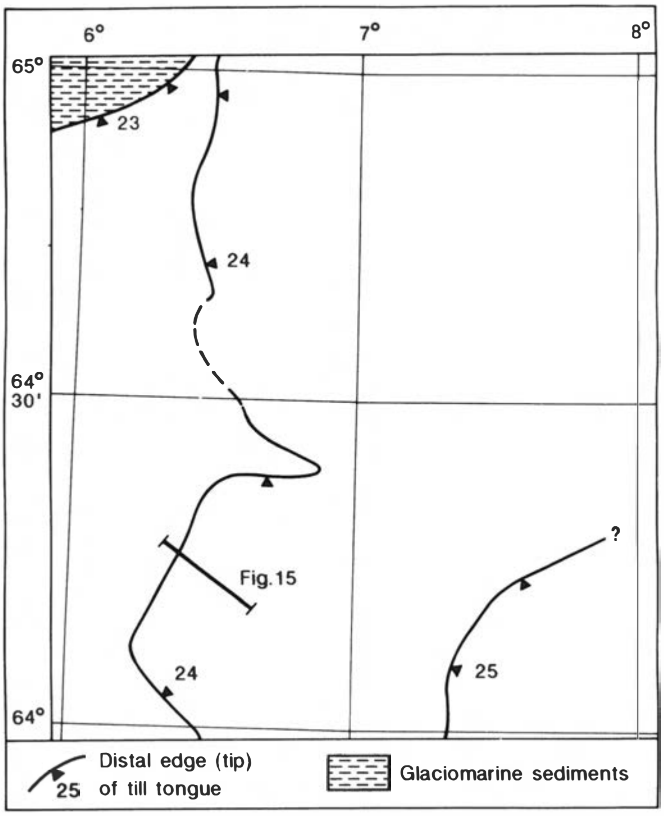

Fig. 17. Distribution, main depositional facies and till tongues in Unit U.

Unit U

The youngest unit mapped is found as a sheet covering the whole study area, although partly quite thin and difficult to map. The widespread distribution is believed to be due to the fact that Unit U represents the last deglaciation and is thus well preserved. A future glaciation would probably remove large parts of it. As the unit represents the youngest glacial sediments, it also shows some striking topographical features on the shelf (e.g. Fig. 15). Fig. 17 shows a sketch with some of the till tongues found in the unit.

The unit consists mainly of tills with varying geotechnical properties, but glaciomarine sediments occur in the northwest (Fig. 17) and in the depressions (Bugge 1980; Gunleiksrud & Rokoengen 1980). An extremely hard till (undrained shear strength 500–1000 kPa) was found in the lower part of the unit at the Draugen Platform site (6–15 m below the seabed).

Correlation with earlier investigations

The Quaternary and upper Tertiary sediments off Mid-Norway are not only thick and extensive, but also extremely complex. Some of othe reflectors are, however, very striking and have been used in several studies even though they have been given different denotations. This section is an overview of some of the previous studies giving a stratigraphic subdivision of the Mid-Norwegian continental shelf. As both seismic data and models for interpretation have varied, there will be deviations in regional correlations, especially in areas with extensive erosion (as on the inner part of the shelf).

The lithostratigraphic correlations of the Haltenbanken–Trænabanken area (Dalland et al. 1988) are based on information from wells drilled in the 1980s. In some units major changes in lithology occur towards the basin margins and along intrabasinal highs. It will thus be necessary to modify the lithostratigraphic scheme presented as more data become available.

The present study covers mainly the upper part of the Nordland Group where the youngest Naust Formation is defined in well 6507/12-1 (northeast of Midgard, Fig. 2). The base is defined by an upward decrease in gamma ray response and an increase in the seismic velocity and the resistivity log reading. The lithology of the Naust Formation is described as interbedded claystone, siltstone and sand, occasionally with very coarse clastics in the upper part. The formation was deposited in a marine environment. A transition to glaciomarine environments occurs in the upper part, but this transition is poorly documented from the exploration wells (Dalland et al. 1988).

West of Units IX and X (Profile VI, Figs. 7 and 10) the base of the Naust Formation corresponds to the oldest reflector mapped in the present study (base Unit IX or rather base Units L and K).

Statoil has made an extensive study of the Tertiary and Quaternary evolution of the Haltenbanken area based on conventional deep seismic data and well information, with special emphasis on the relationship to shallow gas (Amaliksen et al. 1989). They divided the Tertiary and Quaternary succession on Haltenbanken into two main parts, further subdivided into six supersequences. The lower part consists of the supersequences 1–4, mostly with fine-grained sediments and zones within the package that may provide potential source/nutrition for biogenic gas production.

The upper part is believed to be influenced by glaciation and is of assumed Late Pliocene and Quaternary age. It comprises two supersequences; a lower, Upper Pliocene, mainly glaciomarine (5), and an upper, Quaternary, dominated by till (6). The base of supersequence 5 corresponds to base Naust Formation in the west and to the reflector mapped as base IKU Bedrock Unit IX in the present study. The base of supersequence 6 corresponds to the marked reflector at the base of Unit D.

King et al. (1987) studied the Quaternary seismostratigraphy of the Mid-Norwegian shelf, 65°N–67°30'N using the till tongue model for explaining the deposition of till and glaciomarine sediments on the continental shelf.

A till tongue consists of a wedge-shaped deposit characterized by seismically incoherent reflections (till), interbedded with sediments characterized by many coherent reflections (stratified glaciomarine sediments). The layers of the glaciomarine clay may splay at the tip of the wedge (Fig. 15). The uppermost portion gradually terminates in the massive till and this zone constitutes the root of the till tongue. These features with reflectors fading in massive till caused a great many problems in IKU's early interpretation (Bugge et al. 1978; Rokoengen 1980). It appears that till tongues constitute discrete stratigraphic events and their recognition of seismic profiles enables the interpretation and mapping of complex, multiple till successions. The model of till tongue formation is still conceptual and may be modified as more direct study methods are employed. For more extensive descriptions, see King (1980, 1993), King & Fader (1986) and King et al. (1987, 1991).

Three major till units were interpreted north of 65°N: The Lower, Middle and Upper Tills which were further divided by 25 major till tongues. In addition, a number of local events were noted (King et al. 1987). It is very difficult to follow the reflectors around 65°N on the inner part of the shelf, partly due to extensive erosion (Mogensen 1986). The border between units A and B on the outer part of the shelf is also very difficult to map around 65°N, possibly due to deposition from two different ice streams. Nevertheless, we have tentatively correlated the Lower Till to Unit B, the Middle Till to Unit A and the Upper Till to Unit U in the present study. This correlation is taken from the outer part of the shelf and differs somewhat from that given by Mogensen & Rise (1988).

The correlation to Trænabanken is done in the area with interfingering till tongues and thick glaciomarine clays at about 65°N (King et al. 1987). The interpretation of the Lower Till (Unit B) is somewhat uncertain, and Unit B becomes more eroded southwards (Figs. 15 and 16).

The till tongues marked 23 and 24 belonging to Unit U (Figs. 15 and 17) are correlated further to the north (King et al. 1987), and till tongue 24 can be followed for at least 500 km. This tongue corresponds to the outer part of the 'Storegga Moraine' of Bugge (1980). Another quite distinct tongue (25) is found just outside the earlier mapped IKU Bedrock Unit IX that forms a topographic high in the area (Frøyryggen, Fig. 2). We think that these tongues were formed by an ice stream between Frøyabanken and Haltenbanken.

In the area 65°N–65°30'N, 6°E–8°E (Fig. 2) the regional Cenozoic seismostratigraphy and soil properties were studied by IKU for Saga and Statoil (Mogensen & Rise 1988). In the present study the seismic interpretation started in the northern part of the area by correlating to their results (Rise & Rokoengen 1991). Unit C was found locally in the deep area between Haltenbanken and Sklinnabanken by Mogensen & Rise (1988) but has not been defined in the southern area. However, this study includes older sediments that come closer to the seabed in the southeast. The Units L and K have therefore been defined in addition. The upper Unit A in the north has been subdivided into two by a reflector that becomes rather prominent in the southern part of the present study area and is mapped as base Unit U.

Age relationships

The Upper Cenozoic sediment wedge mapped in the present study can be divided into several major units as described earlier and shown schematically in Fig. 10. The three most striking different parts are:

- The deltalike IKU Bedrock Unit IX.
- The large-scale clinoform units L–E (and partly X) downlappping on 'base Unit IX'.
- The topmost more horizontal units D–U.

The Upper Cenozoic sediments on the Norwegian continental shelf have been difficult to date because of a low content of *in situ* fossils and high resedimentation. In the Haltenbanken south area the age information is still rather limited and partly conflicting. We will, however, discuss the age of Base Unit IX (and X), the location of the Plio/Pleistocene boundary and the age of Unit D (and younger units).

Base Unit IX

The 'base IKU Bedrock Unit IX' (Figs. 11 and 12) is the oldest reflector mapped in the present study. It is an angular unconformity with westwards-dipping layers below and downlapping clinoforms above (Figs. 6, 7 and 10). The bedrock Units IX and X on the inner part of the shelf (Figs. 2) seem to wedge out quite rapidly northwestwards (Profile VI, Fig. 7) where Units L and K are found above the angular unconformity (Figs. 6 and 7).

In the western part of the study area with several exploration wells (Figs. 3 and 4) the sediments just above the angular unconformity (Figs. 10–12) have been correlated to the Naust Formation of Late Pliocene age (Dalland et al. 1988). The age of the sediments above the reflector should thus be younger than about 3 Ma. The Late Pliocene age in the west is also found in later studies (e.g. Eidvin & Riis 1991; Sigmond 1992 with information from NPD and IKU; Poole & Vorren 1993).

Towards the coast, the base of the Naust Formation is difficult to follow on seismic data. The most striking reflector continues below IKU Bedrock Unit IX (Profile VI, Fig. 7 and Fig. 10). If this reflector represents the base of the Naust Formation also in the eastern part of the study area, it would imply a Late Pliocene age of the IKU Bedrock Units IX and X. This has also been assumed in some compilations (e.g. Sigmond 1992).

From the regional mapping, IKU Bedrock Units IX and X were assumed to be of Oligocene and Miocene ages respectively (Bugge et al. 1984; Rokoengen et al. 1988). The units were, however, very difficult to date because of the large amounts of redeposited fossils. The foraminifera dated by Løfaldli (Skarbø et al. 1983) in fact indicated a Pleistocene/Pliocene age of Unit IX. The age was rejected and the fossils explained as a result of glaciotectonics or sampling effects with reworking in the uppermost metres of the unit.

There is thus a conflict between the ages of Unit IX in different investigations. But new datings based on foraminifera from wells north of the study area seem to confirm an Oligocene age of Unit IX (Eidvin et al. 1995; T. Eidvin pers. comm.).

If the Oligocene age of Unit IX is correct, the Late Pliocene Base Naust reflector must follow one of the younger unconformities. This could be the top of Unit IX or Unit X (Profile VI, Fig. 7; Figs.10 and 11), but it is still uncertain. The age of the oldest part of the mapped sediment wedge has also implications for the age of the angular unconformity below. With an Oligocene age it would be tempting to link it to the mid-Oligocene lowering of sea level (Vail et al. 1977).

The geological history and ages of the Cenozoic sediment wedge have also caused problems on other parts of the Norwegian continental shelf, such as the northern North Sea and the western Barents Sea (e.g. Rokoengen & Rønningsland 1983; Rise et al. 1984; Rise & Rokoengen 1984; Eidvin & Riis 1992; Sættem et al. 1992, 1994).

Base Quaternary

The Plio/Pleistocene boundary (base Quaternary) has often been defined based on investigations of foraminifera. The species used as Pliocene indicators are mostly *Cibicides grossa* and *Elphidium hannai*. Using these criteria, the base Quaternary boundary on the Mid-Norwegian shelf has been located at the angular unconformity forming base Unit D, Figs. 6, 7 and 10 (e.g. Bugge et al. 1984; Rokoengen et al. 1988; Eidvin & Riis 1991; Vorren et al. 1992; Poole & Vorren 1993).

Some data indicate, however, that the Plio/Pleistocene boundary must be deeper. Soil borings from the Draugen Field have given some age information from the study area (Haflidason et al. 1991). Lack of good seismic tie lines have made an exact correlation difficult, but the palaeomagnetic Brunhes/Matuyama boundary (730 ka) is probably found within Unit I. The transition from normal to reversed polarity combined with a marked step in amino acid values from about 0.3 to 0.4 seems to be correlated with a reflector within Unit I (Rise & Rokoengen 1991). This would imply that a large part of Units L–E is of Quaternary age.

At present we think that Units L–E are best described as a Plio/Pleistocene sediment wedge (Figs. 6, 7 and 10). The age is critical for correlations, but for interpretation of depositional environment and soil properties it is more important that glacial sediments are found at least down to base Unit I and probably deeper (Rise & Rokoengen 1991; Eidvin et al. 1995).

The problems with dating the Plio/Pleistocene boundary are also encountered on other parts of the Norwegian shelf. In the northern North Sea early datings on foraminifera in wells from the Måløy Plateau were interpreted to represent a Pliocene age for the sediments above the main angular unconformity, while amino acid datings indicated a Quaternary age of the same units on the Troll Field (Myrland et al. 1981; Green et al. 1985; Rise et al. 1984). Redating of the foraminifera from the Måløy Plateau wells has, however, given a Pleistocene age (Eidvin et al. 1991).

In the Barents Sea, redating of several wells have shown that the previously assumed ages were much too high (Eidvin & Riis 1989). Investigations of sediments outbuilding the western slope of the Barents Sea have demonstrated that the Brunhes/Matuyama boundary (730 ka) is found quite deep and thus the base Quaternary even deeper (e.g. Sættem et al. 1992, 1994).

Base Unit D

As discussed above, the reflector at the base of Unit D has in most of the previous studies been assumed to represent the Plio/Pleistocene boundary. We believe, however, that this boundary probably is found deeper in the stratigraphy (in or below Unit I?). This will also have consequences for the assumed age of base Unit D.

In the study area (Fig. 2) soil drillings are so far only available from the Draugen Field (Haflidason et al. 1991). The exact correlation to the regional framework is, as mentioned before, difficult due to lack of good tie lines. It seems, however, that the top of a layer with more clayey sediments at about 50 m below the seabed could represent the base of Unit B. The lower sediments could belong to Unit I (Profile I (right), Fig. 6). The amino acid values indicated ages older than the Eemian (ca. 120 ka) for the whole Draugen core, but with several distinct groups of ages. Here, resedimentation can also have given too old ages (Haflidason et al. 1991).

Amino acid datings from the fields north of 65°N (Mogensen & Rise 1988) indicate that parts of the marine and glaciomarine sediments below Unit A could be around 120 ka old. The most detailed information is from the Smørbukk Field (Fig. 2), where samples showed a thin layer of marine sediments correlated to the Eemian and glaciomarine sediments below and above (Sættem et al. 1993).

As described earlier, the outer part of Unit B forms a rather thin unit of glaciomarine sediments directly overlying Unit D in the outer part of the shelf (Fig. 16), and the boundary is difficult to follow (Profiles I and II, Fig. 6). Based on the data available, it seems nevertheless likely that the base Unit D is older than the Eemian and represents a glacial surface, probably of Saalean age.

The three topmost units are dominated by unsorted material interpreted to have been deposited as numerous till tongues. Unit B may represent the first (early) Weichselian glaciation on the shelf, Unit A the maximum of the last glaciation and Unit U the deglaciation period. IKU's regional mapping programme has given ages of about 13,000 years BP in till at the shelf edge, thus possibly representing the last glacial advance (Rokoengen 1979; Bugge 1980).

The detailed absolute age relationships in the study area are thus quite uncertain at the present stage, while the relative age relationships have been improved considerably through the present study.

Summary and conclusions

1. The upper Cenozoic deposits on the Mid-Norwegian continental shelf (Figs. 1 and 2) form an extensive and complex sediment wedge increasing to more than 1500 m thickness westwards at the present shelf edge.
2. A regional stratigraphy is established between 64°N and 65°N based on more than 5000 km of seismic data (site surveys with multichannel tie lines, selected conventional deep seismic lines and IKU's regional analog sparker grid, Figs. 3 and 4), lithological and geophysical well information.
3. The sediments overlying IKU Bedrock Units IX and X (Bugge et al. 1984; Rokoengen et al. 1988) have been divided into 11 informal units (L, K, I, H, G, F, E, D, B, A, and U) separated by regional reflectors. The three main unconformities mapped are at the base of Units IX, I and D (Figs. 6–10).
4. Base Unit IX is the oldest reflector mapped in the present study (Figs. 11 and 12) and forms the base of IKU Bedrock Units IX and X in the east (Figs. 7 and 10). In the western part of the study area the reflector corresponds to the base of the Naust Formation in the formal lithostratigraphy off Mid-Norway (Dalland et al. 1988).
5. IKU Bedrock Unit IX is the most characteristic of all bedrock units mapped from sparker profiles (Fig. 11), and it has been mapped from Møre to Lofoten (Bugge et al. 1976, 1984; Rokoengen et al. 1988). The slope sediments have quite steep dips (mainly 10–15°) and are believed to consist mainly of sand. The unit was probably formed in a wave-dominated depositional environment with extensive longshore drift.
6. The age of Unit IX has been discussed during the last decade and varied from Oligocene to Late Pliocene (e.g. Bugge et al. 1984; Rokoengen et al. 1988; Sigmond 1992). New datings based on foraminifera from wells north of the study area seem to confirm an Oligocene age of Unit IX (Eidvin et al. 1995; T. Eidvin pers. comm.). If the Oligocene age of Unit IX, is correct, the Late Pliocene base Naust reflector must follow one of the younger unconformities. This could be the top of Unit IX or Unit X (Profile VI, Fig. 7; Figs. 10 and 11), but is still uncertain.
7. The units L–E consist of large-scale clinoforms prograding northwestwards and gradually outbuilding the shelf edge (Figs. 6, 7 and 10). In general, the units are sheet-like with erosional boundaries in the inner more horizontal part. They thicken above descending palaeoslopes and downlap on the base Unit IX reflector.
8. The typically undulating base of Unit D (earlier assumed to be base Quaternary) is now interpreted to be a result of glacial erosion in Saalian time. The overlying layered sediments in Unit D consist of glaciomarine and marine (Eemian) sediments (Sættem et al. 1993).
9. The three topmost units are dominated by unsorted material interpreted to have been deposited as numerous till tongues (Figs. 15, 16 and 17). Unit B may represent the first (early) Weichselian glaciation on the shelf, Unit A the maximum of the last glaciation and Unit U the deglaciation period.
10. The present study shows that the glacial history of the Haltenbanken south area is very complex, with a number of large and small ice-front oscillations. A very important result from the interpretation is that the glacial deposition seems to have started much earlier than was assumed from the previous regional mapping by IKU and others, and that sediments from many glaciations are preserved.
11. The detailed absolute age relationships in the study area are still quite uncertain, while the relative age relationships should have been considerably improved through the present study. It is hoped that the established stratigraphy will form a regional framework for future shallow seismic investigations and site surveys, and be an aid in the efforts to obtain more exact information about lithology and ages of the different units.

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