

Submerged littoral sediments, beach ridges and wave-cut platforms off Troms, North Norway: revisiting old questions

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Reinterpretation of sea-floor morphology and modelling of Weichselian relative sea-level history on the continental shelf off Troms suggest that beach-like features and sandy basins are unlikely to have been formed primarily by littoral processes. Sea-floor sand transportation has probably been caused by bottom currents, which still flow today. Two seaward-dipping platforms, one at 50–110 m and one at 75–130 m depth on Sveinsgrunnen, Malangsgrunnen and Nordvestbanken, have previously been interpreted as wave-cut platforms. Their gradients are approximately parallel and 50 and 75 m deeper, respectively, than the extrapolated Late Weichselian North Andøy Shoreline (NAS). These platforms therefore seem to be older features, most likely formed mainly by glacial erosion and accumulation processes during the Pleistocene.

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Introduction

The occurrence of shallow-marine molluscs and rounded pebbles at depths between 100 and 200 m on the Norwegian continental shelf has been considered as possible evidence that these areas have been situated near or above sea level (Sars 1872; Grieg 1896; Nansen 1904; Holtedahl 1940, and others). Holtedahl (1993) has reviewed several views and has discussed the records in relation to Pleistocene glaciations.

The suggestion of former dry land on the shelf areas led archaeologists (e.g. Bjørn 1928) to suggest the possibility of contemporaneous human activity on the shelf. Indeed, this hypothesis has recently been promoted by Johansen & Rokoengen (1994) and Rokoengen & Johansen (1996) for areas at 160–170 m depth off southwestern Norway. However, conclusive evidence of dry land and human activity at these depths is still lacking.

Several scientists have described and discussed the existence of submerged beach and barrier-like morphology, littoral sediments and wave-cut platforms off Troms in northern Norway (Fig. 1) (Nansen 1904; Holtedahl 1940; Andersen 1968; Vorren et al. 1978; Dekko & Rokoengen 1980; Rokoengen & Dekko 1993, 1994). Emerged postglacial shorelines have been studied in adjoining coastal areas of Troms and Vesterålen/Lofoten (Pettersen 1880, 1884; Undås 1938; Grønlie 1940, 1951; Marthinussen 1962; Andersen 1968; Møller & Sollid 1972; Bergström 1973; Hald & Vorren 1983; Corner & Haugane 1993; Møller 1984, 1985, 1986, 1987, 1989, 1995). However, in spite of considerable research effort in the region, few attempts have been made to compare and discuss the relative sea-level history of the entire shelf and coastal area. Dekko & Rokoengen (1980) and Rokoengen

& Dekko (1993, 1994) argued, based on a correlation of shoreline gradients and assuming a similar tectonic history, that two seaward sloping wave-cut platforms at 50–110 m and 75–130 m depths (upper and lower levels) on Nordvestbanken, Malangsgrunnen and Sveinsgrunnen may have been formed in postglacial time. However, older ages were not excluded. Fjalstad & Møller (1994) inferred, to the contrary, that the mapped submerged wave-cut platforms were most likely polycyclic coastal features of pre-Late Weichselian age due to their location and gradients compared to extrapolated postglacial shorelines in the adjoining coastal land areas.

This paper addresses the origin and age of the reported drowned beach ridges, littoral sediments and platforms, specifically on Malangsgrunnen by: (a) comparing the reported submerged beach and barrier-like features on the bank area with emerged beach ridges and platform features in adjoining strandflat areas, (b) modelling the Weichselian relative sea-level history, (c) presenting calculations of appropriate long-term subsidence rates related to possible ages of the mapped platforms, and (d) discussing the influence of repeated glacial areal planation and linear erosion processes on the continental shelf off Troms.

Submerged overwash sediments and beach ridges

Within shore zones, site-specific factors, such as nearshore gradient, sediment size and wave exposure, determine the rate and mode of sediment transfer and beach-ridge building (Møller & Sollid 1972; Møller 1985, 1995; Fletcher et al. 1993; Carter & Woodroffe 1994). Both waves and wave-generated currents are involved, and their

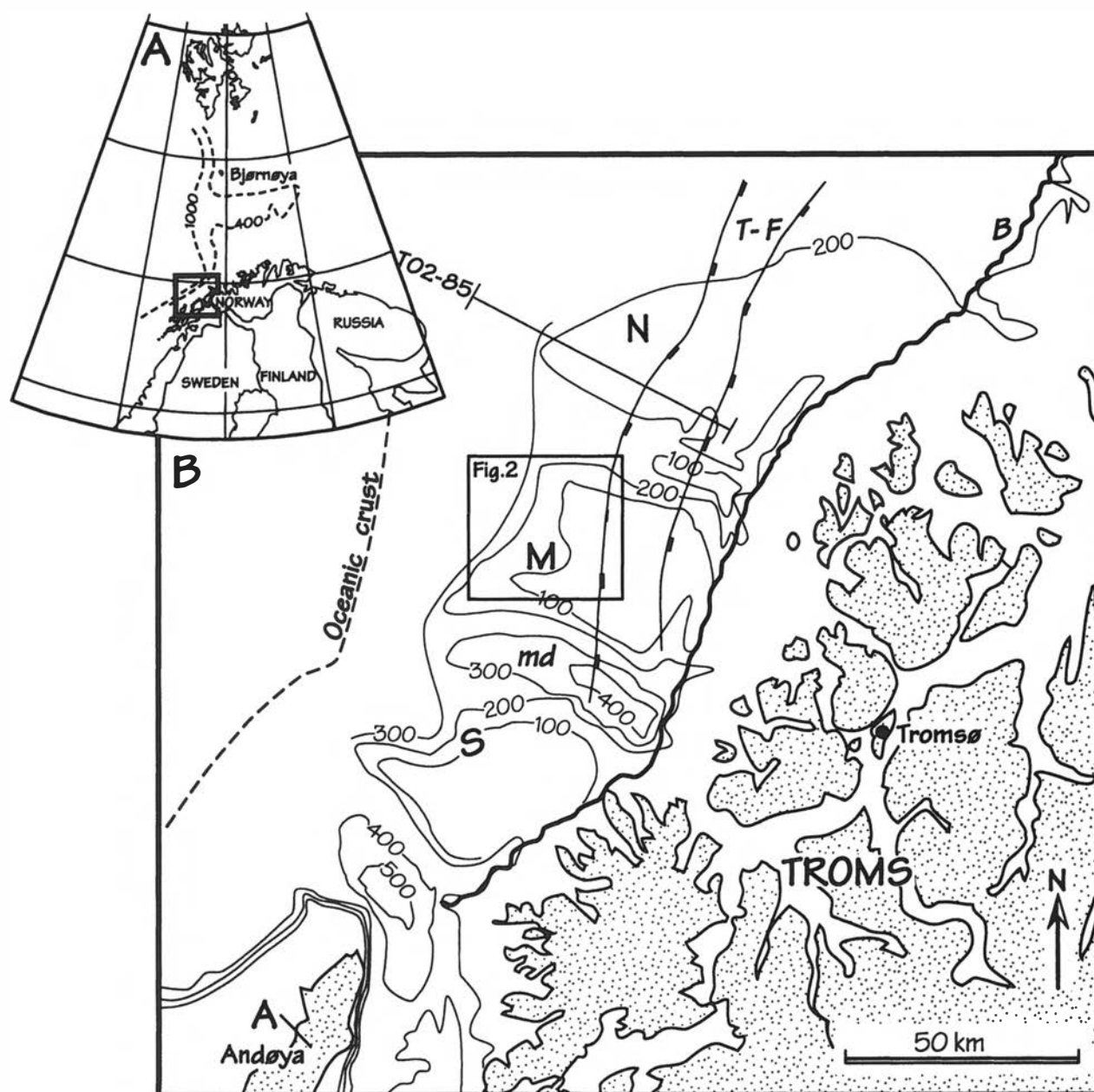


Fig. 1. A. Key map. Study area. B. ad - Andfjorddjupet. S - Sveinsgrunnen. md - Malangsdjupet. M - Malangsgrunnen (Fig. 2). N - Nordvestbanken. A - mid-Andøya profile (Fig. 3). Structural elements: B - boundary between Precambrian and Mesozoic rocks after Rokoengen et al. (1977), T-F - Troms-Finnmark Fault Complex after Løseth & Tveten (1996), and location of the seismic profile TO2-85 after Gabrielsen et al. (1990).

relative importance may vary within the tidal zone and on shallow sea-floors along the coastline. However, there has been little research on erosion, sorting and sediment transfer during the steady sea-level rise along the continental shelf coast of northern Norway in postglacial time.

The northwestern shallow part of Malangsgrunnen (Fig. 2) is one of the bank areas on the shelf off Troms where several ridges are assumed to have been partly wave-modified in the tidal zone. According to Holtedahl (1940), the low ridges of cobbles and boulders in front of shallow basins at 150–160, 140–145, 110 and 95 m depth may best be explained as drowned shore bars, and the sand in the basins as littoral overwash sediments. Several ridges

associated with the platform at 140–150 m depth (Fig. 2, III) were interpreted as possible shore bars or barriers by Rokoengen & Dekko (1994). Andersen (1968) questioned the suggested littoral origin for the ridges at depths below 110 m, and focused instead on extensive ridges situated at 95 m, 85 m and 86 m to 88 m depth (Fig. 2, I and II). The preservation of the beach-like morphology suggested a rapid postglacial transgression. Lien & Myhre (1977) investigated the sea-floor cover on the continental shelf off Troms based on bottom photography, sampling and profiling using side-scan sonar. The top layer on Sveinsgrunnen and Malangsgrunnen consists mostly of boulder and cobble materials indicating a morainic origin, whereas the slightly deeper Nordvestbanken has bottom sediments

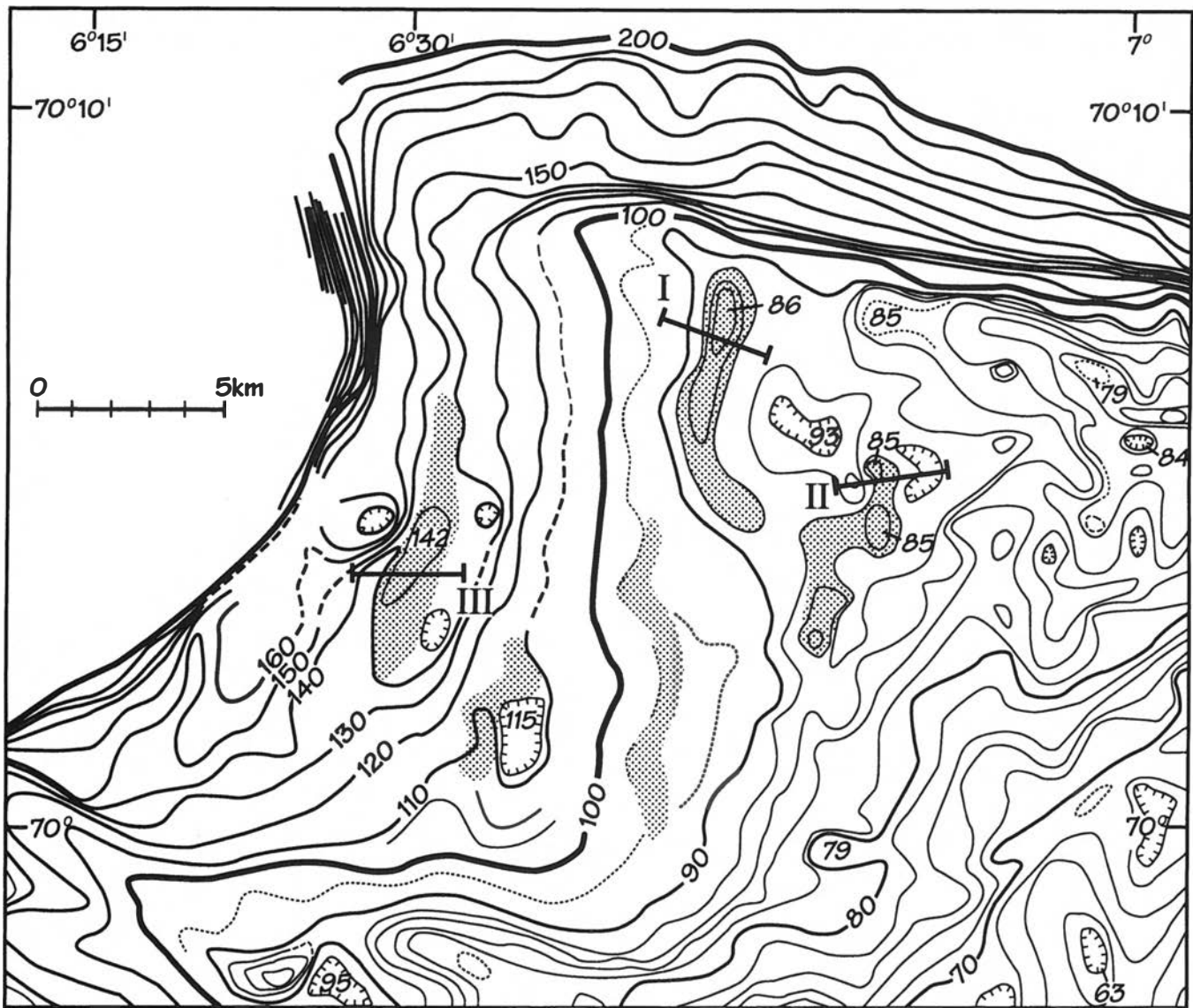


Fig. 2. Bathymetric map of Malangsgrunnen after Andersen (1968), with suggested drowned beach ridges/shore bars (stippled). Locations of three profiles (I–III) are depicted in Fig. 3.

of silt, sand and gravel at depths between 100 and 150 m. In the depressions and in deeper sheltered trough areas, the sea-floor consists mainly of clay and silt. Lien & Myhre (1977) concluded that erosion caused by wave action during former lower relative sea levels had influenced the shallow bank areas, while sedimentation contemporaneously occurred in deeper or sheltered areas. Holtedahl (1955) argued, referring to Helland-Hansen (1907), that bottom currents could move sand on the shelf, even at present. Eide (1978) and Tryggestad (1981) measured current with velocities of 0.5 to 0.7 m/s ca. 5 m above the sea-floor at about 230 m depth near the shelf break on the Malangsgrunnen bank. This agrees with studies of surficial transport of medium to gravely sands at 140–170 m depth by waves and tidal currents of 0.9 m/s ca. 1 m above the sea-floor on the Celtic Banks west of the English Channel (Reynaud et al. 1999). Thus, sea-floor transport of sand on the bank areas off Troms is a feasible process at present.

On Andøya (Fig. 1B), the coastal land areas adjoining Malangsgrunnen, the strandflat has a morphology similar to the submerged areas offshore. The strandflat is a sloping coastal platform in high latitude areas (Nansen 1922), lying between ca. 40 m and 50 m above and below present sea level. To get an impression of the morphology and scale of the suggested drowned beach and barrier-like ridges on Malangsgrunnen (Fig. 2), a comparison (Fig. 3) is made with the Holocene coastal transgression maximum (coastal Tapes, about 6 ka BP, Møller 1986; Fjalstad 1997) beach-ridge complex on mid-Andøya. The geometry demonstrates striking geomorphological differences. However, the 150 m broad and 10 m high Tapes beach-ridge complex on mid-Andøya, which is obviously a result of continuous foreshore landward retreat during sea-level rise, has not been drowned and flattened. Shelf profiles I and II (Figs. 2 and 3) display a relief difference of 4 m and 10 m, respectively, over a distance of 3 km. These do not

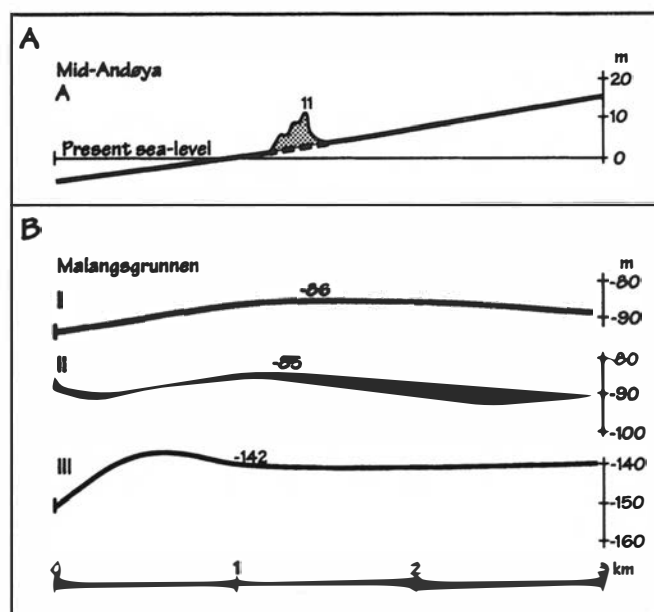


Fig. 3. Morphological profiles comparing: (A) the Tapes beach-ridge complex on mid-Andøya after Fjalstad (1997) and (B) suggested drowned beach ridges on the northwestern part of Malangsgrunnen after Andersen (1968) and Rokoengen & Dekko (1994).

show a beach-ridge or shore-bar morphology. However, their low-relief morphology does resemble suggested submerged barrier islands on the continental shelf off Long Island, New York (Leatherman 1983a, b; Rampino & Sanders 1983; Dubois 1995). The suggested shore-bars or barrier profiles interpreted by Rokoengen & Dekko (1994) at 130–140 m depth (III, Fig. 3B) do not have shore-bar but rather possible barrier characteristics.

At Late Glacial Maximum (LGM), the studied area at the northwestern part of Malangsgrunnen (Figs. 2 and 3) was probably partly located in a proglacial position according to Andersen (1981) and Vorren & Kristoffersen (1986) (Fig. 4B, C), whereas Rokoengen et al. (1979) (Fig. 4A) assumed that the continental ice sheet extended to the shelf break. Farther northeast, on Nordvestbanken and on the southern Barents shelf, discussion continues about the age of the glacial sediments (Rokoengen et al. 1979; Andersen 1981; Vorren & Kristoffersen 1986; Holtedahl 1993; Sættem 1994).

Extrapolating distinct Late Weichselian shorelines in the adjoining coastal area seawards to Malangsgrunnen, Fjalstad & Møller (1994) showed that the lowest post-glacial relative sea level on the northwestern part of the Malangsgrunnen bank area was about 50 m below present sea level. This is consistent with Lambeck's (1995) predicted depth along the shelf margin off Troms at 20–16 ka BP. If these models are correct, the mapped beach ridges at 88–95 m depth (e.g. Holtedahl 1940; Andersen 1968) were at minimum submerged by 38–45 m during the deglaciation period.

Fjeldskaar (1994) modelled the history of the Fennoscandian glacial forebulge for different viscosities of the mantle. As a best fit with the tilt of palaeoshorelines in

peripheral areas of mid-Norway, the maximum glaciation probably produced a forebulge of 60 m at 15 kyr BP, located 100 km distally from the ice margin. During deglaciation, the forebulge collapsed smoothly without any migration. If this was the situation off Troms, the forebulge was located beyond the shelf edge and could not have had any impact on the relative sea-level depth on Malangsgrunnen.

Thus, it does not seem likely that the sediments covering the bank area of the northwestern part of Malangsgrunnen were formed by littoral processes and submerged simultaneously during the early Late Weichselian. An alternative and plausible explanation to be considered is that during a lower relative sea level, LGM-time bottom currents modified older proglacial ridges by transferring sand into basins on the bank area (Holtedahl 1955), while the platform-like formations (Rokoengen & Dekko 1993, 1994) which extend landwards into LGM-glaciated areas are probably of pre-Late Weichselian ages (Fjalstad & Møller 1994).

Weichselian sea-level models

According to Andersen & Mangerud (1989), ice-margin positions in the studied area during isotope substages 5d and 5b (115–85 kyr BP), 4 (75–60 kyr BP) and 3 (60–30 kyr BP) were similar to those during the Early Preboreal, Younger Dryas and Middle Preboreal position, respectively (Fig. 4D). Fjeldskaar (pers. comm. 1997) presumed that these Early and Middle Weichselian stadials produced a forebulge on the order of 10–40 m at the outer part of Malangsgrunnen. These assumptions, together with a composite postglacial shoreline displacement curve for northern Andøya (Fjalstad & Møller 1994) and glacio-eustatic sea-level measurements presented by Chappel & Shackleton (1986), Fairbanks (1989) and Toscano & York (1992), have been used to construct a tentative Weichselian relative shoreline displacement model for Andøya and Malangsgrunnen (Figs. 1B and 5). The model indicates that relative sea-level may have been 20–100 m lower during the Middle and Early Weichselian glaciations than at present. If the maximum forebulge suggestion is correct, the continental shelf off Troms was exposed to littoral processes during substage 3. This agrees with a scanning electron microscope (SEM) analysis of quartz sand surface texture from bottom sediments at 113–122 m depth on the northern edge of Nordvestbanken (Fig. 1B) by Vorren et al. (1978). Mechanical 'v'-shaped forms on fresh glacial grains were interpreted to be a result of a possible late Middle Weichselian high-energy littoral environment. Studies of sandy sediments at 142 m depth and deeper showed no 'v'-shaped forms.

Late Middle Weichselian marine sediments have been investigated and radiocarbon-dated at seven locations in the adjoining coastal area (Fig. 6). Andreassen et al. (1985) radiocarbon-dated *in situ* glaciomarine sediments at two locations, 3–9 m a.s.l. on Arnøya (Leirhola and Lauksun-

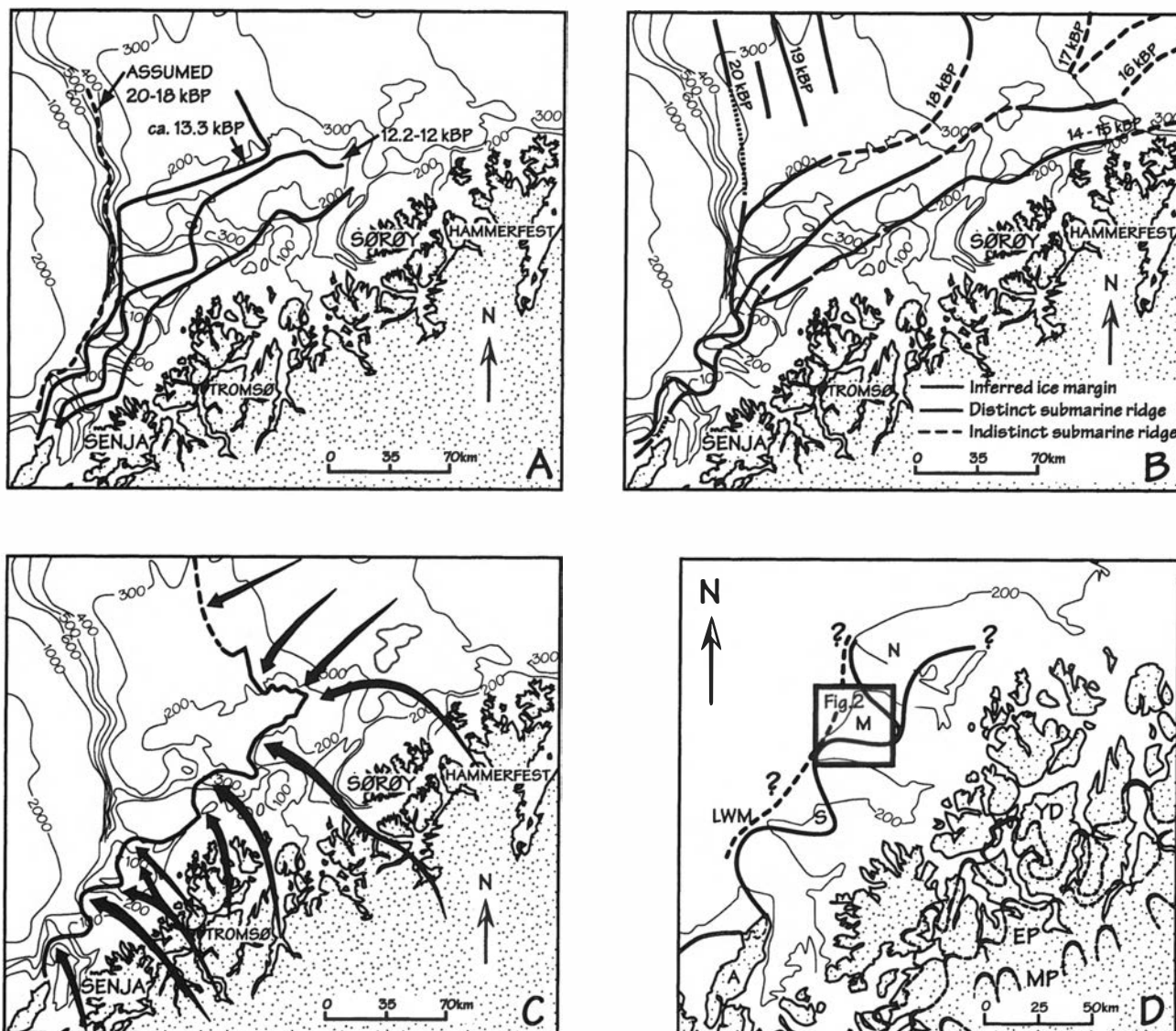


Fig. 4. Ice-marginal positions and deglaciation of the continental shelf off Troms. A. Rokoengen et al. (1979). B. Andersen (1981). C. Vorren & Kristoffersen (1986). D. LWM – Late Weichselian maximum. YD – Younger Dryas, EP – Early Proboreal, MP – Middle Preboreal. The northwestern part of Malangsgrunnen (Fig. 2) is framed.

det) to about 30 ka BP. Near Tromsø (Kvalsundet and Slettelva), at 2–4 m a.s.l. and about 50 m a.s.l., Vorren (1979) and Vorren et al. (1981), respectively, dated reworked molluscs of *Arctica islandica* and fragments of *Mya truncata* to about 41 ka BP. In a coastal cave on the island of Trenyken, southwestern Lofoten, shell fragments in beach sediments at about 19 m a.s.l., corresponding to mean tide level of about 10 m a.s.l., were radiocarbon-dated to about 33 ka BP (Møller et al. 1992). Olsen & Grøsfjeld (1999) ^{14}C -AMS dated one fragment of *Arctica islandica* from *in situ* marine sediments at Storelva, ca. 125 m a.s.l. on the island Grytøya, to about 41 ka BP, and one reworked fragment of *Mya truncata* from a till at Mågelva ca. 160 m a.s.l. on the island Hinnøya to about 46 ka BP.

The fossils at Kvalsundet and Slettelva have been interpreted as representing mixed assemblages glacially transported by the continental ice sheet during the Late

Weichselian (Vorren et al. 1981). Olsen & Grøsfjeld (1999) also suggested that the shell fragment on Hinnøya may have been glacially transported to a higher position. Displayed in a relation shoreline diagram (Fig. 7), the height difference between the sites Kvalsundet, Slettelva and Mågelva is 50 m and 110 m, respectively, which strongly supports this interpretation. However, the extrapolation of the postglacial North Andøy Shoreline (NAS) dated at 14.5 ka BP (Fjalstad & Møller 1994) coincides with the *in situ* marine sediments at Storelva (ca. 125 m a.s.l.), indicating a similar glacio-isostatic component at about 41 ka BP. If correct, the corresponding elevation on Andøya is ca. 25 m a.s.l. (Figs. 5–7).

At Trenyken, the vertical emplacement of the beach sediments was limited because of the shallow strandflat surrounding the island. The pre-Late Weichselian relative sea-level rise had a maximum of about 10 m. Based on the marine sediments at Arnøya and Trenyken, it seems likely

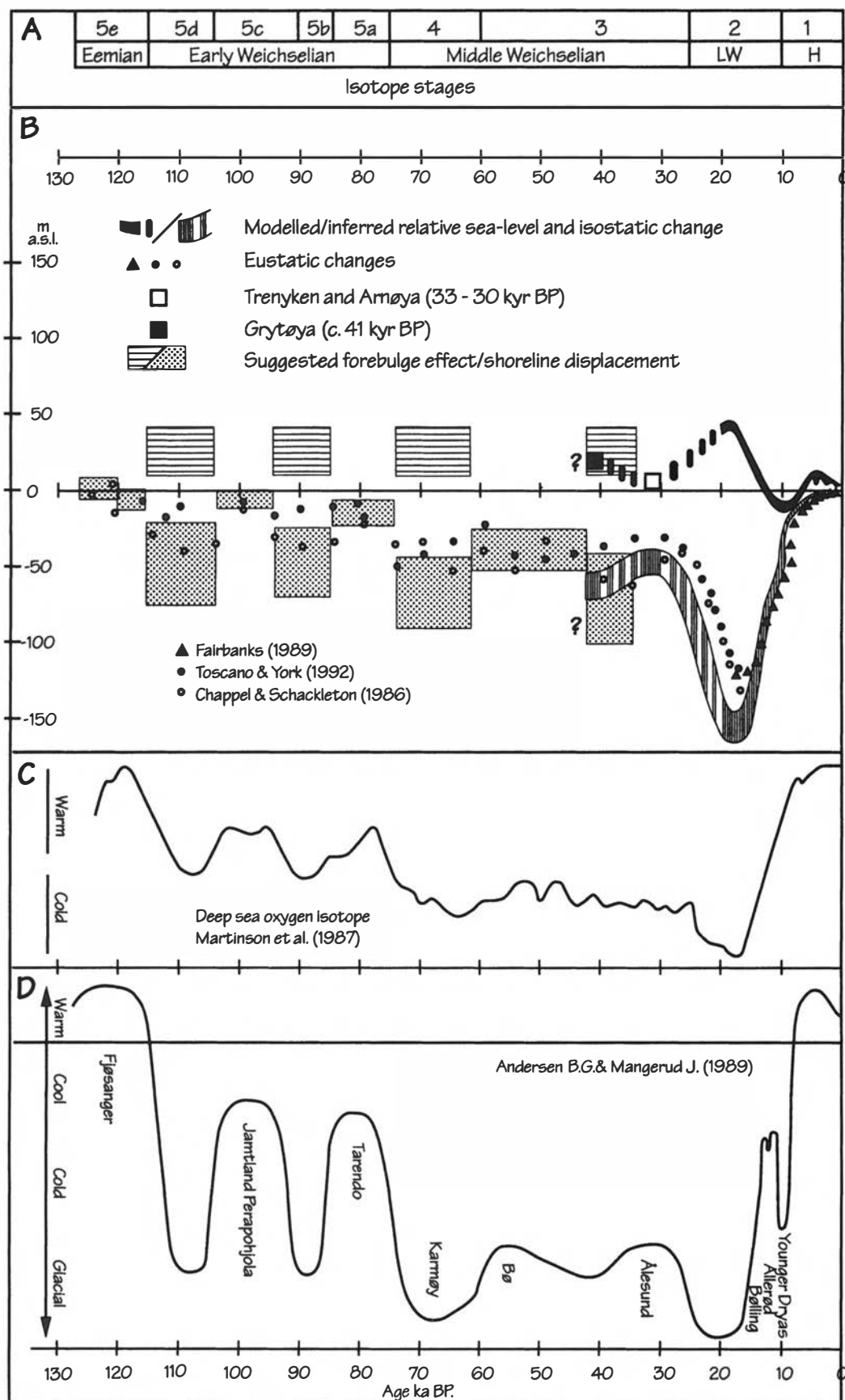


Fig. 5. A. Weichselian isotope stages. B. Modelled Weichselian land-sea interrelation on Andøya and the bank areas off Troms. The shoreline displacement curve for isotope stages 1 and 2 after Fjalstad & Møller (1994). The elevation ca. 125 m a.s.l. of marine sediments on Grytøya (Olsen & Grøsfjeld 1999) is adjusted to ca. 25 m a.s.l. on Andøya (see Fig. 7). C. Deep-sea oxygen isotope curve after Martinson et al. (1987). D. The last interglacial-glacial cycle in Fennoscandia after Andersen & Mangerud (1989).

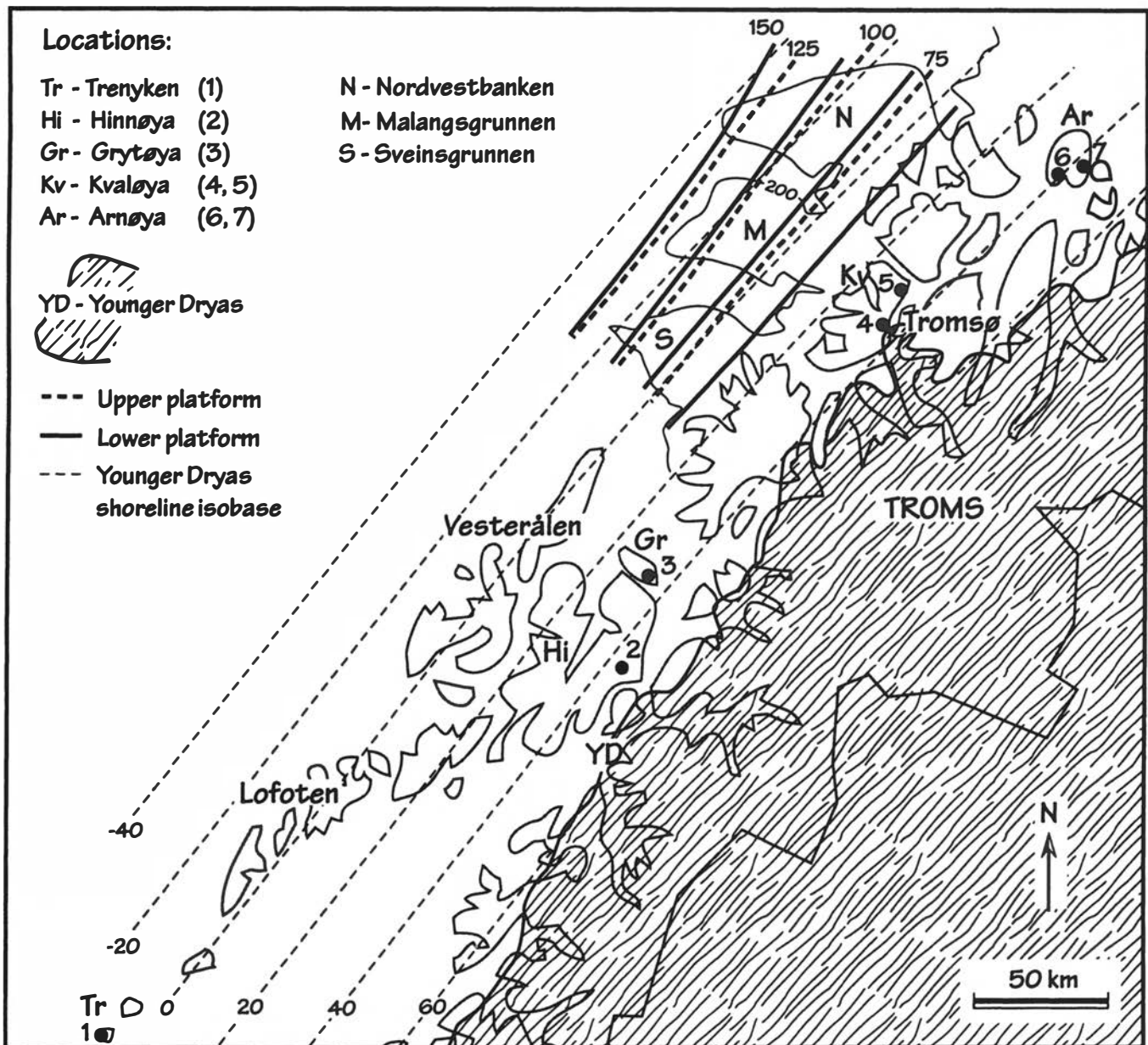


Fig. 6. Shoreline isobases and ice margin position for the Younger Dryas (11–10 kyr BP) after Sørensen et al. (1987). Locations (1–7) for Middle Weichselian dated marine sediments in the study area.

that relative sea-level during late Middle Weichselian at about 30 ka BP was at or up to 10 m above present sea level in the coastal land areas and on the continental shelf areas off Troms (Fig. 7). Thus, the reconstructed late Middle Weichselian relative sea-level history from the adjoining coastal land areas conflicts with the tentative Weichselian relative sea-level model based on the scenario of a forebulge effect on the order of 10–40 m (Fig. 5).

It is assumed, as a first approximation, that the glacio-isostatic depression is equal to about one-third of the ice thickness (Weertman 1961; Hollin 1962; Andrew 1970). This means that the approximately parallel platforms 50–75 m deeper than the extrapolated North Andøy Shoreline (NAS) (Fig. 7) indicate an ice sheet on the order of 150–225 m thicker than at LGM. However, near

ice margins, isostatic depression may be less (Walcott 1970). In addition, partly submerged grounded ice sheets at the shelf break off Troms (Lambeck 1995) probably had an excessively reduced isostatic capability. Thus, it is not likely that the banks and troughs off Troms were formed by a deeper isostatically controlled relative sea-level during pre-LGM time.

Long-term tectonic subsidence

Structural elements seen on a seismic profile across Nordvestbanken (TO2-85, Fig. 1B) on the continental shelf off Troms were analysed and described by Gabrielsen et al. (1990) (Fig. 8). The bank area is bordered to the

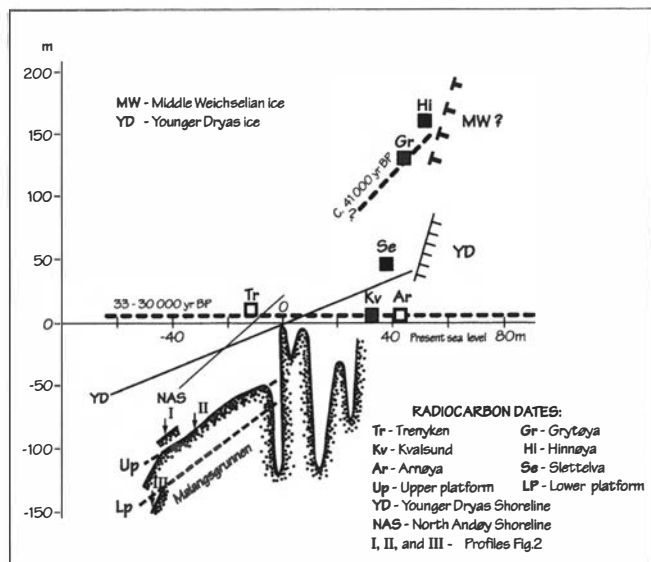


Fig. 7. Shoreline relation diagram for the coastal area of Lofoten, Vesterålen and western Troms. The abscissa shows the altitude of the Younger Dryas shoreline isobases (Fig. 6).

northwest by oceanic crust and to the southeast by Pre-Cambrian crust. Intensive faulting occurred during the Cretaceous and Early Tertiary. The base of the Upper Triassic and Jurassic, Lower Cretaceous and Upper Pliocene have gradients seawards of 200 m/km, 150 m/km and 50 m/km, respectively, indicating a tectonic hinge zone within a distance of up to about 10 km landwards of the seismic profile (Fig. 8). This hinge zone coincides with the boundary between the Precambrian crystalline and Mesozoic sedimentary bedrock complexes (Fig. 1B). However, the base of the Quaternary is nearly parallel to present sea level. Thus, it is reasonable to suggest that the main subsidence of the continental shelf off Troms at Nordvestbanken, and probably also at Malanggrunnen, occurred during pre-Quaternary time.

The late Cenozoic subsidence rate is estimated based on the seismic data from Nordvestbanken. Near the shelf margin, as an example, at shot point 1600 (Fig. 8), the average rate of subsidence (totalling 3000 m) during the Cenozoic (65 Myr) has been on the order of 4.6 cm/kyr. This is close to Pitman's (1978) calculation (2–4 cm/kyr) of subsidence rates at mature passive continental margins. Calculated maximum subsidence rate of the base of the Quaternary at about 425 m depth is 24 cm/kyr.

The mapped upper and lower platforms on the continental margin off Troms at 110 and 130 m depth (Rokoengen & Dekko 1993, 1994) are located roughly parallel to and 50 m and 75 m deeper, respectively, than extrapolated Late Weichselian coastal shorelines (Møller 1985; Fjalstad & Møller 1994, fig. 1B) (Fig. 7). The calculated subsidence rates (4.6 and 24 cm/kyr) give respective ages on the order of 1.1/0.2 and 1.6/0.4 Myr

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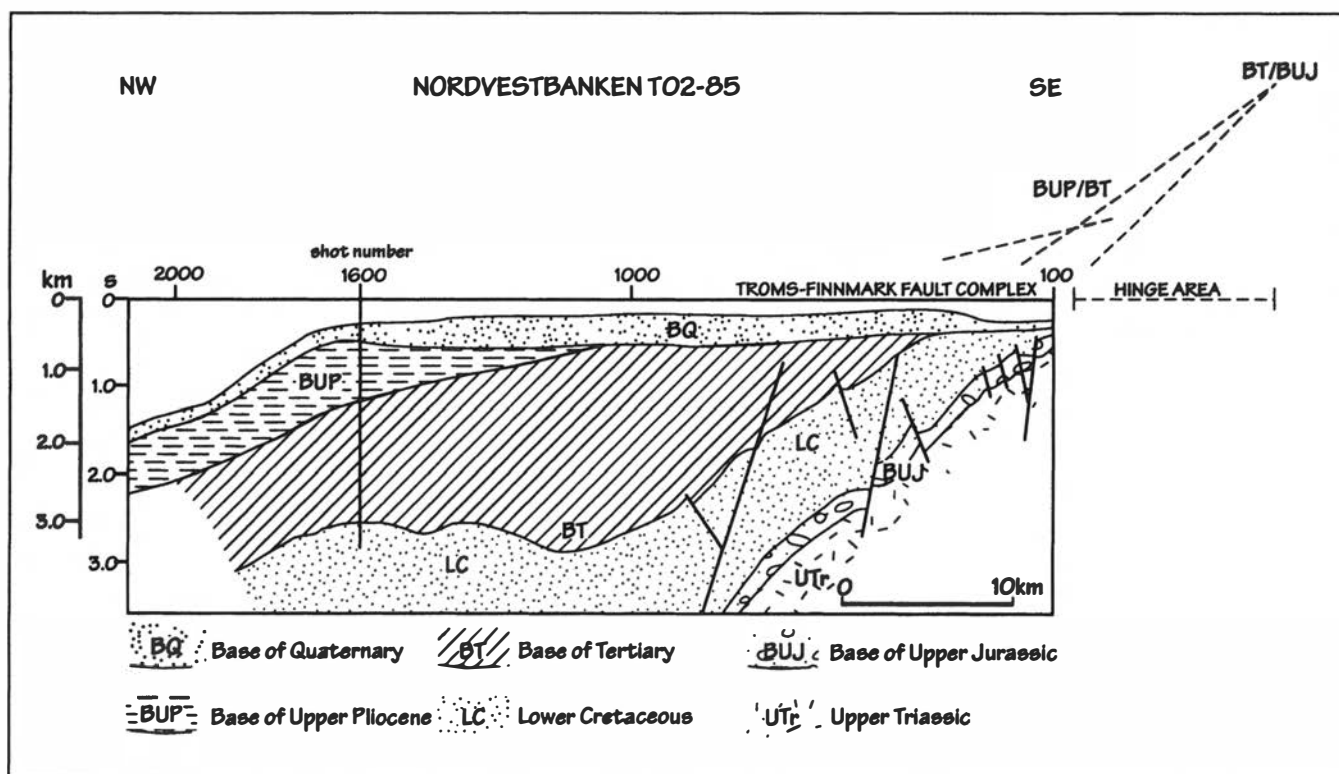


Fig. 8. Seismic profile T02-85 across the Nordvestbanken (Fig. 1B), modified after Gabrielsen et al. (1990). Reinterpretation of the base of the Tertiary according to Riis (pers. comm. 1997).

for glacial and stadial periods and 2.4/0.3 and 2.8/0.5 Myr for interglacial periods. These calculated ages seem to exclude that wave erosion has been involved in the formation of the submerged platforms during the Quaternary. During glacial stages, sea-floor morphology and sediments would be disturbed by erosion and resedimentation.

Glacial planation and erosion

According to Eidvin & Riis (1989) and Sættem (1994), and references therein, significant erosion and accumulation have occurred on the continental shelf off Troms and in the southwestern Barents Sea during the late Pliocene and Quaternary. The discordant boundary between the base of the Quaternary relative to the Lower Cretaceous and structures within the Tertiary (Fig. 8) indicate extensive planation processes, probably of subglacial origin. It is reasonable to suggest that extensive glacial processes have been operative throughout the Quaternary.

Extensive glaciations are, in fact, indicated in adjoining coastal land areas. Fjalstad (1997) studied the morpho- and sediment stratigraphy on the mountain plateau of Trolldalsheia on northern Andøya. Indications of glacial influence were found up to about 400 m a.s.l. A PL-dating, 105 ± 10 ka BP, of a feldspar-rich diamicton under an erratic block at 379 m a.s.l., if correct, indicates glacial emplacement of both the block and the underlying diamicton during isotope stage 5d. Bergström (1973) recorded erratic blocks at Sverigetind on northern Andøya at about 500 m a.s.l. These recorded elevations, which agree with Andersen's (1968) predicted maximum model of the Scandinavian ice sheet, are 200–300 m higher than the mapped LGM ice sheet according to Møller et al. (1992). The Early Weichselian influence of the Scandinavian ice sheet on northern Andøya conflicts strongly the ice-marginal position suggested by Andersen & Mangerud (1989). Extensive pre-late Middle Weichselian glaciations also agree with higher locations of coastal caves in Lofoten and Vesterålen and sub-till *in situ* marine sediments on Grytøya compared to Late Weichselian shorelines (Møller 1985; Olsen & Grøsfjeld 1999).

Owing to the characteristic glacial morphology of the continental shelf off Troms (Holtedahl 1940; Andersen 1968, 1981, and others), it is reasonable to suggest that the upper and lower platforms off Troms (Rokoengen & Dekko 1993, 1994) have been primarily formed by glaciers during the Quaternary (Ottesen et al. 2000). The upper platform, which coincides with the gently sloping Sveinsgrunnen and Malangsgrunnen (about 2 m/km), is probably mainly a result of areal scouring and glacio-tectonics by relatively thin ice sheets, whereas the lower platform along the adjoining slope of troughs probably represents remnants from linear erosion by thick ice-streams, similar to remnants like 'shoulders' or terraces along fjords and valleys in Troms.

Conclusions

(1) The low-relief ridge morphology and sandy sediments in basins at depths between 75 m and 130 m on Malangsgrunnen probably do not represent submerged postglacial beach-ridge features and littoral overwash deposits. More likely, the ridge morphology represents glacial deposits modified, together with the sandy basins, by shallow marine bottom currents during postglacial time.

(2) Modelling of Late- and Middle-Weichselian relative sea levels and calculation of long-term subsidence rates seem to exclude the possibility that the upper (50–110 m depth) and lower platforms (75–130 m depth) on the continental shelf off Troms were formed by littoral processes. Most likely, the upper platform is mainly a result of areal scouring and glacio-tectonics by thin ice sheets, whereas the lower platform mainly represents remnants from linear glacial erosion of troughs by thick ice streams during the Quaternary.

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