Submerged and tilted coastal features off Troms, northern Norway

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Shallow-seismic investigations off Troms show geomorphic features resembling strandlines and wave-cut platforms. Two levels, the Malangsgrunnen and the older Nordvestbanken levels, are described and informally named after the areas where they are best developed. At the middle part of Malangsgrunnen the water depths at the time of formation were ca. 75 m and ca. 100 m below the present sea level, and the two levels have gradients out from the coast of 2.0 and 2.3 m/km respectively. The higher level was formed as a wave-cut platform on Sveisgrunnen and Malangsgrunnen. The level has later been tilted and represents the very flat top of the two banks. During the formation of the older, lower and steeper level, most of Sveisgrunnen and Malangsgrunnen and large parts of Nordvestbanken were dry land. The levels were formed after the deglaciation of the area. Compared with the northern North Sea even the youngest possible age of 13,000–11,000 years BP should have given enough time for formation. In the areas off Troms, however, much work remains before the possible submerged beach levels are confidently mapped, dated and correlated to the extensive system of raised and tilted strandlines on land.

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Introduction

Post-glacial isostatic rebound is clearly expressed by series of well-developed raised shorelines in Scandinavia, especially in northern Norway (e.g. Pettersen 1880; Helland 1899; Grønlie 1914, 1940, 1951; Martinussen 1960, 1974; Möller & Sollid 1972, 1973; Andersen 1968, 1975). It has long been assumed that parts of the Norwegian Continental Shelf are covered with sediments of littoral character, indicating that in periods large areas on the shelf have been dry land (Sars 1872; Brøgger 1901; Nansen 1904). Little is known, however about the regional distribution, age and correlation between the different features of assumed littoral origin.

The purpose of this paper is to describe assumed submerged and tilted coastal features off Troms based on seismic profiling and bathymetry, and to discuss their age compared with data from adjacent land areas.

The study area

The study area (Fig. 1) is dominated by the three bathymetric banks of Sveisgrunnen, Malangsgrunnen and Nordvestbanken, which are separated by deep west–northwest trending channels. Between the banks and the coast is a partly well-developed channel. Further north the extensive banks of Fugløybanken and Tromsøflaket deepen gradually northwards.

Crystalline basement rocks extend some distance from the coast (Fig. 1). They form an area of very irregular sea-bed topography that is overlain by Mesozoic and Tertiary rocks further offshore.

Many features on the North Norwegian Continental Shelf are characteristic of glaciated areas, such as overdeepened troughs and channels, a rough sea bed, unsorted sediments containing boulders and cobbles, and overconsolidated deposits. There seems to be general agreement that the ice has reached the edge of the continental shelf once or several times during the Quaternary (e.g. H. Holtedahl 1993).

Possible submerged shorelines and moraine ridges on the continental shelf were suggested by O. Holtedahl (1940). On land, Andersen (1968, 1975) mapped the Younger Dryas and other ice-front deposits in Troms and northern Nordland. He also suggested the presence of older moraines (the Egga Moraines) on the adjacent continental shelf.

The shallow bank areas of Sveisgrunnen and Malangsgrunnen have a lag deposit of cobbles and gravel. The coarse sediment is believed to have been formed by winnowing during previous lower sea levels. Samples from deeper waters are often sandy (Maisey 1974; Holtedahl & Bjerkli 1975). It is striking that the transition between a gravelly and a sandy sea bed occurs in deeper water far from the coast than close to the mainland (Lien & Myhre 1977). The surface sediments seem partly to be old and formed during high energy conditions, and partly to be younger and formed in depositional environments like those of today (e.g. Vorren et al. 1978, 1984; Rokoengen et al. 1979a, b; Hald & Vorren 1984, 1987).

Shallow seismic interpretation

About 4700 km of analog sparker profiling have been run off Troms (Fig. 2). An EG & G sparker system was
used, mainly with 1000 Joule energy and 50–500 Hz bandpass filter (Bugge et al. 1974).

The entire study area is covered by old soundings with fairly inaccurate positioning, but between 70°N and 71°N the Hydrographic Office of Norway has conducted echo-sounder surveys with maximum profile distance of 1 km, and usually considerably less (Bugge 1975).

Recognition of possible submerged coastal features

The continental shelf has a fairly even surface, and variably developed platform-like features can be found in most areas. The genetic interpretation is therefore not particularly easy.

Based on bathymetric charts, several possible submerged beaches at 150–160 m, 140–145 m and 95–110 m below the present sea level were recognized off Troms (O. Holtedahl 1940). On the outer part of Malangsgrunnen the existence of ancient shore bars was suggested. Andersen (1968) also discussed the topography and sea-level changes off Troms. He concluded that parts of the shallow banks had been dry land, and suggested that the even surface at Malangsgrunnen could represent a sandur plain. Based on seismic records, a possible submerged beach at 115 m water depth was described from Malangsgrunnen by Bugge et al. (1974).

One of the most striking morphological features off Troms is the extremely flat surface of Malangsgrunnen and Sveisgrunnen dipping out from the coast. The most common type of possible submerged coastal features observed on the seismic profiles is, however, small (0–2 km broad) platforms. They often end in what could well be low erosional cliffs (Figs. 10 and 11). We first tried to correlate the beach-like features from profile to
profile using levels at constant water depths in the same way as has been done off eastern Canada (King 1980). Off Troms, this attempt proved unsuccessful (Dekko & Rokoengen 1980). Taking tilting into account, however, it is possible to present a relatively coherent picture of the individual shorelines observed on different profiles.

An independent argument for tilted beach levels off Troms is the increasing water depth for the transition between gravelly and sandy sea bed away from the coast (Lien & Myhre 1977). Tilted levels have also been recognized in the northern North Sea, where submerged coastal features have been studied in more detail (e.g. Dekko & Rokoengen 1978; Rokoengen et al. 1982; Rise et al. 1984; Rise & Rokoengen 1984; Carlsen et al. 1986).

To correlate the beach-like features found on the shallow seismic profiles off Troms, levels with different dip angles was suggested (Rokoengen 1979; Dekko & Rokoengen 1980). Certainly this is a simplification, as the later deformation will probably not be linear in a large scale. The available data, however, are not thought to justify a more sophisticated approach. From all the seismic data the best fit was obtained for two levels, informally named the Malangsgrunnen Level and the Nordvestbanken Levels, after the areas where they are best developed.

The Malangsgrunnen Level

Both Malangsgrunnen and Sveinsgrunnen have very even surfaces. Even at a vertical exaggeration of 50:1 the platform-like shape is striking in a profile across Malangsgrunnen out from the coast (Fig. 3). Large, flat areas slope gently out from the coast with a gradient of about 2 m/km. The location of the dipping plane is marked on the profile (Line A–A, Fig. 3), and the isobases constructed in Fig. 4. The isobases run approximately parallel to both the present coastline and the Younger Dryas isobases (Andersen 1968).

Correlation between the Malangsgrunnen and Sveinsgrunnen banks is based on submerged plains with apparently similar dip and corresponding water depth. Extrapolation of the isobases to Nordvestbanken and further north is very tentative, and only small adjustments of the isobases will result in large changes in the distribution of land and sea.

At the time of formation of the Malangsgrunnen Level the bank areas on Malangsgrunnen and Sveinsgrunnen were very shallow, with less than 20 m water depth and low hills forming islands (Fig. 5). Some of the low hills may represent beach ridges (or younger sand banks). Only small areas of Malangsgrunnen reached more than 10 m above sea level.

In the sparker profiles from Malangsgrunnen (Fig. 6) the main feature is the very flat top of the bank. Yet, on all sides of the bank, small platforms apparently due to erosion can be found, and are used in constructing the Malangsgrunnen Level (Fig. 5).

Some details can also be seen in the subsurface sediments on the sparker sections. The sediments in profile II (Fig. 6), are divided into two units by a probable glacial erosional surface. The flat-lying layers to the north (left) are assumed to represent bedrock of Tertiary age (Bugge & Rokoengen 1976; Rokoengen et al. 1977, 1979a, b). The deposits to the south (right) may represent the sedimentation out from the bank area associated with the erosion of the platform.

Overall, the seismic profiles reveal that the Malangsgrunnen Level are smooth and even, with no evidence of iceberg plough marks (Fig. 6). This may mean that the water was too shallow for large icebergs to penetrate into the area, or that the levelling of the banks happened after icebergs were present, or that the plough marks have been covered by younger sediments.
The Nordvestbanken Level

A profile across the southwestern part of Nordvestbanken is shown in Fig. 7. The dipping Nordvestbanken Level is marked B–B, and the isobases shown in Fig. 8. The level can also be found as erosional terraces and small cliffs on Malangsgrunnen and Sveinsgrunnen. In contrast to the Malangsgrunnen Level, the Nordvestbanken Level seems to have been subject to iceberg ploughing, a process that has been very active on the Norwegian Continental Shelf (e.g. Lien 1983).

The isobases of the Nordvestbanken Level nearly parallel the isobases of the Malangsgrunnen Level, but are somewhat deeper and steeper (Line B–B, Fig. 3). The paleogeography of the area during the formation of the Nordvestbanken Level, when large areas of the bank were dry land, is shown in Fig. 9. Ignoring the amounts of material possibly removed by later erosion, the bank formed a low island with a smooth and even surface with only a few localities with elevations higher than 20 m. A platform is well developed in the northwestern part of the bank (Fig. 10). The width varies between 0.5 and 2 km, being broadest in the outermost part of the bank.

The southwestern part of Nordvestbanken had a lagoon-like depression (Fig. 9) with a low island in the middle. The maximum water depth was about 25 m and only a small inlet was deeper than 10 m. The bay was about 20 km long and 10 km wide, forming a fairly sheltered area. This area on Nordvestbanken corresponds to an area with rather flat sea floor and clayey sediments (Lien & Myhre 1977).

The Nordvestbanken Level seems to be well developed also on Sveinsgrunnen and Malangsgrunnen, with a gradient of about 2.3 m/km. In the northern part of Malangsgrunnen a wave-cut platform partly with adjoining accumulation of sediments is apparent (Fig. 11, I–IV). A possible beach ridge corresponding to the B-level is also present (Fig. 11, II).

Discussion

Origin of the submerged levels

The present study has shown that at least two marked submerged and tilted levels exist off Troms. In particular, the Malangsgrunnen Level forming the present inclined surface of Malangsgrunnen and Sveinsgrunnen is very striking (Figs. 3–6), but also the deeper Nordvestbanken Level seems to be well developed (Figs. 3, 7–11).

Regarding the formation of the submerged levels, large platform-like landforms can be produced by different processes, and we have considered the following:

- Outwash plains or sandur deposits
- Till surface plains
- Glacial erosion
- Wave erosion

The existence of outwash plains or sandur deposits on top of the Malangsgrunnen and Sveinsgrunnen banks has been suggested based on morphological mapping.
Fig. 6. Selected sparker profile sections showing the submerged Malangsgrunnen Level (A–A).
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Erosion by ice could be another possibility. Large, very even, erosional surfaces have been found below marine tills (e.g. King et al. 1991; Sættem 1991). The small (0–2 km broad) platforms ending in assumed erosional cliffs (Figs. 10 and 11) could possibly have been formed by floating ice. The platforms, however, are also formed within the large banks, especially on Nordvestbanken (Fig. 10, V). Furthermore, some of the platforms seem to be formed by deposition in addition to erosion (e.g. Fig. 11, IV). The available shallow-seismic data are not sufficient to map accurately the internal structures of the platforms. Nevertheless, it is considered that deposition occurred in all directions away from the banks, also in the landward direction (Fig. 11, I).

No definite conclusion can be drawn from seismic data alone, but wave erosion is considered the most probable agent for forming the submerged platforms off Troms. The outer part of the Sveinsgrunnen and Malangsgrunnen banks and also the northern parts of Nordvestbanken must have been subject to wave action from the open sea. Between the banks the shores may have been more sheltered and also partly filled with drifting ice.

It seems likely that the wave erosion should have been comparable to that in the northern North Sea. The size of the flat bank areas on Malangsgrunnen and Sveinsgrunnen is also in the same order of magnitude as, but smaller than, the described submerged, wave-cut platform in the northern North Sea, that is ca. 40 x 60 km. The submerged level in the northern North Sea is shown to have been formed mainly in the period 13,000 to 11,000 years BP (Rise & Rokoengen 1984; Rise et al. 1984; Skinner et al. 1986; Long et al. 1988).
Age of the submerged levels and comparison with adjacent land

There have been several erosional events off Norway during both Mesozoic and Cenozoic time, and in subsiding areas the records of these events may be preserved. In the coastal areas of Norway the best known feature from this period is probably the Norwegian strandflat (Larsen & Holtedahl 1985 with older references). Also the bank areas off Troms may have been levelled several times and for most of the Cenozoic they have probably been rather smooth features. What is described in this paper we believe are the last major erosional events. Precise dating of the described levels is not possible from the available data, but some estimates can be made.

Fig. 10. Selected sparker profile sections showing the submerged Nordvestbanken Level (B) on the western part of Nordvestbanken.
Fig. 11. Selected sparker profile sections showing the submerged Nordvestbanken Level (B) on Malangsgrunnen.
It is assumed that beach levels may remain fairly well intact during a glaciation. Supposed wave-cut platforms covered by till are for instance reported from the North Sea (e.g. Thomson & Eden 1977; Skinner et al. 1986; Long et al. 1988). As no till material seems to be present above the Malangsgrunnen and Nordvestbanken Levels, we believe that they formed after the deglaciation of the area. The dating of the levels will therefore be closely related to the deglaciation history of the area.

The youngest till units are thought to have been deposited during the final deglaciation, partly in connection with readvances of the ice front. In this period the ice may have been floating freely over the trenches, but may have grounded on the banks (Rokoengen et al. 1979a, b). Thus the geological development during deglaciation may have been similar to that of the northern North Sea Plateau and the Norwegian Trench (e.g. Rise et al. 1984; Lehman et al. 1991).

Regarding the age of the glacial deposits, and thus the time of deglaciation of the continental shelf off Troms, diverse opinions exist, as summarized by H. Holtedahl (1993). However, the proposed interpretations can be divided into a maximum-ice model that assumes that the ice sheet reached the edge of the continental shelf during the last glacial maximum (e.g. Holtedahl 1940; Andersen 1968; Rokoengen et al. 1977, 1979; Settem 1991) and a minimum-ice model assuming that northern Andøya and the outer shelf were ice-free (e.g. Grønlie 1940; Möller & Solid 1972; Vorren et al. 1978; Vorren & Kristoffersen 1986).

Northern Andøya has been a key area in the discussion of the Late Weichselian glacial maximum in the area (e.g. Vorren 1978; Vorren et al. 1988; Möller et al. 1992). The geographic position of Andøya bordered by the deep channel Andfjorden on the landward side (Fig. 1) may, however, have given special local conditions with ice-free areas even if the ice reached the shelf edge further north.

On the shelf the discussion has been based on very few dated till samples (H. Holtedahl 1993). An important date with regard to the deglaciation was obtained from shells in overconsolidated material from the outer part of Nordvestbanken. The age obtained was 13,310 ± 110 years BP, and the texture and fauna of the sample strongly indicate that the sediment is a glaciomarine deposit mixed and overconsolidated by ice (Rokoengen et al. 1977, 1979a, b). The date thus possibly indicates the time the inland ice sheet last reached the shelf edge in the area. If this is correct, the submerged beaches should be younger than ca. 13,000 years BP. The young date, however, has been disputed by Vorren et al. (1983, 1986).

With an earlier deglaciation, more time would have been available for the formation of the submerged levels. But compared with the North Sea it seems reasonable that even the last suggested ice advance of 13,000 BP should have left sufficient time for the formation of the submerged levels after deglaciation.

Vorren et al. (1978) carried out quartz-surface texture analysis on sediment samples collected from the northern edge of Nordvestbanken. They suggested that there had been a total rise in sea level of 120–140 m since the tentatively dated maximum age in the samples of 12,000 years BP. The depth fits the level of the suggested isobases of the Nordvestbanken Level, but is also only ca. 20 m below the isobases of the Malangsgrunnen Level. Assuming that the sand did not attain its littoral character at an even earlier stage, this supports an age for the levels in the range of 13,000–11,000 years BP.

In Figs. 4 and 8, isobase lines for the Malangsgrunnen and Nordvestbanken Levels are extrapolated onto the mainland areas. Both levels intersect the present sea level along the outer parts of Senja, Kvaløy and Ringvassøy. Immediately offshore, the isobases coincide fairly well with the submerged strandflat in the area (Grønlie 1951).

Since a great amount of detailed work has been carried out on land, an attempt is made to compare the gradients of inclination for the submerged beaches on the continental shelf with the more established system of isobases onshore. There, two levels, the Main Line of Younger Dryas age (11,000–10,000 years BP) and the younger Tapes Line, are both very distinct, while many other lines are found at different heights above sea level. Their correlation is complicated, however.

The Main Line and the Tapes Line (after Andersen 1968) are compared in Fig. 12 with the Malangsgrunnen and Nordvestbanken Levels. The Main Line intersects the extrapolated Malangsgrunnen and Nordvestbanken Levels about 30–40 m above the present sea level. The Tapes Line crosses the other levels in the coastal area.

At the moraines representing the Skarpsnes event (ca. 12,500–12,000 years BP), Andersen (1968) found that the raised beaches corresponding to the event were situated about 7–10 m above the Main Line. This height corresponds fairly well with the extrapolation of both the
Malangsgrunnen and Nordvestbanken Levels in the area (Figs. 4, 8 and 12).

We believe that the Malangsgrunnen and Nordvestbanken Levels were formed after the deglaciation of the shelf, but with ice still present onshore. In the coastal areas, where they could have been formed on land, both Malangsgrunnen and Nordvestbanken Levels should occur below the Main Line (Fig. 12). With several levels crossing near the coast it might be complicated and difficult to determine which level the different features originally belonged to. The height of the Skarpnes shorelines compared to both the Malangsgrunnen and Nordvestbanken Levels could indicate that one of the levels is contemporaneous with the Skarpnes event, assuming the same deformational history.

Based on their gradients of about 2.0 and 2.3 m/km, however, the submerged levels found off Troms should be older than the Younger Dryas Main Line, assuming a corresponding later deformational history. In fact, even the oldest shorelines correlated on land by Martinussen (1960) and Andersen (1968) have gradients that are considerably less. If the gradients on land are correct, and the later deformational history the same, this would indicate that the levels on the shelf are older than all the levels mapped on land.

At present the age of the Malangsgrunnen and Nordvestbanken Levels cannot be precisely defined. The youngest possible age seems to be the period ca. 13,000–11,000 years BP. The time available for the formation of the levels should have been sufficient compared with the northern North Sea, but an older origin cannot be ruled out.

Clearly, it is also yet impossible to correlate correctly the levels on the shelf off Troms with the established system of raised strandlines on land. To find the right connection should, however, be one of the challenges in future work. In many ways the problems are very similar to those encountered further south in Norway (e.g. Rise & Rokoengen 1984; Larsen & Sejrup 1990).

Conclusions

1. Based on seismic profiling and bathymetry, the existence of submerged and tilted landforms off Troms is described and interpreted as coastal features. Wave erosion is believed to have been the most active agent during formation.

2. Two levels, the Malangsgrunnen and the Nordvestbanken Levels, are described and informally named after the areas where they are best developed.

3. The Malangsgrunnen Level has a dip of 2 m/km out from the coast and comprises the very flat top of Malangsgrunnen and Sveinsgrunnen. The size (Fig. 5) is comparable with, but smaller than, the described ca. 40 x 60 km wave-cut platform described in the northern North Sea (Rise & Rokoengen 1984).

4. The older Nordvestbanken Level is somewhat deeper and steeper with a gradient of 2.3 m/km on Malangsgrunnen. During the formation of this level, most of Sveinsgrunnen, Malangsgrunnen and large parts of Nordvestbanken were dry land.

5. The levels are believed to have been formed after the deglaciation of the area. Even the youngest possible age of 13,000–11,000 years BP should have given enough time for formation compared with the northern North Sea. An older age cannot be excluded, however.

6. The correlation with land is difficult. Based on the gradients and assuming the same deformational history, the levels on the shelf should be older than all the levels mapped on land (Martinussen 1960; Andersen 1968).

7. To determine definitively the mode of formation and age of the levels on the continental shelf off Troms and their correlation with land, more investigations will be needed to obtain:

- Bathymetrical data using multibeam echosounder with high precision positioning.
- High resolution seismic profiling showing the internal structures of the submerged features.
- Samples of unquestionable in situ terrestrial or lacustrine deposits to prove definitively the existence and age relationship of submerged land areas.

Acknowledgements. - The fieldwork for the present paper was carried out at IKU Petroleumforskning a.s., and was financed by NTNF. We thank all colleagues who participated during field work, interpretation and later discussions. The illustrations were prepared by A. J. Johannesn., NTH. In particular, we thank E. Larsen, E. Lebesby and I. Aarenth for critical comments and A. Krill for improving the English language of the final manuscript.

Manuscript received February 1993

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