Radiocarbon and seismic evidence of ice-sheet extent and the last deglaciation on the mid-Norwegian continental shelf

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Reconstruction of the ice extent and glacier chronology on the continental shelf off mid-Norway has been severely hampered by the lack of dates from the glacial deposits. Seismic interpretation and new accelerator mass spectrometer radiocarbon dates show that the ice sheet extended to the edge of the continental shelf at the last glacial maximum. The two youngest till units near the shelf edge were deposited about 15,000 and 13,500 BP. The results indicate that the ice sheet partly reached the shelf break as late as 13,000 BP, followed by a deglaciation of most of the continental shelf in less than 1000 years.

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The west coast of Norway and the adjacent continental shelf have been exposed to major climatic, sea-level and glacial changes during the Quaternary, providing a key area for palaeoclimatic studies. In spite of comprehensive surveys, the timing and even the extent of the last glacial maximum on the shelf have remained uncertain (Dawson 1992; Holtedahl 1993). The prevailing view has been that the ice reached the shelf edge at its maximum and remained there until 18,000 BP, followed by a gradual and regular retreat reaching the coastal areas about 13,000 BP (Andersen 1981). The reconstruction of ice-sheet positions has been complicated in default of reliable ages of the glacial deposits on the continental shelf. Conventional radiocarbon dating of shell fragments in one sample off mid-Norway indicated, however, that the ice reached the shelf edge there as late as 13,000 BP (Rokoengen 1979; Bugge 1980).

Setting and background

The Quaternary geology of the continental shelf off mid-Norway has been investigated by IKU Petroleum Research in a mapping program comprising shallow seismic profiling and sampling (Rise 1988; Rokoengen & Rise 1989). Deposits with structureless seismic character, interpreted as till, were recognized to the shelf edge (Bugge 1980; Gunleiksrud & Rokoengen 1980). The interpretation has later been refined, especially after the introduction of the till tongue model. This model provides a tool to map the extent of till material and also partly the fluctuations of the grounding line of the ice (King 1993; King et al. 1987, 1991). Beyond the tip of the wedge-shaped units, defined as till tongues, glaciomarine sediments consisting of silty clay, with typical seismic layering, were deposited.

An informal Quaternary and upper Tertiary stratigraphy has been established on the mid-Norwegian continental shelf based on the data available from IKU and the Norwegian oil companies (Rokoengen et al. 1995). The youngest unit (called Unit U) is mapped as a sheet of till covering the whole area, although it is quite thin in parts and difficult to map on the regional seismic data sets which have been used.

Unit U was deposited during the last deglaciation and is thus well preserved over large areas. It shows some striking topographical features, including several till tongues. Till tongues 23 and 24 (Figs. 1 and 2) were defined by King et al. (1987) north of the present study area, and till tongue 24 can be traced for at least 500 km. This tongue corresponds to the outer part of the "Storegga Moraine" (Bugge 1980). Till tongues 23 and 24 represent the two youngest till units reaching the shelf edge off mid-Norway.

The till material on the mid-Norwegian shelf is commonly quite homogeneous and can be described as a silty, sandy clay with some gravel, with broken shell fragments (Bugge 1980; Gunleiksrud & Rokoengen 1980). This material has been interpreted as being remoulded and deposited directly by the ice as primary till (Dreimanis 1989). Near the outer end of the glacial units, associated with a floating ice front, depositional processes like slumping may have been active, forming secondary till (Dreimanis op. cit.). In this type of material, which may have some layering, shells are found in living position from the time of deposition.

Datings

The samples from IKU's mapping programme were

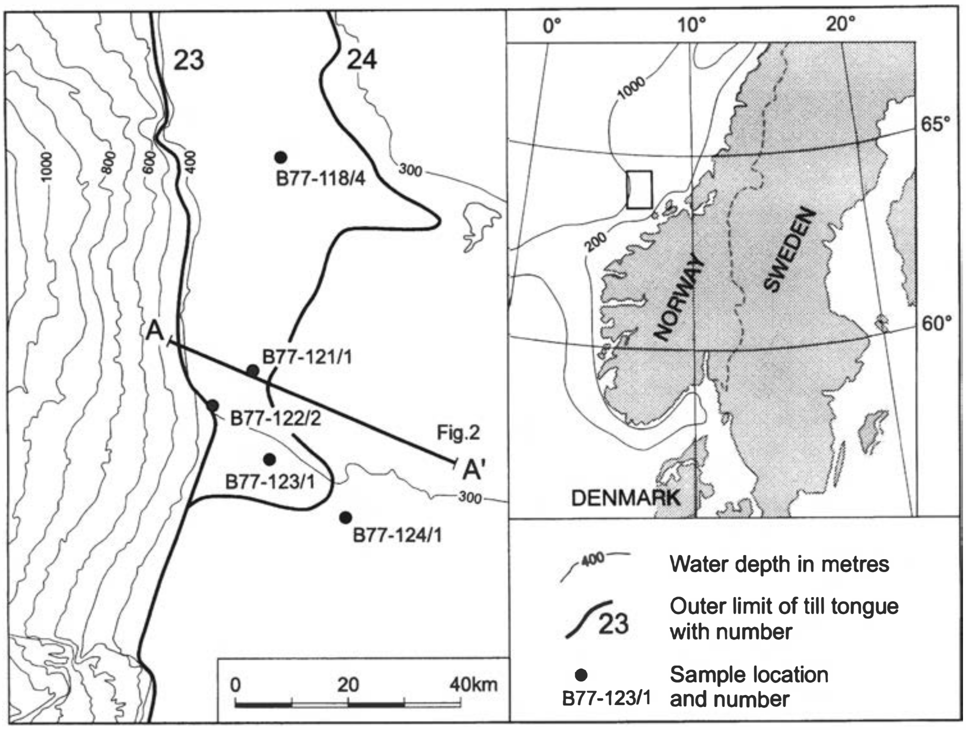

Fig. 1. Location map showing the main bathymetrical features in the study area. The very steep shelf edge in the south is caused by the giant Storegga Slide (Bugge et al. 1987). The slope further north is covered by glaciomarine clays (with a thin layer of younger sediments on top). On the continental shelf the outer limit of two glacial units (till tongues 23 and 24) are mapped. Location of samples and the section shown in Fig. 2 are indicated.

carefully documented and one half of each core was stored as reference material (Rokoengen & Rise 1989). This made it possible to re-examine the samples, partly using the X-ray equipment at the Geological Survey of Norway (NGU), searching for shell fragments dateable by the AMS radiocarbon method.

Samples B77-122/2, B77-123/1 and B77-124/1 were taken at water depths of 320 m, 252 m, and 243 m, respectively (Fig. 1 and Table 1) with few iceberg scours present (Bugge 1980; Lien 1983). All three samples consisted of unsorted material with small shell fragments. High shear strength and overconsolidation support the interpretation of the material as basal till. The AMS radiocarbon age of one single fragment (Table 1) will therefore give the time when the individual shell died, and the till must therefore be younger. The highest age of more than 50,000 years should probably be considered as infinite, but the ca. 43,000 to 40,000 year ages (Table 1) are probably finite and represent ice-free conditions on the shelf.

Samples B77-122/2 and B77-123/1 were interpreted as representing the southern part of till tongue 23 deposited from a grounded ice. The high ages of the dated shell fragments strongly indicate that the shells lived and died in an earlier ice-free period and were later incorporated in the till. Sample B77-118/4 was taken further north on till tongue 23 (Fig. 1). The water depth here is 367 m (Table 1) and, as the thin shell is so well preserved, we believe that it is of the same age as the sediment. If the till tongue 23 in that area was built out by secondary till material, the date gives the age of the deposition of the middle part of the unit as ca. 15,000 BP.

Sample B77-121/1, at 410 m water depth, is taken from a bioturbated glaciomarine clay that must be younger than the underlying till tongue 23. The dated material is an *Astarte*, which has both halves of the shell preserved and was killed by a boring snail. The sample is taken only about 2 km beyond the tip of till tongue 24 (Fig. 2), and our interpretation is that the clay was deposited contemporaneously with till tongue 24.

Table 1. Radiocarbon dates off mid-Norway. TUa- denotes laboratory reference number for accelerator mass spectrometer (AMS) radiocarbon dates with sample preparation at the Radiologic Dating Laboratory in Trondheim and measurement at the Svedberg Laboratory in Uppsala. The dating results have been corrected for the reservoir effect of sea water by subtracting 440 years from the ^{14}C ages.

Sample no. and depth below seabed (cm)	Water depth (m)	Lab. ref.	Radiocarbon date (years BP)	Comment
B77-122/2, 5–25	320	TUa-896	51,585 + 5,505 − 3,235	One shell fragment in till
B77-124/1, 35	243	TUa-1043	43,170 + 1,370 − 1,170	One shell fragment (*Chlamys islandica*) in till
B77-123/1, 5–35	252	TUa-897	40,400 + 1,075 − 950	One shell fragment in till
B77-118/4, 200–205	367	TUa-1042	15,320 ± 115	One shell fragment in till
B77-121/1, 230–240	410	TUa-898	13,545 ± 85	*Astarte* sp. in glaciomarine clay

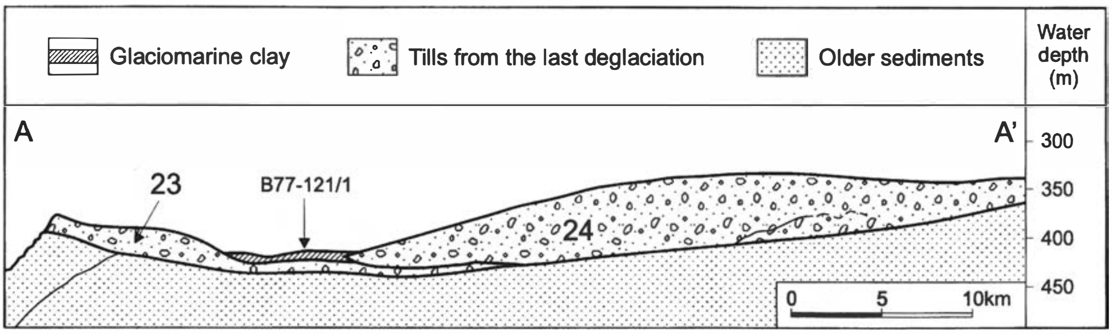

Fig. 2. Interpreted sparker profile section (IKU line B74-143, Rise 1988) 50 × vertical exaggeration. The two main glacial units seen on the surface today are built out as till tongues 23 and 24. Note the small till tongue to the right with the top reflector typically fading in the homogeneous till unit. Sample B77-121/1 was taken in an area with up to 4 m of glaciomarine clay above till.

Discussion

The results presented here demonstrate ice-free conditions on the mid-Norwegian continental shelf around 43,000 and 40,000 BP (Table 1). Compared to investigations in the northern North Sea (Rise & Rokoengen 1984; Rokoengen et al. 1993; Sejrup et al. 1994) and in the Norwegian Sea (Baumann et al. 1995; Fronval et al. 1995), we believe that the mid-Norwegian continental shelf remained ice-free for a long period until after 30,000 BP. This also agrees with the results further north on the shelf (Sættem et al. 1993) and on mainland Norway (Larsen & Sejrup 1990; Mangerud 1991). Our results also support the evidence of rapid shifts in glacial extent during the Mid and Late Weichselian in Norway, as suggested by Olsen (1997).

The tills deposited during the maximum of the last glaciation are mapped below till tongues 23 and 24 (Figs. 1 and 2). The outermost till tongue (23) contained shell material giving an age of ca. 15,000 BP. The seismic profiles show that the grounding line of the ice has fluctuated, however, and the deposition may therefore have taken some time. In the northern North Sea, dates of foraminifera in glaciomarine clay have yielded ages up to about 15,000 BP, indicating when the ice in the Norwegian Channel started to float and break up (Lehman et al. 1991; Sejrup et al. 1994; Andersen et al. 1995).

The next till tongue (24) is probably about 13,500 years or younger. The dates from B77-139/3 (Bugge 1980), 90 km further south, indicate that the youngest part of the till tongue could be less than 13,000 BP. The distance between the sampling points and probable existence of different ice streams makes an exact correlation difficult.

Along the mid-Norwegian coast, a number of dates give ages older than 12,000 BP (Reite 1994; Andersen et al. 1995). The deglaciation of the continental shelf was thus completed in less than 1000 years. If this is correct, it has important implications for the glacial history and for the modelling and reconstruction of the latest and previous deglaciation periods.

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