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The glacier-fed fan at the mouth of Storfjorden trough, western Barents Sea: a comparative study

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Abstract The Middle and Late Pleistocene succession on the glacier-fed fan at the mouth of Storfjorden trough was studied using high-resolution seismic data. Seven glacial advances to the shelf break during Middle and Late Pleistocene resulted in episodic high sediment input to the fan with real sedimentation rates of up to 172 cm/1000 years, separated by sediment-starved interstadials and interglacials. On the upper fan the high sediment input resulted in frequent slides and slumps, generating debris flows which dominate the mid-fan strata. Compared with the larger neighbouring Bear Island trough mouth fan, the Storfjorden trough mouth fan has a steeper fan gradient, narrower, thinner and shorter debris flow deposits and lower frequency of large scale sliding. Glacier-fed submarine fans receive their main sediment input from a glacier margin at the shelf break, as opposed to river-fed fans where sediment input occurs through a channel-levee complex. As a result, the depocentre of a river-fed fan is found on the mid-fan and the upper slope is mainly an area of sediment bypass, whereas the glacier-fed fan has an elongated depocentre across the uppermost fan. The river-fed fans are dominated by deposition from turbidity currents, whereas glacier-fed fans are dominated by debris flow deposits.

Key words Western Barents Sea · Middle and Late Pleistocene · Glacier-fed submarine fan · Comparative study

Introduction

The Barents Sea continental shelf is characterized by shallow banks separated by deeper troughs, whereas large submarine fans are localized in front of the troughs. The most prominent fans are the Bear Island trough mouth fan (TMF) and the Storfjorden TMF (Fig. 1). Smaller fans with a similar physiographic setting are found along the western Svalbard continental margin (Andersen et al. 1994).

During the Middle and Late Pleistocene, the Bear Island TMF evolved differently from many of the passive margin river-fed fans at low latitudes (e.g. Reading and Richards 1994). The main sediment input occurred when the Barents Sea Ice Sheet was at the shelf break. The fan strata deposited during this period are dominated by deposition of large debris flows as first described by Damuth (1978) from 3.5 kHz seismic profiles clearly showing their lense-shaped character. Vorren et al. (1988, 1989) mapped and analysed sets of debris flows separated by high-amplitude reflections on the Barents Sea continental margin using reflection seismics, and pointed to their potential as a palaeoclimatostratigraphic proxy. Long-range side-scan sonar data of the downslope oriented debris flows was presented by Vogt et al. (1993). Laberg and Vorren (1995) found that the lithology and fossil content of the debris flow deposits indicates that they were derived from glacigenic shelf diamictons. Similar debris flow deposits have also been found on other glaciated margins (Aksu and Hiscott 1992). Several large sliding events were also influencing the Middle and Late Pleistocene growth of the Bear Island TMF (Laberg and Vorren 1996).

We will explore if the sedimentary processes previously studied on the Bear Island TMF are unique, or if this is a pattern to be expected on other glacier-fed fans. Based on high-resolution seismic data we intend to elucidate the morphology and seismic facies distribution of the Storfjorden TMF and make a comparison to the Bear Island TMF and river-fed fans in general.

Database

The present database covering the Storfjorden TMF includes approximately 850 km of high-resolution seismic data collected by the University of Tromsø in 1993 (Fig. 2). The geophysical equipment used was a Fjord

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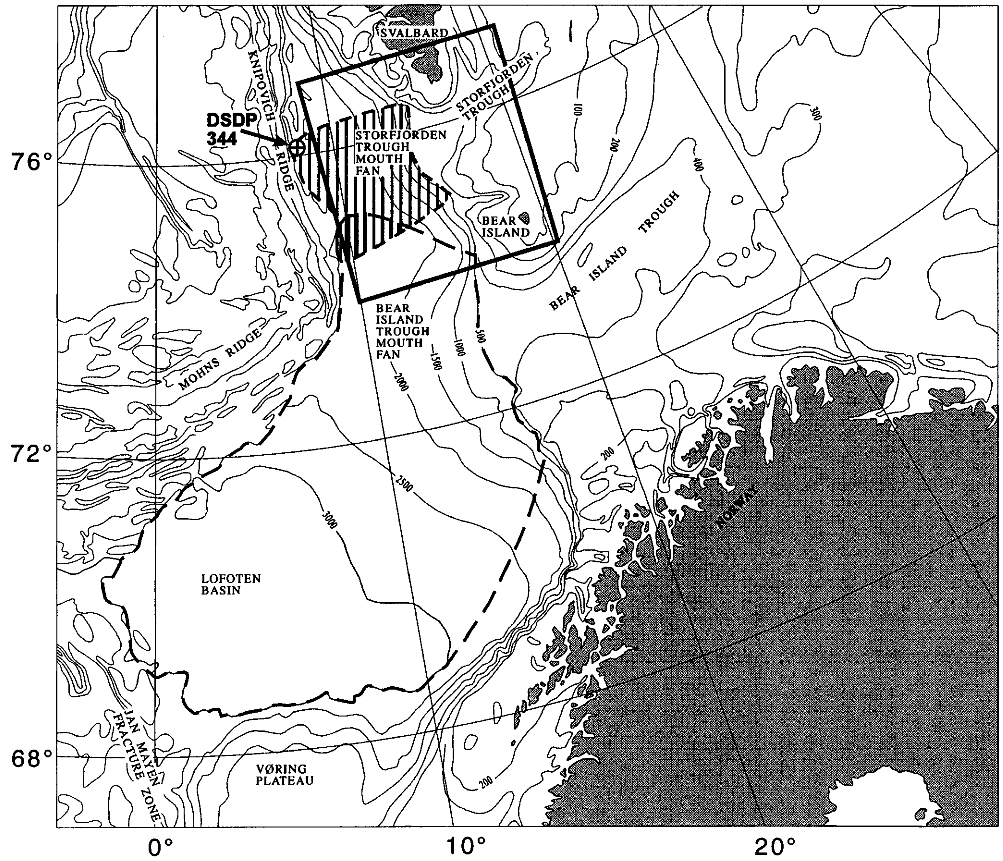


Fig. 1 Bathymetric map of the northeastern Norwegian-Greenland Sea and the western Barents Sea (Perry et al. 1980). Contour interval is 100 m on the shelf and 500 m on the slope and deep sea. The *box* outlines the study area. The areal extent of the Bear Island trough mouth fan (TMF) and Storfjorden TMF is indicated by the *stippled lines*. The location of the Deep Sea Drilling Project (DSDP) Site 344 is given

Instruments ministreamer, consisting of a 6-m active section and a nine-electrode sparker array with energy level 3.6 kJ, with shot intervals between 2 and 4 s. Tow depths were 1–2 m for the sparker and 0.5–1 m for the streamer. The signals were recorded analogue via a single channel.

Physiographic setting

The Storfjorden TMF covers an area of approximately 40 000 km^2 and has a radius of approximately 175 km. Within the studied part of the fan, the water depth varies from 400 to 2300 m (Fig. 2). The fan has developed concentrically off a feeder trough, the Storfjorden trough (Storfjordrenna). The fan extends from the shelf break westward to the Knipovich spreading ridge (Fig. 1), which has prevented fan progradation further westward.

The fan has been divided into three regions based on relief, fan gradient and seismic facies distribution. The boundaries of the different regions are transitional. The upper and middle fan gradients along the central fan axis are 1.8 and 1.0°, respectively, whereas the lower fan gradient is approximately 0.2° or less (Fig. 3). The morphology on the upper part is dominated by uneven areas (Fig. 4). An uneven and hummocky relief is developed on the mid- and uppermost part of the lower fan (Figs. 5 and 6), whereas the lowermost part of the fan has a predominantly smooth relief.

Seismic analysis

Framework

A thick sediment wedge has been deposited west of the Barents Sea shelf break since the opening of the Norwegian-Greenland Sea in Paleogene time (Solheim and Kristoffersen 1984; Myhre and Eldholm 1988; Vorren et al. 1991). The fan systems comprise much of this sediment wedge. On the Storfjorden TMF, the Cenozoic sediments were subdivided into three seismic sequences by Schlüter and Hinz (1978), SPI-III (oldest), SPI-II and SPI-I, and four sequences by Hjelstuen et al. (1996), G0 (oldest), GI, GII and GIII. In this study we focus on the youngest part of seismic sequence SPI-I, which comprises sequence GIII and the youngest part of GII (Fig. 7; Table 1).

Seven allostratigraphic seismic units (NACSN 1983) have been identified within the study area of the Storfjorden TMF, A (oldest) to G (Table 1). The units are bounded by regional key seismic reflections; a (oldest) to g, of which reflection b correlates to reflection R1 of Hjelstuen et al. (1996). However, due to the data coverage and penetration, some of the oldest reflections (a–d) could not be traced with confidence on the middle and lower fan, preventing a precise correlation in these areas.

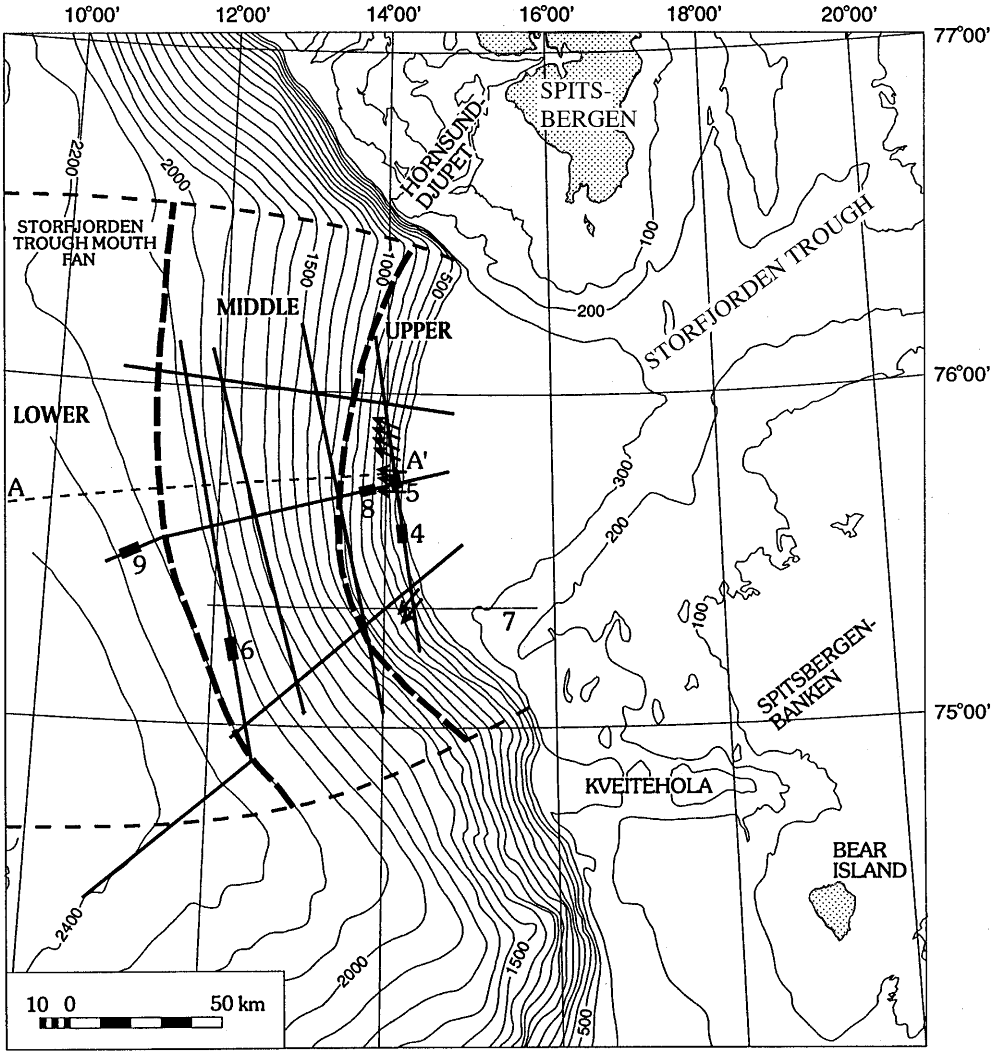


Fig. 2 Bathymetric map showing 100-m contour intervals (Kristoffersen et al. 1989). The seismic database is shown by *solid lines*. Gully locations are indicated by *arrows*. The location of Fig. 3 (*line A-A'*) and Figs. 4, 5, 6, 7, 8 and 9 are given. Fan subdivision is also indicated

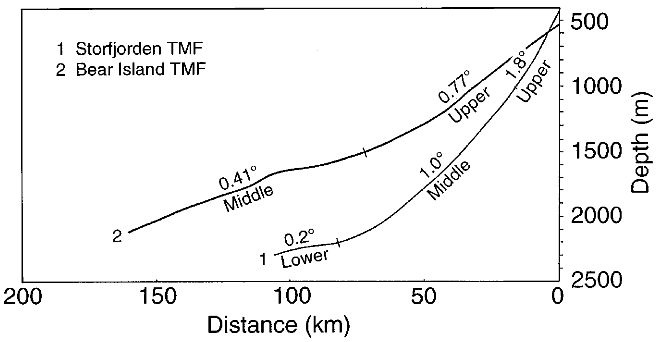


Fig. 3 Slope profiles along the central fan axis of the Storfjorden TMF and Bear Island TMF. (For location of the Storfjorden TMF profile, see Fig. 2)

Table 1 Correlation of the seismic units identified in this study to the seismic stratigraphy of Schlüter and Hinz (1978) and Hjelstuen et al. (1996). Our age estimates are based on correlation to the Svalbard land record (Mangerud and Svendsen 1992) (units E, F and G) and correlation to the oxygen isotope curve (Williams et al. 1988) (units A, B, C and D). See also Fig. 11

Schlüter and Hinz (1978)	Hjelstuen et al. (1996)	Present study	Age (ka)
		G	20– 10
		F	65– 55
SPI-1	G III	E	194–128
	<440 ka	D	313–258
		C	386–359
		B	486–430
	G II	A	544–521

Key seismic reflections

Key seismic reflections separate the identified seismostratigraphic units. The reflections have medium to high amplitude. On the upper part of the fan, they are partly discontinuous (Fig. 4), whereas they are continuous further downslope (Fig. 6). The reflections define units with uneven surfaces, which are due to mound-shaped deposits (Fig. 4), channel erosion (Figs. 2 and 5) and slide deposits (Fig. 8). The key seismic reflections are probably the result of a varying degree of consolidation and/or the presence of thin interbedded units.

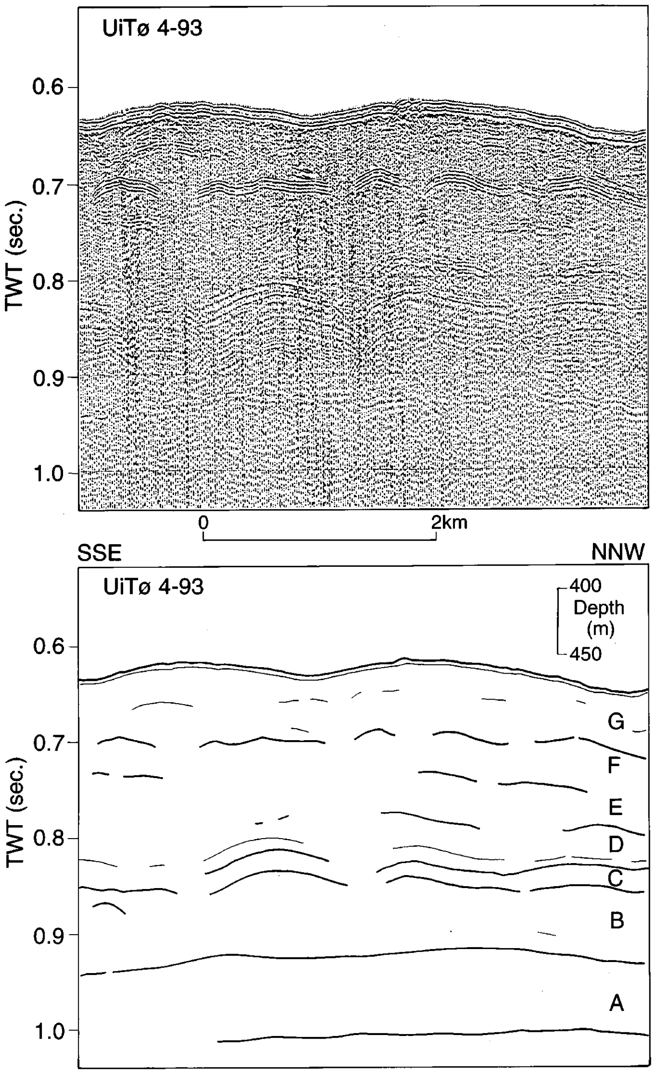


Fig. 4 Part of sparker profile UiTø 4–93 from the upper Storfjorden TMF showing the chaotic seismic signature of the identified units and the discontinuous key seismic markers. In this area the sea floor has an uneven relief due to mounded deposits which are interpreted as sections through debris lobes. No base mound reflection has been found on the upper part of the fan. (For location see Fig. 2)

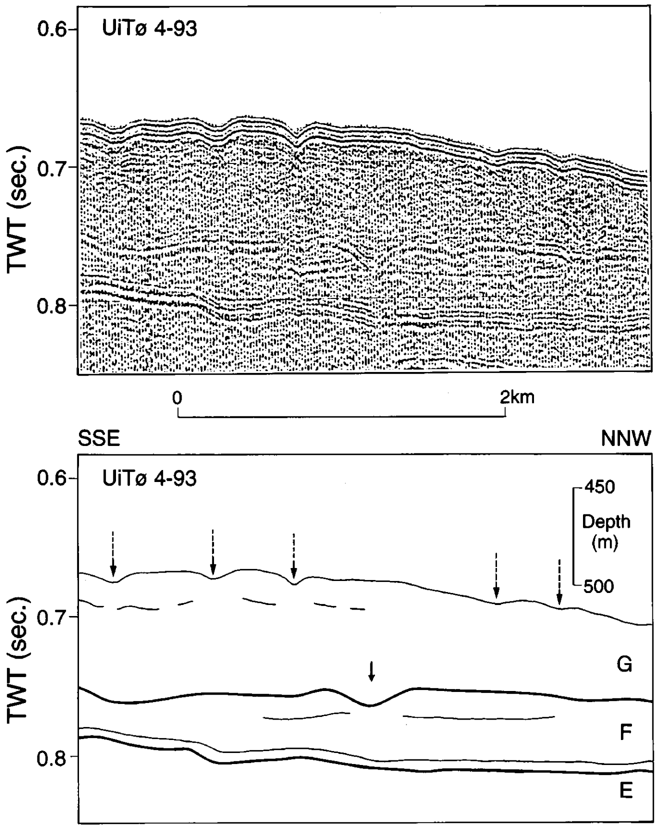


Fig. 5 Seismic sparker profile from the northern, upper Storfjorden TMF (location in Fig. 2) showing modern (*stippled arrow*) and relic (*solid arrow*) gullies

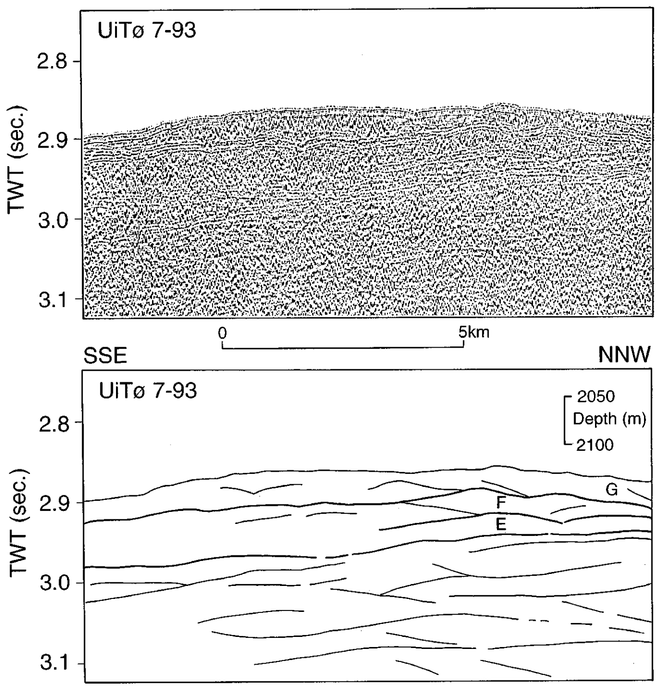


Fig. 6 Segment of seismic sparker profile UiTø 7–93 from the Storfjorden TMF which illustrates the mounded seismic signature and uneven relief on the lowermost part of the middle fan, caused by debris lobe deposits. (Location is given in Fig. 2)

Acoustically chaotic signature

On the upper part of the fan, all the units identified are dominated by a chaotic seismic signature (Fig. 4).

Acoustically mounded signature

A mounded seismic signature dominates the middle and uppermost part of the lower fan (Fig. 6). On strike profiles mounds up to 5 km wide and 15 m thick have been identified, whereas dip profiles indicate elongated lenses up to 80 km long. On the upper fan base mound reflections have not been found (Fig. 4), on the upper

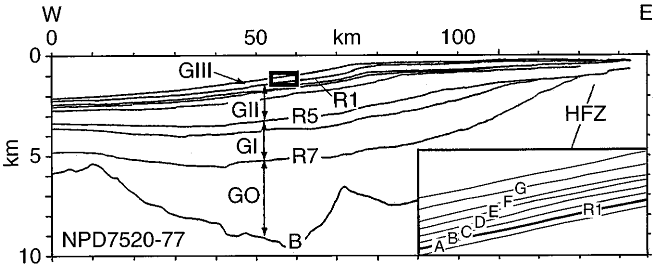


Fig. 7 Depth-converted seismic profile NPD7520-77 including the seismic sequences G0-GIII and sequence boundaries R1, R5 and R7 of Hjelstuen et al. (1996) and the seismic units discussed in this study (see *inset*). Slightly modified from Hjelstuen et al. (1996). *B* Oceanic basement; HFZ Hornsund fault zone. (For location see Fig. 2)

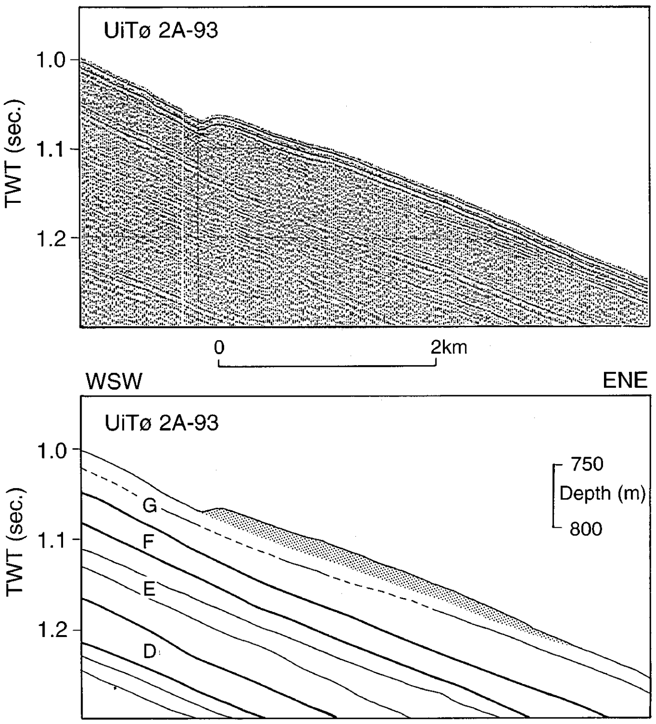


Fig. 8 Segment of seismic sparker profile UiTø 2A-93 from the upper Storfjorden TMF showing transported slide sediments (*dotted area*) which came to rest at this depth (ca. 780–900 m). Notice the disrupted character (*stippled area*) of the immediately underlying reflection. See Fig. 2 for location

mid-fan the reflection immediately underlying each mound is in some areas found to have an irregular character and on the lower fan distinct debris lobe fronts have been found (Fig. 9). The mounds are found to be deposited in bathymetric lows between older mounds (Fig. 6), and some of the mounded deposits have a central, top depression. As revealed from seismic profiles, the depressions are up to 250 m wide and 1.5 m deep.

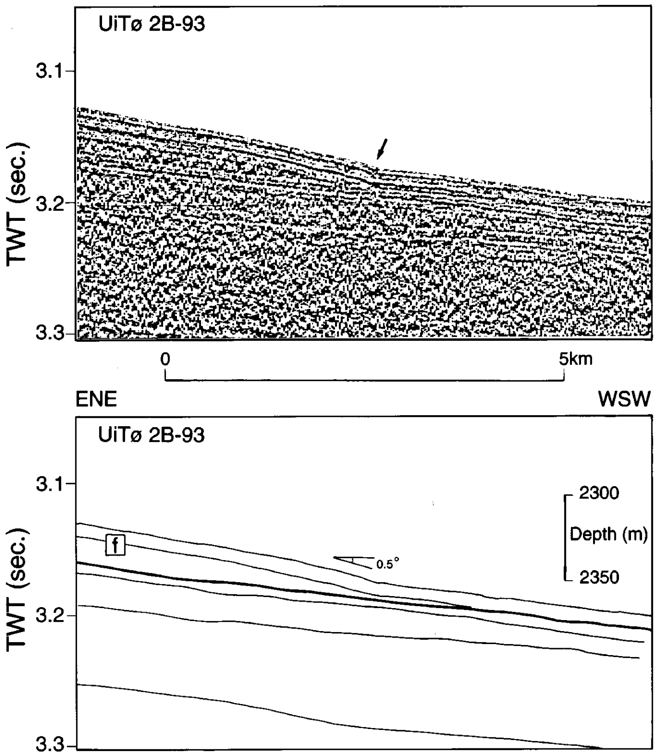


Fig. 9 Seismic sparker profile from the lower Storfjorden TMF. At this depth there is an abrupt termination of debris lobes (*arrow*). *f* base unit F reflection. (See Fig. 2 for location)

Thickness of units

Unit G, the youngest seismic unit identified, is characterized by an elongated sediment maximum at the southern shelf break where the unit thickness reaches values in excess of 75 ms (TWT; Fig. 10a). On the upper fan the thickness decreases to less than 50 ms (TWT), and within most of the study area the thickness is between 25 and 50 ms (TWT; Fig. 10a). The thickness decreases most rapidly downslope on the northern part of the fan, implying that during the unit G time interval, the largest sediment input was to the central and southern part of the fan.

Unit F has a long, elongated depocentre in front of the present deepest part of the trough. The thickness is between 50 and 75 ms (TWT), and locally in excess of 75 ms (TWT) near the present shelf break (Fig. 10b). Within most of the middle fan a thickness between 25 and 50 ms (TWT) was found, decreasing to less than 25 ms (TWT) on the lower fan.

Seismostratigraphic unit E has a southwest-northeast oriented depocentre on the central fan and the maximum thickness is in excess of 75 ms (TWT; Fig. 10c). The sediment maxima is localized in front of the deepest part of the outermost Storfjorden trough, parallel to the trough axis. The thickness decreases to approximately 25 ms (TWT) on the mid-fan. On the lower fan the thickness is less than 25 ms (TWT; Fig. 10c).

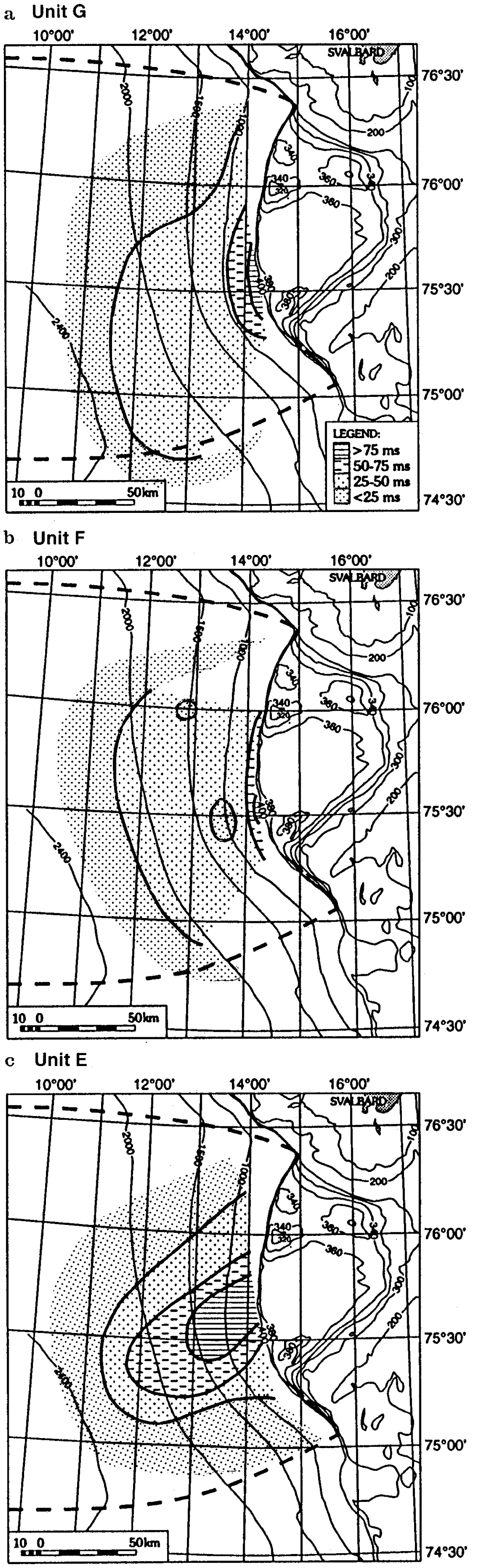


Fig. 10a–c Isopach maps of **a** seismic unit G, **b** seismic unit F and **c** seismic unit E. The bathymetry is also indicated

The gullies

On the southern and northern upper fan flank, several gullies were found (Figs. 2 and 5). The gullies are not sediment filled, suggesting that they are of Holocene age and possibly formed by the bottom water flowing through the Storfjorden trough (Quadfasel et al. 1988). If this is correct, then their downslope termination at maximum 1000–1200 m water depth is due probably to the fact that the bottom water from the Storfjorden trough meets with water masses of similar density. The occurrence of palaeogullies (Fig. 5) indicates that these oceanographic currents may also have existed during previous periods.

Discussion

Age estimate

There are no published dates from the studied part of the Storfjorden TMF or the nearby shelf. The only results available are from the DSDP Site 344, which was located on the distal part of the fan (Fig. 1) and which showed that Schlüter and Hinz's (1978) sequence SPI-I comprises sediments of Pliocene-Pleistocene age (Talwani et al. 1976). By seismic correlation to commercial wells in the southwestern Barents Sea, Hjelstuen et al. (1996) propose that their sequence GIII comprises sediments younger than 440 ka (Table 1).

The age of the identified units on the Storfjorden TMF can be approximated by a tentative correlation to the Svalbard land record (Mangerud and Svendsen 1992). Results from Svalbard have revealed three major glaciations during Weichselian and a glacier advance postulated to have occurred during Late Saalian (Mangerud and Svendsen 1992). The youngest two Weichselian glaciations correlate with increased accumulation of ice-rafted material in the Fram Strait, indicating that these advances had a larger extension as compared with the preceding Weichselian glaciation (Hebbeln 1992). The Saalian glaciation is likely to have also extended beyond the coast, based on the input of ice-rafted material to the deep sea (Mangerud and Svendsen 1992).

Correlation of the Svalbard land record leads us to suggest that the three major glaciations known to have extended beyond the coast of western Svalbard were probably mirrored by ice advances through the Storfjorden trough from the southeastern part of Svalbard. Based on the above considerations and the dating results of Mangerud and Svendsen (1992), we tentatively suggest that there may have been two ice advances to the shelf break in the outer Storfjorden trough during

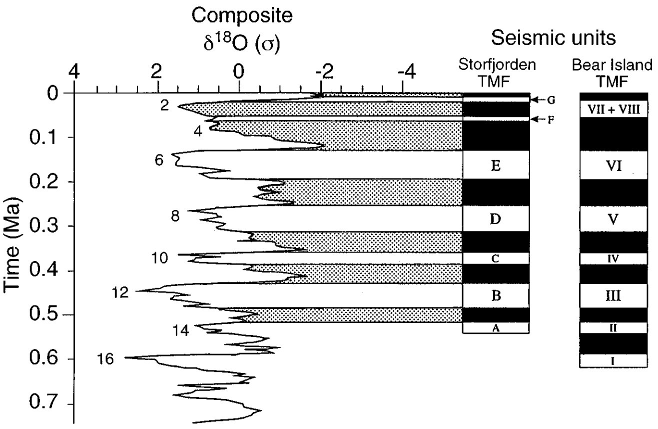


Fig. 11 Tentative correlation of the identified seismic units to the oxygen-isotope curve (Williams et al. 1988). Dating of units E, F and G are based on correlation to the Svalbard land record (Mangerud and Svendsen 1992) and the correlation to the Bear Island TMF units are from Laberg and Vorren (1996; see also Table 1)

Weichselian, in Middle (65–55 ka) and Late Weichselian (20–10 ka), respectively, and additionally one advance during Late Saalian. During these ice advances units E (Late Saalian), F (Mid Weichselian) and G (Late Weichselian) may have been deposited (Fig. 11).

An alternative age estimate is based on correlation to the Bear Island TMF succession (Laberg and Vorren 1996). There, the two youngest units were possibly deposited during Late Weichselian, whereas the Early and Mid-Weichselian was probably characterized by relatively low sediment input. According to this alternative, both units F and G sediments should be of Late Weichselian age. However, given the relatively short distance from the southern Svalbard to the outer Storfjorden trough, we suggest that glacier advances through the Storfjorden trough occurred at the same time as ice advances onto the western Svalbard margin (Mangerud and Svendsen 1992).

As a first approximation the older units (A–D) were tentatively correlated to the oxygen isotope curve (Williams et al. 1988). We suggest that seismic unit D can be correlated to isotope stage 8, unit C to stage 10, unit B to stage 12 and seismic unit A to stage 14 (Fig. 11; Table 2). Hence, the studied succession is found to comprise sediments younger than approximately 600 ka. In this correlation we assume that: (a) most of the fan sediments were deposited during glacial maxima, (b) the ice sheet was at the shelf break during each Middle and Late Pleistocene glacial maxima and (c) the Middle and Late Pleistocene fan succession is complete. However, as illustrated by the Weichselian glaciations, two glacier advances to the shelf break probably occurred through the Storfjorden trough during that period. Thus, the age estimate of approximately 600 ka is inferred to be a maximum age.

Weichselian sedimentation rates

The volume of the Weichselian units on the Storfjorden TMF, units F and G, have been estimated based on the isopach maps produced (Table 2). Net average sedimentation rates (Table 2) were obtained by dividing the volume by the total fan area (ca. 40 000 km^2). This figure was then divided by the time period comprising the glacial event and the succeeding ice-free period.

An average sedimentation rate of 29 cm/1000 years was obtained during isotope stages 1–3 (unit G) and 23 cm/1000 years during stages 4 and 5 (unit F). However, most of the sediments were probably deposited during the glacial events when the ice sheet terminated at the shelf break. This implies that units F and G were probably deposited during the time intervals 65–55 ka and 20–10 ka, respectively. If this is correct, the *real* sedimentation rate during deposition of these sediments was 164 cm/1000 years (unit F) and 172 cm/1000 years (unit G).

Comparison of the Storfjorden TMF and the Bear Island TMF

The fan morphology, seismic signature and sedimentation rate on the Storfjorden TMF bear obvious resemblances to that of the Bear Island TMF (Table 3; Laberg and Vorren 1995, 1996):

Table. 2 Volume of sediments deposited within; A: the Storfjorden TMF during isotope stages 1–3 and 4–5, and B: the Bear Island TMF during isotope stages 1–5d (from Laberg and Vorren 1996). The corresponding average sedimentation rates estimated are also given. (In this calculation we used an interval velocity of 1700 m/s)

A

Unit	Volume (km^3)	Time (stage)	Sedimentation rate
G	687	60 ka (1–3)	29 cm/1000 years
F	655	70 ka (4–5)	23 cm/1000 years

B

Unit	Study area (km^3)	Accumulation area (km^3)	Time (stage)	Sedimentation rate
VII + VIII	2357	4176	117 ka (1–5d)	13 cm/1000 years

Table 3 Summary of fan gradient, water depth, channels, relief, seismic signature, lithology and sedimentary processes of the Bear Island TMF and Storfjorden TMF respectively. The real sedimentation rates for the Storfjorden TMF are calculated for the time intervals 65 to 55 ka (164 cm/1000 yrs) and 20 to 10 ka (172 cm/1000 yrs), while the real sedimentation rate estimated for the Bear Island TMF for the period from 24 to 12 ka (124 cm/1000 yrs) is from Laberg and Vorren (1996)

	Upper fan		Middle fan		Lower fan	
	Bear Island TMF	Storfjorden TMF	Bear Island TMF	Storfjorden TMF	Bear Island TMF	Storfjorden TMF
Gradient	0.8°	1.8°	0.4°	1.0°	0.2°	0.2°
Water depth (m)	500–1500	400–1000	1500–2200	1000–2200	>2200	>2200
Fan gullies; w/d (m)	1500/50	160/10	None	None	None	None
Relief	Hummocky, uneven	Hummocky, uneven	Hummocky, uneven	Hummocky, uneven	Smooth	Smooth
Seismic signature	Chaotic	Chaotic	Mounded	Mounded	Transparent	Transparent
Seismic units; (max. thickness)	250 ms	75 ms	275 ms	50 ms	200 ms	25–50 ms
Sedimentary process	Sliding, debris flows, turbidity currents, hemipelagic sediment	Sliding, debris flows turbidity currents, hemipelagic sediment	Debris flows, turbidity currents, hemipelagic sediment	Debris flows, turbidity currents, hemipelagic sediment	Turbidity currents, hemipelagic sediment	Turbidity currents, hemipelagic sediment
		Bear Island TMF			Storfjorden TMF	
sedimentation rates		124 cm/10^3 years		164 cm/10^3 years (unit F) and 172 cm/10^3 years (unit G)		

1. On the upper part of the Storfjorden TMF, a chaotic seismic signature and an uneven relief dominates. This was also found on the Bear Island TMF and lead us to suggest that small-scale sliding is also an important process on the upper part of the Storfjorden TMF.
2. The middle and lower part of the Storfjorden TMF is dominated by a mounded seismic signature. The mounds are interpreted to represent sections through large debris flow deposits. Based on the results from the Bear Island TMF (Laberg and Vorren 1995, 1996), the debris flows appear to be generated on the upper fan and moved downslope to the uppermost part of the lower fan. Here they stopped, probably due to the marked decrease in slope gradient from the middle to the lower fan.
3. Except for the size differences, the Storfjorden TMF debris flows are more or less identical to the Bear Island TMF deposits: (a) Base mound reflections are often not found on the upper fan. This together with the fact that the regional reflection immediately below the mound has in some places an irregular character indicates disturbance and perhaps incorporation of underlying sediments during downslope flow. (b) The debris flow sediments are deposited in bathymetric lows between older deposits. (c) Their distinctive downslope front is indicative of a sudden halt on the lower fan. (d) On both fans some of the debris flow deposits have a central depression. This was considered to have formed when the slower sides of the flow "froze" earlier while the mobile core continued to move resulting in a channel-like collapse on top of the flow (Laberg and Vorren 1995).
4. The sedimentation rate during deposition of units F and G was 164 cm/1000 years and 172 cm/1000 years, respectively. On the Bear Island TMF, an average sedimentation rate of 13 cm/1000 years was obtained during isotope stages 1– 5d (Table 2). However, most of these sediments were probably deposited during isotope stage 2 as discussed by Laberg and Vorren (1996), which indicates that the *real* sedimentation rate was approximately 124 cm/1000 years, i.e. of the same order of magnitude as on the Storfjorden TMF.

There are three significant differences between the Bear Island TMF and Storfjorden TMF, namely the size of the debris flows, the fan gradient and the frequency of large-scale sliding. On the Storfjorden TMF, the maximum width, thickness and length of the debris flows are up to 5 km, 15 m and 80 km, respectively, whereas on the Bear Island TMF, debris flow deposits up to 24 km wide, 50 m thick (Laberg and Vorren 1995) and 200 km long (Vogt et al. 1993) have been found.

The reasons for the smaller size of the Storfjorden TMF debris flows as compared with the Bear Island TMF may be the different gradients of the two fans (Fig. 3) and/or the differences in their composition.

Due to the steep gradient on the Storfjorden TMF, oversteepening and sediment release caused by sediment buildup on the upper fan (see below) would probably be more frequent as compared with the Bear Island TMF, which possesses lower slopes (Fig. 3). Furthermore, on both fans the debris flows have been found to terminate on the lower fan when the gradient gets down to approximately 0.2°. The distance from the upper to the lower fan on the Storfjorden TMF is less than on the Bear Island TMF. As a result, the run-out distance, and hence, the length of the debris flow deposits, are smaller.

Textural variations might also control the spatial distribution of the debris flows as discussed by Hiscott and Aksu (1994). They suggested that "high-efficiency" debris flows with a long runout distance are more mud-rich than "low-efficiency" debris flows. The higher shear strength of the mud-rich sediments, caused by high cohesive strength (Hampton 1972), results in the buildup of larger amounts of sediment on the upper slope prior to sediment release.

The drainage area of the Bear Island TMF includes Palaeocene, Cretaceous and Triassic claystones, siltstones and sandstones, whereas the Storfjorden TMF drainage area is dominated by early Cretaceous and Triassic claystones, siltstones and sandstones (Sigmond 1992). However, the latter area also includes the southern Svalbard crystalline rocks (Sigmond 1992). This may have resulted in deposition of sediments with a coarser mean size, giving a shorter run-out distance than on the Bear Island TMF. Based on our database, we have so far not been able to test this hypothesis.

Large-scale sliding events seem to have been most frequent on the Bear Island TMF. Here three large sliding events occurred during Middle and Late Pleistocene (Bugge 1983; Knutsen et al. 1993; Laberg and Vorren 1993; Laberg and Vorren 1996) whereas on the Storfjorden TMF, only one large event has so far been reported (Schlüter and Hinz 1978). The cause for this apparent difference is not known at present, but it may simply reflect the fact that to date, the Bear Island TMF has been studied in more detail.

Evolution of glacier-fed fans off the western Barents Sea continental shelf

A three-fold division for glacier-fed submarine fans is suggested based on the results from the Storfjorden TMF and the Bear Island TMF (Laberg and Vorren 1996): the upper, middle and lower fan. The subdivision is based on seismic facies distribution, fan morphology and gradient (Fig. 12), and the transitions are gradual.

The Barents shelf is characterized by shallow banks separated by deep troughs. Due to confluent ice flow, fast-flowing ice streams were probably localized in the large troughs, i.e. the Storfjorden and Bear Island troughs, during the glacial maxima. As demonstrated in studies of modern sediment transport beneath larger ice sheets, large amounts of glacigenic sediments can be transported beneath the ice streams, mainly as a deformable till-layer (Boulton 1979; Alley et al. 1989). Sediments might also be transported to the grounding line as a sediment ridge in front of the glacier by push and squeeze (e.g. Solheim 1991). In accordance with these results and the results of Sættem et al. (1992) from the Bear Island trough, we suggest that large amounts of glacigenic sediments were transported to the shelf break during glacial maxima. As a result, the submarine fans were characterized by high sediment input, whereas the interfan areas, as exemplified by the margin west of Kveitehola (Fig. 2), received less sediment.

The presence of long, elongated depocentres on the upper fan suggest that most of the glacigenic sediments were deposited as long, elongated "till-deltas" (Alley et al. 1989) or "diamict aprons" (Hambrey et al. 1992). Some sediments may also have continued directly downslope. Due to the high sediment input, these sedi-

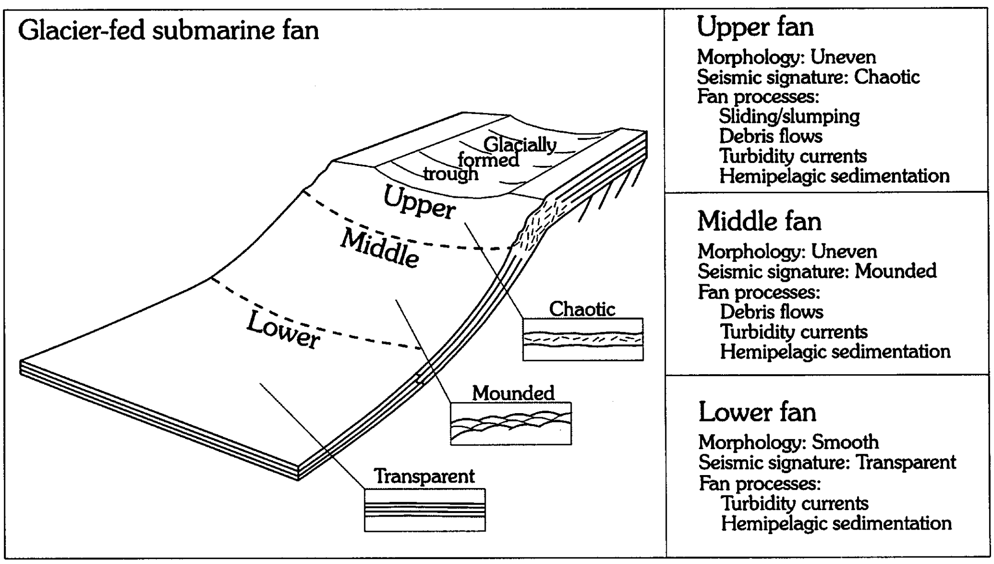


Fig. 12 Diagram showing the subdivision of a glacier-fed submarine fan and its morphology, main seismic signature and fan processes

ments were probably unstable; subsequent downslope movement could have been caused by oversteepening, buildup of excess pore water pressure, smaller ice front oscillations and/or tectonic activity. Hence, on the upper fan important processes are sliding/slumping of the glacigenic sediments and the generation of debris flows from these sediments (Laberg and Vorren 1995). As discussed by Laberg and Vorren (1995) the slides might be retrogressive and lead to removal of most of the sediments deposited above the original sea floor because interglacial/interstadial sediments might act as planes of weakness.

The middle part of the fan is dominated by debris flow deposits (Fig. 12). They repeatedly decorate the fan surface, such that the whole fan progrades seaward when the ice sheet is present at the shelf break. Data from the Bear Island TMF show that debris flow deposits consist of a fine-grained diamicton, overlain by a glacimarine mud with ice-rafted material and interglacial hemipelagic mud on top (Laberg and Vorren 1995). The flow rheology was discussed by Vogt et al. (1993) and Norem (1994).

Debris flows of glacigenic diamicton comprise the main part of the glacier-fed fan sediments. They are separated by glacimarine and/or interglacial/interstadial mud which drapes the fan and generates the key seismic reflections. On the uppermost part of the lower fan, the debris flows terminate when the slope is approximately 0.2° (Laberg and Vorren 1995), and most of the lower part of the fan is probably dominated by turbidites and hemipelagic deposits (Fig. 12). The turbidity currents probably originate from the debris flows moving downslope (Hampton 1972).

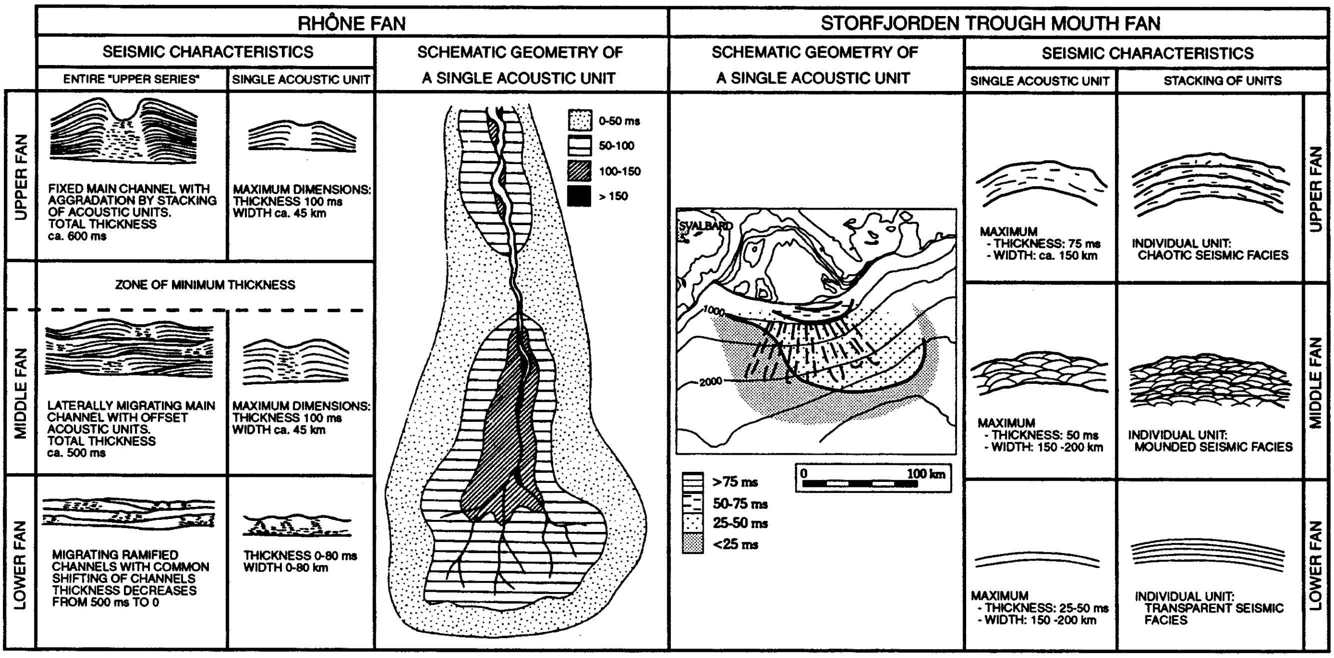
During interstadials and interglacials, contour currents may have been important for the evolution of the uppermost fan. Northward-flowing Atlantic surface current during the Holocene may have winnowed and redeposited sediments on the uppermost part of the fans (Kenyon 1986), thereby smoothing the relief.

The evolution of these large submarine fans through sediment input during glacial maxima, and sediment-starved conditions during interstadials and interglacials, is manifested by debris flow units separated by high-amplitude interstadial/interglacial reflections. Based on the number of debris flow units, Laberg and Vorren (1996) suggested that the ice sheet reached the shelf break eight times during Middle and Late Pleistocene on the Bear Island TMF. Based on the same reasoning, the ice sheet probably reached the shelf break in outer Storfjorden trough seven times during the past 0.6 Ma. However, as discussed above they were possibly not time synchronous during the Weichselian.

Glacier-fed vs river-fed submarine fans

The high-latitude Storfjorden TMF was fed from a line source provided by a glacier at the mouth of the trough. No large channel-levee system has developed. Low-latitude fans, however, as exemplified by the Rhone fan, have a point source and receive their sediments through a single, meandering channel which is connected to a canyon on the slope above the fan (Droz and Bellaiche 1985). Thus, on the latter the fan depocentre is localized on the mid-fan (Droz and Bellaiche 1985), whereas the former has a long, elongated depocentre on the uppermost fan (Fig. 13). Furthermore,

Fig. 13 Geometry of a single acoustic unit and seismic characteristics on the Rhone Fan (Droz and Bellaiche 1985, in Pickering et al. 1989) as compared with the Storfjorden TMF. (See text for further discussion)



whereas the growth of glacially fed fans involves most of the fan, and occurs through stacking of individual units deposited during glacial maxima, this contrasts with river-fed fans where there is a transition from stacking of channel-levee complexes on the upper fan to lateral displacement of units on the middle part of the Rhone fan (Droz and Bellaiche 1985; Fig. 13). Hence, only part of the mid-fan is active during fan growth, which occurs during relative sea-level lowstands.

In addition to the sediment input, there are also major differences regarding the sedimentary processes on the fans. On the river-fed fans, turbidity currents are the most important sediment distributing process. Depending on the sediment source, radial (sand-dominated) or elongate (mud-dominated) fans evolve (Stow 1986). As shown from both the Storfjorden TMF and Bear Island TMF, the sediment distribution occurred mainly through large debris flows; turbidity currents were probably of minor importance. We hypothesize that the grain-size distribution, more fine-grained sediments delivered to the glacier-fed fans and the water content of the sediments, which are on average probably higher for the river-transported sediments, are important controls influencing the different sedimentary processes.

Conclusions

As a result of this research, the following conclusions were reached:

1. As revealed from high-resolution seismic sparker data, the upper Storfjorden TMF was dominated by periodic high sediment input from an ice sheet at the shelf break during the Middle and Late Pleistocene. In the intervening interstadial/interglacial periods, the sediment input was markedly reduced.
2. During periods of high sediment input with real sedimentation rates up to 172 cm/1000 years, frequent sliding occurred on the uppermost fan resulting in generation of large debris flows. The debris flow deposits can be followed several tens of kilometres downslope and are volumetrically the most important Middle and Late Pleistocene fan sediments.
3. Throughout the Middle and Late Pleistocene the evolution of the Storfjorden TMF was very similar to the more southerly Bear Island TMF. The main differences include fan gradient, the size of the debris flow deposits and the frequency of large-scale sliding. The maximum width, thickness and length of the debris flow deposits are 5 km, 15 m and 80 km on the Storfjorden TMF and 24 km, 50 m and 200 km on the Bear Island TMF, respectively. The smaller size of debris flows on the Storfjorden TMF may be due to a steeper fan gradient.
4. Glacier-fed submarine fans, as exemplified by the Storfjorden TMF, receive their main sediment input from a glacier at the shelf break, as opposed to river-fed fans, where sediment input occurs through a channel-levee complex. As a result, the depocentre of a river-fed fan is found on the mid-fan, whereas the glacier-fed fan has a depocentre on the uppermost fan. The former is dominated by deposition from turbidity currents, and the latter by debris flow deposits.

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