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The timing of initiation of fast-flowing ice streams during a glacial cycle inferred from glacimarine sedimentation

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Abstract

Fast-flowing ice streams drain huge basins within modern ice sheets and are a mechanism for rapid iceberg production and mass loss. Some ice streams are known to be unstable, and to switch between fast flow and stagnation. Numerical ice-sheet models and geophysical observations of large-scale streamlined glacial landforms and large glacier-derived sedimentary fans along high-latitude continental margins indicate the presence of ice streams in Quaternary ice sheets. High-resolution AMS dated sedimentary records from an inter-fan area on the Svalbard continental margin yield evidence on the timing of initiation of fast glacier flow during a glacial cycle of ice-sheet growth and decay. Sedimentation rates and iceberg-rafted debris influx show that debris delivery to the Svalbard margin was relatively high during the period of Late Weichselian ice-sheet growth from about 30 000–18 000 yr BP. Both parameters fell dramatically in inter-fan areas when full-glacial conditions, with ice at the continental shelf edge, were established at about 18 000 yr BP. This shift is interpreted to mark the initiation of a fast-flowing ice stream, the convergence of flow from the surrounding ice sheet into this ice stream, and the consequent slowing of ice flow and sediment delivery to the inter-fan area beyond the ice-stream margins. This provides a constraint on the timing of ice-stream initiation during the cycle of ice-sheet growth and decay.

Keywords: ice streams; fast glacier flow; glacial cycles; submarine fans; Svalbard margin

1. Introduction

Fast-flowing ice streams, separated from slower-moving ice by marked shear zones, drain huge interior basins within modern and past ice sheets (e.g. Drewry, 1983; Bentley, 1987; Dowdeswell and Siegert, 1999; Bamber et al., 2000). They provide a mechanism of rapid mass loss from ice sheets through iceberg production (e.g. Reeh, 1985; MacAyeal, 1993). Satellite and marine geophysical evidence of large-scale streamlined sedimentary landforms in terrestrial and shelf sediments (e.g. Boulton and Clark, 1990; Solheim et al., 1990; Shipp and Anderson, 1997; Shipp et al., 1999), together with observations of large glacier-derived sedimentary fans along polar continental margins (Laberg and Vorren, 1995; Dowdeswell et al., 1996; King et al., 1996; Vorren et al., 1998), have been used to infer the presence of

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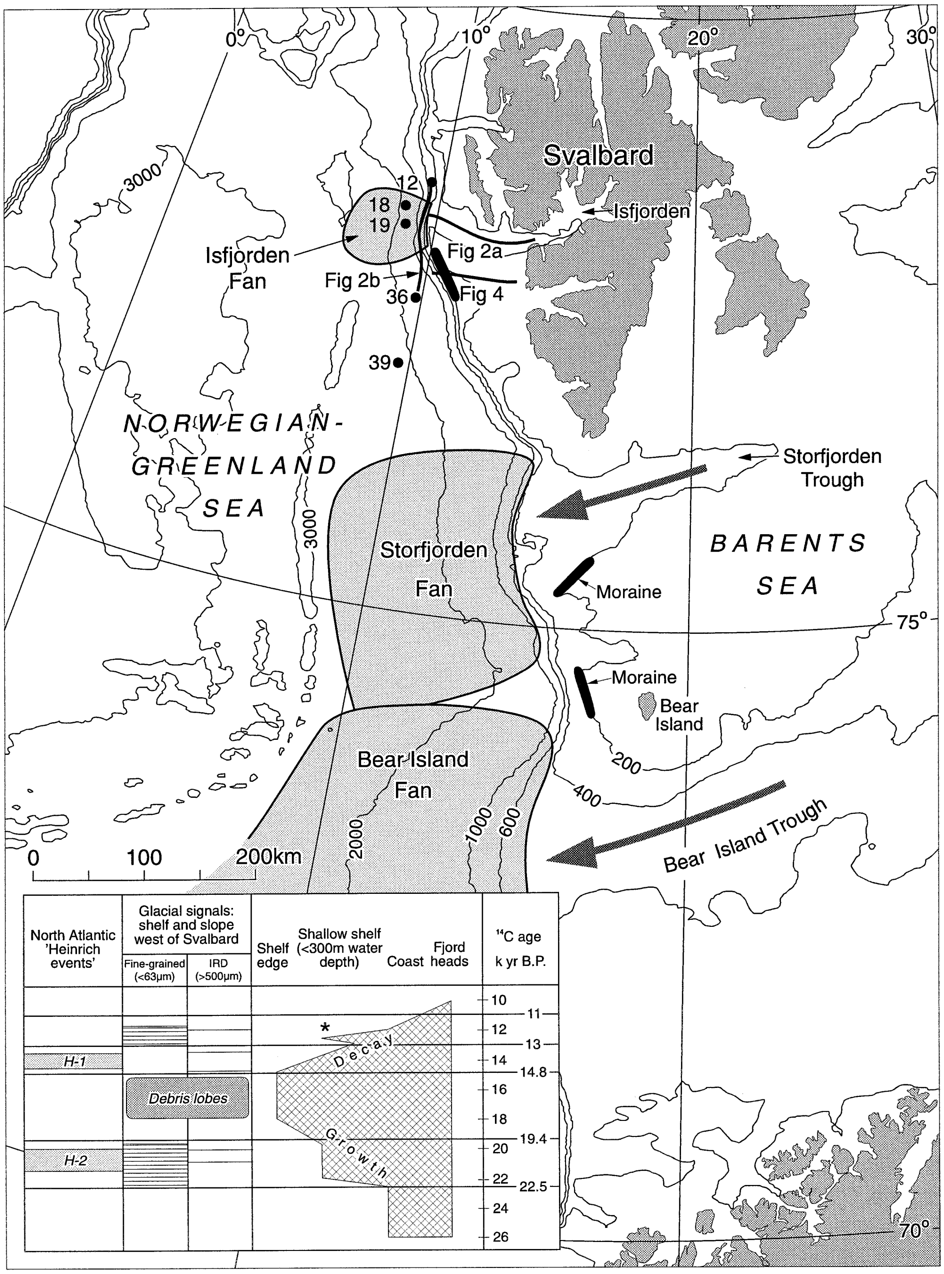


Fig. 1. Map of the Svalbard–Barents Sea continental margin, showing the locations of sediment cores discussed in the text (Table 1). Prograding fans (Vorren et al., 1998), indicating past ice streams, and the submarine moraines (Elverhøi and Solheim, 1983) characteristic of maximum ice extent in inter-fan areas are also shown. The locations of ice streams in the Late Weichselian Ice Sheet are indicated by arrows (Dowdeswell and Siegert, 1999). Inset is the glaciation curve for western Svalbard and the northwestern Barents Sea, showing the timing and extent of the ice sheet during Late Weichselian growth and decay (Landvik et al., 1998).

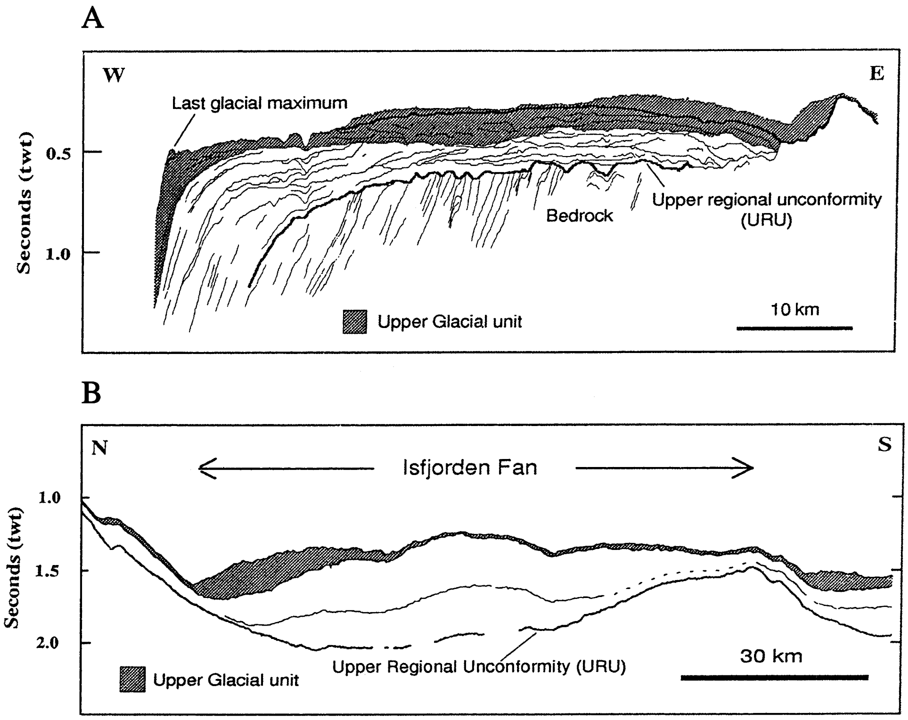


Fig. 2. Seismic records from the Svalbard continental margin (located in Fig. 1), showing: (A) long profile on the prograding Isfjorden Fan; (B) cross profile through the Isfjorden Fan and inter-fan margins. Cores 36 and 12 are located at the southern and northern ends of the cross profile, respectively. The upper glacial unit (shaded) represents sediments deposited over the past 130 000 yr (from Dowdeswell et al., 1998).

ice streams in Quaternary ice sheets. Recently, a set of streamlined linear features, continuous for about 100 and 20 km wide, observed using swath-bathymetry on the Antarctic Peninsula shelf, has provided further compelling evidence for former ice-stream flow (Canals et al., 2000). Numerical ice-sheet models also predict the former occurrence of ice-stream flow within ice sheets (e.g. Payne and Dongelmans, 1997; Dowdeswell and Siegert, 1999). Some ice streams are known to be unstable, and to switch between fast flow and stagnation (e.g. Rose, 1979; Dowdeswell and Collin, 1990; Willans et al., 2001). This is also likely to be the case for ancient ice sheets. However, the timing of initiation of fast glacier flow during a glacial cycle of ice-sheet growth and decay remains unknown.

The Svalbard margin of the Norwegian–Greenland Sea (Fig. 1) provides an example of changes in sedimentation through time on a continental margin that is influenced strongly by the growth and decay of a large ice sheet (Mangerud et al., 1998; Landvik et al., 1998). In this study, we discuss a number of marine sediment cores, combined with high-resolution seismic records and sea-floor imagery from the continental slope and shelf west of Svalbard, in order to address the question of the timing of ice-stream initiation. Sedimentary and acoustic evidence from the continental slope is derived from both fan and inter-fan areas. These cores provide a well-dated and high-resolution record of changes in the rate and style of sedimentation over the past 30 000 yr or so (Elverhøi et al., 1995a; Andersen et al., 1996).

2. Background to the Svalbard margin: sedimentary processes and ice dynamics

The clear contrasts in both sedimentary pro-

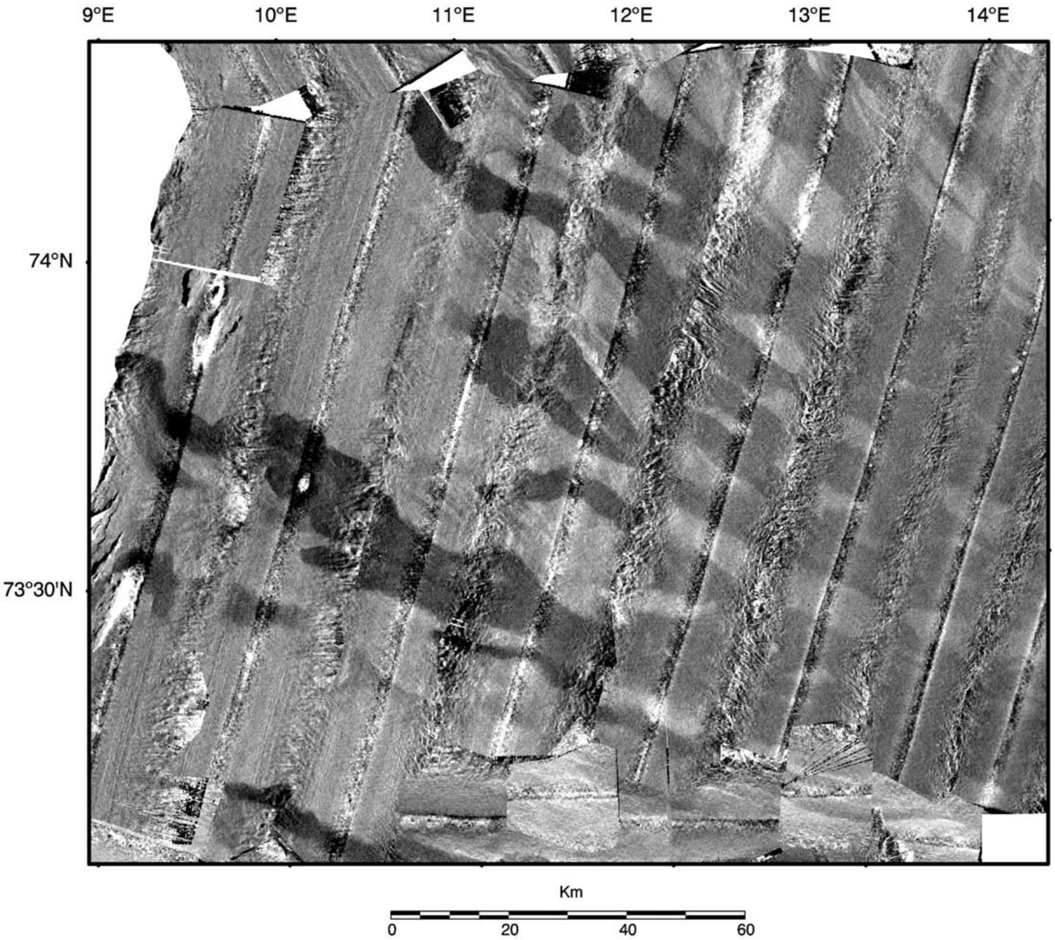


Fig. 3. 6.5-kHz long-range side-scan sonar image of large debris flows on the Bear Island Fan. The debris flows are linear areas of darker tones running from right (upper slope) to left (abyssal depths) across the image.

cesses and style of sedimentation between fan and inter-fan areas along the eastern margin of the Norwegian–Greenland Sea are suggested to reflect the dynamics of former ice sheets. When ice has advanced onto, and to the edge of, the continental shelf, ice sheets have been the dominant mode of sediment delivery to the continental margin over a series of glacial–interglacial cycles (Dowdeswell et al., 1996; Vorren et al., 1998). However, ice dynamics along the Svalbard–Barents Sea margin have varied significantly over space and through time (Dowdeswell and Siegert, 1999).

The series of large, prograding fans offshore of Svalbard and the Barents Sea, at the mouths of cross-shelf troughs, indicates the locations of ice streams in past ice sheets (e.g. Laberg and Vorren, 1995; Dowdeswell et al., 1996; Faleide et al., 1996) (Fig. 1). The seismic architecture of the Isfjorden Fan, west of Svalbard (Fig. 1), is shown in profile and cross-section in Fig. 2. When ice was at the shelf break during full-glacial conditions, fast-flowing ice streams delivered large quantities of sediment to the upper slope and a series of large debris flows formed the building blocks for fan growth (e.g. Laberg and Vorren, 1995; Dowdeswell et al., 1996). Submarine debris flows, up to about 50 m in thickness, several kilometres in width, and up to 150 km in length, are found on many high-latitude, glacier-influenced fans (e.g. Laberg and Vorren, 1995; King et al.,

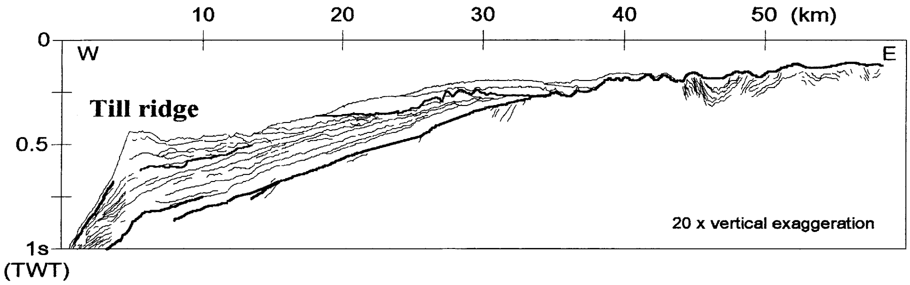


Fig. 4. Long profile showing the interpreted seismic record of a shelf-edge submarine moraine (labelled till ridge) on the Svalbard margin between the Isfjorden and Bellsund fans (located in Fig. 1).

1996; Dowdeswell et al., 1997), whereas offshore of the former Hudson Strait ice stream draining the Laurentide Ice Sheet, sedimentation is from turbidites, debris flows and meltwater plumes (Hesse et al., 1997, 1999). A long-range side-scan sonar image of debris flows on the Bear Island Fan, south of Svalbard, is shown in Fig. 3. The packages of superimposed debris flows appear, from seismic records, to be separated by hemipelagic sediments, which are inferred to represent interglacial deposition of fine-grained material when ice was no longer present at or close to the shelf break and sedimentation rates were reduced greatly (King et al., 1996).

At the continental shelf break, submarine moraine systems have been identified between several large fans on the Svalbard–Barents Sea margin from seismic and side-scan sonar records (Elverhøi and Solheim, 1983) (Fig. 4). These moraines are not found where prograding fan sequences occur. This is evidence for a clear difference in the nature of ice dynamics and sedimentation along the ice-sheet margins. The distribution of moraine systems is inferred to mark the extent of relatively slow-moving ice in inter-fan areas, and probably records the position of parts of the former ice margins of the Late Weichselian ice sheet on the Svalbard and Barents Sea continental margin.

3. Sedimentation through a cycle of ice-sheet growth and decay

The sedimentary record from a transect of three AMS radiocarbon-dated cores located in inter-fan areas off western Svalbard illustrates the changing nature of sedimentation from the growth of Late Weichselian ice, through full-glacial conditions, followed by subsequent deglaciation leading to the Holocene interglacial (Figs. 1 (inset) and 5). The cores are from the lower and upper continental slope, at 2119 and 1360 m water depths, respectively, and from 628 m on the shelf edge

Table 1
Glacial–interglacial variations in bulk accumulation rates (based on radiocarbon years), IRD influx and sedimentary facies in three cores from inter-fan areas on the western Svalbard margin (data from Elverhøi et al., 1995; Andersen et al., 1996; Dowdeswell et al., 1998)

	Bulk accumulation rate ($g\ cm^{-2}\ 1000\ yr^{-1}$)			Grains $>500\ \mu m$ (IRD) (no. grains $cm^{-2}\ 1000\ yr^{-1}$)			Sedimentary facies		
Core site	39	36	12	39	36	12	39	36	12
Holocene	4	25	–	<5	<20	–	Fm	Fm	–
Deglacial	19	140	150	80–150	700–1000	500	Dm/Fl	Fl	Fl
Full glacial	8	15	20	<5	<5	<100	Dm	Dm	Dm
Ice advance	32	–	25	40	–	500–900	Fl	Fl	–

The core locations are shown in Fig. 1. Dm is massive diamicton, Fl is fine laminated, Fm is fine massive facies.

(Elverhøi et al., 1995a; Andersen et al., 1996). All three cores are located adjacent to the Isfjorden Fan, which is suggested to represent the main depocentre of an ice stream draining from the interior part of the former Svalbard–Barents Sea ice sheet (Elverhøi et al., 1995b; Hooke and Elverhøi, 1996). In addition, two cores are available from the fan itself (cores 18 and 19 in Fig. 1).

Both the fan and the inter-fan sediments are well-dated and have been analysed sedimentologically (e.g. Elverhøi et al., 1995a; Andersen et al., 1996). Seventeen AMS radiocarbon dates, obtained from samples of 1500–2000 Neogloboquadrina pachyderma (sin.) tests, were obtained from cores 12, 36 and 39 (Figs. 1 and 5). The age model for each core is based on radiocarbon dates and oxygen isotope measurements (Andersen et al., 1996). Radiocarbon dates are corrected for ^{13}C and a reservoir age of 440 yr (Mangerud and Gulliksen, 1975).

These sediments, therefore, provide an important dataset for analysing the character and rate of sedimentation through a cycle of ice-sheet growth and decay. The three inter-fan cores each show a variable suite of sedimentary facies (Table 1), whereas the two cores from the fan itself were characterised by homogeneous diamiction throughout the entire length of the cores (9 m).

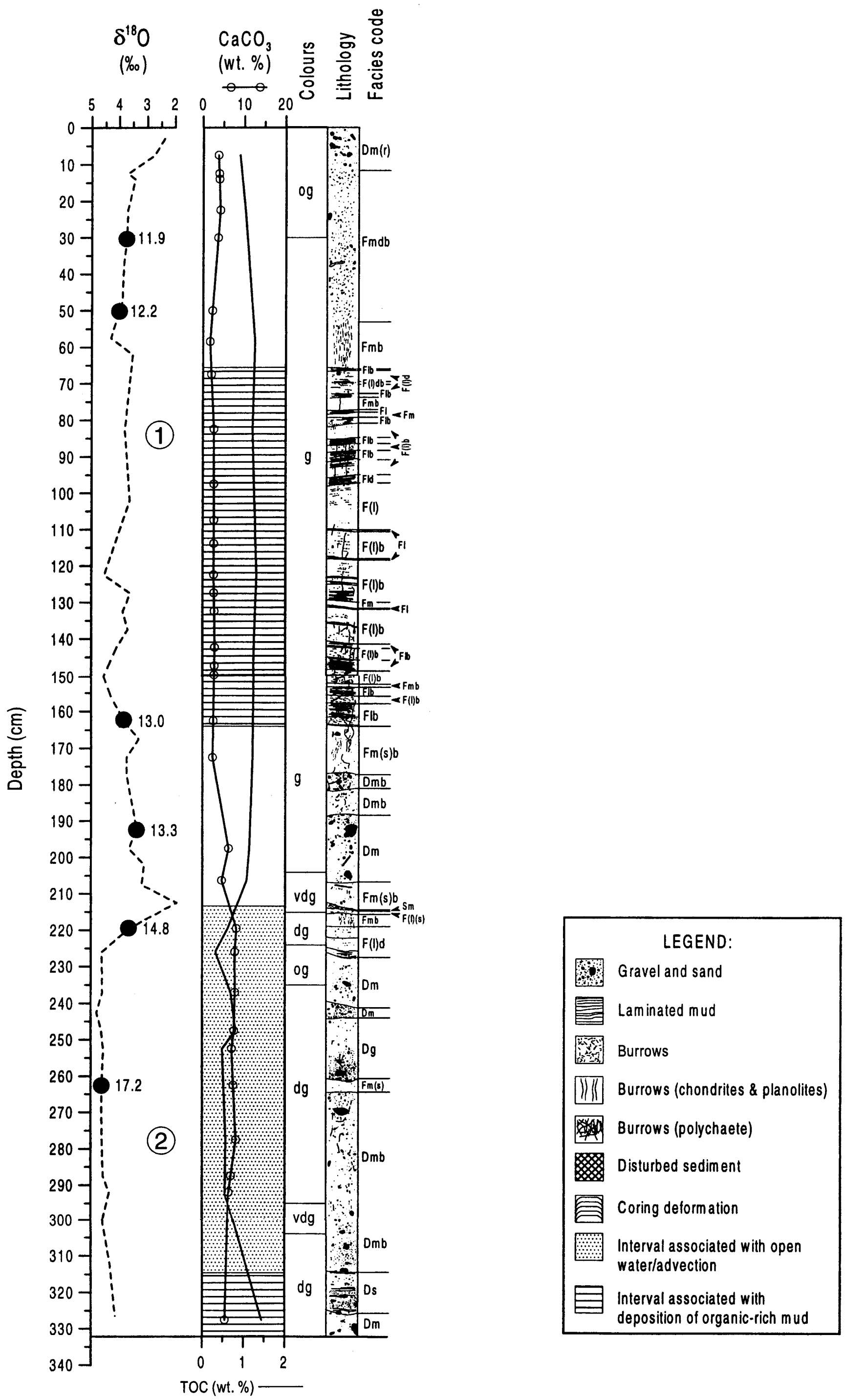
In the inter-fan cores, bulk sedimentation rates and the occurrence of grains >500 μm in diameter, an ice-rafted debris (IRD) indicator, vary in a similar fashion through the last glacial (Table 1). The absolute values for each parameter also follow a systematic spatial pattern, with the most shelf-distal deep-water core having the lowest rates for almost every time interval when compared with the more proximal, shallower water cores. This indicates that distance from the ice front and shelf break was a significant spatial control on sediment delivery to the Svalbard margin. Northward sediment transfer by ocean currents flowing parallel to the margin appears, therefore, to have been a less important influence on the pattern of sedimentation offshore of western Svalbard.

During the period of ice growth and spread across the continental shelf, sedimentation rates and IRD content were both relatively high in the three inter-fan cores (Fig. 5; Table 1). Ice began to build up on Svalbard and the Barents Shelf from about 27 000 yr BP (Elverhøi et al., 1995a). The ice margin advanced to the outer continental shelf by about 22 000 yr BP and reached the shelf edge at approximately 18 000 yr BP, as indicated by the presence of dated debris flows on the slope (Elverhøi et al., 1995a) (Fig. 1, inset). At this time there was no shift towards lighter oxygen isotopic values. Under full-glacial conditions, both bulk accumulation rates and IRD content were very low in all three cores (Table 1). During deglaciation, the two sedimentary parameters regained high values, but their increase was led by a major spike of light meltwater identified clearly in each core at about 14 800 yr BP (Elverhøi et al., 1995a). Ice recession from the shelf was complete by about 12 000 yr BP (Elverhøi et al., 1995a). Bulk accumulation and IRD values also decreased again as ice retreated into the interior of Svalbard during the present, Holocene interglacial (Svendsen et al., 1992). Andrews (2000) presents sedimentation rates from a number of ice-marginal settings at the northeastern margin of the Laurentide Ice Sheet, showing a similar overall pattern of relatively high rates of sediment delivery during deglaciation and low rates during the Holocene. Although much of the Laurentide evidence does not go back beyond 12 000 yr BP, these records also hint at a slowing of sedimentation as full-glacial conditions are approached.

This pattern is also reflected in the changing

Fig. 5. Records from three cores (Elverhøi et al., 1995a; Andersen et al., 1996; Dowdeswell et al., 1998) taken from the continental slope and outer shelf of the Svalbard continental margin (located in Fig. 1). (A) Core NP90-12 in 628 m water depth. (B) Core NP90-36 in 1360 water depth. (c) Core NP90-39 in 2119 m water depth. For each core, oxygen isotope ratios, calcium carbonate and total organic carbon (TOC), sedimentology, AMS radiocarbon dates (black circles) and age estimates based on correlation of oxygen isotope records are plotted.

A) 90-12


δ18O
(‰)
CaCO3
(wt. %)
Colours
Lithology
Facies code
Depth (cm)
TOC (wt. %)
11.9
12.2
13.0
13.3
14.8
17.2
①
②
og
g
g
vdg
dg
og
dg
vdg
dg
Dm(r)
Fmdb
Fmb
F(l)
F(l)b
Fm(s)b
Dmb
Dm
F(l)d
Dg
Ds
LEGEND:
Gravel and sand
Laminated mud
Burrows
Burrows (chondrites & planolites)
Burrows (polychaete)
Disturbed sediment
Coring deformation
Interval associated with open water/advection
Interval associated with deposition of organic-rich mud

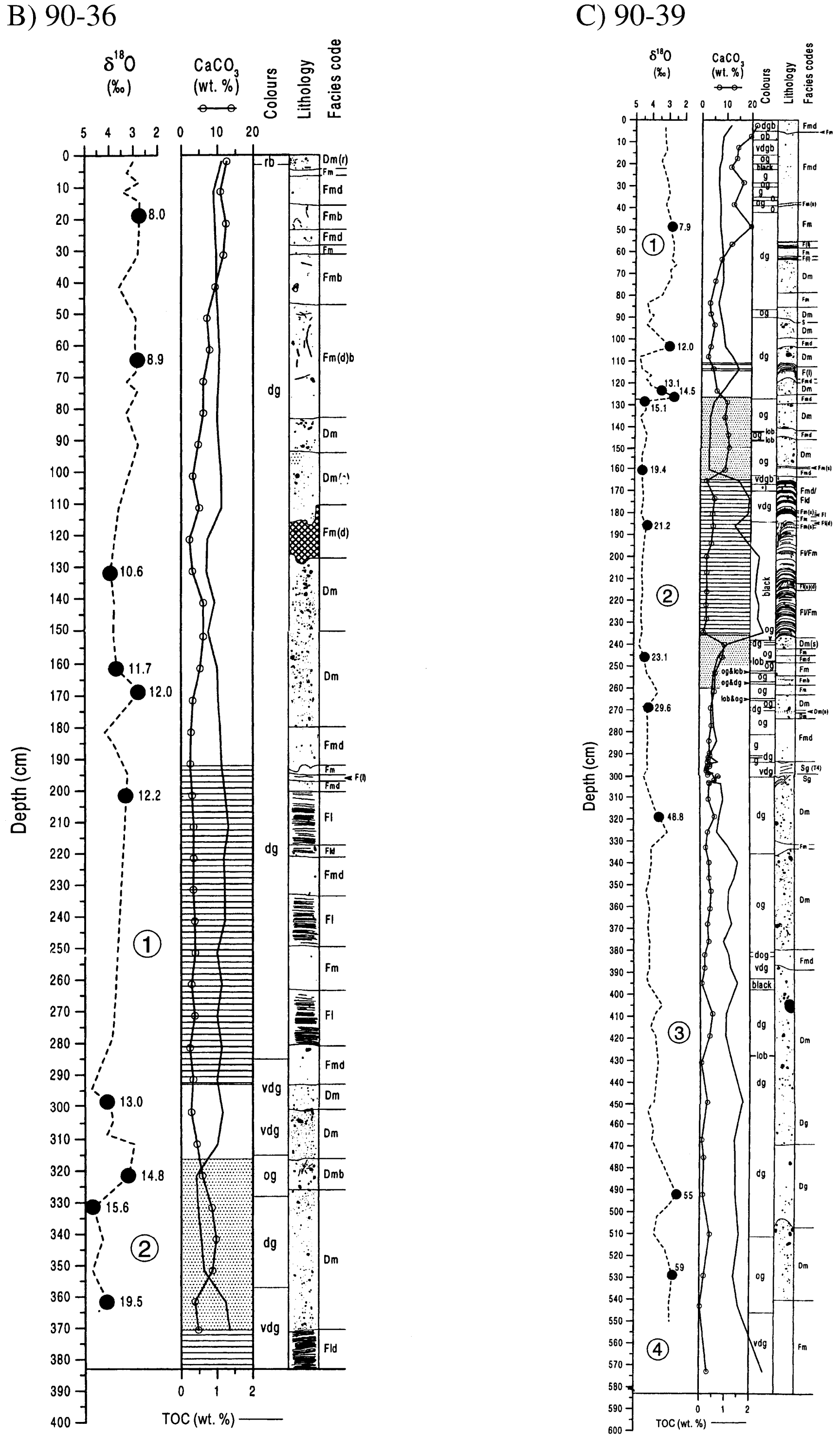


Fig. 5 (*Continued*).

sedimentary facies in each of the Svalbard margin cores (Fig. 5; Table 1). In the most distal core, Core 39, the interval of ice growth is represented by about 80 cm of alternating laminated and massive muds, underlain by older diamictons (Fig. 5c). The two cores more proximal to the shelf edge, Cores 12 and 36, contain a shorter record of sedimentation, but the basal sediments in Core 36 are laminated and may reflect a phase of ice advance (Fig. 5B). Massive diamictons are typical of full-glacial conditions at each core site, but accumulation is low (Table 1). Deglaciation is marked by fine-grained laminated sediments but, at this time, is also associated with bulk accumulation rates and IRD delivery rates that are even higher than during ice advance (Table 1). The Holocene interglacial sediments are mainly massive muds, indicating that the modern environment on the Svalbard margin is ice-distal (Svendsen et al., 1992), with glaciers located mainly at the heads of fjords (Elverhøi et al., 1980, 1983; Sexton et al., 1992).

By contrast with the inter-fan areas, where sediment input falls to a minimum during full glaciation, maximum sediment input to the Isfjorden Fan itself takes place during the full-glacial. High-resolution reflection-seismic records show that the upper part of the fan is characterised by numerous submarine debris flows (Fig. 2). A core (labelled 18 in Fig. 1) composed of homogeneous diamicton, penetrating the flanks of one of these lens-shaped debris flows on the Isfjorden Fan, yielded AMS reservoir-corrected dates of 19 205 ± 210 and 19 195 ± 225 yr BP for the base of the debris flow. This provides a maximum age for debris-flow deposition (Andersen et al., 1996). Correlation of the uppermost sediments that cover the debris flows with dated sediments in adjacent areas, implies that the flows are older than 15 000 yr BP.

4. Interpretation: ice-sheet dynamics and sedimentation

The sedimentary parameters for the deglaciation and Holocene interglacial phases on the Svalbard margin can be interpreted relatively simply. A major pulse of isotopically light meltwater represents the beginning of deglaciation (Jones and Keigwin, 1988; Elverhøi et al., 1995a). It is accompanied by high sedimentation rates and large quantities of IRD (Table 1), combined with the deposition of laminated muds indicating strong sediment delivery from glacial meltwater and iceberg production during deglaciation. Similarly, the Holocene interglacial is a time of predominantly hemipelagic sedimentation of fine-grained debris in a low energy, ice distal environment.

Sedimentation rates on the inter-fan areas of the upper continental slope decreased under full-glacial conditions, when the ice sheet reached the shelf break. Bulk accumulation rates and IRD values were also low for full-glacial conditions, particularly when compared with higher accumulation and IRD values and the deposition of fine, laminated sediments during ice-sheet growth (Fig. 5, Table 1). This appears not to be a result simply of low water temperatures during full-glacial conditions, restricting melting and debris-release from icebergs, because the last glacial maximum was associated with high planktonic foraminiferal abundance and thus seasonally sea-ice free conditions offshore of Svalbard (Hald et al., 1996). We offer the following explanation for this apparently anomalous observation.

During the period of ice-sheet growth, ice flow was fairly uniform along the Svalbard margin, and meltwater and iceberg sedimentation increased along the whole margin with ice advance. As ice reached the shelf break, and maximum ice-sheet geometry was approached, the dynamics of the ice sheet changed and fast-flowing ice streams were initiated in major cross-shelf troughs (Payne and Dongelmans, 1997). A possible explanation for this change in ice dynamics was that ice in the troughs was thicker than that elsewhere around the ice margin. This allowed ice in the troughs to reach the pressure-melting point at the bed, whereas other, thinner parts of the ice sheet were still frozen to the bed (Dowdeswell and Siegert, 1999). Once fast flow was initiated, it was maintained by the down-draw of ice from interior ice-sheet drainage basins.

These ice streams provided a spatial focus for high sedimentation from basal till deformation

(Alley et al., 1989; Hooke and Elverhøi, 1996) and iceberg production (Dowdeswell et al., 1992), and the initiation of fan-forming debris flows during full-glacial conditions (Laberg and Vorren, 1995; Dowdeswell et al., 1996). In addition to the AMS dates of about 19 000 yr BP on debris flows from the Isfjorden Fan, radiocarbon ages are also available from debris flows on the Bear Island Fan, to the south on the Barents Sea margin (Laberg and Vorren, 1995). Here, a maximum age of 17 460 ± 145 yr BP was obtained from a debris-flow lobe. Thus, the dates on both the Isfjorden and Bear Island fan debris flows support the suggestion that fan build-up is associated with full-glacial conditions.

By contrast, between these ice streams, the remaining sections of the ice margin are likely to have experienced a decrease in drainage area due to convergent ice flow into the ice streams (Payne and Dongelmans, 1997). Numerical ice-sheet modelling predicts that ice velocities will be one to two orders of magnitude higher in ice streams, located within the cross-shelf troughs of Svalbard and the Barents Sea, than in intervening areas of the ice-sheet margin (Dowdeswell and Siegert, 1999). The low ice velocities mean that relatively few icebergs and little basal meltwater are produced (Siegert and Dowdeswell, 2002). Modelling also suggests that these ice-dynamic differences result in relatively high sediment delivery from ice streams, with low values from the slower-moving parts of the ice-sheet margin.

The apparently anomalous coincidence of full-glacial conditions, low sediment accumulation and little IRD input (Table 1) can, therefore, be explained by the switching of ice-sheet dynamics from relatively uniform flow, during ice advance, to fast-flowing units within generally slower-moving ice under full-glacial conditions. This suggestion is compatible with the rapid switching between slow and fast glacier flow inferred for modern Antarctic and Arctic ice streams (e.g. Rose, 1979; Dowdeswell and Collin, 1990; Alley and Whillans, 1991; Whillans et al., 2001), and for parts of the last North American Ice Sheet (Boulton and Clark, 1990). Such switching has also been reproduced recently in ice-sheet numerical models (Payne and Dongelmans, 1997). Our interpretation provides, for the first time, a constraint on the timing of ice-stream initiation during the cycle of ice-sheet growth and decay.

Our finding that ice-stream flow is initiated when the parent ice sheet reaches its maximum extent at the continental shelf break is consistent with glaciological theory and observations from modern ice sheets. Fast ice-stream flow requires a considerable flux of mass from a large up-glacier drainage basin in order to be sustained (Bentley, 1987; Bindschadler, 1984). Relatively thick ice is also necessary for basal ice-sheet melting, and the lubrication that goes with it, to begin (Payne and Dongelmans, 1997). These criteria are met more easily in a large, full-glacial ice sheet than in an ice sheet that is growing towards this state.

5. Summary and conclusions

- When ice sheets advance to the edge of high-latitude continental shelves, they become an important source of sediment delivery to the continental margin (e.g. Dowdeswell et al., 1996; Vorren et al., 1998; Hesse et al., 1999). However, ice-dynamic behaviour, in areas such as that to the west of Svalbard and the Barents Sea, has varied significantly over space and through time during the Late Weichselian (Dowdeswell and Siegert, 1999).
- The sedimentary record from a transect of three AMS radiocarbon-dated cores located in inter-fan areas off western Svalbard, combined with cores and high-resolution seismic records from the Isfjorden Fan itself, illustrates the changing nature of sedimentation through a cycle of ice-sheet growth and decay.
- During ice-sheet growth, sedimentation rates and IRD content were both relatively high in the three inter-fan cores. Under full-glacial conditions, massive diamictons were deposited at each core site, and bulk accumulation rates and IRD content were very low in all three cores (Table 1). During deglaciation, these parameters regained high values. Bulk accumulation and IRD values then decreased again as ice retreated into the in-

terior of Svalbard during the Holocene interglacial.

• Through the period during which the ice sheet was expanding across the continental shelf, ice flow was fairly uniform along the Svalbard margin, and meltwater and iceberg sedimentation increased along the whole margin with ice advance. As ice reached the shelf break, and maximum ice-sheet geometry was approached, fast-flowing ice streams were initiated in major cross-shelf troughs, providing a spatial focus for high sedimentation from basal till deformation (Alley et al., 1989; Hooke and Elverhøi, 1996) and iceberg production.

• By contrast, between these ice streams, the remaining sections of the ice margin were likely to have experienced a decreasing ice-drainage area, as a result of convergent ice flow into the ice streams. Relatively few icebergs and little basal meltwater were produced at these slow-moving margins.

• The coincidence of full-glacial conditions, low accumulation and little IRD input appears, at first, to be counter-intuitive. It can, however, be explained by the switching of ice-sheet dynamics from relatively uniform flow, during ice advance, to fast-flowing units within generally slower-moving ice under full-glacial conditions, when ice reached the shelf break. This interpretation provides, for the first time, a constraint on the timing of ice-stream initiation during the cycle of ice-sheet growth and decay.

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