DEVELOPMENT OF A GLACIATED ARCTIC CONTINENTAL MARGIN: EXEMPLIFIED BY THE WESTERN MARGIN OF SVALBARD

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ABSTRACT

The sedimentary evolution of the western continental margin of Svalbard is greatly affected by the history of rifting and seafloor spreading in the Norwegian-Greenland Sea, the late Cenozoic glacial-interglacial shifts, ice-stream dynamics, and eustatic sea-level changes. Transverse shelf troughs, extending from the fjord mouths to the shelf edge, and associated submarine fans are important features of the margin. The troughs are most likely formed by the action of ice-streams draining major parts of the Svalbard-Barents Sea ice sheets. Most of the glacial erosion products may have been transported as a subglacial deformable till and deposited on the outer shelf and the upper slope, resulting in enhanced shelf progradation. The fans are products of various types of mass-flows, dominated by small-scale slumping and turbidites. This is reflected by a chaotic seismic character, distinctly different from that of adjacent areas. Differential sedimentation rates between the fans and the adjacent areas are further enhanced by the hinterland topography, guiding the ice flow. The formation of the fans is directly related to a period of rapid fall in sea level that coincided with the global shift from less extensive to more extensive ice sheets, which occurred around 1 to 0.8 m.y.

INTRODUCTION

The western Svalbard continental margin, typical for glaciated areas at high latitudes, developed during the Cenozoic and is therefore closely related to the history of rifting and seafloor spreading in the Norwegian-Greenland Sea (Myhre and Eldholm, 1988). Additionally, it was subjected to Pliocene-Pleistocene glaciations (Jansen and Sjøholm, 1991). During uplift and subsequent glaciations, approximately 1 km of Barents Sea and Svalbard bedrock was eroded (Vorren et al., 1991; Riis and Fjeldskaar, 1992) and later deposited on major submarine fans of the eastern margin of the Norwegian-Greenland Sea and adjacent Arctic Ocean.

The western Svalbard margin is characterized by a narrow shelf and a steep slope, with a gradient of 4 to 5°. The shelf is cut by wide, glacially eroded troughs that are separated by shallow banks (Fig.1). The largest trough, Isfjorden Trough, is 200 to 300 m deep, while the surface of Isfjorden Bank is less than 100 m deep. The largest submarine fan, Isfjorden Fan, is located at the mouth of Isfjorden Trough. The fan terminates at the presently active Knipovich Ridge spreading axis, which is located near the Svalbard margin. At its northern part, the fan has prograded directly into the axial valley (Fig.1). The dominant surface current, the West Spitsbergen Current, flows northwards along the margin (Aagaard et al., 1985; Rudels, 1989). The current was established during both interglacial and interstadial periods, transporting suspended sediments towards the north (Boulton, 1990).

The main objective of this paper is to define and interpret the principal sedimentary units and relate these to the late Cenozoic history of the western Svalbard margin, with emphasis on the Isfjorden Fan area. The study is based on both single- and multichannel seismic profiles (Fig.1).

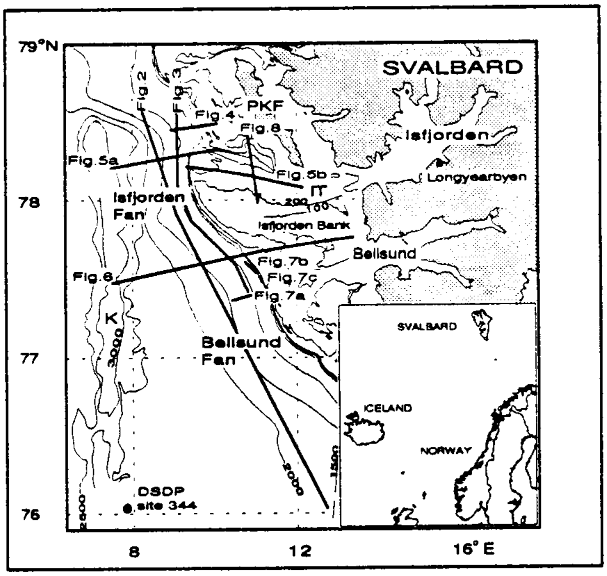

Fig.1. The western Svalbard continental margin: The study area with names described in the text. Lines of sections shown in other figures are marked. The DSDP site 344 is shown in the southwestern corner. IT: Isfjorden Trough. PKF: Prins Karls Forland. K: Knipovich Ridge. Contours in m; contour interval is 500 m at the slope and 100 m at the shelf.

SEISMIC STRATIGRAPHY

The western part of Svalbard and the adjacent inner shelf are dominated by Precambrian and lower Paleozoic metasediments belonging to the Heckla Hoek complex (Sigmond, 1992). These sediments are covered by Cenozoic deposits, which are very thick (> 500 m) on the outer shelf and slope (Myhre and Eldholm, 1988). The distribution of the Cenozoic sediments has been controlled by major east-west drainage systems that presently appear as fjords and troughs (Myhre and Eldholm, 1988). Schlüter and Hinz (1978) recognized three sedimentary sequences (SPI-I, SPI-II, and SPI-III) in multichannel seismic profiles off western Svalbard, separated by two unconformities, U1 and U2 (Fig.2). The U2 unconformity is correlated with the onset of glaciomarine sedimentation on the northern hemisphere (Myhre and Eldholm, 1988), which may have started at 2.6 Ma (Talwani et al., 1976), or as early as 5.5 Ma (Jansen and Sjøholm, 1991). Despite these disagreements on the exact age, an important consequence is that rapid deposition has occurred since early Pliocene and that the sediments above U2 are essentially considered glaciogenic.

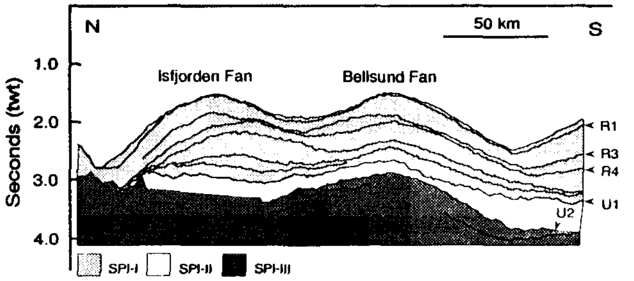

Fig.2. Interpretation of multichannel seismic line BU1-81 along the shelf edge. The section shows the two-dimensional distribution of SPI-I, SPI-II, and SPI-III. Line BU1-81 was provided by the University of Bergen. See Fig.1 for location.

Late Cenozoic Sediments

Three styles of margin growth are identified within the study area: (1) a sediment-starved outer shelf and slope off Prins Karls Forland (Figs.3 and 4); (2) a prograding and aggrading shelf that continues seaward into a slope facies with parallel geometry at the Isfjorden Fan (Fig.5); and (3) a sediment-starved and prograding outer shelf and slope, and a sediment aggrading shelf between Isfjorden Fan and Bellsund Fan (Fig.6). The late Cenozoic succession consists of two primary sequences (A and B), which are separated by a regional unconformity labelled R4 (Fig.3).

The Continental Slope and Rise

Sequence B can be traced over the entire study area. In the central part of the margin, it is characterized by a prograding clinoform pattern, consisting of steeply dipping strata, terminated updip by toplap due to erosion (Fig.5b). The sequence exhibits a prominent ramp on the lower slope in the interfan area (Fig.6), which is defined as the area between Isfjorden Fan and Bellsund Fan (Fig.1). This reflection style is quite different from the style off the Prins Karls Forland, which is characterized by parallel reflectors and deep-seated failure planes (Figs.3 and 4).

The sequence boundary (R4), which is defined as a type 1 sequence boundary (Van Wagoner et al., 1987), forms a regional surface characterized by a basinward shift of facies and onlap of overlying strata (Fig.6). This type of boundary forms when the rate of eustatic fall exceeds the rate of basin subsidence and represents the initial growth of Isfjorden Fan.

Sequence A appears to be more complex than the sequence below and consists of three lens-shaped units, separated by two regional reflectors (R1 and R3) (Fig.3). The distribution pattern of the units shows that the depocenter has migrated northward during fan growth.

There is a prominent lateral change in the seismic pattern within sequence A. Well-defined, seaward-prograding clinoforms dominate the fan proper (Fig.5a). The fan is dominated by zones of chaotic reflectors that are most likely associated with slump bodies (Fig.7a). The bodies are usually less than 3 km wide, 20 to 30 m high, and of variable length (>1 km). They often form an even base and a curved surface, and they are frequently stacked on top of each other (Fig.7a).

Submarine channels incise late Cenozoic sediments in the interfan area and are most common along reflector R4 (Fig.7b). Only one channel has a surface expression (Fig.7c). The channels are attenuated downslope and disappear at 600- to 1,000-m water depth.

The thickness of sequence A is reduced north of Isfjorden Fan, where it is characterized as a sheet drape consisting of parallel reflectors, similar to the sequence below. The seismic character of the interfan area is also quite different from Isfjorden Fan. Primarily, the major part of the sequence is distributed on the lower part of the slope, and the sequence is condensed on the upper part (Fig.6). A similar development also has been observed north of the Kongsfjorden area (Boulton, 1990). The basal unit is characterized as a slopefront fill with parallel reflectors that onlap onto the sequence boundary. The strata represent only apparent onlap, and the sediments are in fact sloping downward and away from the fan apex. The middle unit is wedge-shaped and onlaps onto the slope fan. The internal reflection pattern consists of parallel reflectors separated by thin zones of chaotic reflectors. Several gullies are found along certain horizons within the unit (Fig.3). The upper unit consists of parallel reflectors that drape the underlying units.

Shelf

The sequence boundary (R4) is defined as an angular unconformity on the shelf (Fig.5b), which separates sequence A from older strata that dip at a steeper angle. The seismic nature of the sediments below R4 is less well known because of the lack of high-resolution seismic penetration. The outer part of the shelf is characterized by steeply inclining clinoforms, and the inner part exhibits distorted reflectors, indicating folding and faulting prior to removal.

Sequence A consists of an aggradational-progradational sequence in Isfjorden Trough, which is characterized by truncated, subhorizontal, sheet-like units (Fig.5b), with a structureless to chaotic texture, including hyperbolic reflections. A total of 15 unconformities have been observed within the shelf sediments. The sediment thickness is greatest on Isfjorden Bank (Fig.8), and the clinoforms are dipping at a low angle toward the north, showing that Isfjorden Bank has expanded toward the north. This shows, as explained by

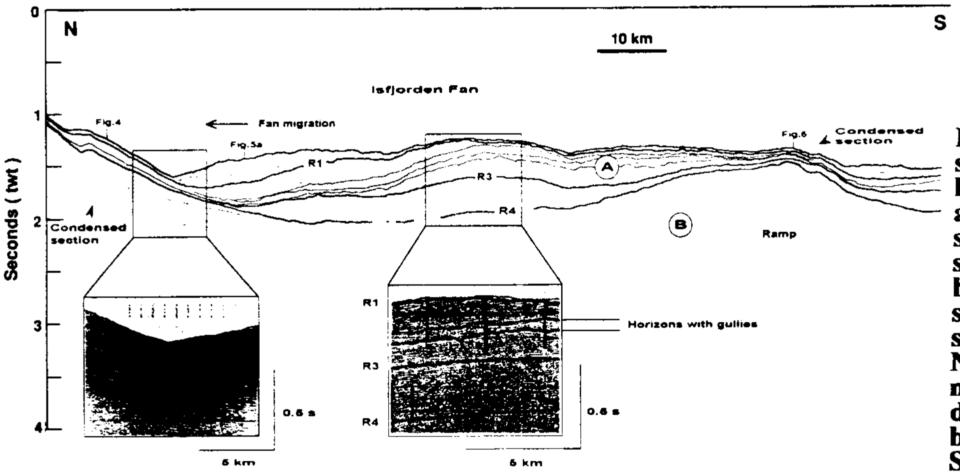

Fig.3. Interpretation of single-channel seismic line (2x40 cu inch sleeve airguns) along the shelf edge. The record shows the sequence boundary (R4) that separates the main sequences A and B. Note the northward migration and the distinct northern boundary of the fan. See Fig.1 for location.

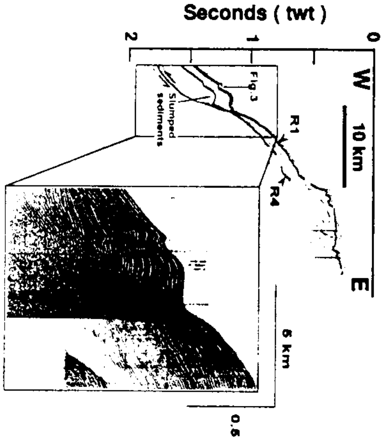

Fig.4. Interpretation of single-channel seismic line across the shelf edge showing a condensed section and major slumps. See Fig.1 for location.

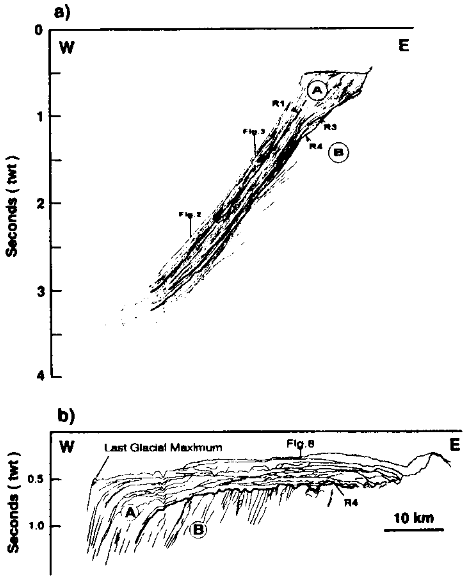

Fig.5. Interpretation of single-channel seismic line across the shelf edge. (a) Section across Isfjorden Fan showing steeply inclined clinoforms truncated by an angular unconformity. The unconformity is most likely caused by glacial erosion during the last glacial maximum. (b) Section along Isfjorden Trough showing the angular unconformity (R4) that separates the main sequences A and B. See Fig.1 for location.

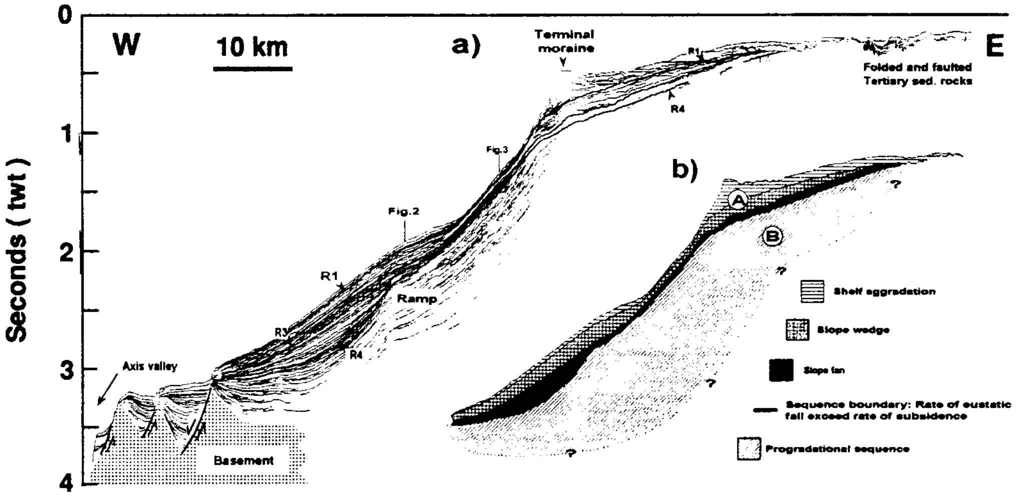

Fig.6. Interpretation of single-channel seismic line showing the internal geometry on the outer shelf and slope. (a) Section showing sequence A and B. (b) Sequence stratigraphic interpretation of the section described in the text. See Fig.1 for location.

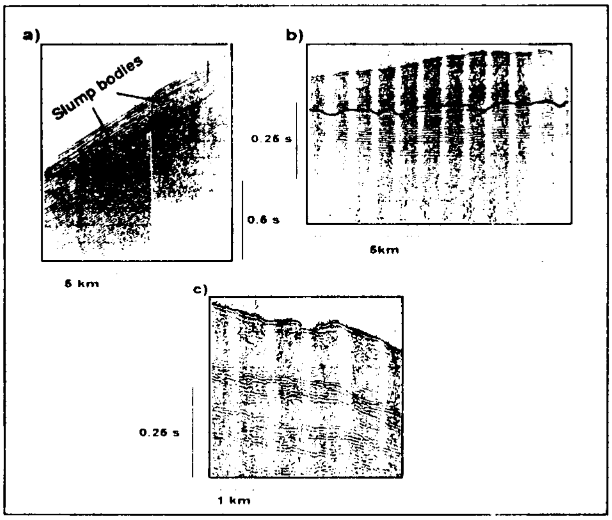

Fig.7. Examples of acoustic facies and erosive features. (a) Alternation of parallel stratified facies and chaotic facies composed of wavy and disrupted reflectors. (b) Channels developed during the eustatic sea-level fall around 1 to 0.8 m.y. (c) Presently active channel. See Fig.1 for location.

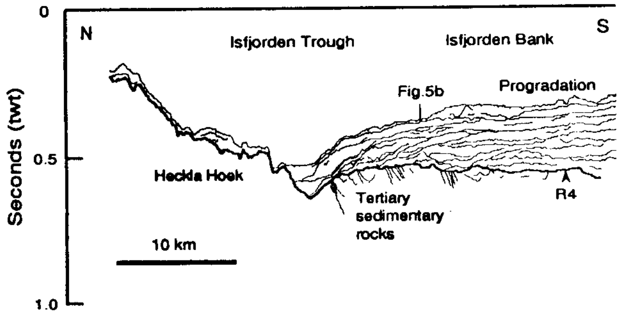

Fig.8. Interpretation of single-channel seismic line across Isfjorden Trough showing northward-inclining reflectors above R4, indicating northward migration of the fan system. See Fig.1 for location.

Boulton (1990), that Isfjorden Trough is not formed by erosion alone, but by deposition on the intervening bank.

The three units of sequence A are easily distinguished on the shelf, south of Isfjorden Bank (Fig.6). The basal unit is relatively thin and evenly distributed, and is characterized by a chaotic reflection pattern. The middle unit is thicker, exhibiting similar seismic character as the sediments in Isfjorden Trough. These two units are clearly tilted and truncated on the central part of the shelf. The upper unit onlaps the tilted package (Fig.6), and the sediment bodies exhibit large reliefs. A prominent ridge is formed near the shelf edge. It is clearly wedge-shaped and displays divergent clinoforms on the upper slope and mounded reflectors in the middle. The upper unit has been exposed to down-cutting erosional truncation since strata terminate against the seafloor (Fig.6).

DISCUSSION

Chronostratigraphy and Correlation

A lack of good chronostratigraphic tie points hampers a detailed interpretation of the seismic sections. The present age control is based on ^{14}C ages of shallow cores from the western Svalbard Shelf (Svendsen et al., 1992), and seismic ties to DSDP site 344 (Fig.1) and drillholes in the southwestern Barents Sea (Sættem et al., 1992).

Myhre and Eldholm (1988) suggest the U2 unconformity represents an erosional surface related to a glacio-eustatic fall in late Miocene (5 to 6 m.y.). This correlates well with the onset of ice-rafted debris (IRD) in the Norwegian Sea, which started about 5.5 Ma (Jansen and Sjøholm, 1991). However, this date is not in agreement with paleontological data from the DSDP 344 site (Talwani et al., 1976), which suggest a younger age (2.6 Ma). Since the short-term fluctuation in sea level that generated reflector R4 was probably related to glaciation, we suggest that R4 corresponds to the intensification of glaciations that according to the global δ^{18}O record (Shackleton et al., 1990) and the Norwegian Sea IRD record (Jansen and Sjøholm, 1991) occurred around 1 to 0.8 m.y. Reflector R3 is correlated with the upper regional unconformity on the Barents Sea margin, dated at 0.44 to 0.73 m.y. (Sættem et al., 1992). Reflector R1 is not dated, but Elverhøi et al. (in prep.) suggest that the age is in the range of 0.15 to 0.3 m.y., which represents 2 to 3 glacial cycles.

Margin Processes

The styles of margin configuration observed on the seismic profiles record the importance of eustatic oscillations, sediment supply, and tectonic events during deposition.

Sequence B

The development of the central part of sequence B is most likely related to progradational phases during relative sea-level drops and lowstands. During such periods, seaward migration of the shoreline produces increased sediment supply and basinward transport, generating seaward building of the margin (Posamentier et al., 1988). Each period of sea-level drop is most probably related to glacial maxima. Submarine fans did not develop during deposition of sequence B, and what appears to reflect a fan body along the strike (Fig.2) is in fact a ramp (Fig.6), indicating that sequence B drapes over the underlying topography. We suggest, therefore, that the lack of fan growth reflects less extensive ice sheets prior to ~ 1 to 0.8 m.y. because the large amounts of terrigenous sediments that were needed to build submarine fans could not reach the slope.

The laminated sediments off Prins Karls Forland most likely reflect hemipelagic mud (Sangree and Widmier, 1977), indicating an environment more distal to the shelf edge. The sediments may possess lower shear strength than the sediments within Isfjorden Fan because slumped sediments associated with deep-seated failure planes are restricted to this area (Fig.4). The slumping must be related to different sediment properties since the upper slope gradient off Prins Karls Forland is less steep than on the fan.

Sequence A

Relative sea level was considerably lower during the ice expansion around 1 to 0.8 m.y. Glaciers covered the entire shelf, eroded the upper part of the sequence B and older shelf deposits, and discharged large quantities of terrigenous sediment on the outer shelf and upper slope. Down-slope sediment transport occurred through small-scale slumping, and turbidity currents seem to be of minor importance since channels are not present in the fan proper. The growth of Isfjorden Fan was initiated because the degree of progradation was greater adjacent to Isfjorden Trough than the nearby banks.

Several features indicate that the sediments were transported by an ice-stream: First, truncated, sheet-like shelf deposits (Fig.5b) are expected to appear in a till delta formed by an ice-stream (Alley et al., 1989). Second, fan development is dependent on a point source at the shelf. We believe that ice-streams are the only point sources on high-latitude margins that are able to replace rivers that act as fan-feeders at low latitudes. Finally, the shape of Isfjorden Trough indicates erosion by an elongated ice body.

Hook and Elverhøi (in prep.) suggest that the various shelf unconformities within sequence A represent periods when glaciers were resting more heavily on the sediments, and thus eroding or deforming earlier deposits. Here, we suggest that the unconformities represent ice advances, and that the ice expanded to the shelf at least 15 times during the last 1 to 0.8 m.y.. Evidence for a late Weichselian advance to the shelf edge is found in a prominent moraine ridge located at the shelf edge (Fig.5b) and tills covered by glaciomarine mud, recovered less than 10 km east of the shelf edge (Svendsen et al., 1992). The mud is younger than 15,000 ^{14}C years B.P. (J. I. Svendsen, pers. commun., 1993).

During the interglacial and interstadial phases, recession of continental glaciers caused sea level to rise. These high stands moved the locus of sedimentation landward. The width and the low gradient of the shelf restricted deposition mainly to the fjord basins (Elverhøi et al., in prep.). Hence, the fan growth took place during glacial phases, and most of the fan sediments consist of weathered continental material formed during interglacials and interstadials (Elverhøi et al., in prep.). Hook and Elverhøi (in prep) show that there was sufficient time during the glacials for ice-streams to transport sediments from Isfjorden to the shelf and slope.

The steeply dipping strata within Isfjorden Fan indicate relatively high sediment supply, slow to no basin subsidence, and a stillstand of sea level to allow rapid basin infill and sedimentary bypass (Bally, 1987). No large depositional break appears to have occurred prior to the fan development since the clinoforms are parallel to the clinoforms of sequence B (Fig.5b).

The southern flank of the fan is less homogeneous (Fig.6), and acts as a record of sea-level fluctuations. As noted, the development of sequence B was followed by a major drop in sea level and subglacial erosion on the shelf and channel erosion on the upper slope (Fig.6b). Hence, the basal unit of sequence A represents a lowstand fan, deposited when the rate of eustatic fall exceeded the rate of subsidence. Throughout deposition, glacial ice most likely expanded to the shelf edge and discharged its sediment load directly onto the upper slope. The middle unit is defined as a lowstand wedge, deposited during a period of minimum sea-level elevation and maximum ice extension. The fan progradation, therefore, was greatest during this phase, due to increased input of terrigenous material. The upper unit, characterized by shelf aggradation (Fig.6b), may represent a period of higher sea level and less extensive ice sheets that terminated slightly inland of the shelf edge in the interfan area. This is in agreement with the presence of a prominent moraine ridge at the shelf edge (Fig.6). Since similar structures are not present in the two basal units, we conclude that the ice terminus was located at the shelf edge prior to R1, and that the terminal dump was deposited off the shelf edge. The internal reflectors indicate that the ridge was developed through a series of glacial advances. The presence of gullies on the slope (Fig.3) is most likely related to these glacial advances, as a result of the corresponding sea-level falls (Vail, 1987).

Each of the three units within sequence A represents several interglacial-glacial cycles, while the two regional reflectors, R1 and R3 (Fig.6), may represent long periods of reduced sedimentation on the margin. These reflectors may thus represent extensive interglacials and/or several succeeding glacial cycles of reduced ice extent. In particular, R1 may represent a substantial time of nondeposition since the units below are tilted and truncated on the shelf (Fig.6). We suggest that the differential subsidence was associated with structural elements related to the rifting and seafloor spreading in the Norwegian-Greenland Sea. Furthermore, we suggest that the halt in sedimentation was caused by reduced ice extension, and that the platform bounding Isfjorden Trough was subaerially exposed during these glacial maxima periods.

The true nature and origin of the marked depression on the outer shelf south of Isfjorden Fan (Figs.1 and 6) cannot be revealed by the limited seismic coverage. However, it appears that the downcutting was caused by grounded ice because the moraine ridge is located at the shelf edge and the uppermost strata terminate against the seafloor.

CONCLUSIONS

This study shows that ice configuration, eustatic fluctuations, and sediment supply are the main factors controlling the development of passive glaciated continental margins of the high arctic. Two primary sequences have been identified, separated by a prominent unconformity. The lower sequence is related to progradational phases during relative sea-level falls and lowstands that appear to be related to glaciations.

The regional unconformity is associated with an amplification of the glaciations that took place around 1 to 0.8 m.y. During glacial phases, sea level was lowered more than 100 m below the present level, and most of the shelf became emergent. The terrigenous material was transported to the outer shelf by ice-streams, initiating the submarine-fan development. Isfjorden Fan is divided into three units that represent different phases of fan growth. The first phase is characterized by slope-front deposition due to rapidly falling sea level. The second phase is related to minimum sea-level elevation and maximum ice extension, by which the fan development was greatly accelerated. The third phase is characterized by reduced ice extension, maximum northward migration of the fan, and shelf aggradation. The depocenter is therefore progressively shifted from the lower slope upslope to the shelf throughout fan development. We conclude that eustatic lowering of sea level during glacial maxima in combination with the presence of ice-streams reaching the shelf edge are the main factors in the development of submarine fans on high-arctic glaciated passive continental margins.

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