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On the origin and flow behavior of submarine slides on deep-sea fans along the Norwegian–Barents Sea continental margin

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Abstract Debris lobes with characteristic lengths, widths, and thickness of 30–200 km, 2–10 km, and 10–50 m, respectively, represent the main building blocks of deep-sea fans along the Norwegian–Barents Sea continental margin. Their formation is closely related to the input of clay-rich sediments to the upper continental slope by glaciers during periods of maximum ice advance. It is likely that slide release was a consequence of an instability arising from high sedimentation rates on the upper continental slope. The flow behavior of the debris lobes can be described by a Bingham flow model.

Introduction

Deep-sea fans located sea board major outlets of the Quaternary ice of Fennoscandia and the Barents Sea are mainly built up of debris lobes (Damuth 1978; Vorren et al. 1989; Vogt et al. 1993; Andersen et al. 1994; Laberg and Vorren, 1995; King et al. 1996). Similar features have also been found on other glaciated margins (Aksu and Hiscott 1992). Individual debris lobes along the Norwegian–Barents Sea margin are elongate bodies consisting of 1–50 km^3 of sediment (Table 1; Figs. 1 and 2). The debris lobes are 2–10 km in width, 10–50 m in height, and have runout distances of up to 200 km (Fig. 1b). Each lobe is well defined with a distinct termination and relatively steep lateral margins. Lobes have a tendency to split into small numbers of minor lobes near their downslope termination (Figs. 1b and 2). In addition, they are stacked successively on top of one another (Figs. 2 and 3).

The origin and rheology of submarine debris flows have been widely discussed, but are incompletely understood (Iverson and Denlinger 1987). However, according to experimental studies and modeling, downslope movement of clay-rich sediments can be characterized as a Bingham viscoplastic fluid (e.g., Johnson 1970; Norem et al. 1990; Jiang and LeBlond 1993). Thus, the main purpose of this paper is to discuss the origin and flow behavior of the debris lobes on the deep-sea fans along the Norwegian–Barents Sea margin. Flow properties have been reconstructed assuming a Bingham rheology.

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Rheology and flow behavior of debris lobes

The few sediment cores (gravity and piston cores) that sample lower parts of debris lobes show that at least the upper two thirds of these debris lobes are characterized by a uniform diamictic composition (Fig. 4; Table 1). On the Bear Island and North Sea Fans, this homogeneity is also indicated by the high-resolution seismic records (3.5 kHz), which show an acoustically homogeneous composition for the lobes (Fig. 2). We interpret the internal homogeneity of debris lobes to indicate that each lobe represents a single flow event that moved downslope without

Table 1 Fan characteristics

Fan	Isfjorden	Bear Island fan	North Sea fan
Runout distance (km)	10–30	100–200	30– >100
Width (km)	1–5	5–25	2–40
Thickness (m)	10–30	10–50	15–50
Volume (km^3)	0.5–1	10–30	10–50
Slope angle (°)	3–4	Mid slope: 0.5 Lower slope: 0.2	0.5–0.7
Grain size (μm, %)	< 2, 35–40% 2–63, 35–40% > 63, 20–30%	< 2, 30–55% 2–63, 30–50% > 63, 10–30%	< 2 30–40 2–63, 30–40 > 63, 20–30
Bulk density ($g\,cm^{-3}$)	2.0	1.8	1.8
Yield strength (see Eq. 5) (Pa)	≈ 9000 Pa ($\alpha = 3.5°$; $h_p = 15$ m)	Mid slope: ≈ 1350 ($\alpha = 0.5°$; $h_p = 20$ m) Lower slope: ≈ 1100 ($\alpha = 20°$; $h_p = 40$ m)	
References	Andersen et al. (1994) Fossen (unpublished data)	Vogt et al. (1993) Laberg and Vorren (1995) Dowdeswell and Kenyon (1995)	King et al. (1996) Sejrup (unpublished data)

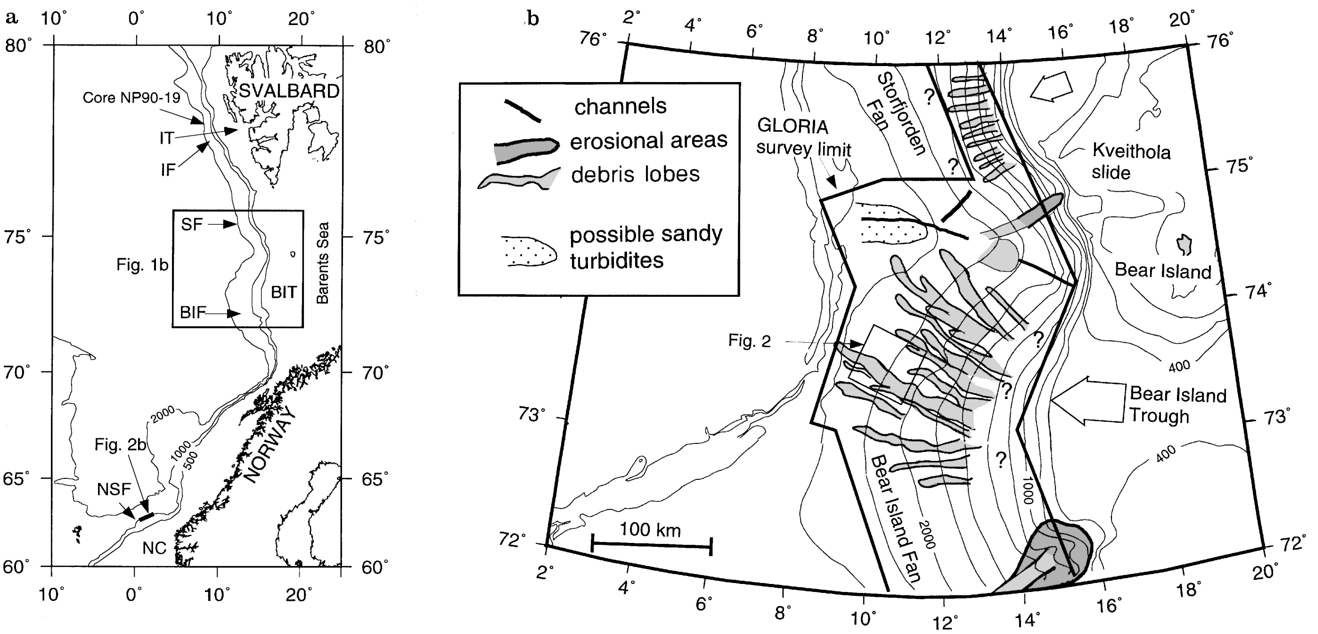


Fig. 1 a: Overview map of the Norwegian–Barents Sea continental margin. NC: Norwegian Channel, NSF: North Sea fan, BIT: Bear Island trough, BIF: Bear Island fan, SF: Storfjorden; IT: Isfjorden trough, IF: Isfjorden fan. **b:** Map of the Bear Island and Storfjorden fans showing the distribution of debris lobes as recorded by GLORIA long range side scan sonar imagery. (GLORIA data modified from Dowdeswell and Kenyon 1995)

significant internal deformation, i.e., as a block or plug. The uniform composition seems also to rule out the possibility of downslope movement due to liquefaction or reduced yield strength and viscosity after slide failure (e.g., Edgers and Karlsrud 1981). In such cases, the flow pattern is characterized by velocity gradients normal to the bed, producing a segregation of the particles wherein larger particles become concentrated in the top (Savage 1987).

The steady, horizontally uniform flow of a debris slurry behaving as a Bingham material is described by the constitutive equation

$$\tau_f = \kappa + \eta\, dv/dy \qquad (1)$$

where τ_f is shear resistance, κ is yield stress, η is dynamic viscosity, and dv/dy is the velocity gradient. Equation 1 predicts that shear stress must be above a certain value, κ, before any flow occurs. Above this value, the velocity gradient increases linearly with the shear stress acting on the sediment.

A Bingham flow consists of two flow zones: an upper plug zone in which yield stress is not exceeded and an underlying shearing zone where the shear stress exceeds the yield stress (Johnson 1970; Norem et al. 1990; Jiang and LeBlond 1993). Equation 1 describes a parabolic velocity profile in the shearing zone and no velocity gradient in the plug zone. Everything else being equal, the thickness of the plug zone increases as a function of increasing cohesion. In numerical runs by Jiang and LeBlond (1993), using representative boundary conditions and material properties, most of a debris flows consisting of cohesive sediments moved as a plug flow. In this case, where most of the debris lobes consist of sediment moving downslope without internal deformation, must of the original structure and composition is maintained, which is compatible with our field observations.

Flow thickness

In general, the thickness of the debris lobes varies between 15 and 50 m (Table 1). However, as demonstrated for the Bear Island Fan, the thickness of the lower or terminal parts of the debris lobes is roughly two times thicker than the upper and central parts of the lobes, 30–50 m versus 15–25 m, respectively (Laberg and Vorren 1995). Based on numerical modeling, Jiang and LeBlond (1993) predicted such a spatial variation for the thickness distribution of a viscoplastic or Bingham flow. According to their model, the frontal parts tends to pile due to resistance induced by the strength of the material. This is in clear contrast to

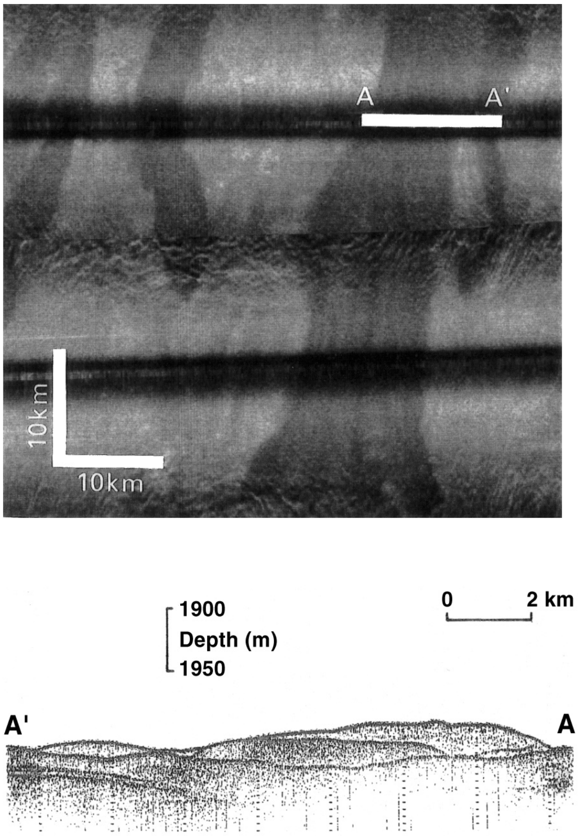
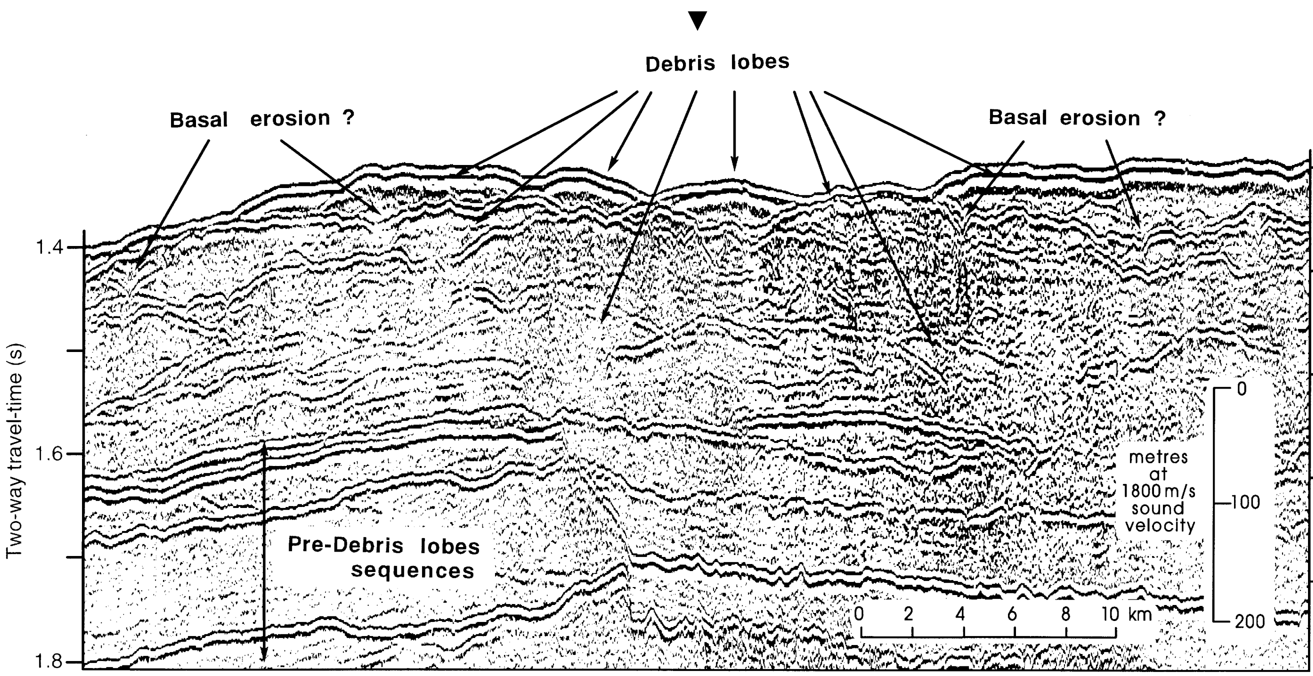


Fig. 2 GLORIA long-range side-scan sonar imagery and 3.5-kHz echosounder data showing distribution and a cross section of debris flows on the Bear Island Fan. Note the stacking of the individual debris flows (for location see Fig. 1). (Modified from Dowdeswell and Kenyon 1995)

Fig. 3 Seismic line (air gun) across the North Sea fan at about the 1000-m water depth contour showing the distribution of debris flows in the upper part of the sediment sequence. Note the possible signs of erosion at the bottom of the individual debris lobes. For location see Fig. 1a. In the North Sea fan, the debris lobes are concentrated in the upper part of the fan sediments, above 0.5 s (TWT). (Modified from King et al. 1996)



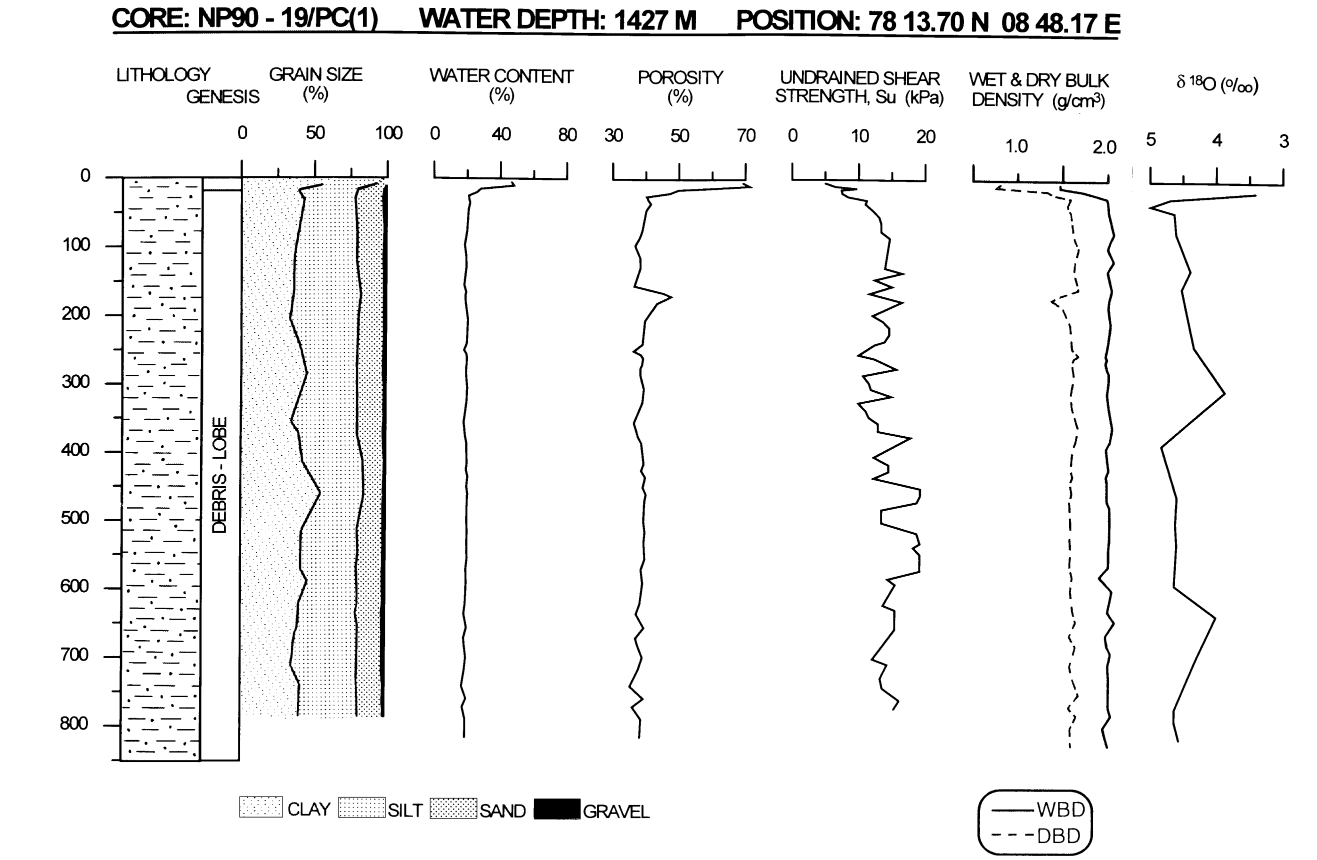


Fig. 4 Diagram showing lithologies and physical properties of sediments from a core in a debris lobe on the Isfjorden fan. For location see Fig. 1a

a purely viscous flow, which shows much less of a tendency to pile up in front (Jiang and LeBlond (1993).

A minimum critical thickness of a debris flow can be estimated from Eq. 1 using experimental data from Locat and Demers (1988). The yield strength, κ, includes both cohesion, c, and Coulomb friction terms:

$$\kappa = c + (\rho' - \Delta u \rho_w) g y \tan\phi \cos\alpha \quad (2)$$

where ρ' is the average submerged density of plug, Δu is the excess pore pressure represented as a ratio of hydrostatic pressure, ρ_w is the density of water, g is the acceleration due to gravity, y is the depth below the top, α is the slope angle, and $\tan\phi$ is the internal angle of friction.

In a steady, horizontally uniform, gravity-driven flow, the shear stress acting on the material due to gravity increases linearly with depth according to

$$\tau = \rho' g h \sin\alpha \quad (3)$$

Combining Eqs. 3 and 2, an expression for the minimum depth, h_p, necessary for flow can be found (e.g., Hampton 1972)

$$h_p = \frac{c}{\rho' g \sin\alpha - (\rho' - \Delta u \rho_w) g \cos\alpha \tan\phi} \quad (4)$$

According to Locat and Demers (1988), the yield strength for clays with a liquidity index between 2 and 3, which may be comparable to the clays found on the Bear Island fan, is between 50 and 500 Pa. Assuming sediment composition of the debris lobes with no Coulomb friction on a 0.5° incline, this shear strength translates into a critical thickness between 1.4 and 14 m. This range of thickness is consistent with deposits observed on the middle parts of the Bear Island fan.

Runout distance and yield strength

The runout distance of a debris flow depends on its effective yield strength and viscosity. Johnson (1970) outlined a simplified field method for estimating the yield strength of a Bingham material. According to Johnson (1970), the yield strength, κ, of a viscoplastic material equals the basal shear stress, τ_b, when the flow comes to its stop

$$\kappa = \tau_b = \rho' g h_p \sin\alpha \quad (5)$$

where h_p is both plug and deposit thickness. This method is used here to examine the range in properties of debris lobes found along the Norwegian–Barents Sea margin. As shown in Table 1, the runout distance is strongly reduced from the Bear Island and North Sea Fans to the Isfjorden Fan, even though the slope angle increases from less than 1° to 4°.

Inserting data from the Isfjorden and Bear Island Fans into Eq. 5, the characteristic yield strength κ of the Isfjorden debris lobes is found to be almost an order of magnitude larger than that of the Bear Island lobes, 9000 Pa and 1100 Pa, respectively (Table 1). It should be noted that calculation of yield strength of the Bear Island lobes by this method shows comparable values on the lower as well as on the middle parts of the fan (Table 1). The typical runout distance for debris flows on the Storfjorden Fan is also relatively short (Fig. 1b), indicating a relatively high yield strength. We hypothesize that the differences in yield strengths are related to the differences in physical properties of the source materials. Support for this idea is found in the difference in the acoustic properties of the deposits. Although the grain-size distribution for all of the debris lobes is almost identical, the debris lobes on Isfjorden and Storfjorden are acoustically opaque, while those on the Bear Island and North Sea Fans are acoustically transparent with regard to the same acoustic sources to high-resolution acoustic systems (3.5-kHz echosounder and deep-towed boomer Huntec). The only measurable difference between Isfjorden and Bear Island Fan deposits is wet bulk density: 2.0 $g\,cm^{-3}$ and 1.8 $g\,cm^{-3}$, respectively. It is well known that only minor changes (2–4%) in sediment concentration may produce order of magnitude variations in yield strength (Major and Pierson 1992). Thus, the variations in yield strength and acoustic properties may be due to the observed 10% difference in bulk density. The reason for these differences is not yet known.

Lower boundary of debris lobes and possible sediment entrainment

The weight of a debris lobes generates an abrupt, undrained loading on the seabed when the sediment is moving down. For fine-grained impermeable materials, this undrained loading may generate high pore pressures, reducing the strength of the bed and its resistance to erosion (Sassa 1988). However, if the seabed consists of coarse-grained particles, where excess pore pressures are released immediately, the resistance to erosion remains high. The process of erosion and entrainment therefore is thought to reflect properties of the seabed, rather than behavior of the overriding debris lobe.

High-resolution seismic data from the North Sea Fan show signs of erosion at the base of the debris lobes (Fig. 3). Hiscott and Aksu (1994) also showed that the snouts of some debris lobes have erosional power and that a remoulded zone occurs beneath some debris lobes. A somewhat similar behavior is also documented by Vogt et al. (1993) and Laberg and Vorren (1995). Although the processes occurring at the base of debris lobes are not well understood, we suggest that erosion most likely occurs and that this process is dependent on the liquefaction potential and erosional strength of the original sea floor.

Release mechanisms

Debris lobes are not present on the upper 20–30 km of the continental slope. This part of the slope is considered to be the source area for the debris lobes, although thorough acoustic investigations (3.5-kHz echosounder, sparker, air gun, and GLORIA imagery) of this zone have failed to reveal distinct scarps corresponding to the sediment volume involved in the debris lobes. In general, the source area is characterized by a hummocky surface and with very minor slide scars. The lack of large scarps may be due to all deposited sediment having been released along old compacted seabed surfaces. Alternatively, later retrogressive slides could hide the original scars, or special flow conditions could increase sedimentation in the scarp area relative to that in the neighboring areas.

In water depths below the influence of tidal changes and wave loading, rapid sedimentation is an important factor reducing sediment strength (increased pore pressure) as well as increasing downslope stress (Hampton et al. 1996). The production of seepage of shallow gas may also be a major factor causing instability, particularly in high-latitude areas (Kayen and Lee 1991). Earthquakes may cause sediment failures both by applying downslope acceleration and by increasing pore pressures (Hampton et al. 1996). Earthquakes along the passive Norwegian–Barents Sea are typically of magnitude 5 or less (Bungum et al. 1991), although larger earthquakes of magnitude of 6.0 and 6.5 may occur over a time scale of 10,000 years (Bugge 1983). The frequent, but minor, earthquakes along the Norwegian–Barents Sea margin increase the downslope gravity forcing by a few percent (Bugge 1983), so such earthquakes are suggested to have only a minor impact on slope stability. On the other hand, the larger, and much less frequent earthquakes, may represent an important triggering mechanism for the large submarine slides along the Norwegian margin (Bugge 1983). The large number of debris flows found within anyone depositional unit is not consistent with an infrequent triggering mechanism. For example, a minimum of 40 debris lobes were released during a period of approximately 3000 years during the last glacial maximum. Such a high number of events seems to indicate a condition of nearly constant sediment delivery to the margin and subsequent sediment failure. Thus, reduction in sediment strength by high sediment input rates seems to act as the main release factor in the study area.

Discussion

Geotechnical analyses suggest that the formation of debris lobes on deep-sea fans along the Norwegian–Barents Sea margin are strongly related to high input rates for clay-rich, cohesive sediments to the shelf edge. Such conditions may have existed during periods of maximum glaciation when the ice front advanced to the shelf edge (Fig. 5).

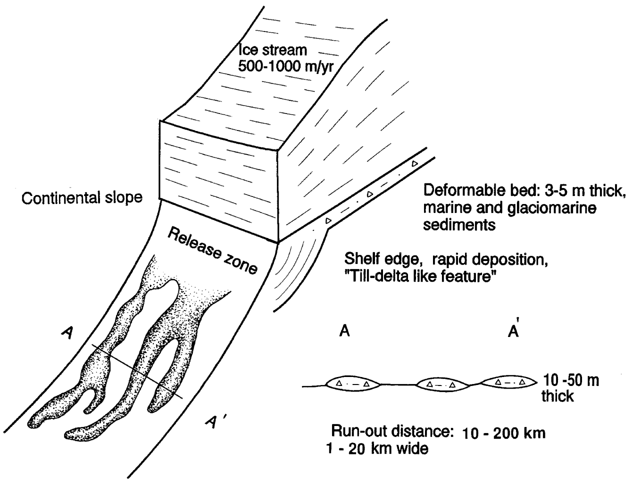


Fig. 5 Conceptual model illustrating: (1) the sediment dynamics beneath and in front of an ice stream draining the major troughs on the Norwegian continental margin, and (2) the geometry of the debris lobes on the high-latitude fans

Sediments, mainly of glaciomarine origin, were brought to the shelf edge in a subglacial layer of deforming drift and deposited at high rates on the shelf edge/upper slope (Sættem et al. 1992; Hooke and Elverhøi 1994). This sediment, with a water content up to 40%, is suggested to have been deposited in "till-delta"-like features in front of the more active parts of the glacier front (Alley et al. 1989; Laberg and Vorren 1995; King et al. 1996). Thus, soft sediments may be piled up at the shelf edge without being brought into suspension (Fig. 5). Some sediments may have also been deposited at sites very close to the ice front by suspension settling from outflowing meltwater and via englacial transport. However, recent calculations of subglacial transport by the Weichselian ice masses on the Svalbard margin indicate that deposition from deforming till represents by far the most important sediment transport mechanism (Hooke and Elverhøi 1994). A similar situation is also envisaged for both the Bear Island and North Sea Fans.

Our model suggests that debris lobes were released during periods of maximum glaciation when the ice front was located at the shelf edge. This is supported by ^{14}C dates and oxygen isotope analyses from the uppermost debris lobes on the fans along the Norwegian–Barents Sea margin, which contain diamictons from the last glacial maximum, while fine-grained sediments blanketing the debris lobes are younger than 15 ka (Laberg and Vorren, 1995; Elverhøi et al. 1995; King et al. 1996).

Comparison of the flow pattern of the debris lobes derived from volcanigenic and glacigenic sources show several similarities. As discussed for the Norwegian–Barents Sea margin, the homogeneous nature of the lobes suggests that they are released in an instantaneous event and move downslope as a plug flow. A similar behavior is assumed by Masson et al. (1992) to prevail for the debris lobes off the Canary Islands and by Moore et al. (1992) for debris lobes off Hawaii. Thus, a Bingham-like flow pattern seems applicable for all of these settings. However, while the fine-grained composition of volcanic slides results from the very fine-grained composition of the ash deposits, on high latitude fans this fine-grained character is due to the input of glacially reworked glaciomarine sediments (Fig. 5).

Conclusions

The main result of the present study is the identification of a close relationship between the sedimentation process on the shelf edge and the formation of debris lobes on the deep sea fans along the Norwegian–Barents Sea margin. During periods of maximum glaciation when the ice front was located at the shelf edge, soft clay-rich sediments were deposited at high rates. Most likely, slope failure was caused by rapid sedimentation and subsequent reduced effective stress combined with increased gravity loading. Due to the cohesive nature of the slope-forming material, sediment is thought to have moved downslope as a plug flow, crudely characterized as a Bingham fluid. Significant variations in runout between debris lobes record variations in the yield strengths of the sediments.

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References

Aksu AE and Hiscott RN (1992) Shingled Quaternary debris flow bases on the north-east Newfoundland slope. Sedimentology 39: 193–206

Alley RB, Blankenship DD, Rooney ST, and Bentley CR (1989) Sedimentation beneath ice shelves – the view from ice stream B. Marine Geology 85: 101–120

Andersen ES, Solheim A, and Elverhøi A (1994) Development of a glaciated Arctic continental margin: exemplified by the western margin of Svalbard. In: Thurston DK and Fujita K (Eds.), Proceedings, International Conference on Arctic Margins, 1992 (ICAM). Department of the Interior, Minerals Management Service, Alaska Outer Continental Shelf Region, pp 155–160

Bugge T (1983) Submarine slides on the Norwegian continental margin, with special emphasis on the Storegga area. Continental Shelf Institute, Norway Publication 110, 152 pp

Bungum H, Alsaker A, Kvamme LB, and Hansen RA (1991) Seismicity and seismotectonics of Norway and nearby continental shelf areas. Journal of Geophysical Research 96(B2): 2249–2265

Damuth JE (1978) Echo character of the Norwegian–Greenland Sea: relationship to Quaternary sedimentation. Marine Geology 28: 1–36

Dowdeswell JA and Kenyon NH (1995) Large-scale sedimentation on glaciated passive continental margin: the Polar North Atlantic: Long-range side-scan sonar investigations of the Polar North Atlantic: patterns and processes and sedimentation on a glaciated passive margin. Cruise report. Aberystwyth: Centre for Glaciology, University of Wales, Report 95–01, 50 pp

Edgers L and Karlsrud K (1981) Viscous analysis of submarine flows. Oslo: Norwegian Geotechnical Institute Publication 143: 1–10

Elverhøi A, Andersen ES, Dokken T, Hebbeln D, Spielhagen R, Svendsen JI, Sørflaten M, Rørnes A, Hald M, and Forsberg CF (1995) The growth and decay of the Late Weichselian ice sheet in western Svalbard and adjacent areas based on provenance studies of marine sediments. Quaternary Research 44: 303–316

Hiscott RN, and Aksu AE (1994) Submarine debris flows and continental evolution in front of Quaternary ice sheets, Baffin Bay, Canadian Arctic. American Association of Petroleum Geologists Bulletin 78: 445–460

Hampton MA (1972) The role of subaqueous debris flow in generating turbidity currents. Journal of Sedimentary Petrology 42: 775–793

Hampton MA, Lee HJ, and Locat J (1996) Submarine landslides. Reviews of Geophysics 34: 33–59

Hooke RL and Elverhøi A (1994) Sediment flux from a fjord during glacial periods. Isfjorden, Spitsbergen. Global and Planetary Change 12: 237–249

Iverson RM and Denlinger RP (1987) The physics of debris flows – a conceptual assessment. In: Beschta RL, Blinn T, Grant GE, Ice GG, and Swanson FJ (Eds.), Erosion and Sedimentation in the Pacific Rim. Corvallis, Oregon: International Association of Hydrological Science Publication 165: 155–165

Jiang L and LeBlond PH (1993) Numerical modelling of an underwater Bingham plastic mudslide and the waves which it generates. Journal of Geophysical Research 98(C6): 10,303–10,317

Johnson AM (1970) Physical Processes in Geology. San Francisco: Freeman, Cooper & Company, 557 pp

Kayen RE and Lee HJ (1991) Pleistocene slope instability of gas hydrate-laden sediment on the Beaufort Sea margin. Marine Geotechnology 10: 125–141

King E, Sejrup HP, Haflidason H, Elverhøi A, and Aarseth I (1996) Quaternary seismic stratigraphy of the North Sea Fan: Glacially-fed gravity flow aprons, hemipelagic sedimentation, and large submarine slides. Marine Geology 130: 293–316

Laberg JS and Vorren TO (1995) Late Weichselian submarine debris flow deposits on the Bear Island Trough Mouth Fan. Marine Geology 127: 45–72

Locat J and Demers D (1988) Viscosity, yield stress, remoulded shear strength, and liquidity index relationships for sensitive clays. Canadian Geotechnology Journal 25: 799–806

Major JJ, and Pierson TC (1992) Debris flow rheology: experimental analysis of fine-grained slurries. Water Resources Research 28: 841–857

Masson DG, Huggett QJ, Weaver PPE, Brunsden D, and Kidd RB (1992) The Saharan and Canary debris flows, offshore northwest Africa. Landslide News 6: 9–12

Moore JG, Normark WR, and Gutmacher CE (1992) Major landslides on the submarine flanks of Mauna Loa Volcano, Hawaii. Landslide News 6: 13–16

Norem H, Locat J, and Schieldrop B (1990) An approach to the physics and the modelling of submarine flowslides. Marine Geotechnology 9: 93–111

Sassa K (1988) Geotechnical model for the motion of landslides. In: Bonnard C (Ed.), Proceedings, Fifth International Symposium on Landslides, Lausanne, Switzerland 1: 37–56

Savage SB (1987) Interparticle percolation and segregation in granular materials: a review. In: Selvadurai APS (Ed.), Developments in Engineering Mechanics. Amsterdam: Elsevier, 347–363

Sættem J, Poole DAR, Ellingsen L, and Sejrup HP (1992) Glacial geology of outer Bjørnøyrenna, southwestern Barents Sea. Marine Geology 103: 15–51

Vogt PR, Crane K, and Sundvor E (1993) Glacigenic mudflows on the Bear Island submarine fan. EOS 74: 449, 452–453

Vorren TO, Lebesbye E, Andreassen K, and Larsen K-B (1989) Glacigenic sedimentation on a passive continental margin as exemplified by the Barents Sea. In: Powell RD and Elverhøi A (Eds.), Modern Glaciomarine Environments: Glacial and Marine Controls of Modern Lithofacies and Biofacies. Marine Geology 85: 251–272