DEEP ICE SCOUR AND MASS-WASTING FEATURES ON THE NORTHERN SVALBARD INSULAR SHELF AND SLOPE

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ABSTRACT

Recent closely spaced, single-beam bathymetric investigations on the northern slope of the northwestern Svalbard insular platform have revealed the presence of a series of nearly parallel, ice-related plowmarks in the seafloor and a complex of nested slumps at the head of a sharp bathymetric embayment in the continental margin. Presumably, the gouges are the result of plowing by icebergs and ice-floe keels grounded between the island of Spitsbergen and Yermak Plateau at a lower sea-level stand during the last 10,000 to 13,000 years.

Bathymetric data and SeaMARC II sonargraphs collected north of Spitsbergen in the vicinity of the northern end of Hinlopen Strait indicate massive slumping has occurred and has selectively eroded back into the continental margin. The slumping processes generated massive gravity slides into the Malene Bukta (Malene Bay) submarine embayment that opens into the Barents Abyssal Plain. They almost certainly occurred during the last 100,000 years (possibly since retreat of Weichselian glaciers), because no major Quaternary sediment fans or features appear to obscure the form of the slump scarps. Extending downslope in water depths from 160 to greater than 2,000 m, the slumps have excavated about 220 km^3 of sediments.

INTRODUCTION

Mass-wasting mechanisms are important factors in the disruption and redistribution of sediments. Sediments normally are subjected to processes of winnowing that grades them into different grain sizes and materials, thus making them more "mature." One of the main attributes of mass wasting is that the normal primary sequence of sedimentation initially generated can be reversed or substantially altered in character by subsequent reworking by wind and water.

Mass redistribution of sediments on the present Arctic Ocean-bounded insular and continental shelves and slopes commonly occurs at lowered sea levels through the action and movement of ice in glaciers and ice caps, and by slumping of the shelf sediments. At the present time, it also occurs by floating ice that becomes grounded, or acts as a source of ice-rafted sediment and debris. For example, in waters normally deeper than 10 m on the Arctic Ocean portion of the North American continental shelf, ice gouging appears to be the major mechanism influencing sediment dynamics (Toimil, 1978; Reimnitz and Barnes, 1974; Brooks, 1974; Kovacs, 1972; see also Goodwin et al., 1985).

ICE GOUGING ON THE NORTHERN SPITSBERGEN CONTINENTAL SHELF

At several intervals during the Pleistocene, ice caps, glaciers, and sea ice were much more extensive in polar regions. As a result, a complete range of very large to very small ice-related erosional features dominate landforms in polar regions today (Syvitski et al., 1987). These landforms range from major subaerial fjords to small, submerged iceberg plowmarks.

Both glaciers calving into the sea and floating sea ice constitute large ice masses in polar oceans. Many icebergs derived from glaciers are commonly in excess of several hundred meters across, and of equal thickness. Sea ice is much thinner, but extensive ice keels from beneath multiyear, pressure-ridged sea ice are common and often reach more than 30 m below the average sea-ice base (Wadhams, 1986), where they and icebergs commonly get grounded on continental shelves (Solheim and Pfirman, 1986). Because floating ice moves under the influence of wind, tide, and surface currents, and because the mass and consequent momentum of icebergs is so great, grounded ice masses can gouge or "plow" seafloor sediments, forming distinct and normally linear furrows.

Although sea-ice gouges from moving ice have been recognized as far south as the Irish continental margin (Kenyon, 1987), currents and subsequent sedimentation under the influence of currents have obliterated many of the fine ice-gouged features on the continental shelves. Ice gouges on the Norwegian continental margin have been finely mapped using multibeam echosounders. Some of these mapping efforts have clearly shown the processes whereby ice gouges have been formed, and then nearly obliterated or overprinted by subsequent iceberg-reworking and northward-current movements and deposition of sediments (Mølbach, pers. commun., 1990). Because ice grounding has, indeed, become recognized as an almost ubiquitous feature on continental shelves in glaciated regions (Reimnitz and Barnes, 1974), understanding of the process of ice-driven mass wasting and the description of its morphological expression is best carried out in regions where ice grounding has only recently ceased, or is still in progress. Further study on the upper northern Svalbard shelf is necessary to determine the full extent of ice gouging.

One location where ice gouging presently is in progress is north of Spitsbergen (Fig.1, after Cherkis et al., 1991), an area that is free of solid pack ice for much of each year, and a locale of active ice movements (Wadhams, 1986; Hibler, 1989). In 1987, Norges Sjøkartverk conducted a precisely navigated, hydrographic survey over the northwestern outer continental margin off Spitsbergen (Fig.2) as part of an effort to ensure safe navigation and passage over an unmapped area of the shelf zone. As a spinoff of this survey, new morphology was documented. Subsequent acoustic-imaging of the sea floor were made by deploying SeaMARC II sidescan sonar from R/V *Håkon Mosby* in 1989 and 1990 (Sundvor et al., 1990). The acoustic images displayed classical signatures of plowmarks on the southern flank of Yermak Plateau in depths of water presently greater than 550 m (Vogt et al., 1991, Fig.3). These were undoubtedly excavated during a Pleistocene low stand of sea level, but the episode of ice maxima presently is unknown.

Predominant northeast trends of the plowmarks clearly demonstrate that most of the icebergs grounded in this area parallel to the northern Spitsbergen margin. The hydrographic-survey data also clearly show the existence of plowmarks in parallel rows on the Spitsbergen insular shelf (Fig.3), in depths approaching and exceeding 200 m. Although presently inconclusive, it is suggested that ice keels alternately grounded and floated, judging by the interruptions of the deepest depths within the gouges. The directions of the gouges were dominated by the West Spitsbergen current, as seen by the parallelism of both the gouges and the current motion. By gridding the hydrographic data and combining it with bathymetric information collected earlier, we were able to portray a low-relief, three-dimensional model of the area (Fig.4). The gridded model clearly shows the parallel gouge patterns in the surficial sediments and provides a basis for future studies in the region.

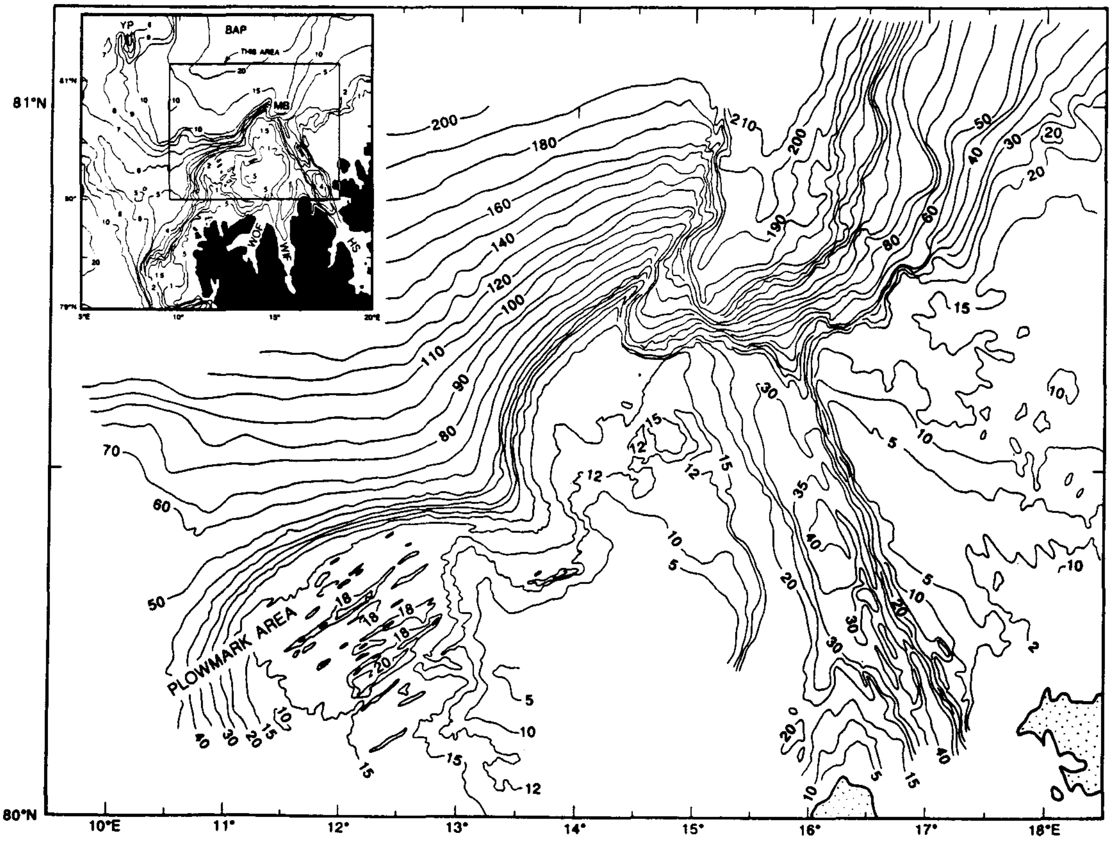


Fig.1. Location map of the area to the north of Svalbard (after Cherkis et al., 1991). Isobaths in inset are in uncorrected meters x 100. Isobaths in main map are in uncorrected meters x 10. In the inset, BAP=Barents Abyssal Plain; HS=Hinlopen Strait; MB=Malene Bukta; WIF=Wijdefjorden; WOF=Woodfjorden; YP=Yermak Plateau.

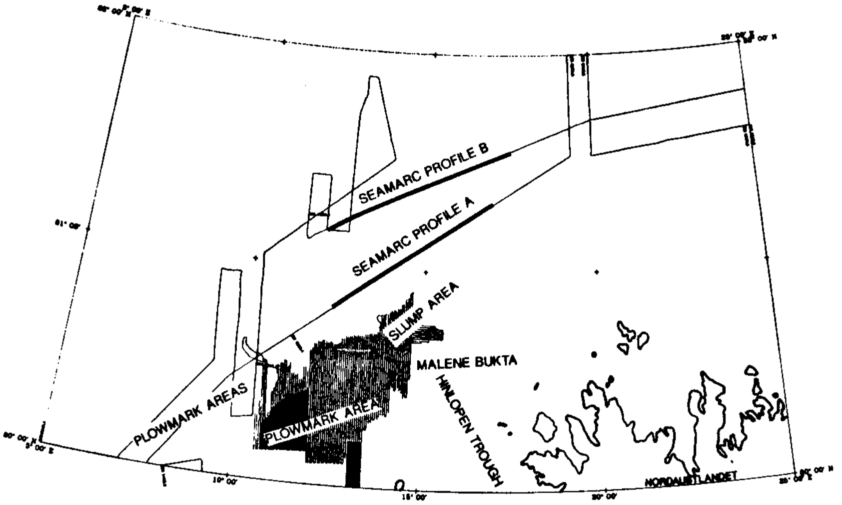


Fig.2. Trackline plot of data coverage. Surveys by Norges Sjøkartverk: M/S Lance, 1987. Reconnaissance lines by R/V Håkon Mosby: 1990. SeaMARC II profiles A and B refer to locations of sonographs in Fig.6.

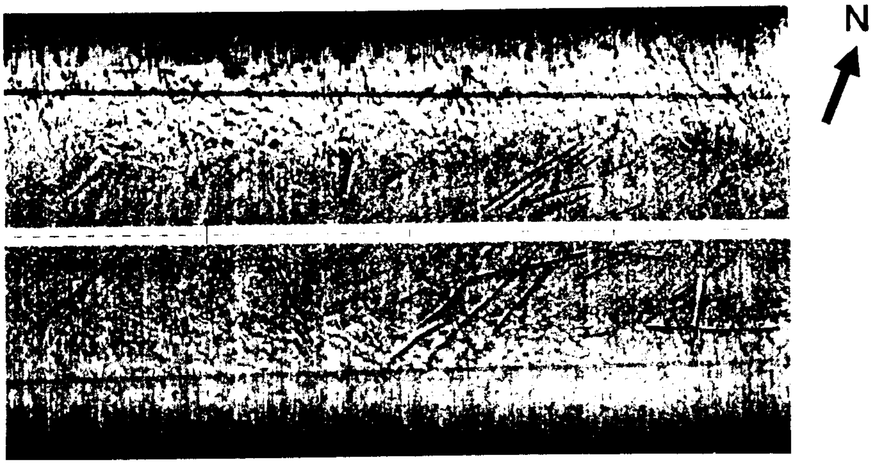


Fig.3. Sonograph of basin on south flank of Yermak Plateau. Black lines indicate iceberg plowmarks, which are observed at depths to 600 m, and possibly to 1,000 m. Predominant north-easterly trends show iceberg motion paralleled northern Spitsbergen margin.

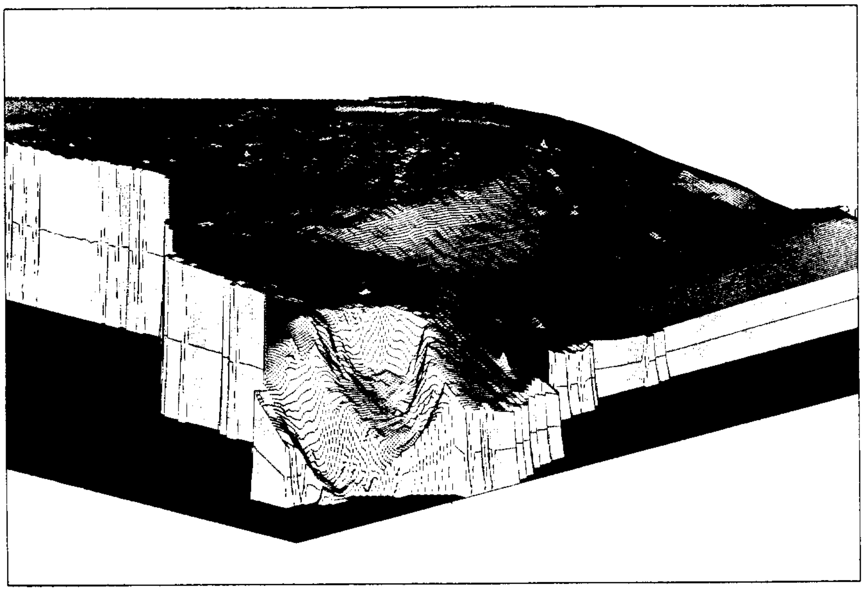


Fig.4. Perspective view looking from northwest to southeast showing ice gouges on upper shelf beyond slump canyons. Partial data set only. Note that isolated conical shapes are unedited bad data-point artifacts.

SLUMPING ON THE NORTHERN SPITSBERGEN CONTINENTAL MARGIN

Where sediments are subject to mass movement, they commonly become mixed. An important mechanism for mass reworking of sediments is slumping at outer continental margins, which results in massive downslope gravity flows. For example, individual slump sites in the Storegga region of the passive Norwegian margin are responsible for displacing over 50,000 km^3 of sediment from the upper slope and shelf into the abyssal depths of the Norway Basin (Bugge, 1983; Bugge et al., 1987), a distance of over 800 km, while modifying the first-order shape of the outer continental margin (Perry et al., 1980, 1986). Along the U.S. Atlantic margin, mass wasting and subsequent transport and redeposition of sediments by episodic turbidity currents are relatively more important than sedimentation (Pratson and Laine, 1989).

The irregular continental margin north of Svalbard contains a number of sharp reentrants on the order of 8 to 15 km. The margins of the reentrants are approximately parallel with projected continuations of major northwest-southeast faults marking terrane boundaries in Svalbard (Ohta et al., 1989). This suggests that at least some of the reentrants may be controlled by the position of older continental crustal features. The most prominent feature reentering the continental margin north of the Svalbard archipelago is the northeast-trending Malene Bukta depression, a submarine continuation of the Barents Abyssal Plain that lies to the east of Yermak Plateau along the north Svalbard margin (Fig.1).

The slump erosion described here occurs at the continental slope north of Spitsbergen, linking Malene Bukta with the northward termination of a bathymetric depression extending north-northwest from Hinlopen Strait. The erosional trough on the shelf has an asymmetrical U-shaped profile, and probably was formed by glacial action predominantly during the Weichselian period, when sea level was about 100 to 150 m lower than it is at present. Three superficially similar, prominent bathymetric depressions in the western Spitsbergen margin can be traced to fjords on Spitsbergen and are thus probably submerged continuations of the western Spitsbergen fjords. These troughs cross geological structures trending north-south (Faleide, 1990; Siggerud et al., 1981) and are, therefore, unlikely to be glacial excavations of existing geological features.

Nested slump scars have been recognized by our investigations at the edge of the continental shelf north of Svalbard (Cherkis et al., 1989). Their occurrence is unusual because the sharp bathymetric feature (Malene Bukta) that they are at the head of may have been formed or at least have been significantly accentuated by headward slump erosion. Repeated slumping is taking place around particular locations, rather than broadly along the continental margin, as is the case with the U.S. east coast (Embley and Jacobi, 1986) and the southeastern coast of Australia (Jenkins and Keene, 1992). While repetitive slumping has been documented elsewhere--e.g., along the southwestern Norwegian continental margin, where at least three successive major slumps have been focused on the same restricted generation area (Bugge, 1983; Bugge et al., 1987; Jansen et al., 1987)--this is the first discussion of this type of feature on the Arctic Ocean margin.

Two sites west of 16° E. longitude show complex slump development (Fig.5). These could be either multiple events or a complex single event. The main site

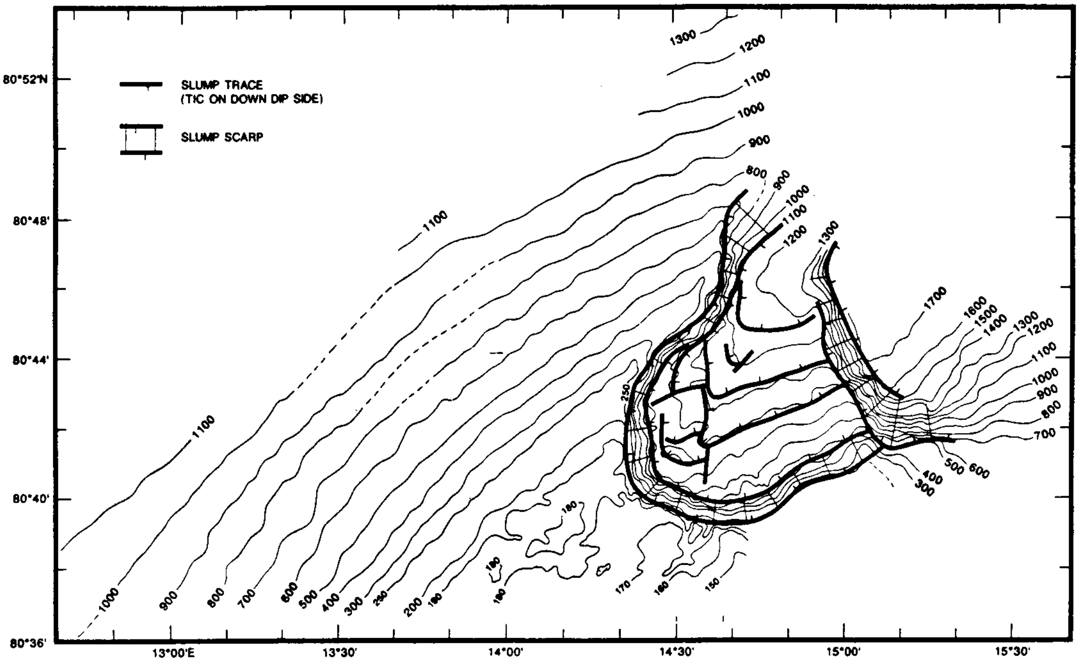
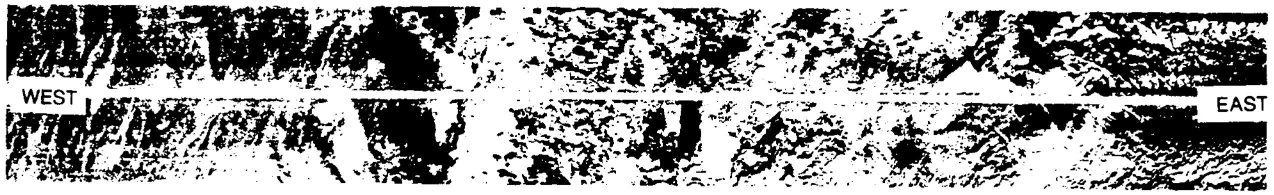
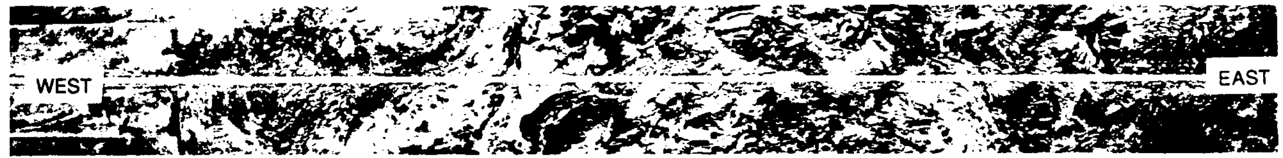


Fig.5. Interpreted slip traces of nested slumps (heavy lines). Combination of head, side, and footwall faults form the slump canyons; morphology of slope immediately beneath normal erosional lip suggests a small deltaic fan but might also be the result of slope creep. Isobaths are in uncorrected meters.



Upslope view



Downslope view

Fig.6. SeaMARC II sonographs across slump area. Upper slope crossing (upslope view) displays small slump blocks and indications of initiation of other slumps in the region. Lower (deeper) section (downslope view) displays much larger slump blocks and greater area of mass wasting, indicating presence of several slumps consolidating into one area.

shows at least three phases of slump development in the southwest part of the bathymetric embayment; slumps to the east do not show a clear superposition. Morphology suggests that an early main event formed slump scarps along the northwest and southeast walls. The southeast wall of this slump canyon has been removed by subsequent slumping in which a high-level slump was superseded by a lower level slump that formed a clean scarp in the high-level debris. It is possible that the high-level slumping occurred at the same time as, or earlier than, the lowest main slump; but because of the development of the midlevel slump, relationships between the one-time southwest wall of the lowest slump canyon and the debris train from the highest level canyon have been obliterated. Sonographs (Figs.6A, 6B) collected aboard the R/V *Håkon Mosby* in 1989 show clear evidence of slumping: small slump blocks are seen in the upper portion, and extremely large, 2- to 4-km-long blocks are deposited on the lower slope. We calculate a total of at least 220 km^3 of sediment would appear to have been excavated, in order to account for the form of the main bathymetric embayment.

High rates of sediment deposition and overloading, with the formation of oversteep slopes, commonly have been used to explain submarine slumping. It has been suggested (Aagaard, pers. commun., 1990) that the West Svalbard current dissipates in this area, which would entrain sediments. Both processes probably contributed to the glacio-marine sediment overburden on the edge of the continental shelf that eventually slumped into the deep Arctic basin in the vicinity of Malene Bukta. However, the bathymetrically shallowest of the nested slumps does not follow the drainage line along which the overloading could be postulated; slump erosion at the head of the embayment extends for several kilometers both east and west. Thus, sediment overloading alone is unlikely to be a controlling factor in slump generation. In fact, bathymetrically low areas west of Spitsbergen show sedimentary accretionary deltas and narrow current erosional channels along the continental slope at the western ends of submarine fjords (Siggerud et al., 1981). A high rate of sediment deposition, which normally would be associated with high sediment loading, appears to be associated with prograding of the shelf edge, rather than with the development of selective sites of slump erosion. Searches of the National Earthquake Information Center database yielded several shallow-focus, low-magnitude seismic events within 100 km of the feature, but it is unknown whether or not any of these assisted in triggering the slump.

The smoother continental margin to the southwest shows no slump generation comparable with that seen at the head of Hinlopen Trough, but a minor embayment occurring at about 80°15' N., 13°30' E. (Fig.1) has two possible minor slump scarps at about 125 m and 150 m, with smaller possible scarps located farther downslope in the small embayment. The slope is reversed below these scarps, with dips generally tilted gently back toward the continental slope rather than into the ocean basin. These slumps do not appear to have mobilized very much sediment. This smaller embayment, which we thus also see as a feature that probably has been formed by less dramatic slump erosion, is eroding into a bathymetric high that may represent a remnant of a shelf delta derived from Wijdefjorden and Woodfjorden. However, the bathymetry presently is unclear because of an extremely sparse data set in the inshore area. Slumping here probably is dependent on sediment loading.

Whereas slope steepening clearly occurs with respect to the slumping at the toe of the Hinlopen trough, a decrease in slope gradient appears to occur in the southwestern embayment. Furthermore, slumping does not appear to be any more common in the steep slope gradients west of the main slump canyons than in the more gentle lower slopes. Apart from the two main slump sites, quite different slope gradients at the same water depth do not show a preferential relationship between steep slopes and slump generation. Along this part of the Arctic Ocean margin, we cannot relate initial steep-slope gradients directly to slumping; once slump scarps develop, however, repeated slumping tends to maintain steep upper slope gradients.

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