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Interactions of River Discharge with Sea Ice in Proximity of Arctic Deltas: A Review

by Erk Reimnitz[1]

Summary: The most important effect an ice cover has on river discharge is forcing water to spread horizontally over very wide sheets of smooth seasonal ice before draining vertically at flow vortices (strudel) into the sea. These strudel excavate craters as deep as 6 m on the seafloor, thereby reworking deltaic strata. Most drainage occurs at and seaward of the 2-m isobath through floating fast ice, and results in supercooling and underwater ice formation. This frazil evidently scavenges and disperses scour-excavation products from strudel, as such sediments are not found in surrounding levees. Kilometer-wide sheets of bottom-fast ice landward of the 2-m isobath stay submerged under flood waters for about one week, evidently by suction rather than „ice bond-ing" with the bed. While the bottom-fast ice finally rises, strudel also form here, although most water probably is introduced into the widening gap between the sea bed and rising fast ice by horizontal intake from the sea. Flood-ing of vast regions of bottom-fast ice also occurs during winter storm surges, when depth of water on the ice should correspond to the height of the storm surge (± 1m). Water import- and export under the ice as much as 2 m thick may cause the very wide 2-m ramps characteristic for arctic deltas. Deposition of alluvial sand on top of the fast ice off river mouths during spring peak river discharge is not well documented, and may not occur at all. There is no evidence that any spring deposits of alluvial sand are exported from deltas by ice rafting. Anchor ice carrying sediment forms on the beds of arctic rivers, but no sediment export by such ice has been observed.

Zusammenfassung: Die wichtigste Rolle des Festeises an arktischen Flussmündungen ist, dass es zur Verteilung des Süßwassers über große Areale führt, bevor das Wasser durch Löcher in der Eisdecke vertikal in das darunter liegende Meerwasser abfließen kann (Strudel). Diese Strudel erodieren bis zu 6 m tiefe Krater, die ein Zerwühlen der deltaischen Ablagerungen bewirken. Die meisten Strudel bilden sich entlang der 2-m-Tiefenlinie und seewärts in schwimmendem Eis, wo das Mischen von Süß- und Salzwasser zur Unterkühlung und zur Bildung von Unterwassereis führt. Dieses „Frazil"-Eis sammelt die vom Boden erodierten Sedimentpartikel und entfernt sie vom Krater, so dass keine entsprechenden Sedimentwälle um die Krater herum gefunden werden können. Auf kilometerweiten Flächen, in denen die Wassertiefe geringer als die Dicke des Eises ist, bleibt dieses noch für eine Woche unter dem darüber strömenden Flutwasser am Boden haften, wobei es jedoch nicht angefroren ist. Wenn dieses Eis sich schließlich an die Oberfläche hebt, bilden sich auch hier Strudel. Allerdings scheint das Wasser hauptsächlich von seewärts in die sich dehnende Spalte zwischen Sediment und Eis zu laufen. Weite Flächen des auf der Rampe liegenden Eises werden auch bei Sturmfluten im Winter überschwemmt, wobei die Wassertiefe über dem Eis der Höhe der Flut entsprechen sollte (±1m). Der Wasserzufluss und -abfluss unter dem Eis könnte für die Bildung der weiten deltaischen Rampen der Arktis verantwortlich sein. Alluvische Ablagerungen der Flüsse werden nicht durch Eistransport in das Arktische Becken gebracht, eine Ablagerung von Flusssanden auf dem Festeis konnte noch nie dokumentiert werden. Ankereis mit anhaftenden Sedimenten bildet sich zwar entlang der Flüsse, wird jedoch nicht in das Meer abtransportiert.

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INTRODUCTION

Nearly 25 % of the major river-drainage basins on the globe discharge their annual water- and sediment supply into the Arctic Ocean (MILLIMAN & MEADE 1983). This discharge is directed through delta systems that are fully ice covered when the short peak-flow season begins. While the processes acting on low-latitude deltas have been studied extensively, those of ice-dominated deltas remain largely unknown. The importance of this lack of knowledge about Arctic delta-building processes is emphasized by a comparison of profiles of seven open-water deltas with that of a typical ice-dominated delta, using the Lena river as an example (Fig. 1). The overall morphology of other Arctic deltas, characterized by this pronounced break in slope at 2 m water depth far from shore, is similar. The wide platform covered by less than 2 m of water or ice will be called the 2-m ramp.

This review illustrates and describes geologic, glaciologic, and hydrologic processes observed on submerged parts of ice dominated deltas in the Beaufort Sea of North America and the Laptev Sea, Siberia. The report speculates about possible causes of the morphology of their 2-m ramps, but can not provide a satisfactory answer. The importance of supercooling and frazil formation for erosion and deposition is discussed. Evidence is presented that sand and coarser sediment is rarely discharged from river mouths. The discussion avoids processes active in those Arctic rivers flowing into funnel-shaped estuaries, like the Ob and Yenissey rivers. Even less is known about such settings, which are not uncommon around the Arctic Ocean.

The paper is based mainly on knowledge gained from field work and research in Alaska, but also on work as consultant in the development of an arctic offshore oil field. This field is located near Prudhoe Bay in a deltaic setting, where processes related to river breakup pose serious design constraints for a buried pipeline. Extensive studies are being conducted for this purpose. Participation in a joint Russian/German study of the Lena River Delta allowed expanding this work to the Siberian Arctic.

BACKGROUND INFORMATION

The setting of Arctic deltas contrasts sharply with that of low-latitude deltas. In low-latitude deltas seasonal ice may exist for short periods in the fringes and in slow-flowing channels, but never dominates the environment. In Arctic deltas, ice forms a

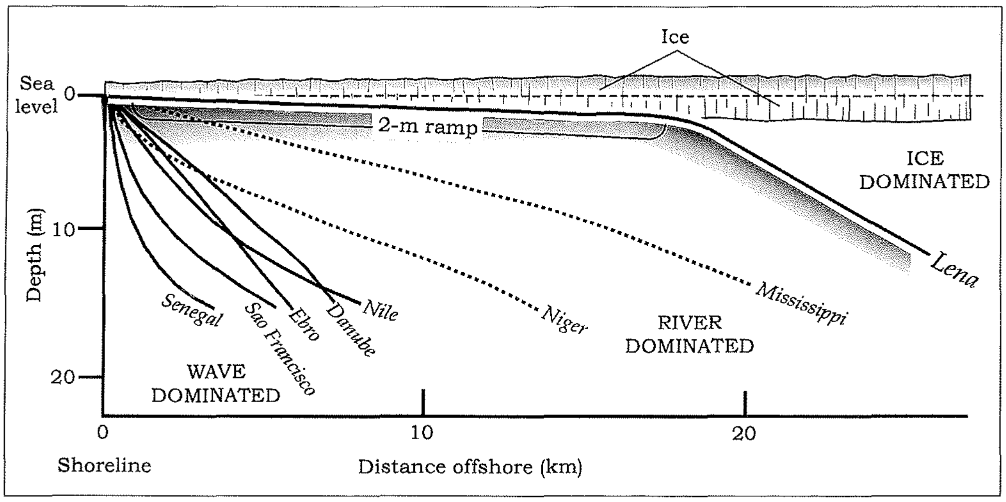

Fig. 1: Comparison of seven low-latitude delta profiles from WRIGHT & COLEMAN (1973) with that of the Lena Delta added. It exhibits the characteristic 2-m ramp, a platform corresponding in depth at its perimeter to the maximum thickness of seasonal fast ice. Other Arctic deltas are similar.

Abb. 1: Vergleich der Profile von sieben Deltas niederer Breitengrade, die unter dem Einfluss von Flüssen und Wellen geformt werden (nach WRIGHT & COLEMAN 1973), mit dem des Lena-Deltas, das unter der Bildung einer jährlichen Eisdecke geformt wird. Das Lena-Delta zeigt die typische 2-Meter-Rampe, die der Mächtigkeit des Eises entspricht, und auch in anderen arktischen Deltas vorkommt.

complete lid, thickening during the winter to 2 m, on all bodies of water including the shallow shelf for about nine months each year.

This report reviews information relevant to the plumbing systems of such ice-covered deltas in Arctic Alaska, Canada, and the Laptev Sea. The sea-ice cover starts forming in early October, gradually eliminating wave action on delta shores. River discharge at this time already has been greatly reduced by freezing of the drainage basins (Fig. 2). A relatively smooth cover of fast ice begins forming at the coast reaching seaward some distance beyond the 2-m ramp, first in form of bulges between still-active channels. This fast ice is attached to the coast, and thereby locked in place horizontally, but is free to move vertically with tides and storm surges. As ice thickness reaches about 2 m by the end of winter, increasing areas of floating fast ice on the ramp become „bottom-fast". As the bottom-fast ice normally does not oscillate with tides while the floating fast ice does, there is a tidal crack between the two ice types. This tidal crack migrates seaward with increasing ice thickness. In the widening region of bottom-fast ice, direct conductive heat transfer from the cold atmosphere leads to permafrost aggradation.

Discharge of all of northern Alaska's relatively small rivers stops entirely in winter, while the Mackenzie and many of the

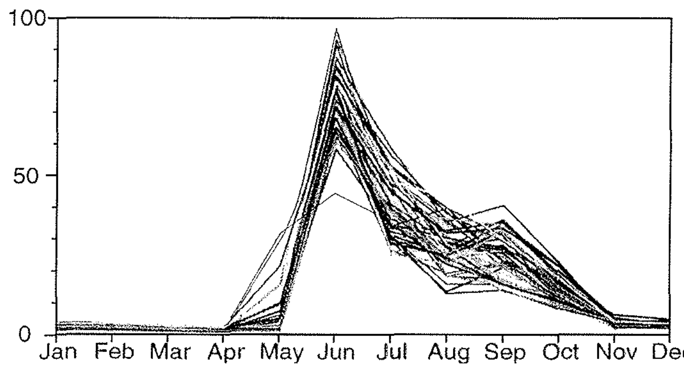

Fig. 2: Daily mean discharge (m^3/s) measured just upstream of the Lena Delta (Kiusiur) for the years 1935 to 1988 (Unpubl. data RUSSIAN STATE HYDROLOGICAL INSTITUTE).

Abb. 2: Durchschnittliche tägliche Abflusswerte (m^3/s) der Lena gemessen oberhalb des Deltas bei Kiusiur für die Jahre 1935 bis 1988 (unveröffentl. Daten, RUSSIAN STATE HYDROLOGICAL INSTITUTE).

large Siberian rivers continue to flow, although at sharply reduced rates. As an example, a 52-yr record of average daily discharge rates for the Lena river is shown in Figure 2. The abrupt rise to a sharp peak in June is typical for Arctic rivers, especially those that stop flowing, and corresponds in time with the maximum extent and thickness of sea ice.

ARNBORG et al. (1967) report that 75 % of the annual sediment load of the Colville River is supplied during a three-week period immediately following river breakup. Such facts coupled with observations of sediment-laden ice reported since early Arctic explorations led to speculations that this sediment observed in distant parts of the Arctic Ocean is introduced near river mouths by turbulent flow during spring breakup. For example, FUCHS & WHITTARD (1930) held that view based on shallow-water clams collected from sea ice exiting the Arctic Ocean through Fram Strait. This would have important implications not only for sediment deposition in deep basins, but also for delta building or the lack thereof in the Arctic. But there was no hard evidence.

The first actual observations seaward of relatively small Alaskan Arctic rivers during breakup suggested that sediment loading of ice was not important for the budget of their deltas (REIMNITZ & BRUDER 1972). This conclusion was reached based on aerial observations and photography of all river mouths along the North Slope of Alaska after flood waters had drained from the ice. These authors recognized the 2-m ramp of the Colville Delta and speculated that it might be due to discharge restriction by the remaining fast ice. River water spills out over the ice for only a few days. Then for weeks after the bottom-fast ice has lifted off the bed, river water flows seaward in the narrow gap between ice and the seafloor (Fig. 3). This flow pattern was thought by REIMNITZ & BRUDER (1972) to cause current-intensification, winnowing and bypassing on the 2-m ramp, and deposition beyond, where flow cross-section increases and velocity decreases. Surface sampling and vibrocoring support this concept: Fine, well sorted sand covers the 2-m ramp and poorly sorted sandy mud accumulates seaward of the break in slope.

REIMNITZ & BRUDER (1972) also found that river water spreading across fast ice leads to the formation of rotating vertical flow vortices, which they called strudel, forming scour craters in the seafloor below (Fig. 4). The downward flow of fresh-

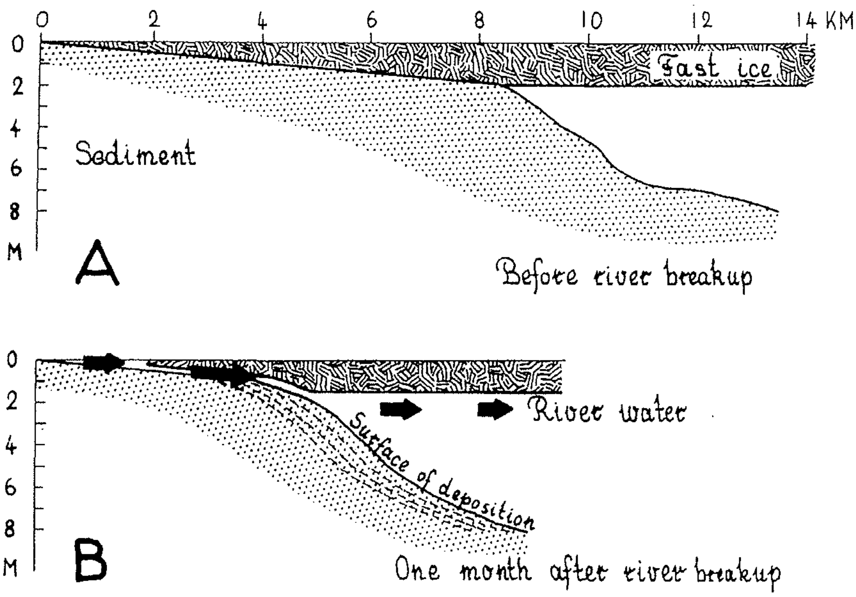

Fig. 3: Initial attempt to explain the formation of the ramp in terms of intensified sub-ice flow during the time of maximum water- and sediment discharge by the Colville River (REIMNITZ & BRUDER 1972).

Abb. 3: Erster Versuch, die Bildung der auffälligen Rampe des Colville-Deltas, Alaska, durch verstärkte Strömung unter der blockierenden Eisdecke während des jährlichen Abfluss-Maximums zu erklären (REIMNITZ & BRUDER 1972).

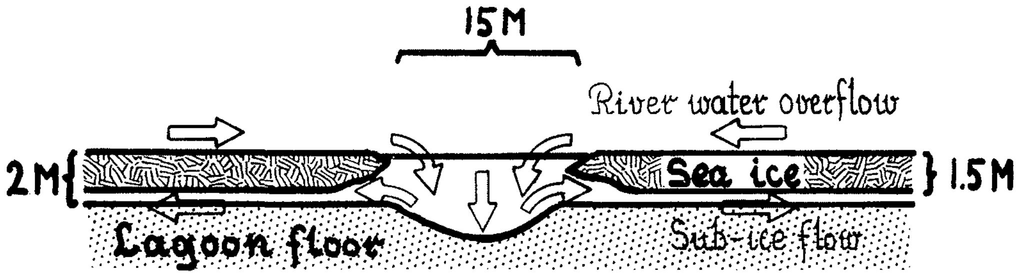

Fig. 4: Cross-section of strudel drain hole with water-flow pattern, and formation of scour crater on the sea floor below.

Abb. 4: Querschnitt durch einen Strudel mit vermuteter Wasserströmung und Bildung eines Kraters auf dem Meeresboden.

water through the ice into seawater of higher density evidently is driven by buoyancy of initially submerged fast ice driven to rise to the surface. This flow phenomenon is not simply a function of hydraulic head, or water depth on top of the ice. After drainage of flood-waters from the ice, the locations of former strudel are marked by characteristic radial drainage channels on the ice (Fig. 5). The density of drain holes per unit area was initially counted from aerial photographs (REIMNITZ & KEMPEMA 1983). Their exact locations now are being surveyed from a helicopter using GPS, followed by summer boat surveys of the resulting craters.

The sea-floor craters, their subsequent in-filling through bed-load sediment transport, and effects of cut-and-fill on small- and large-scale sedimentary structures has been reported by REIMNITZ et al. (1974), REIMNITZ & KEMPEMA (1983), ALPHA & REIMNITZ (1995), and REIMNITZ (1997). Strudel-scour craters are cut as deep as 6 m below the seafloor on Arctic deltas. Their excavation products, however, are not seen in form of corresponding surrounding levees. This fact was illustrated by three fathometer crossings at different headings of a single crater by REIMNITZ (1997). To avoid scour and current-flow damage to the Liberty pipeline near Prudhoe Bay, Alaska from strudel drainage during its assumed 20 yr life span, preliminary studies would anticipate formation of craters more than 7 m deep with 46 m diameter on the delta surface. The burial depth therefore is planned for 3 m. Apparently this drainage phenomenon has not been studied in Siberia and described, but seems to occur on the Lena River Delta, A fathometer profile recorded on the eastern delta shows two steep sided craters of about 2 m depth (ARE et al. 2000).

WALKER (1973) reports that channels of the Colville Delta over 2 m deep contain saline water, and that the ice on such channels oscillates „with river stage". This suggests that intra-delta channels are not isolated from ocean tides by bottom-fast ice on the ramp. WALKER (1974) observed that only 60 km from the ocean the water in the Colville Delta channels is completely fresh. Near the mouth, sub-ice salinities of 40 ‰ were measured. With river breakup, all sub-ice saline water was flushed in two days from the delta in 1973, and the river cleared of ice within three days (HAMILTON et al. 1974). Four days after river water reached distributary mouths, it had spread on the ice to its outer limit 10-15 km seaward (WALKER 1973). River water also started spreading below the fast ice to reach 40 km seaward during the same interval by June 9. By this time, the floodwaters near river mouths had drained from the ice, and a belt of open water 2-10 km wide had formed. Thus the different events follow in rapid succession during this dramatic event. According to WALKER (1974), significant volumes of sediment are left on the fast ice after drainage of flood waters. Between his measurements in 1973, with sediment thicknesses ranging from 0 or 1 to over 20 mm, and 1971, when thicknesses ranged to as much as 170 mm, are great differences. He reports the sediment texture is mainly medium to fine sand, with amounts of sand ranging to as high as 95 % (WALKER 1974). The sediment also includes driftwood and shreds of peat.

Some of the observations of WALKER (1974) also shed light on the morphology of the Colville 2-m ramp. He recognized that ice on channels over 2 m deep on the 2-m ramp soon rises to the surface tracing their configuration during overflow. He

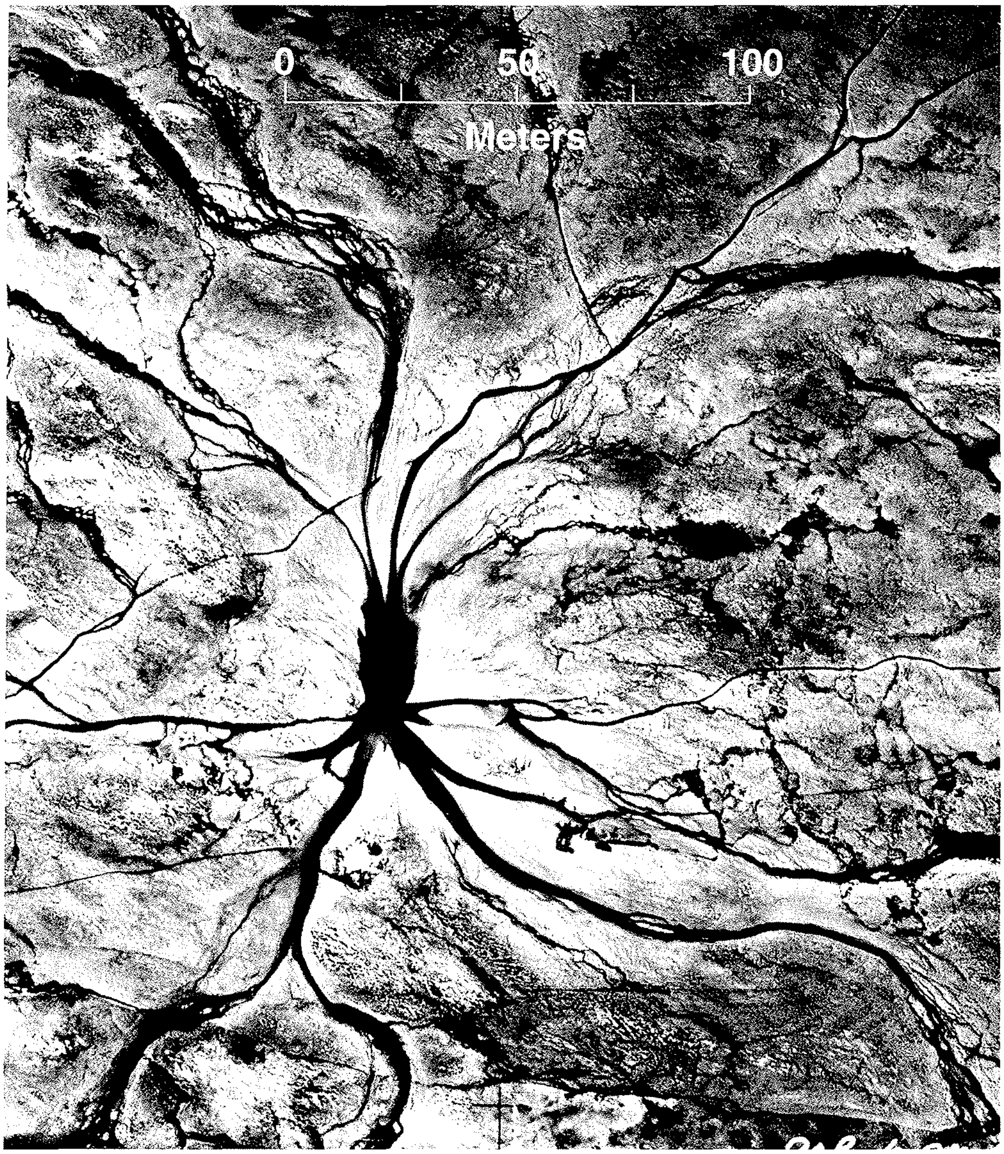

Fig. 5: The locations of former strudel are marked by a drainage hole surrounded by a radial pattern of feeder channels cut into the fast-ice surface.

Abb. 5: Ort eines ehemaligen Strudel, angezeigt durch ein Abflussloch im Eis und die zuführenden Abflusskanäle auf der Eisoberfläche.

also states the thalwegs of only „two of the easternmost channels are deep enough so that freezing does not reach the bottom". His map of the Colville Delta in flood shows 3 sinuous bands of drained ice off the eastern delta, but by far the longest, and most conspicuous one off the western delta, mapped in 1971. The source of data for this map is not reported. The Russians call the early draining channel ice serpentine ice (NALIMOV 1995). WALKER'S (1974) map also shows four 4-6 km diameter patches of ice „floating on floodwater" on the 2-m ramp. But elsewhere the paper attributes the patches to „enough regional irregularity so that some near shore bottom-fast ice areas are not covered" by floodwater. The four questionable patches were observed in three additional years, but are unexplained. According to WALKER (1974), pockets on the 2-m ramp become isolated by the thickening fast ice holding water with salinities reaching 50 to 60 ‰.

MATHEWS & STRINGER (1984) present data recorded by a mooring placed in the tidal entrance to Simpson Lagoon, fed by the Kuparuk River immediately west of Prudhoe Bay (Figs. 6, 11). This small river stops discharging into the lagoon in winter, and therefore salt rejection from the thickening ice cover raises the salinity of the nearly sealed off sub-ice body of lagoonal water to between 44-48 ‰. Water temperature is at its freezing point. Within a few hours after river flow started, discharge velocity in the channel increased to about 50 cm/s, and the salinity dropped to zero, while water level rose by 64 cm (MATHEWS & STRINGER 1984). Bathymetry and configuration of this tidal entrance is shown in Figure 6, and break-up ice- and flow dynamics observed directly at this location are discussed later.

Several studies of winter and spring processes off the Mackenzie river delta relevant to this review have been conducted by DICKINS ASSOC. LTD. (1987), MACDONALD & CARMACK (1991), and MACDONALD et al. (1995). MACDONALD et al. (1995) show that under the fast ice of the large Mackenzie estuary, most of the freshwater supplied by the river during winter remains impounded landward of the stamukhi zone (zone of grounded pressure ridges) as liquid. The ridge keels act as inverted dams inhibiting the spreading of fresh water.

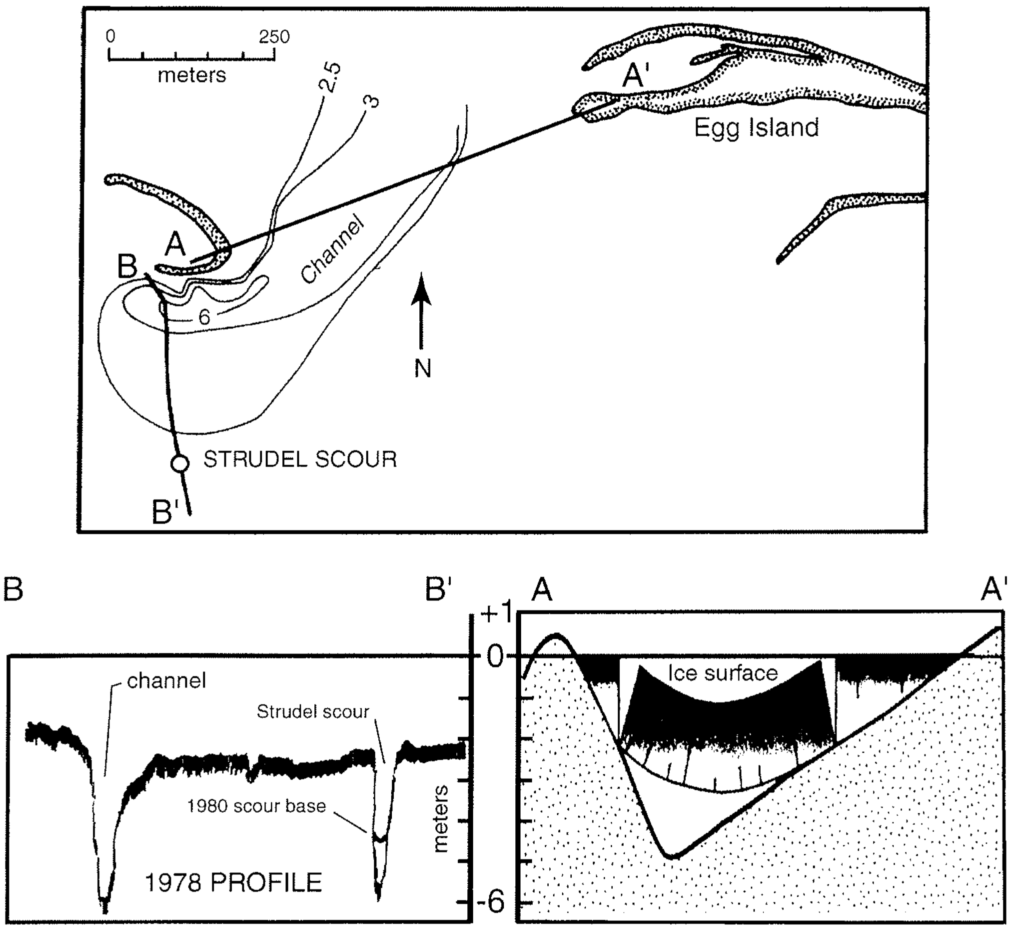

Fig. 6.: A tidal channel of Simpson Lagoon, located off the mouth of the Kuparuk River (see Figs. 10, 11). One inset shows actual fathometer profile of the channel and an adjacent strudel scour crater of similar depth. The other inset (both at a common vertical scale) is a schematic E-W profile of the channel observed during spring flood. Ice floating on the channel initially is broken free from adjacent bottom-fast ice by the weight of flood waters, enabling it then to rise to the surface.

Abb. 6: Gezeitenkanal der Simpson-Lagune, vor der Mündung des Kuparuk-Flusses (vgl. Abb. 10 & 11). Ein Ausschnitt zeigt ein Tiefenprofil des Kanals mit einem Strudelkrater ähnlicher Tiefe. Der andere Ausschnitt (gleiche vertikale Skala) zeigt einen schematischen O-W-Querschnitt des Kanals nach Beobachtungen während des Flussaufbruchs. Das auf der Wasseroberfläche schwimmende Eis wird von dem auf dem Boden liegenden Eis erst durch das Gewicht des Flutwassers freigebrochen. Erst danach kann es zur Oberfläche aufschwimmen.

Only about 15 % of the winter out flow is incorporated into the thickening fast ice, while a small percentage leaks seaward through the inverted ice dams. DICKINS ASSOCIATES LTD. (1987) observed from the air that flooding of the fast ice occurred off the Mackenzie Delta, indicating that the sub-ice channel cross sections are inadequate to accommodate all river water during this seasonal discharge pulse. Some strudel were observed, and small amounts of sediment were seen on the fast ice. The fast-ice edge in the year of the study was not nailed to the shelf by well-developed stamukhi, as in the winter reported on by MACDONALD et al. (1995). Nevertheless, the previously flooded fast ice evidently melted in place before ice drift began in the stamukhi zone.

In the Russian language, there is a rich literature on ice conditions and related water-flow patterns in river deltas of the Laptev Sea, indicating that extensive studies were done. Except for a few articles, such as ANTONOV et. al. (1972) and NALIMOV (1995), however, almost nothing is written in English or other languages.

ARCTIC DELTA MORPHOLOGY AND PROCESSES

Different topics are discussed under the following headings: a) The 2-m ramp, b) Channels on the 2-m ramp, c) Spring flushing of the Lena River drainage system, d) Deposition on ice, and e) Fast-ice flooding by winter storm surges.

The 2-m ramp

When first recognized in Arctic Alaska, the characteristic wide platform covered by less than 2-m of water or ice, and marked by a break in slope at its outer edge, was called the 2-m bench (REIMNITZ & BRUDER 1972). Rather detailed isobaths were prepared from available data for the Colville Delta at that time. In later work dealing with this feature and realizing its importance for Arctic deltas, the choice of the term "bench" seemed inappropriate and in this article therefore was changed to "ramp". DUPRE & THOMPSON (1979) recognized a similar morphological feature off the sub-arctic Yukon River Delta in the Bering Sea, and called it the "sub-ice platform". Their platform, however, lies deeper than the thickness of the seasonal fast ice.

The correspondence of the maximum depth of the ramp's profile with that of the fast ice probably holds the key to its explanation. The full extent of the ramp at the end of the winter, except for channels, is occupied by bottom-fast ice. Here direct, conductive heat transfer from the atmosphere through the ice cover to the sea bed results in an at least partly ice-bonded (frozen) substrate.

The ramp of the Sagavanirktok River Delta east of Prudhoe Bay has the same general profile. But its surface, as observed in numerous diving traverses and detailed side-scan sonar and fathometer surveys, is very irregular. It is marked by scarps and ledges with as much as 50 cm of relief in outcrops of overconsolidated, stratified mud. Between these outcrops are pockets of clean sand. In one study (REIMNITZ & KEMPEMA 1983), a steel pole was driven into the bottom of a new strudel-scour crater, and connected by a 5 mm cable to an anchor, 50 m distant. In the course of relocating the pole in the crater one year later, the cable was recovered with a grapling hook. Swimming along the cable from the anchor, it was found to be covered by as much as 50 cm of sand in pockets between outcrops, where the cable was exposed. In sand pockets, both divers were required to pull together in order to free the cable and continue following it to the crater. Although the best marine fittings, including Nicopress sleeves, were used to secure the cable to the pole, the thimble and shackle were gone. This observation, together with the rapid in-filling of the crater by bedload transport (REIMNITZ & KEMPEMA 1983), demonstrate the extremely dynamic setting of the 2-m ramp.

The first river break-up study and speculations about the causes of the 2-m ramp led to another study off the Colville River. During this study, an ice core was drilled on the 2-m ramp, penetrating 10 cm into the ice-bonded sea bed. This core showed thin sediment layers as much as 50 cm above the ice/bottom contact. Leveling with a theodolite at this site indicated that the bottom-fast ice was elevated an equal amount (50 cm) above the floating fast ice seaward of the tidal crack. These findings led to an alternative explanation for the formation of the 2-m ramp: In a shallow-water, depositional setting, the cross-section for tidal flow is reduced by thickening fast ice during the course of winter. Eventually the floating fast ice rests on the bed, thereby becoming bottom-fast ice. During this period, the tidal prism (~10 cm off the Colville River) remains constant, punctuated by winter storm surges of over 1 m amplitude. Storm surges may last for days, while new ice forms at the bottom. The reduction in sub-ice cross section is accompanied by intensified currents, until ice ultimately rests on the bed.

The ice core discussed above showed that the bond between ice and the frozen bed is weak and easily broken. This bond therefore may not suffice to overcome the force of ice buoyancy during a surge. The ice with a trace of ad-frozen sediment can lift and be held above the bed. During this period, clean congelation ice would grow below the last sediment layer in the bottom of the fast ice. Such events evidently occurred repeatedly during the course of winter, thereby causing inclusion of several sediment layers, and elevation of the bottom-fast ice above the level of the floating fast ice (Fig. 7). The tidal crack therefore is marked by a corresponding step in ice-surface elevation. However, the observation that bottom-fast ice temporarily remains so during river overflow or storm surges could also be due to the fact that over wide regions water must penetrate between ice and the seafloor. During its rise, and the widening of the gap, water must flow landward. Whether this landward flow and the subsequent seaward flow at the end of a surge is strong enough to move sediments is unknown. The process of water penetrating under bottom-fast ice evidently requires days rather than hours, while ice remains submerged.

Increasing tidal-current velocities with thickening fast ice may also cause winnowing of bottom sediments, and aggradation of the bed to the level of the base of floating fast ice (±2 m). The actions of winnowing on the 2-m ramp, and re-suspension of sediments, may lead to inclusions of particles and therefore particle enrichment in newly formed ice layers. Attempts to monitor this on the 2-m ramp off the Colville River failed. The bottom-mounted, well-anchored instrument was lost.

The northward trending profile of the flat, <2m deep, and as much as 16 or 18-km-wide ramp of the Lena Delta (Fig. 1) is constructed from spotty and very sparse public data. But it is typical for profiles of ice-dominated deltas. I have been unable to learn from navigational charts or from people living on the delta about any channels seaward to deeper water, or about the maximum draft of vessels that can be used between the river and the open sea. There are reported, however, to be two navigable channels leading to the sea. The morphology of the Olenek Delta ramp (Fig. 8), 200 km west of the Lena Delta, is different. This ramp, as wide as 10 km, is marked by a chain of bars along its outer edge and is crossed by a 10-m-deep channel entering the river. There are almost no soundings landward of the 2-m isobath, the draft of survey vessels used.

Winter storm surges of as much as 1.4 m amplitude have been recorded for the period of complete ice cover in the Beaufort Sea. The tidal cracks remaining active through the winter and shifting seaward, a surge would cause floating fast ice to rise while for a short time bottom-fast ice remains held to the bed. In this situation, the bottom-fast ice would be flooded by seawater spreading landward from the tidal crack. I studied

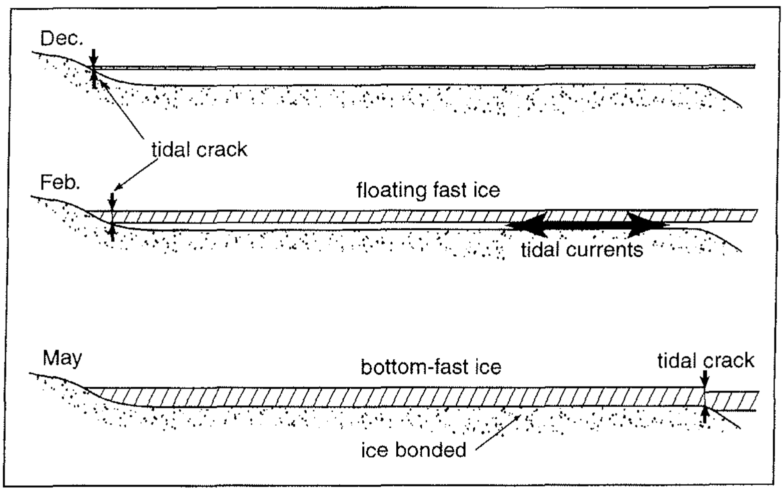

Fig. 7: Development of bottom-fast ice on the 2-m ramp, while the tidal crack migrates seaward. Fast ice increasingly restricts the flow cross-section for tidal currents, while the water volume moved remains constant. Flow restriction and resulting intensified currents between ice and bottom may cause truncation of prograding deltaic deposits at the level of maximum ice thickness.

Abb. 7: Entwicklung des "bottom-fast" Eises auf der 2-m-Rampe, während der Gezeitenriss sich seewärts verschiebt. Die Eisdecke übernimmt zunehmend den Raum, der für die Gezeitenströmung verfügbar ist, während das zu bewegende Wasservolumen gleich bleibt. Diese Vorgänge könnten die Strömungen verstärken, so dass die deltaischen Ablagerungen bis zum maximalen Tiefgang des Festeises abgetragen werden.

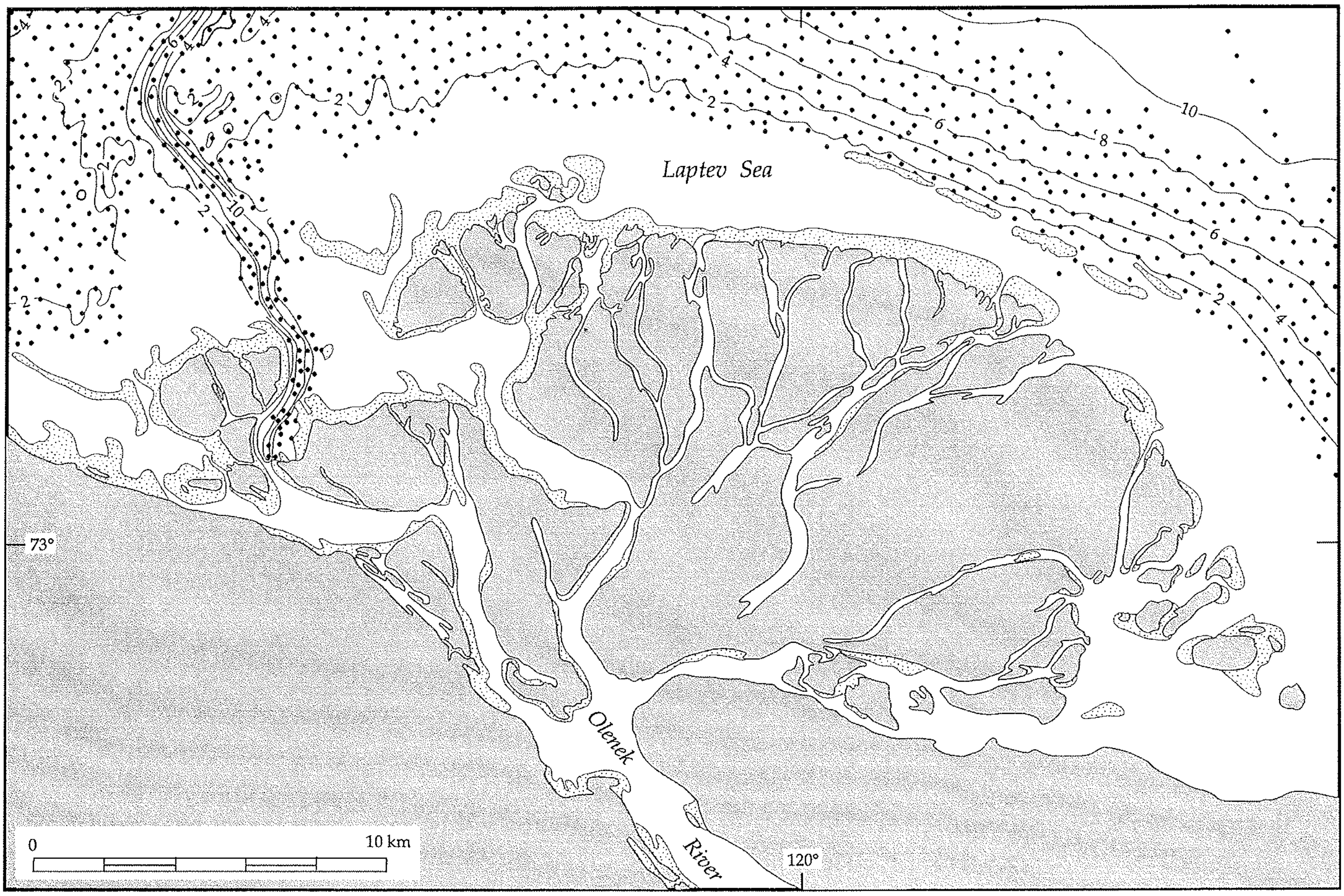

Fig. 8: The Olenek Delta bathymetry contoured at 2 m interval, with locations of soundings indicated by dots. The chain of exposed sand bars along the outer edge of the ramp, and the 10-m-deep channel, make this feature unusual.

Abb. 8: Delta des Flusses Olenok mit den detaillierten 2-m-Tiefenlinien; Messstationen sind durch Punkte gekennzeichnet. Die Kette von Sandbänken entlang der Außenkante und der durchgehende Kanal sind für ein arktisches Delta ungewöhnlich.

satellite images taken mainly along the Beaufort Sea for many years, but have never seen flooded ice on 2-m ramps. However, questioning construction workers plowing snow and traveling over ice, I learned that bottom-fast ice is occasionally flooded. In many ice cores studied, I have not seen evidence for the snow cover to become flooded and saturated by seawater. However, remote sensing of the Yukon River Delta by RAY & DUPRE (1981) showed large regions of bottom-fast ice submerged by a winter surge.

Channels on the 2-m ramp

The USGS R/V "Karluk" was used for several days in attempts to enter the Colville River for seismic surveys in the intradelta. The boat has slightly over 1-m draft, and is so rugged that it can be run aground. Even with the assistance of its skiff reconnoitering ahead of the boat and tracing existing channels, the vessel was unable to follow and enter any of these. They shoal and terminate before reaching the ramp's perimeter. Here waves have been seen breaking during fall storms, thereby perhaps closing off channels. But in the intradelta, channels are locally scoured to depths of 15 m (personal communication with Jim Helmericks, a bush pilot living in the delta). The channel extensions from land onto the 2-m ramp are shown schematically in Figure 9. This figure also shows the behavior of the channel ice during flood.

Figure 10 is a Landsat image of the Colville Delta 1-2 days before maximum flood stage, when already much of the fast ice on the 2-m ramp is inundated. Three channels crossing most of the ramp are seen as sinuous white lines cutting the dark flood waters. Close-up observations of a typical channel were made in a field study off the Kuparuk River near Prudhoe Bay off northern Alaska (Figs. 6, 11). Here a tidal channel with 7 m maximum depth, confined between two barrier islands, connects the open ocean with the <2-m-deep Simpson Lagoon. The weight of the river water advancing across lagoonal bottom-fast ice and reaching the deep channel, depressed its floating ice cover. Breaking of ice was heard at a distance by booming sounds, accompanied by oscillations of water level in drill holes penetrating the ice on the channel. During passage of the water front, the tidal crack at 2 m depth separated floating fast ice from bottom-fast ice, with the latter supported and prevented by the sea floor from being depressed. But the floating ice was pressed downward (Fig. 6). Both were submerged by the flood wave, but the floating fast ice much more (>1.5 m) at the site of my observations. The surface of the ice sloped steeply from the island at the eastern end of the profile (point A' in Fig. 6) into the flowing water

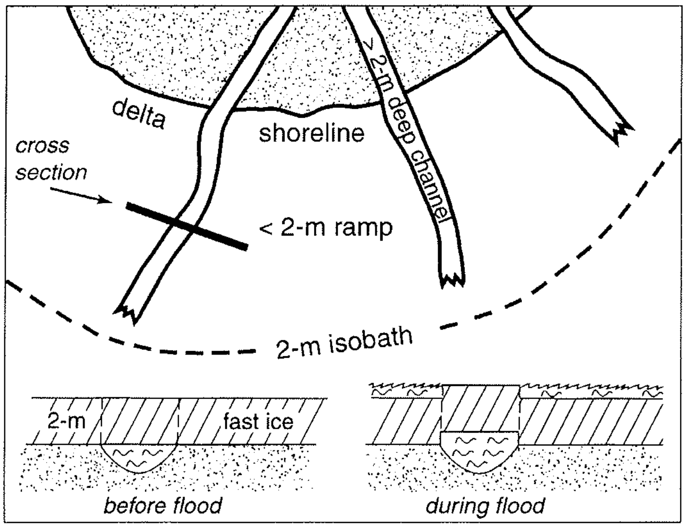

Fig. 9: Schematic view of three river distributaries extending to but not crossing the shallow edge of the Colville River ramp. The existence of seaward-shoaling channels on the ramp was determined from soundings by a skiff navigated relative to the grounded R/V "Karluk".

Abb. 9: Schematische Darstellung von drei Colville-Flusskanälen, die nahezu bis an die Außenkante der Rampe reichen, aber diese nicht überschreiten. Die Kanäle wurden mit Hilfe eines kleinen Bootes verfolgt, das vom der seewärts festliegenden R/V "Karluk" aus navigiert wurde.

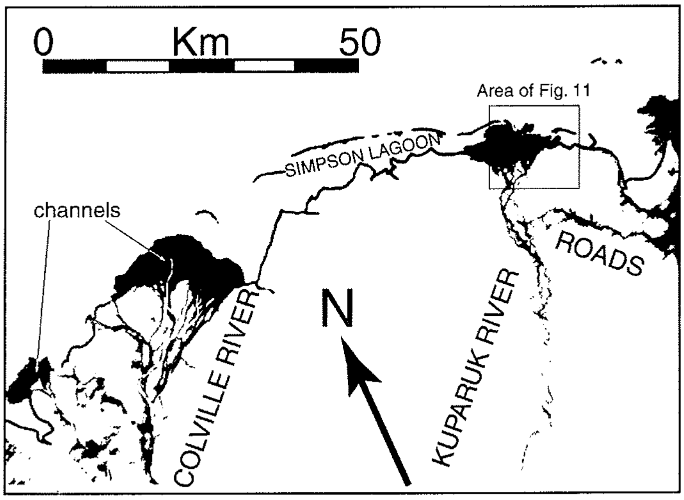

Fig. 10: LANDSAT image (6-6-76) of the Colville River and other deltas close to maximum flood stage. The bottom-fast ice on the Colville ramp is being submerged, while ice in sinuous channels >2 m deep has drained and risen to the surface forming "serpentine ice". Note that sinuous channels do not extend to the limits of flood waters.

Abb. 10: LANDSAT-Aufnahme (6-6-76) des Colville und anderer Flüsse kurz vor der maximalen Ausdehnung der Überflutungen. Das "bottom-fast" Eis, noch am Boden haftend, steht unter Wasser, während das frei schwimmende Eis oberhalb von >2 m tiefen Kanälen bereits an die Oberfläche gestiegen ist.

over floating fast ice to where it was chest deep less than 10 m from the shoreline of Egg Island.

The floating fast ice in the tidal entrance to Gwydyr Bay, part of the large Simpson Lagoon (Fig. 10), was observed soon to rise to the surface from below flood waters. In the drained condition this channel ice would be called serpentine ice, similar to the sinuous white bands on the Colville River ramp (Fig. 10). During drainage of flood waters, the serpentine ice, although 2 m thick, was observed to respond elastically to flowing water both on top and underneath. The originally smooth fast ice was warped into wave forms of 1 m amplitude with 100-120 m wavelength oriented normal to the outflowing current. On the wave crests the ice was nearly exposed in rushing water so that the outboard motor had to be tilted up. Ten meters downstream, the ice was submerged by 1 m of relatively quiet water. Traversed again after a one-hour period, the waves had shifted their location. They were also observed and photographed from the air, but the resolution of the photos is inadequate to show here.

The bottom-fast ice of Gwydyr Bay, shown in the drained state in Figure 11, had stayed submerged for about two weeks allowing motorboat travel from Storkerson Point to the tidal entrance (Fig. 6). River water initially drained mainly along the tidal cracks on both sides of the serpentine ice, allowing it to become exposed and dry. The strudel scour crater shown in Figure 6 probably formed right along the edge of the floating fast ice. As the bottom-fast ice in this area rose to the surface, strudel formed as well. Once all freshwater had drained from the ice and discharge decreased, the Kuparuk River flowed below serpentine ice toward the open sea. The sub-ice flow of this warm river water apparently caused the channel ice to erode from below. During the next stage of river breakup, the channel over 2 m deep is marked by open water (Fig. 11). Recognition of this behavior of the fast ice helped when entering uncharted lagoons far eastward of Prudhoe Bay in the search for shelter during small-boat surveys. Landsat images of late June showing tongues of open water served to identify deep channels for the R/V "Karluk" to enter.

Concerning the development of the sinuous band of open water in Figure 11, and the rate of strudel-hole enlargement, an observation made in this tidal entrance is relevant: A 1 m^2 hole was cut in the channel center prior to the flood for the purpose of suspending a current meter below the ice. This hole became a strudel immediately upon passage of the flood wave. When the instrument was recovered from the still active strudel after eight days, the rectangular hole had kept its size. For instrument recovery, I stood with my assistant on opposite sides of the 1-m-diameter square hole, keeping the boat between us. Yet, Coastal Frontiers studying strudel in the area for British Petroleum in two consecutive years, found drain holes to range in diameter from 0.3-6 m, showing no clear size relationship with distances to river mouths. The question of hole growth must be addressed in the future, because the flow velocity hazardous to man-made structures is thought to be a function both of hydraulic head on the ice and strudel diameter.

Referring to a map of the Lena Delta during spring flood (Fig. 12), kindly provided by Y. NALIMOV, we see that the observations made on small North American rivers may also apply to this giant. Seven river distributaries continue as extensions across the 2-m ramp as marked by serpentine ice, while the two main-discharge arms extend as open-water tongues seaward. We note that all channels as mapped extend beyond the edge of the 2-m ramp. This fact does not fit observations from North America. The only explanation at the present is that either the 2-m isobath I added is incorrect, or that the

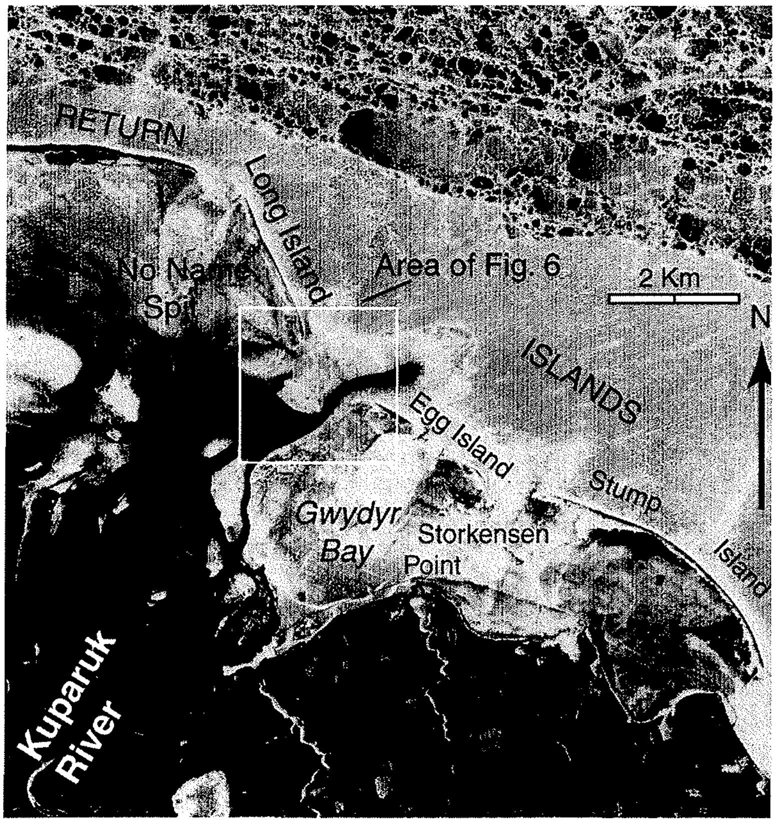

Fig. 11: A late June aerial photograph of a tidal channel of eastern Simpson Lagoon off the Kuparuk river, before the fast ice starts to move. The sinuous tongue of open water corresponds with the outflow of warm riverwater through the channel mapped in Figure 6.

Abb. 11: Luftaufnahme (Ende Juni) des östlichen Teils der Simpson-Lagune mit dem gewundenen Kanal, der durch Abfluss warmen Kuparuk-Wassers verursacht wird, kurz bevor Bewegung in das Eis kommt. Die Zunge offenen Wassers folgt dem in Abb. 6 kartierten Kanal.

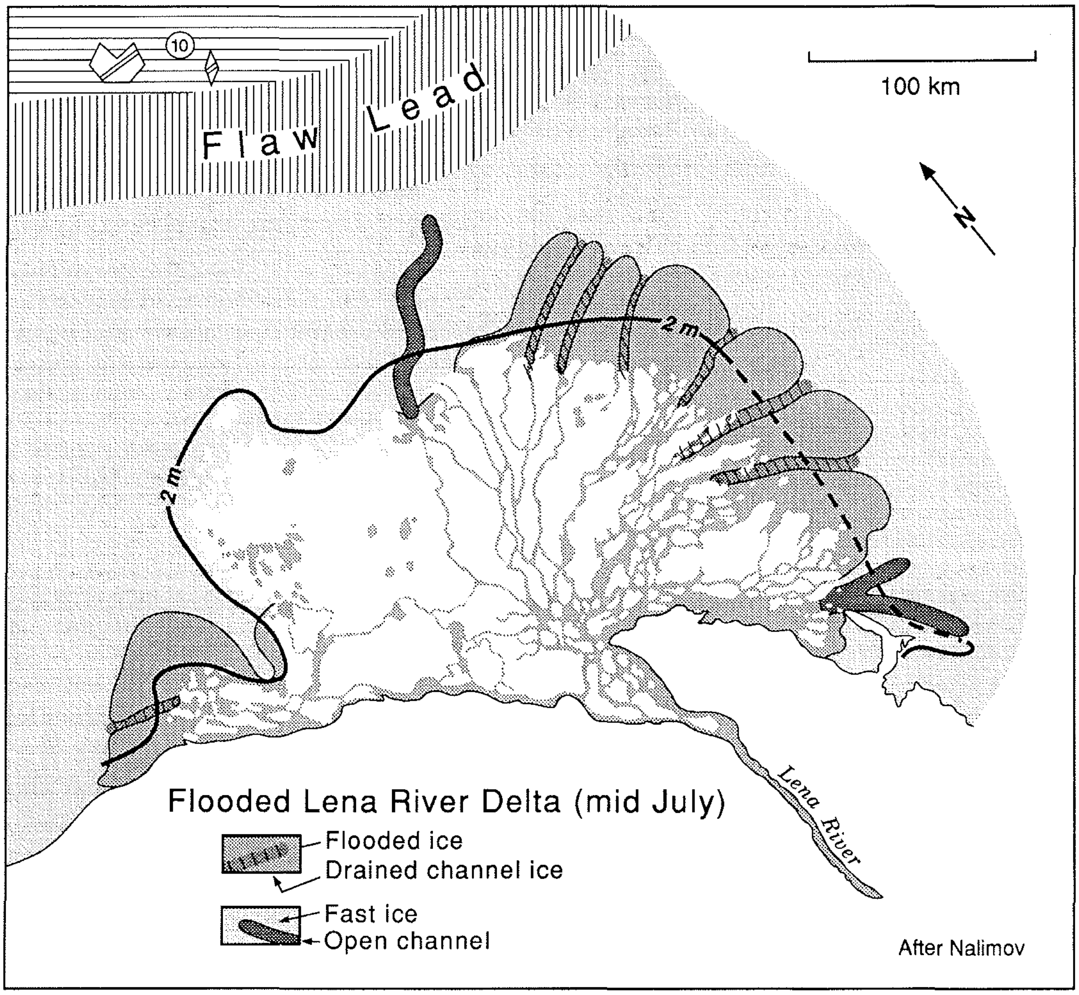

Fig. 12: Map of the flooded Lena Delta during mid July (NALIMOV, AARI, personal commun. Dec. 1994). The approximate 2-m isobath was drawn from very sparse soundings. Map shows the plumbing system of this large delta just prior to breakup of the fast ice, and generally confirms observations made on small Alaskan rivers, but also raises questions as discussed.

Abb. 12: Das geflutete Lena-Delta um Mitte Juli (persönl. Mitteilung NALIMOV, AARI). Die 2-m-Tiefenlinie wurde basierend auf wenigen Messungen konstruiert und ist daher ungenau. Die Abbildung zeigt das durch Festeis gesteuerte Abflusssystem dieses Giganten, kurz bevor das Eis in Bewegung gerät. Das Bild bestätigt Beobachtungen an kleinen Flüssen in Alaska, wirft aber auch Fragen auf.

seaward extent of channels, presumably based on aerial observations, had poor navigational control.

Spring Flushing of the Lena River Drainage System

On a large scale, the influence of Lena River discharge on ice decay in the Laptev Sea is only minor compared to the influence of other factors, such as the polynya (BAREISS et al. 1999). Discharge/sea-ice interactions are mainly confined to the 20 km wide belt of initially flooded fast ice. On a small scale, the manner in which the Lena River dumps its spring melt waters into the Laptev Sea with its fast-ice cover intact, may depend on water depths in the mouths of individual distributaries. If the channel depth is less than ice thickness (2 m) or even close to it, there is inadequate cross section for sub-ice discharge. Here river water would be forced up and over the fast ice, as in the case of Alaskan rivers discussed above. Figure 12 shows flooded ice around the active parts of the Lena River Delta, suggesting shallow entrances for some of its distributaries.

A rising water level in the rivers during spring breakup causes a rise in mean sea level in coastal regions. In the Beaufort Sea, mean sea level during early summer is as much as 40 cm above that of late winter. This sea-level rise roughly corresponds to the depth of flooding on the bottom-fast ice, forcing it to separate gradually from the bed and to rise to the surface. Based on the level to which driftwood was observed along the western river bank at the Lena Delta apex in April 1992, the water level of the river during ice jams can rise 5 to 10 m above winter level. The depth of flooding on the bottom-fast ice, and the rise of mean sea level would be accordingly higher in the southern Laptev Sea. ANTONOW et al. (unpubl.) deployed several water pressure recorders on the bed in the eastern, active part of the delta. One of these was moored at 3.7 m water depth 20 km upstream in Bykov, the major eastward flowing distributary. The river level rose as much as 1.5 m over a 6-day period starting with breakup on May 22, 1996. Another recorder was moored in the sea about 10 km from the shoreline of the eastern delta at 6 m water depth, where sea-ice cover was complete, with tidal oscillations of ca. 10 cm amplitude. Over a period of nearly seven days, starting three days after the breakup recorded in the river, sea level rose about 20 cm. In the very mouth of the river, where channel depth is about 11 m, water level rose 40 cm during a 26 hr period at breakup. According to NALIMOV (1995), however, water-level rise in the very mouth of the eastern distributary discussed is 1-1.5 m. This indicates that the bottom-fast ice off the eastern delta for a short time is submerged by about 1 m of river water. This rise would initiate the gradual separation of bottom-fast ice from the seabed.

The formation of underwater ice (frazil and anchor ice) is a very important aspect of an Arctic river's plumbing system, mainly during spring flushing. Here two fluids, both at their respective freezing points, meet in a commonly turbulent mixing zone. Large amounts of ice can be formed along the boundary or in the mixing zone by the process of double diffusion (MARTIN & KAUFFMAN 1974). The flooded regions on the fast ice of northern Alaska form a crust of ice during cold nights. This water therefore is at its freezing point, and turbulent drainage at strudel into colder saltwater below results in ice formation. ZUBOV (1945) reported that in the Russian Arctic considerable volumes of new ice are produced below the ice cover during the time of river breakup, without giving details on the nature of this ice. A very open framework of 20-cm diameter, randomly oriented ice platelets was observed in one year by divers in a 1-m-thick fresh-water layer below fast ice off the Sagavanirktok Delta immediately east of Prudhoe Bay during flooding. GOLOVIN et al. (1999) used temperature and salinity profiles measured in the Lena River prodelta during a Spring flood to demonstrate that supercooling is widespread, providing at the upper boundary of the pycnocline the conditions for double-diffusion and frazil-ice formation. In their studies they only dealt with the quietly spreading fresh-water layer without strong velocity shear. Even under these quiet conditions, GOLOVIN et al. (1999) calculated frazil-ice production rates of as much as 170 cm/day, which translates to 34 cm of congelation ice. They stress the importance of turbulence for frazil production rates. Suspended particulate matter in the new ice accumulation measured at only one site indicated an upward sediment flux of 7 g/m2 of ice surface per day. Under conditions of turbulent strudel flow in a vertical jet excavating a scour crater, the rates of frazil production and sediment entrainment would be higher because of the turbulence. Thus particle scavenging by frazil crystals (REIMNITZ et al. 1993) in strudel may explain the lack of significant levees around scour craters discussed earlier.

Sediment deposition on ice

Overflow during the period of peak annual river discharge would be expected to deposit the coarsest component of the annual river sediment supply on ice. The finest would drain through strudel into the sea below. Therefore spring ice- observations after the drainage of floodwaters should shed light on the coarse fraction of the sediment budget of Arctic deltas. With excellent visibility, I observed and took large-scale oblique photographs from 350 m altitude of the entire Alaska North Slope shoreline, reaching well into Canada, 20 days after the 1970 river breakup. The previously flooded ice off all river mouths was still in place, including that off the Colville Delta. Having read reports of early explorers, including FUCHS & WHITTARD (1930), with speculations about a river-supplied origin of sediment, wood, plant debris, and shallow-water mollusks on sea ice, I was surprised not to find even a thin film of sediment anywhere. Subsequent USGS studies of Arctic river deltas with sandy and gravelly channel beds showed that they do not flush such coarse materials into the ocean during spring floods (for example REIMNITZ & MAURER 1979). Also, USGS breakup studies of Alaskan rivers show they evidently transport no river ice to the sea. The ice melts within the river system.

The USGS conducted fieldwork off the Colville Delta during the 1983 river break-up, with the principal aim to learn about sediment deposition on ice. The team was unable to collect any sediment from the fast ice, and detected no discoloration of fast ice in LANDSAT images. In 1979, surface ablation of turbid ice resulted in a sediment layer of about 1 cm thickness on the fast ice in July. A Landsat image taken on July 15, 1979, was ideal to detect and map the extent of these on-ice deposits (KEMPEMA et al. 1989). Studies of Landsat images for many years did not show deposition on fast ice around any

Beaufort Sea river mouths. Furthermore, offshore construction crews travelling on ice roads through flood waters and snow-plowing did not see mud on the ice. Also, a researcher mapping from a helicopter with GPS navigation the flood-water extent and locations of strudel off three Alaskan rivers for two years (LEIDERSDORF personal commun.) cannot confirm sediment deposition on fast ice. In any case, studies of satellite images along the Beaufort Sea coast, and particularly the two used by WALKER (1974) in his study, show that the originally flooded fast ice melts in place before large-scale movement of the pack ice begins.

The heavy sediment loads on fast ice reported by WALKER (1974) are not confirmed by other observations. However, if rafted away from the deltas, this would be important for sedimentation in the Arctic Ocean. If not rafted away but released locally on the 2-m ramp, this morphologic feature and the delta front would rapidly prograde seaward. In only 100 years there would be 1 m of vertical accretion on the ramp. There is no evidence for such accretion.

Less is known about deposition on fast ice off the Lena River and other Siberian rivers than about those draining into the Beaufort Sea. Participants in a study of the Lena Delta during breakup in 1996, conducted under a German-Russian cooperative program, reported that no sediment deposition on flooded ice was observed when working on the ground and during ice over-flights. I studied four excellent SPOT satellite images obtained over the area of fieldwork in 1996. In a scene of 6-26, three weeks after the flood, snow still covered the land. Open water was beginning to form near the mouth of a distributary, but the fast ice was intact and not covered by mud. Three scenes of 7-10 and 11 show the smooth and snow-free surface of fast ice in areas previously flooded. The ice was still in place, showing extensive patches of brownish ice cut by a pattern of cracks of varying width filled with clean ice. This surface pattern records the history of the ice during the previous fall and early winter: Turbid, sediment-laden ice evidently had formed by suspension freezing during storms. After the dirty frazil had risen to the surface and the layer of slush congealed, it formed a sheet of turbid ice. This ice calmed the ocean, allowed the water underneath to clear, and being still thin, cracked. In these cracks clean ice formed.

The fact that this pattern is so clearly preserved over thousands of square kilometers is convincing evidence that there was not even a thin film of sediment on smooth fast ice from Lena River floodwaters in 1996. These observations only represent one year, and inter-annual variations in types of breakup are expected. Thus, NALIMOV (1995) reports that the rate of ice-melt depends on its sediment load. If clean, the ice lasts longer into the summer than if dirty. If, however, after the spring flood a thick, drying sediment layer forms and insulates the ice, it may survive the following summer to become second-year ice.

Fast-ice flooding by winter-storm surges

Storm surges are relevant to the theme of this paper because they affect such large regions on the 2-m ramp when compared to the relatively steep shore face of coastlines between river deltas.

As discussed previously, winter surges have been recorded in the Beaufort Sea. Similar to spring floods, extensive areas of bottom-fast ice stay submerged for a short time while water penetrates slowly along the ice/sediment interface, thus allowing the ice to rise. Therefore, bottom-fast ice will be flooded by seawater, upwelling through tidal cracks and any newly formed fissures. Spreading across bottom-fast ice, this seawater will saturate the snow-cover. The water depth on the ice would correspond to the surge height, given enough time for upwelling, and therefore could reach 1 m or more. Before the dropping sea level has allowed the water to drain back to the sea, ice will have formed on the surface. There are no published reports of winter ice floods in the Beaufort Sea, only eye witness accounts by Prudhoe Bay oil field workers I interviewed. However, LANDSAT images of the sub-arctic Yukon recorded flooding of bottom-fast-ice, resulting in the formation of overflow icing or "aufeis" (RAY & DUPRE 1981).

The southern Laptev Sea was under the influence of a powerful cyclone during January 10-12, 1987, with hurricane-force winds. This storm fractured the fast ice and caused a sea level rise of 80-120 cm, measured at a number of polar stations (ASHIK & VANDA 1995). They report that water covered vast areas of fast ice in the southern Laptev Sea. The ice thickness at the time may be estimated at about 1 m, and the water depth on the ice could also have reached 1 m. By the end of the surge, aufeis would have formed from flood waters, with a remainder draining along tidal cracks. In January these lie much shallower (±1 m) than during river breakup in late May. Therefore, winter surges could result in strudel-scour craters forming on the 2-m ramp at <2 m water depth.

CONCLUSIONS

Arctic land-sea interactions are seen in their most dynamic form in river mouths during breakup when deltas and the sea are completely covered by ice. This review describes some of the processes, but in many respects can do no more than highlight important processes and phenomena that should be studied in the future:

- Peak water and sediment discharge occur during the period of complete ice cover.
- Floodwaters ~0.5 m deep originally cover mainly the 2-m ramp of very low relief, where the 2-m isobath and the slope to the shelf lies kilometers from shore.
- The 2-m ramp roughly corresponds to the thickness of seasonal fast ice, and therefore conforms to the base of sea ice at onset of river flooding. This bottom-fast ice leads to ice-bonding of the substrate.
- The 2-m ramp is composed mainly of sandy sediment, material also found on river beds but never seen exported to the sea. The source of sand therefore is unknown.
- Available evidence indicates that no sediment accumulates on sea ice. In any case, the flooded sea ice melts in place and there is no ice rafting of river-borne material to the Arctic Ocean.
- Anchor ice forms attached to the shallow sea bed and in river channels, but there is no evidence for the transport of sediment by anchor ice from river mouths to the sea.
- The principal control of seasonal fast ice on river discharge is the surficial spreading of peak discharge waters over wide regions, from where they drain through holes and cracks in-

to the sea below. These strudel lead to the formation of strudel-scour craters as deep as 6-7 m on the seafloor, a major design constraint for offshore pipelines.

- Strudel are concentrated along the tidal crack between floating and bottom-fast ice (±2 m depth) and occur scattered seaward. They later also form in the area of bottom-fast ice, once this begins to rise from below floodwaters. I suspect strudel also form under thin ice flooded by winter storm surges.
- The sedimentologic effects of frazil ice forming along the river water/sea water interface are unkown. The abrasive action of frazil crystals in high velocity strudel flow may aid bottom excavation. Scavenging action by frazil may be responsible for the lack of levees around the craters.
- A principal effect of fast ice surrounding Arctic deltas is the elimination of any wave action for 9 months of the year, thereby preventing the shaping of a more typical open-ocean shore- face profile.
- The cause of the 2-m ramp, wide-spread in Arctic deltas, remains a matter of speculation. It clearly is a highly dynamic setting, found only in actively prograding regions.

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References

Alpha, T.R. & Reimnitz, E. (1995): Arctic delta processes.- U.S. Geol. Surv. Open File Report 95-843 (a video).

Antonow, M., Haase, V., Fürst, B. & Reimnitz, E. (unpubl.): Lena River Delta spring break-up water- and ice-level changes.

Antonov, V.S., Ivanov, M.V., & Nalimov, Yu.V. (1972): Types of breakup of rivers in Siberian arctic and sub-arctic zones.- The role of snow and ice in hydrology, Internat. Assoc. Scientific Hydrology Publications, UNESCO-WMO-IAHS 1: 541-545.

Are F., Grigoriev, M.N., Hubberten, H.W., Rachold, V., Rasumov, S.O., & Schneider, w. (2000):: Coastal erosion studies in the Laptev Sea.- In: Rachold, V. (ed.), Expeditions in Siberia in 1999, Rep. Polar Res. 354: 65-74.

Arnborg, L., Walker, H., & Peippo, J. (1967): Water discharge in the Colville River, Alaska, 1962.- Geografiska Annaler 48, Ser. A: 195-210.

Ashik, I.M. & Vanda, Yu.A.. (1995): Catastrophic storm surges in the southern part of the Laptev Sea.- In: H. KASSENS, D. PIEPENBURG, J. THIEDE, L.THIMOKOV, H.-W. HUBBERTEN & S.M. PRIAMIKOV (eds.), Rep. Polar Res. 176: 43-46.

Bareiss, J, Eicken, H, Helbig, A., & Martin, T. (1999): Impact of river discharge and regional climatology on the decay of sea ice during spring and early Summer.- Arctic and Alpine Res. 31: 214-229.

Dickens Associates, Ltd.. (1987): Aerial reconnaissance survey of ice break-up processes in the Canadian Beaufort Sea coastal zone.- Prepared for Bedford Institute of Oceanography, Atlantic Geoscience Center, Dartmouth, Nova Scotia: 90 pp.

Dupre, W. R. & Thompson, R. (1979): The Yukon Delta: A model for deltaic sedimentation in an ice-dominated environment.- Proceedings of the 11th Annual Offshore Technology Conf. 3434: 657-664.

Fuchs, V.E., & Whittard, W.F. (1930): The East Greenland pack-ice and the significance of its derived shells.- Geografic J. 76: 419-424.

Golovin, P., Dmitrenko, I., Kassens, H. & Hölemann, J. (1999): Frazil ice formation during the Spring flood and its role in transport of sediments to the ice cover.- In: H. KASSENS, H.A. BAUCH, I. DMITRENKO, H. EICKEN, W.-W. HUBBERTEN, M. MELLES., J. THIEDE & L. TIMOKHOV (eds.), Land-ocean systems in the Siberian Arctic: dynamics and history. Berlin, Springer-Verlag: 125-140.

Hamilton, R.A., Ho, C.L. & Walker H.J. (1974): Breakup flooding and nutrient source of Colville River Delta during 1973.- In J.C. REED & J.E. SATER (eds.), The coast and shelf of the Beaufort Sea, Arlington, VA, The Arctic Institute of North America: 637-647.

Kempema, E.W., Reimnitz, E. & Barnes, P.W. (1989): Sea ice sediment entrainment and rafting in the Arctic.- J. Sed. Petrol. 59: 308-317.

Martin, S, & Kauffman, P. (1974): The evolution of under ice meltponds, or double- diffusion at the freezing point.- J. Fluid Mech. 64: 507-527.

Macdonald, R.W. & Carmack, E.C. (1991): The role of large-scale underice topography in producing property flux divergence in an Arcic shelf/estuary.- Atmos. Ocean 29: 37-59.

Macdonald, R.W., Paton, D.W., Carmack, E.C., & Omstedt, A. (1995): The freshwater budget and under-ice spreading of Mackenzie River water in the Canadian Beaufort Sea based on salinity and 18O/16O measurements in water and ice.- J. Geophys Res. 100, C1: 895-919.

Mathews, J.B. & Stringer, W.J. (1984): Spring breakup and flushing of an Arctic lagoon estuary.- Jour. Geoph. Res. 89, C2: 2073-2079.

Milliman, J.D. & Meade, R.H. (1983): World-wide delivery of river sediment to the oceans.- Jour. Geol. 91: 1-21.

Nalimov, Yu.V. (1995): The ice thermal regime at front deltas of rivers of the Laptev Sea.- In: H. KASSENS, D. PIEPENBURG, J. THIEDE, L.THIMOKOV, H.-W. HUBBERTEN & S.M. PRIAMIKOV (eds.), Rep. Polar Res. 176: 55-61.

Ray, V.M. & Dupre, W. R. (1981): The ice-dominated regimen of Norton Sound and ajacent areas of the Bering Sea.- In: D.W. HOOD & J.A. CALDER (eds.), The eastern Bering Sea shelf: Oceanography and resources. U.S Government Printing Office, Department of Commerce 1: 263-278.

Reimnitz, E. & Bruder, K.F. (1972): River discharge into an ice-covered ocean and related sediment dispersal, Beaufort Sea, coast of Alaska.- Geol. Soc. Amer. Bull. 83: 861-866.

Reimnitz, E., Rodeick, C.A., & Wolf, S.C. (1974): Strudel scour: A unique arctic marine geologic phenomenon.- J. Sed. Petrol. 44: 409-420.

Reimnitz, E. & Maurer, D.K. (1979): Eolian sand deflation as a cause for gravel barrier islands in Arctic Alaska?.- Geology. 7: 507 - 510.

Reimnitz, E. & Kempema, E.W. (1983): High rates of bedload transport measured from the infilling rate of large strudel-scour craters in the Beaufort Sea, Alaska.- Continental Shelf Res. 1: 237-251 (plus erratum in next issue for missing page).

Reimnitz, E. & Kempema, E.W. (1987): Field observations of slush ice generated during freeze-up in Arctic coastal waters.- Mar. Geol. 77: 219-231.

Reimnitz, E., Clayton, J.R., Kempema, E.W. , Payne, J.R. &. Weber, W.S. (1993): Interaction of rising frazil with suspended particles: Tank experiments with applications to nature.- Cold Regions Sci. Technol. 21: 117-135.

Reimnitz, E. (1997): Strudel-scour craters on shallow arctic prodeltas.- In: T.A. DAVIES, T.B., A.K. COOPER, H. JOSENHANS, L. POLYAK, A. SOLHEIM, M.S. STOKER & J.A. STRAVERS (eds.), Glaciated continental margins: An atlas of acoustic images. London, Chapman & Hall: 146-147.

Walker, H.J. (1973): Spring discharge of an arctic river determined from salinity measurements beneath sea ice.- Water Resources Res. 9: 474-480.

Walker, H.J. (1974): The Colville River and the Beaufort Sea: Some interactions.- In: J.C. REED & J.E. SATER (eds.), The coast and shelf of the Beaufort Sea. Arlington, VA, The Arctic Institute of North America: 513-539.

Weeks, W.F. & Ackley, S.F. (1982): The growth, structure and properties of sea ice.- Hanover, N.H., CRREL Monogr. 82-1: 130 pp..

Wright, L.D., & Coleman, J.M. (1973): Variations in morphology of major river deltas as functions of ocean wave and river discharge regime.- Amer. Assoc. Petrol. Geol. 57: 370-398.

Zubov, N.N. (1945): Arctic sea ice.- Translated by Naval Oceanographic Office and American Meteorological Society under contract to Air Force Cambridge Research Center, 1963. U.S. Naval Electronics Laboratory, San Diego, Calif.: 491 pp..