FIELD OBSERVATIONS ON SLUSH ICE GENERATED DURING FREEZEUP IN ARCTIC COASTAL WATERS .

by

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ABSTRACT

In some years, large volumes of slush ice charged with sediment are generated from frazil ice in the shallow Beaufort Sea during strong storms at the time of freezeup. Such events terminate the navigation season, and because of accompanying hostile conditions, very little is known about the processes acting. The water-saturated slush ice, which may reach a thickness of 4 m, exists for only a few days before freezing from the surface downward arrests further wave motion or pancake ice forms. Movement of small vessels and divers in the slush ice is accomplished only in phase with passing waves, producing compression and rarefaction, and internal pressure pulses. Where in contact with the seafloor, the agitated slush ice moves cobble-size material, generates large sediment ripples, and may possibly produce a benchlike feature occasionally observed on the Arctic shoreface. Processes charging the slush ice with as much as 1000 m^3/km^2 of sediment remain uncertain, but our field observations rule out previously proposed filtration from turbid waters as a likely mechanism. Sedimentary particles apparently are only trapped in the interstices of the slush ice rather than being held by adhesion, since wave-related internal pressure oscillations result in downward particle movement and cleansing of the slush ice. This loss of sediment explains the typical downward increase in sediment concentration in that part of the fast ice canopy composed largely of frazil ice. The congealing slush ice in coastal water does not become fast ice until grounded ridges are formed in the stamukhi zone, one to two months after freezeup begins. During this period of new-ice mobility, long-range sediment transport occurs. The sediment load held by the fast ice canopy in the area between the Colville and Sagavanirktok River deltas in the winter of 1978-79 was 16 times larger than the yearly river input to the same area. This sediment most likely was rafted from Canada, more than 400 km to the east, during a brief time period in the previous fall. Ocean turbulence is greatly reduced while the congealing slush ice drifts about. Therefore, new ice then forming in intervening open-water areas is clean. These events explain the patchy appearance of the fast ice after the summer snowmelt. More work on the important phenomena reported here is needed to close a major gap in the knowledge of the Arctic marine environment.

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INTRODUCTION

The short period when a new ice canopy forms may be geologically the most important time of the year in arctic seas. At this time processes are intensely dynamic, and the ice cover that forms influences the environment most of the following year. Freezing fall storms remove heat from the water and in a very short time may generate large amounts of frazil ice that rises and is incorporated into the new ice canopy, thereby speeding up its formation. The ice canopy initially is a slush composed of ice grains and water. *This* slush often contains entrained sediment, and in glossaries is called grease ice, ice gruel, frazil slush, sludge, slob, lolly ice, cream ice, new ice, and shuga (for example, U.S. Navy Hydrologic Office, 1952; World Meteorological Organization, 1970; Bates and Jackson, 1980). The distinctions (if any) between all these terms are subtle and appear unclear to us. In our own work we therefore initially followed the recent usage by Martin and Kaufmann (1981), where the term grease ice was applied to accumulations of granular, water-saturated ice of any thickness. A reviewer, however, pointed out that the usage intended for the term was for the soupy layer formed from the first frazil ice rising to the surface and giving the sea a greasy or matte appearance. Since there is no satisfactory, generally accepted term among those listed above we here use the descriptive phrase "slush ice" to denote a water-saturated, internally mobile surface layer of granular (not restricted to frazil) ice that may vary in thickness from a few centimeters to several meters. The thicker accumulations described later clearly are not greasy.

Marine research traditionally is done either in the summer open-water season with standard oceanographic techniques or from the winter ice canopy once it is firmly established. For this reason, almost nothing is known about processes that occur during the transition period from the navigation season to that of winter ice travel. During the past 15 years of arctic marine research, we have witnessed this transition several times, at first involuntarily and later deliberately. Such experiences led us to read accounts by early explorers in search of descriptions of the unique properties and behavior of slush ice. In this report we repeat some of those observations on how the sea virtually turns to "applesauce" and document some of our own reconnaissance observations made during freezeup. We believe that huge volumes of sediment move during such sporadic events, and that the bottom is reshaped by slush ice in very shallow water. Because processes during the period are important geologically, we review here sparse information that may shed light on them, but this work can be considered no more than a small step toward the basic knowledge on the topic needed for the rapid offshore development in the Arctic.

BACKGROUND INFORMATION

During an open-water storm with freezing air temperatures, frazil-ice crystals 1 to 5 mm in diameter may form throughout the upper mixed layer of the turbulent, slightly supercooled sea (Martin, 198 1). On the surface, the frazil ice, sometimes mixed with snow, is aligned in long wind-parallel plumes (fig. 1) marking **secondary (Langmuir) circulation patterns (Martin and Kauffman, 1981). The equivalent of as much as 2 m of ice can be produced at a site within a 20-hour period, as long as enough open water remains between plumes for heat transfer to the atmosphere (Weeks and Ackley, 1982). Frazil ice under the influence of strong winds moves across polynyas, and at the downwind end of these may be swept underneath solid ice sheets in accumulations more than 4 m thick (Bauer and Martin, 1983). When the wind subsides, all frazil ice, sometimes along with dislodged anchor ice, rises to the surface** where it may mix with snow and form a layer of slush ice. Surface circulation may drive this slush ice into lagoons, embayments, and against flow obstacles (fig. 2), where thicknesses of 4

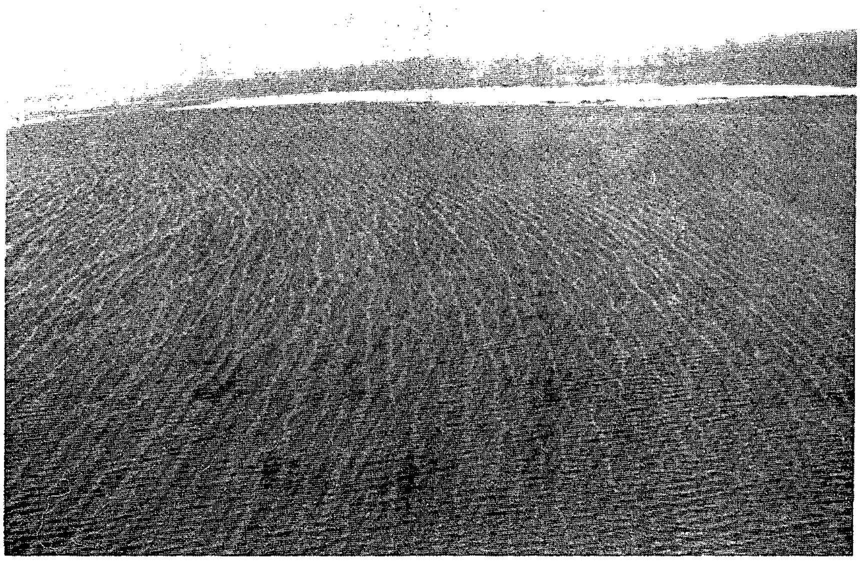

Figure 1. Wind-parallel streaks of newly forming slush ice marking secondary circulation patterns within a 2-m-deep lagoon.

Figure 2. Accumulation of slush ice herded by wind and waves against a snow-covered beach. The white bands in the ice, oblique to the beach, mark advancing wave fronts where slush ice is compressed and the ice surface dry.

m and greater have been reported (Collinson, 1889; Morecki, 1965; Reimnitz and Dunton, 1979). The only study of the physical properties of the slush ice in a wave field is that by Martin and Kauffman (1981), who conducted experiments in a tank. They found that waves in the tank are damped within 4 to 6 wavelengths of travel through the slush ice. The slush ice is a non-Newtonian fluid, behaving as a solid at low shear rates, where sintering between ice crystals becomes effective and as a fluid at high shear rates.

When large volumes of frazil ice are produced on the shallow Beaufort Sea shelf by freezeup storms, the resulting slush ice is enriched with fine-grained sediments by unknown mechanisms (Barnes et al., 1982; Osterkamp and Gosink, 1984). Osterkamp and Gosink (1984) discussed nine possible mechanisms that might result in the observed high sediment loads earned by ice over that of open-water suspended-sediment loads. Our field observations shed some light on several of the proposed mechanisms. Whatever the sedimentary particle-entrainment mechanism, sediment is later exposed by summer melting of snow and upper-ice layers and consequently reveals the extent of slush ice during the previous fall. This is shown in Figure 3, a computer-enhanced Landsat image. Melting of the seasonal fast-ice canopy was aided by reduced albedo resulting from sediment inclusions, which have highest concentrations in shallow coastal waters. The water beneath this turbid ice canopy is in total darkness even on sunny spring days, thereby restricting primary biological productivity to a few summer months (Dunton et al., 1982).

SLUSH ICE OBSERVATIONS

Sailing-Ship Observations

An older glossary of ice terminology (U.S. Navy Hydrographic Office, 1952) listed "slob" as a dense form of sludge, originally delined as being so dense as to impede the progress of sealing vessels. The scientific literature has not previously discussed the properties and behavior of slush ice in nature, as far as we know. An informative encounter with such slush ice, however, is described in the journal of *H.M.S. **Enterprise*** (Collinson, 1889, p. 239). In late September 1852, the *Enterprise* sailed toward Cambridge Bay in the Canadian Arctic. During the night of September 24, the temperature fell to -11 'C with the onset of a northerly gale that lasted through the 27th. Collinson feared the bay would get choked with "bay ice." The vessel ran aground on the 28th, surrounded by water depths of 3 to 5 m, while the gale was subsiding. The wind was still strong when Collinson recounted: "the sludge was so thick that we had great difficulty in laying out our stream anchor" (a light bow anchor). The ship's sailing cutters were used to transfer winter stores and gear to shore. On the 29th, "the sludge rendered the communication with the shore very precarious, the boats sometimes being within half a cable's length of the ship, and not getting on board for an hour. The cutter in one instance remained stationary half an hour, although there was as much wind as the mast would stand. " After four days (October 2), the ice was firm enough to walk to shore. On October 3, "the sludge about the ship was 10 to 12 ft [3-4 m] deep; and such was its consistency that immediately after a block of ice was cut out and removed, the hole filled, and having exactly the same appearance as the firm ice, many of the men fell in." In May of the following year, the ice thickness was 8 ft 2 in [2.5 m] around the vessel.

A quite similar experience is told in "Captain Bob Bartlett's briny boast: Shipwrecked fourteen times" (Bartlett, 1927). In early March, the sailing ship *Leopard* was on a seal hunt in foul weather with slush ice forming along the rocky Labrador coast. "This ice had formed a sludge, fathoms deep, so that we couldn't even use our hand lead." At midnight, "it began to

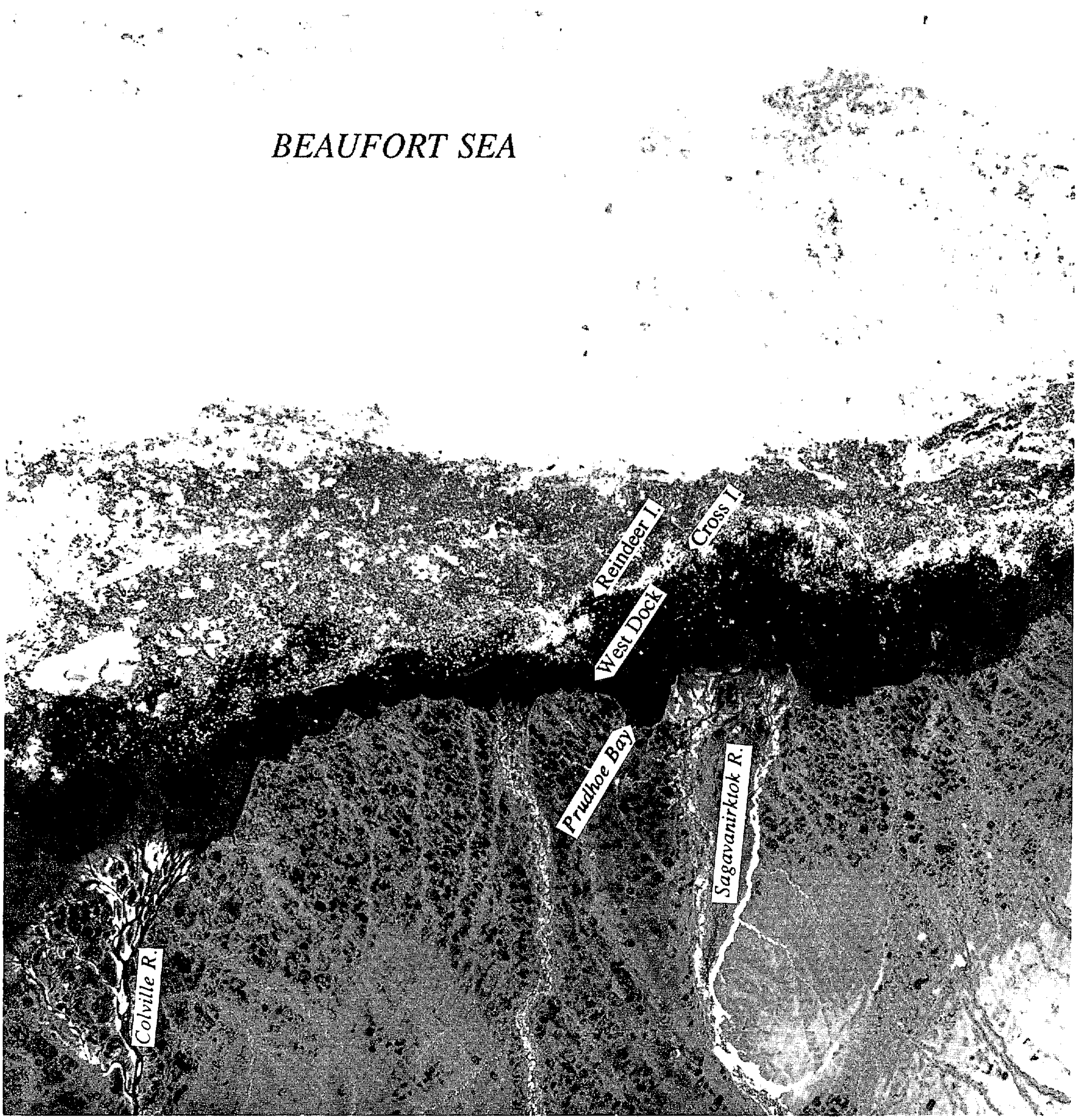

Fig. 3. Landsat image of July 15, 1979, computer-enhanced to show the sediment layer on the ice surface, and thereby the extent of sediment-laden slush ice during October 1978. The ice between the Colville and the Sagavanirktok Rivers is estimated to carry 16 times more sediment at this time than the yearly input by these two large rivers. Image produced by William Acevedo, U.S.G.S.

snow a perfect smother. You couldn't see your hand before your face." Shortly thereafter, they shipwrecked on a rock. "I set them to work right away ripping off sheathing, oars, spars, and other spare timber. These they laid on the slush ice, forming a sort of roadway over to the other wreck. It sounds simple enough, but the ice was just wet slush, a sort of snowy quicksand with water all through it."

Recent Observations

Several sets of observations that we made in the Alaskan Beaufort Sea shed additional light on the extremely viscous nature and strange behavior of the slush ice and therefore are described in some detail. These observations were made in the fall of 1982, when we extended field studies to include freezeup.

The R/V Karluk. On September 30, the air temperature was about -5 "C, the wind was blowing from the northeast at 15 m/s, and frazil ice was forming in coastal waters near Prudhoe Bay. The West Dock, a 4-km-long gravel causeway at nearly right angle to the wind direction, was trapping frazil ice on its east side, particularly in bights between moored barges. In one such place, steep waves of 1.2 to 1.5 m height and 3.5 s period were subdued as they traveled through a 120-m wide accumulation of slush ice, where the water depth was nearly 3 m. Because the sea was too rough for any kind of Oceanographic work, we chose the area with slush ice for a diving investigation. From shore we observed that the waves propagated through the slush ice all the way to the beach, giving us the false impression that the slush ice had the consistency of pea soup and would be suitable for diving. Sailing the 12-m *Karluk* downwind into the calm part of the slush ice, with a steep following sea and whitecaps, the wave motion of the boat gradually decreased. In order to anchor the vessel at a point about 60 m into the slush ice, she first had to be turned 180° to point into the wind. Now the unique characteristics of the slush ice became apparent. At half-power ahead and hard-right rudder, the vessel neither advanced or turned. Only after several minutes, a slight heading change was noted, and we realized that minute cyclic heading changes occurred in phase with passing waves. Eventually, when the boat was properly positioned, the anchor and chain were lowered, but they initially came to rest on the very surface of the slush ice. About eight waves passed before the anchor broke through the bottom of the slush ice. The cyclic settling rate again made cyclic strength changes of the slush ice very apparent: settling of the anchor occurred between passing wave fronts, which were marked by dry-appearing white patches or bands (fig. 4).

A Grease-Ice Dive. The scuba-diving operation held similar surprises. Jumping fully equipped feet-first from a height of 1 m from the boat, our fall was first arrested about waist-deep into the slush ice, and we then settled with each passing wave. Unable to extract our arms from the dense slush ice, or to rotate around a vertical axis, we needed assistance from the deck to keep our heads above ice. Wave motion of the slush ice produced pronounced cyclic pressure pulses on our chests. These pressure pulses expelled the air from the dry suit around our face seals until all excess buoyancy was lost. Only with the aid of a heavy weighted line were we able to force our way down and back up through the 75-cm thick slush ice. The lower part of the layer was distinctly more fluid than the upper part. Figure 5 shows a diver resting on the viscous slush ice agitated by surface waves. Lying thus on the surface felt rather similar to resting on a waterbed.

A small pressure-sensitive transducer coupled to a recorder was used to measure the surface-wave amplitude and related pressure fluctuations within the slush ice. For the latter

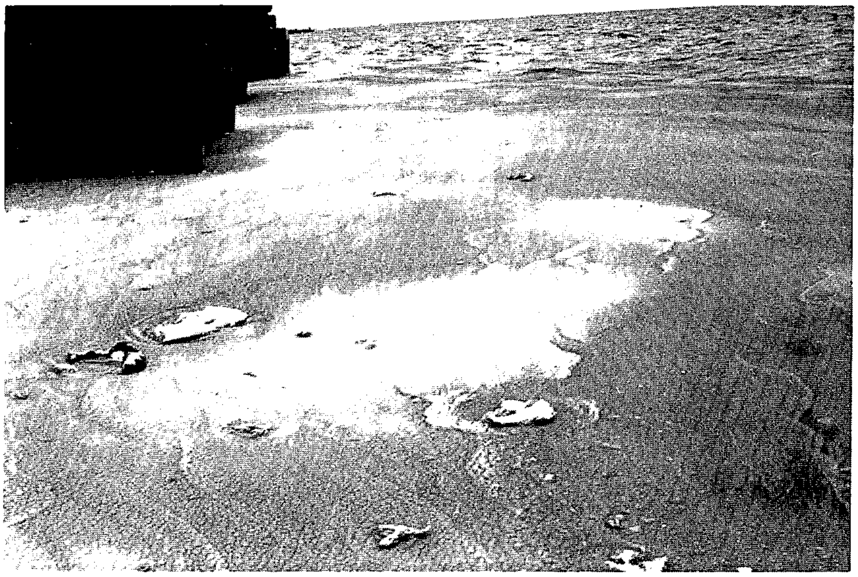

Figure 4. Accumulation of slush ice driven by wind into a bight between two barges along the Prudhoe Bay West Dock. While the passage of waves makes the slush ice appear fluid, both the R/V Karluk *and divers had difficulty maneuvering within it. The white patches of dry-appearing slush ice mark pressure pulses traveling in phase with advancing surface waves.*

Figure 5. Fully equipped diver supported by the wave-agitated slush ice. Lying on this slush ice felt similar to lying on a (cold) waterbed.

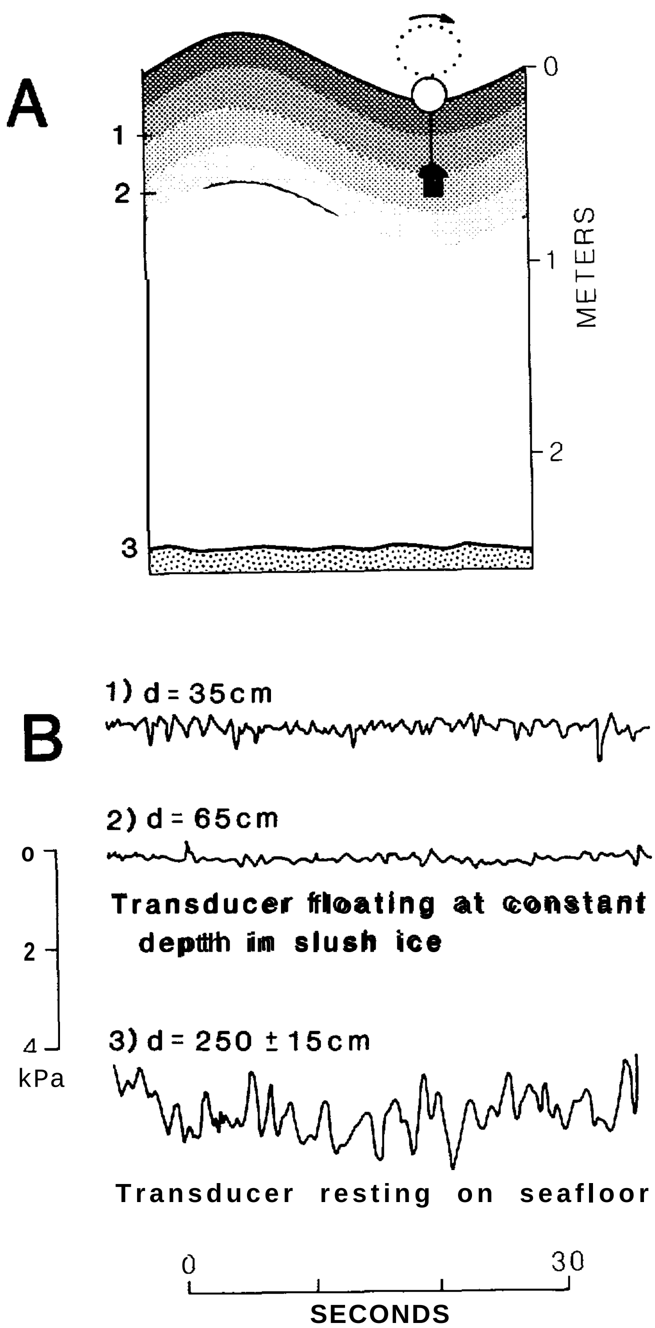

Figure 6. A) Schematic view of pressure transducer suspended in slush ice layer, and the three points at which pressure oscillations were measured sequentially within a half-hour period. B) Traces of pressure oscillations recorded at points 1, 2, and 3. The bottom trace represents the surface-wave amplitude.

measurements the transducer was held first at 35 cm and 5 minutes later at 65 cm depth within the slurry by hanging from a buoy that was allowed to freely follow the waves orbital motion. This is shown schematically in figure 6A. To measure the amplitude of surface waves shortly thereafter, the transducer was simply laid on the bottom at 2.5-m depth. The three traces of pressure fluctuations thus recorded are shown in figure 6B. The irregular surface-wave pattern is a result of refraction and reflection interference from large nearby obstacles. At 65-cm depth, in the lower more fluid part of the slush-ice layer, the pressure pulses have less amplitude than at 35-cm depth.

Throughout the 5-hour period anchored at the site we observed a slow but constant shoreward flux of individual ice pieces 10-cm to 30-cm-across incorporated into the slurry and floating on its surface.

Miscellaneous Observations off Cross Island. On October 4, a small swell from the northwest with a 2-s period was driving frazil ice into a small bight on the seaward side of Cross Island (fig. 3). The belt of slush ice accumulating at this site was 100 m wide. During a preceding time of slightly higher sea level, the wave train apparently had shoved such slush ice onto the beach, forming a layer of well-drained granular material. Right along the water's edge this deposit was terminated by a 50-cm-high vertical scarp against which the slush-ice waves were lapping without breaking (fig. 7). Wading seaward from the scarp, the force of the wave-agitated slush ice became noticeable and increased with water depth, until at 10-m distance and 95-cm depth, the excursions of the slush ice with passing waves caused our feet to slide across

Figure 7.- View of the Cross Island study site, where wave-agitated slush-ice in bottom contact to 95-cm depth was generating 50- to 75-cm-long ripples in coarse sand, and cobbles were rolling to and fro.

the bottom. At this point, the slush ice was in contact with the seafloor. We felt 20-cm-high sharp-crested ripples with an estimated wavelength of 50 to 80 cm in coarse sand. When we shifted weight to one foot, firmly implanting it in the sand, our ankles were struck by fist-size cobbles rolling to and fro.

A 24-hr experiment was begun at about 1-m depth to investigate the behavior of sediment within the framework of larger ice crystals where the mixture was subjected to oscillating pressure pulses. For this purpose, we mixed slush ice with medium-grained sand from the site and put the seawater-saturated slush into three 75-cm-long, 10-cm-diameter clear plastic bags. The bags were inserted vertically into the slush ice, and their lips nailed to a l-m-long "two-by-four" board floating on the slush. The board in turn was secured to a buoy with an anchor rated at over 1-ton horizontal holding power in sand. Measured over a 3-minute period, the array was oscillating an average of 35 cm with each wave, with a maximum displacement of 75 cm. The maximum wave amplitude measured during that time was 25 cm. Upon returning to the experiment site on the next day, we found that the anchor had been moved 8 m obliquely onshore into 30-cm water depth. Only one of the bags remained intact. All sand had settled to the bottom in this bag, leaving the slush ice entirely clean except for several remaining fine pieces of organic matter.

At the experiment site, a flexible 20 x 25-cm hot-water bottle fitted with a sight-glass was suspended vertically in the slush ice, with the sight-glass protruding above the surface. This crude manometer was allowed to oscillate freely with passing waves, while the fluid level in the sight- glass was monitored during the passage of 20 waves. The amplitude of the pressure pulses thus measured ranged up to 1 kPa (about 11 cm of water column), and thus were similar to those recorded in figure 6. The ice content in the slush surrounding this bottle measured 62% by volume.

General Observations. Beaufort Sea aerial observations between longitude 147° and 15 1°W during and after numerous freezeups give us the following general impressions of the fate of slush ice, and of how the winter ice canopy is initially established.

Large volumes of slush ice are produced only in those years in which the navigation season is terminated by freezing winds with velocities of at least 10 m/s and temperatures of - 10"C or colder. Such combinations usually occur with east to northeast wind directions, an important factor to consider when speculating on the sources and dispersal of sediment incorporated within the ice. This typical wind direction also determines the most efficient trapping orientations for flow obstacles, such as lines of grounded ice (fig. 3) or islands. We believe that the largest amounts of sediment are incorporated into the slush ice in years when the pack is 50 km or more from the coast, resulting in a long fetch.

The period in which there is 50% or more of open water for the generation of frazil ice on the inner shelf may last from just a few days to nearly a month. It generally starts in the last week of September, but has been known to start and terminate as early as the first week of September (Stefansson, 1921). Freezeup can also be delayed until the second half of October. Judging by the volume of soft ice with sediment seen under the winter ice-canopy by divers in about 6 years of records, and by the amount and extent of sediment found in the seasonal ice canopy in 15 years, we believe that during the past 15 years the fall of 1978 produced the most slush ice with sediment (fig. 3). This freezeup, apparently lasting only for a several-day period around October 6 to 8 (Reimnitz and Dunton, 1979), was also of the shortest duration.

Freezeup in the fall of 1982, in which the above described experiments were conducted and our first direct observations on anchor ice were made (Reirnnitz et al., 1986), was spread out over a period of a month. The first threat of freezeup, restricting our research operations to the close vicinity of Prudhoe Bay, was seen on September 18. **A lack of open water and rapid thickening of new ice eventually forced us to haul out the boat on October 7. However, on October 19 and 20, a 25 m/s storm from the southwest broke up and drove off the new 20-cm-thick ice. The storm also broke the moorings on Arctic Marine Freighters' fleet of tugs and barges that had** long ago been winterized, and drifted much of this equipment 175 km eastward to the vicinity of Barter Island during a two-day period. Here the equipment was secured, while the new ice that had been displaced along with the barges kept on moving eastward. Because of a small offshore component in the wind direction, a zone of the inner shelf 20 to 30 km wide, including many of the lagoons was swept clean of first-year ice (Kenneth Vaudrey and Steven Amstrup, oral commun., 1982). On the second day of the storm, notable frazil ice was generated. This event demonstrates how mobile the new ice canopy can be under certain conditions, and also the minimum distances over which the sediment load in the ice canopy can be transported before the true fast ice has been established.

Some open-water seasons end without climactic events, and therefore without the production of large volumes of frazil ice. The summer of 1985 was such a season. We extended our field work to include freezeup, but neither large amounts of slush ice nor anchor ice were generated. Such freezeup conditions lead to the growth of a clean fast-ice canopy without a significant amount of sediment. As a result, light easily penetrates through the ice canopy. In such winters, the water turbidity under the ice cover also is low. An extreme case was the winter from 1970 to 19'71, when the horizontal visibility in the water beneath the ice canopy near Prudhoe Bay in May measured over 60 m (Thomas Scanland, Marine Advisors, written commun., 1971). The 1978 freezeup (fig. 8), on the other hand, locally resulted in 4-m-thick masses of slush ice with large sediment loads (Reimnitz and Dunton, 1979) and led to almost total elimination of sunlight below the ice (Dunton et al., 1982). Within one month after freezeup, large amounts of suspended matter slowly released from the slush ice reduced visibility in the water to 1 to 2 m, but sediment fallout from disturbing the slush temporarily reduced visibility to 0.5 m.

During the climax of frazil-ice production, waves are propagated for several kilometers through fields of slush ice, depending on the thickness of the **layer.** From wave tank studies **(Martin and Kaufman, 198 1) and our field observations, the slush ice thins in a windward direction toward open water.** Even short steep storm waves propagated into slush ice do not break over the fringes of the slush fields, but are gradually subdued over the distance traveled (fig. 9). The slush ice, whether in large fields, in patches, or in wind-parallel **streaks, moves** with the wind-driven surface water, except where it is piled up against stationary ice or land. Waves may agitate the slush ice for several days before it congeals. Our observations indicate that pancake-ice formation is relatively uncommon in the Alaskan Beaufort Sea. With continuing cold after a storm subsides, the slush ice congeals from the surface down, Once congealed, this somewhat turbid ice canopy usually is broken again under shearing or tensional forces. Tensional forces acting on a congealed slush ice sometimes result in the formation of elongate floes with geometric shapes (fig. 10). The resulting floes of a large variety of shapes and sizes subsequently may be extensively rearranged. As discussed earlier, the rearrangement may displace such **new ice floes** over distances of hundreds of kilometers before a continuous ice canopy forms. **Because the sea,** cluttered by new ice floes, is no longer agitated by storm waves during this period, suspended matter settles out of the water, and the new ice growing in the spaces between the floes may be entirely clean and transparent.

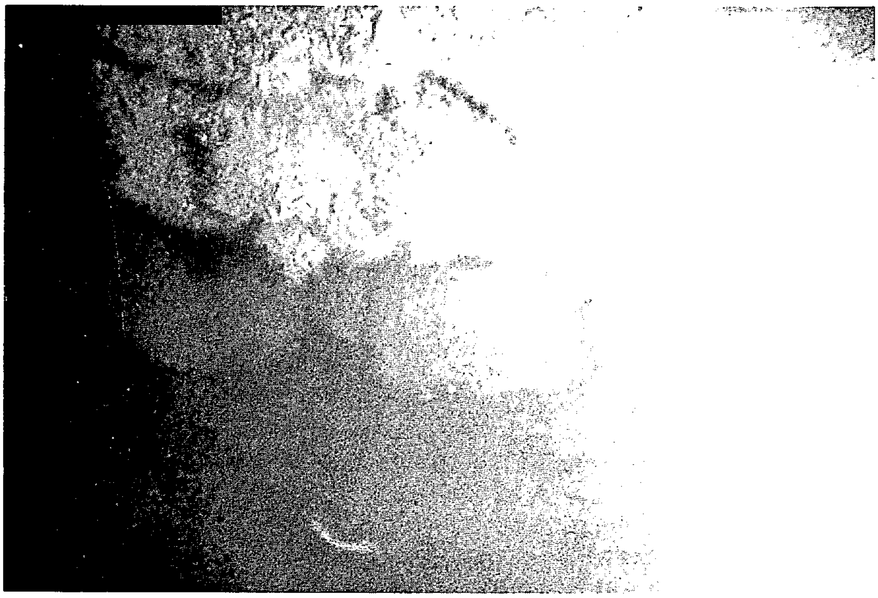

Figure 8. Bottom view of soft, sediment-laden slush ice in March 1979. Any disturbance by divers resulted in a rain of sediment into the water. The field of view in the background is 2-3 m.

Figure 9. Storm- whipped waves traveling from open water in the background into 15-cm-thick slush ice without breaking over the windward edge.

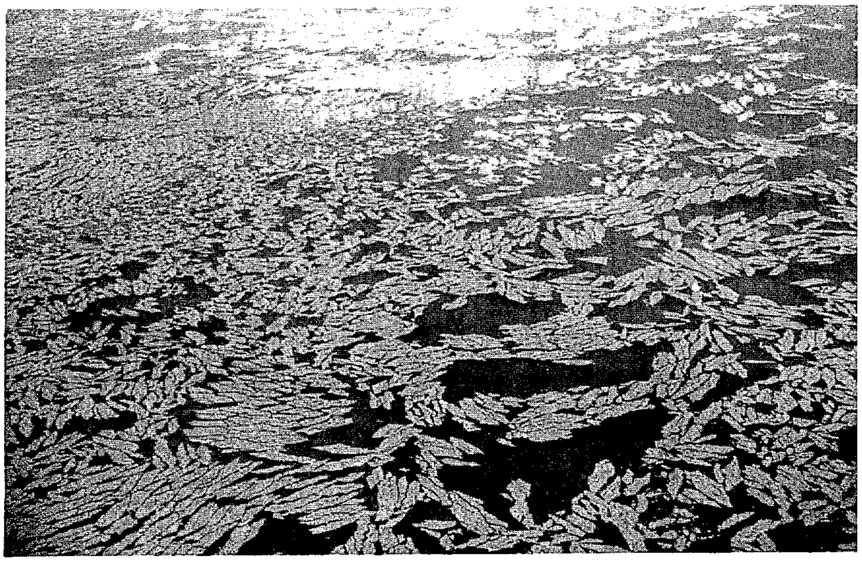

*Figure 10.- Congealed slush ice breaking up under tension. The breakage pattern suggests that the ice is anisotropic, possibly due to ice-crystal orientation caused by **waves passing through** slush ice. The estimated sliver length is 8m.*

Within a month or two after freezeup, a zone of grounded pressure and shear ridges on the midshelf, called the stamukhi zone, is established, thereby stabilizing the fast-ice canopy on the imer shelf (Reimnitz et al., 1977). After this, major ice movement over the inner shelf is rare. During years in which this new ice is composed largely of slush ice containing sediment, pressure ridges are constructed of brown ice, which is very conspicuous in the following navigation season.

DISCUSSION

The field observations serve to illuminate one aspect of sea ice that has been largely ignored where geologic processes are concerned. As far as we know, almost no work has been done on sediment dynamics related to slush ice, nor on its behavior and effects in a wave train.

Where frazil-ice crystals are concentrated by wind and waves against a beachface, they are compacted into a highly viscous slush. While further agitated by waves, this viscous ice blanket provides for littoral processes different from any studied so far. At the Cross Island site, cobbles were moving with each small passing wave in a zone at least 10 m wide out to a depth of 95 cm. The observed 50- to 80-cm wave length of sediment ripples matches the average orbital diameter measured at that site. These two facts indicate that the slush ice actively shaped the bottom during the two days of the experiment. A very gently sloping, smooth shoreface 10 to 30 m wide, extending out to the 2- or 3-m isobath, characterizes the seaward side of nearby Reindeer Island in some years (Reimnitz and Barnes, 1974; Reimnitz and Kempema, 1982, Reimnitz et al., 1986). In **other years that** same shoreface is marked by a well-defined, narrow trough directly adjacent to the beach and paralleling it for several kilometers (Reimnitz and Kempema, 1982, fig. 2). A possible explanation for the occasionally very flat shoreface off Arctic beaches is the abrasive action of slush ice worked by a wave train.

The 2 to 3-m depth of the sharply defined outer edge of the shoreface then could record the thickness of the slush ice during the previous freezeup. A wave-agitated slush ice may also lead to sediment sorting. Thus, a strip of pea-size gravel was noted forming on the beach face at Barrow, Alaska, during a storm when the surf zone turned into a rolling slush of frazil ice (Sackinger, oral commun., 1985).

Our observations do not suggest any new mechanisms for sediment enrichment of frazil ice in the sea, besides those that were proposed by Osterkamp and Gosink (1984), but two of the methods they proposed clearly can be eliminated from consideration. First, turbid water carried by waves overtopping the slush ice was suggested to percolate down through the ice, which in turn filters out the particulate matter (Osterkamp and Gosink, 1984). Waves do not break over slush ice, but they can propagate through the ice for kilometers. Second, currents were suggested to flow past slush ice, to result in a pressure differential through slush, which in turn leads to percolation of turbid water through the slush and filtration of particulate matter (Osterkamp and Gosink, 1984). In the sea, unlike rivers, the surficial slush ice normally moves with the surface water. The proposed mechanism therefore could operate only in very special settings of limited aerial extent.

In tank experiments, waves seem to travel only several wavelengths into the slush ice, beyond which a "dead zone" with no motion is established (Martin and Kaufman, 1981). We believe that this dead zone is an artifact of slush ice confinement in a tank and does not apply to the open spaces of the sea. Here waves are propagated for at least several kilometers through an ice slush as thin as that observed in wave tanks. Studies of slush ice generated in a wave tank indicate an imbrication of individual crystals at right angles to the wave orthogonal (Martin and Kaufman, 1981). W.F. Weeks (oral commun., 1986) also saw indications of crystal alignment in nature. The breakage pattern in congealed slush ice into elongated slivers (fig. 10) suggests that the ice is indeed anisotropic, perhaps from wave-reworking resulting in preferred crystal orientation.

Any disturbance of the slush ice, such as from wave action, has a cleansing effect. This was demonstrated by the Cross Island experiment, in which downward particle movement under the force of gravity probably was aided by oscillatory flow of interstitial water. Purging of sediment was also observed in winter diving, when we thrust our arms into the slush ice overhead (Reimnitz and Dunton, 1979). From this we infer that individual frazil crystals in a slush are not sticky, even if they originally acted as scavengers adhering to sedimentary particles (Osterkamp and Gosink, 1984). The property of the slush ice to release sediment on agitation supports the suggestion by Osterkamp and Gosink (1984) that sedimentary particles reside mainly in interstitial water, rather than within ice crystals. Cores taken from sediment-laden ice in winter reveal a characteristic downward increase in concentrations of finely disseminated sedimentary particles in that part of the ice canopy that originated from frazil ice accumulations. The origin of the turbid ice has been ascribed to processes at time of freezeup, but the downward increase in sediment concentration was uncertain (Barnes et al., 1982; Osterkamp and Gosink, 1984). The downward mobility of particles in agitated slush ice demonstrated by our field observations provides a satisfactory explanation for the downward gradient in sediment concentration. Where the slush ice layer is less than 2 m thick, clear columnar ice grows below later in the season. A sharp boundary between upper turbid ice and lower clear ice has commonly been noted in late-winter ice cores.

The self-cleansing **property** of **fresh** slush ice, coupled with the evidence ruling out subsequent processes of sediment enrichment, indicate that the enrichment occurs by the scavenging action of **frazil** ice or floes in the water column or on the bottom (**Osterkamp** and Gosink, 1984; Kempema et al., 1986). Particles as large as coarse sand have been observed within actively forming slush ice in 2 m water depths (Reimnitz et al., 1986). The occurrence of frazil ice and floes on the Beaufort Sea shelf probably is **restricted** to the upper 20 m of the water column, the approximate thickness of the mixed layer (**Reimnitz** et al., 1986). Thus the sediment scavenging action on the seafloor is restricted to the shelf surface landward of the **stamukhi** zone, Whatever the precise mechanism of particle scavenging may be, the **frazil** ice must remain undisturbed after rising to the surface in order to retain the original sediment load. Such optimum conditions for achieving maximum sediment concentrations in the fast ice probably are rarely met, since wave and other processes continue to agitate the slush layer for several days before congelation arrests the sediment.

The 1978 **freezeup** may have provided nearly optimum conditions for sediment retention by slush ice. The regional extent of the slush-ice cover for that season, as delineated by a surface sediment cover, is shown in figure 3. At the time of the Landsat image, the surface sediment layer was between 0.1 cm and 1 cm thick near **Prudhoe** Bay, and the sediment load on top of the ice was estimated at 1000 m^3/km^2 (Northern Technical Services, 1981). But this estimate considers only the sediment concentrated on the ice in mid July by **surficial** melting, and excludes that still held within the remaining ice, The **total** sediment load carried by the ice prior to melting therefore probably was higher. We applied the above sediment load to the total area of discolored ice between the **Colville and Sagavanirktok** Rivers in figure 3, to calculate a total sediment load **carried** by ice. Comparing the results to the sediment supplied by rivers yearly to the same area from **Reimnitz** et al. (1985), we find the sediment load on the ice 16 times larger. This comparison implies that the processes leading to the formation of slush ice are erosive.

During the following summer we observed that most of the sediment-laden ice still seen intact in figure 3 melted locally and discharged its load to the water column before breakup allowed long-distance ice excursions. Sediment-rafting during the decay of first-year ice therefore is insignificant in the overall transport regime (**Reimnitz** and Barnes, 1974). As shown earlier, rafting during the dynamic period of incipient ice growth can cover long distances. **Frazil** ice with entrained sediment within the fast ice may have originated far away. **Reimnitz** and Dunton (1979) showed that most of the slush ice incorporated in the winter ice canopy in **figure** 3 must have formed during the **first** few days of October 1978. From October 5 through October 9, wind from **the** east was gusting to 20 **m/s** at Barter Island, and averaged 12.5 rids. From spot measurements of **currents, local** tracking of ice floes, and many years of summer field observations, surface currents of 1 m/s (2 knots) are common on the imer shelf under such wind conditions. Assuming a westward **drift** rate of 1 **m/s** for 5 days, all of the slush ice and sediment seen in figure 3 had traveled 430 km before coming to rest within the study area. The sediment seen discharged by melting ice in the study area therefore may have had ita origin in Canada.

SUMMARY AND CONCLUSIONS

Large volumes of slush ice generated over several-day periods during strong fall storms at freezeup may math thicknesses of 4 m in coastal waters of the Arctic. Waves propagate through the slush ice for kilometers, resulting in internal pressure oscillations associated with compression and rarefaction. The compacted slush ice may be nearly impenetrable for small vessels and divers, allowing progress only in small increments, in phase with advancing waves. Where slush ice is in contact with the bottom, large ripples develop and cobbles roll to and fro. Flat ramparts seen on the arctic shoreface in some years also may possibly result from the abrasive action of the slush ice layer.

The slush ice may carry up to 1000 m^3/km^2 of mainly fine grained sediment. This sediment probably is entrained by individual frazil-ice crystals or floes scavenging from the bottom or the water column during storms and subsequently rising to form a slush-ice layer up to 4 m thick. Contrary to theory, post-frazil-ice filtration processes do not seem to add sediment to the slush ice, The sediment particles reside in the interstices of slush ice. Any disturbance of the layer, such as the passage of surface waves, results in a downward migration of individual particles in the water-filled interstices and a rain of particles from the slush ice. Downward particle migration and particle loss from the bottom of the slush ice explains the characteristic downward increase in sediment concentration in the winter ice canopy, and the sharp contact between upper turbid ice and lower clean ice. Downward migration of sediment particles in slush ice indicates that individual frazil crystals at this stage are not adhesive.

Slush ice in coastal regions does not become fast ice until formation of grounded ridges in the stamukhi zone, 1 to 2 months after freezeup begins. During this period of new ice mobility, long-range sediment transport occurs. The sediment load of 1000 m^3/km^2 held by the fast ice off Prudhoe Bay in the winter of 1978-79 probably had its source on the Canadian shelf surface, at least 400 km to the east. Ocean turbulence is greatly reduced while the congealing slush ice drifts about; therefore, new ice forming on open spaces is clean, This series of events explains the patchy appearance of the fast ice after the summer snowmelt.

The processes related to the formation and movement of slush ice are not only important for the sedimentary environment. Major slush-ice production during the fall affects the overall marine environment in the fast-ice zone for the following 9 months. Sediment incorporated into the slush ice leads to a strong reduction of fast-ice albedo, and therefore increases the summer melting rate. Sediment entrainment also affects the strength of the ice, and could be very important for dispersal of future pollutants. Water below turbid ice also is very turbid from sediment settling out. Most important of all are the effects on life below the ice canopy. A heavy load of sediment in slush ice results in almost total elimination of sunlight to primary producers below the ice and therefore affects the entire food web for a long period of time. Full-scale slush-ice production in the Alaskan Beaufort Sea is restricted to a short period of time, and does not even occur each fall. Similar processes may be occurring each year, and for longer periods of time, in perennial polynyas of the Canadian Arctic (Dunbar, 1986) and recurring polynyas in the Chukchi and Bering Seas. Our lack of full understanding of the important phenomena reported here represents a major gap in the knowledge of the Arctic marine environment.

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