Freezeup Processes on Arctic Beaches

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ABSTRACT. Observations made along the northern Alaskan coast during 1972 served to indicate the processes by which arctic winter beach features are formed. In sub-zero (centigrade) temperatures ice forms on the surface of brackish lagoonal and estuarine waters, and is often moved offshore by wind-generated and tidal currents. When waves, wind, and storm surges coincide with the presence of ice in the nearshore zone, the ice and frozen swash mass are deposited contiguously with sediment on the beach as distinctive ice and ice-sediment structures. These structures include ice-slush berms, ice-sediment interbedding, and buried ice boulders.

RÉSUMÉ. *Processus d'engel sur des plages arctiques.* Des observations menées le long de la côte nord de l'Alaska en 1972 ont servi à indiquer les processus selon lesquels les traits hivernaux des plages arctiques se forment. Par des températures sous zéro (Celsius), la glace se forme à la surface des eaux saumâtres des lagunes et des estuaires et est souvent emportée vers le large par les courants d'origine éolienne et tidale. Si les vagues, le vent et la houle de tempête coïncident avec la présence de glace dans la zone côtière, cette glace et la masse d'écume gelée se déposent avec les sédiments sur la plage, sous forme de structures bien distinctives de glace et de sédiments mêlés de glace. Parmi ces structures, on compte des banquettes de boueige, des lits alternés de glace et de sédiments et des blocs glaciels enfouis.

РЕЗЮМЕ. *Процессы образования льда на побережье Арктики.* Наблюдения, проведенные вдоль северного берега Аляски в течение 1972 года, позволили выявить особенности формирования зимнего микрорельефа полярных берегов. При температуре ниже 0°C лед формируется на поверхности солоноватых лагунных и устьевых вод и обычно перемещается в прибрежную зону ветровыми и приливными течениями. Когда волны, ветровой и штормовой нагон совпадают с наличием льда в прибрежной зоне, лед и мерзлые буруны откладываются на побережье в перемешку с осадками в виде характерных структур из чистого льда и смеси льда с осадками. Эти структуры включают ледяные и снежные бермы, переслаивание льда и осадков и погребенные ледяные глыбы.

INTRODUCTION

As part of a comprehensive project to study arctic coastal processes, two sites, Point Lay and Pingok Island (Fig. 1), were occupied from early spring until mid-fall 1972 (Short 1973; Wiseman *et al.* 1973). Point Lay lies on one of a series of long, low barrier islands separated by narrow inlets and backed by an elongated, shallow lagoon. Offshore of Point Lay the sea-bed drops rapidly to 10 m. and then slopes gently to depths of at least 50 m. Pingok Island is backed by a wider, shallow lagoon. Offshore the sea-bed consists of 4- to 5-km.-long offshore bars (average crest depth 3 m.) extending laterally from the shore for several hundred metres seaward. In this paper are discussed the processes which were observed modifying beach topography at these sites, directly or indirectly, during the freezeup period of 1972.

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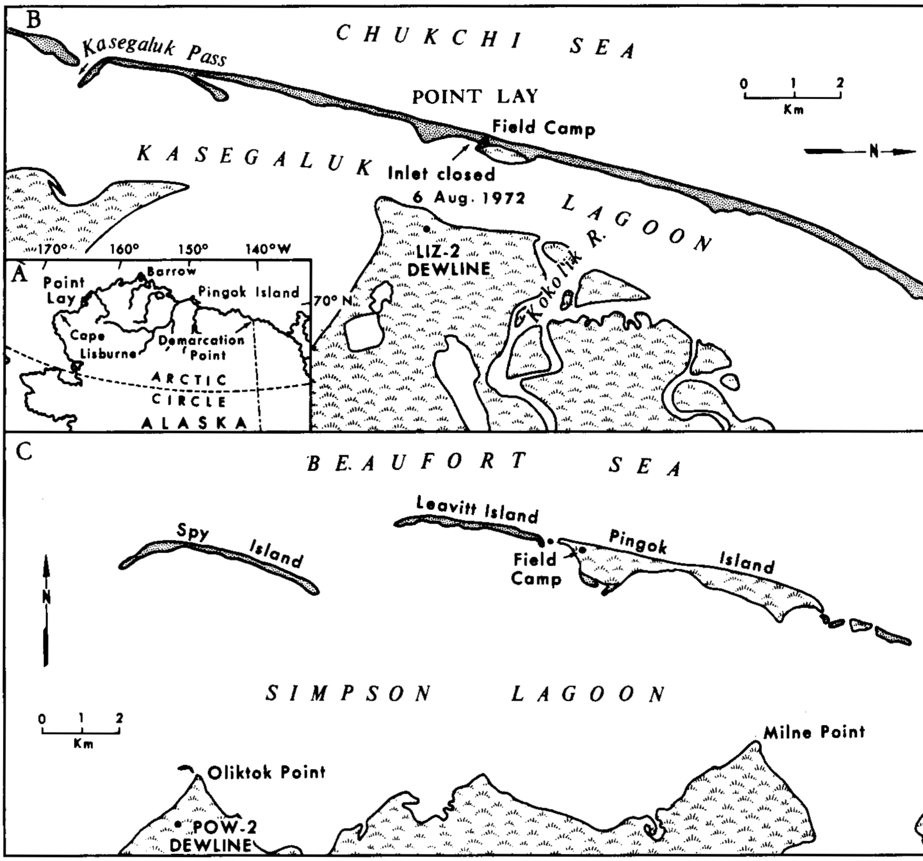

FIG. 1. Location map of field sites. A. North Alaska. B. Point Lay. C. Pingok Island.

Freezeup commences when air temperatures remain below 0°C., causing frazil (ice crystals) to form on the surfaces of lagoonal, estuarine, and nearshore waters of low salinity, and gradually thicken into continuous ice slush (2-3 cm. thick). At the same time water freezes within the sediment interstices of the upper beach and areas not actively affected by swash, while normal wave-tide processes and the resultant beach changes interact with the freezing process to produce winter beach features. The freezing process in the Arctic varies in intensity and chronology, both spatially and from year to year. The sequence of events observed in 1972 was, in chronological order: (1) solidification of the upper beach face, (2) formation of snow cover, (3) deposition of ice cakes (single pieces of sea ice smaller than 10 m. in diameter) on the beach, (4) formation of ice slush in the lagoons, (5) deposition of ice slush berms on the beach face, (6) formation of interbedded layers of sediment and ice, and (7) formation of icefoot features. Some of the observed features created during freezeup influence beach processes when the features thaw the following spring. The melting of these features may induce beach collapse, with the formation of kettle holes, pitting, and distorted bedding, as well as depositional structures, including micro-fans and micro-deltas.

FREEZEUP SEQUENCE

Freezing of upper beach surface

With the onset of "ice" days (days on which both the maximum air temperature does not rise above 0°C. and ice on the surface of water does not thaw) the exposed beach surface between the prevailing swash zone and the vegetated backshore solidifies when water within the sediment interstices freezes. At this time aeolian action can no longer affect the beach surface, and all topographic features are preserved. Below the surface, the beach freezes slowly downward as winter progresses.

At Pingok Island, the beach first froze on 1 September when the minimum air temperature was −3°C., as recorded by a Bendex thermograph in a climate hut 1.5 m. above the tundra surface. There followed an oscillation of temperatures between −3° and 6.5°C., producing diurnal freezing and thawing of the beach. On 14 September the temperature remained below −1°C., but on 22 September it again began to oscillate about 0°C. When the camp was evacuated on 25 September, the temperature was below 0°C. and the beach was completely frozen. A thaw could have occurred after that date.

Formation of snow cover

Snow cover prevents aeolian reworking of beach sediment, insulates the frozen beach crust, and may be incorporated in beach structures. Such effects were observed at Point Lay in October 1972. After a 5-cm.-thick layer of snow had been deposited on the beach, strong southerly winds caused sea level to rise approximately 1 m. (Astronomical tidal range along the Alaskan Arctic coast is of the order of 30 cm., but storm surges of 100 cm. are not uncommon.) Swash was, thus, permitted to move higher up the beach over snow-covered areas but did not melt the snow; rather, a thin layer of sediment was deposited over the snow cover, and as sea level dropped, the snow, and the swash percolating through it, solidified. A thin ice crust also formed on the beach surface within the snow-free, active swash zone as the water level dropped. Subsequent "nonice" days (ones on which either the maximum air temperature rises above 0°C. or ice on the surface of water thaws) caused the snow and ice crust to melt, but if the air temperature had remained below 0°C. the feature would have been preserved within the winter beach.

Deposition of ice cakes

Ice cakes are single, unbroken fragments of ice smaller than 10 m. across. These cakes of ice are readily supplied to the beach by offshore ice floes and pack ice. Strong arctic winds cause a drift of the ocean's surface layers and a consequent movement of ice cakes into or out of the nearshore zone. However, during the present authors' stay at Point Lay, from June to October 1972, the pack ice remained well offshore, although at Pingok Island it entered and left the nearshore zone five times during August and September.

When atmospheric processes produce, simultaneously, high stands of sea level, high waves, and ice cakes in the nearshore zone, cakes of ice are deposited on the beach surface, as was observed on Pingok Island (Fig. 2). The ice cakes were

FIG. 2. Ice cakes being deposited on Pingok Island during a period of 1-2-m.-high waves. Note the decrease in size of boulders up the beach and their partial burial. Ice in the lower centre averages 1-2 m. in diameter. (6 September 1972.)

sorted according to their draught; the larger cakes tended to ground on offshore bars and smaller ice cakes were deposited on the beach. In May 1973 slabs of ice up to 10 m. in diameter and 60 cm. thick were observed resting on the beach surface 1.5 m. above sea level on Pingok Island. These slabs were deposited during a westerly storm in the late fall of 1972. Reimnitz *et al.* (1972) reported that ice boulders (ice cakes rounded by abrasion, up to 5 m. in diameter) were deposited on the upper beach during a 3-m. storm surge along the Alaskan Beaufort Sea coast. The surge accompanied a westerly storm in September 1970.

Ice boulders often grind holes in the beach as they are turned and worked by the swash. If wave activity is sufficient, they may be wholly or partially buried by swash deposition of sand and gravel. During nonice days, the ice boulders will melt rapidly unless isolated by a thick covering layer of sediment. At times, aeolian action rapidly coats the ice boulders with a thin layer of sand, which decreases their albedo (i.e., reflection coefficient for solar radiation) and accelerates melting. Beach erosion may expose previously-buried ice boulders to further mechanical and thermal erosion. Kettle holes resulting from the melting of ice boulders have been described for Spitzbergen by Thompson (1953), for Antarctica by Nichols (1961), for northern Scandinavia by Collinson (1971), for Canadian lakes by Dionne and Laverdière (1972), and for Alaska by Greene (1970) and Short and Wiseman (1973).

Deposition of ice slush

Along the Alaskan Arctic coast, ice slush first forms in the calmer, brackish waters of the lagoons and offshore in the brackish waters off large river mouths. Later, ice begins to form on the more saline waters of the coastal zone. On Simpson

Lagoon, which separates Pingok Island from the mainland (Fig. 1C), and is often diluted by runoff from the Colville River, 27 km. southwest of the island, frazil first appeared in pockets around the lagoon's shore on 18 September. During the cold, relatively calm nights of 19 and 22 September, ice slush covered large areas of the lagoon. However, this presence of ice slush did not imply total freezing of the lagoon surface. Wind-driven and tidal currents regularly flushed the ice out of the lagoon and into adjacent nearshore areas. In September and October 1972, this activity was observed at numerous inlets and passes along the northeastern Alaskan coast, and tongues of ice extended alongshore from single inlets for over 10 km. At Pingok Island ice was flushed out of the lagoon daily after its initial formation on 19 September.

Lagoon ice slush may cover all the nearshore water surface for a distance of 50 to 100 m. out from shore. Waves passing through this ice-covered region are considerably attenuated and therefore often prevented from breaking. Wave-induced motion, however, disturbs the ice slush and breaks it into small pieces 1-20 cm. in diameter and 1-2 cm. thick. Whenever ice slush enters the surf zone, it is washed onto the beach. The broken pieces of ice slush, because of their flatness, buoyancy, and small size, are deposited at the upper swash limit, often accumulating in piles large enough to be called ice slush berms (Fig. 3). Sediment is scattered throughout the berm, and, at times, subsequent deposition of sediment may bury an ice slush berm completely.

Because ice slush forms on brackish lagoons before it forms on the saline coastal water, that from lagoons is more likely to be deposited on the beaches than that formed in coastal waters. The amount of ice slush from lagoons deposited on a beach is dependent upon (1) the relative size of lagoonal and estuarine

FIG. 3. Two ice slush berms on Pingok Island. Note remnant frozen swash and foam on the upper beach (white band). The depositional zonation is a result af variations in sea level. Distance from swash to landward side of upper ice slush berm is 3 m. (24 September 1972.)

areas on which the ice is formed, (2) the prevailing temperature and wind regime, which determines the rapidity of ice formation, (3) wind- and tide-generated currents which move the ice out of the lagoons, (4) the presence of inlets through which the ice may move out into the nearshore zone, (5) waves and tides to transfer the ice from the nearshore zone onto the beach, and (6) the beach morphology, which, combined with the waves, affects the form of ice structures deposited.

Deposition of frozen swash mass and spray

Swash mass, i.e., the mass of water carried in the swash (Waddell, 1973) and spray will begin to freeze on the beach when the air and water temperatures fall below 0°C. On Pingok Island, swash-mass freezing was first observed on 19 September. The air temperature was −4°C., and the water temperature −1°C. The swash mass began freezing after 15 seconds on gravel and within 20 seconds on sand, forming a continuous crust of frazil within 30 seconds. The following swash destroyed the crust, and the process began anew. With falling sea level or decreasing wave energy, the frozen swash mass is preserved, either combining with the sediment to form a frozen beach matrix or forming a separate layer of ice on the beach face. These processes can occur a few weeks before frazil and ice slush form on the ocean surface offshore of the beaches.

During severe surf agitation, foam is produced and deposited as foam banks at and above the upper swash limit (Fig. 4). The foam is readily preserved on ice days, rapidly freezing into a porous ice. Sediment grains are often interspersed throughout the frozen foam. On Pingok Island, foam was laid down in beds interlayered with sediment (Figs. 5 and 6A). Following deposition of the foam and sediment, the waves began to subside and sediment and small pieces of ice were

FIG. 4. Frozen swash mass and foam on Pingok Island. Note sediment-covered ice to the right. Two persons, upper centre, give indication of scale. Photograph *by J. M. Coleman* (19 September 1972.)

FIG. 5. Beach section of Pingok Island showing frozen foam and swash interbedded with sediment. Note the small pieces of ice and snow on the surface. Section shown is 3 m. wide. (21 September 1972.)

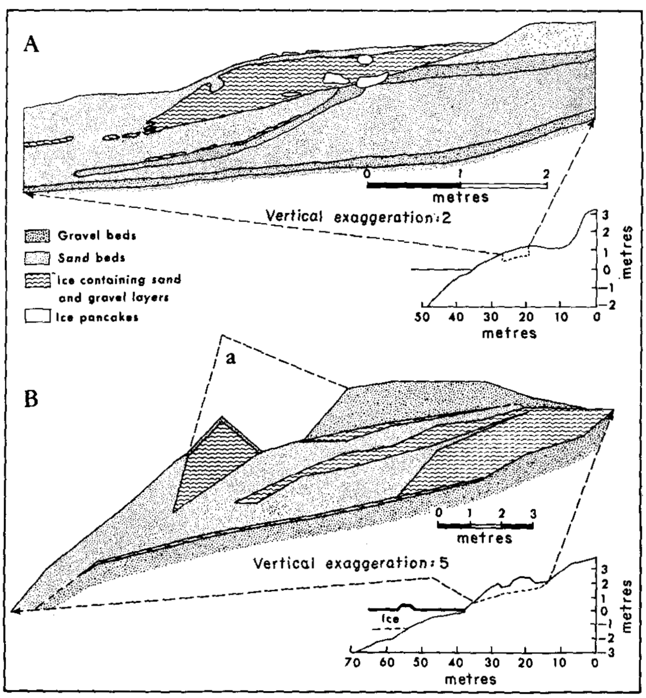

FIG. 6. A. Diagram of beach section at Pingok Island made on 21 September 1972.
B. Diagram of beach section at Point Lay made on 7 June 1972.

deposited on top of the beds of frozen foam and sediment. The foam had already solidified sufficiently to prevent the warping that could result from overloading of the feature by accumulation of sediment. A sample of the frozen foam had a salinity of 5 parts per thousand. If much more salt were removed by brine migration during the winter, it would be difficult to use salinity to distinguish the foam from frozen snow.

Freezing of the beach face

The freezing of the beach face within the swash zone coincides with freezing of the swash mass. The freezing produces a hard, smooth crust on the beach face down to the lower low-tide swash limit. At low water, or under low wave conditions, the beach face may freeze near, or just above, the sea level. Subsequently, the face may be either eroded by wave action or covered by sediment. If it is eroded, frozen slabs of crust may be broken off and redeposited higher on the beach, while if accretion occurs, the frozen surface will be buried and insulated against thaw.

At Pingok Island, deposition of ice on the beach in the form of snow, ice boulders, ice slush, frozen swash mass, spray, and foam was observed to occur simultaneously with the deposition of contiguous sediment and the freezing of the beach face. Under ideal conditions of incidence of ice days and accretion of upper-beach-face ice and sediment, the depositional features accumulated rapidly. Most of the feature shown in Fig. 5 was deposited within a few hours. The frozen layers form a structure which is moderately resistant to mechanical reworking, while the increased thickness of the structure insulates the subsurface layers from thaw on possible subsequent nonice days. During such days, additional unfrozen layers of sand and gravel may be deposited on the structure. These sediments increase the insulation of the feature and may later freeze during ice days.

Freezeup in the coastal region of the Alaskan Arctic occurred late in 1972, so that the entire sequence of events at the field sites was not observed that year. The processes which are important in the final stages of freezeup are the formation on the coastal waters of frazil and ice slush (as opposed to lagoonal ice earlier in freezeup) and their deposition in the intertidal zone on the beach. It is at this time that icefoot development occurs. An icefoot is sea ice firmly frozen to the shore at the high-tide line and unaffected by tide. A good review of icefoot features is given by McCann and Carlisle (1972).

Formation of a storm icefoot (Rex 1964) from lagoonal ice slush was witnessed at Point Barrow, Alaska, in October 1972. Lagoonal ice slush formed on Elson Lagoon, east of Point Barrow, was flushed out of Eluitkak Pass by tidal and wind-driven currents. Out of the pass the ice slush formed a mass approximately 30 m. wide and moved alongshore from the pass to Point Barrow, a distance of 5 km. The ice slush was several centimetres thick and exerted a significant dampening effect on the approximately 1-m.-high waves. Only the largest and longest waves reached the shore with any appreciable amplitude. Most of these were impeded by the ice slush from breaking. Occasionally a larger wave was able to break, and in so doing threw small pieces of ice slush up on the shore. In this fashion a storm icefoot was built out into the Beaufort Sea in the form of a platform approximately 1 m. above sea level. When the structure was observed, it had become built out approximately 10 m. from shore by the adfreezing of ice slush at the water level and accretion from ice slush thrown up by breaking waves.

FIG. 7. Beach section at Point Lay. Note the buried ice layers and beach subsidence resulting from melt of the large ice lens in the foreground (layer "a" in Fig. 6B). The trench is 15 m. long and averages 0.7 m. in depth. (5 June 1972.)

OBSERVATIONS OF A WINTER BEACH

The beach at Point Lay was sectioned in spring 1972 prior to breakup. A layered structure, resulting from a combination of the processes described above, was observed (Figs. 7 and 6B). Layer "a" (Fig. 6B) may be a storm icefoot. It is also similar to the asymmetrical ice-gravel ridges noted by Barnes (1972). The other layers are assumed to have been formed by repeated sediment burial of new snow layers. The salinities of the ice layers were very low (less than 1 part per thousand). The layering was smooth rather than mottled, as in the case of the structure observed being formed by the freezing of swash mass and foam at Pingok Island (see Fig. 5). Smooth layering occurs when layers of sediment are deposited over layers of snow. Finally, the freezeup period of 1971-1972 was accompanied by several storm surges. Such rises in sea level would permit the deposition of sediment over snow high up the beach and the resultant development of ice-sediment structures. Short and Wiseman (1973) and Greene (1970) describe the characteristic features resulting from the melting of such structures.

DISCUSSION

The progression of freezeup along the northern Alaskan Arctic coast introduces ice and snow into the beach and nearshore zones. These, in turn, interact with and modify the normal type of beach processes observed in lower latitudes, in particular wave and swash action. The result is a set of ice-sediment beach structures characteristic of cold regions. The interactions are complex, depending on thermal, wave, and current regimes. Many of the features observed in process of formation at Pingok Island were a result of unusually high wave activity and are probably uncommon along the northeastern Alaskan Arctic coast during most years. The features observed at Pingok Island are probably more common along the northwestern Alaskan coast, where the pack ice is generally farther offshore, and high wave activity therefore occurs during the early fall.

Nonetheless, the observations reported here were of the actual formation of features which have previously been described but whose formation was not actually witnessed. It is likely that other processes not witnessed also generate similar features, and more field observations under the somewhat inclement conditions of the freezeup period are to be recommended.

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