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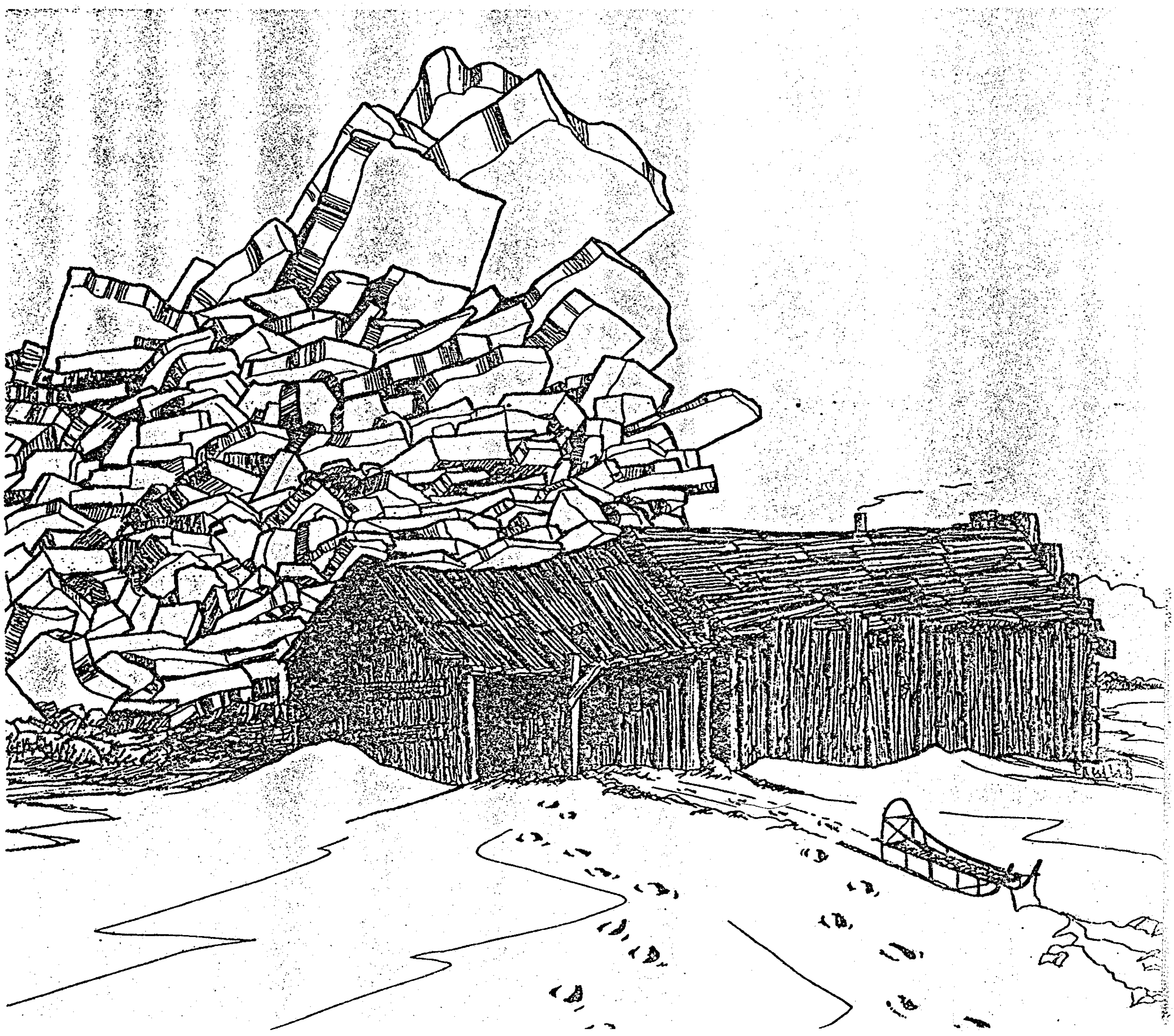
Shore ice ride-up and pile-up features

Part II: Alaska's Beaufort Sea coast



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Austin Kovacs

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Recent observations of shore ice pile-up and ride-up along the coast of the Alaska Beau fort Sea are presented. Information is given to show that sea ice movement on shore has overridden steep coastal bluffs and has thrust inland over 1S0 m, gouging into and pushing up mounds of beach sand, gravel, boulders and peat and, inland, the tundra material. The resulting ice scar morphology was found to remain for tens of years. Onshore ice movements up to 20 m arc relatively common, but those over 100 m are very infrequent. Spring is a dangerous time, when sea ice melts away from the shore, allow-rig ice to move freely. Under this condition, driving stresses of less than 100 kPa can push thick sea ic onto the land.

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PREFACE

This report was prepared by Austin Kovacs, Research Civil Engineer, Applied Research Branch, Experimental Engineering Division, U.S. Army Cold Regions Research and Engineering Laboratory. The study was funded in part by the U.S. Bureau of Land Management through the National Oceanographic and Atmospheric Administration's Alaska Outer Continental Shelf Environmental Assessment Program and by Gulf Canada Resources, inc.

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SHORE ICE RIDE-UP AND PILE-UP FEATURES
Part I: Alaska's Beaufort Sea coast

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INTRODUCTION

Sea ice acting on arctic coasts modifies the shore, producing unique beach morphology. A number of the morphological features produced by onshore ice movement are depicted in Figure 1. Sea ice thrusting up onto the shore can also produce gouges, furrows and striations, and when it melts it can leave a pitted beach topography. But one *severe* storm during the open water season can eliminate all of the ice scars on the beach (Zenkovich 1967). Sea ice as an abrasive-transport agent has frequently been described qualitatively, for example byTarr(1897), Kindel (1924), Sverdrup (1935), Stefansson (1969) and Rodeick (1979). Even though there is evidence indicating that sea ice transport of detritus has been going on for over 4 million years (Margolis and Herman 1980), this process has not been well documented quantitatively.' It is known that both fine-grained material and boulders are still being removed from the shore zone by drifting sea ice (Fig. 2 and 3). However, sea ice thrusting against the land can also move offshore fine-grained sediment and boulders landward (e.g. Kovacs and Sodhi 1980, Barnes 1982), and in this way it helps to restore beach material displaced by wave erosion. Ice-pushed beach ridges and boulder barricades help protect the shore from wave attack and run-up onto the land. The topographic landforms created when sea ice advances onto the shore are signatures which can provide information on the frequency of occurrence and magnitude of the forces at play, and maximum transgression beyond the water's edge.

Sea ice pile-up (Fig. 4) and ride-up (Fig. 5) on arctic and subarctic shores are frequent and unpredictable events (Kovacs and Sodhi 1980). These phenomena have pulverized boats, destroyed piers and wharfs, and on occasion crushed houses along with their unlucky inhabitants (Kovacs and Sodhi 1980, Yates 1982, Dekin 1982). Stefansson (1969) stated: "houses which stand one or two hundred yards from the beach are in danger" of onshore ice movement. These events cause concern today about the safety of facilities located along these shores and on man-made islands. Questions arise as to the frequency and severity of these events.

A survey of shore ice pile-up and ride-up along the coast of Norton Sound and the Alaskan coasts of the Bering, Chukchi and Beaufort seas in the winters of 1979-80, 1980-81 and 1981-82 revealed many locations where significant (greater than 5 m) onshore ice movement had occurred, both recent and old. This report discusses our recent observations and current findings related to onshore ice incursions along *the* Alaskan Beaufort Sea coast. Its purpose is to provide some record, in advance of future shoreline development, of the location and relative severity of these events, and the type of shore on which they occur (steep bluff or low-lying beach). The information presented is an extension of previous reports (Kovacs and Sodhi 1980, Kovacs et al. 1982, Kovacs 1983), and includes the observations of Kovacs and Kovacs (1982) on sea ice movement onto arctic and subarctic shores. The former reports include extensive historical and contemporary field observations and theoretical analyses on the processes of shore ice

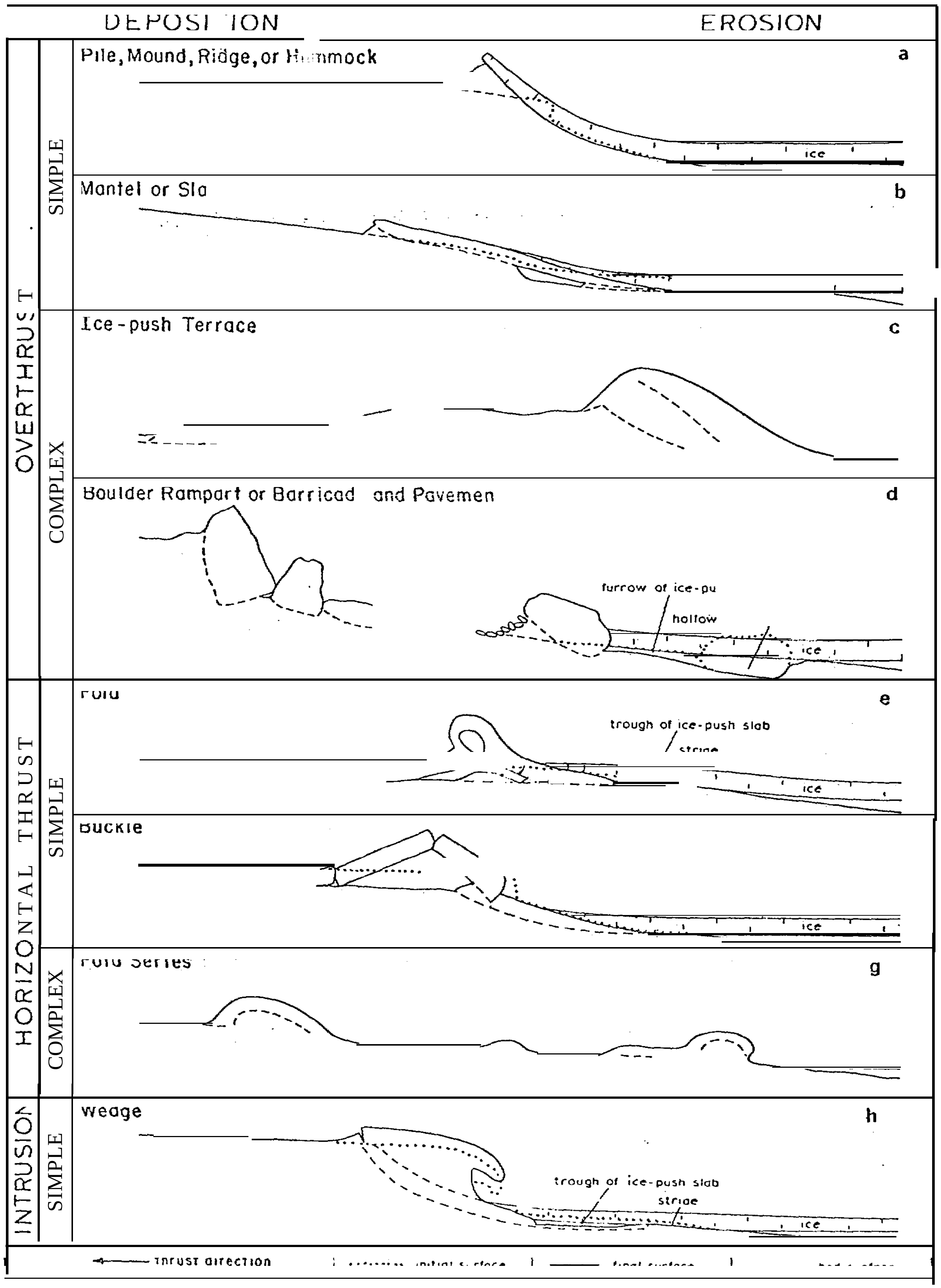


Figure *Ice-thrust* *(After Alestalo and Häikiö 1979.)*

Figure 2. *Example of thick [up to* 5 cm) *accumulations of* mud found in *1977 on* numerous ice *floes* off *Flaxman Island* and *Brownlow Point,* Alaska.

Figure 3. *Rocks found in May 1976 on small multiyear ice floe about 30 km northeast of Cross Island, Alaska. Rock source is Yelverton Bay, Ellesmere Island, Canada. A slide off the steep moun rain slopes probably carried the rocks* out *on to the sea ice.*

Figure 4. *Eleven-meter-high spring shore ice pile-up, about 1914. (From Stefansson Collection, Baker Library, Dartmouth College.)*

Figure 5. Spring ice ride-up on gravel beach, about 1914. (From Stefansson Collection, Baker Library, Dartmouth College.)

pile-up and ride-up and the relative forces active during their formation. These reports are recommended for further information on the subject. A future report in this series will present information on shore ice pile-up and ride-up on the Kotzebue Sound and Chukchi Sea coast of Alaska.

WINTER 1979-80 OBSERVATIONS

The 1979-80 winter shore ice observations along the Beaufort Sea coast were made from Pt. Barrow to Barter Island (Fig. B 1 and B2). Records were made of ice ride-ups which extended 5 metres or more in from the sea. Lesser ice thrusts onto the shore were very frequent events and considered of limited significance to expected shoreline development.

In November 1979 an ice pile-up was observed west of Cape Halkett (position 1, Fig. B1) that extended nearly 300 m along the coast. The ice blocks were 0.25 m thick, and were piled up to 3?4 m high on top of the 2-m-high coastal bluff (Fig. 6). In places, the ice blocks were found up to 30 m inland from the edge of the bluff. In summer, the sea extends to the base of this bluff. The water offshore is shallow. Rapid erosion of up to 10 m/yr of the ice-rich permafrost in the bluff by current and waves (Lewellen 1977, Hartz 1978) gives rise to very turbid offshore water.

In April 1980, sea ice under ½ m thick and over 50 m wide had thrust 8 m inland on Igalik Island and 13 m inland on Kulgurak Island (positions 2 and 3, respectively, Fig. B1).

West of Cape Simpson (position 4, Fig. B1) 0.40-m-thick sea ice had thrust inland 16 m, and east of

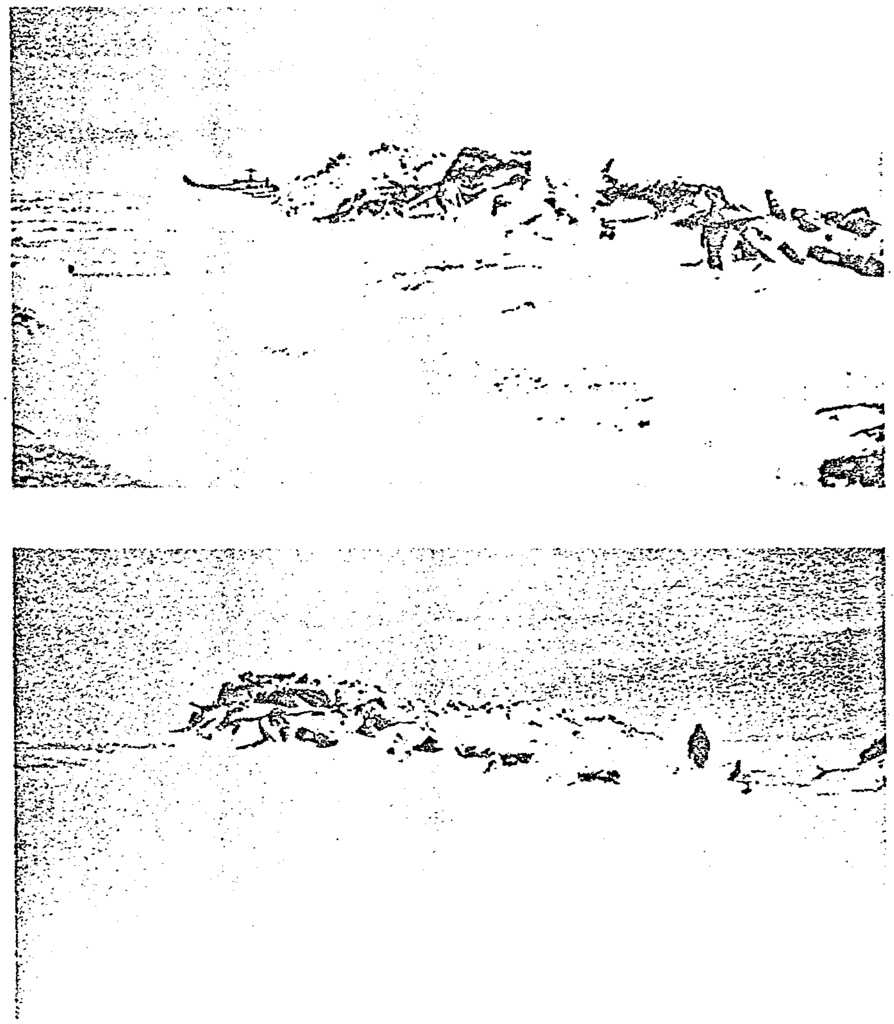


Figure 6. Shore ice pile-up west of Cape Halkett in November 1979. Note the dirty ice blocks which indicate ice formed in very turbid water.

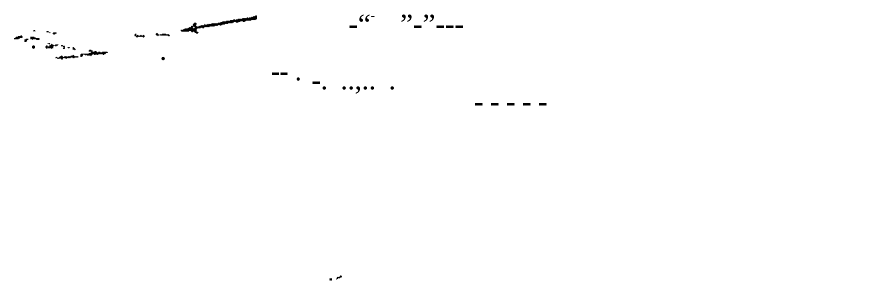


Figure 7. Ice pile-up and ride-up on the west side of A rey Island located west of Barter Island. Arrow points to ice-thrust features on the island.

Drew Pt. at position 5 ice of similar thickness was found up to 10 m inland on top of the 6- to 7-m-high coastal bluffs. At positions 6 and 7, the sea ice extended 5 to 10 m inland.

Spy Island (position 8, Fig. B1) was overridden by ice of unknown thickness. The ice override distance could not be determined because of drift snow, but was in excess of 80 m. During the summer, Jim Helmericks (persona! discussion) noted that island sand and gravel material had been pushed up into piles by the sea ice ride-up and that the island had been cut down in places so that storm wave overwash occurred. This action was reported to have cut the island into four sections.

At position 1 in Figure B2, %-m-thick ice overrode the 1 %-m-high Collinson Pt. spit for a distance of 50 m. At positions 2 and 3 ice 1.1 m thick had ridden up the 2-m-high beach and moved 5 to 20 m inland. Long sections of the coast at positions 4,5 and 6 had ice pile-up on the beach. At position 4, ice ½ m thick had thrust "up to 60 m inland on the 'island (see Fig. 7). At positions 7 arrd 8 ice ½ m thick piled up to 5 m high and moved over 10 m inland on the barrier island.

WINTER 1980-81 AND SUMMER 1981 OBSERVATIONS

The Beaufort Sea coast from Pt. Barrow to the U.S.-Canadian border was followed in April 1981. As in April 1980, sea ice was again observed on Kulgurak Island (position 3, Fig, B1). This year ice less than ½ m thick had piled up or thrust inland 7 to 18 m.

At Point Drew (Fig. B1) 0.30-m-thick sea ice had invaded nearly the entire spit, which is over 1 km long. Ice pile-ups to 3 m high existed along most of the spit, and complete ice override of 75 m of the spit at the west end had occurred. In August, even {bough most of the beach on the seaward side of the spit had been modified by storm wave run-up, much ice-thrust beach topography still existed. The spit was found to consist for the most part of peat and fine-grained silt, which the sea ice had pushed into piles up to 2 m high. Sea ice and driftwood were found incorporated into the debris of the larger piles (Fig. 8). In some locations, large slabs of peat material about 0.25 m thick had been displaced and stacked layer upon layer (Fig. 9). Aerial photos show that this spit is extending westward with time and is undergoing changes in shape. This section of the coastline is also receding at a rate of 6 to 10 m per year (Lewellen 1977, Hartz 1978). Therefore, summer storm waves, overwash and coastal currents rapidly modify the coastline and in so doing not only remove ice ride-up scars from the spit but also those which may form on the 2-to 4-m-high bluffs to the east of Drew Pt.

On 26 June, at about 1030, sea ice up to ½ m thick moved in upon the beach along a broad section of the coast near Lonely (Fig, B1). Witnesses stated that the ice piling lasted less than 10 minutes and reached a height of 4 m (Fig. 10). In late August we found that the ice ride-up had dozed up beach gravel for a distance of 30 m from the water's edge along an unbroken stretch of shoreline over 500 m long. The farthest inland ice advance as determined by ice gouge length was 59 m. No ice remained exposed on the beach, but ice was found under several of the gravel piles (Fig. 11).

Along the beach at Lonely, several old tundra ice scar features not detected on previous reconnaissance flights were discovered (Fig. 12). The ice-pushed tundra

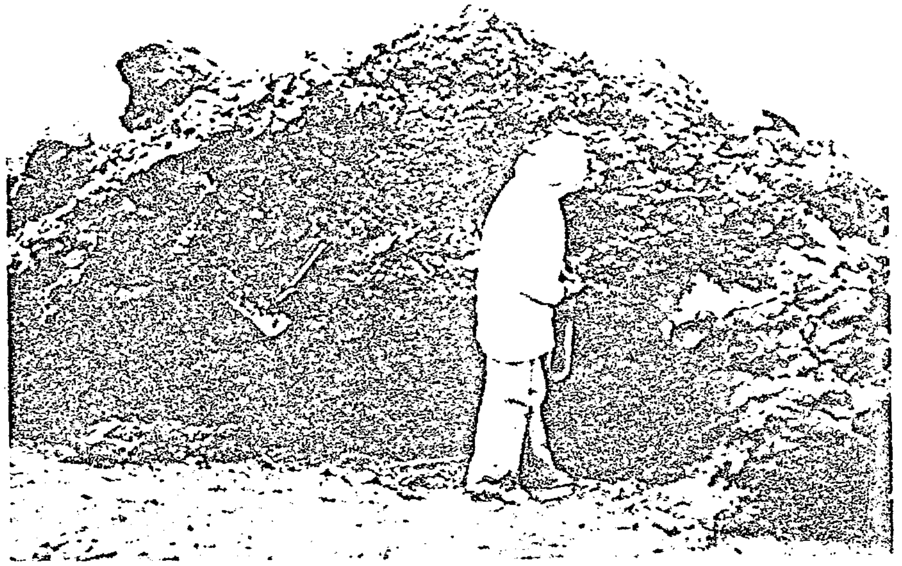


Figure 8. Ice-pushed silt and peat pile, August 1981. White material in front of observer is sea ice. Arrow points to driftwood incorporated in the pile.

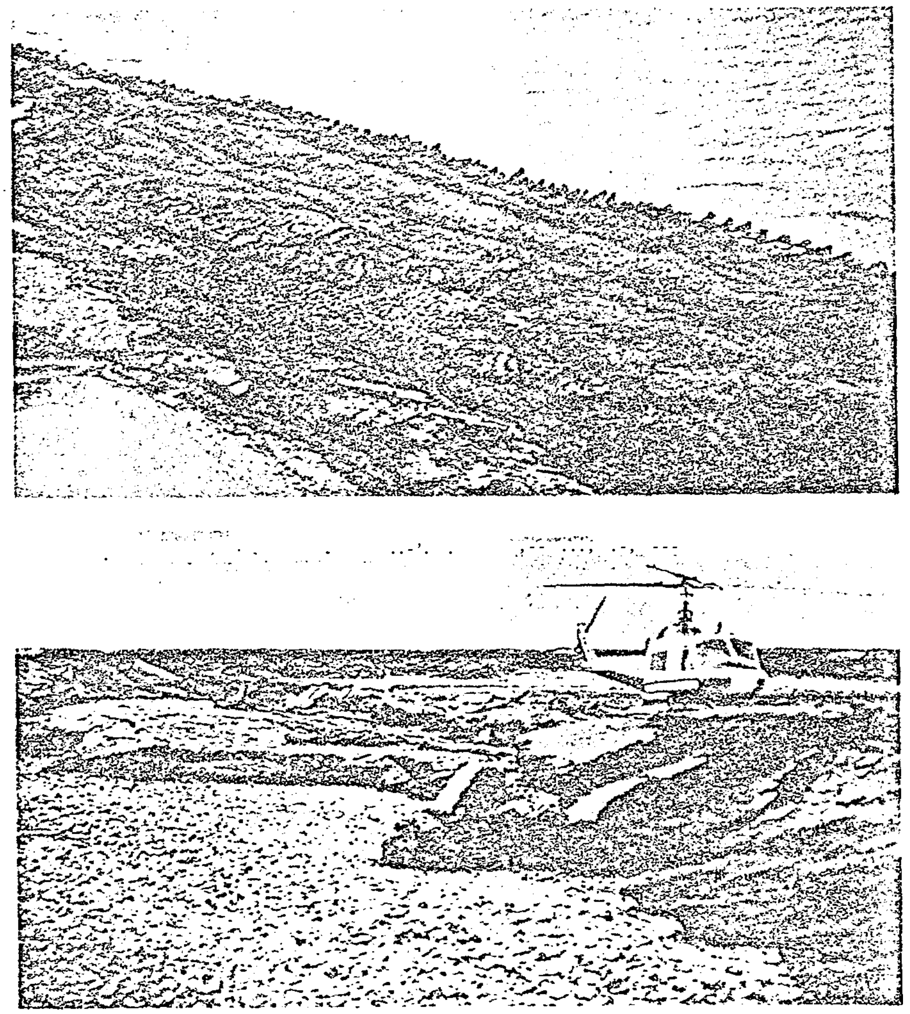


Figure 9. Aerial (top) and ground (bottom) views of peat slabs displaced by ice ride-up on spit at Drew Pt., August 1981.

Figure 10. Ice pile-up on beach near Lonely DEW Line Station in July 1981. Note ice-pushed gravel. (Photo courtesy F. Crory.)

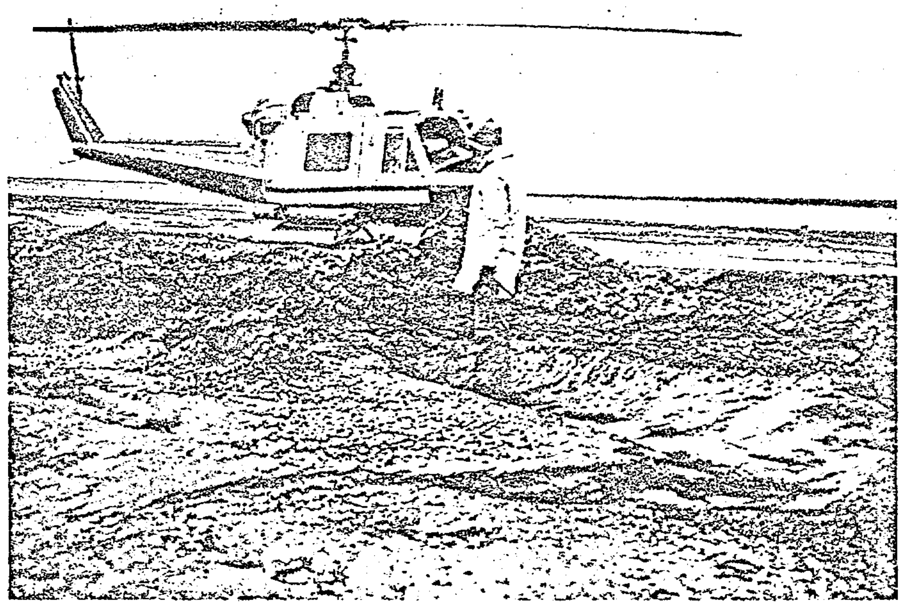


Figure 11. Ice-pushed gravel ridge and "pothole" beach relief remaining after shore ice pile-up melted away, August 1981.

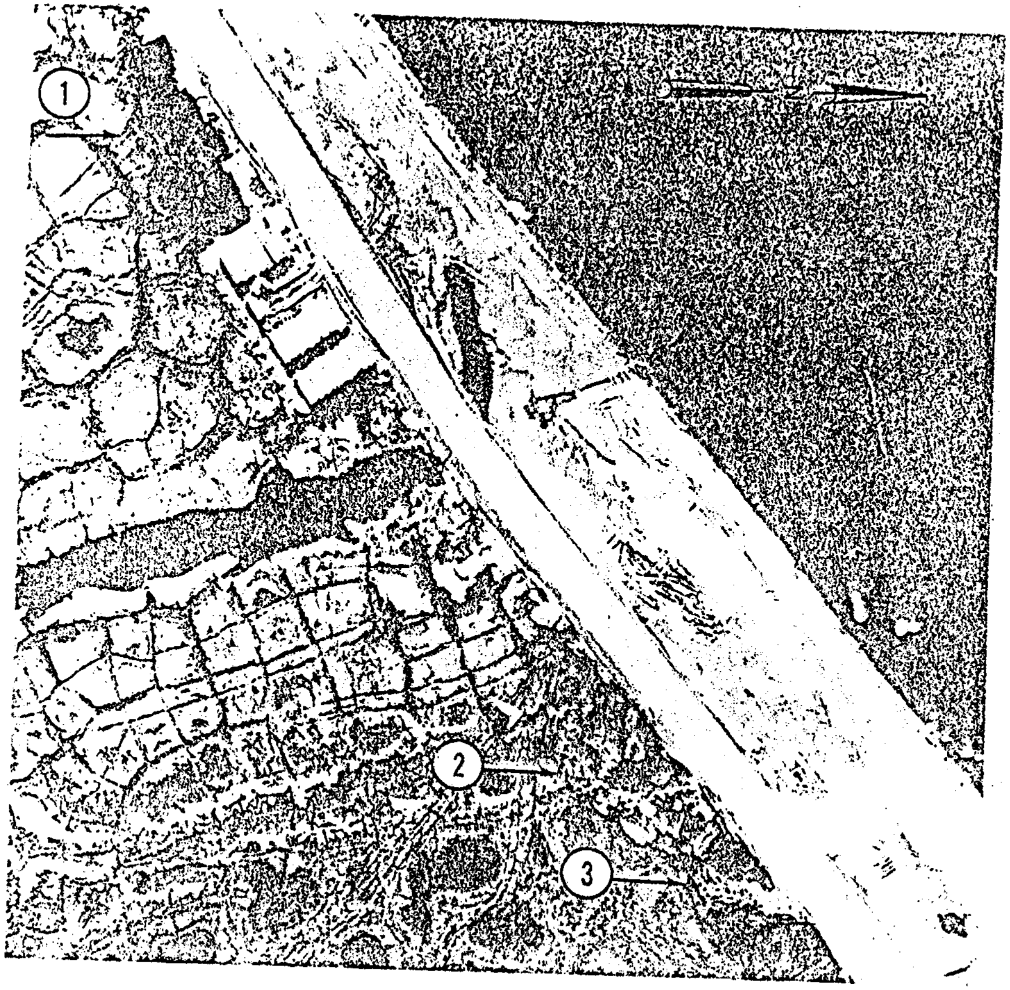


Figure 12. Arrows mark three old ice-scarred tundra relief features near Lonely DEW Line Station. (BLM aerial photo, July 1979.)

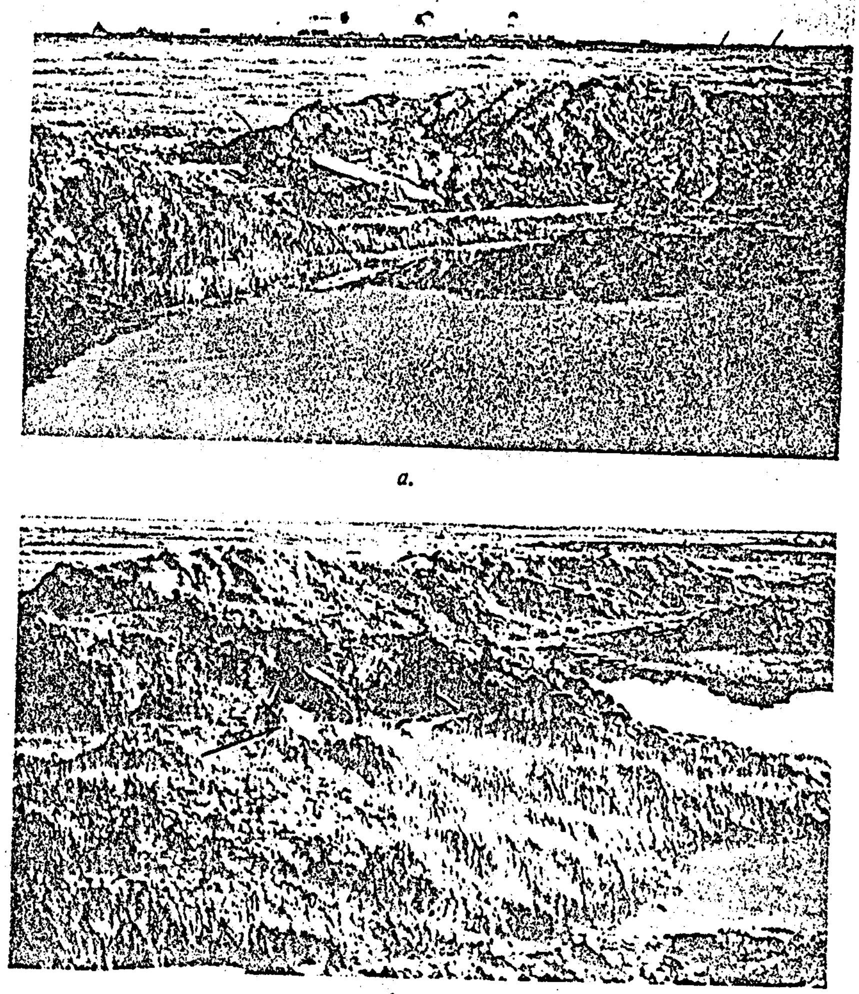


Figure 13. Ice-pushed tundra berms (August 1981). The features in photos a and b are at arrows 3 and 2 respectively in Figure 12. Arrow in 13b points to driftwood log protruding from base of ice-pushed tundra berm.

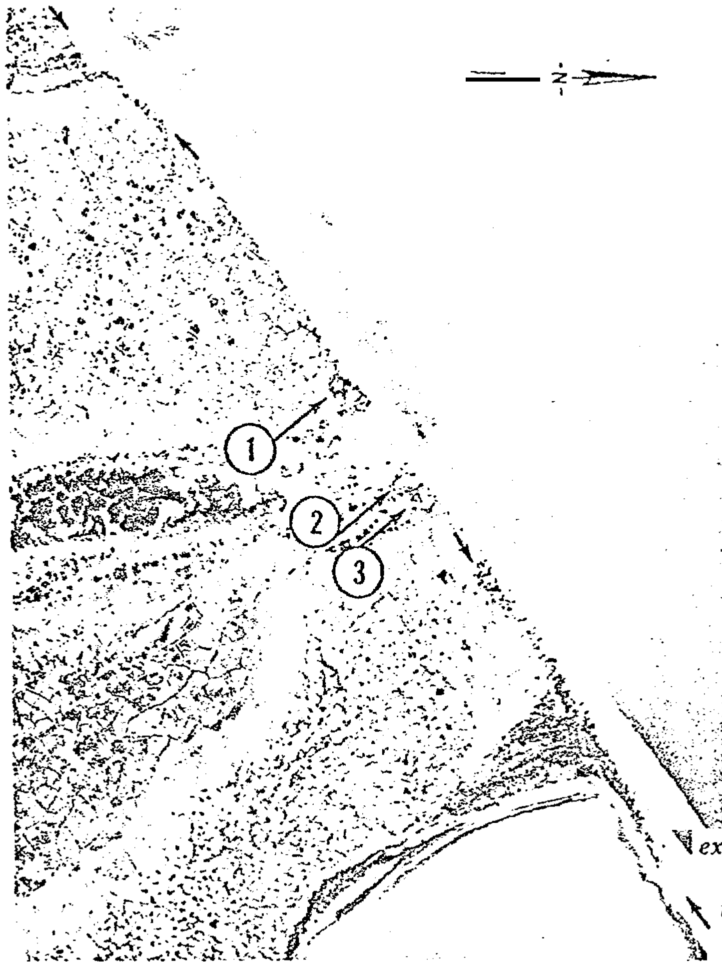


Figure 14. Summer 1949 aerial photo of the three ice-pushed tundra scars shown in Figure 12. The arrows parallel to the shore mark the extremities of other ice-scarred terrain not observed in 1981 due to shoreline road construction and sea current and wave modification processes.

furthest from the sea was 85 m inland. The berms were about 1 m high and were impregnated with driftwood, which was incorporated into the soil during ice dozing (Fig. 13).

Aerial photos of this coastline taken in 1945, before development had occurred, show *that these ice* scar tundra features were in existence then. A better-quality 1949 aerial photo of these features is shown in Figure 14. Our aerial photo assessment of shoreline retreat in the immediate area of the ice scars is about 0.5 m per year. Therefore, in 1945 the furthest-inland ice-pushed tundra berm we measured in 1981 must have been around 100 m from the ocean. How far inland the ice-pushed features were at the lime the ice ride-up event occurred is, of course, unknown.

In May, at Ksook (Fig. B1), the site of a turn-of-the-century trading post, the shore ice pile-up and ride-up formations shown in Figure 15 were “observed. The higher ice pile-ups, extending westward away from the house in Figure 15, were situated on a low-lying coast. These ice piles were up to 5 m high and 20 m inland from the sea. Fingers of sea ice extended inland up to 35 m. The ice pile-up directly *north* of the hut (Fig. 15) was 1 m higher than *the* 2-m-high bluff (Fig. 16) on which the ice came to rest.

Aerial views taken in August 1981 of the ice-pushed tundra relief and coastline are shown in Figure 17. These views show that the previous winter’s shore ice ride-up displaced and scarred a significant area of the shoreline. Ground views of the ice-pushed relief are shown in Figure 18. We found the coastline west of the hut where the ice had moved inland to be composed of’ peat. Large slabs of this material up *to* 0.25 m thick were found to have been peeled loose and displaced inland by the ice {Fig. 18, bottom).

An elevation profile of one of the ice-pushed peat piles and the shoreline relief is presented in Figure 19. This pile reached an elevation of *2.4 m,* or about 1.6 m above the undisturbed terrain. Other ice-pushed features *were* either higher or further inland (up to *29* m). The seabed off shore was shallow and was composed of “stiff’ peat and silt. The shallow slope

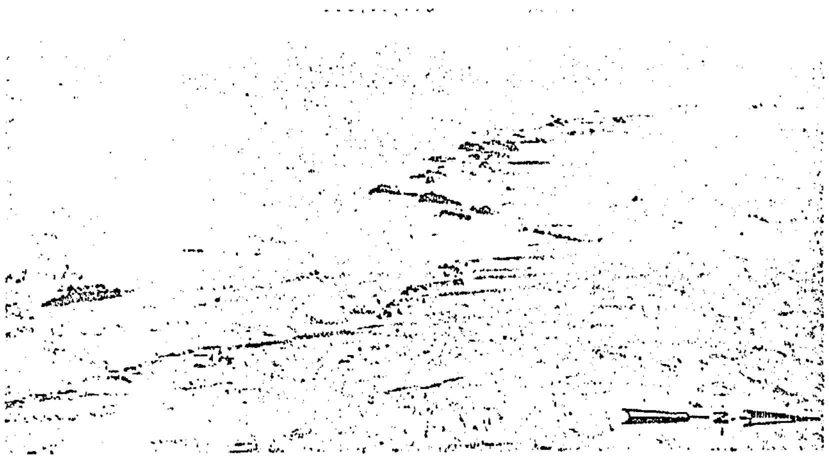


Figure 15. Shore ice pile-up at Ksook, May 1981.

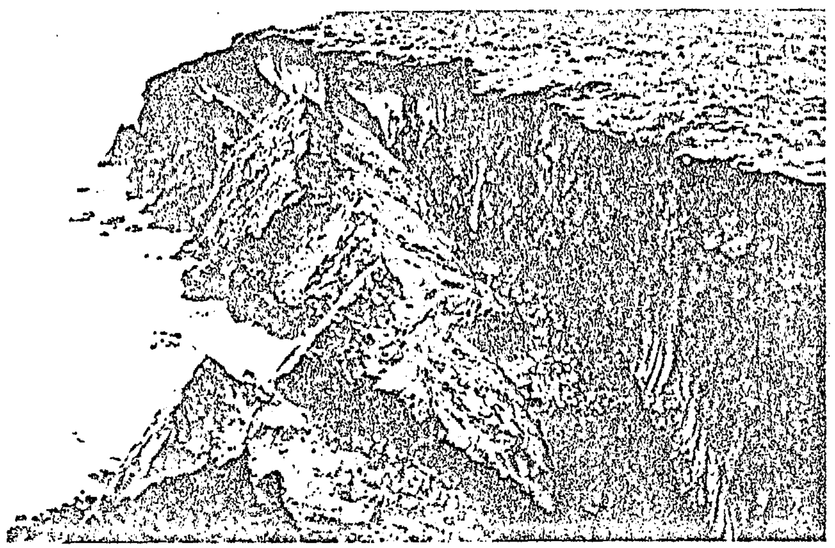


Figure 16. View of 2-m-high coastal bluff showing 0.25-m-thick tundra mat and underlying massive ice and ice-rich silt, May 1981. The latter is easily undercut and eroded by the sea,

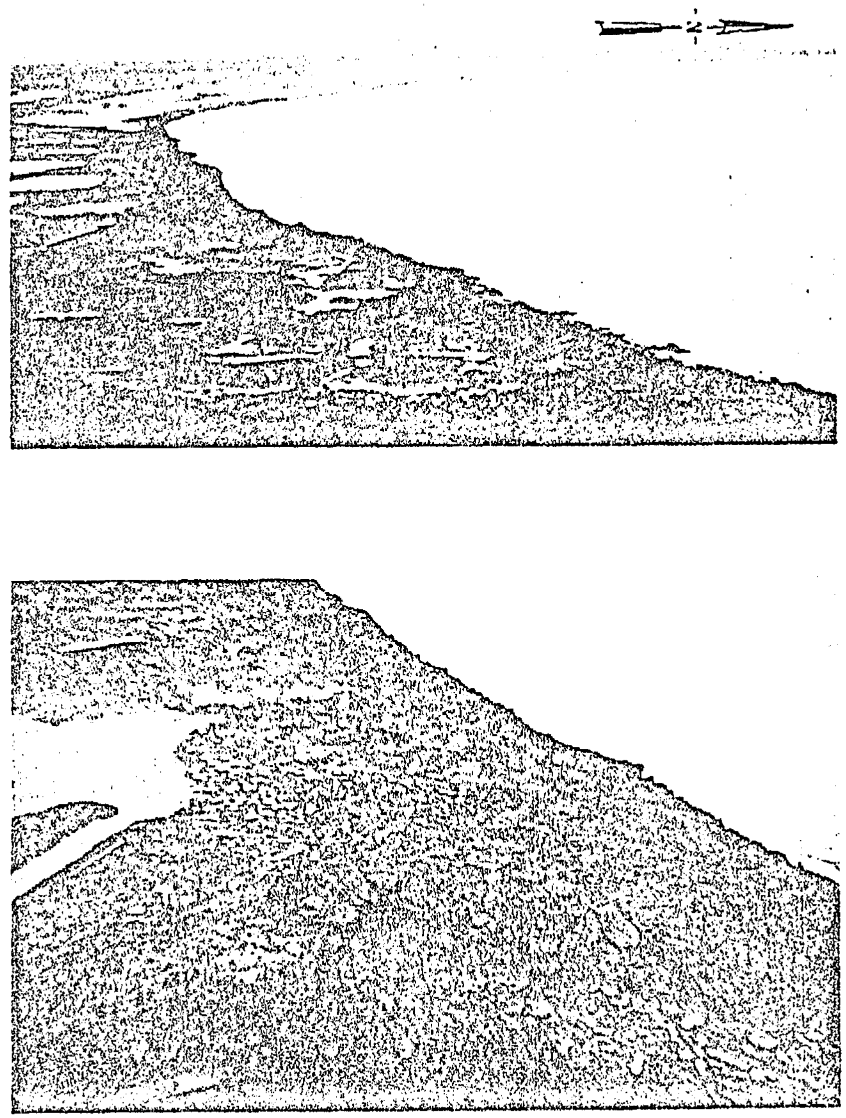
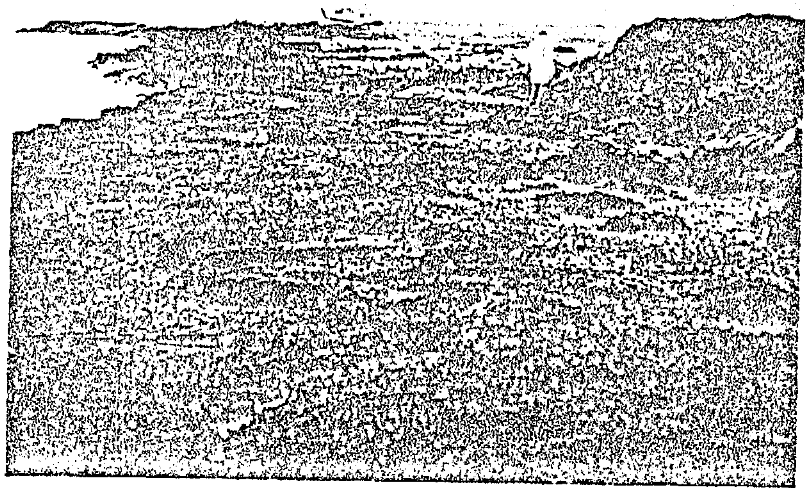


Figure 17. Ice-pushed peat piles along the coast near Ksook, August 1981. Note the general size and stacking configuration of the displaced peat slabs. Arrow in upper photo indicates pile shown in lower photo.



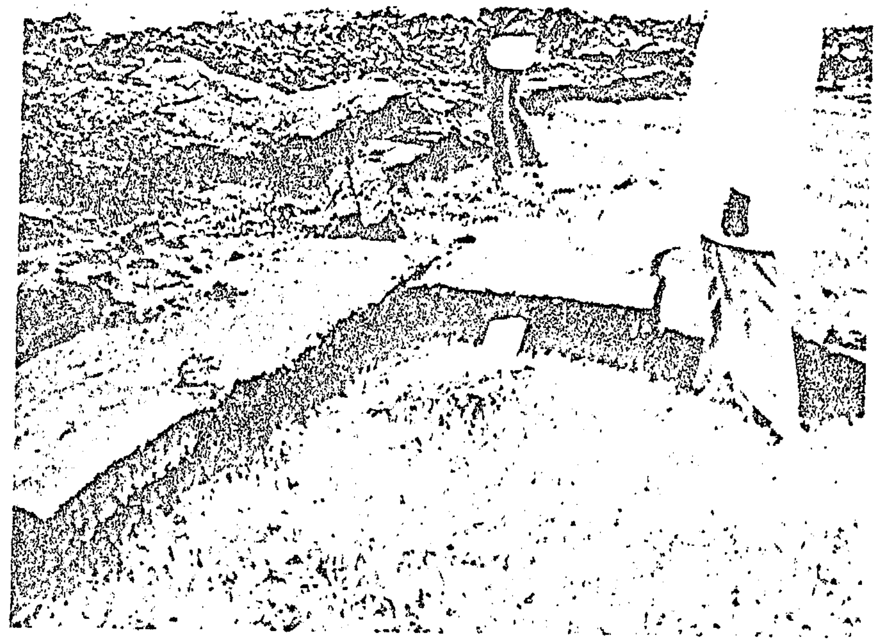


Figure 18. Ice-pushed peat on the coast west of Ksook, August 1981. The Ksook house is behind the helicopter in the left-hand photo,

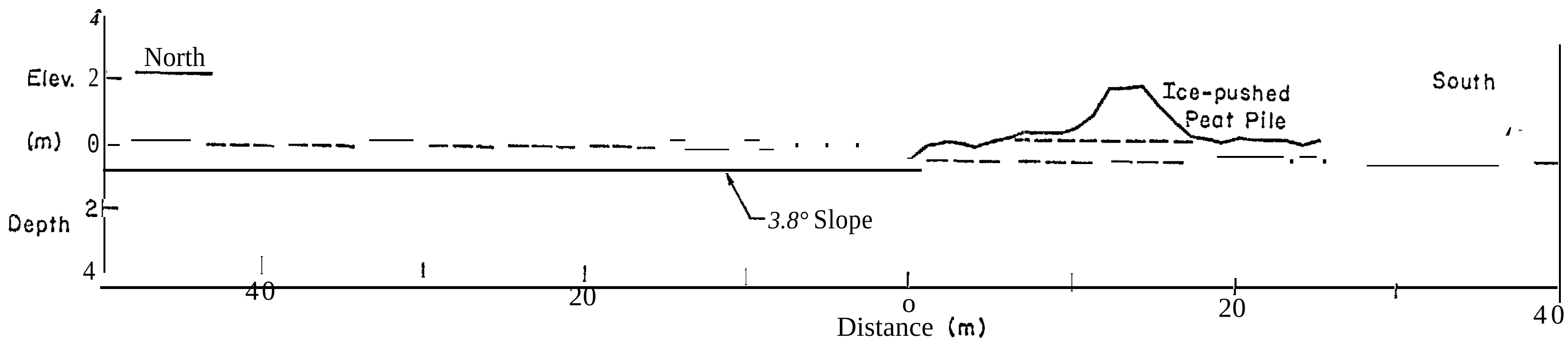


Figure 19. Offshore and beach profile across one of the ice-pushed peat piles near Ksook.

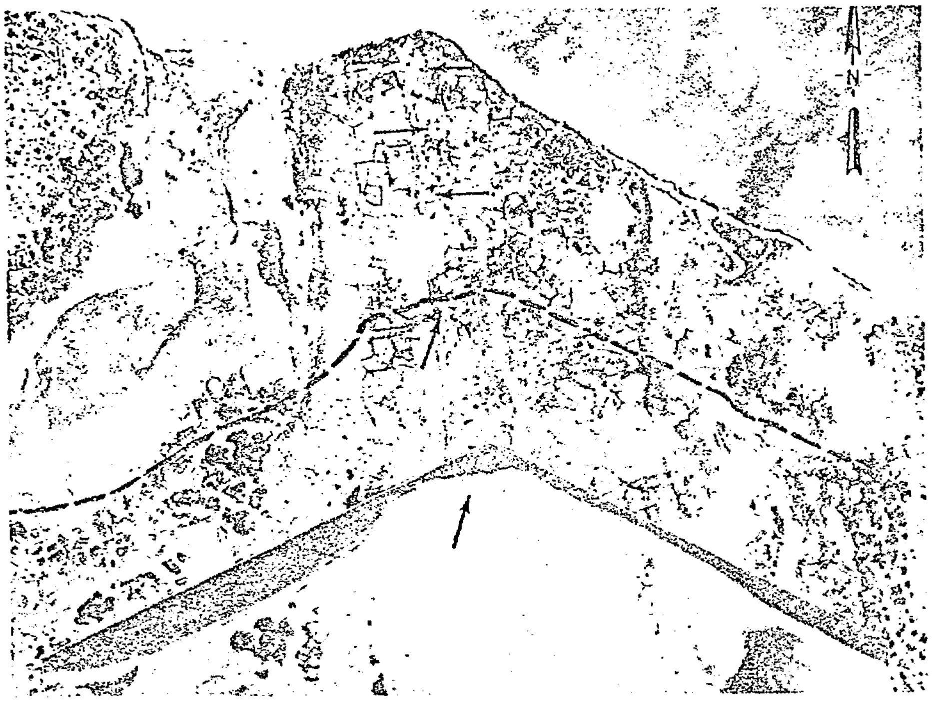


Figure 20. Aerial view of the coast at Ksook in 1949. Insert at bottom shows the coast outline in 1981. Near-vertical arrows point to same house.

of the seabed, 3.8°, is probably the result of the high rate of coastline erosion in this area. Indeed, this coast is retreating faster than any other area on the entire Alaskan Arctic Ocean. Typical annual retreat is reported to be 10 to 25 m per year, depending on summer storms and the specific site (Lewellen 1977, Hartz 1978). This retreat can be illustrated in the 1949 photo shown in Figure 20. The arrows point to five structures. Those north of the dashed line, which represents the shoreline location obtained from the September 1981 aerial photo inset at the bottom of Figure 20, are now gone. Since 1949, some 410 m of coastline has eroded north of the remaining house, This represents an average of 12.8 m of erosion per year. The last remaining Ksook structure was 19 m from the edge of the bluff in late 1981. In front of the bluff is about 5 m of block rubble calved from the eroding bluff. Therefore, the last Ksook building could be destroyed sometime during the next several open water seasons if annual shoreline retreat continues to average over 10 m per year. Of course sea ice ride-up or pile-up may severely damage the structure first.

East of Ksook, at position 9 in Figure B 1, sea ice less than ½ m thick was observed piled 1 to 3 m high along some 150 m of the 2-m-high coastal bluff. The ice extended 5 to 15 m inland.

On the north side of Thetis Island and Spy Island (positions 8 and 10 respectively, Fig. B1) sea ice less than ½ m thick was piled up to 3 m high and 12 m inland.

Along the north side of Pingok Island (position 11, Fig. B1) sea ice was observed piled 3 to 4 m high and" up to 30 in inland on the coastal bluff, which is 3 to 4 m above sea level. This ice extended about I km along the coastline.

Two- to four-meter-high pile-ups were also noted along most of *the* western end of Long Island (position 9, Fig. B2).

It is worth noting that in mid-March off the eastern end of Long Island a broad area of 1.55-m-thick ice moved from the northeast to within 100 m of the shore. Significant rafting and ridging occurred, as shown in Figure 21. Ice movement stations located on either side of this area recorded little or no ice movement at the time, but a station some distance "upstream" experienced movement in excess of its recording capacity. We measured three grounded ridges (A, B and C) over 8 m high (Fig. 22) and one finger raft between ridges A and B which was 155 m long. In short, 1.55-m icc came close to riding up onto Long Island.

In late October, 0.15-to 0.2-m-thick ice moved from the west onto No Name Island (position 11, Fig. B2). It completely overrode a steep-slopccl 1X-m-high gravel berm placed near the water's edge by construction crews and moved inland 20 to 30 m. Later in the winter another icc ride-up and pile-up event

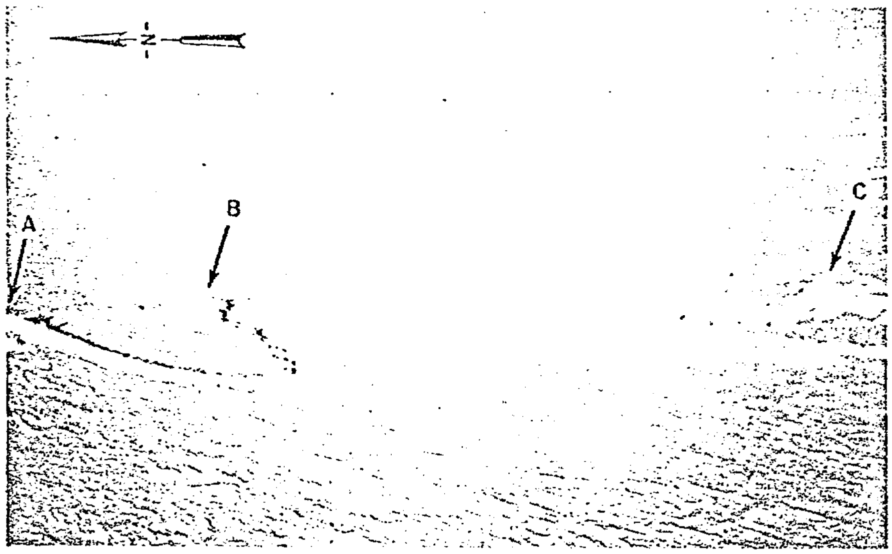


Figure 21. Rafted sea ice off Long Island, May 1981.

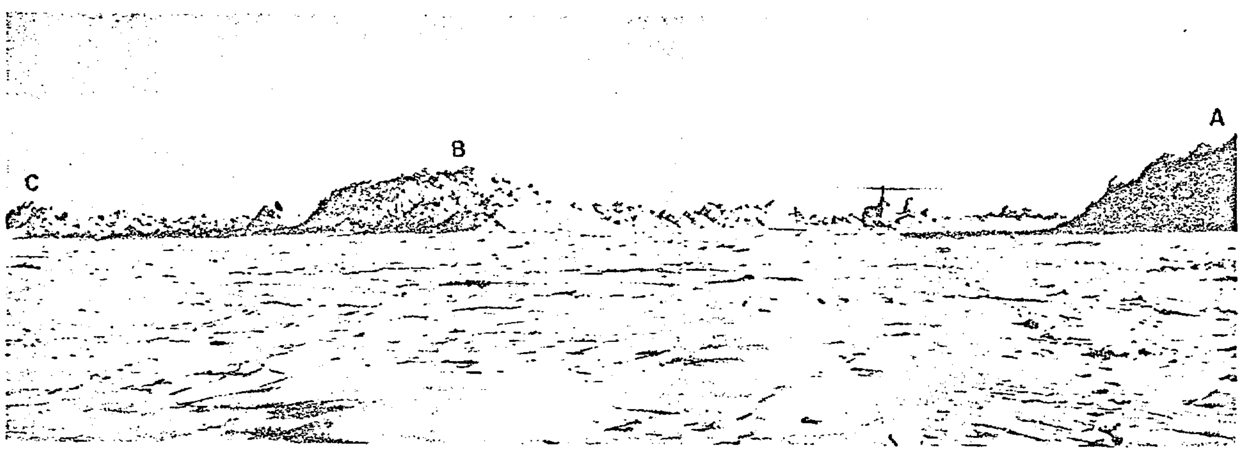


Figure 22. Surface view of ridges shown in Figure 21, May 1981.

occurred, this time on the east side of the island where the sea ice moved up to 15 m inland over a width of about 50 m.

Sea ice about 0.2 m thick was driven 10 to 15 m up onto the north side of several islands at position 12 in Figure B2. On one of these islands the ice was estimated to have moved at a relatively slow rate of 0,6 to 1.5 m per hour (Vaudrey and Potter 1981).

Along the beach east of Collinson Pt. (from positions 1 to 13, Fig. B2) most of the shore (≈2 km) was covered with 0.30-m-thick sea ice debris piled up to *4 m* high. In late August, we measured one area where 510 m of beach was continuously scarred by ice ride-up. These scars extended inland up to 30 m from the water's edge (Fig. 23). Ice-pushed gravel piles up to 1 m high, but typically less than ½ m high, were observed (Fig. 24).

Bathymetric and elevation survey measurements made along the line shown in Figure 23 were used to construct the profile shown in Figure 25. Above *the* 2-m depth, the seabed was found to slope at an angle of 11°. From the water's edge to a distance of 10 m inland, the beach profile has been modified by storm wave run-up. As a result, the forebeach profile shown in Figure 25 is concave and devoid of all ice-scar relief, as shown in Figure 23.

Some of the most important ice ride-up features to be studied were first observed in May 1980 on the southeast side of Camden Bay (position 14, Fig. 132). Only aerial photos of the features could be obtained at the time (Fig. 26). The features were not recent ice ride-ups but were scars plowed into the tundra by a major onshore ice movement some years before. In May 1981, the length of the longest tundra ice sear

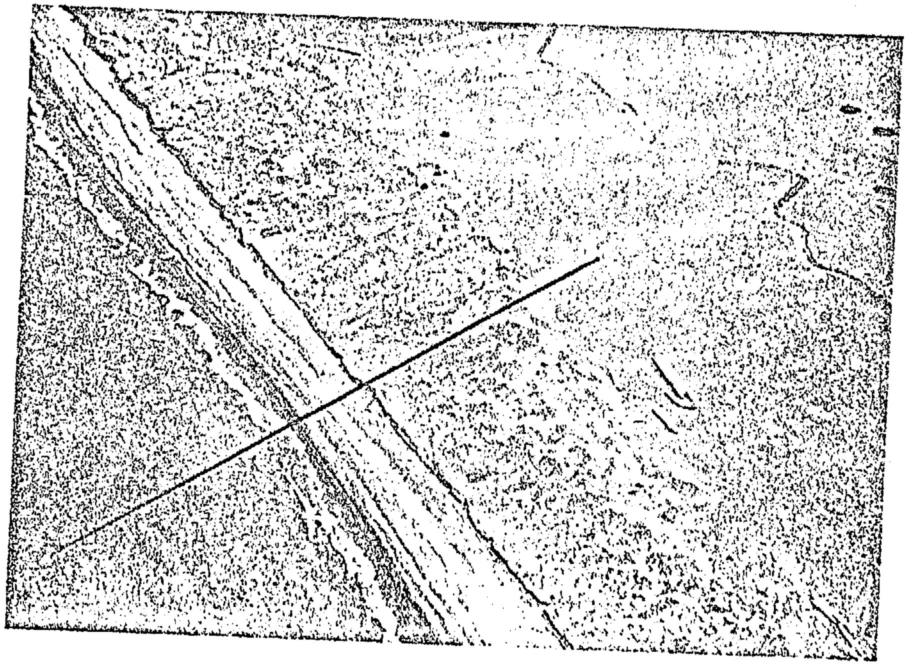


Figure 23. Ice-pushed beach morphology along coast east of Collinson Point, August 1981. Line is along profile shown in Figure 2.S,

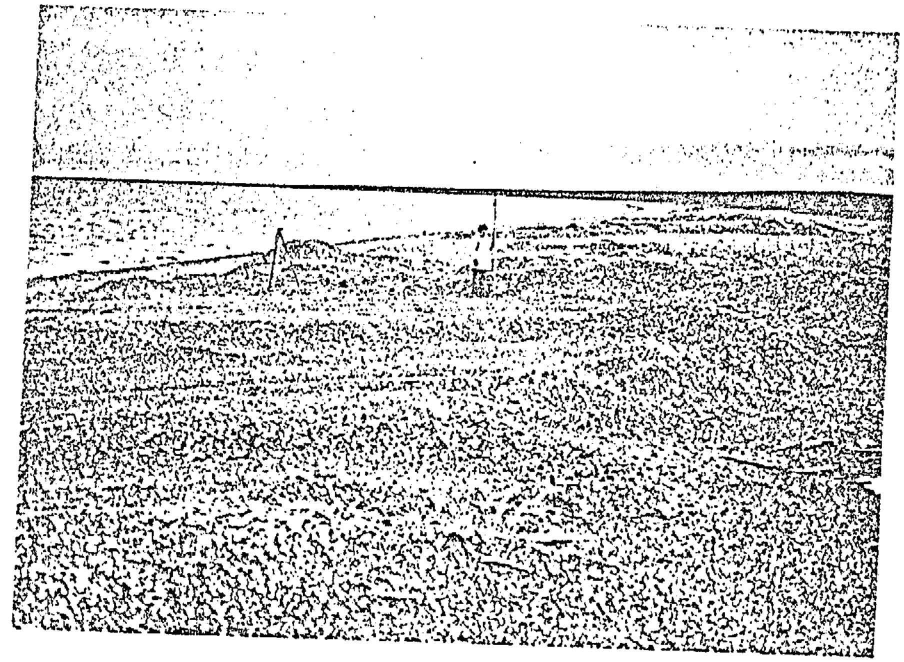


Figure 24. lee-thrust beach striations and gravel piles along the shore east of Collinson Point, August 1981.

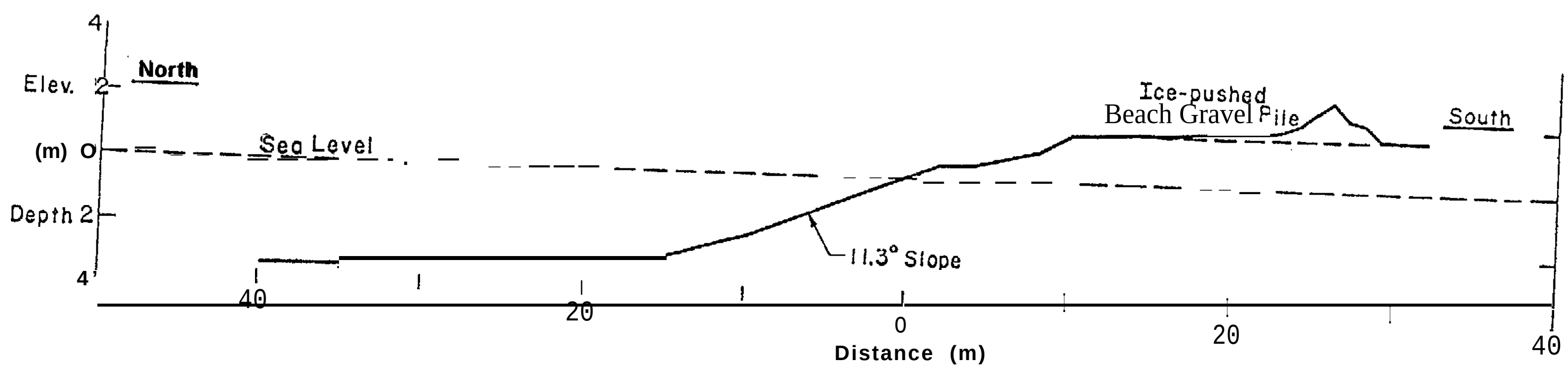


Figure 25, Seabed-beach profile along line drawn in Figure 23,

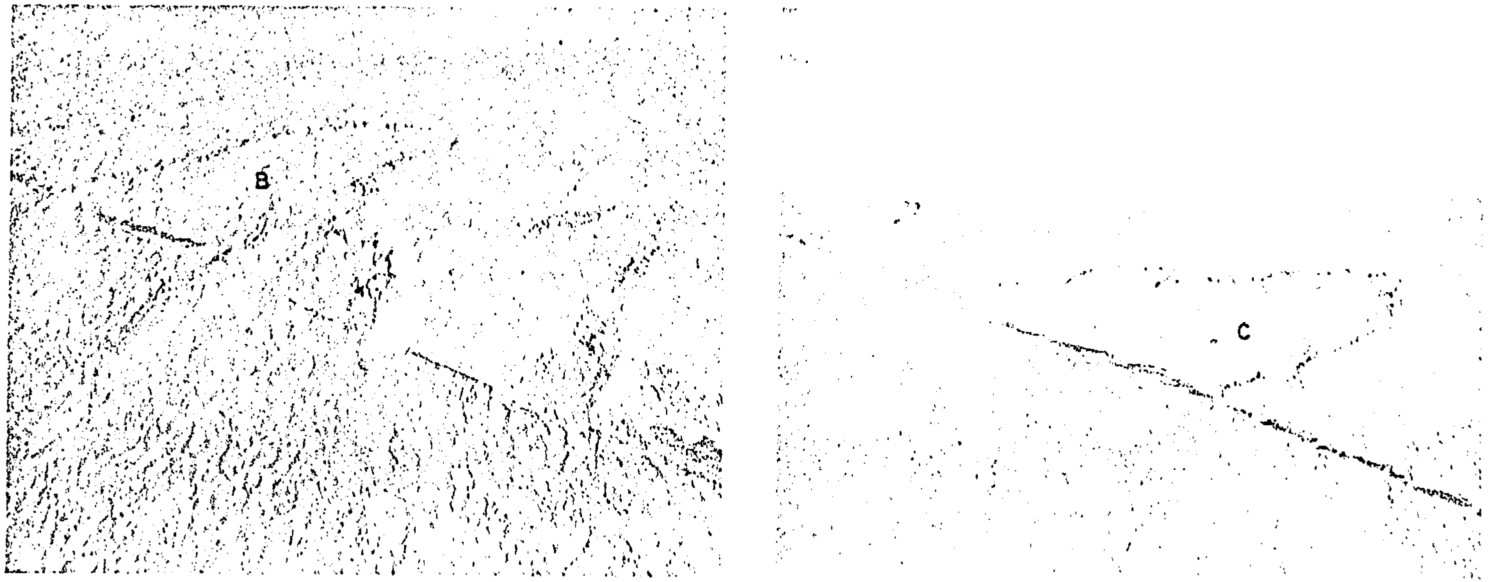


Figure 26, Typical winter view of ice-scared tundra relief, east shore, Camden Bay, May 1980. Note the lobate form of the ice-pushed tundra berms.

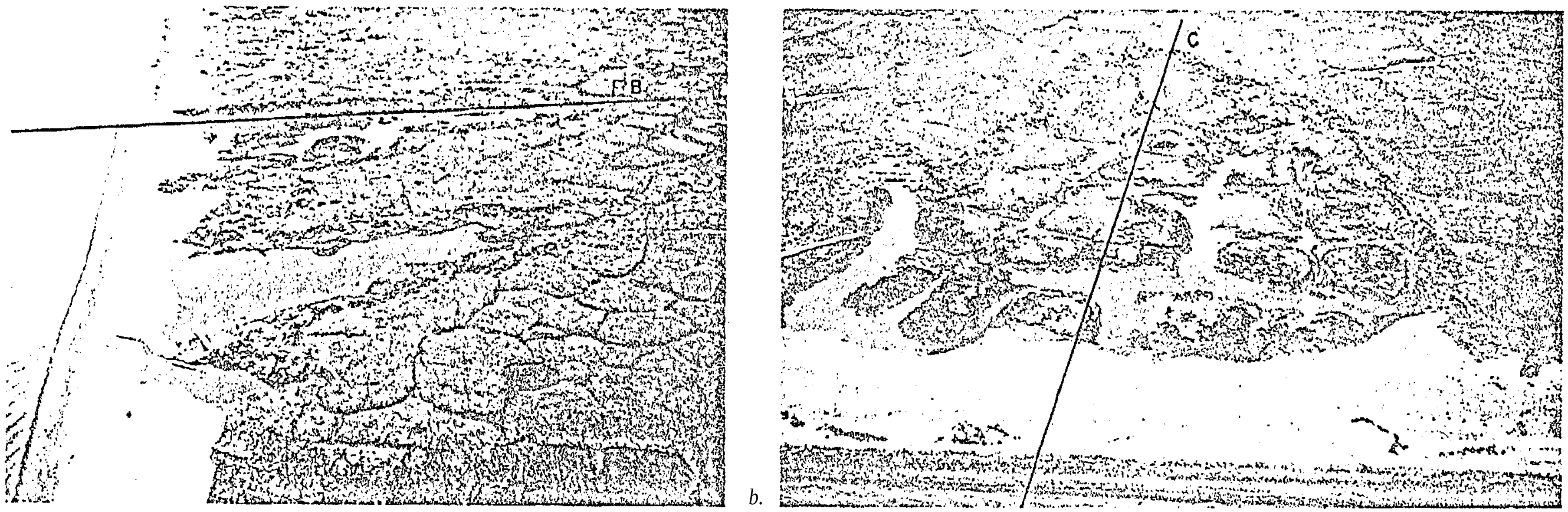


Figure 27. Summer view of ice-scarred tundra features shown in Figure 26, Note the driftwood deposits carried ashore during high seas, August 1981. Lines B and C are along profile shown in Figure 32b and c.

Figure 28. Aerial view of ice-scarred coast, east shore, Camden Bay, August 1981.

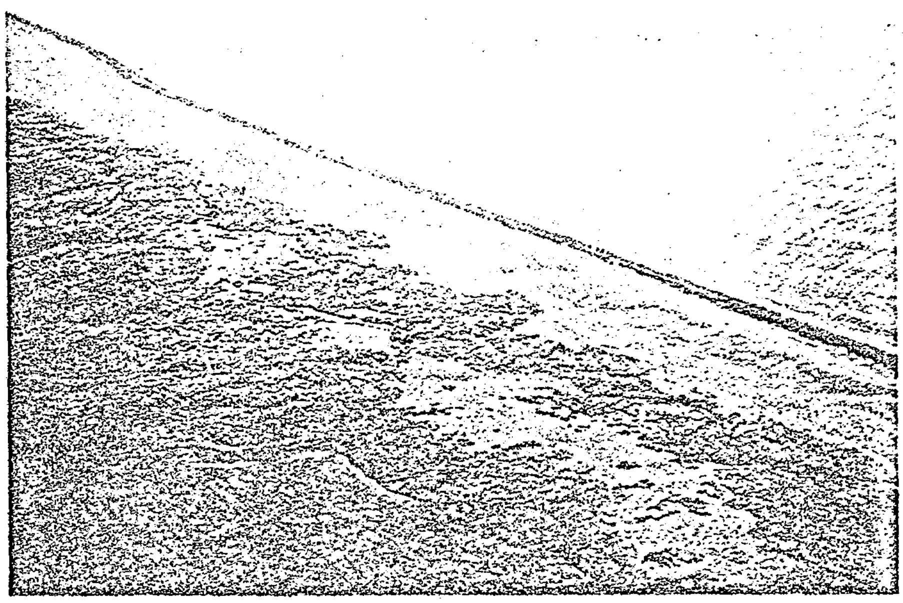


Figure 29. Old ice-pushed tundra berms and beach gravel on the southeast shore, Camden Ray, August 1981. Ice-pushed gravel piles on the beach were the result of the previous winter's ice ride-up.

was measured and was found to exceed *120* m, a major inland advance.

In August 1981 more detailed observations along this section of the coast were made. These included additional aerial photography, elevation surveys and offshore bathymetric measurements. Summer views of the tundra ice scars, shown in winter in Figure 26, are presented in Figure *27. The* scars are surrounded by ice-pushed soil berms. Some of the scars also contain a sizable area of water, suggesting that the terrain is depressed. Another aerial view of the surrounding shore area is given in Figure 28, and a view of the coast about 1 km to the southwest is shown in Figure 29. These photographs show other ice-pushed soil berms which we did not observe during the win. ter due to excessive snow cover. We also saw a significant number of additional ice-scarred tundra features along this section of the coast which were not apparent during the winter due to snow cover. These scars indicate that a major onshore ice movement occurred at some time in the past, and that this event left intermittent ice scars in the tundra along a large section of the coast. In addition, we saw numerous recent ice-pushed gravel piles which extended up *to* 20 m inland from the water's edge (Fig. 29). These features indicate that onshore ice movement is a frequent event along this coastline.

Panoramic views of the tundra ice scar shown in Figures 27a and b are shown in Figures 30a and b, respectively. These views show a beach composed of coarse gravel, much driftwood debris, and ice-pushed tundra berms over 1.5 m high. While much of the driftwood is believed to have been carried on shore by high storm seas, we also found wood deeply embedded in the ice-pushed tundra berms, indicating that this wood was incorporated into the soil during ice dozing, The back of the berm behind the person in Figure 30b is shown in Figure 31. Note the apparent difference in elevation of the berm from the two sides.

An elevation survey was made along each of the lines shown in Figure 27. An elevation survey was also made of the undisturbed tundra just north of the berm beyond the B profile line drawn in Figure 27a. The seabed relief was determined by taking tape soundings at 3-m intervals from an inflatable raft. The survey results are shown in Figure 32. The seabed near the beach is shown to slope at an angle of 8° to a depth of 2 m. Beyond this depth, the seabed has a very shallow slope. The steeper slope near shore, above the 2-m depth, is believed controlled in part by ice-push, which transfers submarine gravel up onto the beach. The natural or non-ice-scarred tundra surface (profile A) is shown to have an elevation which is more than twice that of the ice-scarred terrain along profile B. It should be noted that profile B does not represent the deepest area of this ice-scarred feature. The deeper area was up to ½ m below the pond water level, an area we did not attempt to profile.

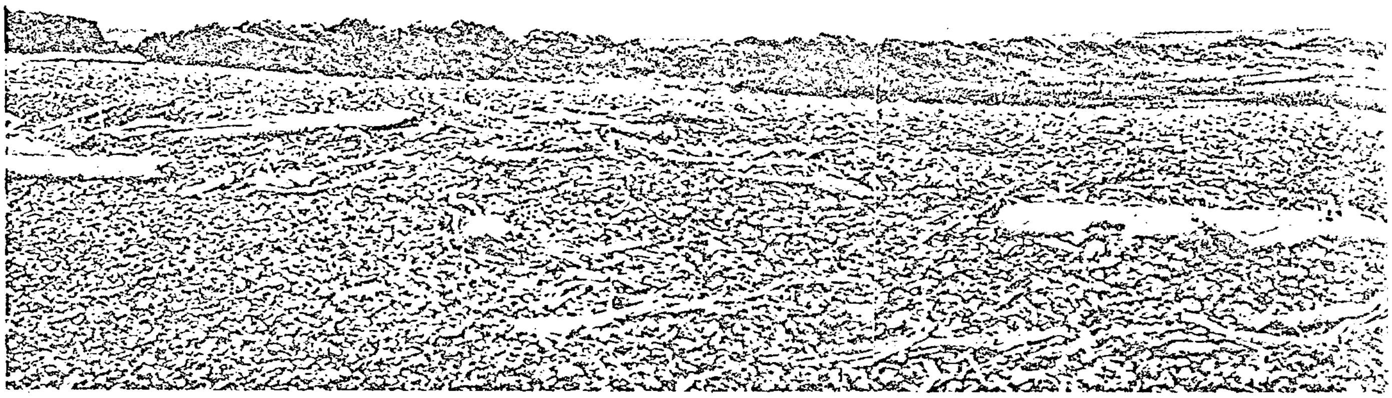
Ice dozing clearly resulted in the displacement of surface material. This in turn exposed the underlying material, which allowed solar radiation to thaw the ground ice. Differential subsidence then occurred in the scarred area. A striking feature of the ice-scarred tundra terrain was that all surfaces were covered by vegetation, indicating that these scars are quite old. The longest ice scar profiled was found to have an ice-pushed tundra berm extending 130 m in from the water's edge.

The ages of these ice-scarred features are unknown. A July 1950 view of *the* coastline (Fig. 33) shows the features existed at that time, and ice ride-up had intermittently scarred the tundra along a 2.9-km-long section of the coast. A 1 '?43 image of this coastline revealed the same scars. Thus the features are over 35 years old. We estimate from comparison of the 1950 and 1981 aerial photos that the shoreline is receding at 0.35 m per year, or about 14 m since 1943. The ice-pushed berms we measured were, therefore, farther from the water in 1943 than they are today.

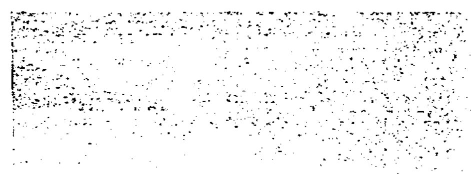
It is interesting to speculate whether these scars were formed at the time of the 2 July 1914 Camden Bay ice ride-up event described by F. Johansen in his daily log:

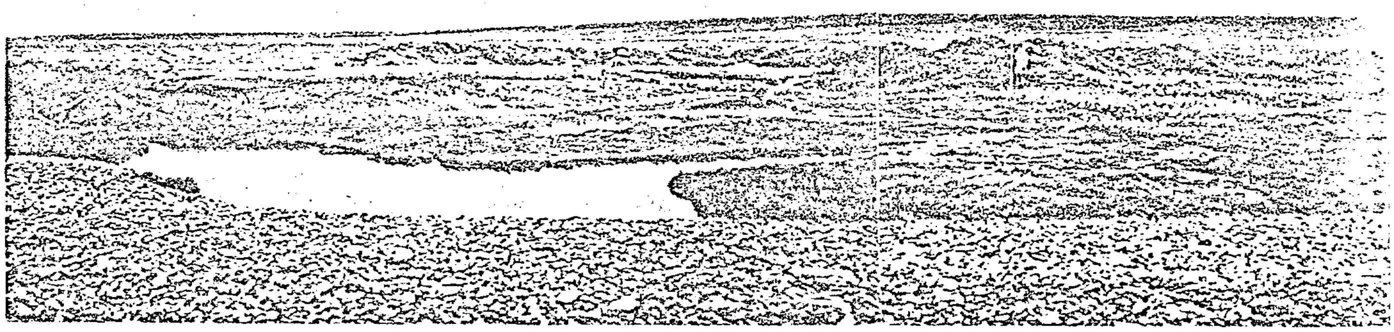
> "First some ice was screwed Up close to the beach here and there; then came an immense and continuous pressing of the ice from far offshore onto the beach. Like the movement of a glacier the whole body of sea ice moved eastward; without regard for shallow water the coastal ice was pressed up on the beach and during this slow but continuous movement the ice ploughed down into the sand where this was the beach material. On the coast of tundra-bluffs the ice first shoved away the boulder gravel wall in front, tearing it up, going over it and raising often immense boulders and driftwood trunks *on* its 'back' after which it ploughed into the tundra-. bluffs and overlapped these. The movement of the ice lasted for almost an hour. Some parts of the higher tundra-bluffs had their seaward side covered by the coastal ice stretching to the upper margin of these, and immense blocks of. ice, boulders or tree trunks from the beach were raised and pushed still further in on the tundra."

At the end ofa report by () 'Neil] (1924), several photos appear which show an ice ride-up with ice-pushed tundra soil, boulders and driftwood before it. This



a.





b.

Figure 30. Beach views of ice-scarred tundra, August 1981. Views

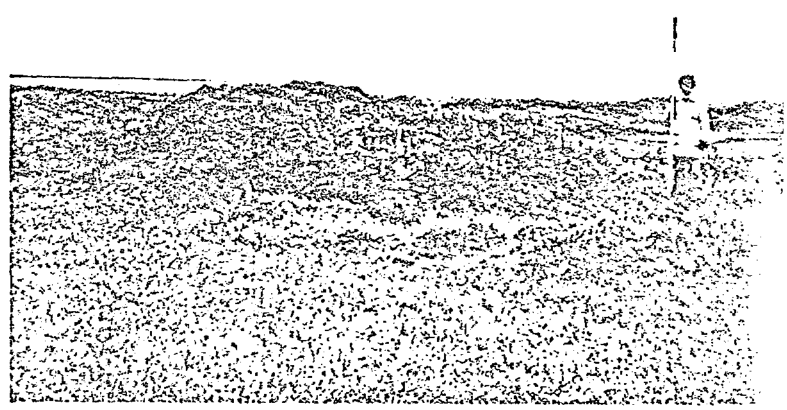
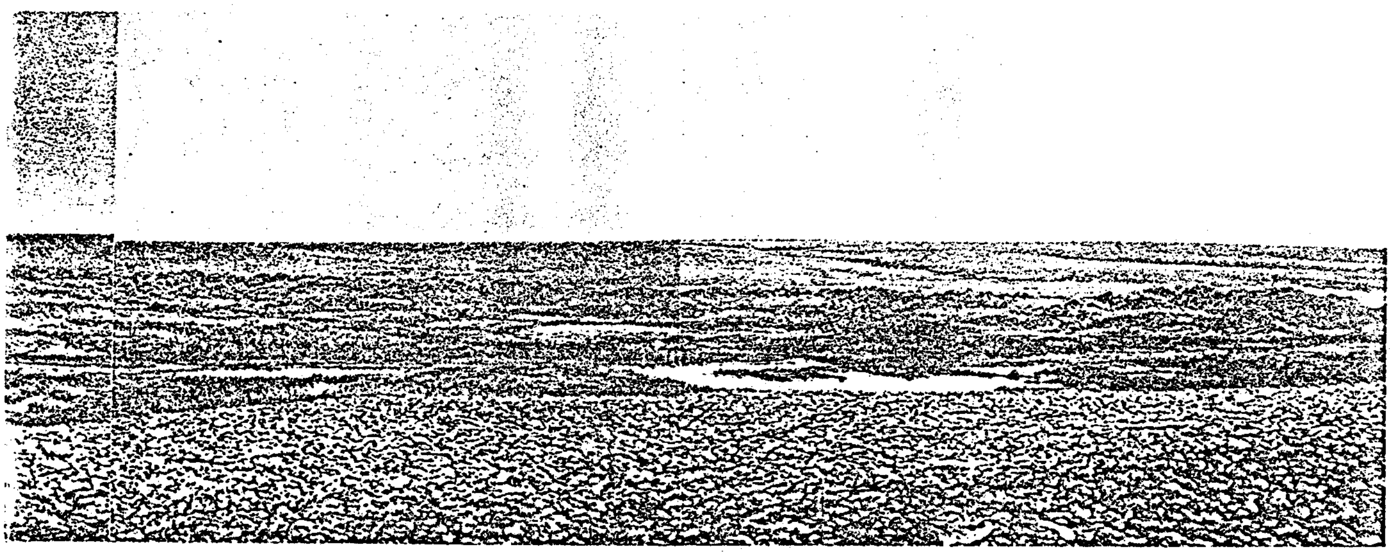
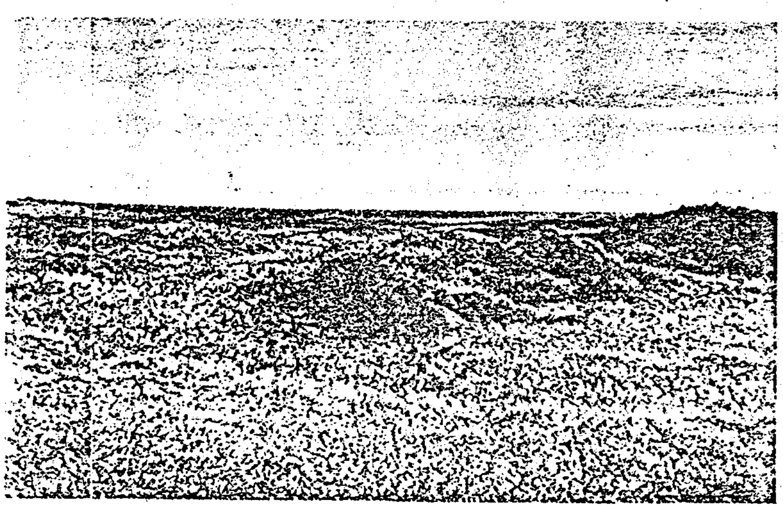


Figure 31. Ice-pushed tundra berm behind person in Figure 30b as seen



a and b ***show*** *interior* ***of*** *features B and* ***C respectively*** *in Figure 27.*



from landward *side,* ***August 1981.*** *Note height of gravel beach in background.*

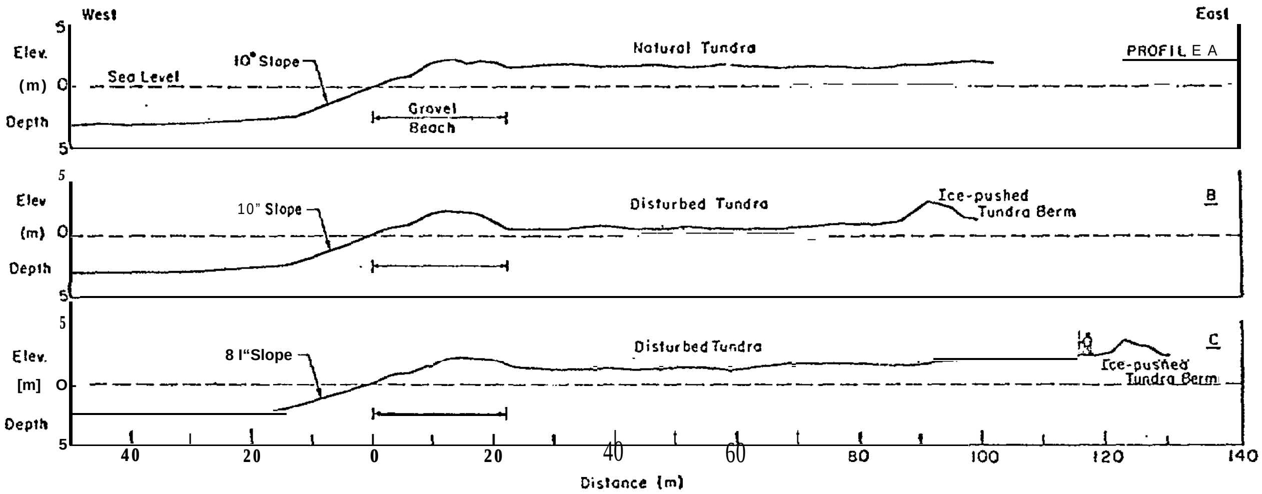


Figure 3.2. Profiles across coast of undisturbed tundra (A) and ice scars B and C shown in Figure 30.

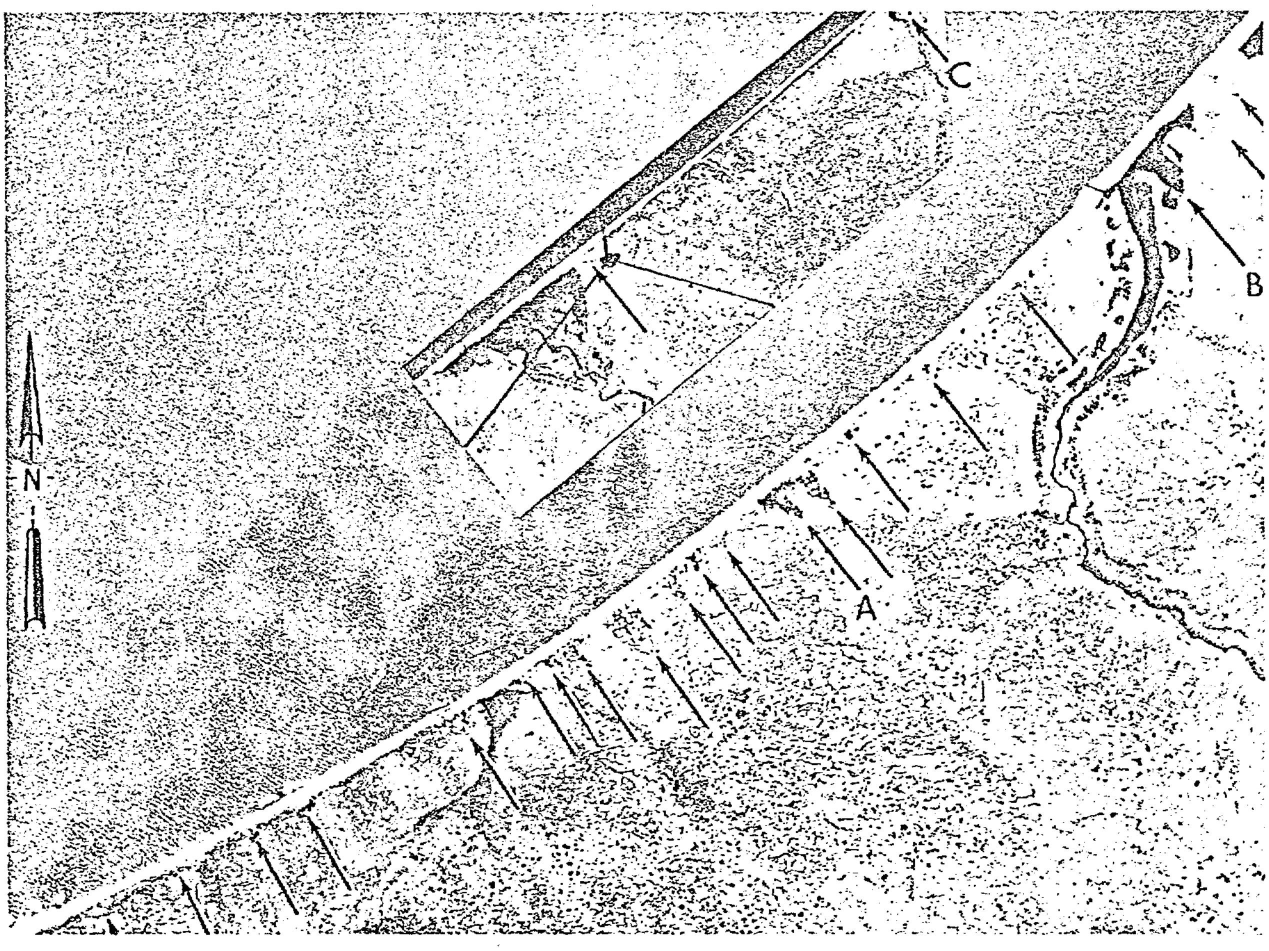


Figure 33. Ice-scarred tundra features along southeast shore of Camden Bay, 1950. Insert is 1947 imagery showing the northern con tinuation of the coast beyond the last arrow in the upper righ t-hand corner of the larger 1950 aerial photo. Arrows point to many of the major ice scars. The arrow at the bottom left points to the terrain shown in Figure 29.

event apparently occurred in Camden Bay in 1914 when Johansen reported his observations. If the tundra ice scars were formed at this time and the shoreline erosion averaged 0.35 m per year, then the ice-pushed tundra berms would have been about 23 m further inland from the sea in 1914.

The pond at arrow A in Figure 33 is in the ice scar shown in Figure 27a. It is interesting that this feature appears on maps as a pond (NOAA 1976). This may be the only pond ever shown on a map which was formed as a result of an ice ride-up. We have named this feature Ice Scar Pond in Figure B2.

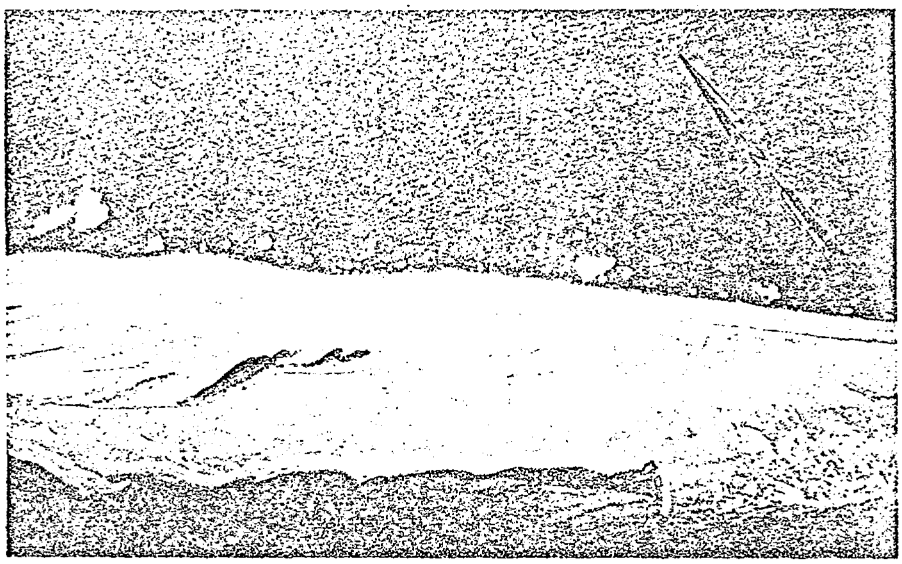


Figure 34. Typical ice-scarred relief observed on Icy Reef, August 1981.

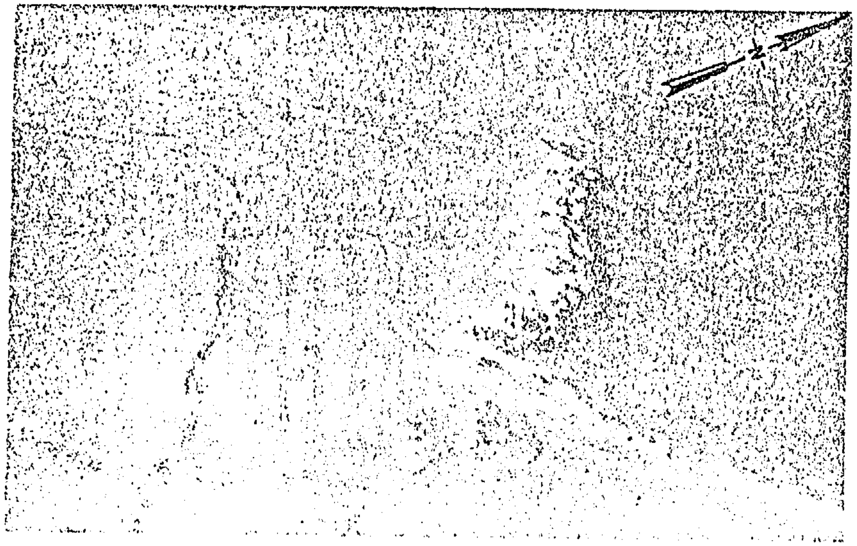
The ice scar at position B in Figure 33 was found to have a ½- to 1 %-m-high ice-pushed tundra berm along the northeast side and along its inland terminus. This mostly water-filled sear, on the north side of the nearby river outlet, was taped and found to extend 148 m inland from the sea. If indeed this feature was formed in 1914 and shoreline erosion averaged 0.35 m per year as previously determined, then the ice thrust which formed this tundra scar, would have advanced some.1 70 m inland.

Continuing along the coast in April 1981, we observed ice ride-ups to 20 m inland at numerous locations between positions 14 and 3 on the east side of Camden Bay and at positions 7 and 15 east of Barter Island (Fig. B2). No significant onshore ice movements were noted from position 15 on to the U. S.-Canadian border. However, in early September we overflew the Icy Reef barrier islands northwest of Demarcation Bay and noted that the islands had many ice-pushed gravel ridges and were highly gouged and pitted over much of their surfaces (Fig. 34), indicating that sea ice invades these islands.

WINTER 1981-82 AND SUMMER 1982 OBSERVATIONS

In early April 1982 the coastline from Pt. Barrow to the U.S.-Canadian border was again followed. On an island just southeast of Martin Island (position 12, Figure B1) and on Igalik (positions 13 and 2) and Kulgurak (position 3) Islands, large shore iee pile-ups existed. Aerial and ground views of the ice pile-ups at positions 12 and 2 are shown in Figures 35 and 36, respectively. We made numerous measurements of the angles of repose of the 0.55-m-thick ice blocks in the ridges. The angles varied from 30" to 45° and averaged 37°. This angle is representative of the angle of internal friction of the sea ice rubble. Offshore water depth measurements were also made, and these indicated a relatively shallow seabed slope of 3°. The highest ridges wc measured at positions 12 and 2 were 11.4 m and 11.9 m, respectively. Portions of the shore ice pile-ups extended up to 25 m inland on the island at position 12 in Figure B1. One ice thrust extended 36 m across northwest Igalik Island (Igalik Island is now two islands, having been cut by the sea). On southeast Igalik Island, position 2 in Figure 131, the ice rubble extended across the 21-m width of the island to 13 m beyond on the lagoon side. This represents an indirect form of ice override. On Kulgurak Island, position 3 in Figure B], sea ice advanced about 30 m inland.

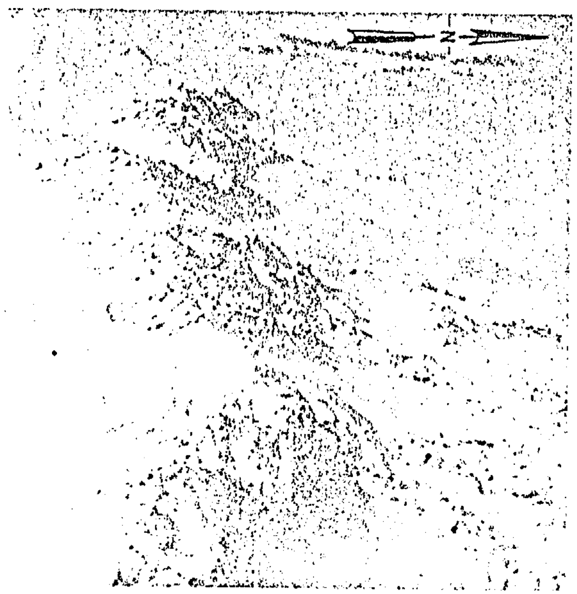
We revisited these islands on 10 August and found them ice-scarred, with many ice rubble piles still in existence. On the island at position 12 in Figure %1, the ice formations shown in Figure 37 were observed. The largest ice pile was 7 m high. A significant layer of pebbly sand, scooped up from the seabed by the ice as it moved shoreward, covered portions of the ice piles and was observed scattered internally along the ice block structure (Fig. 38). From the air the gravel sea floor to a depth of about 1½ m could be seen, as were places where the ice had gouged up the sediment. These ice gouges appeared quite shallow and will be quickly erased by wave action when the ice pack, which was still close to the coast in early August, moves away from the shore. On northwest Igalik Island (position 13, Fig. B1), the ice-scarred beach topography shown in Figure 39 was observed, while



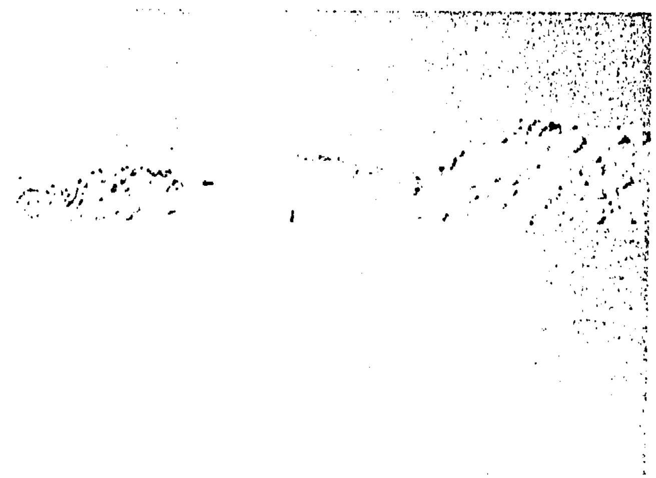
a.

b.

igure Aerial (a) and ground (b) views of ice Island, April 1982.



a.



b.

Figure 36. (b) views of ice pile-up on Igalik Island, April 1982. Note size of person in relation to ice pile-up in photo b.

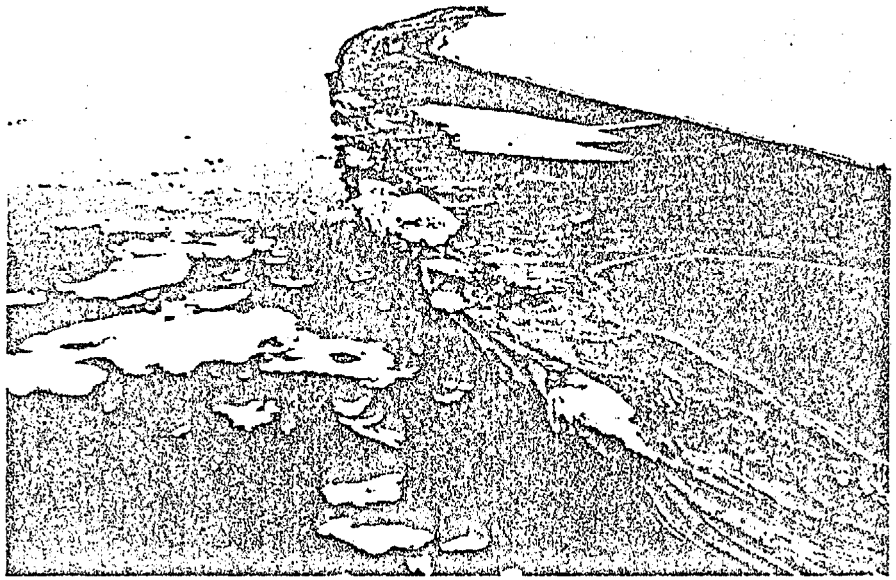


Figure 37. Remains of ice pile-up on island southeast of Martin Island, August 1982. Note that the ice extends out over the water.

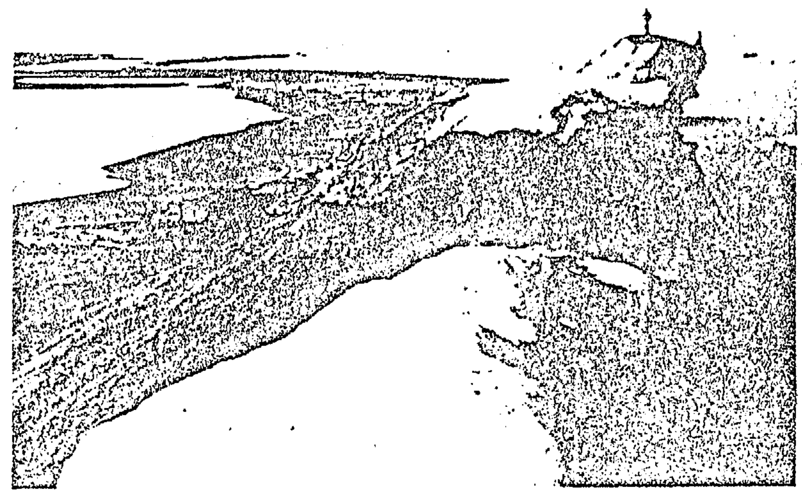
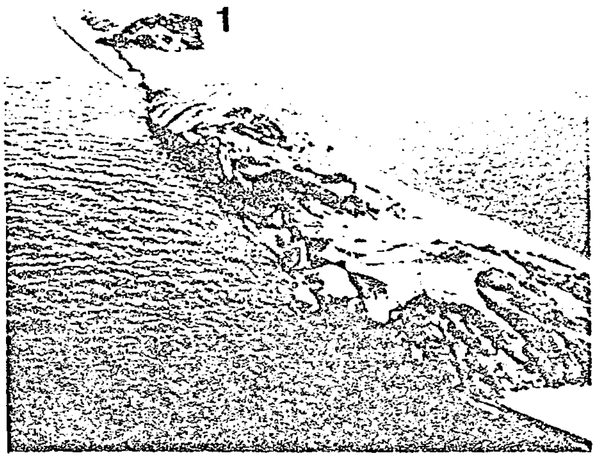


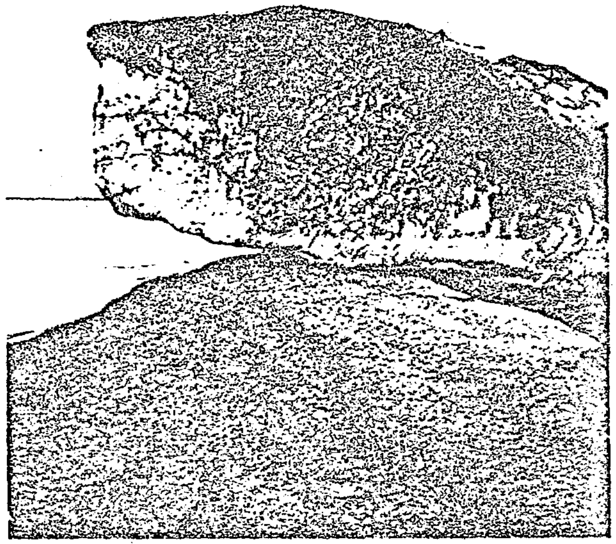
Figure 36'. Thick layer of sand- and gravel-covered portions of the ice pile-up on the island southeast of Martin Island, August 1982. This protective layer will help to retard the melting rate of the underlying ice.

a. b. c.

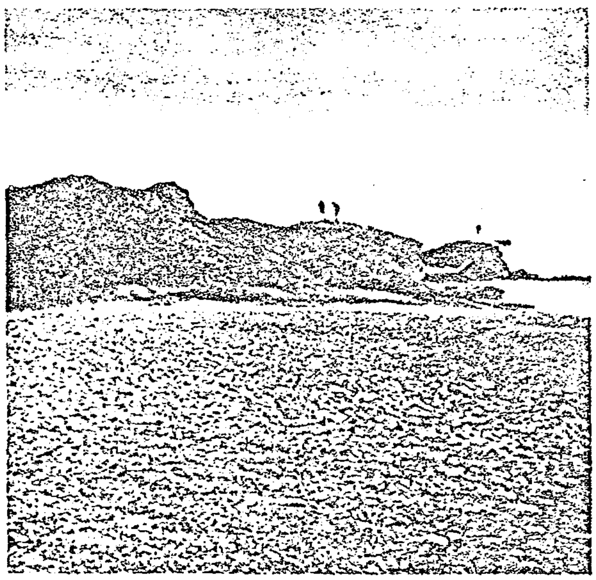
Figure 39. Two major ice scar features on northwest Igalik Island (a) and close-up views (b and c), August 1982. Under the ice-pushed gravel berms much ice existed, which, upon melting, will reduce the height of the berms.



a. The island in the background is Kulgurak Island, which is seen to have an ice pile-up remaining at the north west corner..



b. The back side of the ice pile-up (1) showing the wave-undermined ice extending out over the waters of Elson Lagoon. Note the general lack of ice block detail and absence of voids in the ice face.



c. The back (lagoon) side of the largest of th e ice pile-up remains. Note that most of the ice is covered with sandy gravel.

d. A side view of the fur end of the large ice pile-up. The internal block structure and sediment are visible, as is one portion of an ice sheet which had buckled into *a convex shape, as outlined by the dotted line.*

Figure 40. Aerial (a) and ground views (b, c and d) of ice pile-up remains on southeast Igalik Island, August 1982.

on southeast Igalik Island (position 2) ice pile-ups to 5½ m high still existed (Fig. 40). The Kulgurak Island beach was found to have a number of ice-pushed gravel piles and ice ride-up striations which extended up to *29* m from the sea.

In April, west of Lonely at position 14 in Figure B1, thick sea ice was observed up to S m inland along about 2S m of the 2-m-high coastal bluff.

East of Lonely (position 6b, Fig. B1) sea ice was observed in April piled up along some 100 m of the beach. ‘he ice rubble reached a height of 7 m and extended up to *25 m* inland. Much sand and gravel sediment was carried by the ice and incorporated into the ice rubble.

On 10 August most of the sea ice rubble had wasted away .except for a thick mass remaining under a 10- to 20-cm layer of gravelly sand. A view of the shoreline

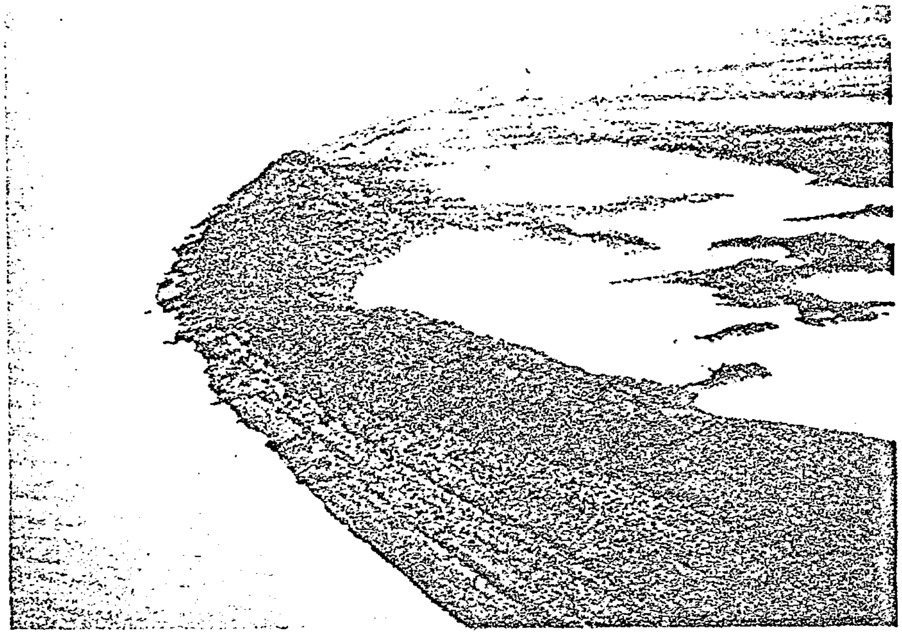


Figure 41. Debris pile in August 1982 of remains of winter shore ice pile-zip at position 6b, Figure B1.

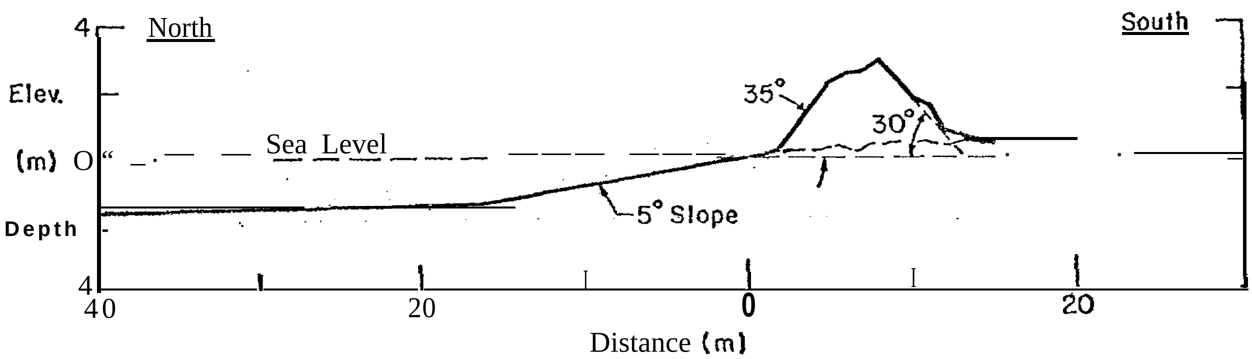


Figure 42. Profile across coast and old pile-up feature (position 6b, Fig. B1).

showing this formation is given in Figure 41. An elevation survey of the shore rubble and offshore topography (Fig. 42) revealed that the gravelly sand covering was at or near its angle of repose of 30° to 35° and the pile was still 2.9 m high and extended up to 15 m inland.

This year again we observed %-m-thick sea *ice* piled up on the 2-m-high bluff at Ksook (Fig. 43). The ice piled up to 3 m high on top of the bluff in front of the old Ksook hut and about 30 m to the west of the hut it moved 6 to 7 m inland. At the latter site in August, we observed where the tundra had been scarred by the ice ride-up. Portions of the organic mat had been peeled off or folded. Rocks and pebbles transported by the ice from offshore lay scattered around the area invaded by the sea ice. An aerial view of the bluff at Ksook and a photo of the above ice-formed features are given in Figure 44.

In August, at position 9, we observed many ice-pushed tundra berms 5 to 10 m in from the edge of the coastal bluff. These scars were apparently caused by the ice ride-up and pile-up noted at this location during the 1981 spring reconnaissance.

In April, the low-lying beach at position 913 in Figure B1 was noted to be piled with ice estimated to be 4 to 5 m high and extending up to 15 m inland. The ice had ploughed up much peat material, which on 10 August was found up to ½ m thick on top of the remaining sea ice rubble (Fig. 45).

On Thetis Island (position 15, Fig. B1) 0.6-m-thick early winter sea ice was pushed up to 6 m inland and piled 2 to 4 m high along several hundred meters of the shore. Offshore water depth measurements revealed a seabed slope of 3°.

Large shore ice pile-ups and long onshore ride-ups were observed on many of the Jones Islands. The ice

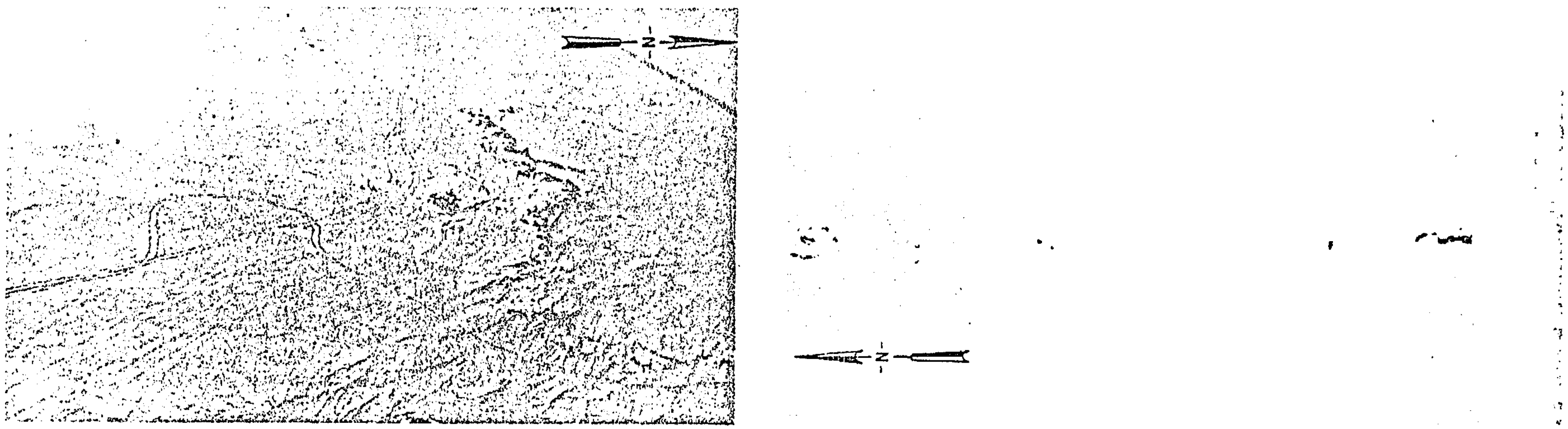
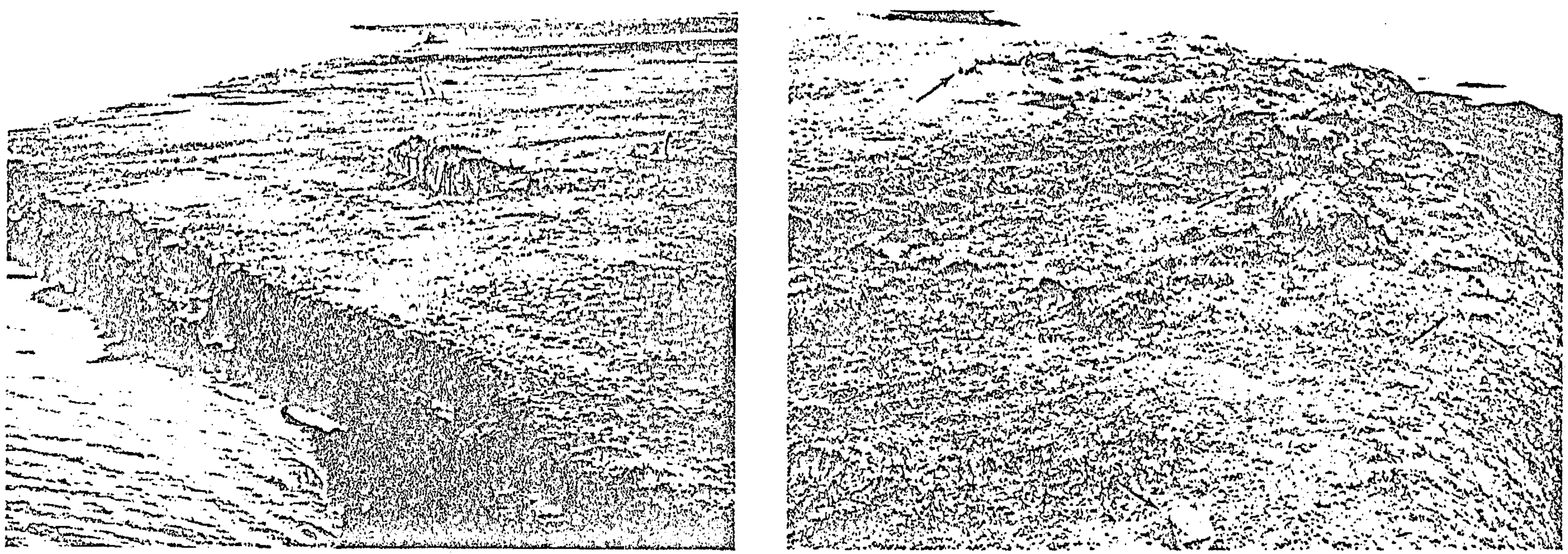
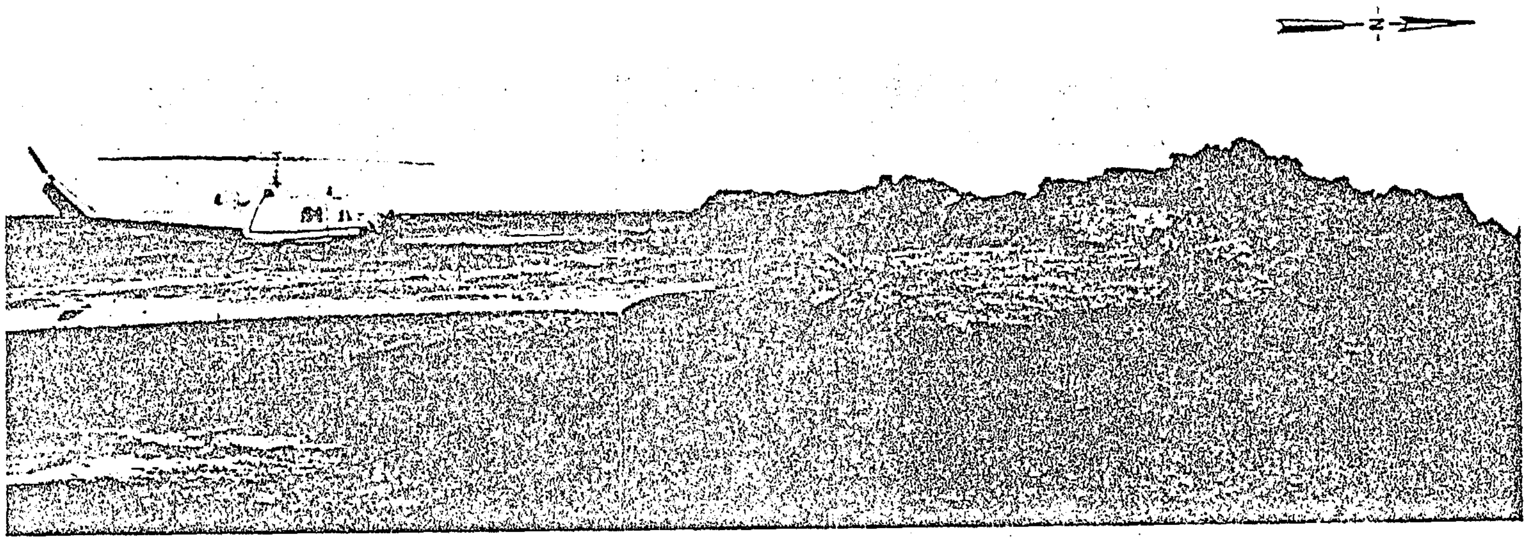


Figure 43. Aerial and ground views of ice pile-up at Ksook in April 1982.



a. b.

Figure 44. Bluff morphology and ice-scarred tundra at Ksook, August 1982. Note the folds and slabs of tundra matting peeled loose and the rock, at arrows in (b), transported up onto the bluff by the sea ice.



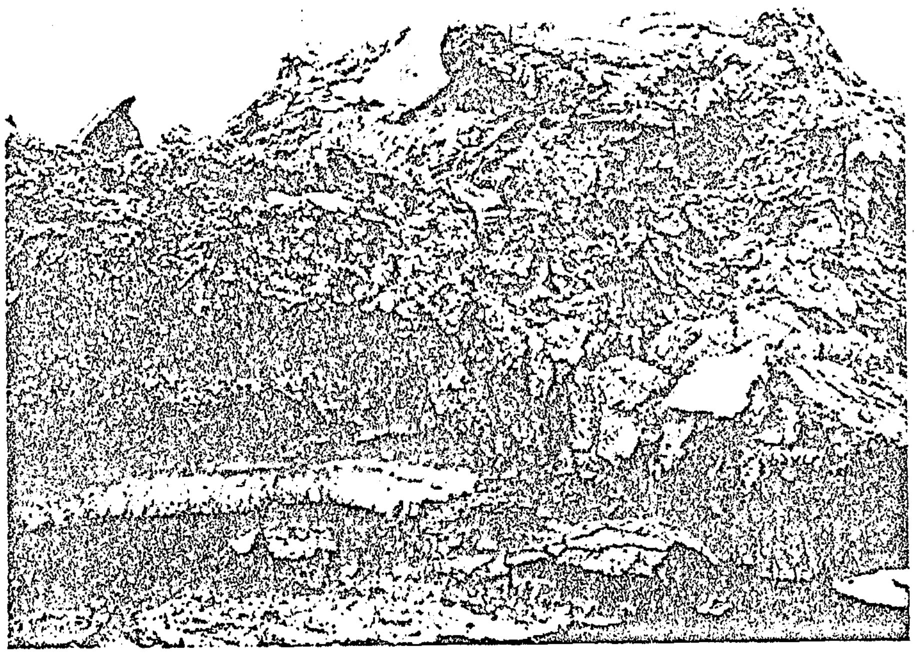


Figure 45. Portion of the 250-m-long, peat-covered ice piles (August 1982) at position 9b, Figure B1. Individual peat slabs were up to 0.3 m thick. Note the sea ice exposed under the seaward side of the peat pile in bottom photo.

Figure 46. Sea ice pile-up along entire length of Spy Island, April 1982.

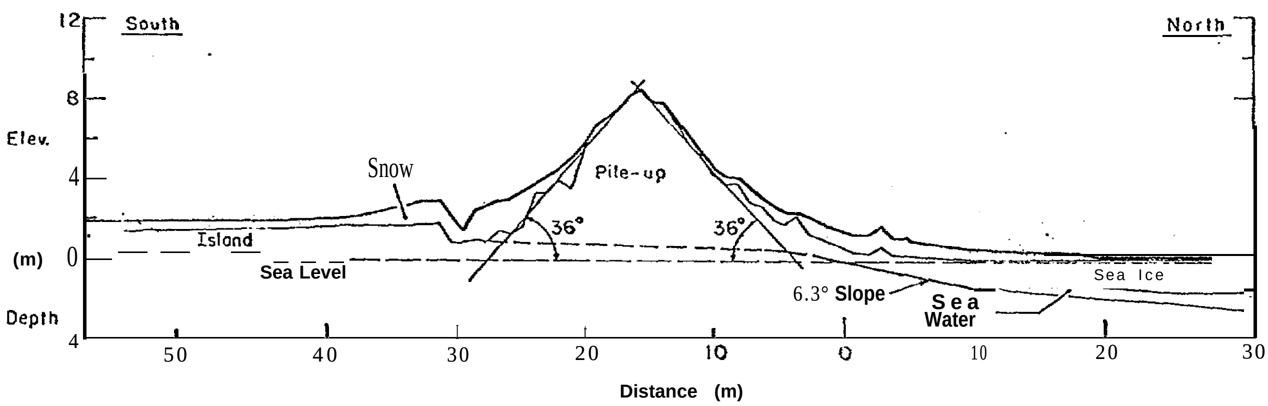


Figure 4 Z Cross section of 1982 Spy Island sea ice pile-up.

incorporated in these formations varied between 0.4 and 0.65 m thick, indicating that the pile-ups formed in early winter. An aerial view of the ice pile-up on the west end of Spy Island (position 8, Fig. 131) is shown in Figure 46. As shown in Figure 47, the ice pile-up at one site extended over 25 m inland on the beach, reached a height of 8.5 m, and had side slopes of 36". Near the beach the seabed *is* shown to have a slope of 6.3°.

On Leavit Island (position 16, Fig. B1) 0.45-m-thick sea ice completely overrode a 275-m-long sec. tion of the island (Fig. 48). The length of the ice thrust, from *the* sea side to where it stopped on the lagoon side, was 66 m. The island appeared to be 1 to 1½ m high at the ice override site.

An elevation survey over one section of the ice pile-up on Pingok Island (position 11, Fig. B1) is shown in Figure 49. At this location sea ice piled up to a height of 7.4 m and toppled onto the 3%-m-high island "bluff." The ice extended over 30 m inland from the sea at this site.

On the barrier islands 5 to 10 km southeast of Brownlow Pt. (position 16, Fig. 132) several 5- to IO-m shore ice ride-ups were observed along more than 400 m of the beach. On 13 August we measured the longest ice-scarred beach striation, which extended 63 m inland. Small %-m-high ice-pushed gravel piles were a common feature along the heath.

On Konganevik Pt. (position 17, Fig. B2) an old ice scar was observed on the tundra. This feature was estimated to end 5 m from the sea.

On 13 August we observed the coastline at position 17b in Figure B2 for the first time in summer. The beach, which varied from 2 to 6 m wide, was found to be composed of coarse gravel which had been extensively modified by onshore sea ice movement events. The coastal bluffs were typically 2 *to*

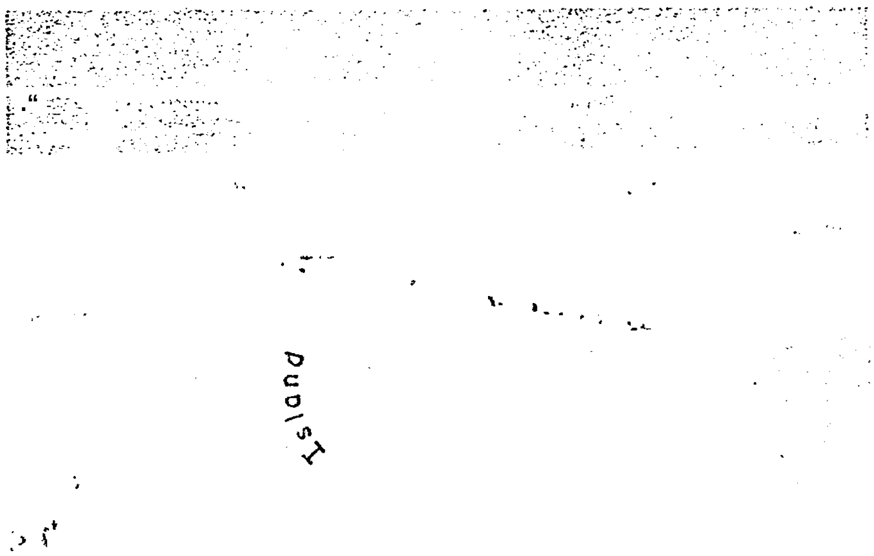


Figure 48. *Ice override on Leavit Island, April 1982.*

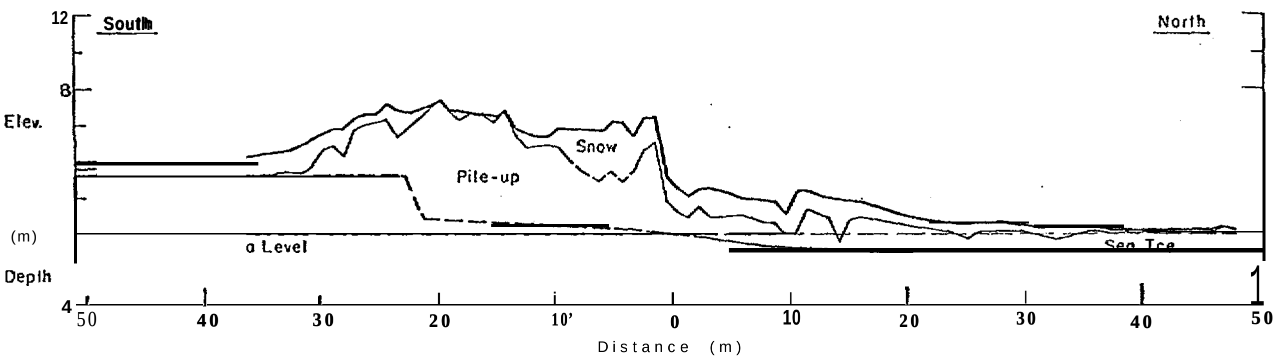


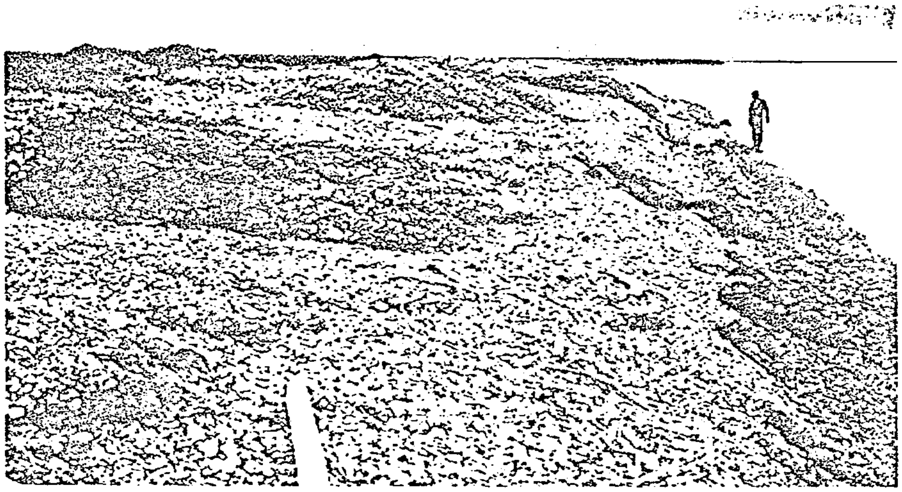
Figure 49. *Cross section of Pingok Island* sea ice *pile-up.*

4 m high. In winter deep drift snow extends from the top of the bluffs out onto the sea ice. This snow would probably have covered any shore ice pile-up or ride-up feature which may have existed but was not observed during our winter reconnaissance surveys.

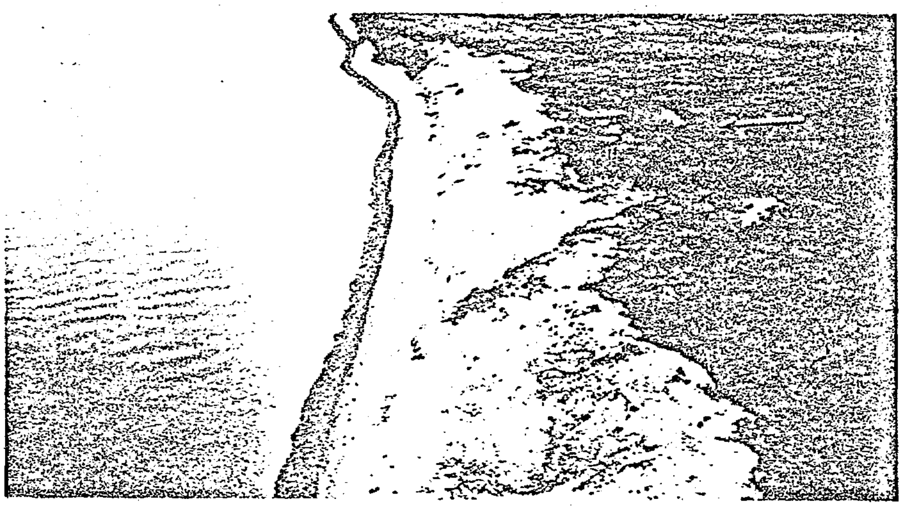
Ice-pushed gravel piles were a common beach feature, as were ice-pushed gravel overlays extending in places to the top of the tundra bluffs (Fig. 50). Ice-pushed tundra berms were observed at several locations. These extended 10 to 15 m in from the edge of the bluff. AI-I elevation survey made at one of these sites is given in Figure 51. The top of the bluff at this site was about 9 m from the sea, and had a %-m-high ice-pushed gravel pile along its edge. Behind the bluff the tundra elevation was 2½ m high and there was a scar left by an old ice ride-up. This scar terminated at a ½-m-high i,:. ·ushed tundra berm located 22 m from the curren· ·ition of the coastline.

At posit· -I18 in Figure B2, a 36-m-long old ice scar was measured in August. The scar ended about 4.5 m up the side of the steeply sloping coastal bluff. A veneer of beach gravel outlined the ice thrust (Fig. 52).

On 13 August we visited the site of the ice-scarred feature at position C in Figure 33. An aerial view of the scarred terrain and a view from seaward of the bluff are shown in Figures 53 and 54, respectively. The bluff area where the ice ride-up occurred is not as steep as it is to the north (Fig. 53). The implication is that-disturbance of the tundra by ice-ploughing accelerated permafrost melting and related subsidence in the scar area. The longest ice scar was found to extend 118 m inland and terminated at a ½- to 1-m-high ice-pushed tundra berm. The middle scar was profiled; its relief is shown in Figure 55. This scar extended 95 m inland. The top of the bluff as it existed at the time of our survey was 2½ m high and 15 m in from the sea. Inland from the edge of the bluff the terrain sloped upward



a.



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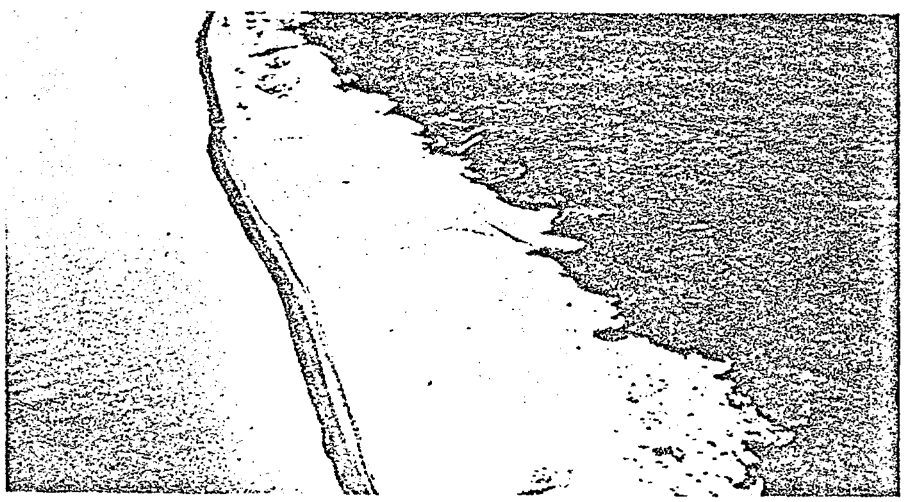

c.

Figure 50. Ice-pushed gravel piles (u), tundra berms (b) and grave! overlay (c) along the Camden Bay coastal bluffs at position 17, Figure B2, August 1982. Arrow in (b) points to elevation survey site.

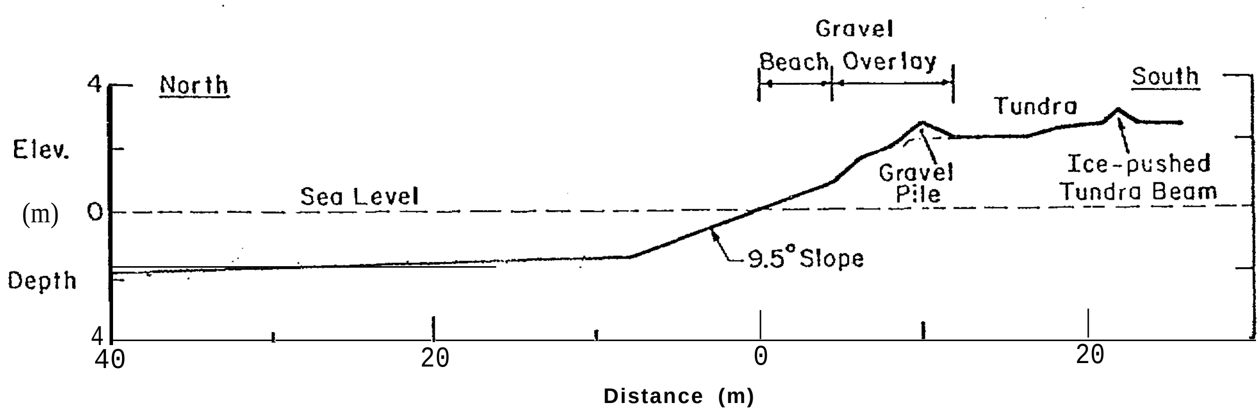

Figure 51. Profile across coast at old ice ride-up tundra scar near left arm of position i 7b bracket in Figure B2.

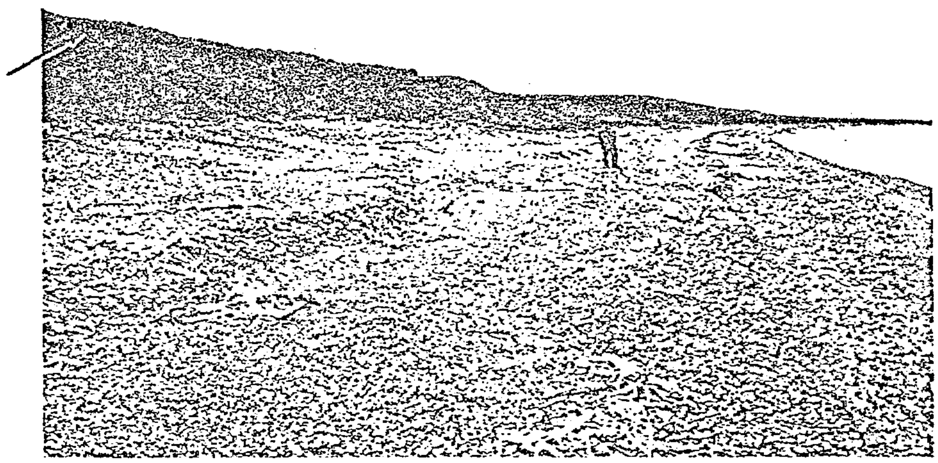

Figure 52. Terminus of old ice scar (arrow) on side of bluff at position 18, Figure B2, August 1982. Darkness of photo obscures grave! overlay left by ice thrust.

Figure 53. Aerial view of ice-scarred tundra (August 1982) at coastal site C, Figure 33. Arrows mark landward ends of the ice scars.

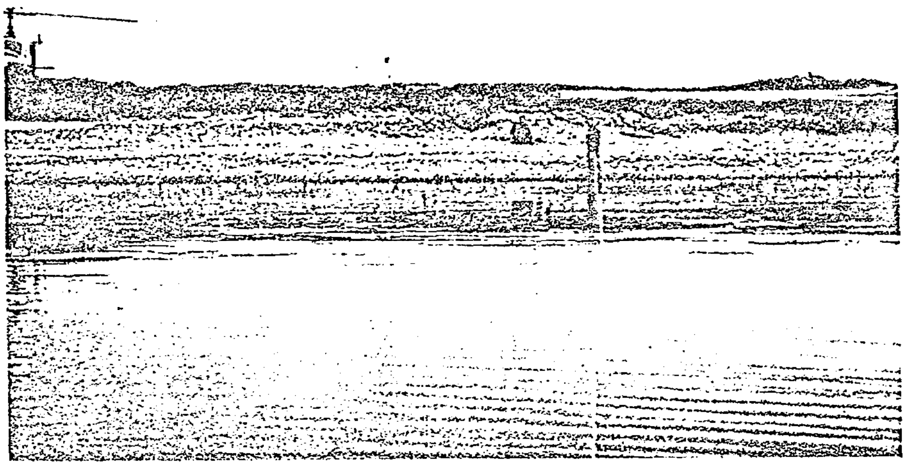

Figure 54. Sea view of the gravel beach and tundra bluff (August 1982) at the site of the elevation survey shown in Figure 55.

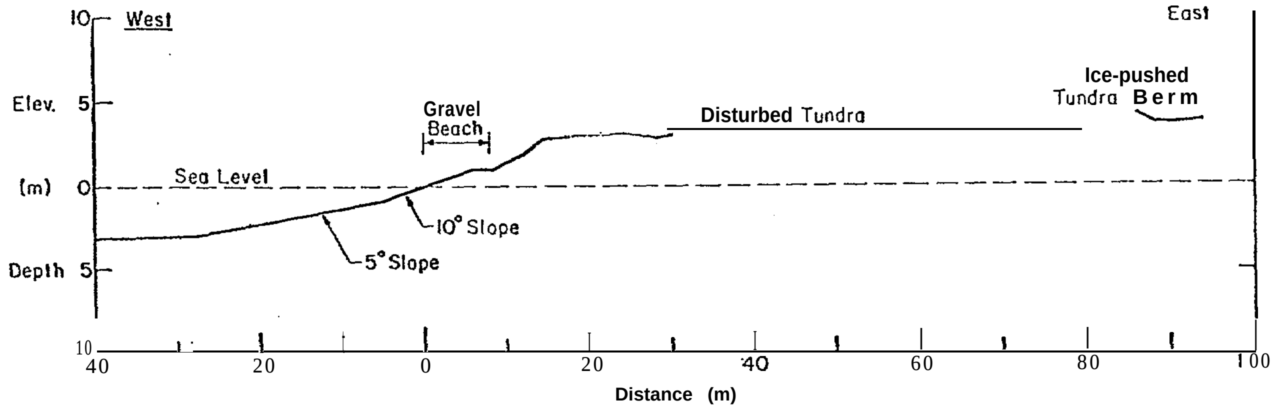

Figure 55. Profile across ice-scarred coast at position C in Figure 33.

Figure 56. Some of the numerous outcropping of driftwood embedded in the ice-dozed tundra berms, August 1982.

Figure 57. Ice ride-up on the beach at Clarence Lagoon, Canada (Stefansson Collection, Baker Library, Dartmouth College).

at about 1°, reaching 3.6 m at a distance of 80 m from the sea. Embedded in the ice-pushed tundra berms were severely rotted driftwood logs, as shown in Figure 56.

In mid-April, on the barrier island at position 19 in Figure B2, dirt-laden ice was observed pushed in piles up to 6 m high and up to 7 m inland on the shore. The dirt was carried ashore by ice which had gouged up the offshore sediment,

Ice scars extending 5 to 20 m inland were noted at position 4 in Figure B2. These features are probably related to the ice pile-ups observed on this island in the spring of 1980.

At positions 5 and 6 in Figure B2, sea ice ride-up had occurred along many hundreds of meters of the coast. The longest ice thrust extended 43 m in from the sea.

This year again, we observed no significant onshore ice movement between Barter Island and Clarence Lagoon, which is located about 10 km east of the U.S.-Canadian border. Nevertheless, a photo taken about 1914 gives evidence that thick spring ice can be thrust ashore along this coastline (Fig. 57).

Information on ice pile-up and ride-up was also obtained from discussions with several natives in Kaktovik, Barter Island. Archie Brewer and Tommy O. Gordon mentioned that in the spring of 19S3 or '54 ice piled against the steep (70°+) bluff at Barter Island. Some. ice blocks were pushed onto the edge of the bluff, which they estimated was 7 m above the sea.

Alfred Linn, Sr. mentioned that in September or October 1964 ice was pushed inland on the spit leading to the Barter Island airstrip. The ice rode up the beach and over the road, stopping within a few meters of the telephone poles located along the south side of the spit. In 1982 the distance from the seato the poles was measured at about 75 m. The ice ride-up may, therefore, have thrust inland some 70 m during the 1964 event.

Gordon also mentioned that he had lived in the area of Demarcation Bay many years ago, and on a number of occasions had seen ice pile-ups over 20 m high on Icy Reef, the barrier islands which extend to the northwest from the bay. In our two spring reconnaissances along this coast we observed no significant ice pile-ups or ride-ups. Two years of observation is clearly not sufficient to document the recurrence interval or severity of such events.

It was also of interest to hear from several Kaktovik villagers that they believed sea ice conditions today are not as "severe" as existed several decades ago. We have heard similar views from natives living in the Norton Sound area.

At the abandoned Bullen Point DEW Line Station, on the mainland southwest of the Maguire Islands (position 20, Fig. B2), we inspected a garage which had been damaged by shore ice ride-up and pile-up. During the 1973-74 winter, Walter Audi of Kaktovik, Barter Island, observed ice that had moved inland and piled on top of the 4- to 5-m-high garage roof. The 0.30-m-thick ice, which moved from the west-northwest, caved in and entered portions of the steel-framed building shown in Figure 58. We found this building to be located 25 m from the water at an elevation of about 5 to 6 m. (This garage was removed during the 1982 summer cleanup of the site; the main building complex and tanks remain.) The interesting aspect of this icc movement event is that it occurred in a relatively sheltered location which is not only inside the barrier islands but also protected in part by the Bullen Point spit.

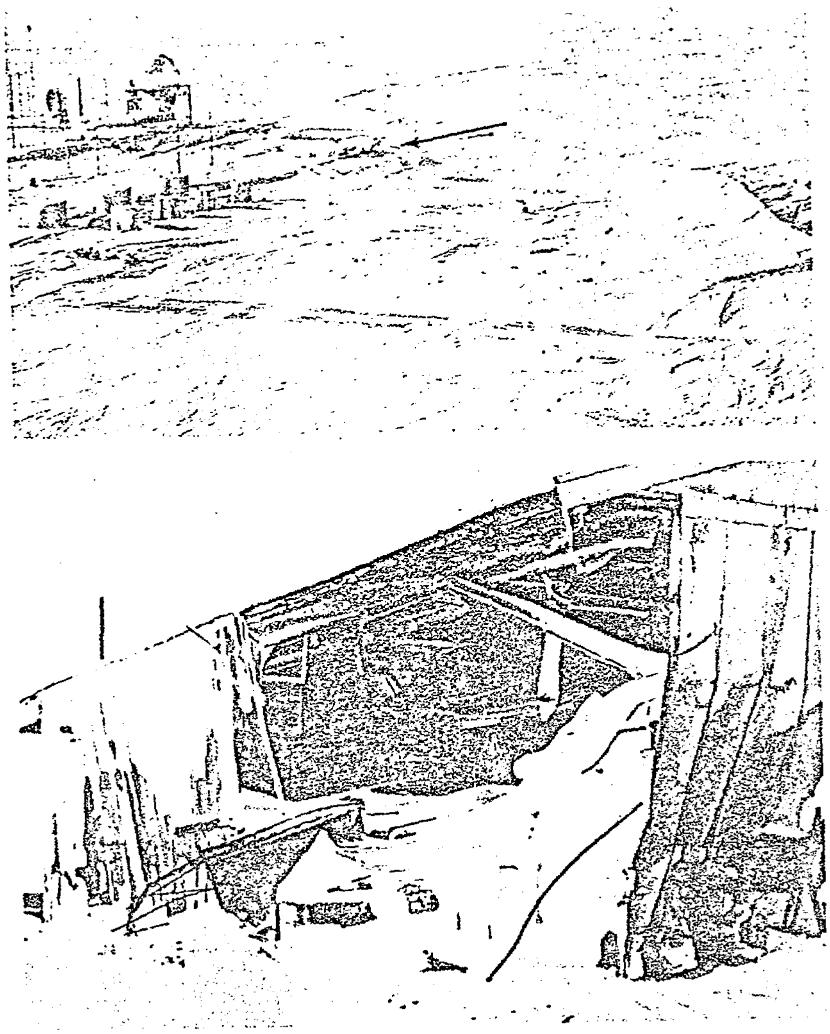

Figure 58. Bullen Point DEW Line Station, April 1979. Arrow points to garage damaged by ice and also indicates the direction of onsh ore ice move-men t.

Niel (Sparky) Bogert provided information on an ice pile-up which reached 6 m high on the Prudhoe Bay west dock causeway. The event occurred in July 1979. The ice blocks in the pile-up were over 1 m thick. Some sections of the causeway were also overridden. The ice was reported to be easily removed from the surface by bulldozers.

OLD ICE RIDE-UP FEATURES

Most of the old ice-pushed tundra scars on the east side of Camden Bay were clearly visible during our winter reconnaissance flights. Other ice scar features were difficult *to* detect or were not observed because of drift snow obscuration. This led to an inspection of CRREL summer aerial photography of the Cape Simpson to Cape Halkett coastline *to* determine if old shore ice ride-up scars could be observed. While this analysis was limited by the airphoto coverage available, numerous sites were observed where sea-ice-thrust features existed over 5 m from the sea.

In a 1949 aerial photo of the coast northwest of Cape Simpson, near position 4 in Figure B i, a 200-m-wide ice ride-up scar existed (Fig. 59). The farthest inland portion of the ice-thrust scar was 60 m.

other 1949 aerial imagery revealed the following for the coastline between Point Drew and Cape Halkett (Fig, B1). West of Lonely at position 14, a I-km-long section of the beach and back shore contained ice ride-up

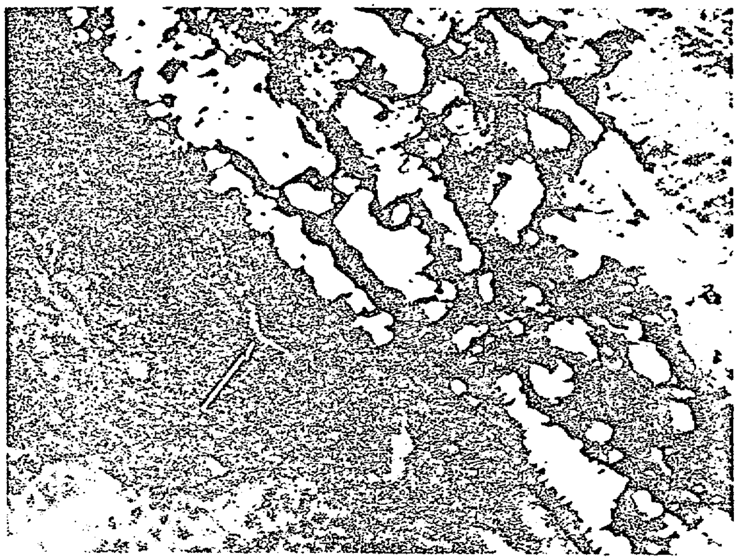

Figure .59. Ice ride-up scar on coast northwest of Cape Simpson, summer 1949.

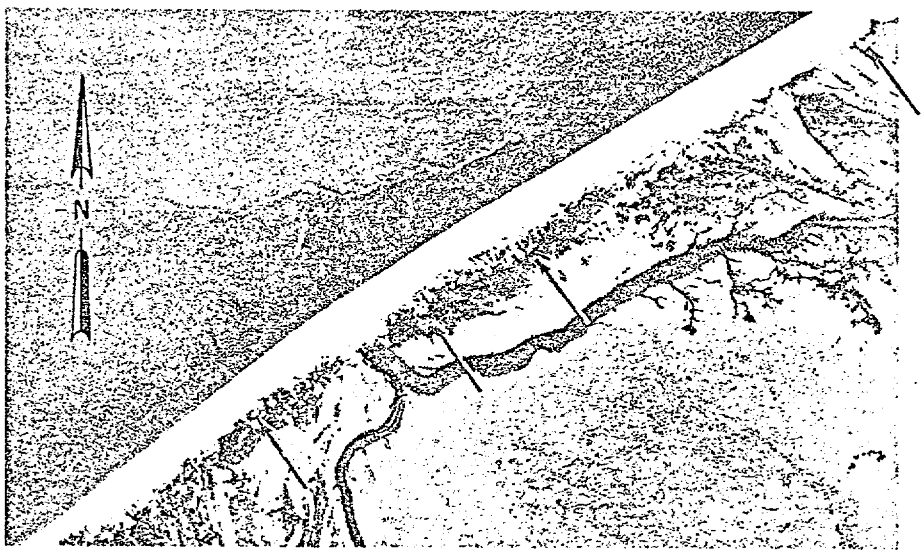

Figure 60. Ice ride-up scars on coast west of Lonely, summer 1949.

scars. Most extended over 50 m from the sea, but some were nearly 100 m inland (Fig. 60).

Along the coast at Pitt Pt. several old ice scars existed that extended from the beach up onto the tundra bluff (see insert, Fig. 61). The longest scar extended some 70 m inland from the sea. Along the low-lying beach to the east of these scars many ice-thrust beach striations existed which terminated up to 100 m inland at an ice-pushed gravel ridge (Fig. 6 1).

Several kilometers further east was another scar which ended 60 m from the sea up on a tundra bluff.

Four kilometers west of Ksook was a 1 -km-long section of coast where continuous ice ride-up striation scars existed. This ice-thrust feature extended up to 65 m inland, but was more typically 30 to 40 m long (Fig. 62).

Coastal erosion since 1949 has removed most of these ice thrust features but newer ones can be observed on recent aerial imagery. For example, in a 1978 aerial photo of Pitt Point, ice-pushed gravel ridges can be observed which extended along much of the coast. These features, shown in Figure 63, are typically 45 to 50 m in from the sea, but on occasion extend IO to 20 m further inland. In addition, 1981

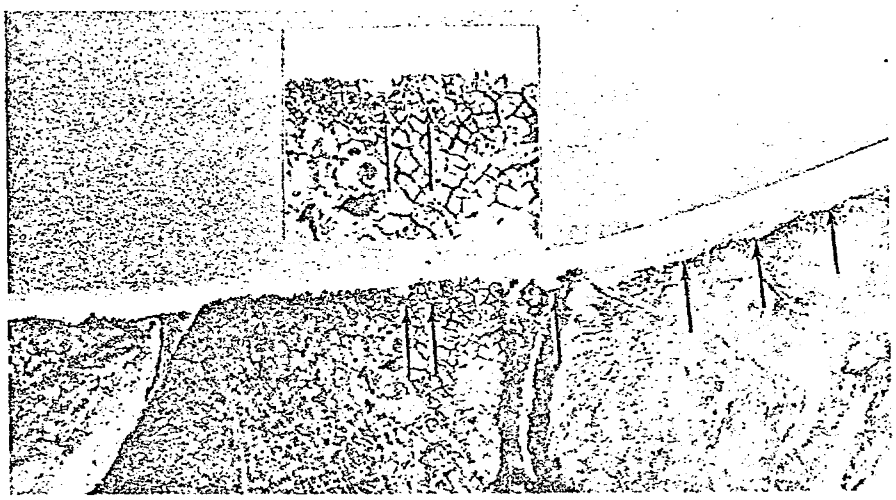

Figure 61. Ice ride-up scars on tundra bluff (insert and two arrows on left) and ice-push gravel piles on low-lying coast (three arrows on right), summer 1949.

Figure 62. Arrows point to coastline highly scarred by ice ride-up, summer 1949.

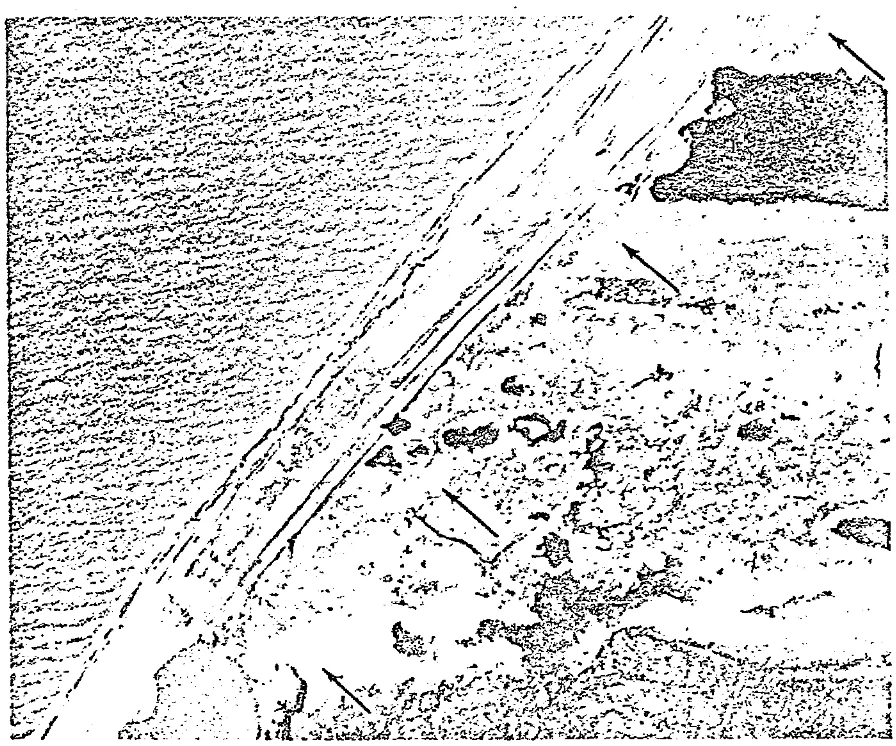

Figure 63. Recent ice-push gravel ridge formations along Pit t Point, July 197c9.

acrid imagery of the coast about 2.3 and 3.4 km west of Ksook revealed ice scars and ice-pushed soil piles which extended 3 S to 25 m inland, respectively. These distances were verified by on-site measurements in August 1982.

DISCUSSION

The data assembled in this report and by Kovacs "' and Sodhi (1 980) and Harper and Owens (1981) show that sea ice along the shores of the Beaufort Sea has thrust inland significant distances, both over gentle, sloping terrain and up onto steep coastal bluffs. We have shown here that shore ice ride-up is a destructive phenomenon in that it cm push aside and doze up beach and tundra material as well as damage coastal facilities. Shore ice ride-ups and pile-ups to 20 m inland from the sea appear to be relatively frequent events along the Alaska Beaufort Sea coast. Inland ice thrusts of 50 m are not very frequent, and 100-m penetrations are relatively infrequent but do occur. However, the existing data base on the occurrence of shore ice ride-up and pile-rip is limited and as such is inadequate for drawing meaningful conclusions on the frequency or severity of these events in general, as attempted by Harper and Owens (1981), and for specific coastal sites in particular. In short, these phenomena occur under poorly defined and unpredictable conditions along most of the Beaufort Sea coast and on occasion on the shores inside the barrier islands. The data suggest that shore ice ride-up and pile-up is more frequent west of Narwhal Island (Fig. B2). However, this may be due to the fact that fewer aerial photo and reconnaissance missions have been flown to the east of Narwhal Island.

It appears from historical reports (Kovacs and Sodhi 1980) and from observations made during this study that shore ice pile-up and ride-up along the Beaufort Sea coast is primarily a fall event that occurs when the sea ice is less than ½ m thick. Winter events do occur but appear infrequent. The most dangerous period, however, may be springtime, when the sea ice melts away from the shore, allowing the ice to move freely. The numerous old ice-thrust scars observed along the east coast of Camben Bay may have formed under these conditions. The free boundary between the sea ice and the shore is conducive to allowing low driving forces of 100 kPa (≈ i 5 psi) or less (Kovacs and Sodhi 1980) to push ice onto the land. Stresses larger than this can be generated within the pack ice. In addition, low transmitted stresses can be concentrated at ice/shore contact points, thereby increasing the local stress level above that required to cause ice pile-up or ride-up. Recent model tests and theoretical considerations (Kovacs and Sodhi 1980, Sodhi, pers. comm.) also support the view that pack ice not in contact with the shore requires a relatively low driving force to propel it up onto *the* land.

The findings of this brief study are that ice ride-up leaves seal-s and soil berms on the coast which can remain visible for many decades. Old ice scars and ice-pushed soil berms revealed inland ice movements over 150 m long. Some of these features were found to be over 35 years old, as revealed by aerial photography. Transport of offshore sediment onto the beach during shore ice movement appears to be a frequent phenomenon. Many other ice-thrust features were found to have been removed or modified during one summer by coastal erosion and storm wave run-up processes. The slope of the sea floor was typically 5° to 10° at the sites of the ice ride-ups or pile-ups surveyed. This slope appears representative of most of the exposed Beaufort Sea coastline.

Harper and Owens (1 981) conclude from their study that ice override is a rare event. We concur with this statement, but only in the context that ice override is the process wherein ice has thrust across an island from one side to the other. These authors use the term "ice override" to describe this phenomenon as well as the case in which ice has thrust across a beach. In addition, they use the term "severe override" to describe an event which had the potential to damage structures near the shore zone. They support their conclusions by:

> "personal observations of all of the North Slope shorelines and the Canadian Beau fort Sea s.horelines over a number of seasons, along which only two override events have been directly observed by the authors. Our cumulative observations cover tens of thousands of kilometers of shoreline, suggesting an overall frequency in the same order as *the* estimates obtained . from the [historical] aerial photograph analysis."

(The analysis gave 0.018 event/km of coast.) The authors back up these findings by further citing records of interviews with the elders at Barrow by Shapiro and Metzner (1979) and the observations of Leftingwcll(19 19). The former gave one ice override account and the latter none. It would appear that our survey revealed significantly more events.

In the few years of this study, we observed ice override of both of the Igalik Islands, Point Drew spit, Spy and Leavit Islands, and Collinson Point, and reported on an override of the Prudhoe Bay west dock causeway. Previously, ice override of several small islands southeast of Narwhal Island and of Jeanctte and Tapkaluk Islands was reported (Kovacs and Sodhi 1980). These 11 events are significant, but more important is the fact that many of them and a significant number of the ice ride-ups reported in this study extended over 50 m inland, both on low-lying and steep-sloping terrain. The 50-m and longer ice ride-ups take on special importance when one considers that the exploratory man-made islands being built off the Arctic coast today are on the order of 100 m in diameter. It is clear that in the design of these islands, ice ride-up defense must be considered. This has not been overlooked by industry, which is actively evaluating the problem in terms of island elevation, beach slope configurate ion, onshore and offshore defensive structures, and ice weakening concepts. How effective these efforts will be, however, remains to be determined under long-term field evaluation.

To better understand the potential hazard of shore ice ride-up and pile-up to coastal development, we need to know the frequency, magnitude and inland limits reached by these events. Further reconnaissance flights coupled with on-site observations and surveys are vital to achieving this understandirrg.

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APPENDIX A: THE BOULDER RAMPART AND ROCK LITTERED SHORE WEST OF KONGANEVIK PT.

INTRODUCTION

A section of the Beaufort Sea coast which was not discussed in the *main* body of this report is located in the bay immediately west of Konganevik Pt. (position 17 in Fig. B2). This coast is unique because it is littered with rocks which vary in size from gravel to boulders. The rocks have been rearranged by ice-shove and ride-up processes to form a boulder rampart (or pile) and pavement similar to that depicted in Figure 1, illustration d. In addition, folds and buckled tundra features, as illustrated in Figure 1, also exist. An aerial photo showing this coastline is given in Figure Al. Also shown is the location where rocks cover much of the beach.

The fact that boulders exist along the coast is of itself not unique. Boulders can also be seen at many other coastal sites, such as on the northeast side of Prudhoe Bay, on the west side of Mikkelson Bay south of Tigvariak Island, off the east end of Flaxman Island and along the coast running south-southwest of Brownlow Pt., along the Konganevik Pt. coast (position 17, Fig. B2), and at intermittent locations along the coast from the Canadian border to Herschel Island. As pointed out by Barnes (1982), the boulders are associated with or transported from the marine sediments of the Flaxman formation, a segment of the Gubik formation characterized by striated glacial erratic dropstones. At these locations, boulders as large as 1% m can be observed either partly exposed above the water or resting on the beach. Natives who operate boats in the Flaxman Island area and along the Konganevik Pt. coast report that they enter these waters with care to avoid damage to their craft. There are also many locations where boulders are found scattered on the tundra (MacCarthy 1958) and in drained lake beds such as the lake (position A, Fig. Al) located on the east side of the Canning-Tamayariak River delta. This lake was lowered in two stages, with the final drainage occurring during the spring of 1981. The old shoreline and lake bed are visible in the 1979 aerial photo shown in Figure Al. Boulders can be seen scattered over much of the old lake bed exposed by initial lowering (Fig. A2). On the lake bed most recently exposed, boulders are also present. They were observed in quantity only within about 100 m of the last shoreline (arrows in Fig. A2) or at a depth of less than about 1½ m below the surrounding tundra surface. No boulders were noted out in the deeper area of the drained lake. The implication is that 1) the boulder-rich zone along this section of coast extends to a depth of about 1½ m below the tundra surface, or 2) that ice-push processes have driven all boulders in the lake shoreward, or 3) that frost-jacking processes have been most active to this depth, and through these processes many boulders have pushed upward to the surface. Of these, 1) and 3) seem more plausible.

Two aerial views of the rock-laden Beaufort Sea beach west of Konganevik Pt. are shown in Figure A3. The large number of rocks littering the shore is quite evident. The highest boulders are found where the tundra bluff is typically 1% to 2 m high. Here the boulders rest along the edge of the bluff for a distance of 50 to 75 m and are piled up to 1 m high, with the top of an occasional boulder reaching a height of 1 ?4 m (Fig. A4). Inland, boulders of various sizes can be seen. Some are fully exposed on the tundra, while others are in the process of becoming exposed by frost jacking. Most of the exposed boulders have some lichen growth on their surfaces (Fig. A5). Many of the boulders, as well as those becoming exposed as the bluff is eroded away (Fig. A6), have smooth or rounded features, but some are also scarred with gouges or striations (Fig. A7). In addition, we noted many boulders with angular faces. Some of these surfaces are of recent formation, as a number of boulders were observed which had recently been split apart by frost action, the two pieces still resting side by side.

A recent report by Barnes (1982) describes the boulder formation along this shore which he "discovered" in the summer of 1979. He suggests that the boulder rampart is of recent origin, post-1977, as sand and gravel lag existed on the upper surface of a number of the boulders. In addition, a sand-rock berm left on the beach by a boulder that had ploughed through this beach material under the driving force of an onshore ice movement event appeared recently made. The reasoning is that these features would not survive many summer seasons due to rain, wave and high water erosion effects. We visited this coast during the winters of 1980, 1981 and 1982, and in April and August of 1981 and 1982. Indeed, the sand-rock berm left by the boulder, shown in Barnes's report as Figure 5, has been reduced by high seas, - as would be expected since the boulder is less than 4 m from the sea and rests less than ½ m above it (Fig. AS). However, on every visit we have found deposits of sandy gravel resting on boulders in the rampart (Fig. A9), which suggests that there is either some permanence to these deposits or that their existence is associated with the overall dynamics of this eroding coast. In short, the 300-m-long rocky coast is not of recent origin. Instead, we believe that the rocks, which vary in size from gravel up to boulders over a meter in length, have been piled and rearranged here for a long time. The boulder rampart is simply the result of long-term reworking, by ice-shove processes, of the rocks exposed during coastal erosion. The white line drawn beyond the 1979 coastline in Figure AlO represents the position of the coast in 1950. Significant coastal retreat and modification are apparent when the two coastlines are compared. The variability in coastal retreat is also apparent: from a few tenths of a meter to 1.8 m/yr.

During the three winter visits to this coast, no ice pile-ups or ride-ups were noted. However, rearrangement of the boulders has occurred, either due to minor ice shove or wave erosion of the underlying fine-grained material. Ice shove may have been the result of forces in the offshore pack being transmitted through the fast ice to the coast, from thermal expansion within the fast ice, or from onshore movement of a -free-floating ice sheet in the spring. Whatever the cause, boulders can be expected to move about in time under one or more of these effects.

This movement can be illustrated in Figures A11-Al 3. Figure Al 1 is a view of the beach taken in the summer of 1979. The top arrow points to the upright boulder which is also shown by the arrow in Figure Al 2, taken in the winter of 1980. A view of the same beach area taken in the summer of 1981 shows this rock has been removed from view (Fig. Al 3). In addition, the upper two arrows in Figure Al 3 point to two pieces of driftwood not in existence in the 1979 beach scene (Fig. Al 1). This suggests that high seas between the time of the two summer photos had moved this wood inland. However, while high water had moved this wood, waves had not dislodged the sandy gravel pile on the boulder shown by the lower arrows in both figures. Given the distance inland that the wood was moved, it would appear that this boulder would have been awash at the same time, removing the sandy gravel.

Another indication of boulder movement in the rampart is evident when Figure A14 is compared with Figure Al 5. The 1979 view of the boulder rampart (Fig. A14) was taken when the sea was lower than when the 1981 photo (Fig. Al 5) was taken. The positions marked A and Bin these photos are of the same feature. However, note that boulders in the rampart have been rearranged. In the 1981 photo there are two boulders which have been pushed higher on the rampart than the boulder at position B. In addition, even though the sea was higher in 1980, two large boulders now appear partly submerged at the base of the ridge at position C.

Sea ice ride-up scars and rock debris along this section of the coast indicate that ice ride-ups to 15 m inland have occurred.

To the east of the boulder rampart, there is a gradual decrease in rock debris (Fig. A 16). At the next point of land, at position C in Figure Al and at position A in Figure Al 6, there is an interesting crescent shaped ice-pushed boulder barricade (Fig. Al 7). Beyond this point on over to Konganevik Pt. (shown in the background of Fig. A17), there is only a scattering of boulders visible either on the beach or in the water. When the sea is calm they can also be seen from an aircraft, submerged in the shallow nearshore water.

SUMMARY

West of Konganevik Pt. a rock-littered coast exists. This shoreline varies in elevation from a low-lying beach area to a 1%-m-high bluff. The rocks vary in size from gravel to boulders up to 1½ m long which have been reworked from the Flaxman formation. The rock debris is exposed as the shore is eroded back. These gravels and boulders are then reworked by ice-shove and ride-up processes to form. a 1-m-high rampart about 75 m long on the edge of the tundra bluff and a beach area eastward from the bluff. The length of coast where this debris is concentrated is about 300 m. Ice-pushed rock debris is found up *to 15* m inland from the existing shores. Erosion of the coast and reworking of the rock debris into a boulder rampart is an active, ongoing process unique to this Beaufort Sca coast site.

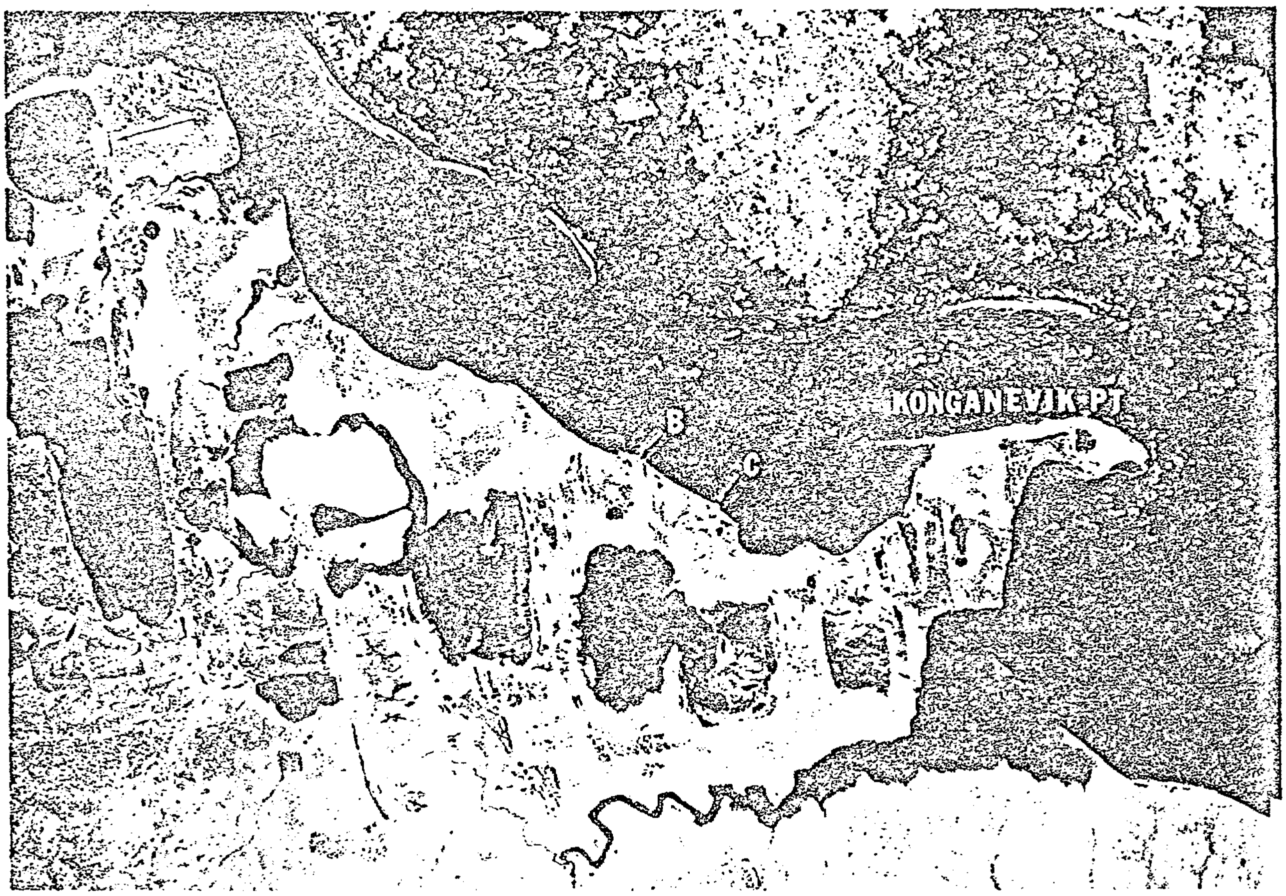


Figure AI. July 1979 aerial photo of the Beaufort Sea coast near Konganevik Pt. Position A is a lake which is no w drained. Position B is the site of a boulder rampart. Position C is the location of a crescent-shaped boulder barricade.

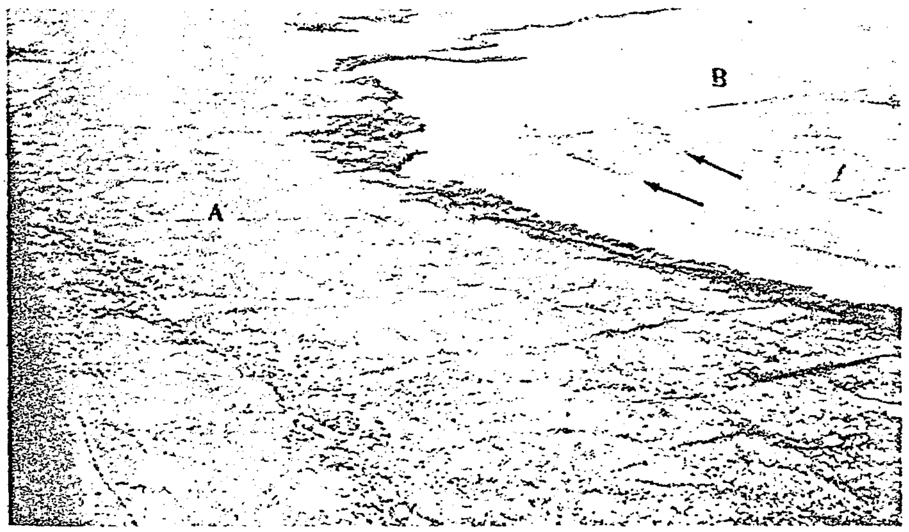
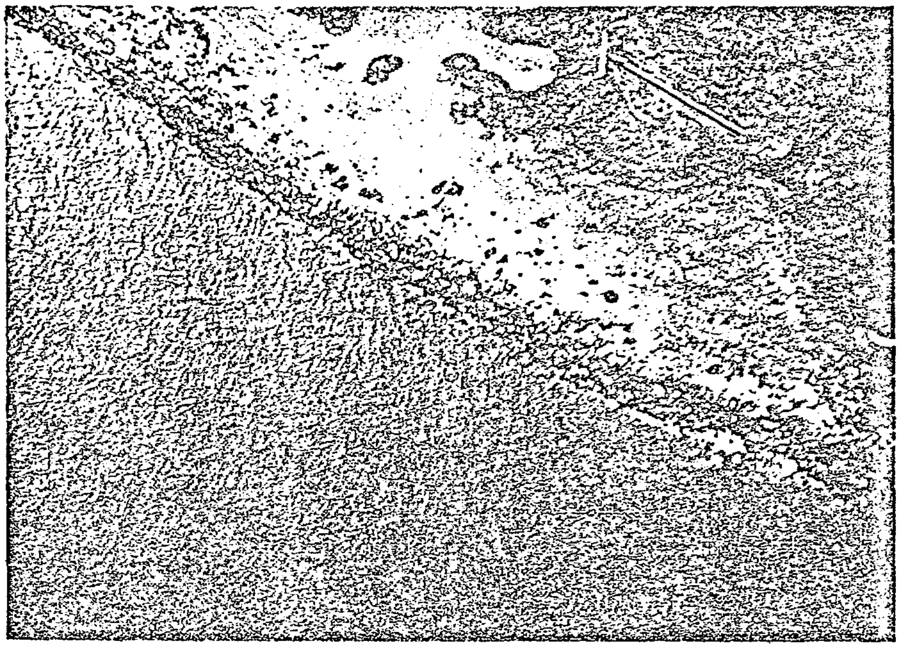


Figure A2. Drained lake, August 1982. Old drained lake bottom (A} is shown littered with boulders. Recently drained lake bed (B} is presently a mud flat. Arrows point to two rows of boulders.



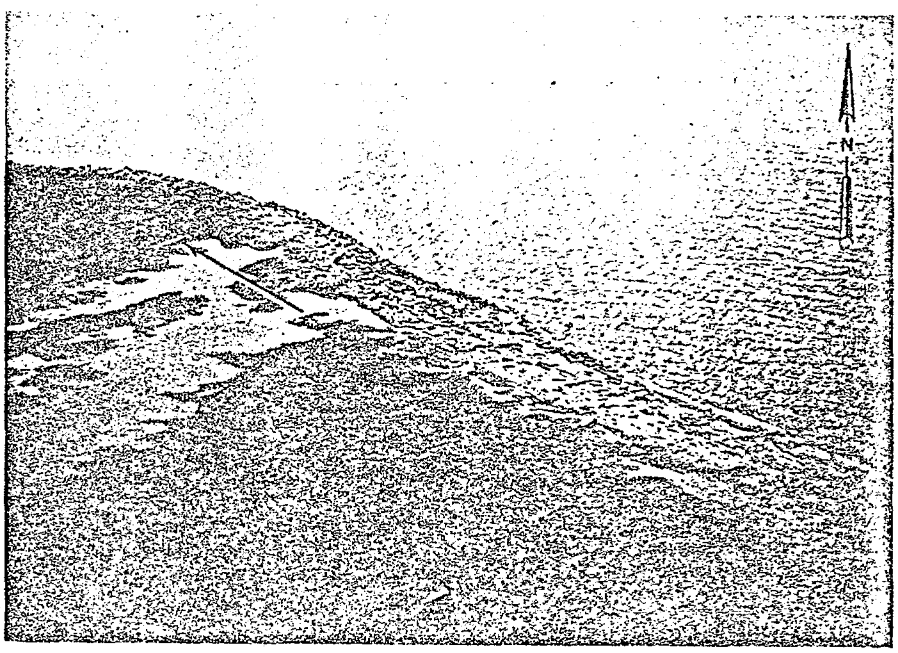
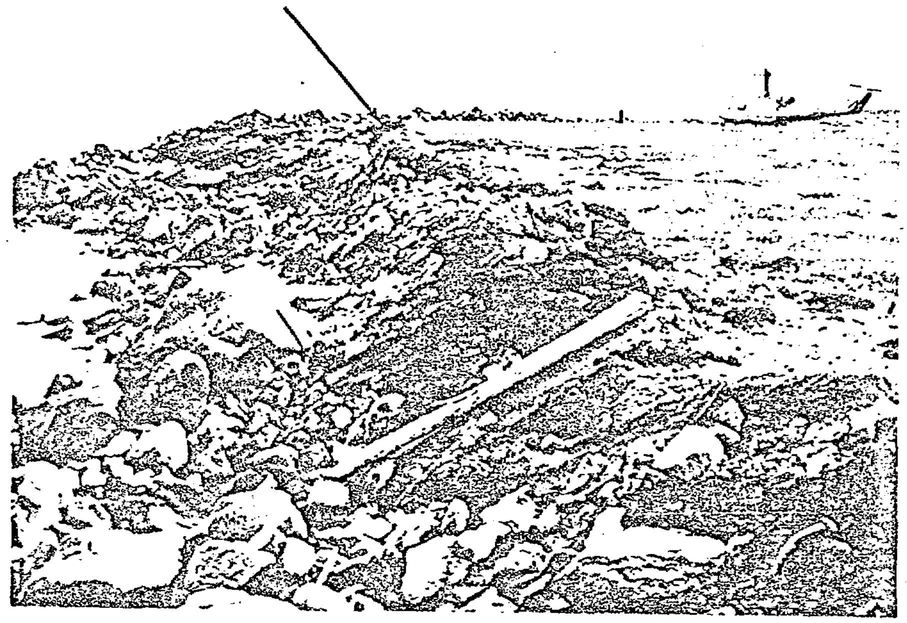


Figure A3. August 1981 aerial views of rock-littered coast. Arrow in each figure points to same driftwood log. Boulders rest on top of 1½-m-high tundra bluff at location A.



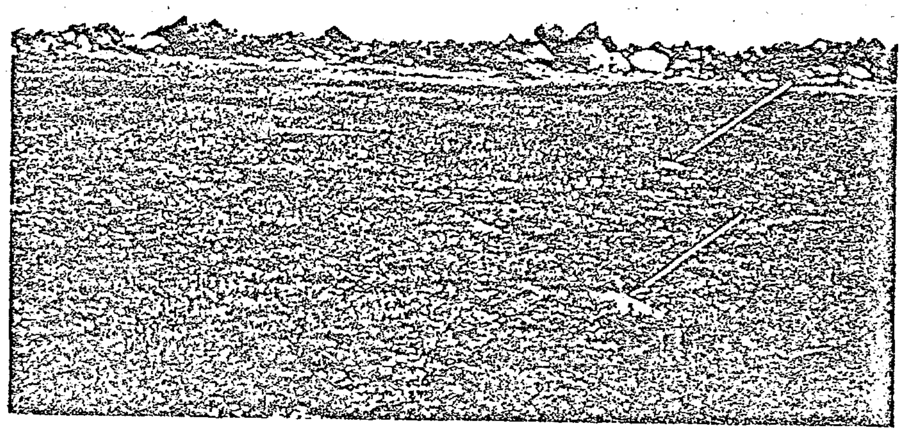
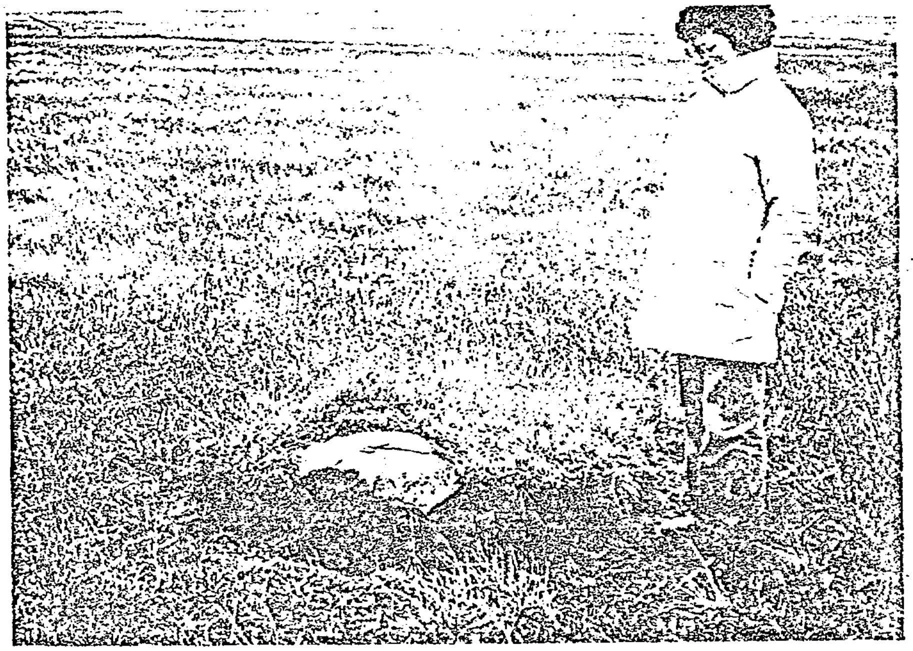


Figure A4. Configuration of boulder barricade in August 1982. Arrow in top photo points to tundra sod on top of boulder. Arrows in bottom photo point to partly exposed boulders in the tundra.



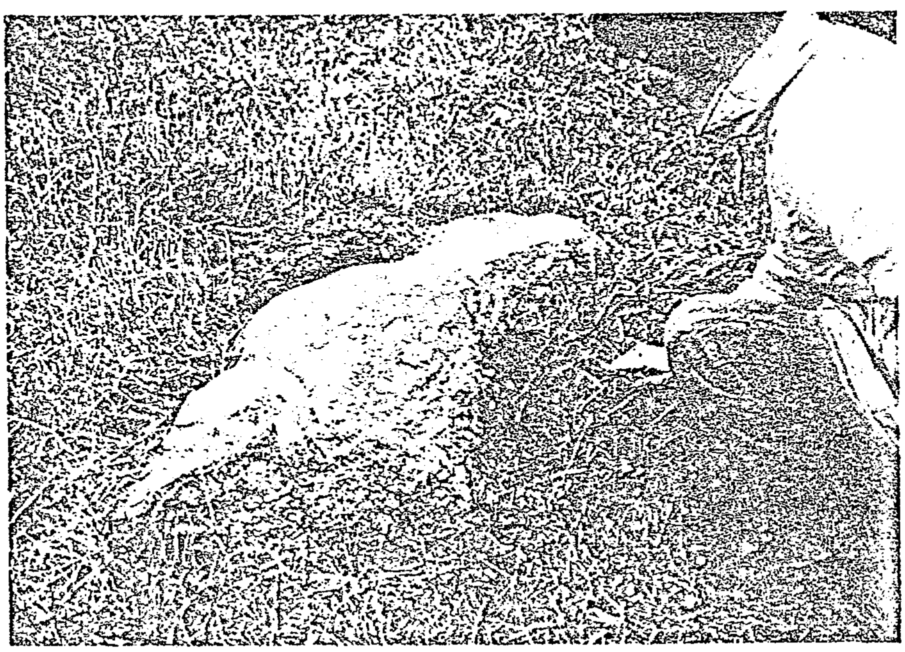


Figure A5. Boulders on the tundra several tens of meters south of the boulder barricade, August 1981. Note lichen growth on the boulder in bottom photo,

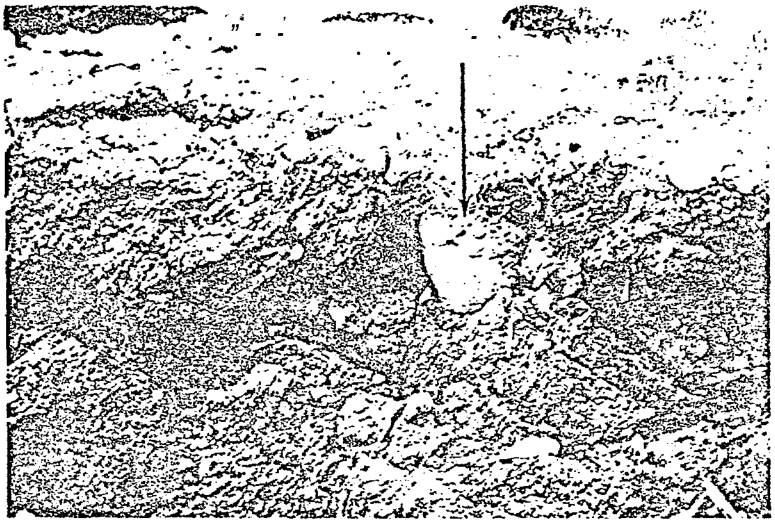


Figure A6. Eroding bluff at boulder barricade site showing variation in rock debris, August 1981. Boulder at arrow is about 0.35 m wide. Note rocks on tundra surface which were carried there by ice ride-up. Also scattered on the tundra surface are lumps of sod (dark material).

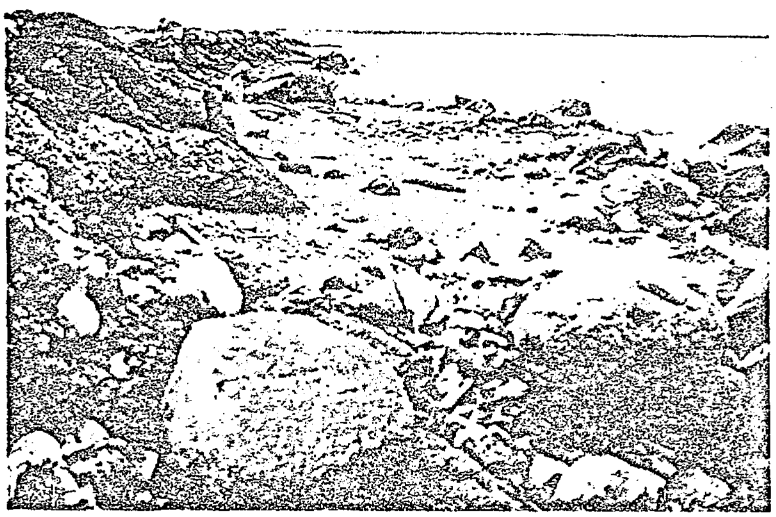


Figure A 7. Bluff to the west of main boulder rampart. Here only a few boulders have been pushed on to the edge of the bluff. Note the scarred boulder in the foreground.

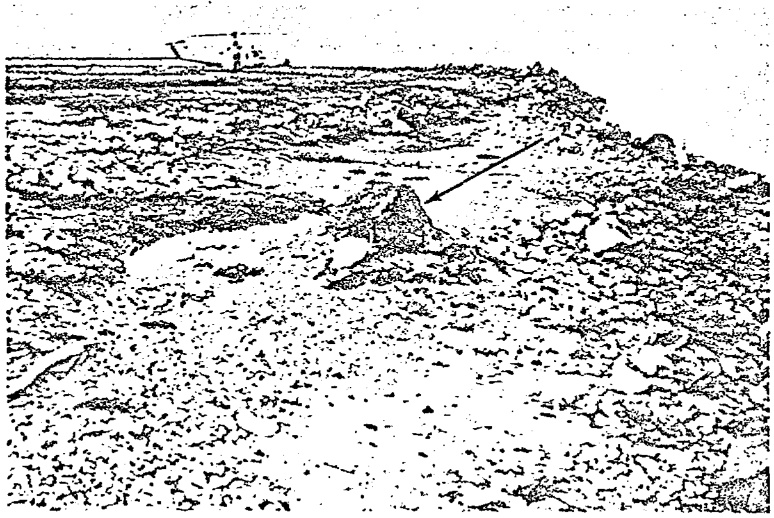


Figure A8. View looking west to boulder rampart from low-lying beach area, August 1982. Boulder described by Barnes (1 982) is at arrow and no longer has a gouge leading up to it from the sea as a result of wave run-up erosion processes.

a. April 1980.

b. August 1981. Large boulder is about 1½ m long.

Figure A9. Sand and gravel deposits on boulders.

Figure A 10. July 1979 aerial photo of the coast west of Konganevik Pt. wtih 1950 coast drawn in as white line. Note the larger variation in coastal re treat, as indicated by relative distance between the present coast and the line representing the 1950 coast. Between arrows is section of coast containing boulder rampart (near left arrow) and rock-littered beach (near right arrow).

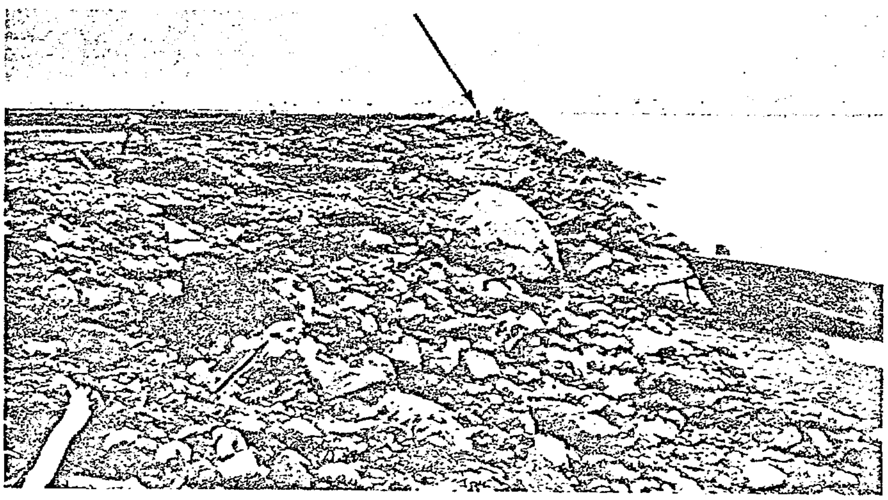


Figure A11. View of boulder rampart from the east taken in summer 1979. (Photo courtesy P. Barnes.]

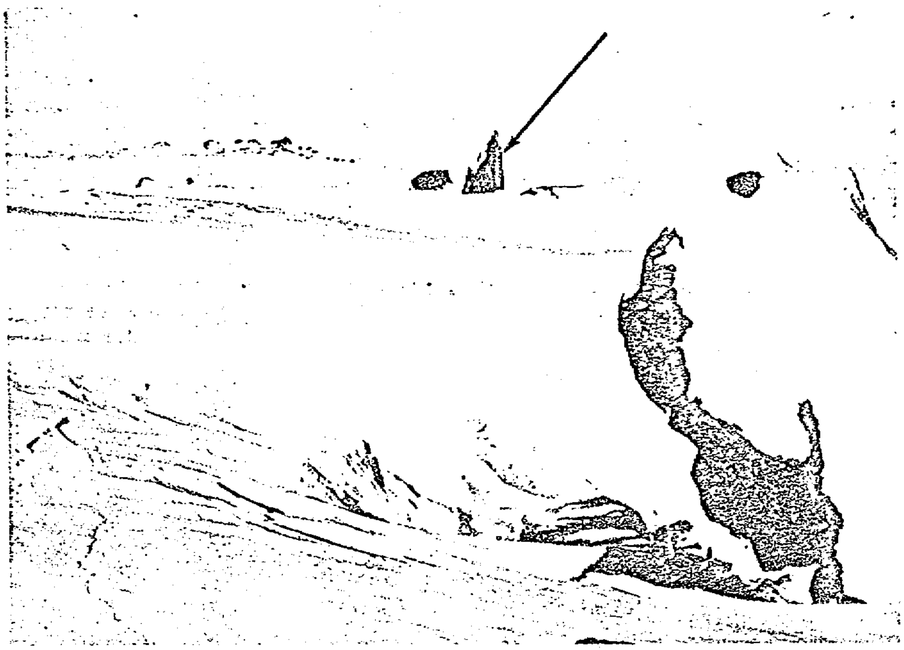


Figure A12. View of west end of boulder rampart, April 1980.

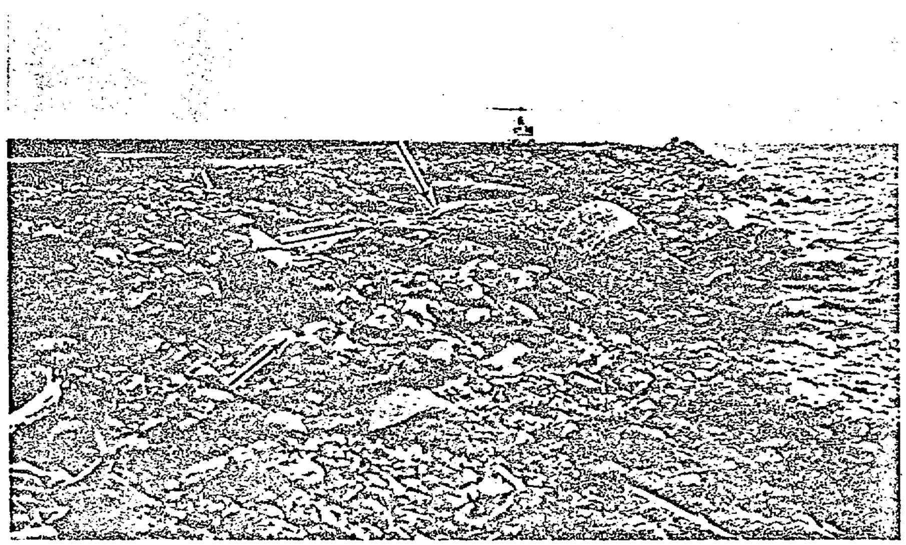


Figure A13. View of boulder rampart from the east end, summer 1982.

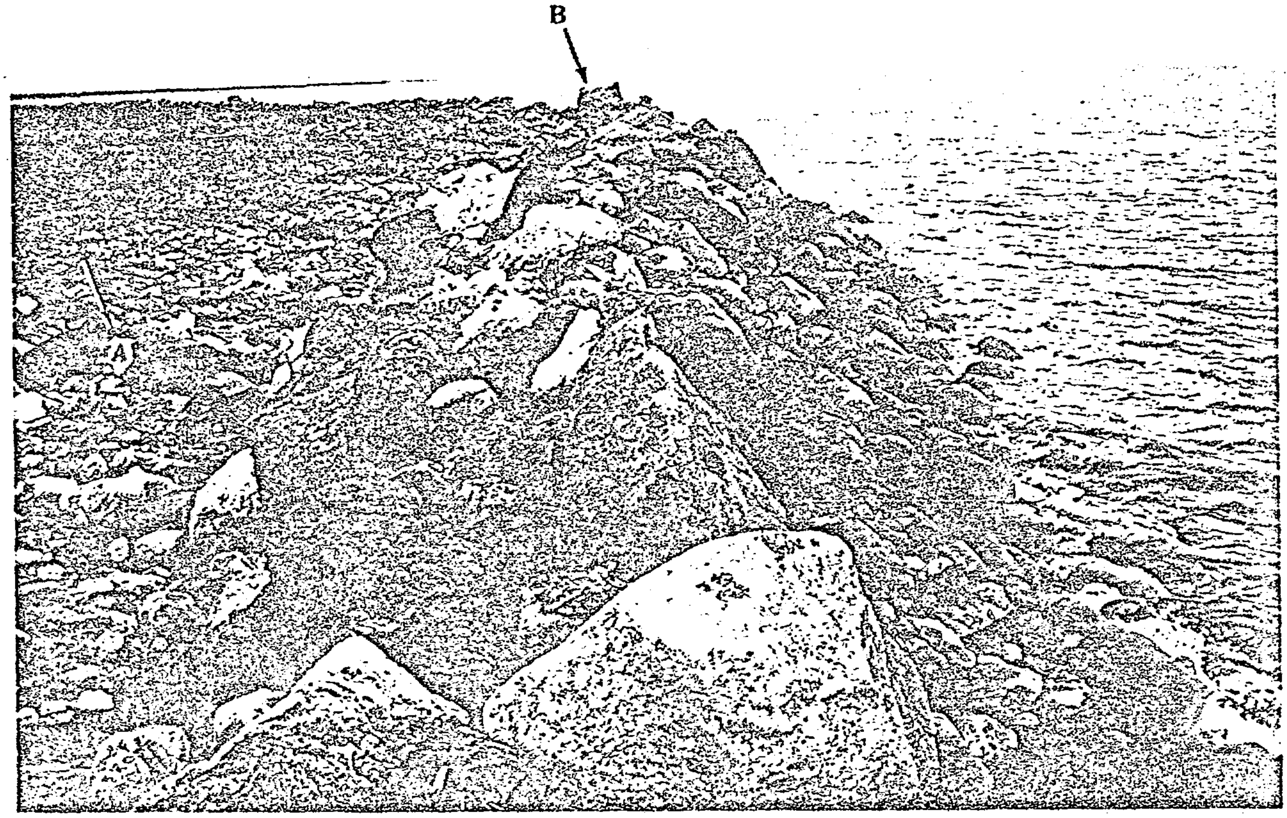


Figure A 14. View looking west along boulder rampart, summer 1979. (Photo courtesy P. Barnes.)

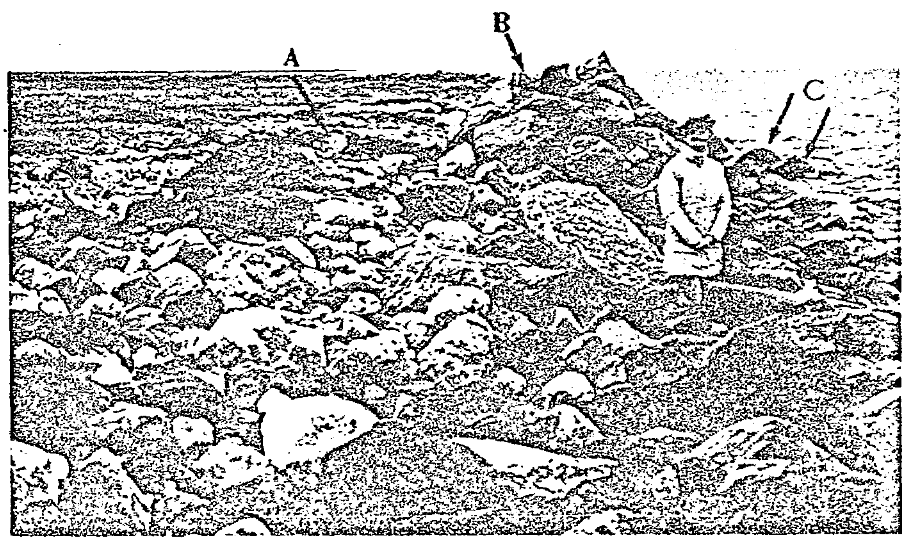


Figure A15. View looking west along boulder rampart, summer 1981.

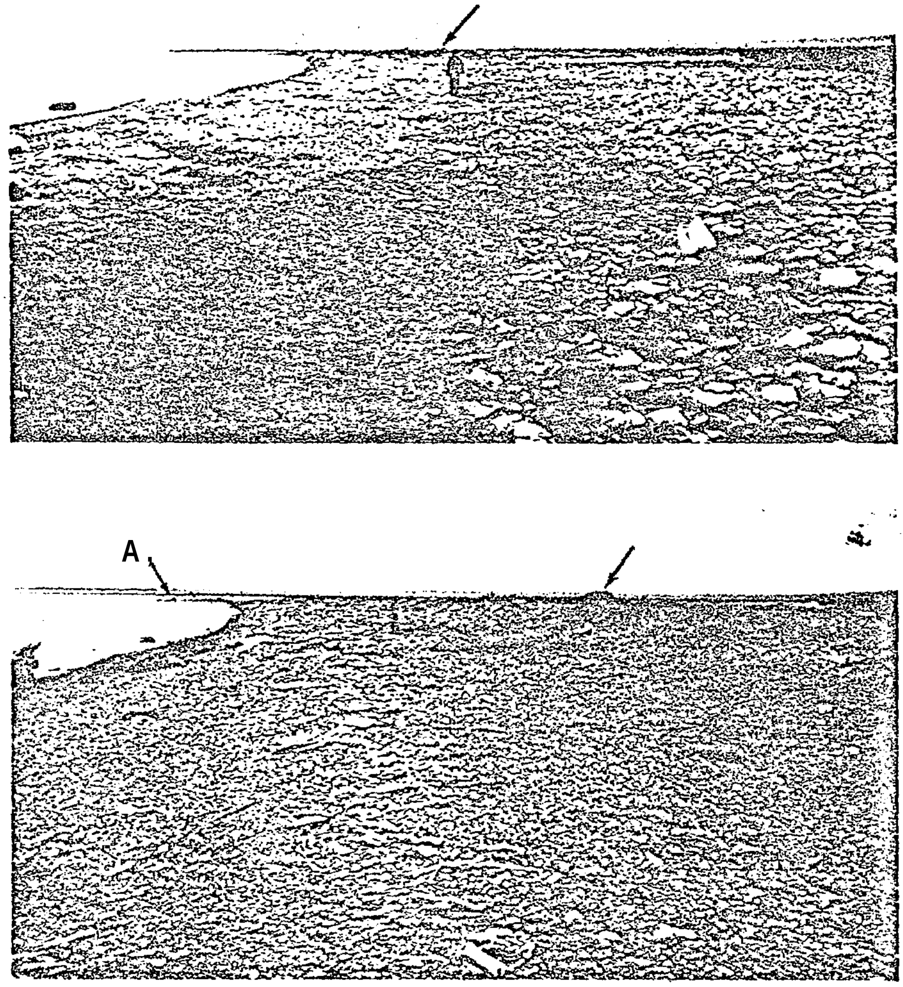


Figure A16. View of the beach to the east of the boulder rampart, summer 1982. Top photo is of beach further east than the view in bottom photo. Right arrow points to same boulder. Position A is site of boulder barricade.

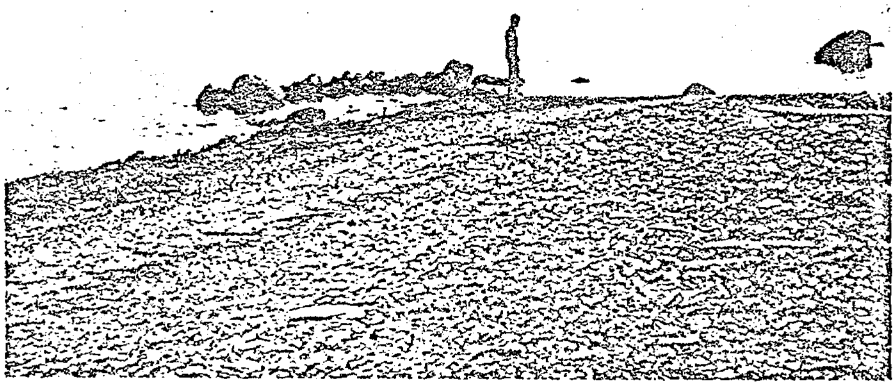


Figure A17. Boulder barricade at position C in Figure A1 and position A in Figure A16. Konganevik Pt. is to left in background.

APPENDIX B. SITE LOCATION MAPS

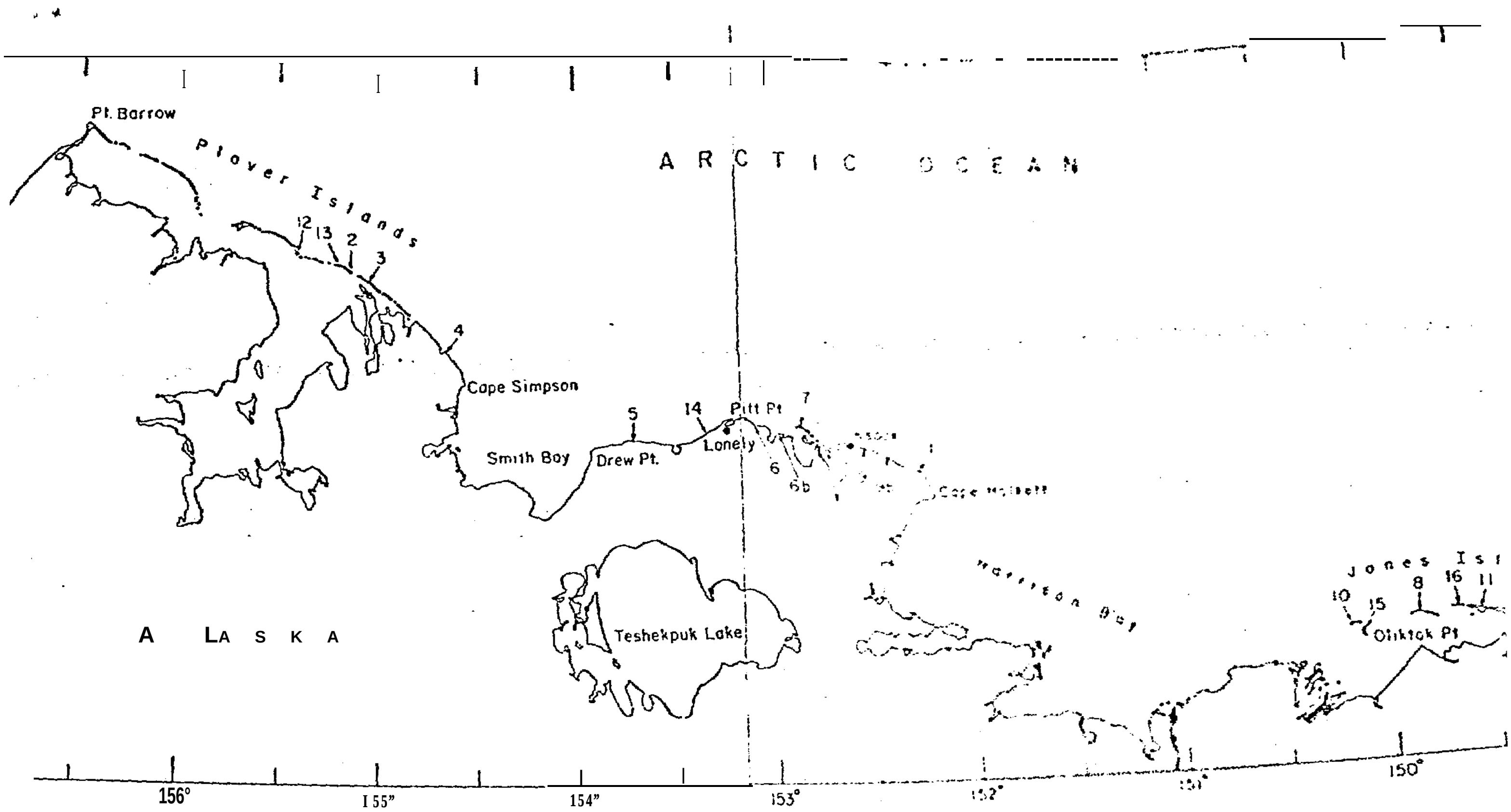


Figure B1. Western Alaska Beaufort Sea coast. Numbered arrows mark location of shore ice ride-up or pile-up sites discussed in text.

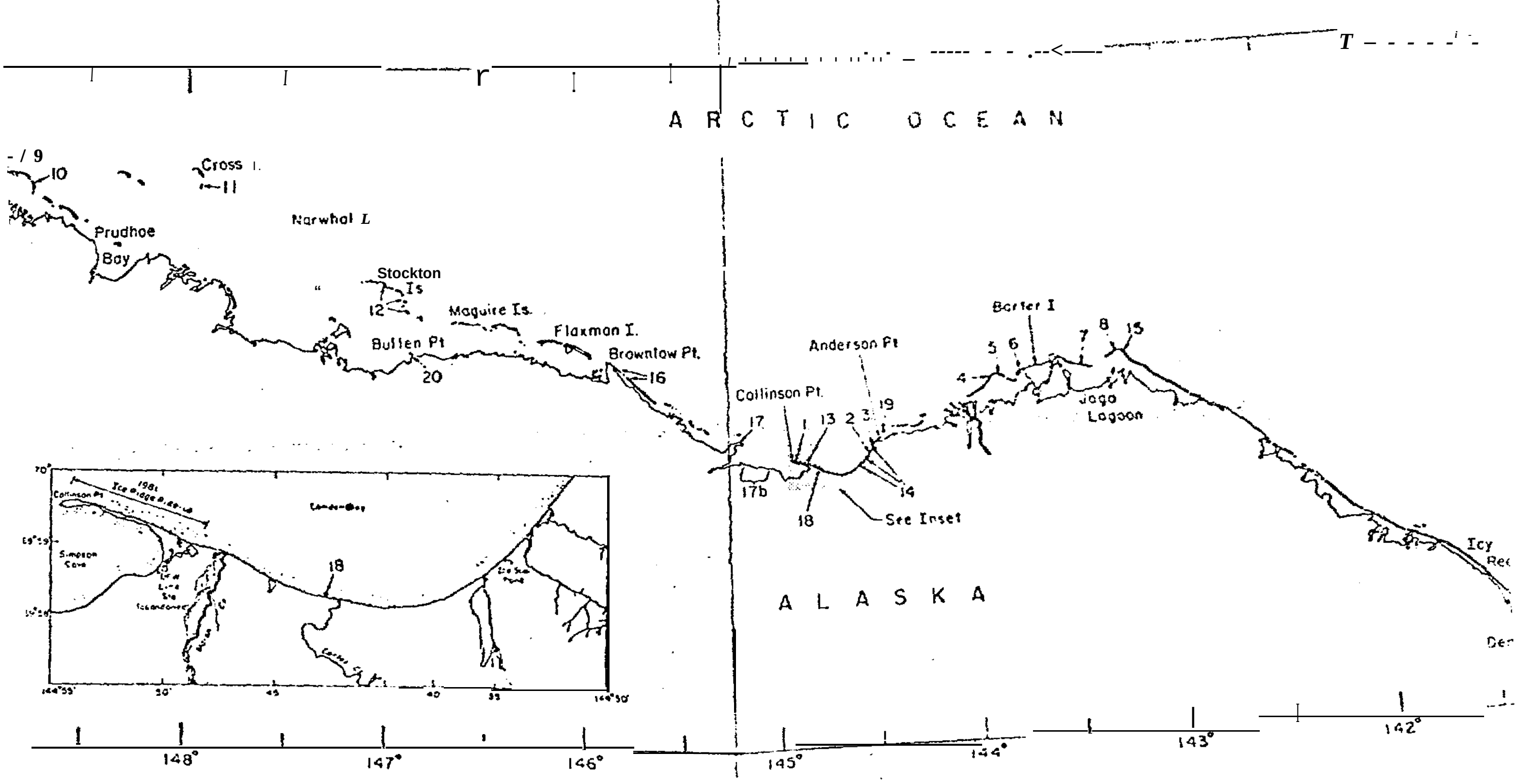


Figure B2. Eastern Alaska Beaufort Sea coast. Numbered arrows mark location of shore ice ride-up or pile-up sites discussed in text.

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Kovacs, Austin
Shore ice ride-up and pile–up features. Part I: Alaska's Beaufort Sea coast / by Austin Kovacs. Hanover, N.H.: Cold Regions Research and Engineering Laboratory. Springfield, Vs.: available from National Technical Information Service, 1983.
v, 59 p., illus.; 28 cm. (CRREL Report 83-9.)
Bibliography: p. .38.
1. Arctic Ocean. 2. Arctic regions. 3. Beaches. 4. Beaufort Sea. 5. Coastal regions. 6. Cold regions. 7. Ice. 8. Sea ice. 9. Shore ice pile-up. 10. Shore ice ride-up. 11. Shores. 1. United States. Army. Corps of Engineers. II. Cold Regions Research and Engineering Laboratory, Hanover, N.H. 111. Series: CRREL Report 83-9.