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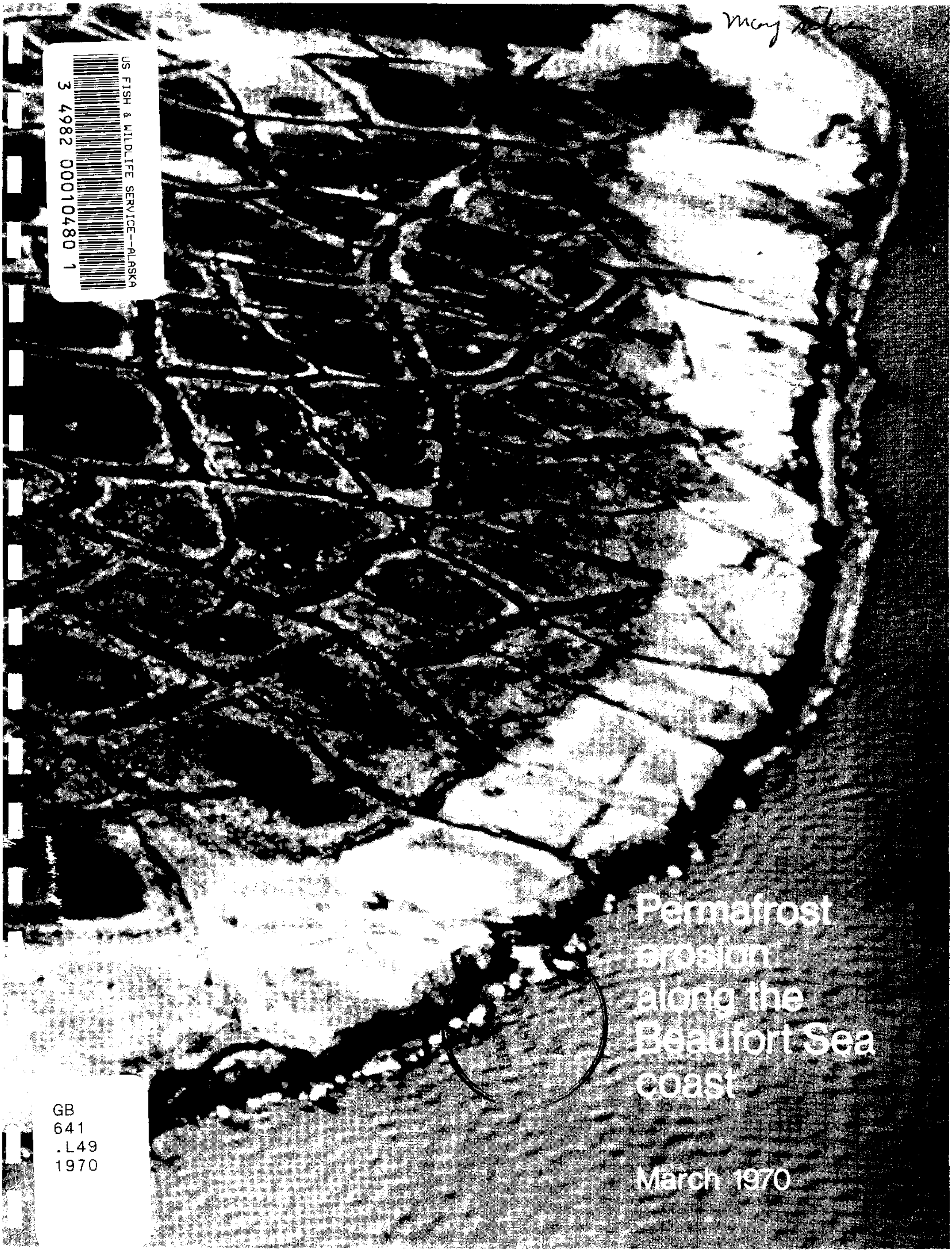

# Permafrost erosion along the Beaufort Sea coast

March 1970

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## ABSTRACT

The purpose of this report is to illustrate and focus attention on the permafrost erosion along the Beaufort Sea coast of Northern Alaska. The thermal erosion of permafrost along the coast results in shore line recessions as great as ten meters (33 feet) per year. The recession is caused by wave action and air temperatures thawing the frozen sediments. The two areas which are discussed in detail are Elson Lagoon and Flaxman Island. Elson Lagoon is located south of Point Barrow, Alaska. Flaxman Island is adjacent to the Prudhoe Bay oil development activity. The receding shore lines must be considered before a logical definition of this region is possible.

**COVER PHOTOGRAPH:** An aerial oblique photograph of Olukralik Point (Ross Point, 71° 13′ N, 155° 56′ W). The photograph was taken by the author on 11 August 1966.

# PERMAFROST EROSION ALONG THE BEAUFORT SEA COAST

## INTRODUCTION

Man must consider all possible aspects of his physical environment before he can intelligently live and work in the Arctic. A precise definition of the arctic environmental processes is very important for successful arctic operations. This report discusses and illustrates the nature and rates of thermal erosion along the Beaufort Sea shores from Point Barrow to the Mackenzie River (Fig. 1).

The report was written and illustrated in an effort to: (1) define selected aspects of the physical environment of Northern Alaska, and (2) focus attention on one aspect of Leffingwell's research in this region.

The report consists of seven sections: (1) an introduction, (2) a section of preliminary considerations, (3) a review of related literature, (4) a discussion of the Elson Lagoon area, (5) a discussion of the Flaxman Island area, (6) a definition of the Flaxman Island marine climate, and (7) conclusions.

## PRELIMINARY CONSIDERATIONS

All of Northern Alaska, including Flaxman Island and parts of the offshore area is characterized by continuous permafrost. Permafrost is the naturally occuring earth material whose temperature is below 0°C (32°F) for several years regardless of the state of any moisture that might be present (Lachenbruch, 1968, p. 833). A shallow soil layer, overlying the permafrost thaws to a depth of a few decimeters annually. This layer, called the seasonal thaw zone, consists of tundra vegetation and organic and mineral soils. Tundra is the undulating treeless area of weak soil development and small shrub, sedges, and grasses.

The polygonal ground patterns of this region are indications of permafrost. The polygonal form is generated by the thermal contraction of frozen ground during the arctic winter. The ground contraction processes form vertical tension cracks in a honeycomb pattern. During the thaw season, waters from the melting snow and ice drain down into the contraction cracks and form a vein of ice (Fig. 2). This annual cycle produces a wedge-shaped ice mass (Lachenbruch, 1968, p. 837). The ice wedges are one to two meters (3 to 7 feet) wide and two to three meters (7 to 10 feet) deep. In addition to the wedges, tabular ice masses a few meters thick and small ice lenses up to a few centimeters thick can occur together or singly over the entire North Slope of Alaska. Leffingwell's work published in 1915 and 1919 was some of the most significant research on the origin and nature of ice wedges in Alaska. More recently, the research of Lachenbruch, 1962, considers the theoretical aspects of ice wedge formation.

## REVIEW OF SELECTED LITERATURE

Coast line recession by thermal erosion has been reported from Point Barrow, Alaska to the Mackenzie River, Canada. MacCarthy (1953) studied the shore line changes near Barrow. He reported on the processes and rates of erosion near the U.S. Coast and Geodetic triangulation stations, and on the accelerated shore line retreat near the Barrow native village. This accelerated retreat, from the village to the base of the Point Barrow sand spit, was a result of borrowing beach material for road maintenance.

In 1964, Hume and Schalk reported quantitatively on the Barrow shore line recession as a result of man's activity. They cautioned that large amounts of borrow relative to the net shore line sediment transport will result in shore line erosion. Since the report by Hume and Schalk, large quantities of gravel were borrowed from the shore line. The beach gravel was used to construct the Barrow village airfield. The native dwellings are now endangered by the rapid thermal erosion of the permafrost shore line.

Leffingwell (1919, p. 171) reported shore line recession rates for selected sites between Elson Lagoon and Camden Bay. The four sites listed and the erosion rates are: (1) Cape Simpson and Point Drew, greater than 30 meters (100 feet) per year; and (2) Flaxman Island and Brownlow Point, nine meters (30 feet) per year.

Mackay (1963) discussed the erosion of the Pleistocene silts, sands, gravels, and ice between Herschel Island and the Mackenzie River delta. Coastal bluffs up to 50 meters (164 feet) high are receding by wave action and the melting of tabular masses of ground ice. The Mackay report indicates how historical records document the coastal recession. He reports the greatest rates of retreat occur in the low bluffs of high-ice content, fine-grained sediments. The recession rates may exceed one meter (3.3 feet) per year. The lowest rates were observed in sand and gravel bluffs.

## A DISCUSSION OF THE ELSON LAGOON AREA

Sequential aerial photography and ground photographs were used by Lewellen (1965) to study the thermal erosion along the Elson Lagoon shoreline near Point Barrow (Figs. 3, 4, 5, 6, and 7). Rates of erosion varied from a few decimeters to 10 meters (33 feet) per summer thaw season. The maximum rates were observed where the permafrost shore line was exposed to the open sea by a pass in the barrier islands.

The western and southwestern shores of Elson Lagoon are receding rapidly (Fig. 8). The shore line south of Brant Point to Ikpik is protected from the easterly storms by the sand and silt bar which has been deposited north of Tekegakrok Point (Fig. 9 and Fig. 10). The Brant Point to Ikpik shore is a two to three meter (7 to 10 feet) high bluff. The bluff thaws and erodes by the air temperatures and the gentle wave action. The ice-cemented sediments thaw, slump, and move downslope as saturated soil movement. The tundra vegetative mat may slump down over the permafrost and offer temporary protection.

Except for the sheltered estuaries, the remainder of the west Elson Lagoon shore line is receding by thermo-erosional niching. Wave action results in the formation of a thermo-erosional niche which is the process of undercutting, thermally, into the permafrost bank. The thermo-erosional niche will intersect with the vertical ice-wedges. The wedges are a zone of weakness. Huge blocks of frozen ground will break-off along these zones and collapse onto the beach. The blocks will then thaw on the existing beach. The collapsed blocks will offer temporary protection from further thermo-erosional niching.

The shore line south of Tekegakrok Point is exposed to water three to four meters (10 to 13 feet) deep and a fetch of 16 kilometers (10 miles) for the easterly winds. A set of stereograms are presented which illustrate the thermo-erosional niching of the Tekegakrok shore line by wind generated waves (Figs. 11, 12, 13, and 14). Figs. 15, 16, and 17 illustrate the thermal erosion of ice-cemented sands and gravels at Point Barrow. Point Barrow is exposed to the greater wave and ice action of the open sea.

Fig. 18 is an aerial photograph taken 5 September 1956. It illustrates the strand lines of frazil ice and skim ice which develop in the initial phases of ice formation. The location is Brant Point on the west shore of Elson Lagoon. The strands of ice eliminate wave action and halt thermo-erosional niching. The ice formed after a seven day storm which began on 24 August and ended 1 September 1956. The storm was typically characterized by easterly winds averaging 27 kilometers per hour (17 mph) with the fastest speed at 42 kilometers per hour (26 mph). The air temperatures were –0.6°C to –4.4°C (31° to 24° F) with a trace of snow and sleet.

## A DISCUSSION OF THE FLAXMAN ISLAND AREA

The erosion of Flaxman Island was investigated by utilizing the historical record and recent aerial photography.

Leffingwell commenced working in the Flaxman Island vicinity in 1906. He returned to civilization in 1908. For three years beginning in 1909, he continued his research in Northern Alaska. In 1913-1914 another year was spent in the area (Leffingwell, 1919, p. 11).

Flaxman Island is composed of silt-like clay, sand, gravel, boulders, organic muck, and ice. Leffingwell named this material the Flaxman Formation of Pleistocene age. The boulders reach 3 meters (10 feet) in diameter; however, the majority are 0.6 meter (two feet) or less in diameter. As the shore line recedes, the finer particles are washed away thus concentrating the boulders along the beach (Figs. 19, 20, 21, 22, 23, and 24) (Leffingwell, 1919, p. 143). The eroded sediments from Flaxman Island are deposited to the west of the island by the wind-generated shore current.

Sir John Franklin, during his 1826 exploration of this vicinity, reported that Flaxman Island was 6.4 kilometers (four miles) long, 3.2 kilometers (two miles) wide, and 15 meters (50 feet) in elevation. When Leffingwell studied the area, Flaxman Island was not over 1.6 kilometers (one mile) wide and nowhere was the elevation greater than 7.6 meters (25 feet). Franklin reported difficulty with shoal water in the passage adjacent to the east end of Flaxman Island. Leffingwell reported water depths of 2.7 meters (nine feet) and about 5.5 meters (18 feet) within 15 meters (50 feet) of the beach (Leffingwell, 1919, p. 170). If the Flaxman Island shore line has cut back 0.8 kilometers (one-half mile) between 1827 and 1919, a recession rate of nine meters (30 feet) per year is indicated (Leffingwell, 1919, p. 171).

The study of sequential aerial photography and published maps reveal many interesting facts about the erosion of the island. Aerial photography taken in 1949 and 1955 by government agencies was compared with the 1968 project photography. Fig. 25 gives the linear amounts of erosion and the rates of recession for eight selected stations along the north shore of Flaxman Island. Also, Fig. 25 illustrates the observed shore line changes for the periods 1949 to 1955 and 1955 to 1968. The lowest recession rates occur along the protected shore on the south side of the island. The scale was not sufficient to illustrate the small amounts of recession along the protected shore.

The rapidly receding (actively transgressing) shore line has left permafrost below the sea which is not in balance with the present thermal regime. Lachenbruch (1957, p. 1524) suggests that along this coast, hundreds of meters (a few thousand feet) offshore, permafrost will extend only 60 to 90 meters (two or three hundred feet) below the sea bottom if the shore line has been stable. This shore line has not been stable; therefore, considerable permafrost is expected offshore.

Leffingwell's map of 1906-1914 shows that Mary Sachs Island was detached from Flaxman Island (Fig. 26). A study of the later maps and aerial photography reveals that sedimentation has combined the two islands. (Figs. 25, 27, and 28). The U. S. Coast and Geodetic Survey map of 1956 indicates symbolically the occurrence of the Flaxman Formation boulders on the beach (Fig. 28). The survey target was probably destroyed by the sea ice pushing on the low sandy beach. The triangulation station was destroyed by the thermal erosion of the foundation.

## THE FLAXMAN ISLAND MARINE CLIMATE

The marine climate and winds responsible for the generation of waves are defined in Figs. 29, 30, 31, 32, and 33 (Lewellen, 1969). The marine observations cover the thaw period, for all years of record (1900-1967) for July through October. The sea is generally free of ice during this period. The data are expressed as frequencies and percentage frequencies.

The wave heights are less than one meter (3.3 feet) 98 percent of the time during the thaw period. Tides and currents are almost nil, irregular, and unpredictable. The currents are wind generated. The winds are bimodal, easterly and westerly. The wind velocities are between six and 37 kilometers per hour (3 and 20 knots) 80 percent of the time. The air temperatures are between −1.1° and 3.9°C (30° and 39°F) 73 percent of the time during the period July through October. The sea water temperatures are between –0.6° and 1.1°C (31° and 34°F) 57 percent of the time. Fog occurs about 37 percent of the time during the thaw period.

In the shallow areas around the island, the ice begins to decay during the first part of June. By late September, skim and frazil ice can form which helps to protect the shore from further wave action (Figs. 18 and 34). The 1968 Flaxman Island aerial photography mission was flown on 21 October. The Beaufort Sea was covered with frazil ice. The lagoon between Flaxman Island and the mainland was frozen over by 21 October; approximately three centimeters (one inch) of snow was overlying a few centimeters of ice. The lagoon began to freeze on 23 September. Between 23 September and 21 October westerly winds of 21 kilometers per hour (13 miles per hour) predominated. However, the fastest velocity was about 61 kilometers per hour (38 miles per hour) from the east. Air temperatures were always below freezing for the 29 day period preceding the photography mission. The lowest air temperature was about –16°C (4°F). Freezing degree-days are used to compare the magnitude and duration of freezing air temperatures. The freezing degree-days for one day are computed by subtracting 0°C (32°F) from the average daily air temperature. The accumulation or summation of freezing degree-days for a period of time gives the freezing index for that period. Normally, by 21 October, only 156°C-days (281°F-days) have accumulated for the Flaxman Island area. However, by 21 October 1968, 182°C-days (327°F-days) had accumulated. The greater freezing index for 1968 indicates a more abrupt halt to thermal erosion and a more rapid freeze-up environment for the year.

At any time during the thaw season, the pack ice can shove onto the shore and thus reduce or eliminate wave action. Thawing air temperatures and warm, surface waters will continue to melt the permafrost even though the sea ice may be onshore. Air temperatures will commence to thaw the frozen ground in June long before the decay of the shore fast ice.

## CONCLUSIONS

The entire coast from Point Barrow to the Mackenzie River is characterized by the thermal erosion of permafrost during the annual thaw period. The shore line recession and permafrost degradation is caused by wave action and thawing air temperatures. Historical records of natural physical processes and rates, when compared to the present natural environment, will allow the prediction of natural physical processes. Therefore, if the aspects of the natural environment are defined, the impact of disturbance upon the physical environment by man can be identified. Man must understand the physical environment of Northern Alaska before the region can be developed.

## ACKNOWLEDGEMENTS

This report is the first of a series of reports on permafrost terrain research. The research began in 1962 and has been supported by the U. S. Army Cold Regions Research and Engineering Laboratory, the Arctic Institute of North America under contractual arrangements with the Office of Naval Research, and the Naval Arctic Research Laboratory.

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## CONVERSION FACTORS

| *TO CONVERT* | *TO* | *MULTIPLY BY* |
|---|---|---|
| Celsius | Fahrenheit | (°Cx9/5) +32 |
| Fahrenheit | Celsius | 5/9(°F-32) |
| Feet | Meters | 0.3048 |
| Kilometers | Statute Miles | 0.6214 |
| Knots | Kilometers/hour | 1.8532 |
| Knots | Statute Miles/hour | 1.151 |
| Meters | Statute Miles | $6.214x10^{-4}$ |
| Miles (Statute) | Kilometers | 1.609 |
| Miles (Statute) | Meters | 1609 |
| Miles (Statute) | Nautical Miles | 0.8684 |
| Miles (Nautical) | Statute Miles | 1.1516 |

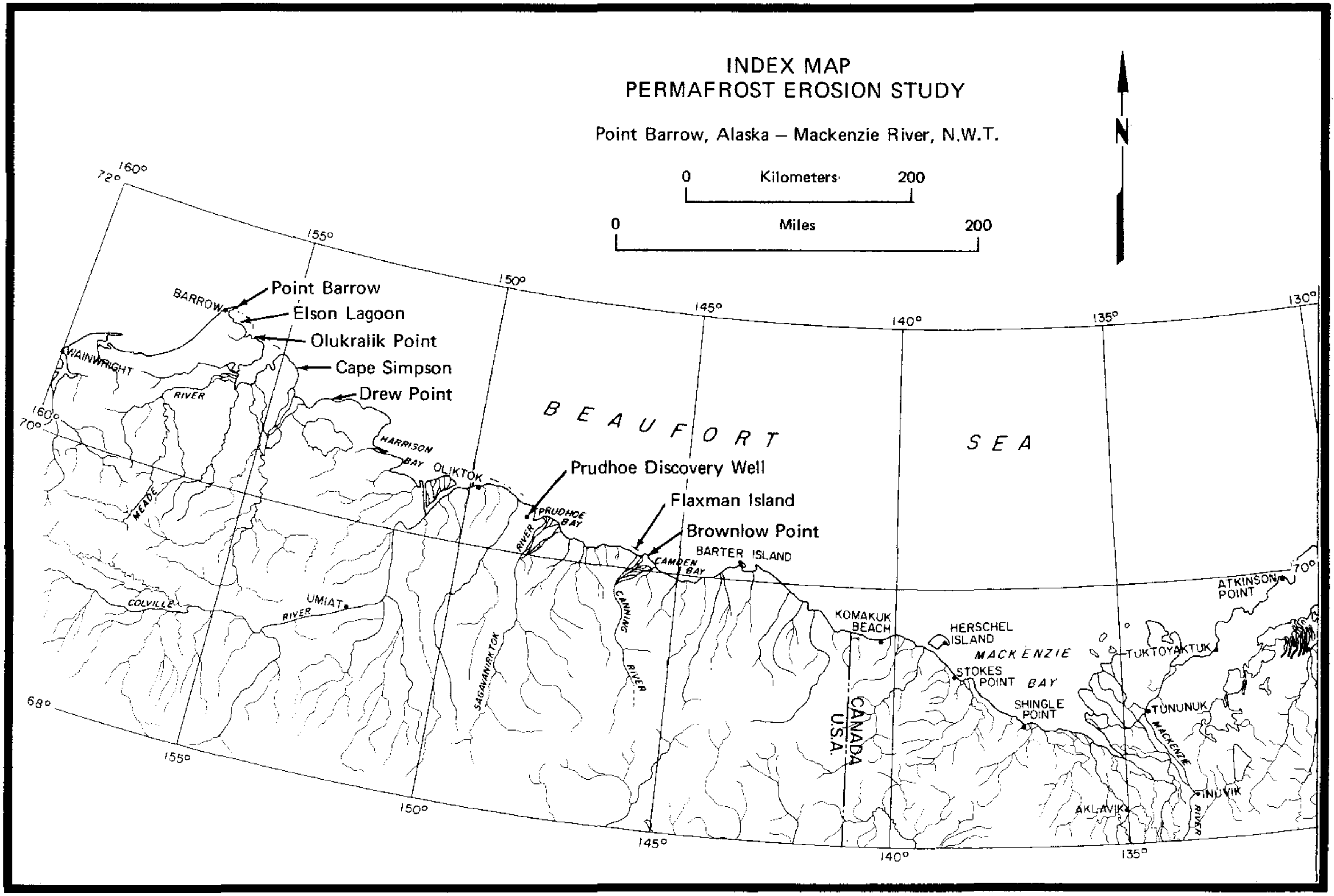


*Fig. 1. Index Map of the Permafrost Erosion Study.*

*Fig. 2. This photograph illustrates the vertical tension crack in the tundra soils. This crack overlies a vertical wedge-shaped vein of ice.*

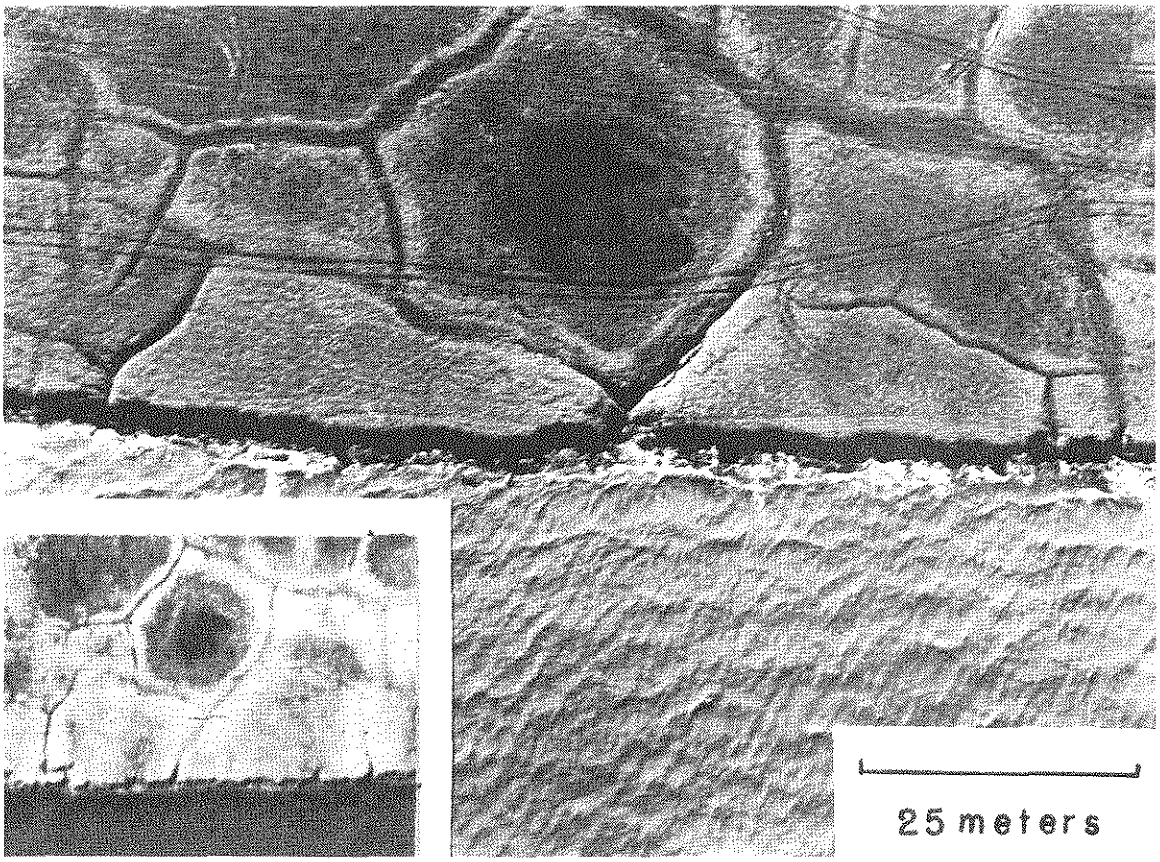


*Fig. 3. A 1963 aerial photograph of the west shore line of Elson Lagoon near Brant Point. The wave action is removing the thawed and slumped tundra soils at the bottom of the eroding bank. The bank is about 2 meters (6.6 feet) in height. The inset aerial photograph (at a smaller scale) was taken in 1948. These sequential photographs are utilized in the study of the erosional characteristics and recession rates of permafrost shore lines. Note the dark troughs which surround the polygons. Surface drainage develops along the polygon troughs.*

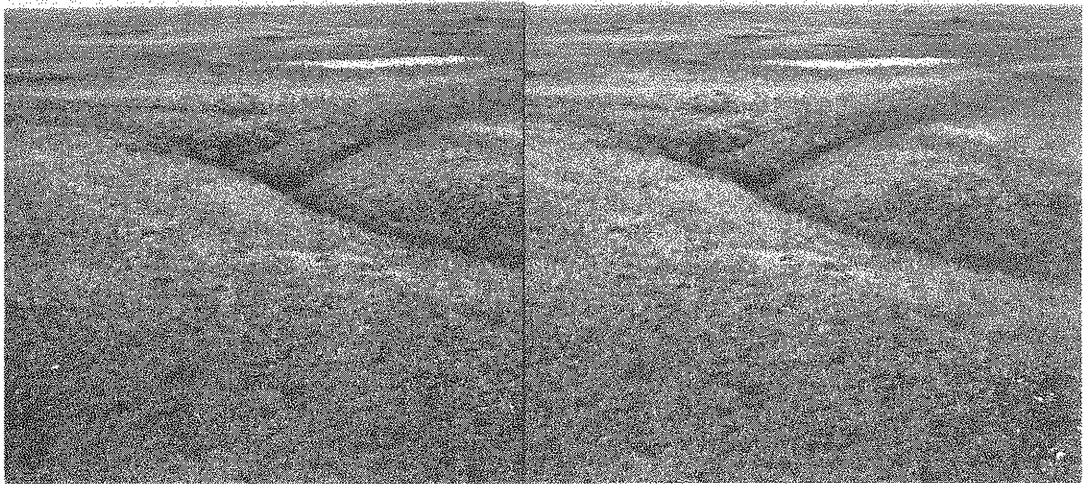


*Fig. 4. The stereogram shows the initial thawing of ice-wedge ice by warm (18°C, 64°F) surface waters which drain via the polygon troughs. The surface drainage can develop and entrench landward by the thawing of underlying ice-wedge ice and subsequent subsidence of the tundra surface (see Fig. 3). The warm surface waters are routed directly to the ice-wedge ice via the vertical tension crack. This photograph is the first of a series of four stereograms which illustrate the degradation of ice-wedge ice and permafrost away from the receding coastline near Tekegakrok Point. The total topographic relief is about 50 centimeters (1.5 feet).*

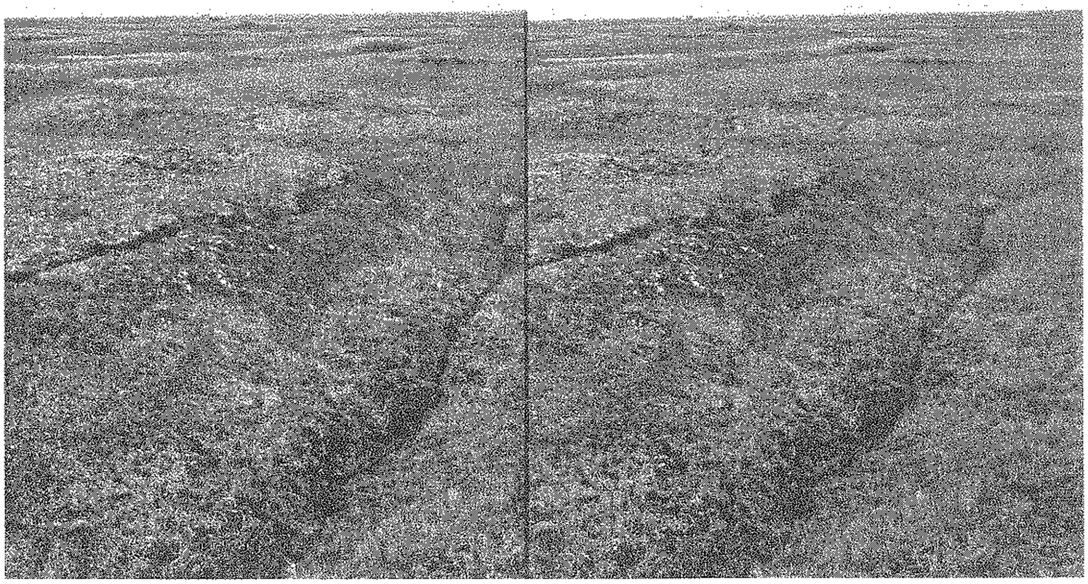


*Fig. 5. The second stereogram of the degradation of ice-wedge ice and permafrost by surface drainage. Note the slumping of tundra soils along the edge of the polygon. The total topographic relief is about 1 meter (3.3 feet).*

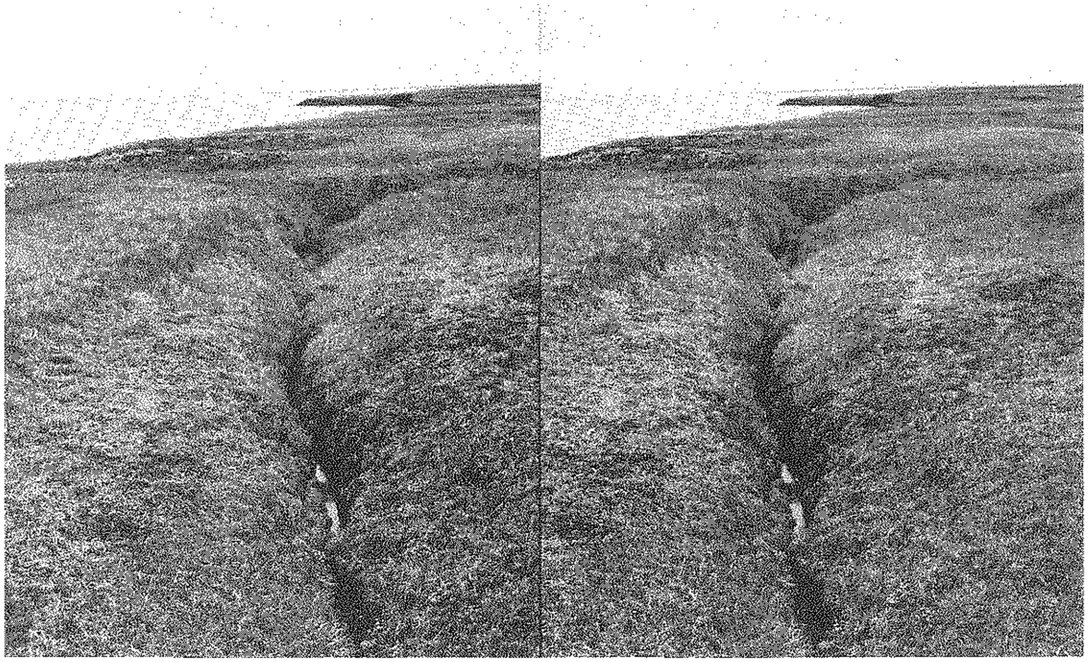


*Fig. 6. The third stereogram of the erosion of ice-wedge ice and permafrost. The total topographic relief is about 1.5 meters (5 feet).*

*Fig. 7. The fourth stereogram illustrates the advanced stage of ice-wedge ice and permafrost degradation along the polygon trough which overlies the ice-wedge ice. The tundra surface subsides and slumps as the volume of ice decreases. The total topographic relief is about 2 to 3 meters (6.6 to 10 feet).*

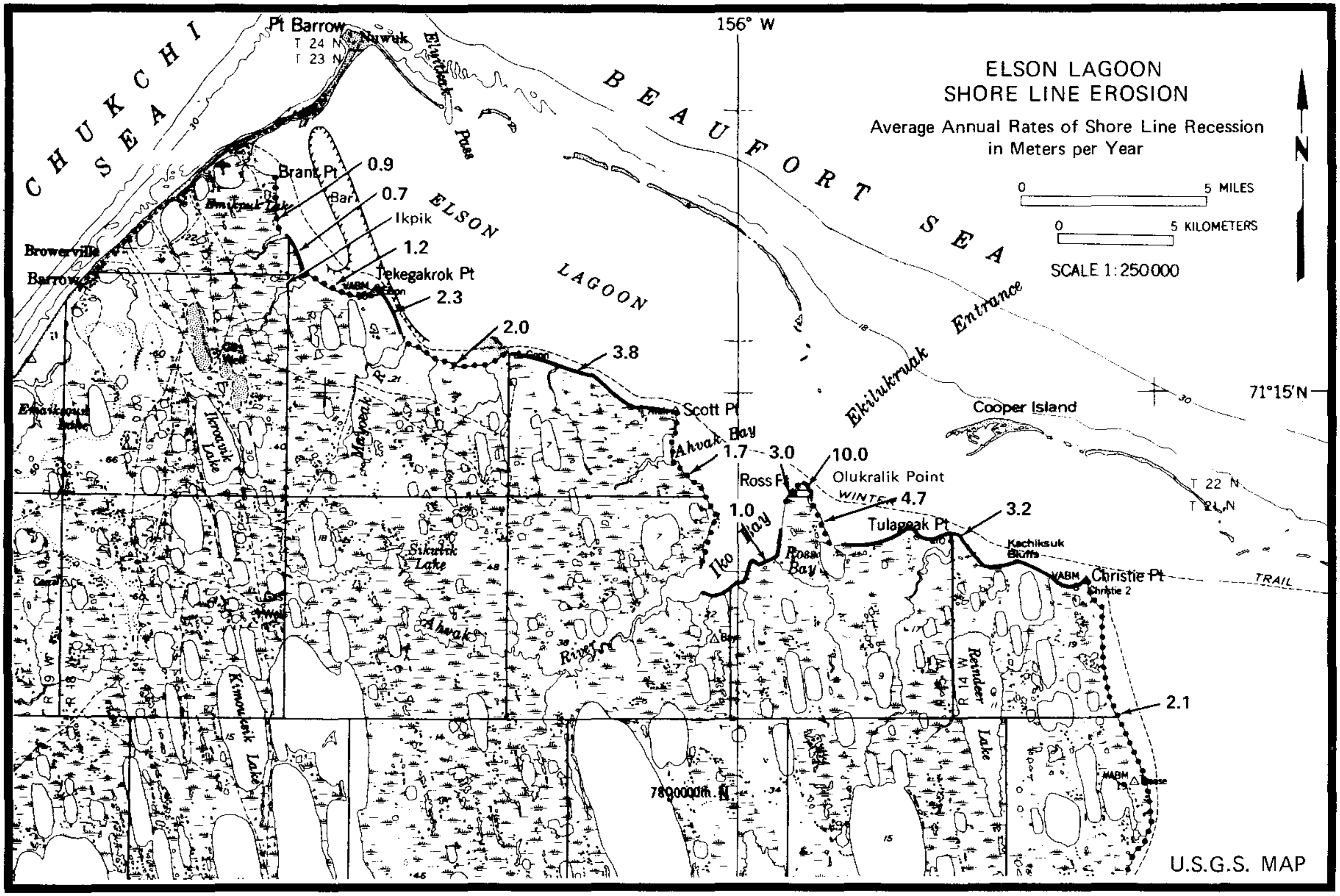


Fig. 8. *Elson Lagoon Shore Line Erosion. Average Annual Rates of Shore Line Recession in Meters per Year.*

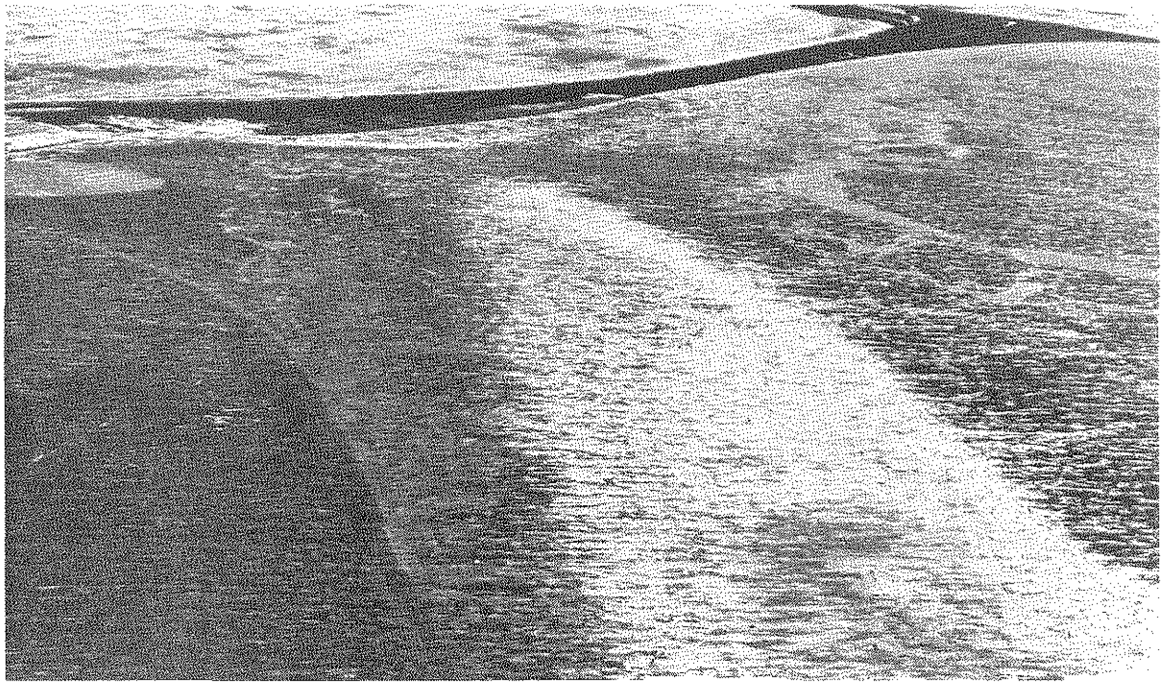


*Fig. 9. An aerial oblique photograph showing the large bar of fine sands and silts which have been deposited north of Tekegakrok Point, Elson Lagoon (see Fig. 8). The bar outline is accentuated by the decaying ice. This bar protects the western coastline from Brant Point to Ikpik. Point Barrow can be seen in the right background of the photograph. The patterns made by the decaying ice are useful in the study of the near shore environments. The photograph was taken 15 June 1967.*

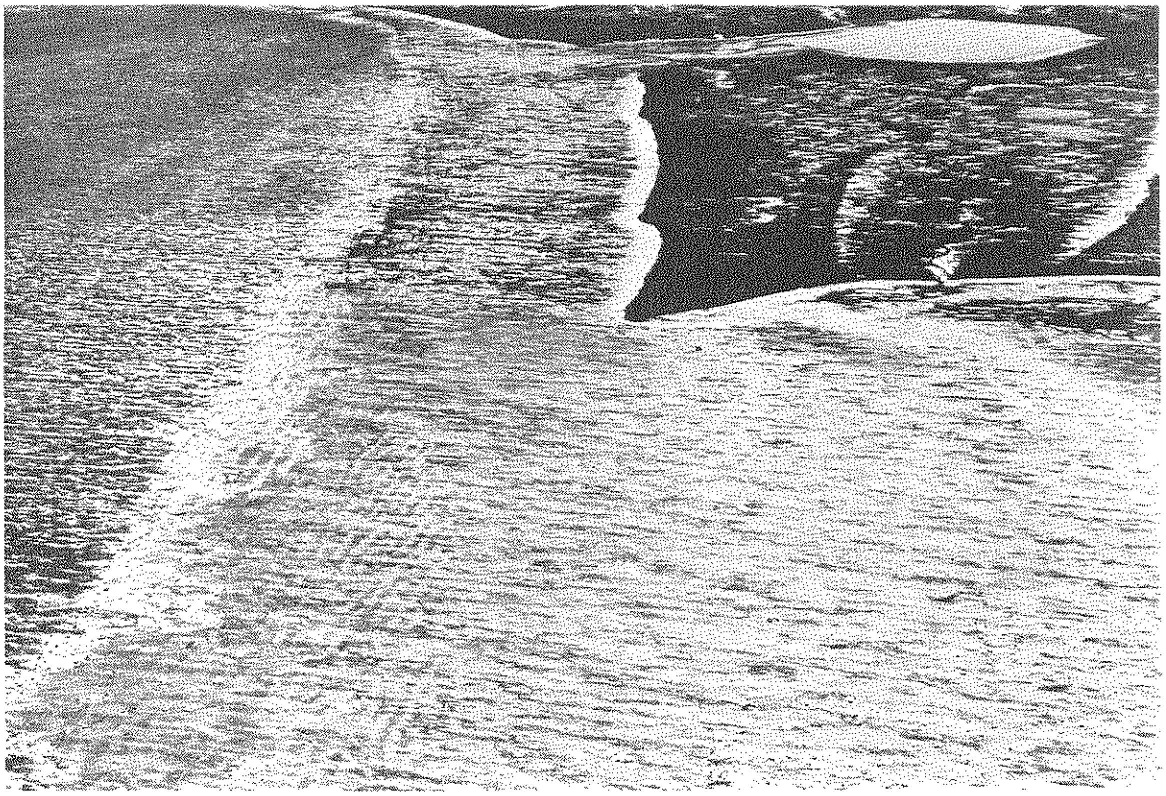


*Fig. 10. Another view, looking south toward Tekegakrok Point, of the large bar in Elson Lagoon. Note the giant ripple marks on the bar. The ripple marks are accentuated by the differential thawing of the ice. The photograph was taken 15 June 1967.*

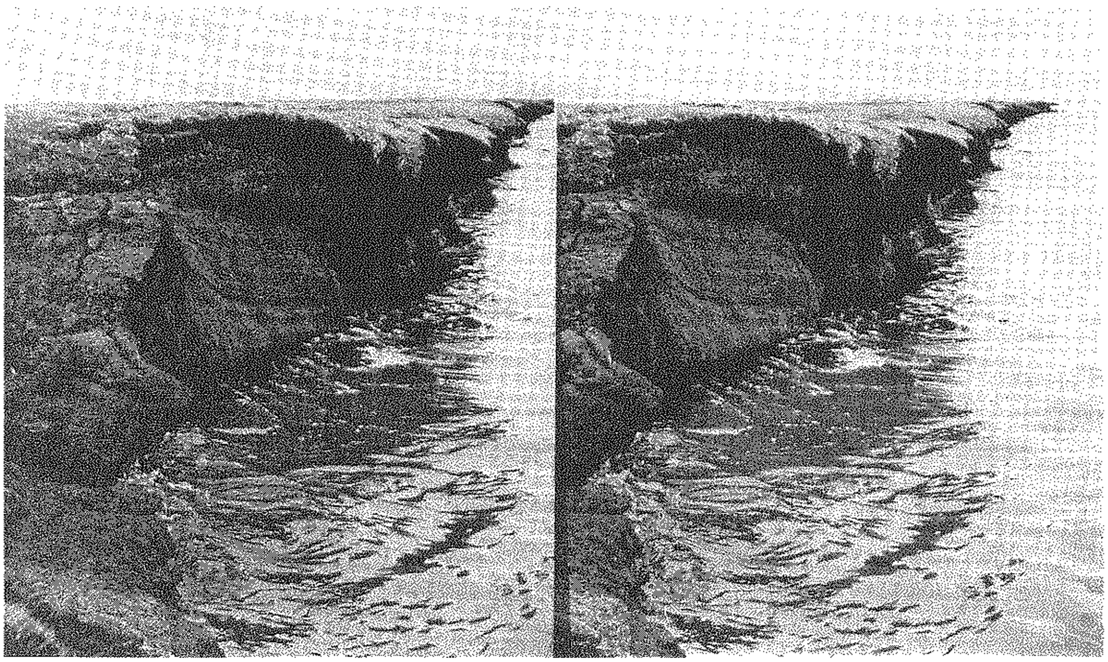


*Fig. 11. A stereogram of the permafrost erosion by thermo-erosional niching along the water level. The eroding bank is 2 to 3 meters (6.6 to 10 feet) in height. The photograph was taken 16 August 1965, south of Tekegakrok Point.*

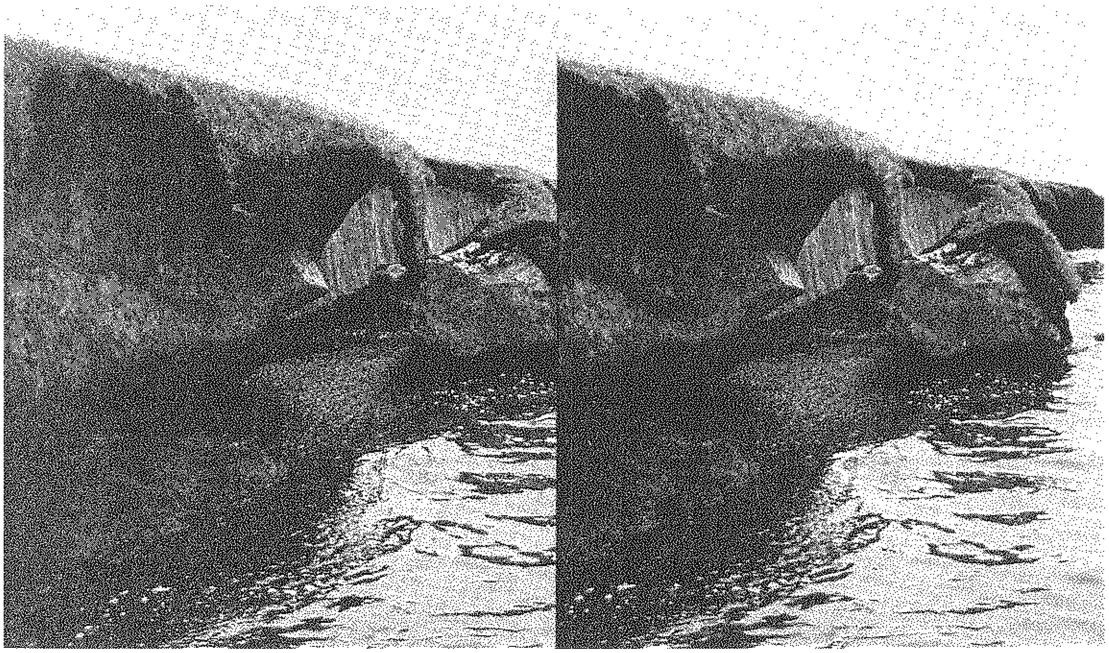


*Fig. 12. A collapse block of permafrost caused by the thermo-erosional niche intersecting with a vertical vein of ice-wedge ice. This block will offer temporary protection from further niching. The photograph was taken 16 August 1965, south of Tekegakrok Point. The bank is 2 to 3 meters (6.6 to 10 feet) in height. Note the overhanging tundra vegetation mat, the organic muck in the water, the frozen silts, and ice.*

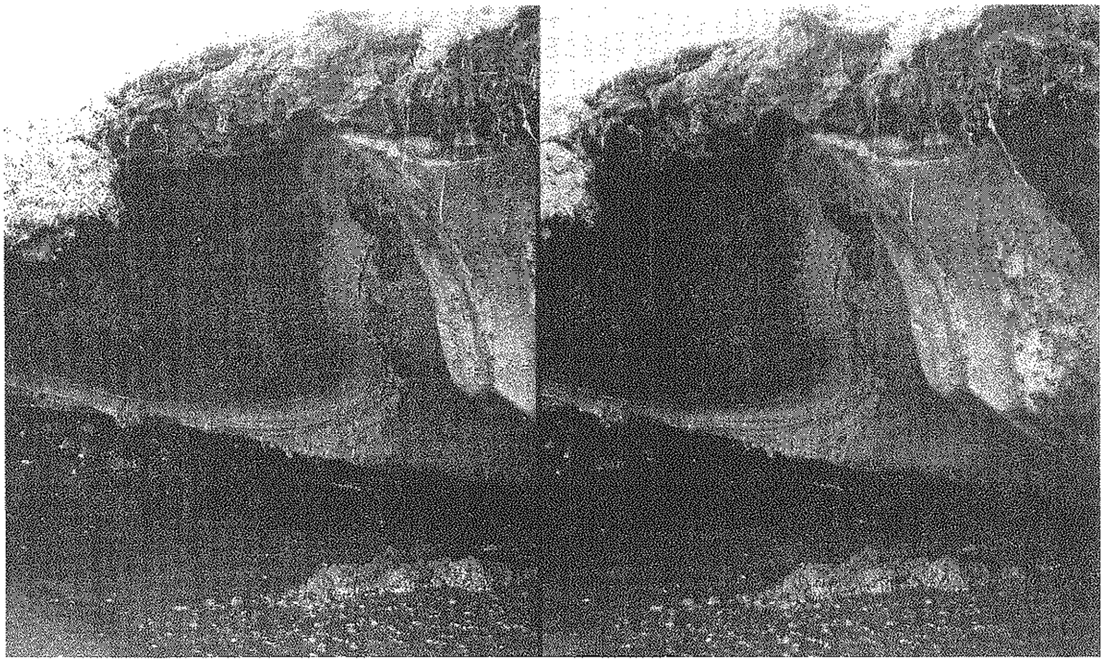


*Fig. 13. An ice-wedge is visible at the right center of the stereogram. The annual contraction and expansion of the polygon deforms the adjacent soils. The soils consist of a gray silt overlain by an organic soil. The soils have a very high ice content. The seasonal thaw zone is indicated by the interval of tundra soil overlying the ice-wedge ice. Note the thermo-erosional niche and the organic muck in the water. The photograph was taken 16 August 1965, south of Tekegakrok Point.*

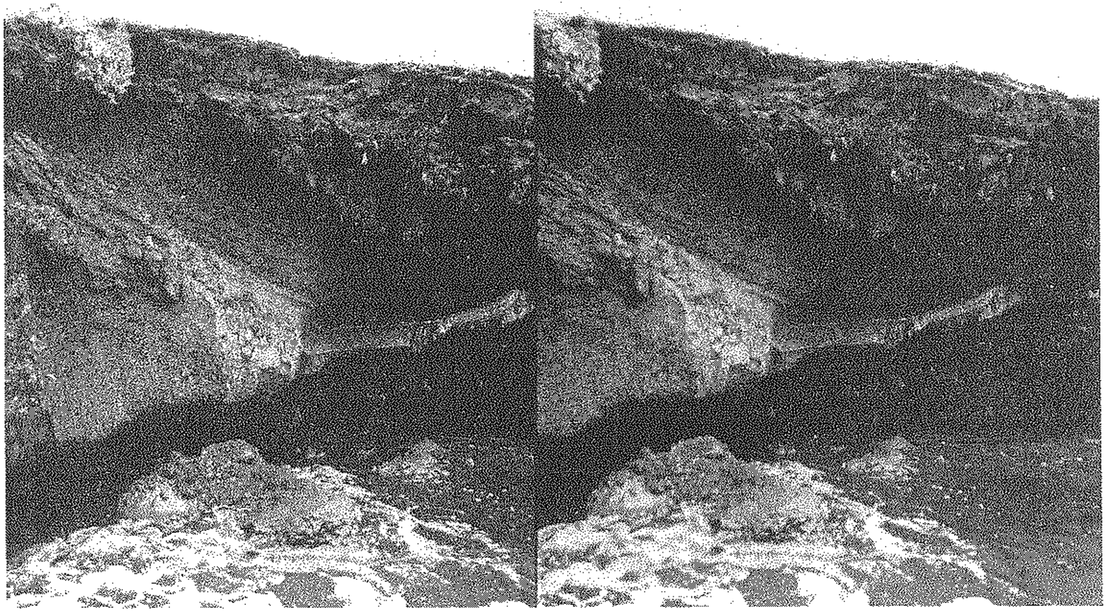


*Fig. 14. This is another stereogram taken 16 August 1965, south of Tekegakrok Point. Note the thermo-erosional niche, the deformed soils, and the organic muck.*

*Fig. 15. A photograph taken of Point Barrow (September 1963) just before the marine storm of 3 October 1963. The normal coastline retreat is about 3 meters (10 feet) per year. Compare this photograph with Fig. 16.*

*Fig. 16. Point Barrow after the storm of 3 October 1963. About 8 meters (26 feet) was eroded by this single storm. Whale bone and debris from an old Eskimo village litter the foreground. The photograph was taken 16 August 1965.*

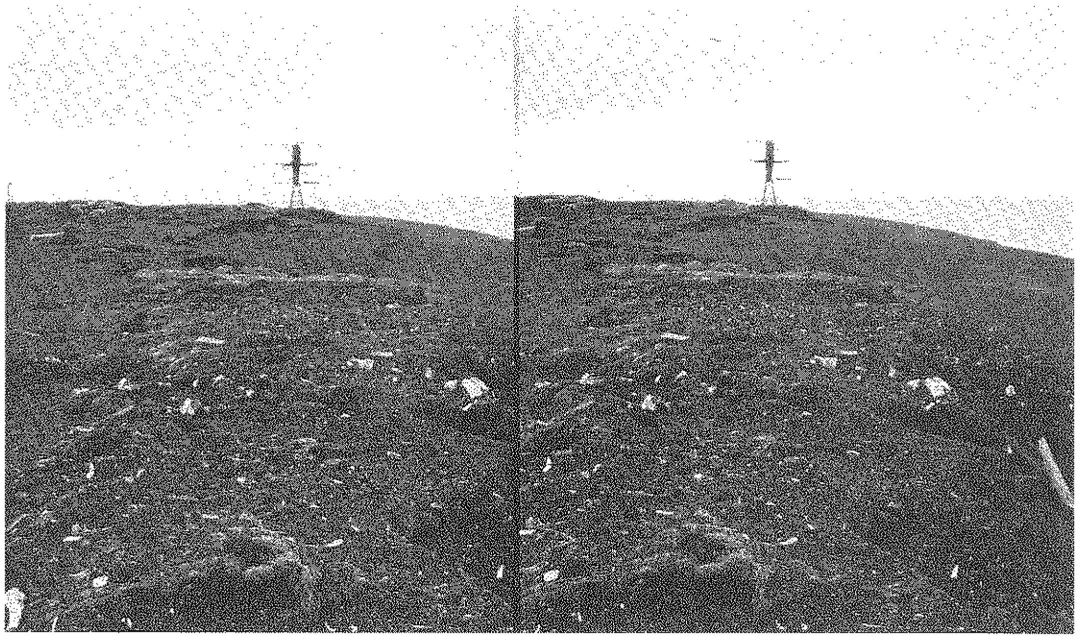


*Fig. 17. A stereogram of Point Barrow taken 16 August 1965.*

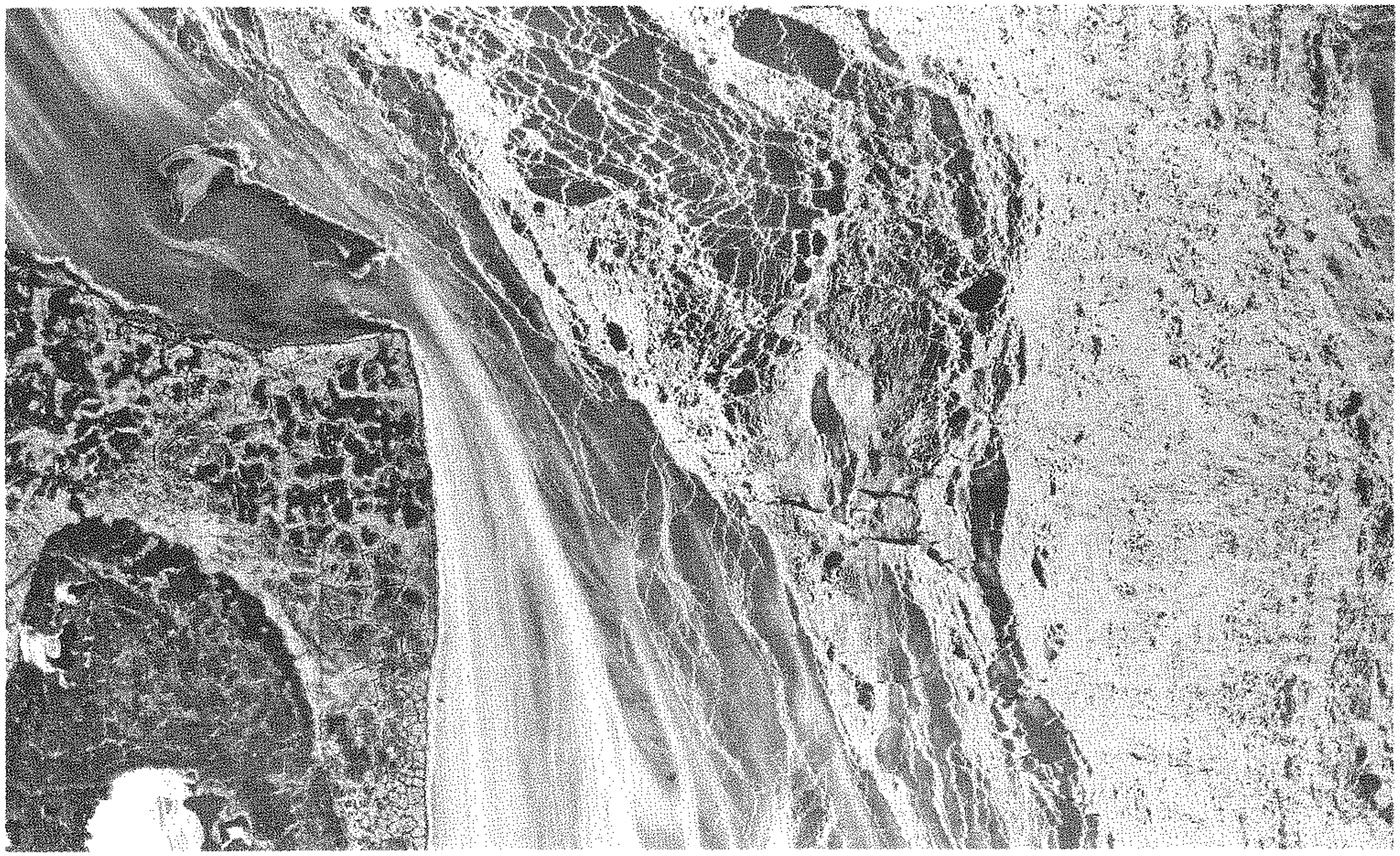


*Fig. 18. This aerial photograph illustrates the strands of frazil ice and skim ice which form during the initial phase of the annual freeze-up. The formation of frazil and skim ice stops the erosive wave action. The photograph was taken over Brant Point, Elson Lagoon on 5 September 1956 at a scale of 1/10750.*

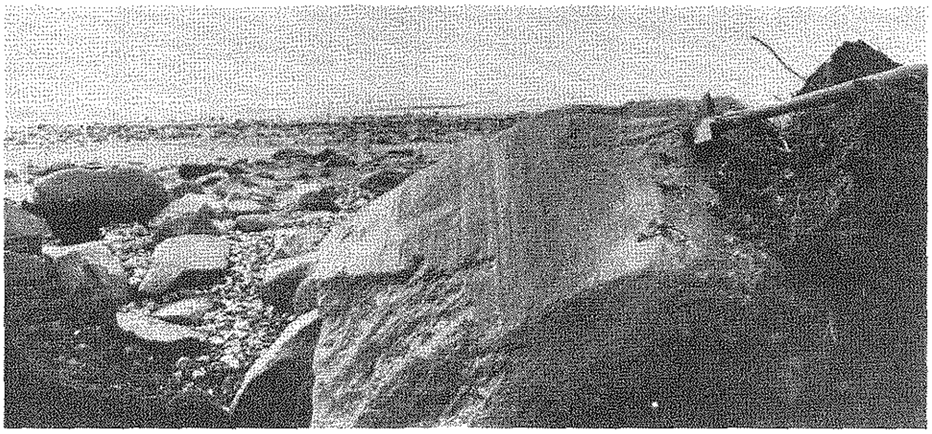


*Fig. 19. A striated greenstone boulder of the Flaxman Formation (photograph by Leffingwell, 1919, Plate XVI).*

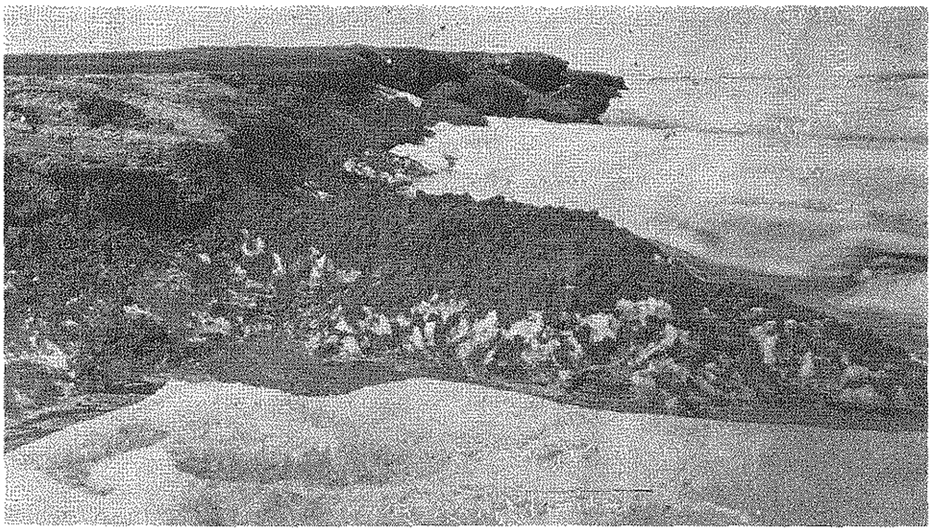


*Fig. 20. Temporary preservation of sea ice under a slumping bank on Flaxman Island (photograph by Leffingwell, 1919, Plate XXVI.)*

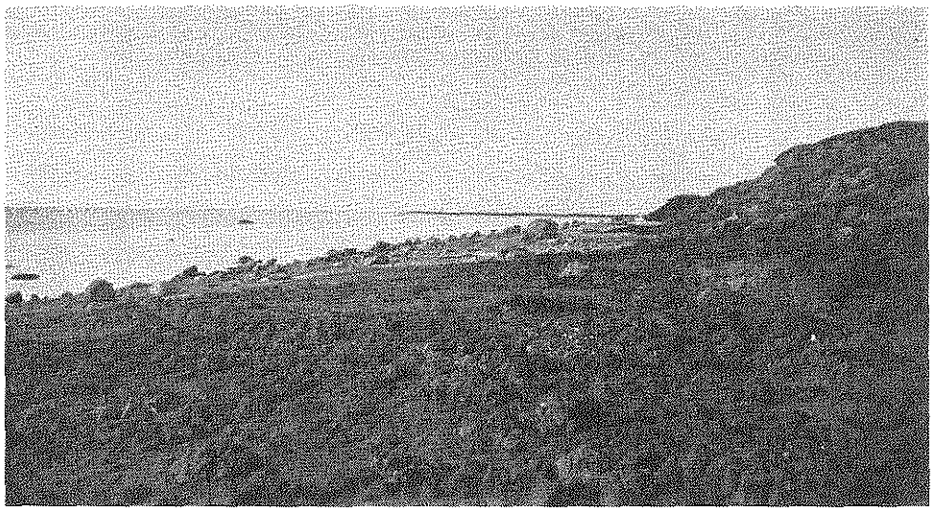


*Fig. 21. Fine organic soils slumping in the foreground. Flaxman Formation boulders in the background along the Flaxman Island beach (photograph by Leffingwell, 1919).*

*Fig. 22. Polygon or permafrost block broken off along ice-wedge ice, north shore of Flaxman Island. An ice-wedge can be seen in the left central part of the photograph (photograph by Leffingwell, 1919, Plate XXXI).*

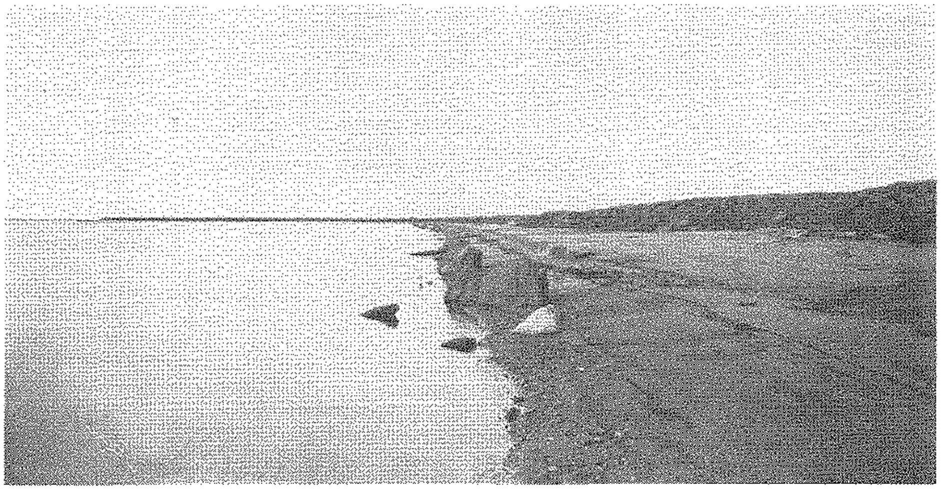
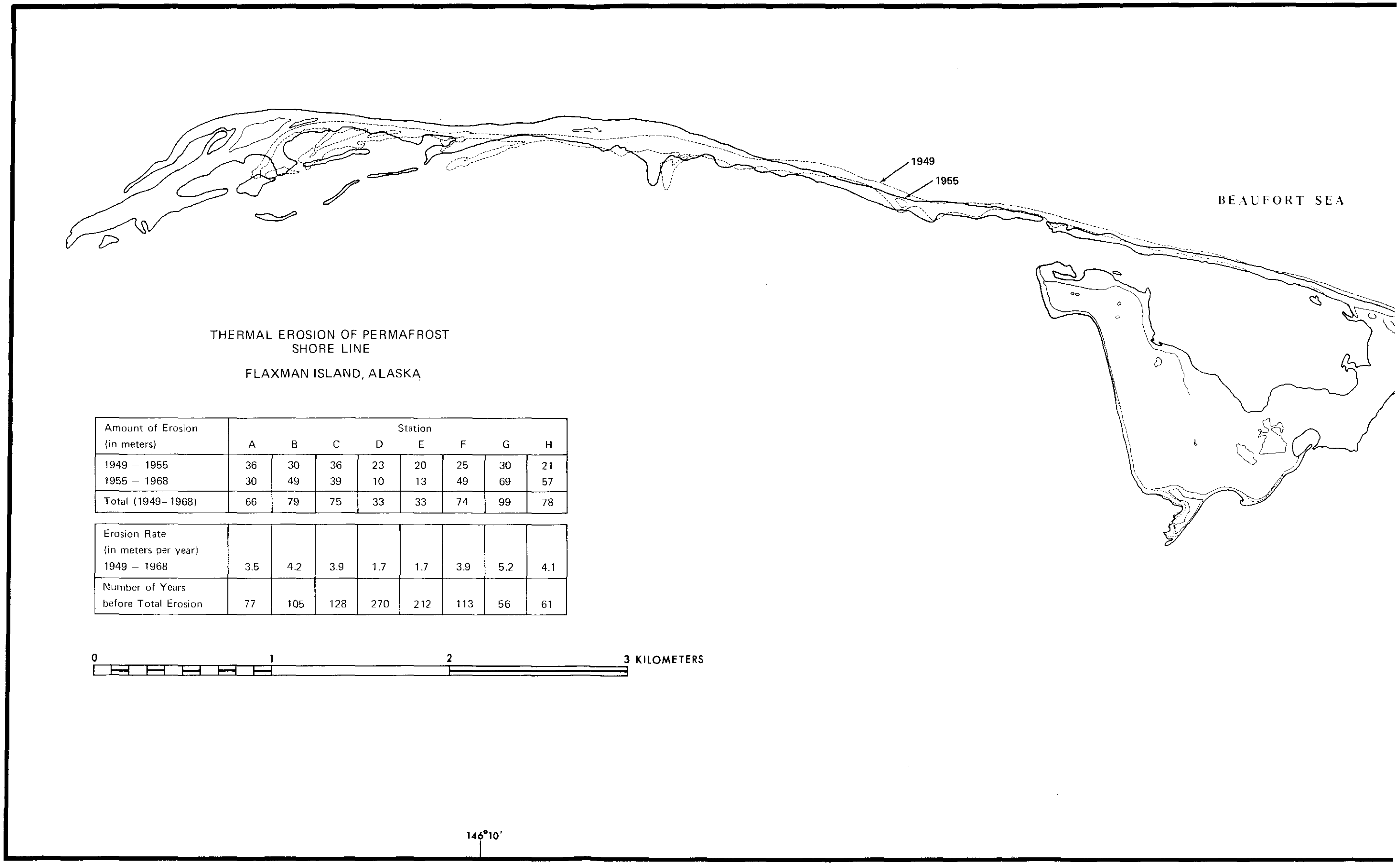


*Fig. 23. Flaxman Formation glacial boulders on the beach of the west shore of Flaxman Island (photograph by Leffingwell, 1919, Plate XVI).*

*Fig. 24. Mound of sand, gravel, and boulders shoved up by the sea ice as the ice mounts the beach (photograph by Leffingwell, 1919, Plate XXV).*



# THERMAL EROSION OF PERMAFROST SHORE LINE

## FLAXMAN ISLAND, ALASKA

| Amount of Erosion (in meters) | Station | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | A | B | C | D | E | F | G | H |
| 1949 – 1955 | 36 | 30 | 36 | 23 | 20 | 25 | 30 | 21 |
| 1955 – 1968 | 30 | 49 | 39 | 10 | 13 | 49 | 69 | 57 |
| Total (1949–1968) | 66 | 79 | 75 | 33 | 33 | 74 | 99 | 78 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Erosion Rate (in meters per year) 1949 – 1968 | 3.5 | 4.2 | 3.9 | 1.7 | 1.7 | 3.9 | 5.2 | 4.1 |
| Number of Years before Total Erosion | 77 | 105 | 128 | 270 | 212 | 113 | 56 | 61 |

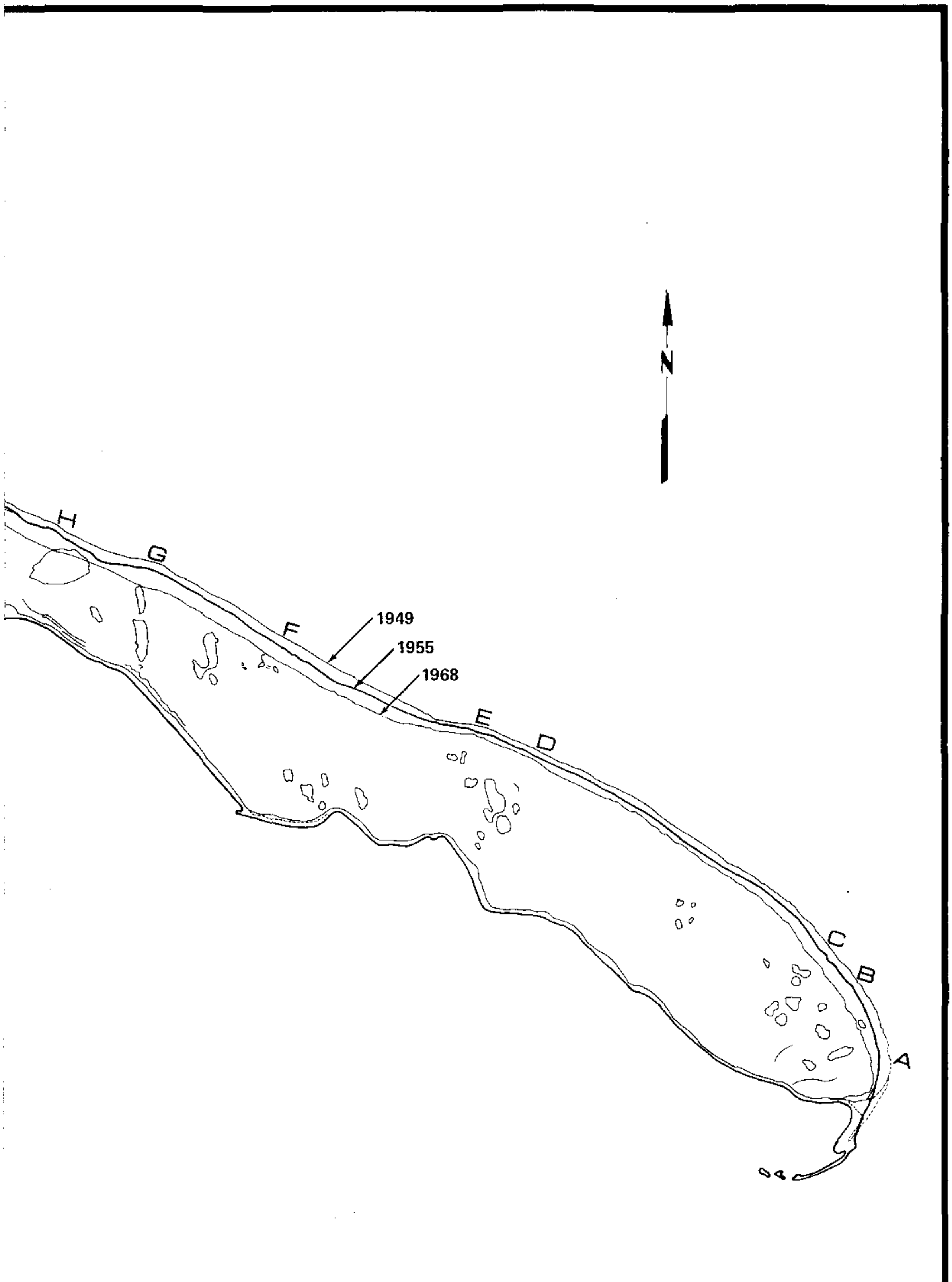


*Fig. 25. Flaxman Island Erosion, 1949-1968.*

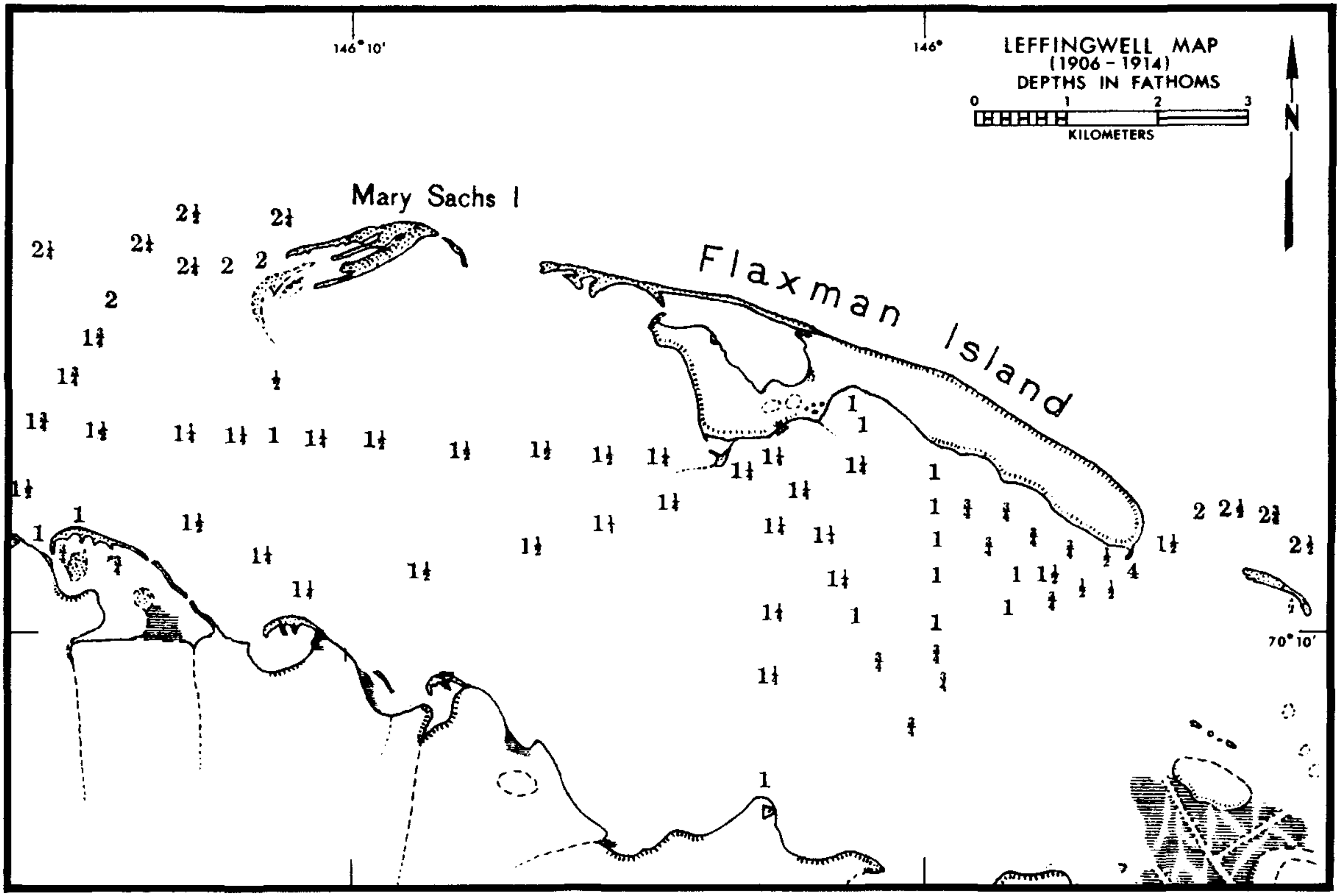


*Fig. 26. Leffingwell's Flaxman Island Map, 1906-1914.*

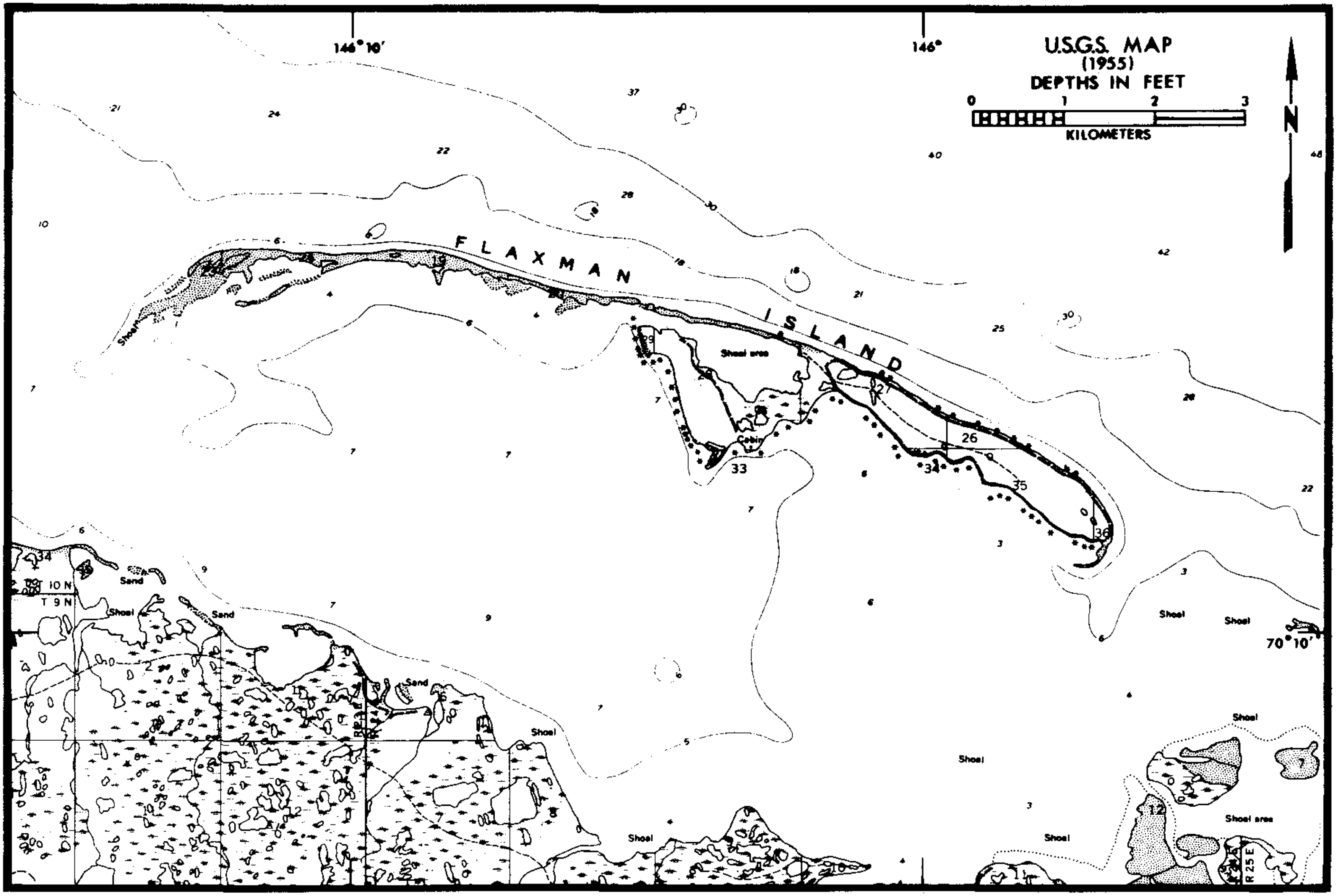


*Fig. 27. U. S. Geological Survey Flaxman Island Map, 1955.*

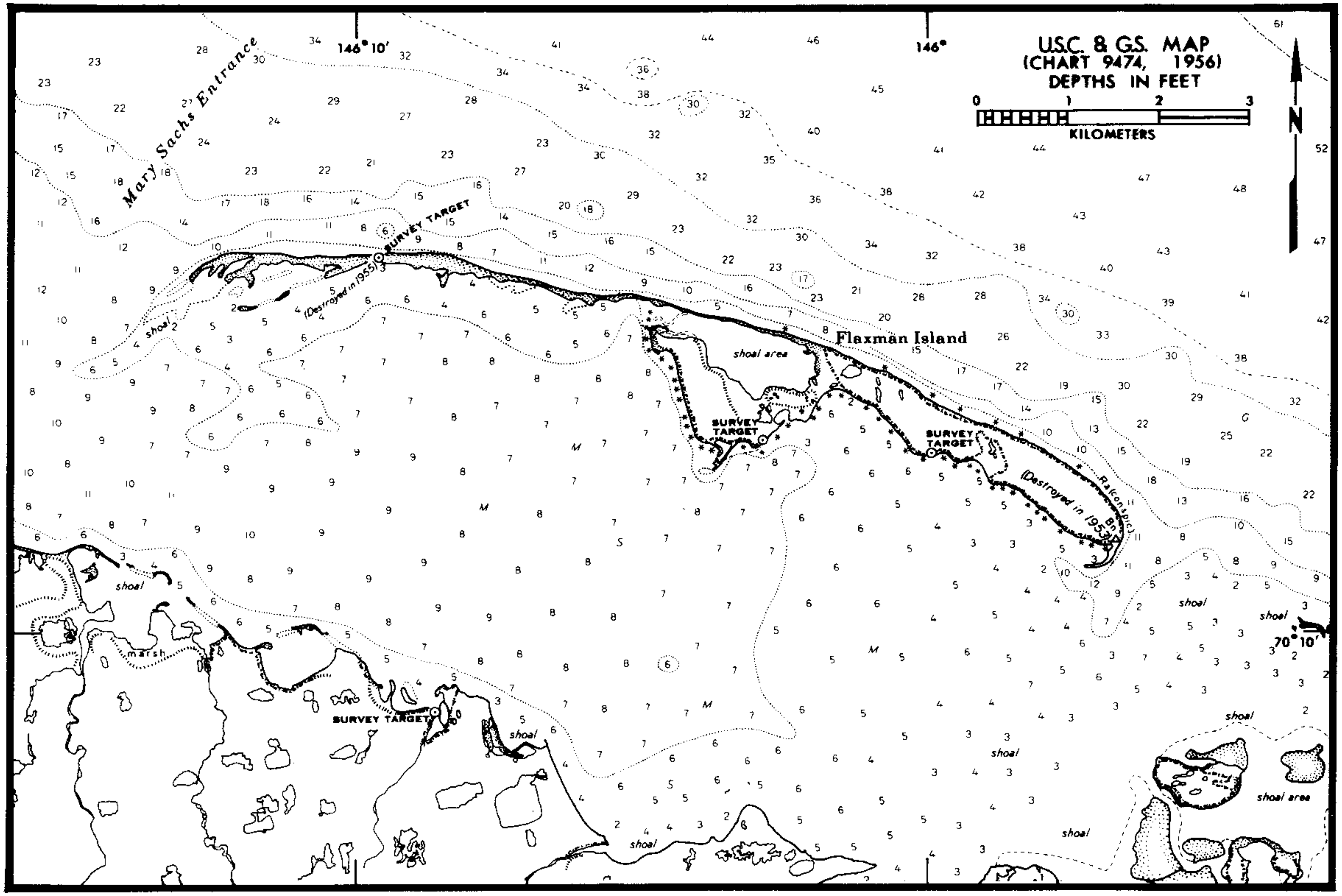


*Fig. 28. U. S. Coast and Geodetic Survey Flaxman Island Map, 1956.*

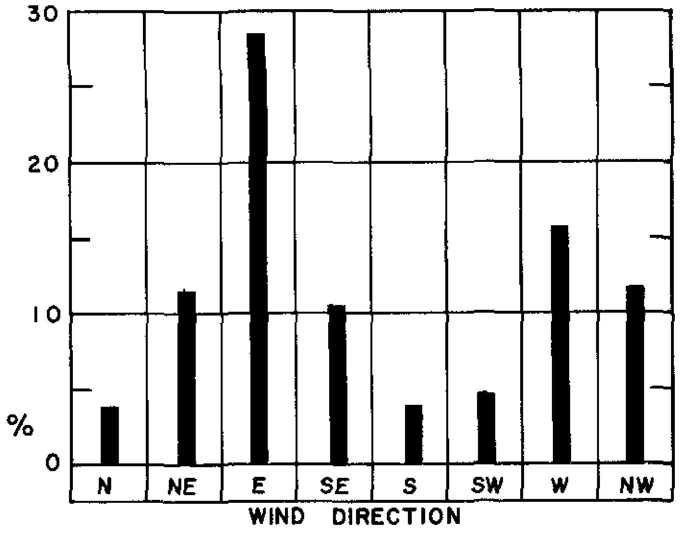


Fig. 29. Percentage frequency of wind direction for all years of record (1900-1967), July through October, Flaxman Island (Lewellen, 1969).

WIND SPEED GROUPS
(KNOTS)

| WIND DIRECTION | 0-2 | 3-7 | 8-12 | 13-20 | 21-40 | 40+ | TOTAL | % |
|---|---|---|---|---|---|---|---|---|
| N | 5 | 48 | 19 | 7 | 3 | | 82 | 3.9 |
| NE | 20 | 88 | 85 | 58 | 16 | | 267 | 12.6 |
| E | 24 | 122 | 159 | 245 | 67 | 2 | 619 | 29.2 |
| SE | 12 | 57 | 86 | 52 | 13 | 1 | 221 | 10.4 |
| S | 4 | 36 | 26 | 10 | | | 76 | 3.6 |
| SW | 9 | 22 | 34 | 17 | 12 | | 94 | 4.5 |
| W | 17 | 78 | 107 | 91 | 37 | 2 | 332 | 15.7 |
| NW | 8 | 71 | 82 | 87 | 18 | | 266 | 12.6 |
| CALM | 161 | | | | | | 161 | 7.5 |
| TOTAL | 260 | 522 | 598 | 567 | 166 | 5 | 2118 | |
| % | 12.3 | 24.6 | 28.3 | 26.8 | 7.8 | 0.2 | | 100/100 |

Fig. 30. Frequency of wind speed groups (in knots) by wind direction for all years of record (1900-1967), July through October, Flaxman Island (Lewellen, 1969).

WIND DIRECTION

| AIR TEMPERATURE °F | N | NE | E | SE | S | SW | W | NW | CALM | TOTAL | % |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 55/59 |  | 1 |  | 2 | 2 |  | 2 |  |  | 7 | 0.5 |
| 50/54 |  |  |  | 1 | 1 | 4 | 5 | 1 |  | 12 | 0.9 |
| 45/49 | 2 | 5 | 18 | 11 | 5 | 8 | 15 | 2 | 3 | 69 | 5.0 |
| 40/44 | 6 | 11 | 37 | 26 | 8 | 18 | 49 | 20 | 10 | 185 | 13.5 |
| 35/39 | 20 | 31 | 99 | 42 | 18 | 24 | 60 | 62 | 38 | 394 | 28.8 |
| 30/34 | 18 | 94 | 233 | 34 | 7 | 10 | 87 | 79 | 54 | 606 | 44.3 |
| 25/29 | 8 | 22 | 18 | 7 | 1 | 1 | 5 | 14 | 3 | 79 | 5.8 |
| 20/24 | 3 | 3 | 3 | 1 |  |  | 1 | 2 |  | 13 | 1.0 |
| 15/19 |  |  | 2 |  |  |  |  |  |  | 2 | 0.2 |
| TOTAL | 57 | 167 | 400 | 124 | 42 | 65 | 224 | 180 | 108 | 1367 |  |
| % | 4.2 | 12.2 | 29.3 | 9.1 | 3.1 | 4.8 | 16.4 | 13.2 | 7.9 |  | 100 100 |

*Fig. 31. Air temperature classes versus wind direction for all years of record (1900-1967), July through October, Flaxman Island (Lewellen, 1969).*

| SEA TEMPERATURE °F | JULY | AUG | SEPT | OCT | TOTAL | % |
|---|---|---|---|---|---|---|
| 50/49 |  | 2 |  |  | 2 | 0.1 |
| 48/47 |  | 6 |  |  | 6 | 0.3 |
| 46/45 | 2 | 35 |  |  | 37 | 1.9 |
| 44/43 |  | 29 |  |  | 29 | 1.5 |
| 42/41 | 7 | 41 | 6 |  | 54 | 2.7 |
| 40/39 | 16 | 55 | 7 |  | 78 | 3.9 |
| 38/37 | 37 | 67 | 4 |  | 108 | 5.4 |
| 36/35 | 44 | 199 | 6 |  | 249 | 12.5 |
| 34/33 | 107 | 311 | 36 |  | 454 | 22.8 |
| 32/31 | 62 | 429 | 185 |  | 676 | 34.0 |
| 30/29 | 19 | 184 | 72 | 7 | 282 | 14.2 |
| 28/27 | 1 | 4 | 1 | 1 | 7 | 0.4 |
| <27 | 1 | 2 | 2 |  | 5 | 0.3 |
| TOTAL | 296 | 1364 | 319 | 8 | 1987 | 100.0 |

*Fig. 32. Sea temperature classes by month for all years of record (1900-1967), July through October (Lewellen, 1969).*

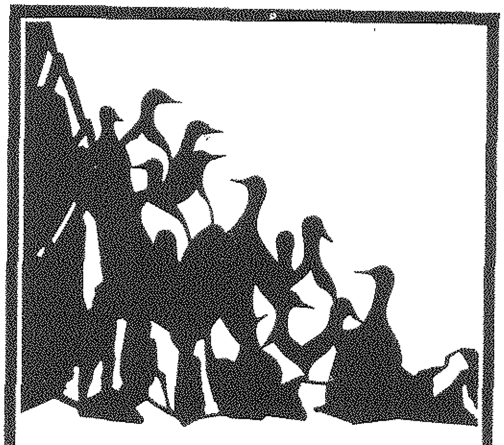
FREQUENCY OF OCCURRENCE OF WEATHER

| WIND DIRECTION | RAIN | RAIN SHOWERS | DRIZZLE | FREEZING PRECIP. | FROZEN PRECIP. | FOG | HAZE SMOKE | NO WEATHER | TOTAL |
|---|---|---|---|---|---|---|---|---|---|
| N | 6 | | 2 | 1 | 4 | 16 | | 24 | 53 |
| NE | 15 | | 6 | 3 | 31 | 78 | | 51 | 184 |
| E | 46 | | 13 | 4 | 42 | 178 | 1 | 145 | 429 |
| SE | 4 | 1 | 3 | 4 | 9 | 60 | | 72 | 153 |
| S | 2 | | | 1 | 2 | 13 | | 26 | 44 |
| SW | 12 | | 3 | | | 6 | | 29 | 50 |
| W | 27 | 2 | 11 | 2 | 31 | 62 | | 88 | 223 |
| NW | 17 | 1 | 19 | | 36 | 43 | 2 | 55 | 173 |
| CALM | 11 | | 2 | | 6 | 65 | | 28 | 112 |
| TOTAL | 140 | 4 | 59 | 15 | 161 | 521 | 3 | 518 | 1421 |
| % | 9.9 | 0.3 | 4.2 | 1.1 | 11.3 | 36.7 | 0.2 | 36.5 | 100.2 |

*Fig. 33. Frequency of weather occurrence by wind direction for all years of record (1900-1967), July through October (Lewellen, 1969).*

*Fig. 34. Frazil ice and freezing spray accumulating along the western shore of Imikpuk Lake, Barrow, Alaska (27 September 1966). This lake is the fresh water supply for the Barrow Naval Camp. The water collection point is marked by the small building in the background of the photograph. Generally, the waves propagate about 10 to 15 meters (33 to 50 feet) into the strands of frazil ice before the waves are completely damped.*

# Permafrost erosion along the Beaufort Sea coast



IN THE MEMORY OF

Dr. ROBERT D. BERGMAN

LEONARD A. BOUGHTON

J. LARRY HADDOCK

SEPTEMBER 30, 1974

by

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March 1970

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