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THE UNIVERSITY OF ALBERTA

BANK EROSION IN THE SOUTHERN MACKENZIE RIVER DELTA, NORTHWEST TERRITORIES, CANADA

by

© DAVID N. OUTHET

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE

DEPARTMENT OF GEOGRAPHY

EDMONTON, ALBERTA

FALL, 1974

THE UNIVERSITY OF ALBERTA

FACULTY OF GRADUATE STUDIES AND RESEARCH

The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research, for acceptance, a thesis entitled Bank Erosion in the Southern Mackenzie River Delta, Northwest Territories, Canada, submitted by David N. Outhet in partial fulfilment of the requirements for the degree of Master of Science.

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Date October 10, 1974

ABSTRACT

Analysis of 2-week time lapse photography in the field and from the air, along with other data collected in the field, indicates that in the southern Mackenzie River Delta, the shape of an eroding bank is positively correlated with the erosion process and the rate and character of erosion. Poor correlations between bank erosion and the following factors indicate the complexity of erosion processes: current velocity; channel orientation to the wind; ice content of the bank sediment; vegetation; roots; water temperature; and ice during break-up. Prediction of bank erosion cannot be made by measuring these factors. There are five different easily-distinguished bank shapes in the study area each with its own maximum and minumum erosion rates and manner of erosion. This information allows the short-term prediction of eroding bank behavior on the basis of bank shapes and the production of a map showing the erosion rate category into which each bank fits. This map may be used in the planning of construction in the area to avoid rapidly eroding banks such as those that may erode up to 30 m/yr.

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CHAPTER 1

INTRODUCTION

1.1 THE PROBLEM

Bank erosion processes in deltas that have permafrost-bonded banks are not fully understood. Literature concerned with erosion in such an environment is generally descriptive; only a few authors (Gill, 1972b, Smith, 1973) have attempted to quantify specific processes. The Mackenzie River Delta is a site of increasing human activity involving the construction of buildings, wharves, and petroleum storage tanks on various levee banks in the delta. In order to avoid poor choices for sites of such facilities, "specific information about the behavior[1] of all types of banks in the delta is required". This study provides specific information about bank erosion in the Mackenzie Delta so that this behavior can be predicted. Stable or prograding banks were not studied.

The word "erosion" as used in this study implies removal of material from a bank site.

1.2 ALTERNATE APPROACHES TO THE STUDY

During the early part of this study, 3 approaches were considered as methods of solving the problem of predicting

[1]Behavior may include: rates, shapes, and locations of deposition or erosion; and whether these processes are constant or catastrophic

bank erosion behavior:

1. Erosion rates can be predicted by comparing bank positions on air photographs of different years. This approach was rejected because average discharge in any delta distributary may vary with time (Kolb and Van Lopik, 1966). The distribution of flow among distributaries becomes more variable with increasing distance from the delta apex. Erosion rates in the last few years of a 20 year period may be different from the rate averaged over the 20 years as a whole. However, where erosion and deposition are found to be constant over a period of years, the channel may be considered to resemble a channel in dynamic equilibrium. A channel which maintains a constant plan shape or width over many years usually indicates that it is in equilibrium or "regime" (Blench, 1966). An extrapolation of erosion rates determined from different-aged air photographs of these channels can be made with more assurance than from channels which do not have ground-checked erosion rates similar to long-term average rates or from those which are changing in width or shape.

2. Erosion rates can be predicted by considering the ages of successional vegetation on advancing point bars and slip-off slopes across the channel from a retreating cut-bank. This approach was rejected as it assumes incorrectly that all channels are in dynamic equilibrium with deposition balancing erosion. Also, it will not apply where hydraulic geometry is being altered by the deposition of a mid-channel

bar or where erosion is being locally accelerated by the exposure of very ice-rich sediment.

3. Eroding bank behavior in terms of rate and character of erosion (catastrophic vs continuous), can be predicted knowing the process of erosion and the bank shapes that result from this process.

1.3 THE APPROACH USED IN THIS STUDY

The third approach was considered to be the most practical for testing in this field study. Observations and measurements were obtained at bank sites in an area of the delta south of 68° N (Figure 1) by the methods outlined in Chapter 3. The data gathered are described in Chapter 4. Bank sites were established in late August 1972 and then studied from June 7 to August 29, 1973. Measurements were limited to eroding channel banks and factors considered relevant to bank erosion. These factors are current velocity, potential for wave erosion, and bank material characteristics. Other minor factors and the effects of erosion on bank appearance were noted.

1.4 ASSUMPTIONS

Use of the third approach involves 3 major assumptions:

1. Long-term (annual) erosion vs 2-week summer erosion of delta banks is a consequence of channel shift either with erosion balanced by deposition or with slow changes in hydraulic geometry to accommodate changes in water, bed, or

bank characteristics. Basically, this assumption implies that the principles of hydraulic geometry as found by Anderson and MacKay (1973) apply reasonably well to the study area.

2. Short-term (week to week) behavior of eroding banks is not a result of changes in the basic hydraulic geometry of channels. This assumption implies that summer flows relative to high flows during and after break-up[2] are not responsible for major alterations of channel geometry. Most alluvial channels of the world are altered only during bank-full or high-water periods (Leopold et al., 1964). This leaves minor variations in bank shape or erosion rate being caused by factors such as thermal erosion, wave action, permafrost characteristics, or root bonding.

3. The 1972 and 1973 years of discharge were close to "normal"[3]. This assumption is necessary for the reliable prediction of erosion rates using the 1972-1973 annual rate but is not necessary for the prediction of bank behavior or a description of the manner of erosion as current velocities at bank sites were measured relative to each other. For example, a certain type of bank with a certain current velocity is expected to always erode in the same manner.

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[2]Break-up is defined as the time when a channel contains moving or broken ice. Termination of break-up is when a channel does not have bank-to-bank ice and the flood peak has passed.

[3]Quantity and pattern of flow (including peak flows) close to long-term averages.

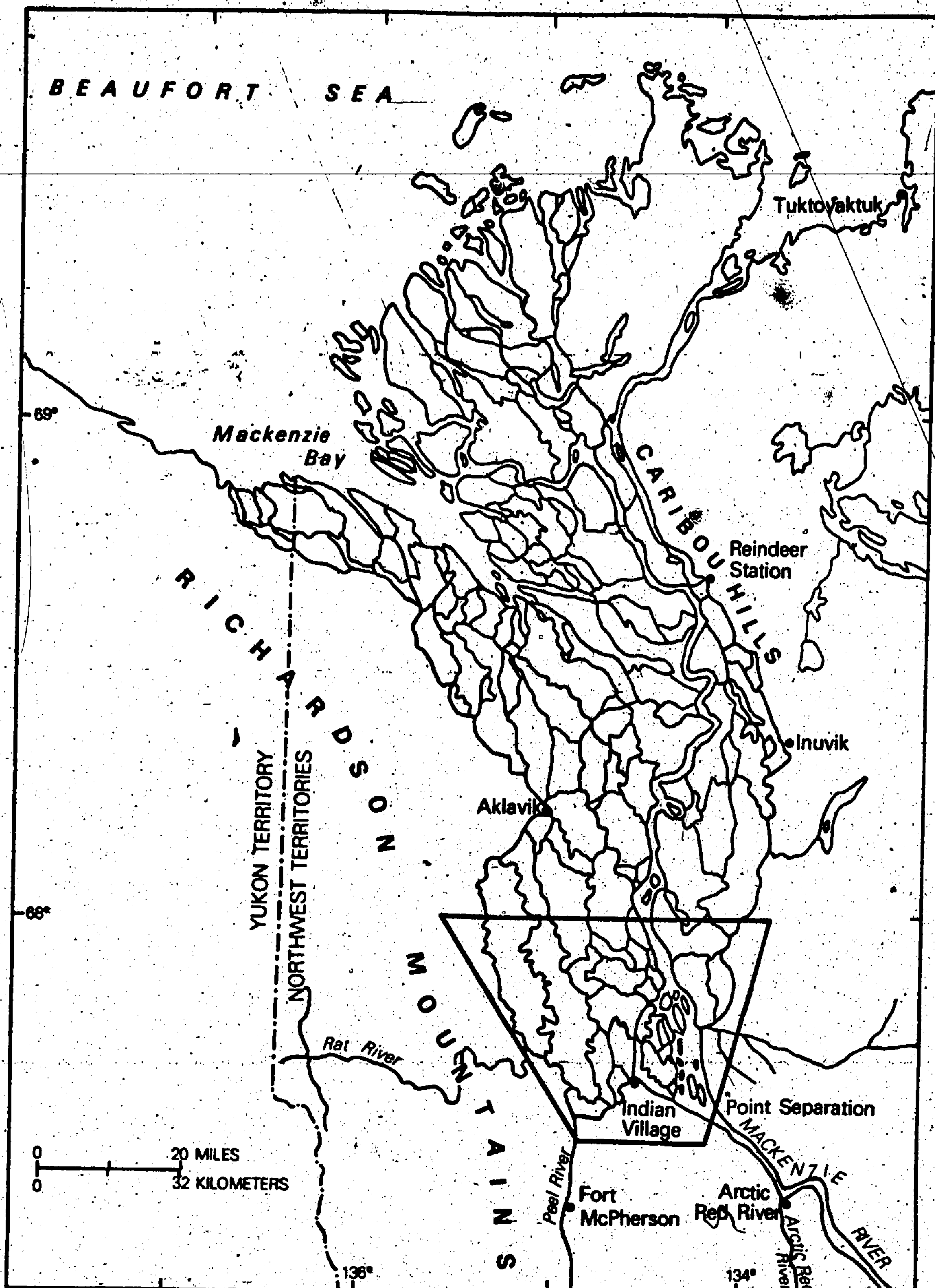

Figure 1 The Mackenzie Delta, N.W.T.. Outlined Location is the Study Area in Which Erosion was Observed and Measured

A major problem is the determination of a "normal" annual flow for the Mackenzie and Peel Rivers. Stage-discharge stations have been established only very recently on the Arctic Red River and on the Mackenzie River above its confluence with the Arctic Red River. Discharge measurements of the Peel River above Ft. McPherson are recent and sporadic with the record of break-up discharges missing. One can only judge "normalcy" by experience with the rivers. Natives of the area and H.L. Wood of the Water Survey of Canada in Inuvik agreed that the Mackenzie River water levels were close to "normal" in 1973 and that the Peel River water levels were above normal. This is the prime reason why erosion rates for different bank types were given such broad ranges in this study to allow for the fact that there are variations in flow into the delta from one year to the next that have not been accurately measured.

CHAPTER 2

THE STUDY AREA

2.1 THE MACKENZIE DELTA

The physical geography of the Mackenzie Delta area has been well described by Mackay (1963). The following sections review the aspects important to a study of erosion in the delta.

2.1.1 GEOLOGY

The Mackenzie Delta occupies a former estuary between the Richardson Mountains to the west and the Caribou Hills to the east (Figure 1). It has been estimated that the modern delta has been aggrading at 5 mm/yr for the past 7,000 years (Johnston and Brown, 1965) due to land submergence. The same investigators reached bedrock at 85 m in bore-holes near Inuvik. The Pleistocene Mackenzie Delta has undergone emergence and is no longer part of the active present-day delta. Tectonic movements will have a long-term effect on erosion as submergence would decrease it and emergence would increase it. Johnston and Brown (1965) describe the top 30 m of the sediment as "thinly stratified sandy silt, with layers of decomposed organic material throughout". This statement is only partly correct, as much undecomposed material such as roots and driftwood is present, due to becoming permanently frozen before it can be decomposed.

The delta has an area of approximately 6,500 km^2 representing an accumulation of sediment from the mountainous basins of the western tributaries of the Mackenzie River such as the Liard, Mountain, Keele, Arctic Red, and Peel Rivers.

2.1.2 HYDROLOGY AND CLIMATE

Much of the Mackenzie River basin of 1,801,600 km^2 is within the subarctic climatic zone. This climate results in low winter flows, a very high spring flow, and a moderate summer flow. As an indication of these flows, the Mackenzie River at Norman Wells may have a late winter flow of 2800 m^3/sec, a spring peak of 19,500 m^3/sec (late May or early June), and the summer flow may exceed 14,000 m^3/sec in June and July (Anderson and MacKay, 1973).

Break-up of the Mackenzie River occurs over a 2 week period as described by MacKay (1965). It progresses downstream from the warmer regions of the southwest, finally reaching the delta in late May. Break-up is accomplished by a [illegible] rise in water level (often aided by ice jams) which [illegible] flushes the ice from the delta and floods most of its s[illegible]rial portions. Bank-full stage and the annual flood[illegible] in the delta, therefore, occur during break-up.

[illegible] usually takes place early in October (Mackay, 1963) when distributaries freeze over and the ice stops moving. Many smaller channels and lakes may freeze to the bottom during winter.

A study of the distribution of delta flow has been started by Anderson and MacKay (1973) with preliminary results indicating that flow is greatly altered by the formation and development of an ice cover which varies with many different factors in addition to climate. The extent to which these alterations affect spring and summer flow distributions is not yet known. Hydrologic and geomorphic studies in the delta would be significantly aided by a complete record of discharges into the delta from both the Mackenzie and Peel Rivers.

2.1.3 PERMAFROST

The climate of the region surrounding the Mackenzie Delta is one with mean annual temperatures significantly below 0° C and can be classed as arctic (warmest month less than 10° C). This results in permafrost thicknesses of up to 365 m in the adjacent tundra areas (Jessop, 1970). Gill (1973c) has shown that break-up ice flushing significantly reduces the delta albedo compared to the surrounding tundra. The air is also warmed by Western Arctic low-pressure systems causing a wedge of warm air to extend down the Mackenzie Valley from the south (Abrahamsson, 1966). The resulting subarctic climate in the southern and central parts of the delta, together with the influence of large numbers of water bodies, causes permafrost to be discontinuous (Gill 1973d; Smith, 1973) and generally less than 100 m thick (Johnston and Brown, 1964). No permafrost is found beneath larger distributaries, many of the lakes, or recent slip-off slopes and point-bar deposits (Brown, 1956; Gill, 1973d; Smith, 1973). Permafrost is found in levee sediments and older point-bar deposits.

Smith (1973) has described in detail the permafrost distribution factors in the delta. As all erosion sites occur at places where permafrost is present, Smith's description of permafrost degradation is of interest although he neglects latent heat effects and does not give a maximum possible rate of thaw penetration. More geographical research is needed on the relation between thaw penetration and bank erosion as ice in permafrost is a sediment cementing agent and consequently the maximum rate of thaw is a limiting factor for erosion.

2.1.4 GEOMORPHIC CHARACTERISTICS

Without the presence of permafrost causing detailed differences, the Mackenzie Delta would have geomorphic characteristics similar to other active deltas in the world. There are many thermokarst lakes in the delta, locations of ice wedge formation, and places where ice-lensing has raised parts of the delta above flood levels. Wind erosion of point-bar deposits occurs in the delta during winter (Gill, 1972a) as it does in many other periglacial environments. The presence of permafrost alters the appearance of eroding banks from what would be expected for such banks in a warmer climate. The thermo-erosional niche (hereafter referred to as niche), for example, is a significant feature and will be discussed along with other factors in Chapter 4.

The Mackenzie Delta has general features common to most deltas including levees, convex banks with point-bars and slip-off slopes, concave banks undergoing erosion, inter-levee basins containing lakes, a complex pattern of shifting distributaries, reversing channels, and low islands. The subaerial landforms are built by irregular sediment deposition during spring floods under the processes of alluviation common to other world deltas.

2.1.5 VEGETATION

Plant ecology of the delta is described by Gill (1971; 1972a; 1973a,b,c,d,e). Vegetation has a distribution closely tied to the fluvial environments and the irregular deposition of alluvium mentioned above. Sites of active deposition are dominated by equisetum (*Equisetum fluviatile* and *E. arvense*) and felt-leaf willow (*Salix alexensis*). Less active depositional locations are colonized by balsam poplar (*Populus balsamifera*), alder (*Alnus crispa*), willow (*Salix* spp.), and a variety of forbs and mosses. High seldom-flooded sites (usually the upper portions of levees) with lower deposition rates are occupied by an edaphic climax association dominated by white spruce (*Picea glauca*).

Since most erosion takes place below the rooting level of living plants, vegetation has little direct effect on erosion. However, vegetation affects the character of the permafrost beneath it. This is expressed by Smith (1973, p.143): "Vegetation cover affects the ground thermal regime through controls exercised on the surface energy balance." As new layers of alluvium are added to the soil surface, the permafrost surface rises, freezing another lower layer of sediment. Material freezing beneath the cold and humid microclimate of a spruce forest is more likely to have a higher ice content than material frozen under the influence of the comparatively warmer and drier microclimate of the balsam poplar association. The presence of ice-rich sediment has an effect on the behavior of eroding banks as shown in Chapter 4.

2.1.6 HUMAN ACTIVITY

The human activity in the Mackenzie Delta most relevant to bank erosion involves boat traffic. Wave action may be an important erosion agent. Many of the delta channels are used by boats of various sizes ranging from small canoes to pusher-tugs up to 4500 hp with their loaded barges. Channels with heavy boat traffic are expected to be eroded more due to man-made wave action. This effect is less significant on large channels eroded by much natural wave action but is highly significant on smaller channels. Boat waves may be adding to the erosion rate of 2 m a year (Mackay, 1963) of the bank of Husky Channel at the town of Aklavik. The erosion hazard along the channel bordering Aklavik is one of the reasons why the Government of Canada decided in 1953 to move the town.

2.2 CHOICE OF THE STUDY AREA

The study area in the delta south of 68° N was chosen for several reasons:

1. The apex of the delta is the site of highest fluvial energy and therefore the site of highest banks and highest erosion rates. The higher the rate and the larger the scale of erosion at a bank studied, the more accurate the measurement of its behavior for the methods used in this study.
2. Based upon extensive field reconnaissance during 1971 and 1972, I found that the area has all varieties of eroding bank types on all sizes of channels at many different orientations to the prevailing wind.
3. Most of the channels in the area are deep enough to be navigated by a boat with an outboard motor. A hovercraft or airboat would be required in the northern or "outer" delta because of shallow water.
4. The study area is sufficiently accessible from Inuvik to aid field logistics.
5. No previous studies of erosion had been done in the study area.

Most eroding banks in the study area are found on levees and islands which on August 16, 1973, averaged 8 m above summer low water level. The area has all the deposition and vegetation features discussed earlier. There are small reversing channels and one large one, the section of Peel Channel above and below Indian Village (Figure 2). Many large ice wedges (Plate 1) and frequent occurrences of ice-rich sediment (Plate 2) are found in exposed sections of levees indicating relative stability in the past of many levees and their white spruce plant association.

2.3 CHOICE AND DESCRIPTION OF THE BANK SITES

Banks that are not significantly eroding annually are: prograding point-bars which may be temporarily eroded by strandline erosion* (Plate 3); stable banks of small channels covered with vegetation (Plate 4); and relatively stable banks eroding at such a slow rate that vegetation is able to grow on them (Plate 5). Eroding banks were classified into the 5 major families of shapes discussed in section 4.1. In August, 1972, a total of 20 sites were selected with at least 3 representing each category of bank shape. Sites were chosen from channels of different sizes and compass orientations. Locations are shown in Figure 2. Five sites were not measured during 1973 as 15 were found to be the most that could be handled by myself and one assistant. Details of the locations and appearances of the remaining 15 sites assigned letters in Figure 2 are

*A term used by Gill (1972b) to describe minor erosion by wave action, creating step-like forms on a bank, each step corresponding to a water level (see section 4.2.6).

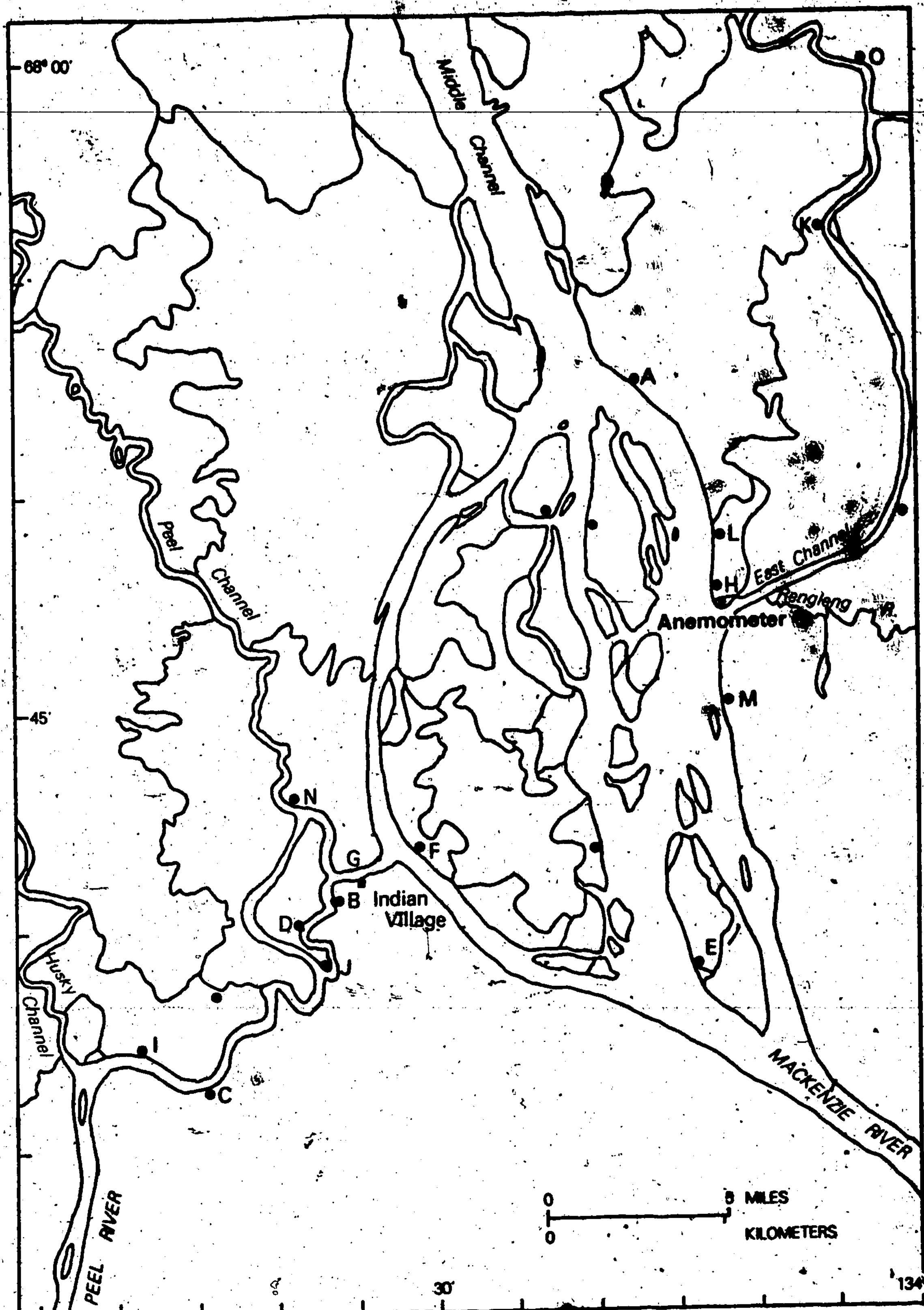

Figure 2 Bank Sites Established for the Observation and Measurement of the Erosion in the Study Area. Lettered Sites are Described in Section 2.3

Plate 1 An ice wedge in a bank with ice-rich sediment. Alluvium layers have been upturned by its formation.

Plate 2 Taking a sample from a bank with ice-rich sediment. Note the wet appearance of the thawing sediment and ice layers.

described as follows.

Site A (67° 53' N 134° 18' W)

Site A was located along a reach orientated in a NW direction. The bank was overhanging and had a deep niche. Ice layers were visible in the thawing bank face and current velocity was fairly high. The site was occupied by a mature white spruce forest and represented the erosion of a former stable levee location. Large stumps with well-developed adventitious rootings[5] were seen in the bank material.

Site B (67° 41' N 134° 37' W)

At site B, erosion of a previous point-bar deposit was occurring. Current velocity was very high as shown by large boils and eddies. The bank was overhanging and had a shallow niche. No ice layers were visible in the bank face. The reach of the Peel River at this site has reversing flow during break-up.

Site C (67° 37' N 134° 43' W)

This site appeared to be representative of the concave bank at this bend of the Peel River. Similar to site A, it was an eroding levee. However, this channel reach did not have an orientation favourable (see section 4.2.2) to the

[5]White spruce can send out lateral roots into new additions of alluvium enabling it to survive the associated upward movement of the permafrost surface occurring in such environments.

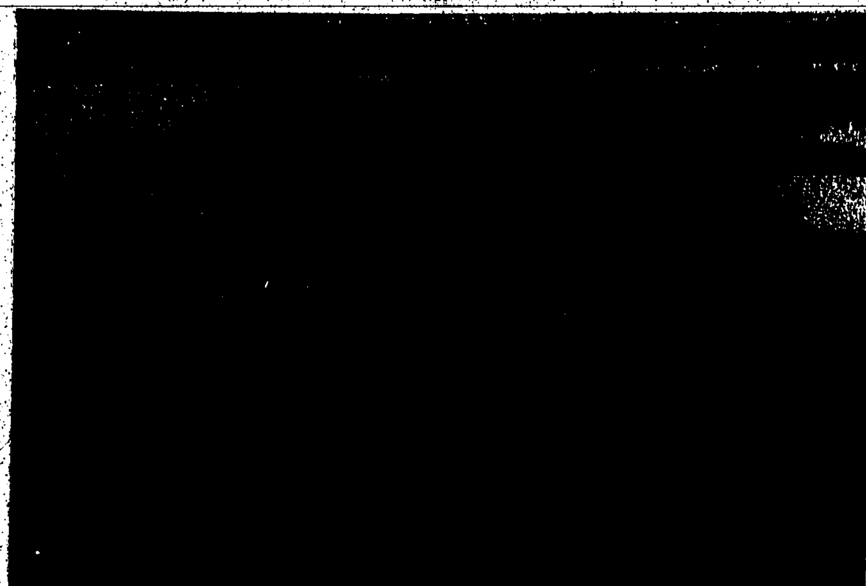

Plate 3 A point-bar near Reindeer Station eroded by strandline erosion (by permission, Don Gill).

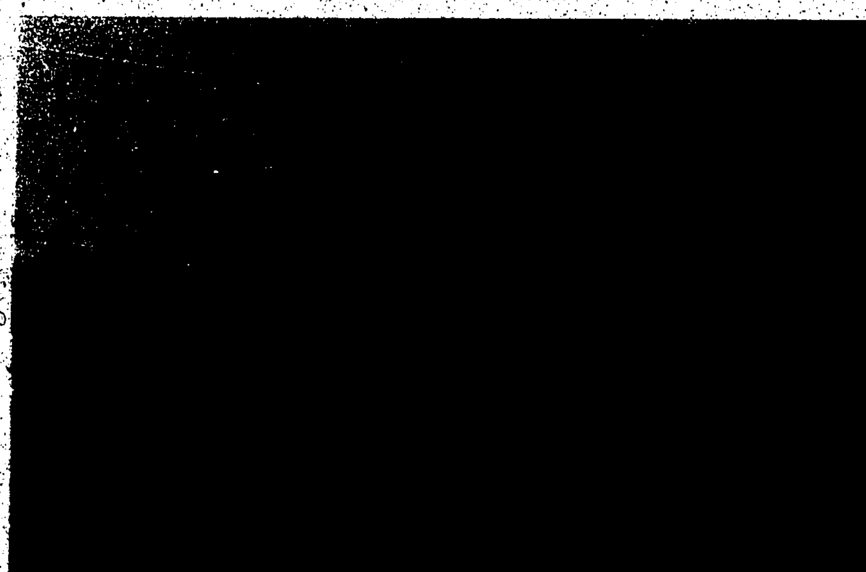

Plate 4 A stable bank of a small channel.

Plate 5 A relatively stable bank of the Peel Channel.

prevailing wind direction. Ice layers were visible in the bank face.

Site D (67^{o} 40' N 134^{o} 34' W)

Site D was situated on a concave bank of the reversing part of the Peel River. The appearance of the bank was similar to that of site C.

Site E (67^{o} 39' N 134^{o} 14' W)

Site E was typical of an eroding island with a willow-alder plant association, low ice-content sediment, and very little vegetation mat overhang. Current was fairly strong and the orientation of the channel reach was NW.

Site F (67^{o} 42' N 134^{o} 32' W)

This site was very similar to E. Although site F was on a convex bank, it was being eroded by the current coming out of the channel running past Indian Village. Orientation to wind was similar to E but fetch in a NNW direction was less.

Site G (67^{o} 42' N 134^{o} 37' W)

Site G was on a convex bank being eroded by current coming from the Peel River to the south and entering the Peel Channel to the north. This bank was much lower than the others (4m instead of 8m) and was an eroding slip-off slope.

Site H (67° 48' N 134° 12' W)

Site H was on a short concave levee bank of the Middle Channel just downstream from the entrance of a very small channel at a clearing for navigational markers. There were no trees at this site although balsam poplar was present before the clearing was done.

Site I (67° 37' N 134° 48' W)

Similar to site C, this site was on a concave bank of the Peel River.

Site J (67° 39' N 134° 37' W)

Although located at a convex bank, site J was a short section of concave levee being eroded by current coming from the Peel River entering the branch that flows toward Indian Village.

Site K (67° 56' N 134° 6' W)

Site K was on a concave levee of the East Channel and was chosen as a representative erosion site for this size of channel.

Site L (67° 48' N 134° 12' W)

Site L was selected as representative of the many locations along the concave series of eroding levees of the Middle Channel that have beaches. A NNW orientation and many kilometers of open-water fetch make natural wave erosion a significant factor along this reach of the Middle Channel.

Site M (67^{o} 45' N 134^{o} 12' W)

Site M was very similar to L except for a larger beach and a few pebbles on it carried by ice from banks upstream of Point Separation. There was no measurable current velocity at sites L and M when they were chosen. All other sites had measurable current within 2 m from the bank.

Site N (67^{o} 43' N 134^{o} 34' W)

This site was chosen as being representative of eroding levees along channels the size of the Peel Channel. It was on a concave bank, some parts of which had vegetation growing on its slopes.

Site O (67^{o} 49' N 134^{o} 3' W)

Site O was very similar to site N, being on a channel of roughly the same size at the same orientation, although the bank material was more bonded by roots and driftwood.

As a summary, the following groups of bank sites had common characteristics:

1. A,B,C,D.
2. E,F,G.
3. H,I,J,K.

4. L,M.

5. N,O.

CHAPTER 3

RESEARCH METHODS

3.1 MEASUREMENT OF EROSION

3.1.1 AIR PHOTOGRAPHS

In August, 1973, a helicopter was used to determine the location at that time of an eroding bank with reference to landmarks such as large trees or the shoreline of a lake. These locations were marked on the largest scale of photographs available for the particular area. Later, I compared these with relevant locations found on air photographs of the area for the years 1950, 1962, 1965, 1971, and 1972. Using a scale rule, the distance and constancy of bank retreat over a 23 year period could be measured.

3.1.2 IN THE FIELD

Horizontal control points were established in late August of 1972 at the sites described in section 2.3. These points were either trees marked with survey tape or stakes driven into the ground. Vertical movement of the trees or stakes through frost-heave would not affect the accuracy of horizontal measurements. A metal tape was used to measure from the control point to the end of a portable scale marker affixed to the edge of the bank by means of a pipe driven into the ground. An example of such an installation is shown diagrammatically in Figure 3.

Stereo photographs such as the pair illustrated in Plate 6 were taken of the bank and scale markers. From them I was able to obtain the distance of the bank face to the horizontal control point; the height of the bank above water level; the shape of the bank; and the extent to which roots and driftwood were incorporated in the sediment. The purpose of stereo photography was to ensure that measurements were taken as close as possible to the scale markers, as scale in photographs varies with perspective. These photographs were taken at each site once in August 1972 and every 2 weeks in 1973 from the termination of break-up to the end of August. The difference between the 2 August measurements was regarded as 1 year of erosion and the difference between 2 bi-weekly measurements was taken as being 2 weeks of erosion. The vertical bank face was used as the area of erosion for each bank if sloughed material was being removed by current or wave action. Some banks had slough material removed for only a limited time during the year. For these banks, the erosion face of the slough slope was used for measurement.

The time period of 2 weeks was chosen as a result of preliminary observations in 1972 which indicated that no measurable changes occurred over a 1 week period at any except the fastest-eroding banks.

3.2 MEASUREMENT OF THE EROSION FACTORS

3.2.1 CURRENT VELOCITY

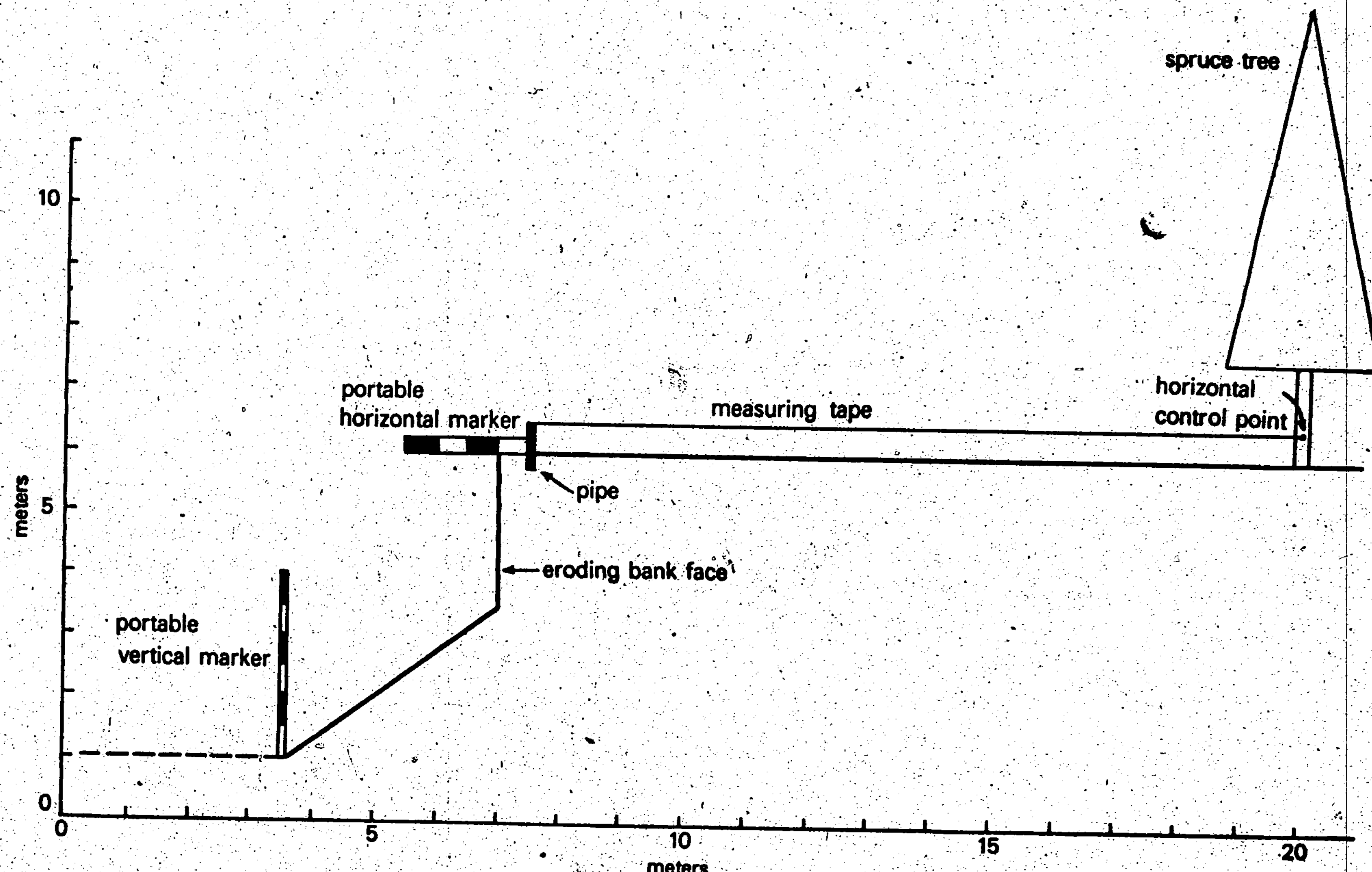

Figure 3 Typical Bank Measurements and Scale Marker Placement Prior to the Taking of Stereo Photographs

Current velocity differences at bank locations were measured with a current meter (OTT propeller type) at a distance of 5 m from the bank and 1 m below the water surface. Water depths at this location were always 2m or more. For shallow flows this method of current measurement is not suitable due to the reduction of velocity near the bed of the channel. The distance and depth used was necessary to reduce the turbulence effects of fallen trees and submerged stumps. Appearance of the water surface was noted at the same time. Current velocity was measured every 2 weeks at each bank site where there was a measurable current.

3.2.2 WIND

Wind direction and speed was measured by a continuously-recording anemometer (Lambrecht mechanical wind recorder, Woelfle type) at the site indicated in Figure 2. This location was bare of vegetation and far from any large obstructions. The anemometer was put in position at the termination of break-up and removed the last week of August, 1973.

3.2.3 WATER DEPTH

Water depth close to each bank site was measured either with a long pole or a recording electronic echo sounder (Raytheon Fathometer). This method was used to obtain information on the underwater slope at each bank. Soundings

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Plate 6 (In the pocket) A stereo pair taken at site G from which bank retreat was measured (see Figure 3). All scale markers have 0.5 m divisions.

were not taken near large overhanging banks or beneath niches because of the danger to life and equipment. Current is usually quite strong at such locations and blocks of several tons may fall unexpectedly.

3.2.4 SEDIMENT CHARACTERISTICS

Samples were taken from each bank and tested in the laboratory for field moisture content, liquid limit, and size.

Integrated sampling of the bank face was attempted but was found to be impractical because of the 8 m height of many bank faces and the fact that ice was present in the sediment in irregular layers. Where no segregated ice layers were present, samples for moisture content and liquid limit were taken from at least 3 representative locations on a bank face. At sites where ice layers were found, a sample was taken from an ice-rich layer and from an adjacent layer. In all cases, samples were taken from frozen bank faces as thawing may cause water to move to other locations in the bank toward or away from the sample location. Material was chiseled from the bank face with a shovel or axe, put into "Zip-Lock" plastic bags, and sealed. All samples were shipped by air to Edmonton Alberta as there was a lack of time and equipment for analysis in the field.

In the laboratory, all sealed bags were weighed, opened, and then weighed after being open for 1 week. After removal from the bag, each sample was oven dried and weighed again. In this way, moisture content as a percentage by weight was obtained. As all samples were taken when frozen, these weights can be considered to be the percentage by weight of ice in the soil assuming unfrozen water content to be minimal.

Liquid limit, the arbitrary point at which a fine-grained soil becomes a liquid, was determined using the American Society for Testing and Materials procedure D423-54. The particle sizes in the samples did not allow the test to be run on all samples such as those with high sand contents.

Particle size distribution of the samples was obtained by sieve and hydrometer methods (ASTM D422-60T). Fifteen samples were analyzed to obtain upper and lower limits for particle sizes in the samples. Sediment size will have an effect on the cohesion and moisture content of thawed sediments.

Depths to frozen material were not measured at every site due to the many variations in depth and lack of time to take an adequate number of measurements. A pit such as the one shown in Plate 24 was dug at representative locations to give an indication of a typical profile of the frozen material surface.

3.3 OBSERVATIONS OF BANK BEHAVIOR

Extensive notes were taken regarding the visible effects of the erosion process at each bank.

Sloughing occurs at many bank faces. Sloughing is the falling away of small blocks (several cm^3) from the vertical face of a bank. The size of these blocks, where they accumulated, and the type of surface left on the bank face were all noted.

Soil flow occurs at bank faces with ice-rich sediment. Thawing releases water from segregated ice layers which saturates surrounding thawed sediment layers causing them to become unstable. The movement, appearance, and location of these flows were noted.

Wave action tends to undercut a bank at the waterline and build up a beach with loosened material by swash and backwash. The extent and location of undercutting and beaches were noted along with the approximate heights of waves producing both features.

The thermo-erosional niche has been observed by many authors working in deltas with permafrost-bound banks. Depths and locations of these features were noted although penetration of the larger niches (more than 3 m) was only estimated due to the hazardous situation at such locations. Undermining and the weight of the overhanging block of soil increases the tension in the bank along a vertical line from the apex of the niche to the top of the bank. Eventually, the tension outbalances the tensile strength of the sediment, failure occurs, and the block falls into the channel. Notes were made on the size of the blocks, the size and location of tension cracks, and the nature of features that provide zones of weakness such as the sides of ice wedges.

CHAPTER 4

RESEARCH RESULTS

This chapter presents the data obtained by the methods outlined in Chapter 3. This is done by tables and graphs with explanations of each in appropriate sections. Where appropriate, subjective observations are illustrated with photographs.

4.1 BANK SHAPES

In section 2.3, 5 groups of bank sites were described, each with common characteristics. Figures 4 to 6 illustrate diagrammatically the "typical" shape for each group. Even though no bank appears exactly the same as in the diagram, each fits into one of the 5 categories. Banks appear most similar to the diagrams during the month of August. Plates 7 to 13 are of banks in each category. Note that the major characteristics such as slough accumulation slopes (hereafter referred to as "slough slopes"), faces, and niches appear the same as in the diagrams.

Bank shape categories are referred to as "shapes" in this study. Each shape may be described as follows: shape 1 has an overhang of bank material (excluding vegetation mat overhang); shape 2 has a vertical bank face for the entire height of the bank or has a slough slope extending less than halfway up the bank face; shape 3 has a slough slope extending more than halfway up the bank face; shape 4 is a shape 3 with a beach; shape 5 is a shape 3 with strandline

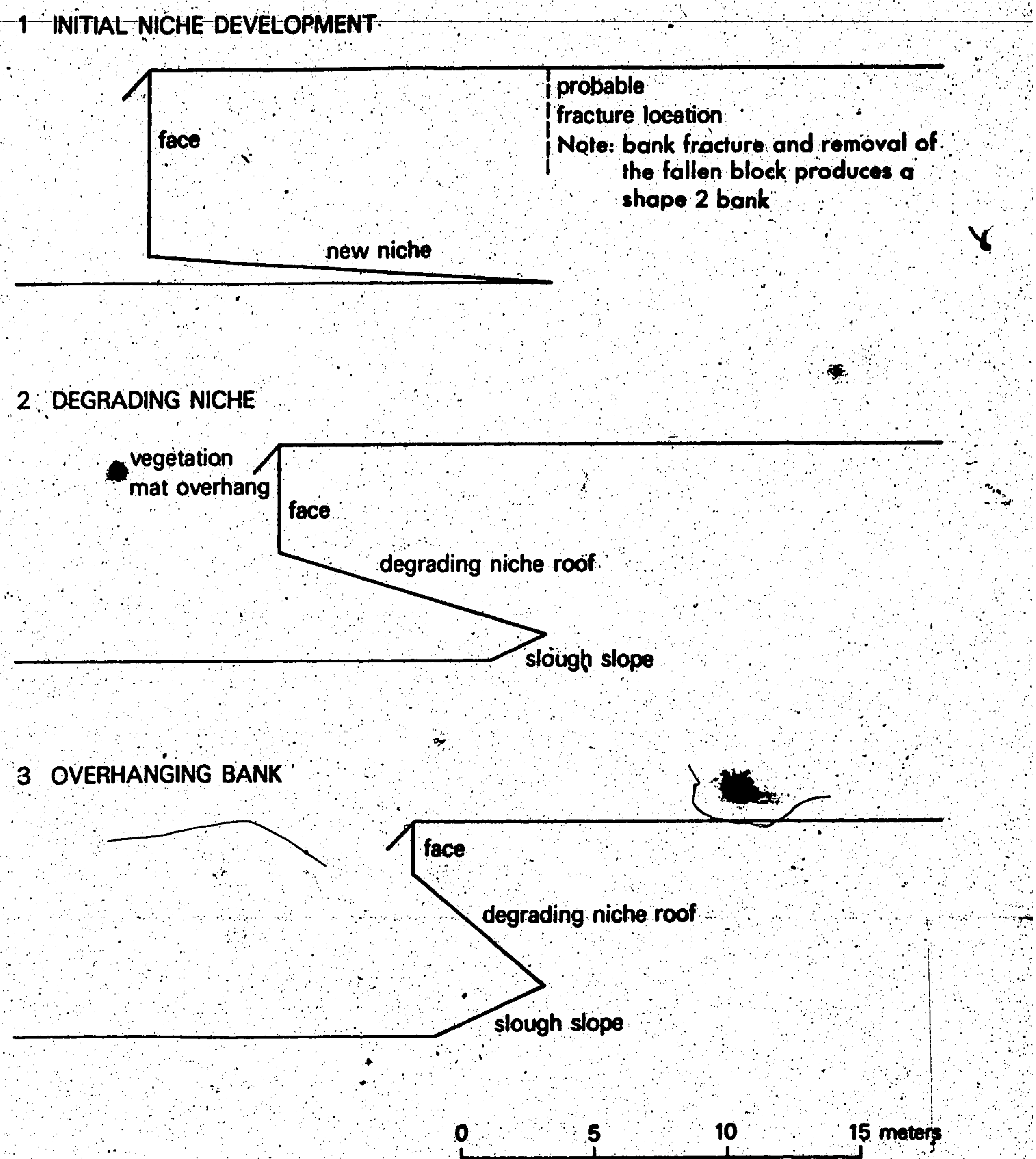

Figure 4 Diagrammatic Side Views of Bank Shape Category 1, in 3 Stages

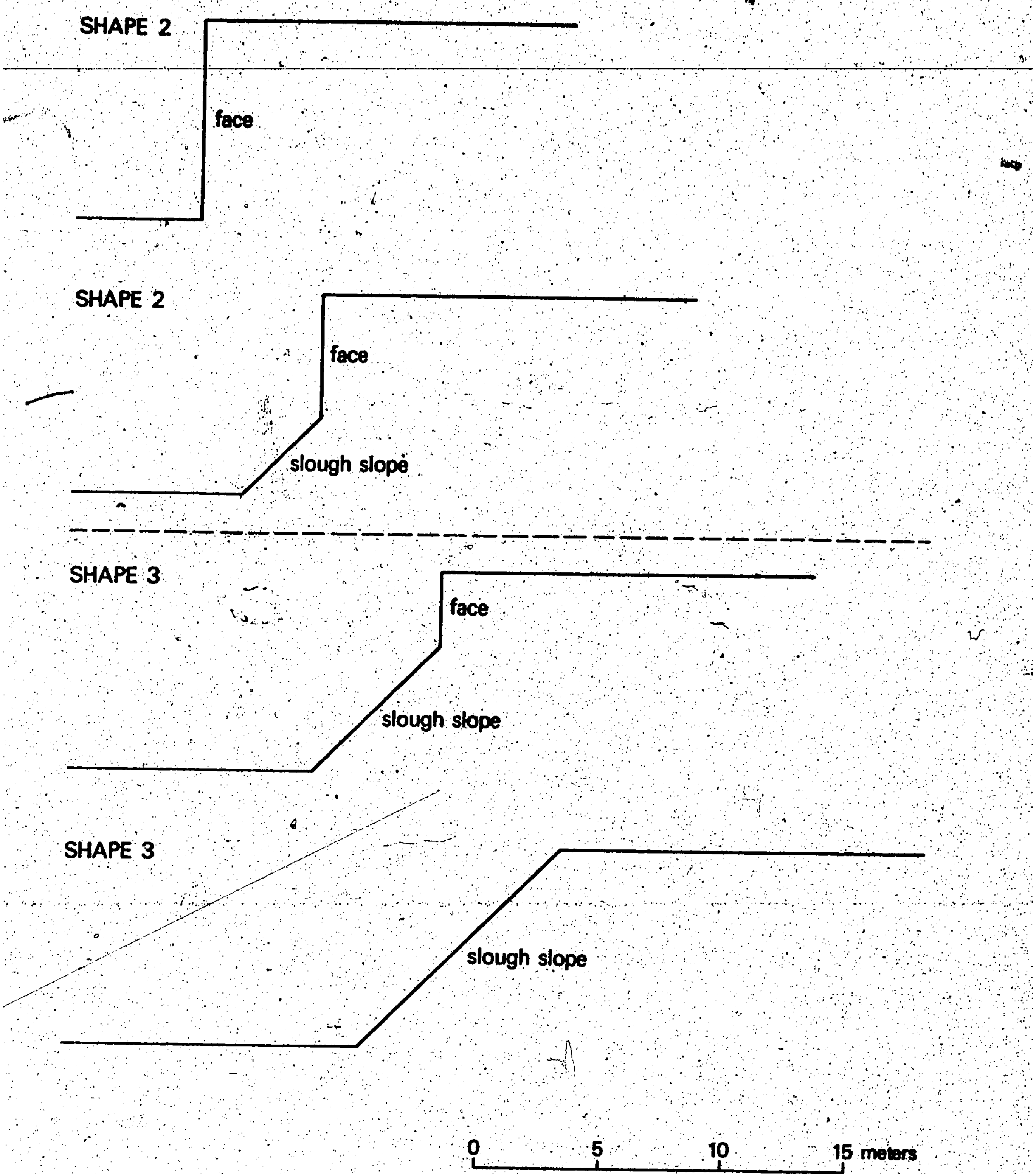

Figure 5 Diagrammatic Side Views of Bank Shape Categories 2 and 3

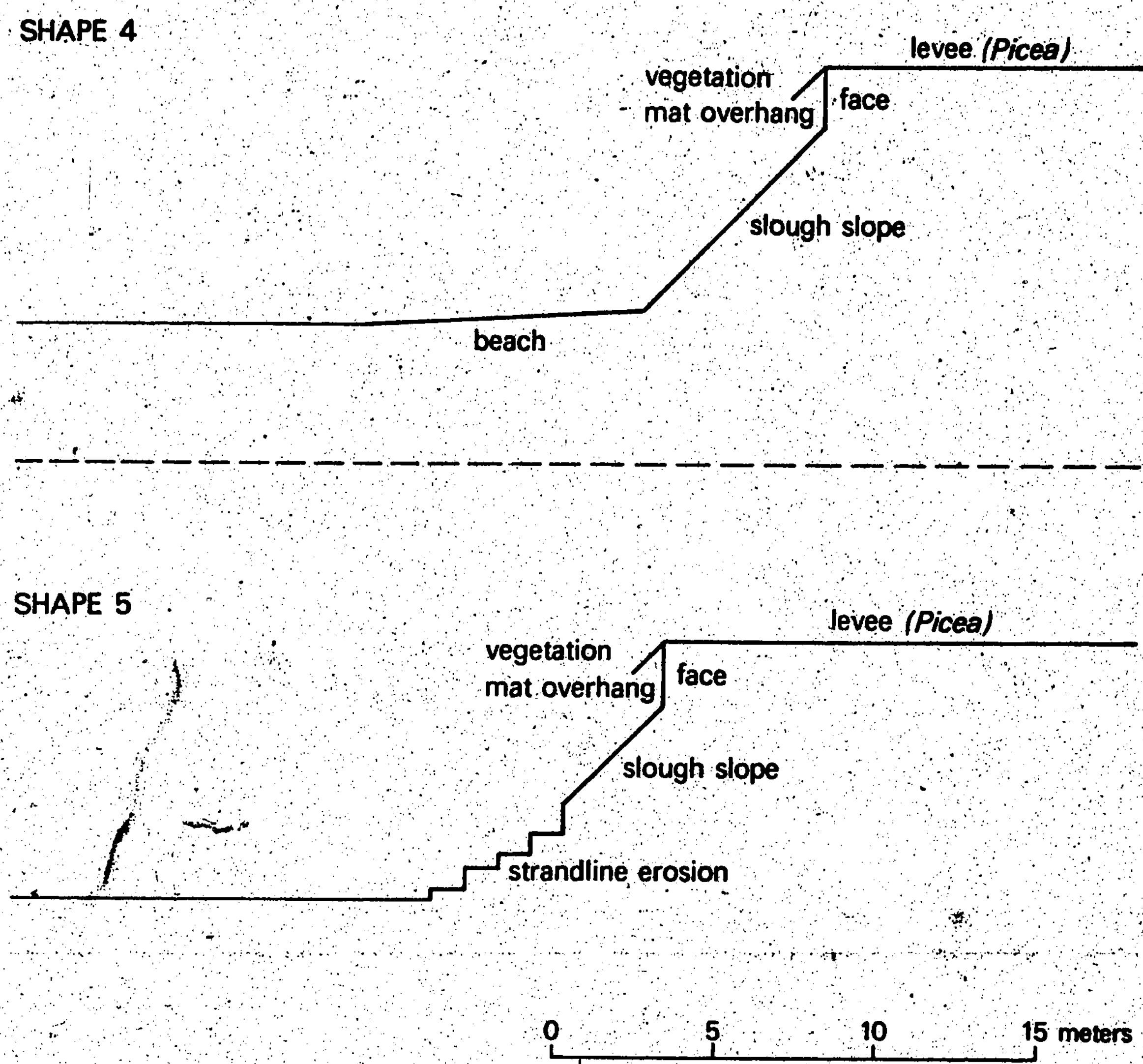

Figure 6 Diagrammatic Side Views of Bank Shape Categories 4 and 5

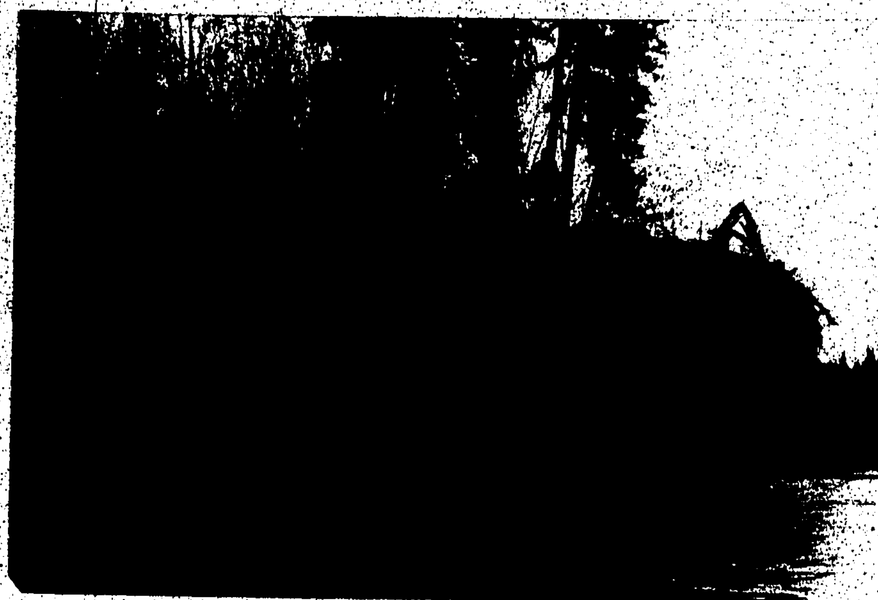

Plate 7 A bank with shape 1, at stage 1, within a few days of initial niche development (June 8, 1973).

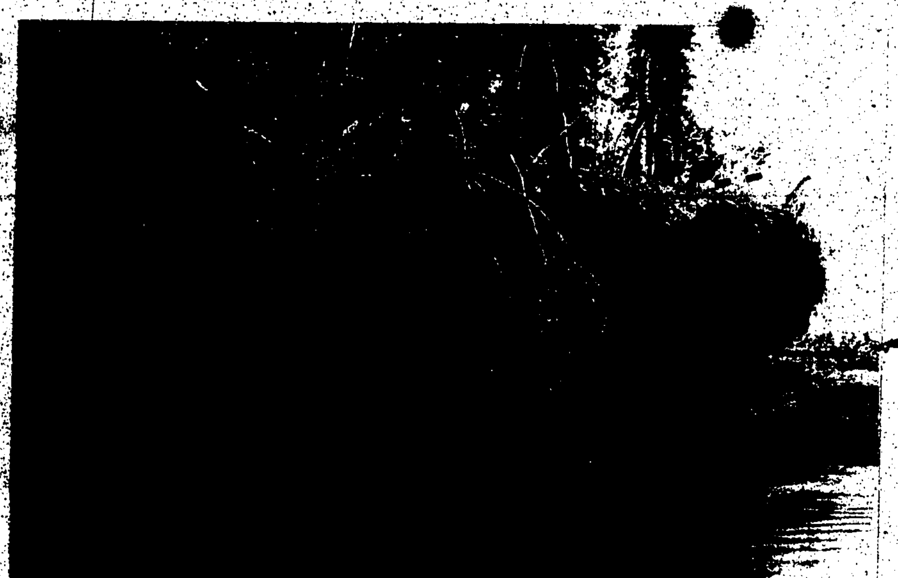

Plate 8 The same bank as in Plate 7, at stage 2, 13 days later. (June 21, 1973).

Plate 9 The same bank as in Plate 7, at stage 3, 40 days later (July 18, 1973).

Plate 10 A bank with shape 2 (site F).

Plate 13 A bank with shape 5 (site 0).

erosion steps below the slough slope. Shape 5 is the most common eroding bank shape in the Mackenzie Delta with over 50% of the eroding banks in the study area having this shape.

4.2 THE MAJOR EROSION FACTORS

4.2.1 CURRENT

Table 1 is abstracted from current velocity measurements for each site. Measurements taken between June 7 and 9, 1973, are used to represent current velocities at the termination of break-up. Some sites were not measured at this time. "Summer average" is the average of all measurements after June 7-9.

Variations in current velocity 5 m from a bank vary with other factors in addition to channel discharge. These factors may be fallen blocks, beaches, or large trees obstructing water flow.

4.2.2 WIND

Figure 7 is a wind rose for the location marked in Figure 2 from June 7 to August 25, 1973. The prevailing winds are from the N and NW although the strongest winds come from the SW.

Table 2 lists the length of open-water fetch in a NNW direction from each bank site. Wind blowing upstream and over an open-water fetch of 1 km or more produces much larger waves than the same wind velocity blowing downstream

Table 1 CURRENT VELOCITY (cm/sec)

Site	Shape	Velocity at the Termination of Break-up June 7 - 9 1973	Average Summer Velocity	Highest Recorded Velocity	Date of Highest Recorded Velocity	Lowest Recorded Velocity	Date of Lowest Recorded Velocity
A	1	----	15.4	32.4	June 22	0	July 18
B	1	33.5	45.0	77.5	Aug. 21	16.2	June 21
C	1	35.7	41.0	46.5	June 22	30.5	July 6
D	1	49.5	46.3	61.0	Aug. 2	34.0	July 6
E	2	----	38.1	50.5	June 20	0	Aug. 2
F	2	----	33.5	34.5	June 21	32.3	July 5
G	2	24.4	0	24.4	June 8	0	All summer
H	3	46.5	15.3	46.5	June 9	0	July 18
I	3	36.0	39.0	56.5	Aug. 18	28.0	June 21
J	3	49.5	23.6	61.0	Aug. 2	0	July 6
K	3	----	12.2	15.3	July 7	6.1	July 31
L	4	0	0	0		0	All summer
M	4	0	0	0		0	All summer
N	5	24.4	21.4	26.9	July 7	15.0	Aug. 17
O	5	----	22.2	25.6	July 7	19.8	Aug. 17

---- no measurement taken
0 velocity too slow to measure

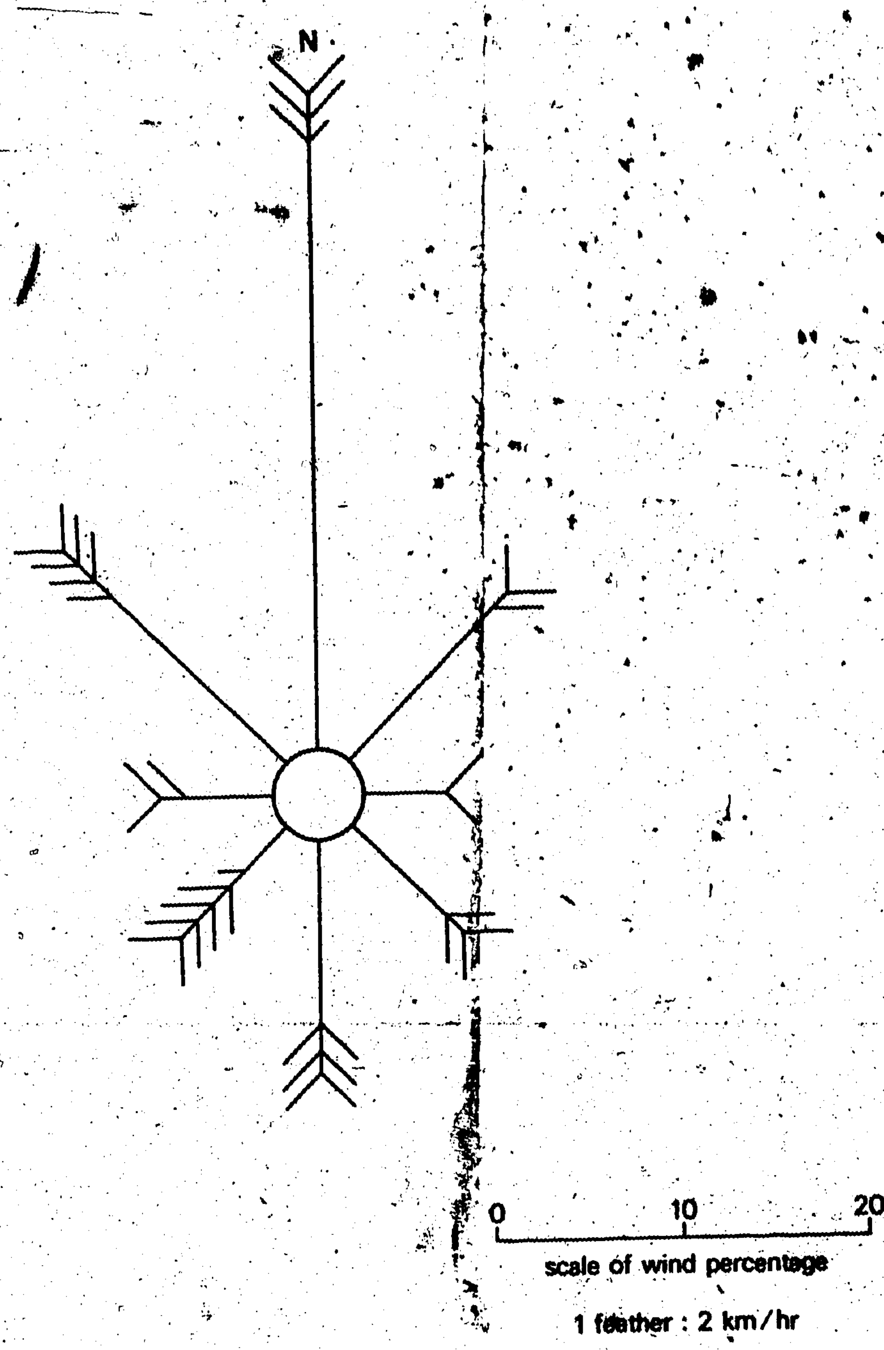

Figure 7 Wind Rose for the Anemometer Location Shown in Figure 2, June 7 to August 25, 1973

Table 2 OPEN-WATER FETCH IN A NNW DIRECTION (337.5°)
FROM EACH BANK SITE IN KILOMETERS
(Measured from NTS Maps: 106M/9; 106M/10; 106M/16)

Site	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
Fetch km	0	0.4	0.4	0	7.0	0	0	10.3	0	0	0	5.8	5.6	0	0
Channel Orientation	NW-SE	NW-SE	NE-SW	NW-SE	NW-SE	NW-SE	E-W	N-S	E-W	N-S	NE-SW	N-S	N-S	NW-SE	NW-SE

or over a short open-water fetch. Channels orientated in a N or NW direction display more evidence of wave erosion along their banks than channels orientated in other directions. Evidence of wave erosion is in the form of either beaches (section 4.4.4) or strandline erosion steps (section 4.4.5).

Williams (1952) concluded that banks along channels orientated favourably to the prevailing wind have accelerated erosion rates.

4.2.3 SEDIMENT CHARACTERISTICS

Table 3 lists average field moisture content and liquid limits for all samples taken from each site. The sites have been divided into two groups. The first group had ice-rich sediment as indicated by visible segregated ice layers in the eroding bank face. The second group did not have these layers. Bank sites of the first group exhibit soil flow down the thawing bank face. The second group exhibits sloughing of blocks less than 75 cm^3 in volume.

Figure 8 shows the upper and lower limits of particle size distribution in all samples taken from thawing bank faces. The D50 sizes are 0.05 mm (site M) and 0.09 mm (site J).

A bank material sample becomes darker in color with the addition of moisture. Oven dry, most samples are a very light tan color. In a liquid state, they are a very dark brown (10YR3/2 on the Munsell soil color chart). Frozen

Table 3 AVERAGE MOISTURE CONTENT AND LIQUID LIMIT FOR ALL SAMPLES TAKEN FROM EACH BANK SITE (%)

	Group 1: sites with segregated ice						Group 2: sites with no segregated ice								
Site	A	C	D	J	L	M	B	E	F	G	H	I	K	N	O
Moisture Content	53	60	73	38	43	54	33	30	35	28	29	42	26	40	26
Liquid Limit	27	39	37	26	31	38	27	23	25	26	28	35	25	40	27
Difference	26	21	36	12	12	16	6	7	10	2	1	7	1	0	-1

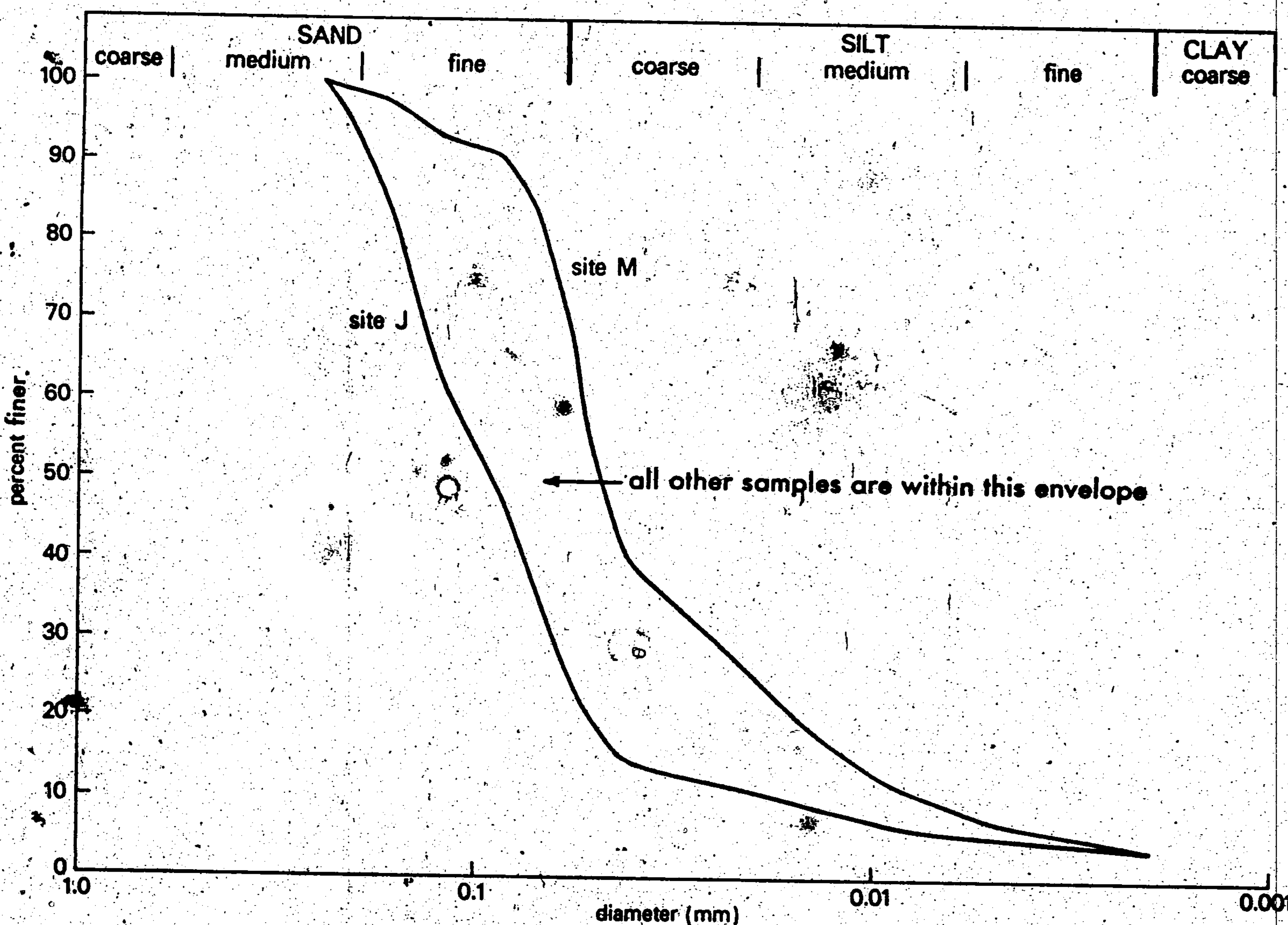

Figure 8 Particle Size Distribution Curves for the Largest and Smallest-sized Samples (M.I.T. Classification)

bank material in the process of thawing will have a dark brown color if it contains much ice. The distinctive color of banks with ice-rich sediment makes their identification very easy. Their dark color is in contrast to the light brown (10YR5/3) of low ice content material and the tan color (10YR6/3) of sloughed material. Even though moisture contents of bank faces varied from week to week, the color difference between low and high ice content material remained distinct.

4.3 THE MINOR EROSION FACTORS

4.3.1 ROOTS

Plate 14 illustrates the effect of bonding by roots in the bank material. The center of the niche roof has retreated less than the surrounding parts of the niche roof containing less roots.

4.3.2 WATER TEMPERATURE

Gill (1972b) found that water temperatures during break-up are close to freezing. This confirms my own temperature observations at Inuvik during the 1973 break-up. Temperatures were measured within 1m of the water surface but observations in previous years indicate that temperature is uniform throughout a channel due to mixing. Immediately after the final passage of ice, water temperatures rise very quickly (approximately 1°C/day) and then remain relatively high (13°C to 15°C) for the rest of

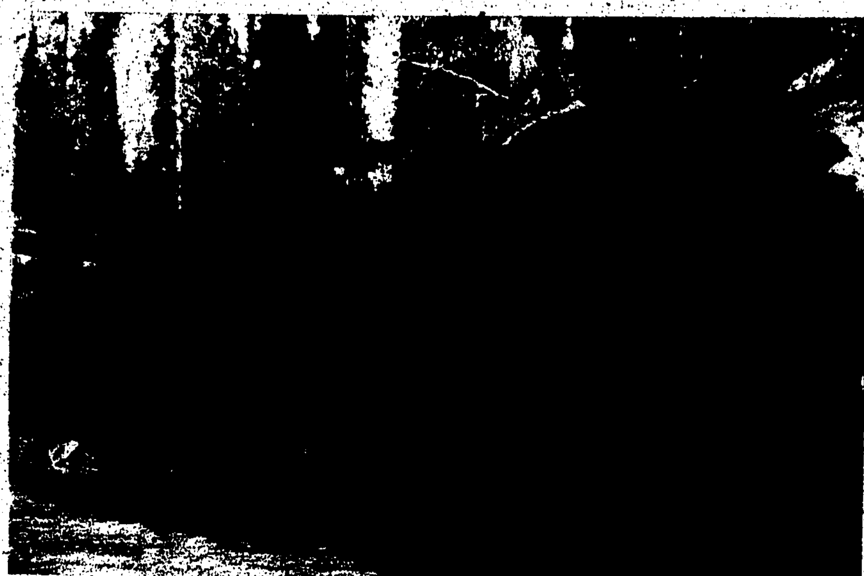

Plate 14 Roots retarding the perturbation of a niche roof (center of photo).

the summer. A high of 20°C was recorded on July 31, 1973 in the Middle Channel.

Frozen silt is more difficult to erode than unfrozen silt. Erosion is therefore expected to be less during break-up when water temperatures are low even though current velocities are high. A complicating factor is sediment density. A loose slough slope, even though it is frozen, will be eroded more easily than denser in-situ bank face material.

Figures 9 and 10 show that erosion of in-situ bank face material is greatest just after the termination of break-up when current velocities are high and water temperatures are rising rapidly above freezing. A location where a thermo-erosional niche normally develops on a bank of the East Channel near Inuvik was observed daily during and after break-up. The niche was not initiated during break-up but in the week after the termination of break-up when water temperatures had risen sufficiently to supply enough heat to the soil to overcome the latent heat of fusion.

Figures 11 and 12 show that most erosion occurs at shapes 3, 4, and 5 during break-up when loose slough slopes built during the previous summer are carried away.

4.3.3 BREAK-UP ICE

Ice abrasion against banks during break-up would normally be expected to cause significant erosion. This was found both by myself and Gill (1972b) not to be the case for two reasons:

1. Except for south-facing banks, most banks are frozen at the time of break-up.

2. Delta ice "candles" at break-up. Melting of crystal boundaries forms individual "candles" that normally range 1 m in length and 5 cm in diameter. This weak, broken ice builds up along cut-banks, protecting them. A shear line separates moving and stationary ice (Plate 15).

Massive Mackenzie River ice not weakened by candling tends to ride up over the tops of banks (Plate 16) at sharp bends or channel divisions causing broken stems of willow (Plate 17) and small ice-pushed ridges (Plate 18) in places where some of the bank material has thawed. These features were also described by Gill (1972b).

4.3.4 VEGETATION

Ice-rich sediment and the resulting flow of thawed material down bank faces is seldom associated with sites occupied by a willow or a balsam poplar plant association.

An overhanging vegetation mat, which shades the bank face from solar radiation and retards thaw penetration, was found to be less at sites that were occupied by a willow-alder plant association.

4.4 MORPHOLOGIC EFFECTS OF MAJOR AND MINOR EROSION FACTORS

Bank shapes, discussed in section 4.1, reflect the sum total of the smaller-scale effects observed in the field and

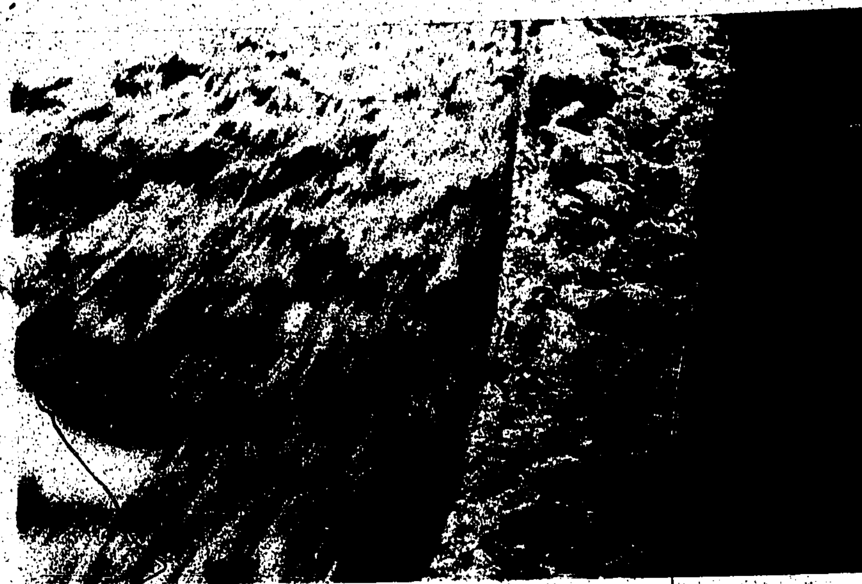

Plate 15 Break - up. Moving ice on the left is separated from bank - protecting stationary ice on the right by a shear line.

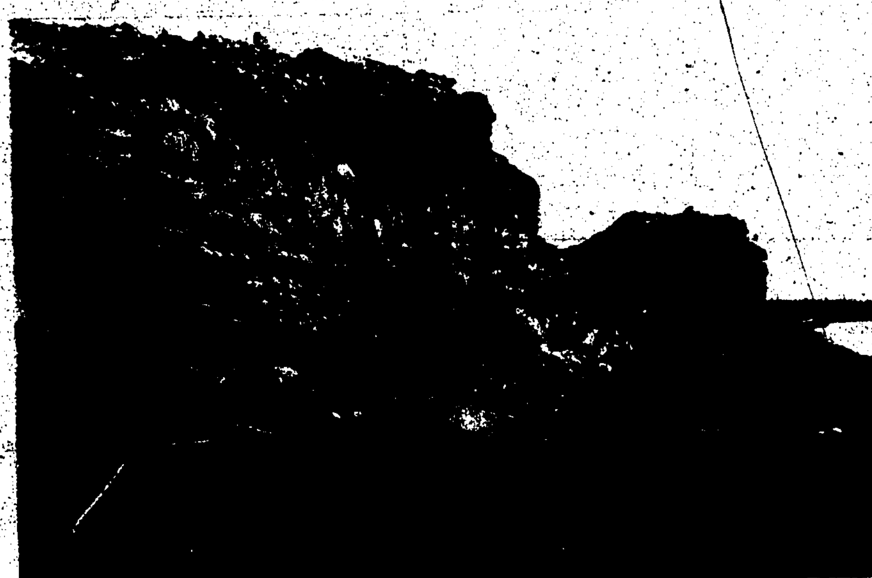

Plate 16 Massive Mackenzie River ice pushed onto a bank at the junction of East and Middle Channels.

Plate 17 Willow stems broken by the ice pushed up in Plate 16.

Plate 18 Ridges of alluvium formed by the ice shown in Plate 16.

described in the following sections.

4.4.1 THERMO-EROSIONAL NICHES

The thermo-erosional niche was the most obvious effect of ero[illegible]erved in the study area. Niches in three differen[illegible]of destruction are shown in Plates 7 to 9. These[illegible] illustrated diagrammatically in Figure 4. A typical [illegible] is initiated by a combination of efficient heat supply by the water along with current and wave action which remove insulative thawed material, penetrating the bank 3 to 5 m in less than 48 hours (Gill, 1972b). The roof of the niche then begins to thaw through exposure to heat transferred from the air and infra-red radiation from the water. Deposits of material (flowing or sloughing) accumulate on the niche floor to build up a small accumulation slope (stage 2). Approximately a month after the niche is initiated, it has been completely destroyed, leaving a large accumulation slope and a minor overhang (stage 3). If current velocity or wave action increases, the accumulation slope may be flushed away and a new niche initiated. All thermo-erosional niches develop in frozen bank material at locations of current velocity in excess of 30 cm/sec. Niches are much deeper in ice-rich sediment than in sediment without visible ice layers (approximately 10 m vs 5 m).

Wave-eroded niches (thermo-erosional niches formed without the aid of current) are found in frozen bank

Plate 19 A wave - eroded niche at site H.

material at locations with moderate average summer current velocity and high wave action. A wave-eroded niche is shown in Plate 19. There is a niche at a higher level than the one being eroded at the time of photography.

4.4.2 BLOCKS, TENSION CRACKS, ICE WEDGES

Tension cracks, fallen blocks, and ice wedges are associated with sites where deep niches have developed in ice-rich sediment (shape 1). Before a block falls from a bank undermined by a niche, a tension crack appears in the levee surface (Plate 20). After a block falls into the channel (Plate 21), the sides of ice wedges may be exposed (Plate 22) in the former location of the tension crack. This will happen where ice wedges are common and if one is orientated parallel to the bank in a tension zone. The ice wedge, being a plane of vertical weakness, will be exposed upon breakage of the bank. This process has also been observed by Walker and Arnborg (1966). Ice wedges only appear at sites where ice-rich sediment is present. Generally, sizes of fallen blocks are much smaller at sites that do not have ice-rich sediment (Plate 23) because of shallower niches at such sites (section 4.4.1).

4.4.3 DEPTH TO PERMAFROST

Plate 24 shows an excavation on a shape 3 bank dug into the top of the slough slope where it met the thawing bank face. All unfrozen material was removed. It can be seen

Plate 20 A tension crack in the top of a bank with shape 1 (site A).

Plate 21 A block (outlined) that has fallen from a bank with shape 1 and ice-rich sediment.

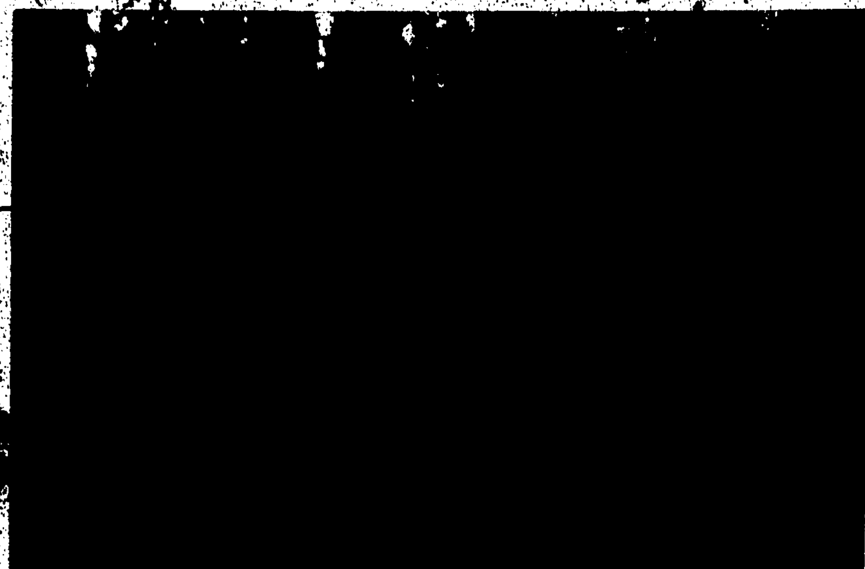

Plate 22 The side of an ice wedge exposed by the breaking away of a block.

Plate 23 A small block fallen from a bank (site F) with shape 2 and low ice content sediment.

Plate 24 A pit dug to the surface of frozen material at a bank with shape 3. The stick is 1 m long.

that there is very little thawed material on the bank face and that the top of the frozen material beneath the slope parallels the surface. A similar situation was found at all other sites with slough slopes. A photograph resembling Plate 24 was published by Walker and McCloy (1969, frontispiece) indicating the similarity of bank erosion processes in other deltas.

Where these slopes were not present (shapes 1 and 2) a near-vertical face of the bank is found. In ice-rich sediment banks, frozen material is within 2 cm of the surface which is liquid and flowing. In low ice content banks, depth to frozen material is up to 10 cm from the surface which is undergoing sloughing.

4.4.4 BEACHES

Plate 12 illustrates bank shape 4 and the beach associated with this shape. Plate 25 is a closer view of the waterline at one of these beaches. Beaches are found at all sites that do not have any measurable current velocity during the summer. These sites have a location on a channel orientated to the prevailing wind with a long open-water fetch in a NNW direction.

4.4.5 STRANDLINE EROSION

Plate 13 illustrates strandline erosion steps as they appear on the lower part of a shape 5 bank as observed while standing on the bank slope. The features can be described

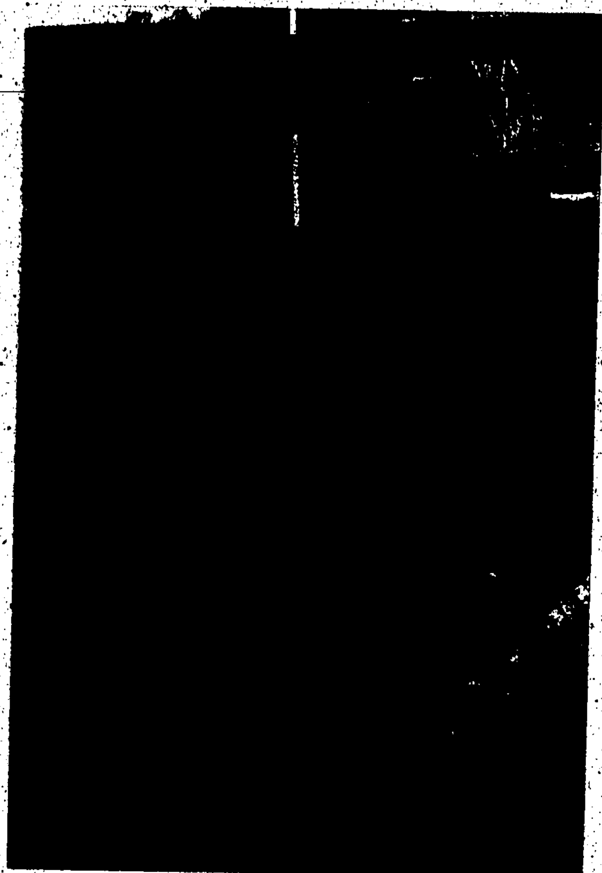

Plate 25 A close view of the [illegible]ch shown in [illegible] 12.

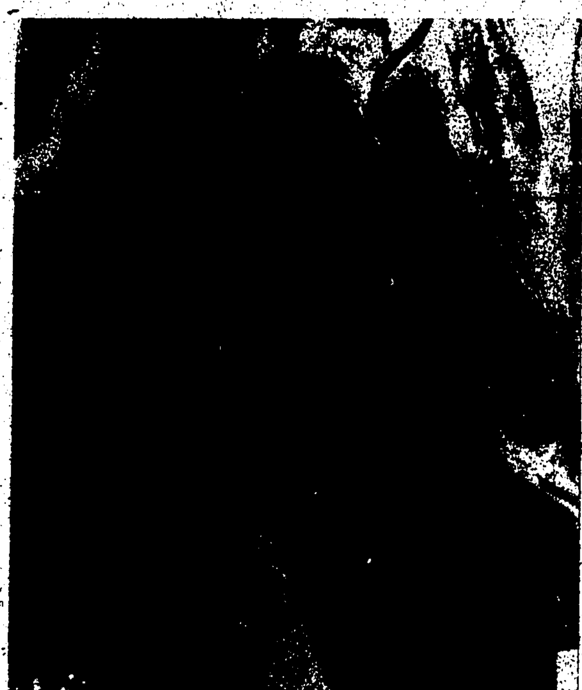

Plate 26 A part of Government of Canada air photo A12848-11 (1950, from 6,100 m altitude). Erosion is approximately 8 m/yr at this location (near site E).

as steps of varying sizes or a series of miniature beaches and cliffs. Each line of steps corresponds to a water level.

Erosion of the small "riser" (normally less than 1 m in height) and development of the "tread" is accomplished by waves from both boats and natural wind-induced wave action.

Strandline erosion is found only on banks with shape 5 or on point-bars (Plate 3).

4.5 EROSION WITH TIME

Plate 26 is a portion of Government of Canada air photo number A12848-11 (1950). It is an example of how the August 1973 positions of many bank lengths were plotted so that measurements of bank retreat could be made. These measurements are listed in Table 4.

Figures 9 to 12 illustrate variations in erosion rates (slopes of the lines) during the 1973 field season as measured at each of the sites described in section 2.3. The earliest point for each line (measured at the termination of break-up) approximates break-up erosion though it includes the small amount of erosion, if any, that occurred in September, 1972.

Figure 9 reveals that there are two types of bank shape 1. Sites A and B have high erosion rates two weeks after the termination of break-up. Sites C and D have relatively constant erosion rates through the summer. Blocks fell from both sites A and B two weeks after the termination of break-

Table 4. EROSION RATES MEASURED FROM AIR PHOTOGRAPHS AT LOCATIONS CHECKED BY HELICOPTER SURVEY. SHAPES DETERMINED BY BOAT SURVEY.

Bank Length Location	Erosion Rate m/yr.	Common Shapes
Upstream and downstream of Site A	9-11	1 and 2
" B	7	2 and 3
" C	8	1 and 3
" D	5-8	2 and 3
" E	6-8	2 and 3
" F	7	2 and 3
" G	9	3
" H	4-6	3 and 4
" I	4	3 and 5
" J	5	3
" K	1-3	5
" L	2-4	4
" M	1-2	4
" N	2	5
" O	1	5
East Channel-East Bank	1-2	4
Across from Site J	3	3 and 5
67°39'N 134°37'W	6	3

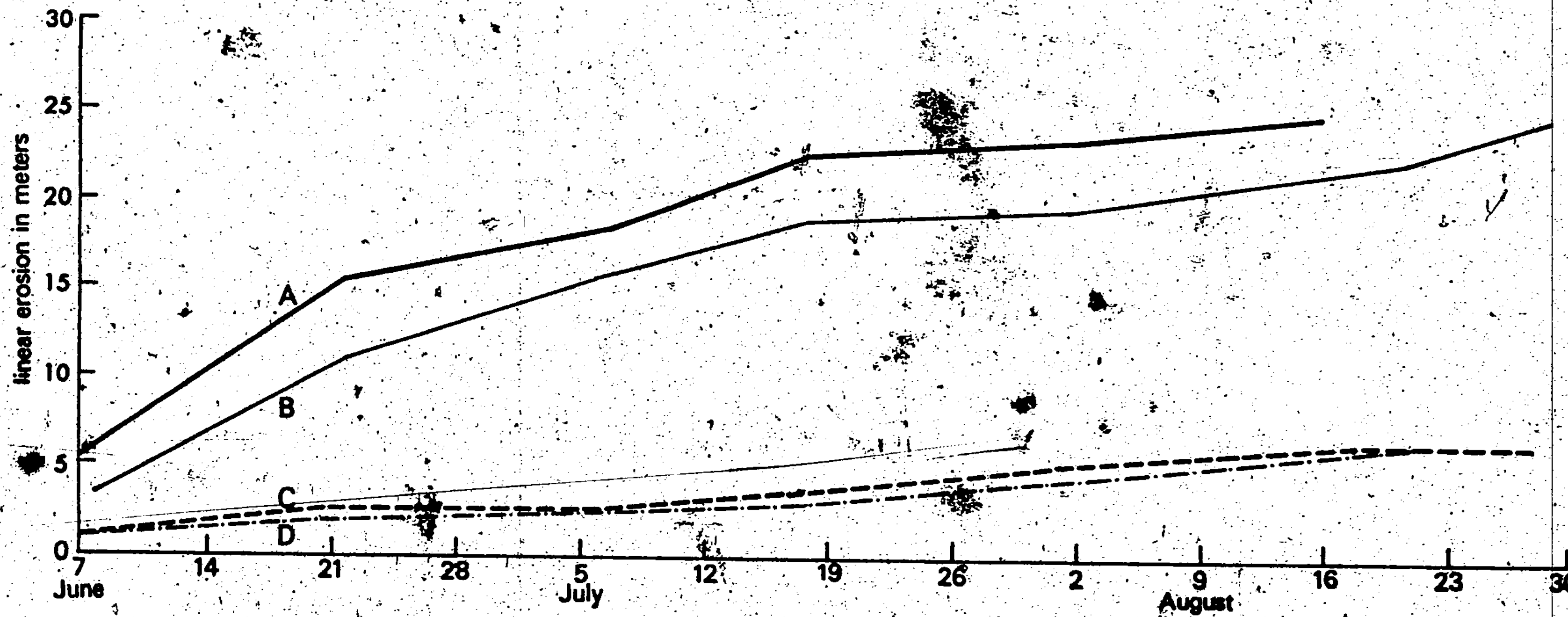

Figure 9 Cumulative Erosion with Time, 1973, for Sites with Shape 1

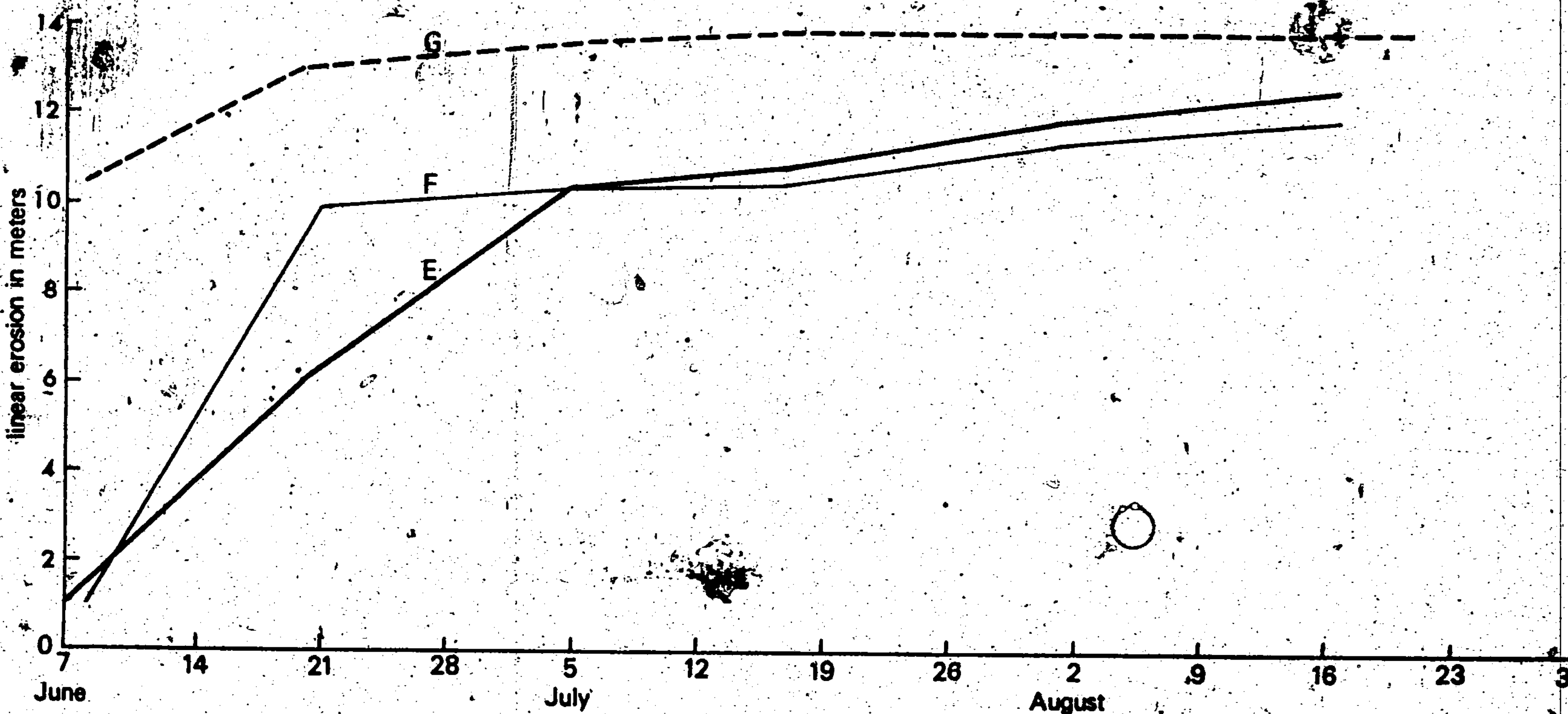

Figure 10 Cumulative Erosion with Time, 1973, for Sites with Shape 2

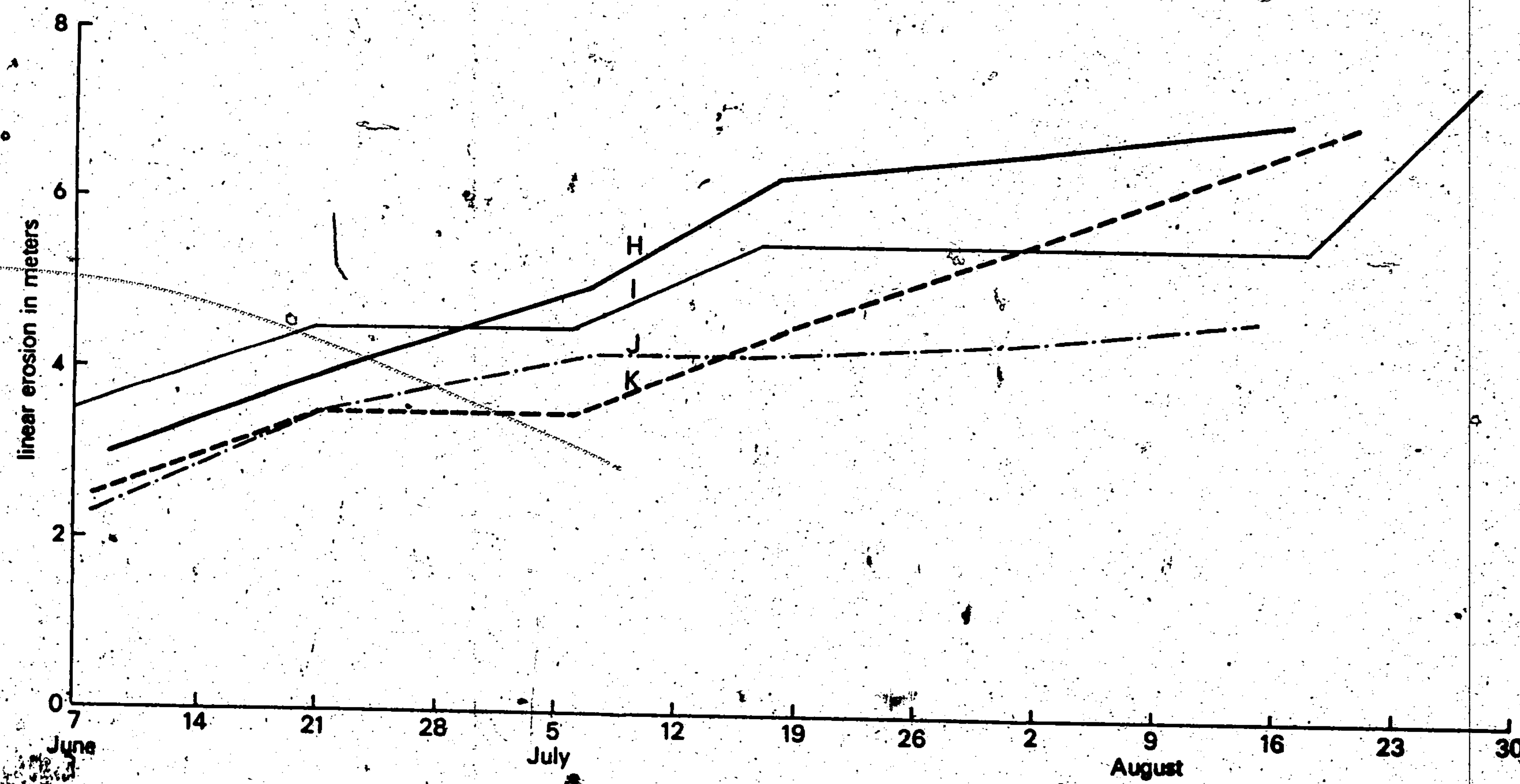

Figure 11 Cumulative Erosion with Time, 1973, for Sites with Shape 3

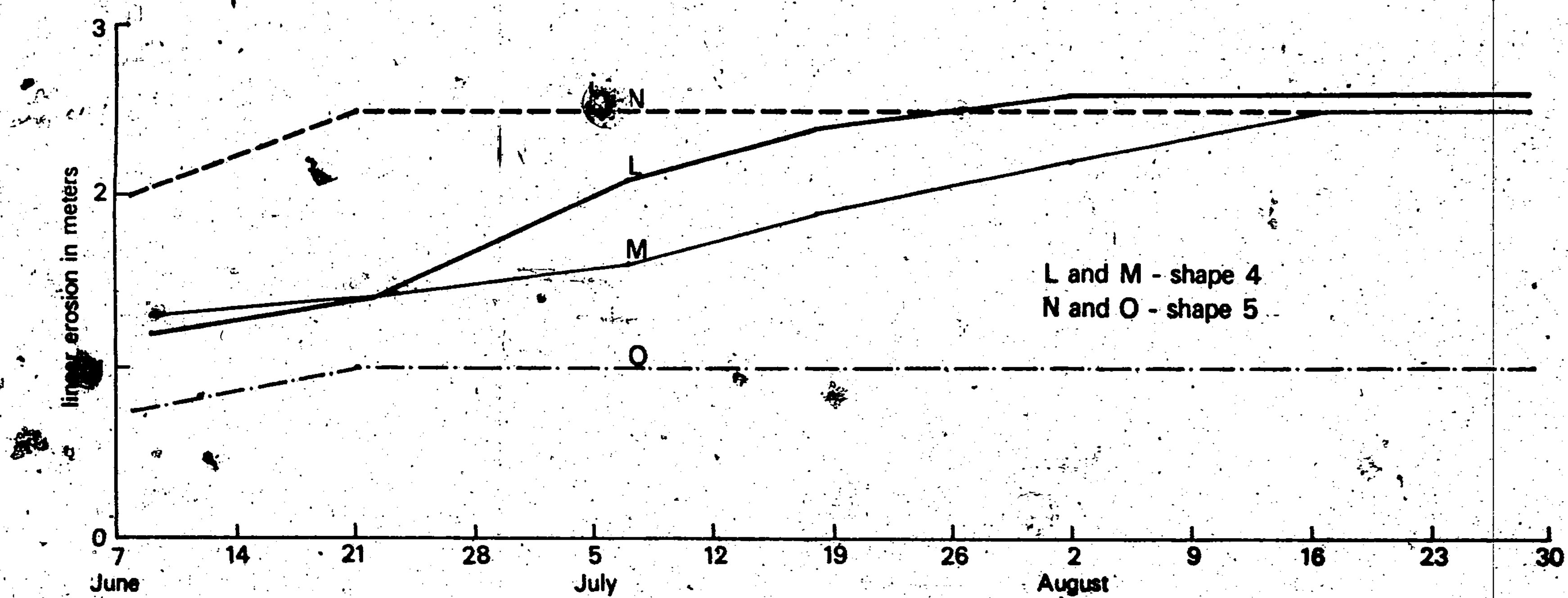

Figure 12 Cumulative Erosion with Time, 1973, for Sites with Shape 4 or 5

up. Blocks did not fall from sites C or D.

Figure 10 shows that two sites, E and F, had the same erosion pattern as sites A and B but erosion rates were generally lower. Blocks fell from both sites E and F two weeks after the termination of break-up but the blocks were only half the size of the ones that fell from sites A and B. The curve for site G seems to fit better with the curves for sites N and O (Figure 12). Site G had a very low bank elevation (3.7 m) compared to the other banks and current velocity after break-up was quite high (Table 1).

Figure 11 shows that banks with shape 3 have a high erosion rate during and immediately after break-up with erosion continuing erratically throughout the summer.

Figure 12 shows a difference between the behavior of bank shapes 4 (L and M) and 5 (N and O). Both shapes are most eroded during and immediately after break-up when slough slopes are removed. No further removal of material occurs at shape 5 banks but some material is removed by wave action from shape 4 banks. No slough slopes were found at banks with these shapes at the termination of break-up. Erosion faces of banks with shape 4 or 5 and having ice-rich sediment retreat continuously during the summer. Faces of such banks with low ice content sediment retreated too slowly (less than 0.5 m/yr) to be measured by the method used.

Mackay (1963) found an erosion rate of "over 2 m/yr" for a low ice content, low root content, shape 3 bank at

Aklavik. For similar banks, Lomachenkov (1959), Walker and Arnborg (1963), McCloy (1969), and Gill (1972b) all found erosion rates of 1 to 3 m/yr. For thermo-erosional niche locations (bank shape 1), the same authors found erosion rates of close to 10 m/yr.

Walker and Arnborg (1963) describe bank shapes and erosion processes in the Colville Delta identical to those found in my study area.

4.6 REGRESSION ANALYSES

In an attempt to determine which of the erosion factors are dominant in the dynamic process of bank erosion, a multiple regression analysis was applied to the annual erosion data obtained at the 15 bank sites described in section 2.3. The dependent variable used was linear erosion in meters from August 1972 to August 1973. The independent variables used were: average summer current ("current factor"); length of open-water fetch in a NNW direction ("wave factor"); and the average difference between liquid limit and moisture content for erosion face samples ("sediment ice factor"). The results of this analysis are listed in Table 5.

The regression coefficients are the values for f in the multiple regression equation: $y = a + f(x1) + f(x2) + f(x3)$. The y values are values of the dependent variable, and x1, x2, and x3 are the values of the independent variables. The a value is the y axis intercept.

Table 5 MULTIPLE LINEAR REGRESSION ANALYSIS OBTAINED USING THE UNIVERSITY OF ALBERTA PROGRAM *MLREGR ON IBM 360/67 COMPUTER

Variable Erosion Factor	Regression Coefficient
Current (cm/sec)	7.36
Wave (fetch in km)	1.02
Ice (% weight)	-0.07
Y axis intercept:	1.83
Multiple Correlation Coefficient (R):	0.40
Coefficient of Determination (R^2):	0.16

Table 6 LINEAR CORRELATION ANALYSES OBTAINED USING THE UNIVERSITY OF ALBERTA PROGRAM *CORRLT ON IBM 360/67 COMPUTER

Variables	Regression Equation	Correlation Coefficient	Square of Correlation Coefficient	Sample Size
Annual				
Fetch vs Erosion	y = 2.13 + 0.17x	0.63	0.40	10
Current vs Erosion	y = 5.21 + 5.12x	0.31	0.10	15
M.C. — WL vs Erosion	y = 8.11 + 0.10x	0.14	0.02	15
M.C. vs Erosion	y = 10.47 + 0.03x	-0.05	0.01	15
Bi - weekly				
M.C. — WL vs Erosion	y= -4.75 + 221.75x	0.81	0.66	23
M.C. vs Erosion	y= 23.[illegible]5 + 28[illegible].89x	0.76	0.58	23
Current vs Erosion	y= 0.68 + 5.61x	0.57	0.33	24
Water Level vs Current	y= 6.39 + 1.17x	0.29	0.09	33
Wind Velocity vs Erosion	y= 1357.[illegible] - 6443.86x	-0.27	0.07	35
Water Temp. vs Erosion	y= 17.13 - 14.56x	-0.19	0.04	43
Air Temp. vs Erosion	y= 12.87 - 2.31x	-0.04	~~0.01~~	43

Table 7 BANK BEHAVIOR, SHAPES, AND EROSION FACTORS

Site	Shape	Meters of Annual Linear Erosion	Average Summer Current	Sediment Ice Factor	Wave Factor	Height (m) Above Water Level Aug. 16	% of Annual Erosion at Break-up	Current Pattern	Character of Erosion
A	1	25.0	moderate	high	moderate	7.0	61	1	1 and 2
B	1	28.0	high	low	moderate	5.5	13	1	1 and 2
C	1	6.2	high	high	low	6.5	16	1	2
D	1	6.5	high	high	moderate	7.5	15	1	2
E	2	12.6	high	low	high	8.5	48	1	1 and 2
F	2	11.8	high	low	moderate	8.[illegible]	9	1	1 and 2
G	2	13.8	low	low	low	3.7	76	2	3
H	3	7.0	moderate	low	high	[illegible]	43	1	3
I	3	7.5	high	low	low	[illegible].0	47	1	3
J	3	7.0	moderate	high	moderate	6.5	36	1	3
K	3	4.7	moderate	low	low	5.0	45	1	3
L	4	2.6	low	high	high	6.0	54	2	4 or 5
M	4	2.5	low	high	high	6.5	52	2	4 or 5
N	5	2.5	moderate	low	moderate	6.0	80	1	4 or 5
O	5	1.0	moderate	low	moderate	6.0	50	1	4 or 5

The multiple correlation coefficient indicates the combined interdependence of all 3 erosion factors with annual erosion. It is the product moment correlation between the actual values of the dependent variable (annual erosion) and the values as given by the regression equation. It may also be regarded as the maximum of the correlation coefficient between the dependent variable and all functions of the set of the 3 independent variables. The number 1 indicates complete interdependence, 0 indicates no interdependence or a random scatter of y values without relationship to the x values. The value of 0.40 in this case indicates a very weak relationship between y values and x values.

The coefficient of determination is simply the square of the multiple correlation coefficient. It indicates in this case that only [illegible]% of the variation in the dependent variable is explained by the independent variables.

The above statistics indicate that there are other important variables that affect bank erosion or that there are complex relationships among the entire set of erosion factors found in this study besides the 3 used in this analysis. A larger sample size would add to the meaningfullness of the analysis.

Simple correlation and regression analyses were applied on different variables in different combinations for both annual and bi-weekly erosion p[illegible]. Results of these analyses are listed in Table 6.

The relations in Table 6 are ranked in order of decreasing interdependence between variables as indicated by the correlation coefficient in which 1 indicates complete interdependence and 0 indicates a random scattering of values.

The square of the correlation coefficient indicates what percentage of the y values are accounted for by the x values. The only relations that have more than 50% for this statistic are: the relation between the moisture content minus liquid limit of bank sediment; and the relation between erosion and moisture content alone of the bank sediment.

4.7 SUMMARY OF BANK BEHAVIOR, SHAPES, AND EROSION FACTORS

The information in Table 7 is abstracted from the data presented in this chapter. It shows the associations between different levels of the erosion factors, bank behavior in terms of rate and character of erosion, and bank shapes.

Following is a list of the erosion factor levels coded in Table 7:

Current Factor:

Low: below 10 cm/sec.

Moderate: 10 to 30 cm/sec.

High: above 30 cm/sec.

Wave Factor:

Low: channel orientation NE-SW or E-W.

Moderate: channel orientation N-S or NW-SE and down-channel open-water fetch less than 3 km.

High: channel orientation N-S or NW-SE and down-channel open-water fetch 3 km or greater.

Sediment Ice Factor:

Low: segregated ice layers not visible.

High: segregated ice layers visible.

Current Pattern:

Code 1: measurable current velocity all summer.

Code 2: measurable current velocity for only approximately 2 weeks after the termination of break-up.

Height:

Vertical distance between the highest ground elevation on the top of the bank and the water level on August 16, 1973.

Percent of Annual Erosion at Break-Up:

The bank face retreat occurring before June 7, 1973, which was the approximate date of termination of break-up in the study area.

Character of Erosion:

1: catastrophic (falling blocks).

2: contiauous removal of material by current and/or wave action.

3: intermittent removal of material by current and/or wave action.

4: continuous retreat of the bank face
with most removal of material during break-up
(sites with ice-rich sediment).

5: as above, but bank face retreat at
sites with low ice content sediment
is very slow (less than 0.5 m/yr).

CHAPTER 5

CONCLUSIONS

5.1 THE EROSION PROCESS

As shown in Table 5, the statistical analysis did not indicate which were the significant factors contributing to bank erosion rates. One cannot predict erosion rates by measuring any of the factors such as current discussed in this study. Predictions must be made by using the shape of a bank which is the end result of the complex interaction of many factors. There is a close association between bank shapes and erosion rates and between bank shapes and erosion characters. From Table 6, it can be concluded that the factor of ice content affects minor changes in erosion rate of a bank during the open-water months after break-up.

Banks along channels orientated favourably (NW-SE or N-S) for the production of wave action by upstream winds will have their erosion rates accelerated by wave action. Such banks may have beaches (section 4.4.4), strandline erosion steps (section 4.4.5) or wave-eroded niches (section 4.4.1).

A bank containing ice-rich sediment will have soil flow down its face (section 4.2.3); frozen material will be within 2 cm of the surface (section 4.4.3); the bank face will be dark brown in color (section 4.2.3); it may have a deep niche (section 4.4.1); and vegetation will most likely be white spruce (section 4.3.4).

A bank containing low ice content sediment will have sloughing of material from its face (section 4.2.3); frozen material will be up to 10 cm below the surface (section 4.4.3); the bank face will be brown to light brown in color (section 4.2.3); it will not have a very deep niche (section 4.4.1); and vegetation will most likely be willow-alder or balsam poplar (section 4.3.4).

Although there is little difference in size between the smallest and largest-sized samples, high ice content sediments tend to have a higher percentage of coarse silt and the low ice content sediments have a higher percentage of fine sand.

Some banks are not entirely composed of low or high ice content sediments. I have observed locations where there are several layers of each sediment type or upper and lower halves of the bank face with different sediments.

Roots retard erosion by current, soil flow, and sloughing (section 4.3.1). Low water temperature delays the erosion of in-situ bank material until after break-up (section 4.3.2).

5.2 BANK SHAPES AND EROSION RATES

It is clear from Tables 4 and 7 that banks with shape 1 erode at a rate more than 5 m/yr and banks with shapes 4 and 5 erode at a rate less than 5 m/yr. The minimum for shapes 4 and 5 is almost 0 m/yr. Shapes 2 and 3 are transitional between shapes 1 and 4, so their erosion rates are transitional also. Most banks of shape 2 have a rate

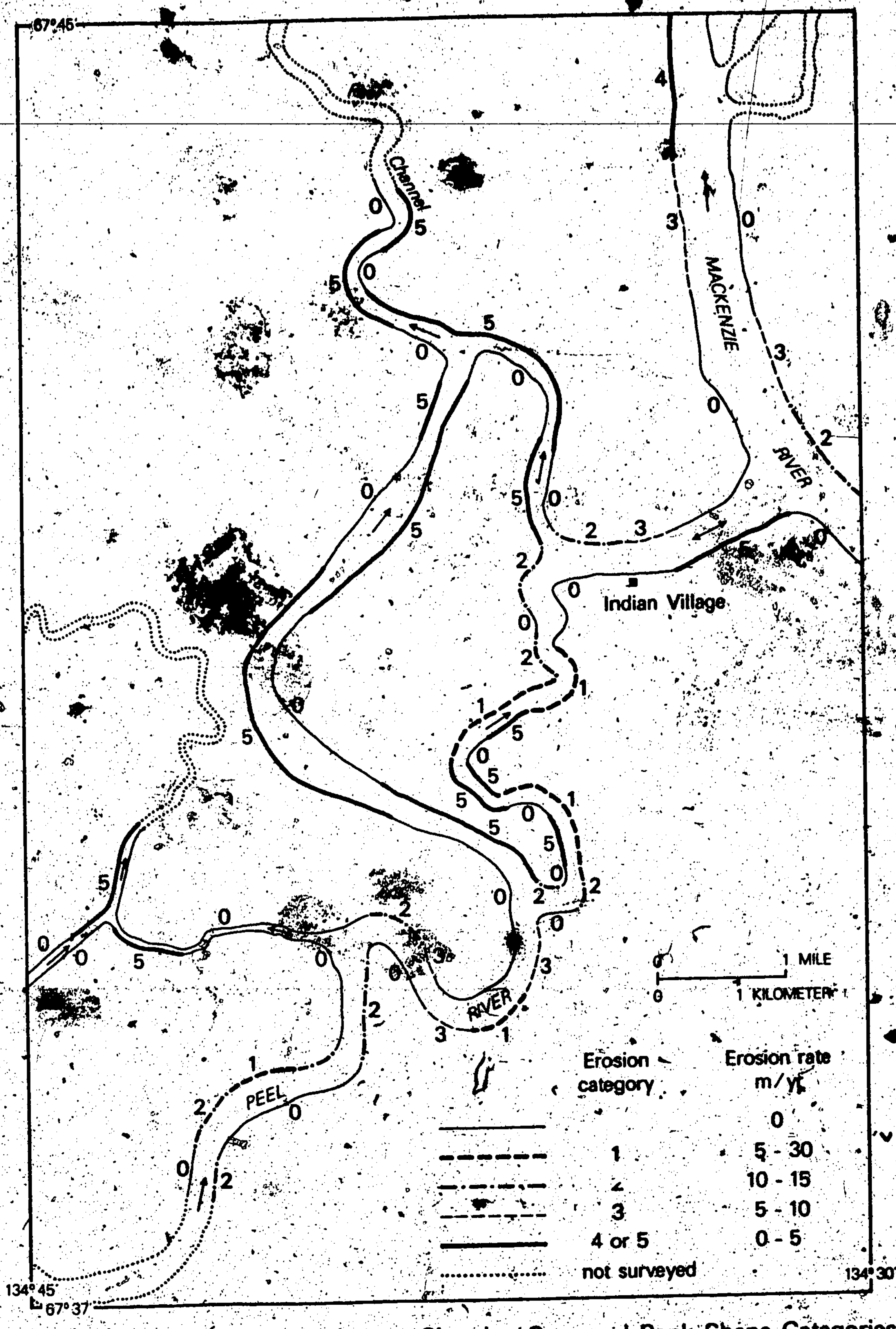

Figure 13 Portion of the Study Area Showing Surveyed Bank Shape Categories

between 10 and 15 m/yr. Most banks of shape 3 have a rate between 5 and 10 m/yr. The results of these conclusions are the following erosion categories used in Figure 13:

1: 5-30 m/yr.

2: 10-15 m/yr.

3: 5-10 m/yr.

4: 0-5 m/yr.

5: 0-5 m/yr.

5.3 CHANGES IN BANK SHAPE AT THE SAME SITE :

The final outcome of the erosion of a shape 1 bank may result in a shape 2 at the end of an erosion season. The niche roof and bank face may retreat to such an extent that the bank may appear vertical. The next year, however, a new niche will be initiated by warm water and high current velocities, resulting in a shape 1 again. All other bank shapes will not change at the same location as long as the erosion factors at the site retain the same relations from year to year.

If the long-term erosion factor relationships change, a bank shape may evolve into another one. For example, an increase in current velocities at a site may lower the bank shape number and a decrease in current may increase the number. Continued observation of the 15 bank sites over the next few years is needed to properly assess the extent of long-term changes. There is no evolution between shapes 4 and 5 as their distinction is the result of differences in the orientation and open-water fetch of a channel reach for upstream winds.

5.4 THE CHARACTER OF EROSION

Five different types of erosion were observed at eroding banks. These are described at the end of section 4.7. Table 7 shows that each bank shape exhibits 1 or 2 of these erosion types. The only exception to the association of bank shape to erosion character is site G. This may be caused by its location at a channel junction, its low height, or abnormally high break-up current velocities. Such exceptions point out where the character of erosion may be different outside the study area or in other periglacial deltas. There may be significant differences in: bank heights; average break-up date; average freeze-up date; annual hydrograph; bank material texture; mesoclimate; vegetation; prevailing wind direction; water temperature; suspended sediment; and boat traffic.

The causes for each of the different types of erosion are found in section 5.1. Catastrophic erosion (type 1) is caused by the undermining of a bank by a niche which may cause a block to fall. This may occur at both bank shapes 1 and 2 if niches are deep enough. Continuous removal of material by current and wave action (type 2) also happens at bank shapes 1 and 2 which have moderate to high current velocities all summer. Continuous removal is why these bank shapes have higher erosion rates than other shapes. A combination of erosion types 1 and 2 may produce the extremely high rate of 25 m/yr found at sites A and B. Intermittent removal of material (type 3) is caused by variations in channel discharge or variations in wind velocities and directions. Type 3 erosion is associated with bank shape 3. Because of soil flow, banks of shape 4 or 5 with ice-rich sediment will have continuously-retreating bank-faces all summer (type 4). Banks with low ice content sediment will have very slowly-retreating bank faces all summer. Mass wasting by sloughing is much slower than by soil flow. Both types 4 and 5 are characterized by the removal of sediment during break-up when unconsolidated slough slope material is carried away.

5.4 SUMMARY

Short-term eroding bank behavior can be predicted knowing the bank shapes that are a manifestation of the erosion process. There is a positive correlation between bank shape and erosion rate, and between bank shape and character of erosion.

Figure 13 is a section of the study area which illustrates locations and predicted behavior of many banks. This map was made by marking the shape of each bank on a 1:50,000 NTS base map during a boat survey. A map such as this could be used in the planning of construction in the area and demonstrates the practical nature of the information revealed in this study.

RECOMMENDATIONS

The following recommendations arise specifically from this study and do not include the many other factors that may have to be considered such as the processes of deposition and various engineering works (river training, bank armouring, and sheet piles).

The construction of any permanent facility should be avoided in the delta. Raised, portable buildings such as trailers may be located on a short-term basis near eroding banks with shapes 4 or 5 in that these banks are eroding slowly and there would be time to have buildings removed. No construction should be done near any other shape of eroding bank because of their high erosion rates. Stable banks such as those in Plates 4 and 5 are obviously the safest locations for construction and the best for docks and wharves although such sites may become sites of erosion or deposition after long periods of time (20 years or more).

SUGGESTIONS FOR FURTHER RESEARCH

Fluvial geomorphology is a neglected subject in the Mackenzie Delta. Studies similar to this one should be done in the central and northern sections of the Mackenzie Delta to facilitate wider application of erosion behavior associated with each bank shape and the production of a series of maps similar to Figure 13.

More data such as current velocities, sediment ice contents, sediment sizes, wave action measurement, and channel orientations should be obtained to facilitate an exact establishment of the complex relationships between erosion rate and the erosion factors.

A specific study can be made of bank armouring. Bank protection with sheet metal has been attempted on a short bank section near Aklavik. The effects on erosion of a meander cut-off (near Aklavik) or an avulsion of one channel into another (northwest of Reindeer Station) would also make an interesting study.

Broader studies would include a study of depositional features, the behavior of channels as a whole, or a comparison of the Mackenzie Delta geomorphic features with those of other northern and southern deltas.

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