Environment Canada Environnement Canada

National Hydrology Research Institute
Institut national de recherches en hydrologie

PATTERNS AND PROCESSES OF CHANNEL CHANGE,
MACKENZIE DELTA, N.W.T.
1983 - 84 PROGRESS REPORT

by

M.F. Lapointe

NHRI·INRH

INLAND WATERS DIRECTORATE
OTTAWA, CANADA

DIRECTION GÉNÉRALE DES EAUX INTÉRIEURES
OTTAWA, CANADA

PATTERNS AND PROCESSES OF CHANNEL CHANGE, MACKENZIE DELTA, N.W.T.
1983 - 84 PROGRESS REPORT

by

M.F. Lapointe

Northern Hydrology Section
Surface Water Division
National Hydrology Research Institute
Environment Canada
Ottawa, Ontario.
K1A 0E7

April 1984

Abstract

In 1983, a study was initiated of fluvial processes in the Mackenzie Delta. Between spring break-up and autumn low-flows, reconnaissance observations of channel conditions and processes were carried out mainly in the eastern-middle Delta, along Napoiak Channel to Shallow Bay and along East Channel and beyond to Point Separation. Preliminary conclusions on channel morphology, channel shifting and sediment transport are presented, based on reconnaissance and previously published data. Further research avenues are also discussed.

Characteristics of delta channel morphology confirmed by the author's bathymetric surveys include widespread "inner channels" as well as chaotic "hole and mound" zones on channel beds. Analysis of published cross-sectional data also suggests that channel depths increase particularly slowly with increasing widths in the Mackenzie Delta. Extensive 30-year air photo comparisons disclose rapid shifting along Middle Channel, which contrasts with subdued shifting along most other Delta channels. The study of these shifting patterns as well as observations of erosion processes during and after breakup suggest that flow strength may exert the main control on channel shifting, while hydrothermal and ice-run erosion appear to play minor roles. Exploratory bed material sampling supports a model of summer-long sand evacuation from distributary channel beds, with the morphology of distributary junctions playing a major role in controlling the sand supply. Avenues for further research include the genesis of "channel within channel" cross-sections, the controls on distributary abandonment, as well as further testing of the conclusions on channel shifting and sediment transport.

Acknowledgements

The author wishes to thank the staff of the Inuvik Scientific Resources Center as well as Water Survey of Canada at Inuvik, Yellowknife and Ottawa for advice, assistance and the loan of equipment. Special thanks go to Lyn Kriwoken (NHRI) and Marc Suzor (NEED Program) for field assistance. Sediment analysis were done by the Sedimentology Lab. of the Geological Survey of Canada. Finally, many thanks to Alain Labelle (NEED Program) for having done the large number of air photo comparisons required for the study, as well as for much of the figure drafting.

TABLE OF CONTENTS

LIST OF FIGURES

Patterns and Processes of Channel Change, Mackenzie Delta, NWT

1983-84 Progress Report

1.0 Introduction

In 1983, a study was initiated of the fluvial processes at work in the channel system that covers the Mackenzie Delta plain. Of particular relevance to this study are the interrelated issues of channel form as well as lateral and vertical stability, sediment transport patterns and creation or abandonment of channel reaches. The aim of this progress report is to clarify, in the light of previous knowledge, some background questions related to these issues, as well as discuss preliminary results obtained during reconnaissance surveys in the first field season. Further research avenues and methods will also be discussed.

Insights into Mackenzie Delta fluvial processes are of direct relevance to a range of development and management activities in the area. For example, although channel migration in the delta is relatively subdued overall (Mackay 1963, and this report), the need for shore revetment works at Aklavik, and for frequent relocation of navigation ranges on certain rapidly shifting channel reaches, must nonetheless be kept in mind. In the Mackenzie Delta, local rates of cut bank shifting will be seen to range from negligible to 30 m per year (as averages over recent decades); clearly, basic information on shifting trends can contribute greatly here to the proper location and protection of shore

facilities. The maintenance of safe navigation routes through the channel network may also be aided by an understanding of the controls on shoal location and evolution; in the delta apex area, for example, shoal activity appears to be particularly intense. Avulsions, or the relatively sudden abandonment and relocation of channel courses, also are typical occurrences in delta environments which may have grave consequences for human activities. New Orleans most probably would have become landlocked as a result of such a process if the Mississippi Delta had been left unregulated (Cunningham, 1981). Examples of creation and abandonment of small channels abound on the Mackenzie Delta, and an understanding of conditions controlling avulsion could be of long term relevance, for example, to Inuvik port activities.

Finally, as Gill (1971, 1972a) has emphasized, fluvial processes are also directly involved in the dynamics of the rich flora and fauna of the delta. Not only do plant habitats adjust closely to sedimentation zones along channel margins, but fish populations may also respond to patterns of flow in the channel system. It appears, for example, that large schools of whitefish congregate in a major eddy zone near Horseshoe Bend (E. Jessup, Freshwater Institute, per. comm.); these fish will gradually be deprived of this particular habitat by virtue of sedimentation and channel shifting trends over the coming decades. In the following sections, preliminary data bearing on some of these issues will be discussed, under three broad headings: channel morphology, channel shifting, and sediment transport across the delta plain.

2.0 Channel Morphology

Some general morphological properties of the channel system, as it is seen both in planform and in cross-section, can be briefly discussed. They raise a number of questions concerning fluvial processes at work in the Mackenzie Delta, some of which will be discussed further in coming sections. Mackay (1963) has provided an interesting first approach to these questions, based on data gathered from field and air photo observations.

2.1 Channel Planforms

The channel network extending over the Mackenzie Delta plain can best be described as anastomosing. Such a system is characterized by branching multiple channels of moderate to high sinuosity, with relatively stable and well vegetated islands (Schumm, 1968; Rust, 1978) (in contrast, multi-channel low sinuosity systems, with rapidly shifting islands/bars, are referred to as braided in this particular classification scheme). Anastomosing systems are quite typical of delta settings, without being restricted to these. Progradation of the delta plain into standing water leads to vertical aggradation in active delta channels, and this, in turn, encourages repeated avulsions exploiting shorter channel routes to base level (sea level). The relatively low energy gradients that occur over delta plains may condition fine sediment deposition, and lead to relative lateral stability of slow-flowing channels that have much cohesive material in their boundary.

Within the channel network, individual channel reaches have been described by Mackay (1963) as generally "wandering" in nature: in his opinion "true meanders" are a minority in the Mackenzie Delta. Such a distinction may be confusing, firstly, because the term "wandering" generally denotes, in current usage, transitional channel patterns displaying both meandering and braided characteristics. In this technical sense, the term does not apply to typical Mackenzie Delta channels. Secondly, the notion of a typical meander form is itself problematical. Many delta channels do fail to display the regular sinuous trace and relatively rapid shifting that is referred to as "ideal" meandering in textbooks: on the contrary, considerable irregularity (in wavelengths, amplitudes) and varying degrees of tortuosity are the rule on the delta plain. Fig. 1 illustrates the contrast between two meander styles in the Mackenzie Delta. Nonetheless, it must be remembered that irregular meanders, comparable to those of the Delta, have been observed elsewhere; for example, Mollard (1973) seems to associate low gradient, "high-cohesive" valley settings with similar "contorted" meanders that display considerable irregularity. Thus, because of the great variety and continuous gradations in style of alluvial channel traces, there is some merit in adopting the old convention (Leopold et. al., 1964) that classifies as meandering any free alluvial channel having a sinuosity greater than 1.5. According to this definition, most Mackenzie Delta channels do meander. Moreover, Mackay (1963) provides data which indicates that, given the usual scatter, these channels do show the same regularities in ratios of wavelength and radius

Fig.1 The style of meandering in Mackenzie Delta channels. Notice the contrast between the rather regular meanders of Peel Channel at the left, and the irregular "contorted" style of two smaller channels to the right.

Dept.of E.M.R. photo A21583-131.Near 67° 50'N, 134° 45'W.

of curvature to channel widths, that characterize most meanders. Furthermore, channel traces typically exhibit the "delayed-inflection" and, occasionally, the "gooseneck loop" asymmetric styles (Carson and Lapointe, 1983) inherent to most meanders, and by which flow direction can usually be inferred. There is thus reason to expect that many sediment transport and channel migration patterns may be shared with those of meandering channels elsewhere, as they reflect certain general properties of flow in bends. In the next section, it will be seen that, as regards channel shifting patterns, this view is generally substantiated. In the last section, possible reasons for the "irregularity" of meandering on the delta will be suggested, in the light of local conditions.

2.2 Channel Cross-sections

Mackenzie Delta channels also present interesting particularities in cross-sectional form. Little is known about the hydraulic geometry of these channels, i.e. the way channel width and depth, as well as slope and roughness, etc., mutually adjust over a range of channel sizes, to convey different water and sediment discharges. Mackay (1963) and Hollingshead and Rundquist (1977) provided a number of transverse profiles from which morphometric information may be extracted. Anderson and MacKay (1973) produced extensive data on channel widths, average depths, velocities and discharges at summer low flow stages, from which they extracted power law relationships. Unfortunately, the latter are not directly comparable with published downstream-hydraulic-geometry relations for other environments, since

such data are as a rule collected at bankfull or some other "formative" discharge. As a preliminary exercise, plots of width versus depth at bankfull were nonetheless extracted from Mackay's (1963) and Anderson and MacKay's (1973) data. In the latter case, complete section profiles to bank top were not available, and so a minimum of information on the relationship of low flow to bankfull sections was brought to bear. Approximate ratios of bankfull widths to low flow widths were obtained from summer air photography of the reaches where the sections are located. Average depths at bankfull (D_{bf}) were approximated by the following formula:

$$D_{bf} = \frac{W_1D_1 + W_2D_2 + W_3D_3}{W_1 + W_2 + W_3}$$

where W_2 is the low-flow channel width, W_1 and W_3 are the widths of the right and left side flooded banks at bankfull, D_2 is the sum of average depth at low-flow and stage rise to bankfull, and both D_1 and D_3 are half this stage rise. The latter values, stage difference between summer low-flow and bankfull conditions, were extracted from Mackay's (1963) Fig. 57, giving heights of levees above late summer low-water levels. As is generally the case, any flow-related scour and fill was assumed to be localised at channel constrictions and near bend apices, without affecting average bed elevations over channel reaches. Fig. 2a and 2b present Mackay's (1963) and Anderson and MacKay's modified data, respectively. Because of the added assumptions involved in producing the second set of data, it was best plotted separately.

Fig.2a Plot of average depth against bankfull width for middle and outer delta channel sections, taken from Mackay (1963; fig. 50, 51, 52).

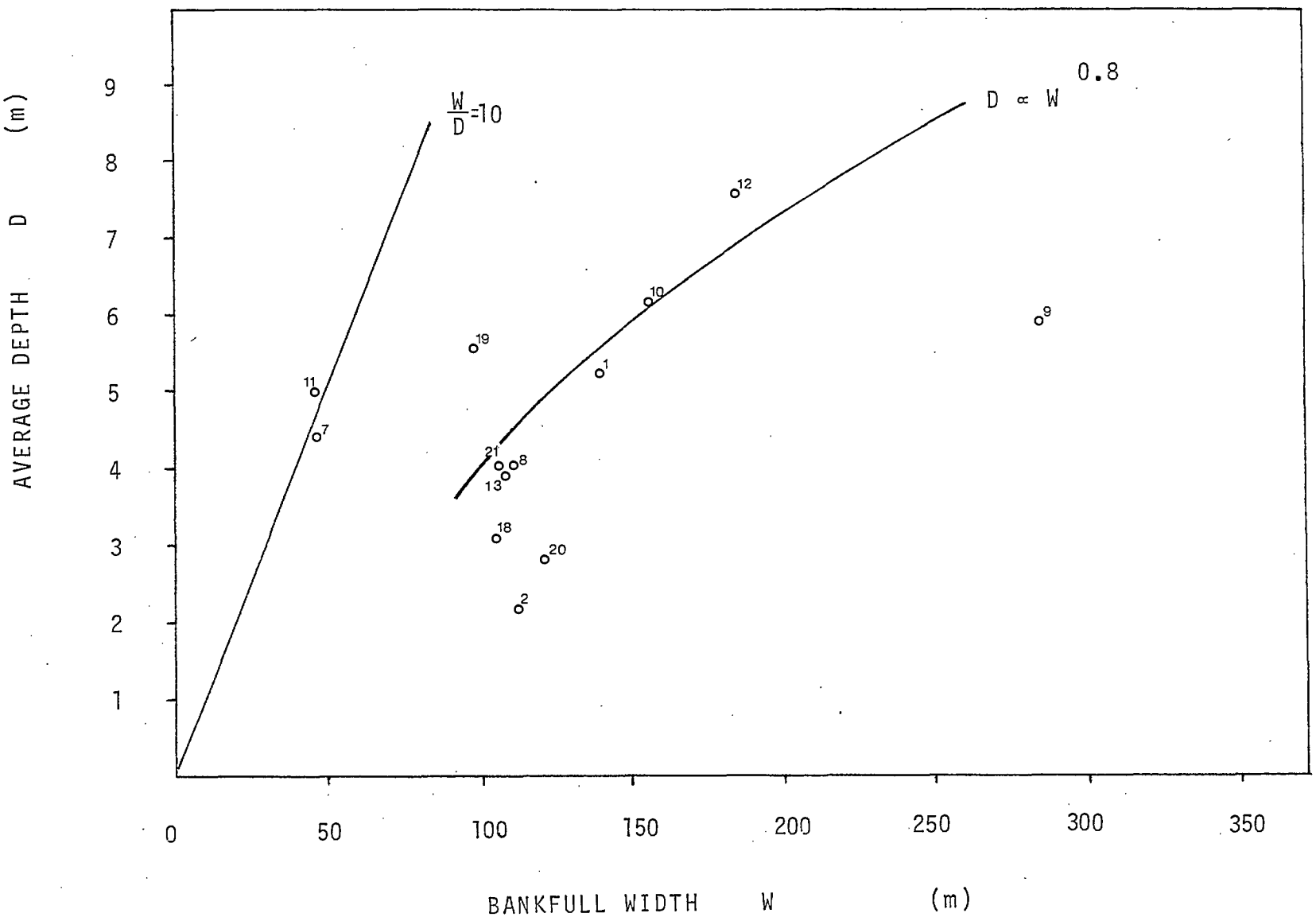
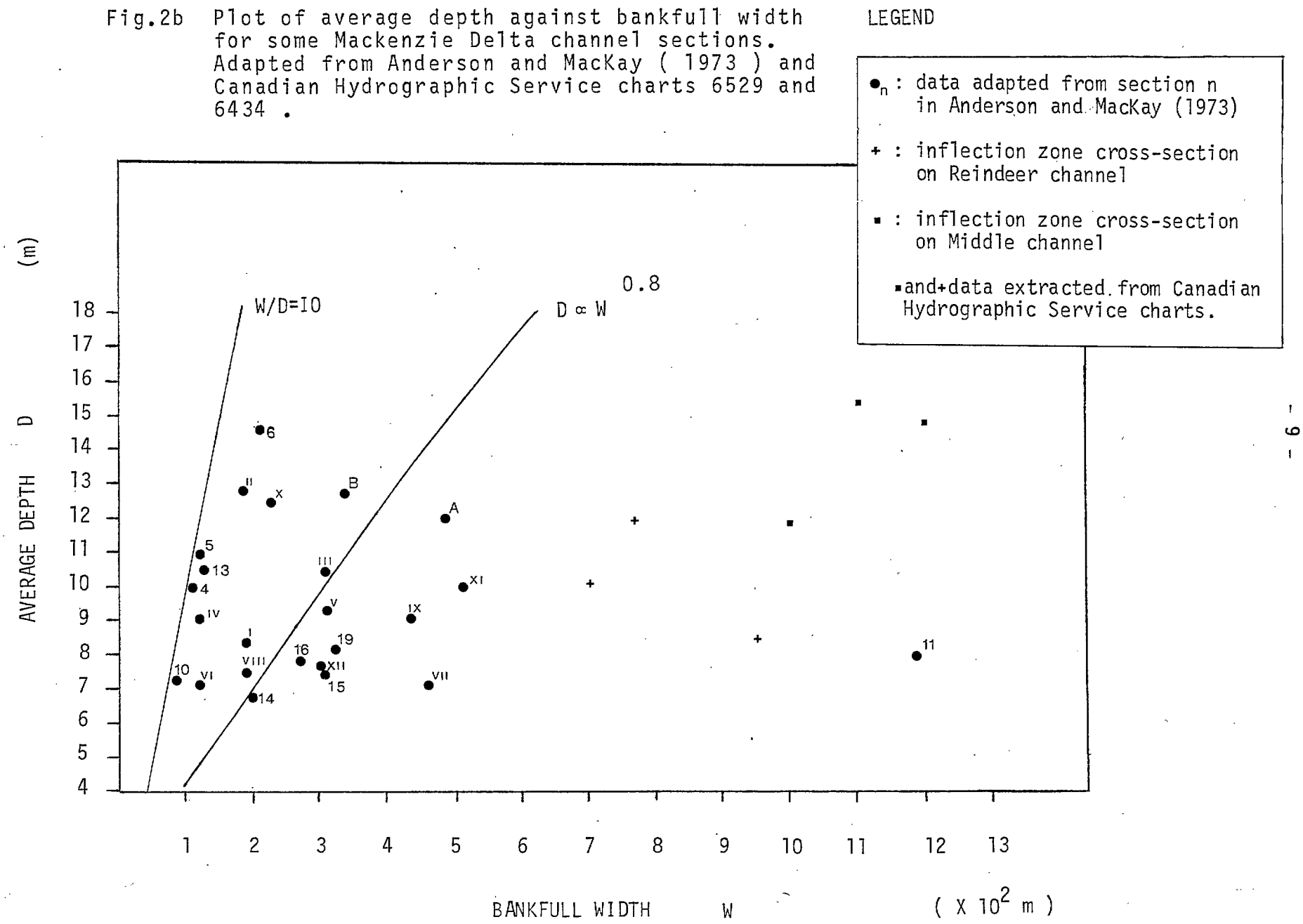


Fig.2b Plot of average depth against bankfull width for some Mackenzie Delta channel sections. Adapted from Anderson and MacKay (1973) and Canadian Hydrographic Service charts 6529 and 6434 .



The results are necessarily tentative, especially since the representativeness of depth data for wide channels may be affected by the relatively small number of such sections surveyed. Middle and Reindeer Channel data for open water conditions were extracted from National Hydrographic Survey charts, again modified to flood level. The data appear to indicate that bankfull channel depths in the Mackenzie Delta increase notably slowly as channels of greater width and discharge are considered. Furthermore, analysis shows this trend to be relatively insensitive to the exact regional pattern of stage difference from low-flow to bankfull. As a basis for comparison, the relationship $D \alpha W^{0.8}$, which follows from some commonly found hydraulic geometry relations $W \alpha Q^{0.5}$, $D \alpha Q^{0.4}$ (Richards, 1977) was plotted on both figures, adjusted to fit the average depth of narrow channels. As a corollary, it is seen that even relatively small channels have width to depth ratios well above 10, although they generally have very important silt-clay fractions in their boundary materials (see Sediment Transport). This contrasts with findings elsewhere: Schumm (1968) for example reported width to depth ratios less than 5 when silt-clay exceeded 30%, in a range of small and medium size channels in semiarid to subhumid areas of the U.S. and Australia.

Clearly, much more field work would be necessary to verify and completely document these trends, let alone establish complete hydraulic geometry relations. Yet such information not only has important predictive interest, but may lead to insights into the particular set of

controls at work in the creation and maintenance of Mackenzie Delta channels. In the section on sediment transport, some hypotheses concerning these controls will be suggested.

2.3 Bathymetry

The detailed bathymetry of Mackenzie Delta channels also presents interesting features. For this preliminary survey, many tens of echo-sounder traces were obtained by the author in small and medium-size channels ($50 \leq W \leq 400$ m), usually over sets of 2 to 5 closely spaced cross-sections. For lack of automatic distance measuring instruments, these surveys did not incorporate accurate horizontal control on the cross-sections. Nonetheless much qualitative information was obtained on channel bathymetry. A first notable feature was the very frequent occurrence of underwater ledges separating the thalweg zone from the steep facet of channel banks. Similar ledges have also been reported by Mackay (1963) and Hollingshead and Rundquist (1977). At late-summer low stages, these ledges usually extend under shallow water, up to a sharp break of slope marking the transition to the thalweg zone. They are most conspicuously developed on relatively straight channel reaches, where a distinct central inner-channel may occupy roughly half the bankfull channel width. The lower Middle Channel in the straight reach going up to the trifurcation near point Tununuk offers a striking example of this, as do certain upstream reaches of East Channel.

Smaller but distinct ledges are also in evidence along many cut banks in bends of small and medium channels. Figure 3 is a generalized

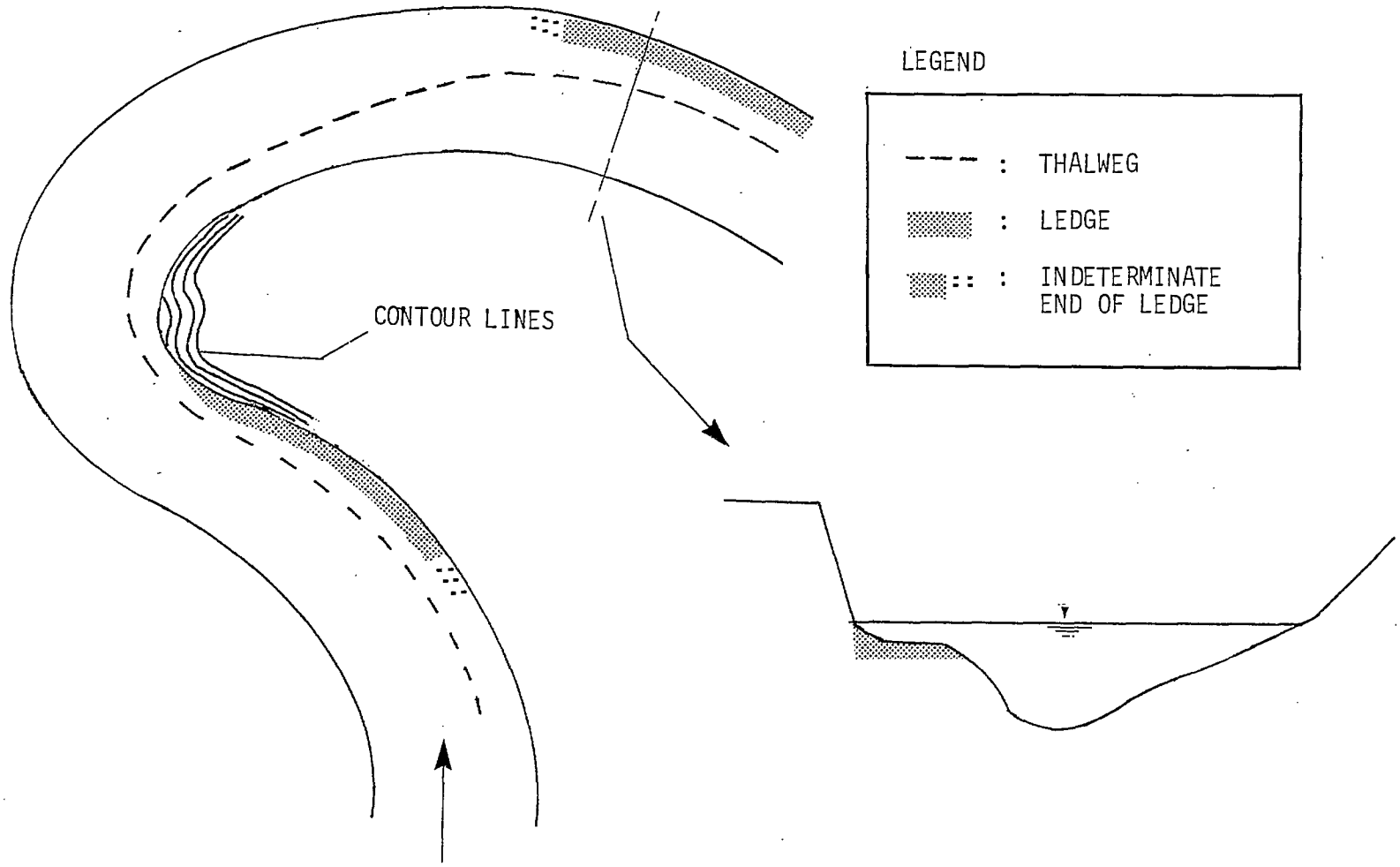


Fig.3 Generalized sketch of bathymetry in abrupt bends of small and medium sized Mackenzie Delta channels .

sketch indicating the path of the thalweg and the location of ledges in numerous bends that have abrupt (tight-curvature) entrances. Overall, the bathymetry shares the main features usually reported in field studies of meanders. The thalweg hugs the inner bank at the entrance to a bend, then shifts in the direction of the outer bank, where it remains until the bend exit. Yet the narrow ledge that quite often intervenes between thalweg and cut bank in the downstream part of bends in Mackenzie Delta channels is an unusual feature, which again may reflect particular local erosional or depositional processes. Another characteristic of sharp bends in these channels is depicted in Fig. 3: starting at the bend entrance, the thalweg typically hugs the inner (point bar) bank over a considerable distance. In many cases, this feature is associted with a well defined erosional embayment on the steep slope of the point bar, at bend entrance.

Another striking feature of channel beds in the Mackenzie Delta has been noted by Mackay (1963) and Hollingshead and Rundquist (1977): their bathymetry is often remarkably irregular. Our surveys showed that, quite commonly, the thalweg trace is very tortuous, if not discontinuous. Particularly in relatively straight reaches, repeated soundings may show the thalweg intermittently, and irregularly, on either side of the channel, and varying greatly in depth. This was very well expressed in certain reaches of Napoiak Channel for example. In addition, the bottom often displays multiple and apparently chaotic mounds and holes, both in transverse and downstream profile. To

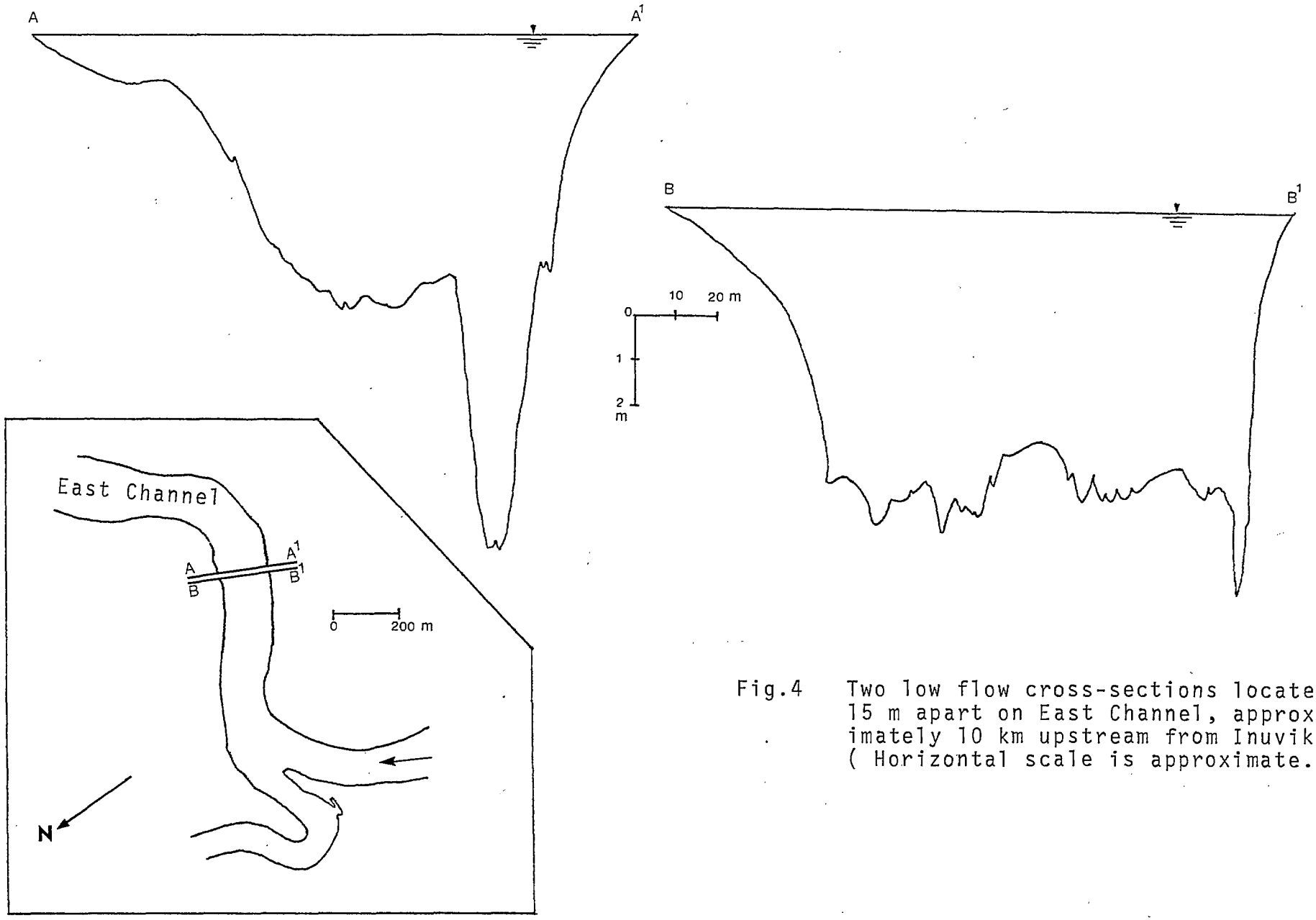


Fig.4 Two low flow cross-sections located 15 m apart on East Channel, approximately 10 km upstream from Inuvik. (Horizontal scale is approximate.)

illustrate this, Fig. 4 presents two transverse sections spaced 15 m apart in a 150 m wide reach of East Channel, 10 km upstream from Inuvik. Horizontal scale is approximate. One to two metre depth variations within 5 to 10 m horizontal distances, as those in cross-section BB', are quite common in small and medium-sized Mackenzie Delta channels. Starting in the next section, a discussion of basic fluvial processes at work in the Delta will clarify some of the morphological features described in previous paragraphs. Better definition of these features should result from bathymetric soundings in 1984.

3.0 Channel Shifting

The objective of this major component of the study is to determine the patterns of channel shifting over the Mackenzie Delta plain, as well as their controlling processes. In particular the goal is to clarify the relative contribution of hydrodynamic (current, wave), hydrothermal (permafrost melting) and ice-run processes in cut-bank erosion. Outhet (1974) has discussed erosion rates and processes, as well as resultant cut bank forms in the southern Delta, while Gill (1971) briefly commented on conditions in the Reindeer Depot area. In the context of the present study, a program of 20 to 30-year time-lapse air photo comparisons was completed, covering a range of channel types and areas of the Delta. The information on shifting patterns obtained was then compared with preliminary field observations of bank erosion processes occurring from breakup to summer low-flow conditions. Some conclusions of this study follow.

3.1 Shifting Patterns

Figure 5 (in back cover) presents a map of cut bank migration rates over a sample of channel reaches in the Mackenzie Delta, obtained through air photo comparison. Where space allowed only one value to be reported on a meander arc (between consecutive inflection points), this value is the peak for the arc. The comparisons were based on 1950, 1971 and 1981 air photos, at scales of 1:40,000, 1:70,000 and 1:52,000 respectively (Fed. Department of Energy, Mines and Resources). Extensive coverage was possible at a reasonable level of accuracy, using 1 and 2 power magnification on a Bausch and Lomb Zoom Transfer Scope. The average migration rates reported are thus mostly based on a 31-year time span (occasionally 20 years), and accuracies are generally better than $\pm$ 0.5 m/year. A slightly more accurate compilation is in preparation. As always, care must be exercised when comparing these average rates with field measurements of erosion conducted over a few seasons.

Many factors must be considered in interpreting these results. Cut bank erosion rates depend, in a direct way, on near-bank flow strength and duration, as well as nature and condition of cut banks. Flow strength along a particular cut bank can itself be related to channel slope, transverse profile (width, depth, etc.) and local alignment (bank line curvature and location of cut bank relative to adjacent inflection points in the channel trace). Cut bank properties relevant to lateral erosion include bank material textures, cohesiveness, chemical cementation, water and ice contents, vegetation cover, bank height and roughness, as well as seepage conditions, etc. Many of the

relevant variables are difficult to measure in a field setting and so the precise dependencies have generally not yet been established.

3.2 Flow Strength as a Shifting Control

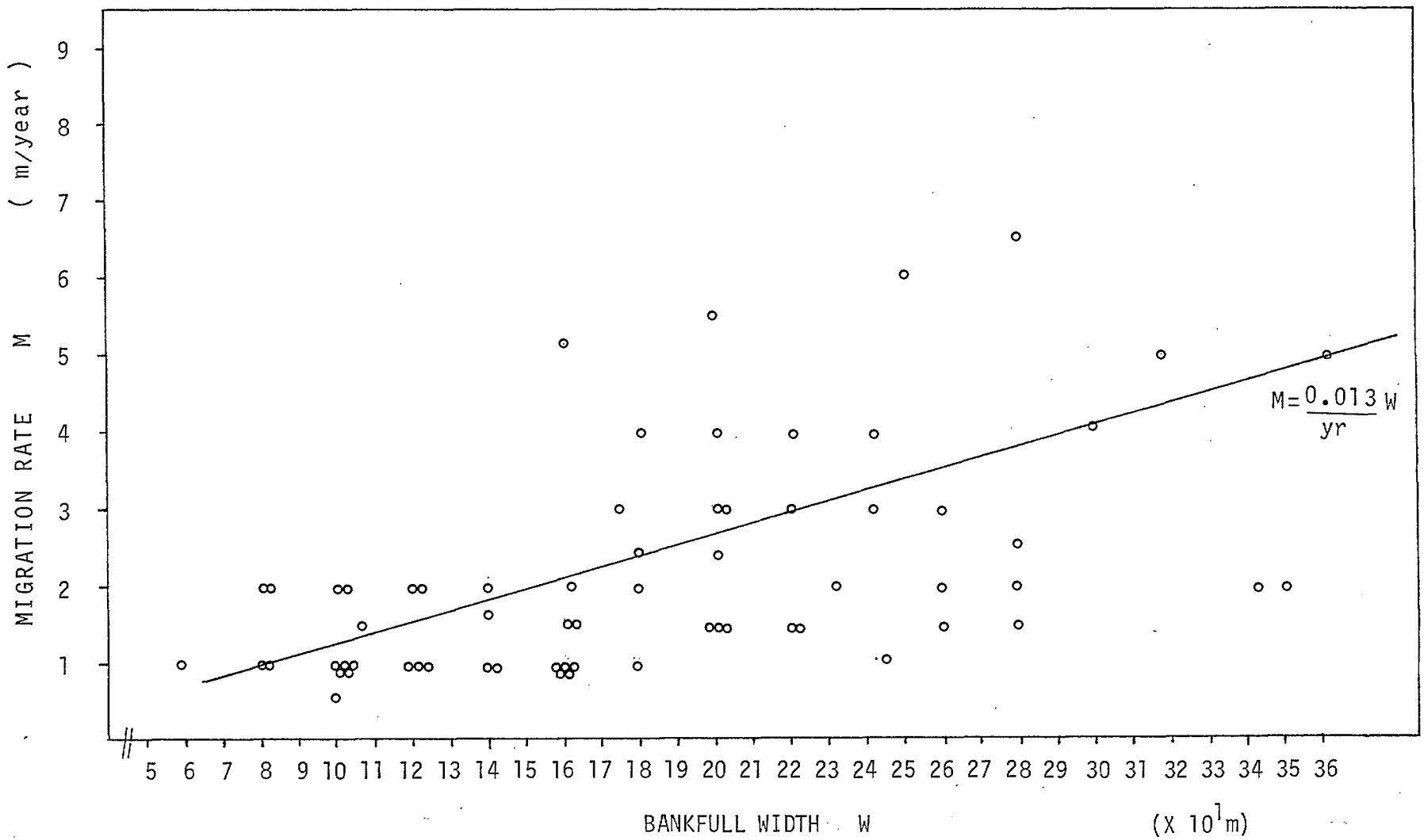
As will be seen in the next paragraphs, flow strength does appear to have a strong influence on bank migration in the Mackenzie Delta. Little detailed information is available on spatial patterns in energy slopes and flow strengths, but two inferences can be made concerning broad trends. The first one is that energy slopes should generally decline as Beaufort Sea is approached, if tidal and storm surge effects are neglected. The second one is that the slopes may not vary much between different channels in the same area of the delta, as long as they trend generally in the same direction with roughly the same distance to base level. This is because of the great degree of interconnection that prevails as a rule. As a consequence of the latter constraint, flow strength in distinct channels over a given area may correlate strongly with channel size; in particular, average flow shear stresses on the channel boundaries should depend on flow depths. That this holds at least at the extremes of the scale was confirmed by some rough determinations of bed shear stresses conducted in the two weeks following breakup in 1983. Stresses were evaluated through 4 to 5-point vertical velocity profiles, measured in relatively straight and uniform-bedded channel zones, and making use of the log. "law of the wall". In the large and deep Middle Channel, shear stresses in the 10 Pa range were measured

in 15 m of flow (near lat. 68°12'N), while in the deeper parts of smaller neighbouring channels, stresses remained in the 1 to 3 Pa range (4 to 5 m depths). These very approximate values can be put in the following perspective: Shield's curve indicates that, at 1 Pa, flat-bedded uniform sands of less than some 1.5 mm diameter are mobile while, at 10 Pa, 1 cm gravel should just be entrainable (Vanoni, 1975).

These variations in the scale of flow stresses appear to be reflected in bank migration patterns: in fig. 5, impressive shifting rates are to be found along Middle Channel, as well as along the higher gradient upstream reaches of Peel and Phillips Channels. Furthermore, within a given delta area (relatively constant energy slopes), shifting activity in seaward trending channels appears to increase with channel width, and hence to some extent with its correlates, channel depth and shear stresses. This trend is illustrated in figs. 6a and 6b, where the relationships between peak migration rates and local bankfull widths are plotted, respectively for conditions in the southern (below 68° N) and middle delta (between 68° and 68°30' N). Shifting values are only plotted for relatively tight bends, in order to standardize somewhat the influence of channel alignment.

A trend of decreasing shifting activity as Beaufort Sea is approached and energy slopes are reduced is also apparent in figs. 6a and 6b. For channels less than 400 m wide in the southern delta, migration rates roughly equal 1.3% of channel width, per year; this figure is of the order of 0.5% in the middle delta. For larger channels, while there are no tight bends on Middle Channel in the southern area to allow

Fig.6a Plot of peak migration rates versus local bankfull widths along relatively tight channel bends in the southern Mackenzie Delta. (below 68 N)



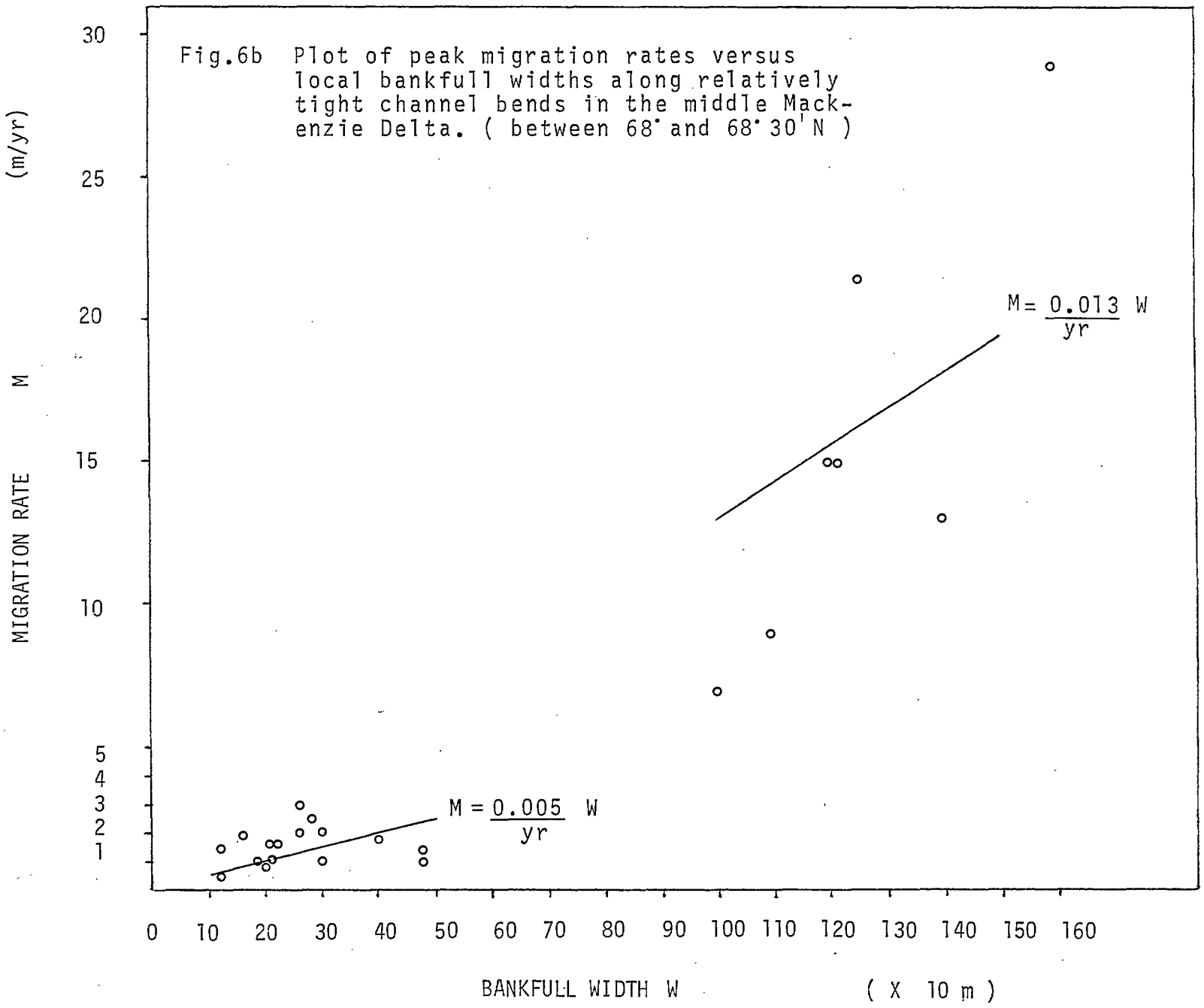


Fig.6b Plot of peak migration rates versus local bankfull widths along relatively tight channel bends in the middle Mackenzie Delta. (between 68° and 68° 30' N)

comparison, peak rates are some 1.3% of width in the middle Delta, while they are of the order of 0.5% on Reindeer Channel in the outer Delta, and generally of the order of 0.1% on the lower reaches of West Channel.

That flow stresses are an important control on bank shifting in the Mackenzie Delta, as in most environments, is also apparent from the detailed migration patterns in these channels. Fig. 7 is a map of 1950 to 1981 cut bank shifting patterns in the central reach of Middle Channel. Typical meander migration patterns are in evidence: peak migration is generally found in, or slightly downstream of, the bend apex area (area of maximum curvature). This usually corresponds to the early part of the developed-flow zone in channel bends (Apmann, 1972; Jackson, 1975) where the maximum velocity filament has completed its crossover to the new outer bank, and near-bank stresses are greatest. Although the scale of channel shifting is much reduced in small and medium-sized delta channels, here again maximum shifting typically occurs at the outer bank in the bend apex area. In addition, many of the latter channels have abrupt bend-entrances (as in fig. 3), in which case stronger erosion also affects the outer bank immediately upstream of, and at the entrance to, the bend. This also corresponds to the area where the thalweg was seen to approach the bank and occasionnally erode an embayment in the point bar just downstream. Strong erosive stresses have been reported in this location in many tight meanders elsewhere (Jackson, 1975; Hickin, 1978; Yen, 1970), they are linked to the "free vortex" acceleration of flow at inner banks in bend entrances.

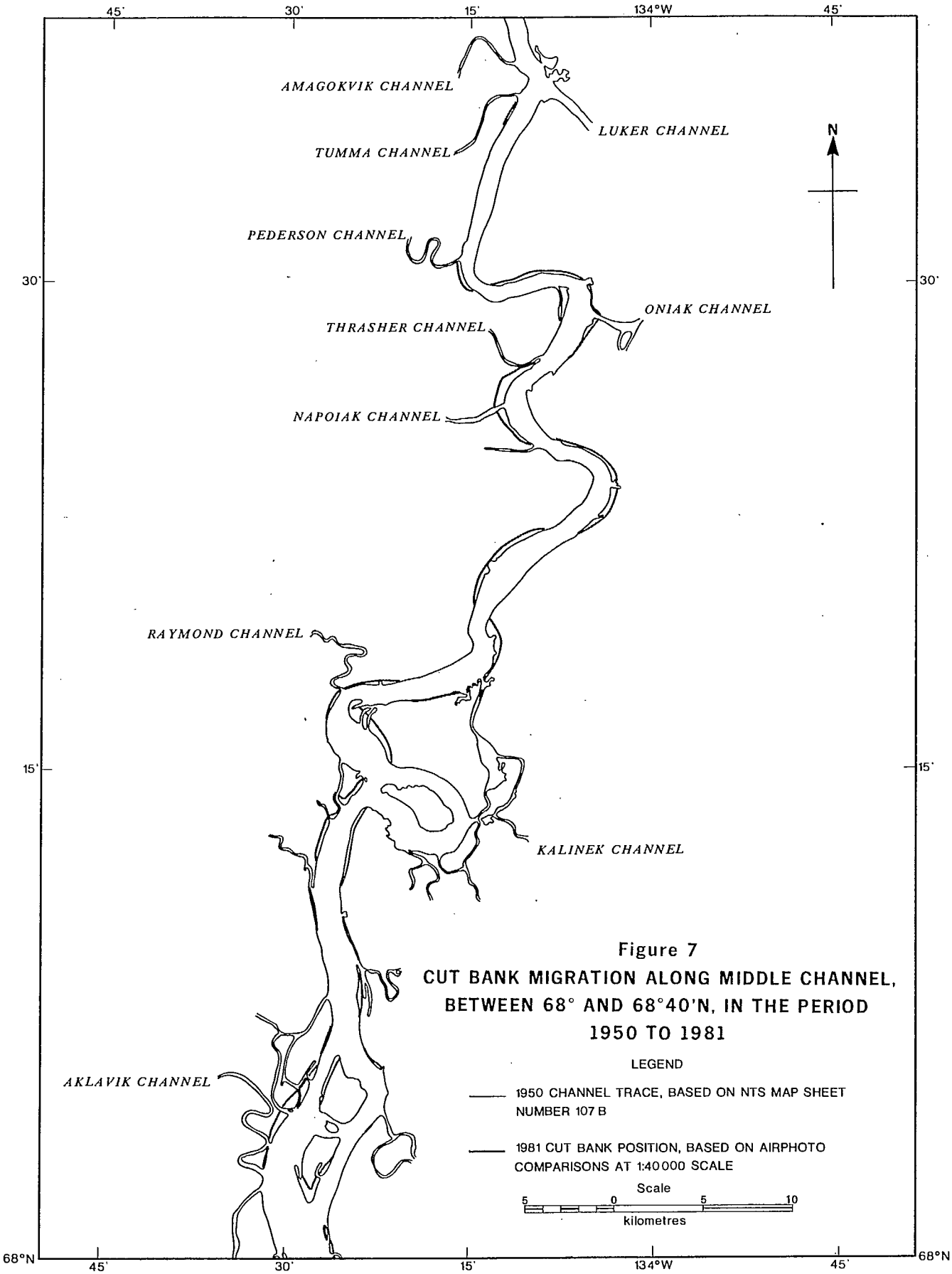


Figure 7
CUT BANK MIGRATION ALONG MIDDLE CHANNEL, BETWEEN 68° AND 68°40'N, IN THE PERIOD 1950 TO 1981

3.3 Bank Characteristics as Shifting Controls

The great control flow strength exerts on channel shifting is not surprising, although the disparity in strength between Middle and ambient channels is noteworthy. But what control do bank characteristics exert on the scale and patterns of shifting illustrated in fig. 5? Apart from bank heights and bank-top vegetation, little is known about the regional variations in other bank characteristics; while these two factors may not, by themselves, have a strong influence on bank erodibility in the Mackenzie Delta. In this preliminary study, much attention was paid to the simpler question: How do the general characteristics of delta channel banks affect shifting rates? Much has been said about the considerable resistance to erosion of "frozen-mud" delta banks (Gill, 1972b). While the thermal effects involved in erosion will be considered shortly, some preliminary comments on inherent sediment strength are appropriate here.

3.3 1 Bank Material Textures

It is generally recognized that cohesiveness of bank materials significantly reduces erodibility. Nonetheless, Grissinger et al. (1981) have demonstrated that for sandy silts with minor clay fractions, typical of much of the materials found in delta banks (Outhet, 1974; Gill, 1971; this study), critical erosive stresses may be quite low, although they vary strongly with percentage clay contents. Little is known about the

variability in bank material clay contents over the Delta, unfortunately. Data collected by Gill (1971) and Johnston and Brown (1965) confirm the limited preliminary sampling results from the present study and indicate clay contents in the 15 to 25% range, for the most part. Grissingers experiments suggest critical erosive stresses under 1 Pa, in such conditions, especially since the frictional strength component is reduced on sloping cut banks. Such stresses should be available locally, on outer banks in bends, even in relatively small channels where bed stresses may be in the same 1 Pa range (Ippen and Drinker, 1962). Direct field observations of the sandy-silt bank materials suggest that, once melted, they indeed loose much coherency.

There is nonetheless evidence of significant local variations in cut bank material stiffness in the delta, capable of affecting shifting patterns. A striking example of this was encountered at an abrupt constriction on Napoiak Channel near 68°28'N and 134°35'W. Cut bank strata at water level there were composed of bluish, plastic and quite stiff fine materials. Bed material sampling indicated as well that similar materials extended downwards towards the base of the deep scour hole at this constriction. Examples of lateral confinement at bends in smaller channels (with scroll patterns indicating purely downvalley meander shifting) can also be found on air photos, and these may be related to impingement on clayey deposits in lakes or abandoned channels.

3.3 2 Permafrost and Hydrothermal Effects

The erodibility of cohesive sediments depends on a multitude of factors and remains a vexed question. It will be briefly discussed again in the next section, in the context of bed material transport in Delta channels. Yet, permafrost and segregated ice are further complicating factors affecting the erodibility of bank materials by running water in the Mackenzie Delta. Hydrothermal effects in the form of "thermo-erosional niches" (Czudek and Demek, 1970; Walker and Arnborg, 1966) that undermine cut banks can be observed here; fig. 8a presents a typical example of niching in the Delta. Interestingly, reconnaissance expeditions by air and river during the spring and summer of 1983 also disclosed a clear pattern in the distribution of thermal niching; while deep niching was prevalent along "rapidly" eroding banks of Middle Channel and the Peel in the southern delta, other smaller channels, inspected in the eastern portion of the Delta presented only very rare examples of localized and shallow niching. This raises an interesting question: does thermal niching cause, or merely reflect, higher rates of cut bank erosion in the Mackenzie Delta? To try to answer this question, the complex controls on hydrothermal erosion must be considered. This will be done after a brief review of current knowledge on niching.

3.3 2 1 Thermal-Niching: A Brief Review

Thermo-erosional niches are deep and relatively narrow hollows, carved, at or near water level, out of cut banks containing significant

Fig.8a A thermo-erosional niche along a cut bank on Middle Channel, in the Mackenzie Delta, N.W.T.

Fig.8b Non-niched but actively eroding cut bank in the Mackenzie Delta, N.W.T.

amounts of segregated ice, by the interaction of thermal and hydrodynamic (current, wave) effects. In some environments, erosion of niches into cut banks has been reported to be very rapid; Williams (1952) reports 11 m of incision in two days, which is not atypical. The following scenario appears to be common: after incision, the frozen bank overhang above the niche degrades subaerially and eventually collapses, often along a failure plane determined by ice-wedges. By the end of the next high flow event, if not earlier, slump materials have been washed away and fresh niches have usually been excavated out of the bank face.

Much remains unclear about the precise controls and geomorphic implications of niching however. The exact vertical location of niches may depend on stratigraphic characteristics of the bank section: strata rich in segregated ice are prime candidates, because of the great erodibility of thawed sediments saturated with excess waters (although the high latent heat of fusion of ice may put an upper limit on this effect). Scott (1978) observed that niche apices tended to occur on coarser, possibly more thermally conducive materials, in composite bank sections. Such stratigraphic effects are nevertheless difficult to verify under deep and very unstable bank overhangs. Concurrently, random high wave-energy events, combined with water level changes, may play a great role in locating niches. It is also unclear whether strong currents can, by themselves, excavate niches below water, that will only become exposed subsequently at the water surface. Lateral depth sounder profiling as well as time-lapse photography of a niched cut bank along Middle Channel during the 1984 field season many shed some light on the latter questions.

The implications of permafrost erosion and niche development in fluvial settings are also disputed. In various studies, permafrost has been held to retard or to regularize lateral erosion by stabilising bank materials against flow stresses (Cooper and Hollingshead, 1973; Scott, 1978); or, on the contrary, to accelerate bank undermining and retreat through hydrothermal effects (Walker and Arnborg, 1966; Ritchie and Walker, 1974). Preliminary evidence will help to shed light on some of these issues as they relate to the Mackenzie Delta.

3.3.2.2 Controls on Niching in the Mackenzie Delta

The regional distribution of thermal niching in the Delta that was mentioned earlier suggests that flow strength, here again, may exert a decisive control: greater migration rates as well as thermal niching appear to coincide with the relatively stronger flow regime of Middle Channel, and upstream Peel reaches. To clarify the importance of flow strength, other factors that may exert a control on this distribution must nonetheless be considered: in particular these are sediment textures, ice contents, and wave regimes.

Repeated observations of cut bank materials over the eastern half of the Delta and below 68°20'N failed to disclose clear textural differences between niched sites and sites devoid of these. It was also

impossible to establish reliably, short of a laborious sampling program, the existence of any systematic difference in segregated ice contents through casual and necessarily biased observations. Large ground-ice masses (wedges and veins) are indeed readily observable in many niched bank profiles, and a characteristic scalloping of the bankline along high-energy cut banks of Middle Channel appears to betray overbank polygonal wedge networks. Yet, niched bank profiles by their very nature tend to reveal large ice masses, in addition to exposing fresh permafrost faces, while a relatively stable thawed layer mantles and conceals the permafrost in non-niched bank sections. Fib. 8b (p. 26) illustrates the latter type of active cut bank. Spot excavations conducted in such bank faces nonetheless revealed considerable ground ice in the form of closely spaced veinlets, although odds did not favor hitting important ice masses.

In the final analysis however, it seems improbable that regional differences in bank ice content (averaged over lengthy river reaches) could explain the prevalence of niching on Middle Channel to the exclusion of neighbouring smaller channels. Many of the latter channels run alongside and only a few kilometers away from Middle Channel on the delta plain. With no significant textural differences in bank materials, ice content should be comparable. At the local scale however, high ice contents may play a role in some cases of localised and restricted niching along minor channels.

Wave regimes must play a role in controlling the rapidity or extent of niching that so often seems to occur at water level. Clearly, smaller channels do not provide the large fetches that lead to high-energy wave attack on cut banks along Middle Channel. Nonetheless, fetch or orientation may not exert a determining influence on the distribution of niches in the Mackenzie Delta. For example, niches are uncommon along upstream reaches of East Channel that are as wide as niched sections of Peel Channel. More importantly, the evidence presented in figs. 5 and 7 indicates that dominant northerly and westerly-sector winds (Outhet, 1974) do not translate into clearly preferred shifting of eastern or southern banklines along Middle Channel.

3.3 2 3 Geomorphic Implications of Niching

If flow strength does play a crucial role in the distribution of niches, an interesting side-question remains however: why are niches generally absent, rather than only underdeveloped, along minor delta channels, as repeated observations during and after breakup have shown? On many of these channels, steep unvegetated cut banks testify to erosion during spring high-flows, and air photo comparisons disclose shifting rates of the order of 1 m per year. As was argued above, in many cases segregated ice content is appreciable, while the water temperature regime is similar to that of Middle Channel; consequently, this limited

erosion might be expected to involve some hydrothermal niching. The solution to this problem appears to be provided by end of summer observations of the thawed layer on the exposed portion of these cut banks. Depths of thaw of 1 to 1.5 m were measured, with excess waters mostly drained from this mantle. Arguably then, thermal niching will occur the following season only where flow and wave strengths combined are sufficient to erode well beyond this refrozen, lower ice-content layer. This threshold involving active layer depth appears to be confirmed by the relationship between shifting rates and thermal niching in the Delta. For example, moderate 2 to 3 m/yr shifting along side channels to Middle Channel near 67°50'N and 134°30'W (fig. 5) was seen from the air to involve clear niching of cut banks. Erosion pins at non-niched cut bank sites, driven beyond the frost plane in the autumn of 1983, should help verify the relationship between eroded and active layers after 1984 breakup.

A more important issue is whether hydrothermal erosion, beyond this threshold, entails accelerated bank retreat i.e.: greater retreat rates than those produced by the same flow regime, acting on materials devoid of segregated ice. In silty banks with high ice contents, for example, the rate of niche excavation should be limited by the rate of melting at the frozen face since, ideally, any melt releases saturated muds that can be eroded away almost effortlessly, exposing the melt front. This does not necessarily cut down on erosion: heat transfer to the melt front directly from running or splashing water increases with

its temperature, but also with flow rate at the face. Hence, as in "non-thermal" erosion, the erosion rate will increase with current or wave strengths. Whether it is relatively accelerated or not should depend on the nature of the materials, the geometry of the niche, the temperature of the water, etc., and is best determined experimentally.

Available field evidence suggests that retreat rates <u>at niche level</u> may be accelerated compared to non-permafrost conditions, in many cases. Depending on the rate of disintegration and evacuation of the failed bank overhang, this may be true also for retreat from niche level to bank top. But it must be kept in mind that, in a meander setting, sustained cut bank migration involves all the bank profile, down to the thalweg, and not just the section above water level. In the context of deep channels, this may severely limit the importance of hydrothermal effects. Near the apex of Middle Channel bends, for example, the cut bank plunges 30 to 40 m below the low water plane, while the subaerial section rarely exceeds 7 m in height. Do hydrothermal effects on the underwater slope insure erosion rates that are in line with potentially accelerated niche erosion above water? Different lines of evidence suggest that this may not be the case. Although peak shear stresses are found underwater, the contribution of wave erosion is of course eliminated. More importantly, conditions at the submerged bank face may be much less conducive to hydrothermal effects. The frost plane may be somewhat deeper into the face because of melt resulting from adjacent waters through the winter season. In addition, theory (Williams, 1968)

as well as data from borings near Inuvik (Johnston and Brown, 1965) indicate that segregated ice contents rapidly decrease in the first 10 m below the delta plain surface, further reducing the potential for hydrothermal erosion.

There is also some indirect evidence for a concentration of hydrothermal erosion above the low-flow water plane. It is interesting to note in this respect that a narrow shelf usually extends riverward from the floor of deep niches in Middle Channel. Usually 5 to 10 m wide, it allows boat groundings and even observations on foot to be made in front and outside of the niche. It is conceivable that this beach-type feature, as it insures some reduction in current and wave energies at niche level and curtails upper bank retreat, may come about as a response to the unequal subsceptibilities to erosion of lower and upper bank sections. If this is correct, bank migration in Middle Channel is ultimately controlled by mostly hydrodynamic processes over the lower cut bank and may not be accelerated significantly by hydrothermal effects. This may also explain the dominance of a fluvial over an eolian signature in shifting patterns observable in figures 5 and 7. Similarly, but in the case of minor delta channels, the weakness of flows rather than the resistance of frozen banks may be mostly responsible for the subdued shifting activity. This is supported by evidence from sporadic probing of underwater cut banks in these channels during breakup high flows. Shallow (2-15 cm) thawed layers were generally encountered, indicating local thaw rates that exceed erosion rates. More extensive probing will further test this conclusion.

3.4 Ice-Run Erosion

Ice-run erosion is another process mainly concentrated near the high-flow water surface. Ground and airborne observations during the 1983 breakup revealed that, locally, strong ice floes, used as tools by channel currents, gouged out shallow indentations into frozen cut banks, or were driven overbank. As channel stages lowered, such tool marks were occasionally observed in the upper half of cut banks. Nonetheless, our limited field observations confirmed Gill's (1971) impressions that, at least certain years, the extent of ice candling in many Mackenzie Delta channels at breakup, weakening the ice, generally limits the importance of ice-run erosion. Furthermore, what erosion does occur near the high-flow water surface must be matched by flow-induced erosion of the cut bank down to the thalweg, if steady state channel shifting is to be maintained. Further airborne observations during the 1984 breakup may add some detail to the preliminary conclusion that ice-run erosion does not play an important role in lateral channel shifting in the Mackenzie Delta. In particular, the morphological effects of any important ice jams on Middle Channel remain to be clarified.

3.5 Conclusions

In conclusion, preliminary evidence suggests that channel shifting patterns in the Mackenzie Delta are essentially controlled by current strengths, with secondary roles played by hydrothermal and ice-run effects. Nonetheless, the importance of hydrothermal effects, especially in channels shallower than Middle Channel, has yet to be

completely determined. Ideally, this might be done by comparison of erosion data from field settings differing only on the basis of bank temperatures and ice contents. Unfortunately, ideal conditions are rarely encountered. Laboratory tests might also provide basic answers.

4.0 Sediment Transport

As part of the 1983 reconnaissance surveys, exploratory samples of bed materials were collected in various channels over the eastern half of the delta, and attention was paid to channel-lake sedimentary interactions. Such geomorphological evidence can help identify local sediment transport patterns worthy of study; it can also better direct detailed (and expensive) sediment load monitoring programs. Ultimately, from a geomorphological standpoint, sediment transport patterns are of relevance to regional aggradation or degradation over the delta plain, to lateral channel shifting, as well as to the sediment budget at the delta front.

4.1 Spatial Patterns in Bed Materials

The contrasts in flow strength and shifting activity between Middle Channel and its tributaries and distributaries are, to some extent, paralleled in the nature of their bed materials and transported sediments. Gravels and medium to coarse sands were sampled on Mackenzie River just downstream from Point Separation. In this area a sudden

change in channel slope and resistance of bank materials has induced deposition of parts of the sediment load; as well, 30-year air photo comparisons indicate extensive shifting among the numerous shoals in the area. Limited sampling downstream appears to indicate that medium and fine sands dominate on the bed of Middle Channel, at least as far as Oniak Channel (68°25'N), while streamwise bed profiling reveals extensive dune fields on the channel bed. In contrast, mid-summer sampling along most smaller delta channels indicated a predominance of high water content, silt-slurry bed materials, with variable but usually minor fine-sand fractions admixed. Along Napoiak, East Channel and their distributaries, these percentage sand fractions were very variable within short reaches or even within individual cross-sections: isolated pockets of fine sands surrounded by muds were often encountered on the channel bed. General accumulations of sands are found, however, near the entrance to Napoiak Channel and in the upstream reaches of East Channel; and fine-sands also appear to predominate in the downstream reaches of Napoiak Ch. and at the entrance to Shallow Bay. Fig. 9 illustrates the range of bed material grain-size curves for samples collected in tributaries and distributaries of Middle Channel, during mid-summer of 1983.

The localised distribution of sandy bed materials in Mackenzie Delta channels appears to result from the morphology of channel junctions off the main sand thoroughfare, Middle Channel. Due to differences in equilibrium depths, the entrances to distributaries are generally perched

LOGARITHMIC-PROBABILITY GRAPH OF GRAIN-SIZE DISTRIBUTION

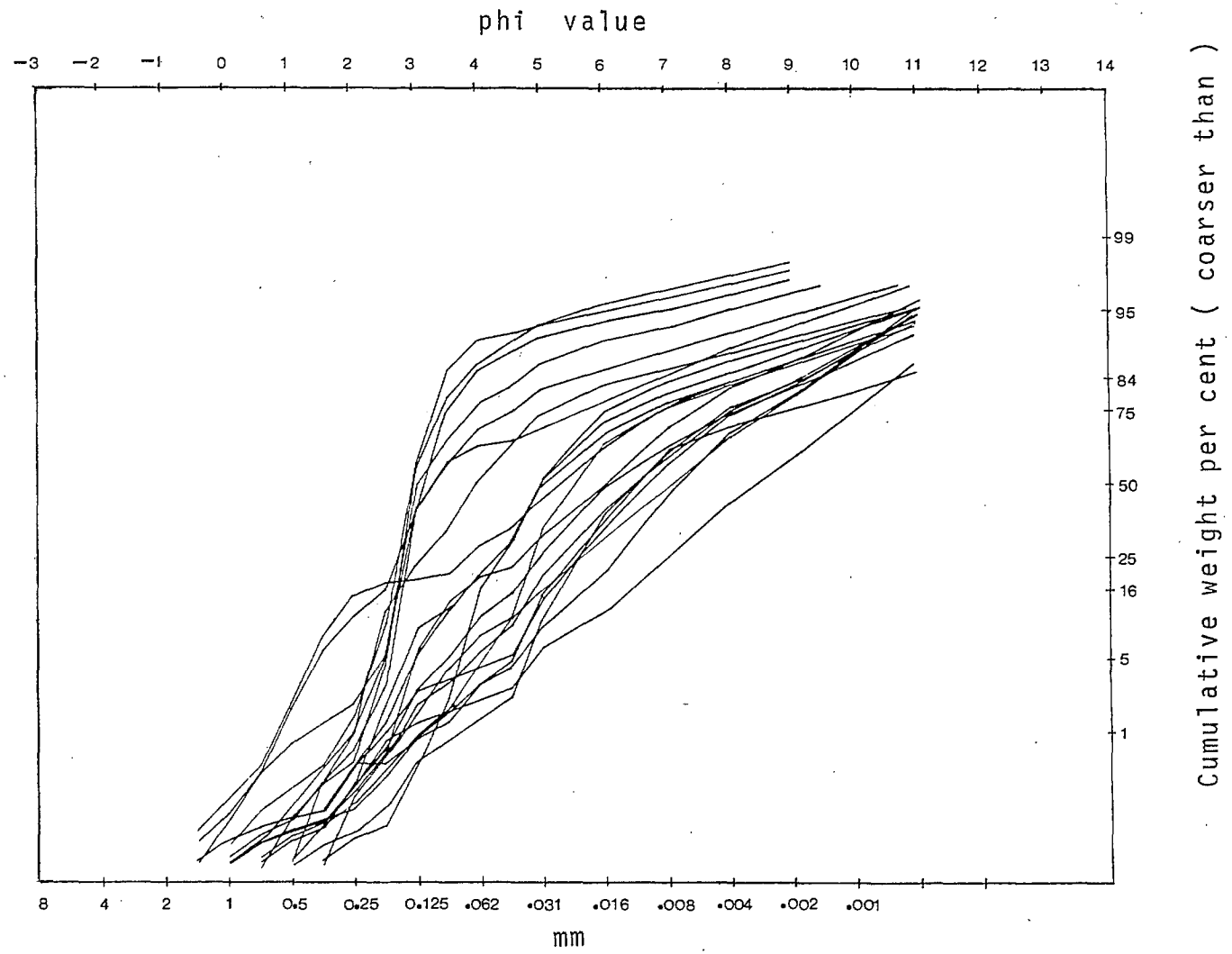


Fig.9 Representative grain-size curves for bed material samples collected in mid-summer along tributaries and distributaries of Middle Channel in the Mackenzie Delta .

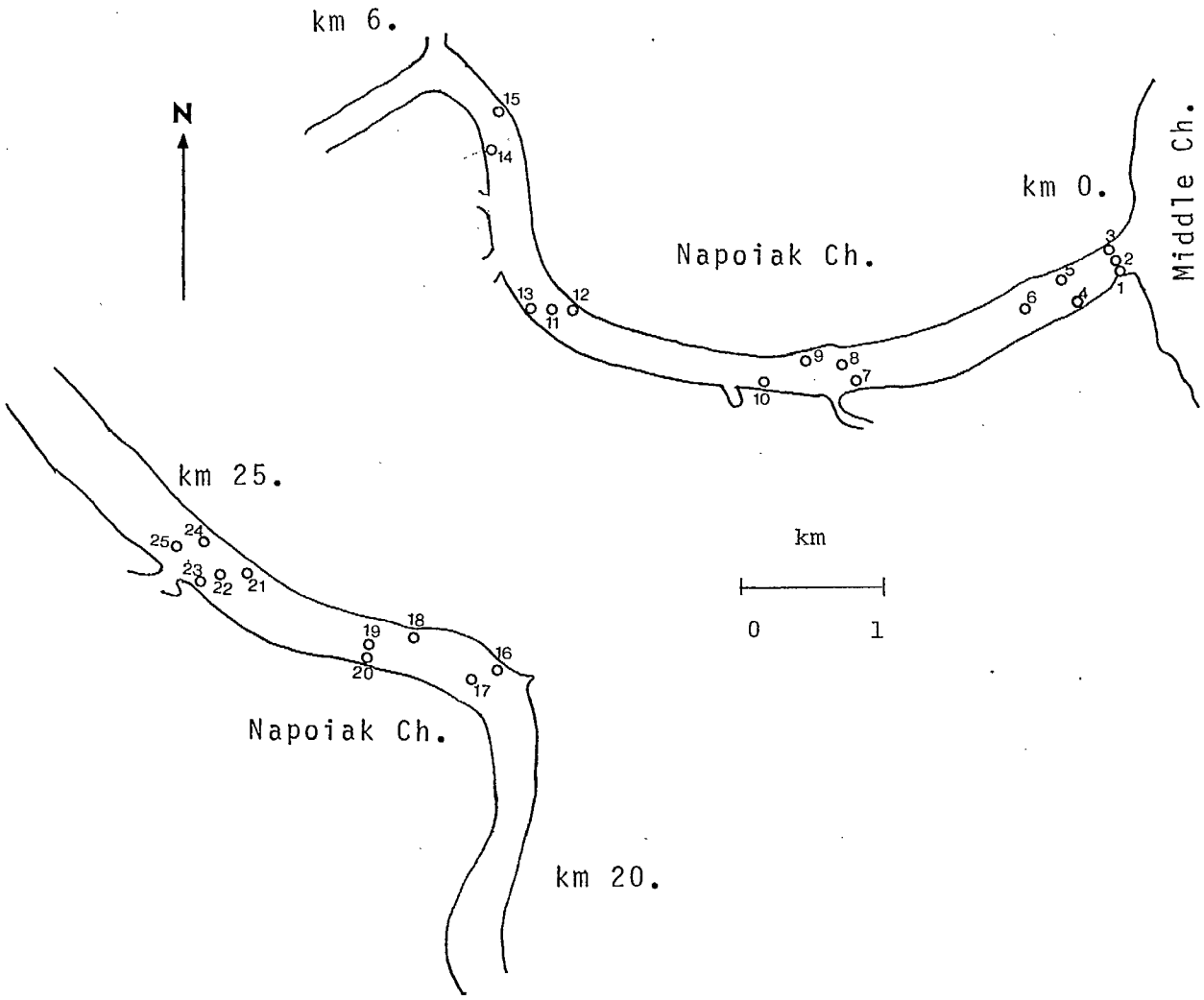
high above the thalweg of the parent channel. The Canadian Hydrographic Charts for the Mackenzie Delta illustrate this well: for example, East and Napoiak Channel junctions with Middle Channel are set by thresholds at roughly 10 and 20 m above the local Middle Channel thalweg, respectively. The following scenario may thus be envisaged: high flows on Middle Channel, during and in the days following breakup, bring up appreciable concentrations of fine sands tens of meters above thalweg (aided in this by the reduction in fall velocities in near-freezing waters). Concurrently, large amounts of these sands are dropped over the thresholds and in the upstream reaches of the distributary channels. Later on, with lowered stages (and higher water temperatures) in Middle Channel, the supply of sands to these delta distributaries is reduced radically. Yet, bed shear stresses in the distributaries themselves, over the summer period, are apparently sufficient to evacuate much of these fine sands downstream (fine sands have critical erosive stresses as low as 0.2 Pa; Vanoni, 1975). Thus, with a limited supply of fine sands, distributary beds are gradually swept clean over many reaches, leaving behind the (possibly) slightly less erodible (or less supply-limited) clayey-silt bed materials. Sands ultimately accumulate in delta front areas such as Shallow Bay.

Church (1981) mentions data on outer-delta channel bed materials which also support a sand evacuation model. It is further sustained by the detailed location of sandy bed materials in the distributaries, sampled at mid-summer of 1983. The large accumulations

of sands near the head of distributaries have not been completely evacuated: in particular, relic dune fields are still observable on sandy shoals in the upstream reaches of East Channel, in autumn. More interestingly, there is some indication that sands preferentially linger in lower-energy channel zones. Fig. 10 presents data on bed material textures in mid-July of 1983 along two reaches of Napoiak Channel. The spatial variability in the importance of the sand fraction is obvious. There also appear to exist trends towards greater sand contents in straight reaches, as well as in the inner bank zone in curved channel reaches. The latter trend, in particular, appears to be confirmed by sporadic sampling along East Channel and one of its distributaries near Inuvik. In these last two areas, however, greater distances from Middle Channel translate into sand fractions that are smaller, overall, that those on Napoiak Channel. Further sampling in 1984 will clarify the distribution patterns of sandy bed materials and, in particular, verify whether this mobile fraction is indeed preferentially evacuated from the thalweg in bends.

4.2 Aggradation, Degradation and Sediment Transport

Over the longer term, regional aggragation or degradation determine how the sediment discharges from Mackenzie River are modified quantitatively during their transit over the delta plain. Local influxes of sediment to the channel system from retreating cut banks are, for the most part, compensated by simultaneous deposition onto point bars facing



Sample	Depth (m)	%Sand	%Silt	%Clay	Sample	Depth (m)	%Sand	%Silt	%Clay
1	5.5	70	24	6	14	5.2	2	58	40
2	5.8	73	21	6	15	6.1	6	77	17
3	3.7	35	52	13	16	3.0	0	78	22
4	3.0	16	73	11	17	4.6	3	72	25
5	4.6	5	77	18	18	3.7	2	72	26
6	4.6	64	29	7	19	7.0	91	7	2
7	6.1	10	70	20	20	4.6	19	55	26
8	3.0	80	17	3	21	5.2	20	68	12
9	2.4	20	71	9	22	4.9	85	13	2
10	9.1	7	78	15	23	4.6	37	56	7
11	6.1	63	33	4	24	5.8	89	10	1
12	6.1	87	12	1	25	3.0	31	58	11
13	3.7	11	72	17					

Fig 10. Percentage of sands, silts and clays in bed material samples along two reaches of Napoiak Channel in mid-July 1983.

these cut banks. Nonetheless, one way this rough balance may be upset is for long term lowering or raising of channel beds to occur in a particular area. As a rule, aggradation dominates in a delta setting, unless severe erosion of the delta front or lowering of base level occurs. Yet some erosion of the delta front of the Mackenzie, particularly in Shallow Bay, is occuring (Mackay, 1963). Vertical channel movements may be detectable through systematic differences in elevation between retreating cut banks and accreting inner-bank margins, across channel from them. Surveying will be conducted along selected transverse profiles, where wide scroll plains are found, in an attempt to assess any such effects. This analysis, however, may be complicated by the effects of segregated ice buildup on bulk sediment densities at the surface of the delta plain.

One of the major processes of aggradation on the Mackenzie Delta Plain consists in delta-lake infilling during the breakup flood period. Similar occurrences in the Colville River Delta are discussed by Walker (1978). Thirty-year airphoto comparisons reveal that, on a regular basis, small and isolated lakes that are approached by shifting channels become completely filled with sediments. Typically, due to the short approach distances involved, considerable energy gradients are developed between lake and channel during rising and falling flood stages, and a shallow connecting channel is incised over bank top. These channels are nonetheless generally short-lived, as their purpose is eliminated with the complete infilling of the isolated lake they feed. Many infilled

lakes are then partially "eaten-up" by the migrating channel. Given some information on the bathymetry of these small lakes, it may be possible to estimate the importance of this component of delta plain aggradation through time-lapse air-photo comparison.

4.3 Avulsions

A different and geomorphologically more interesting situation occurs where channels overflow into a larger lake system, particularly when the latter becomes integrated into the delta channel network and can maintain throughflow. In such cases of avulsion, a new channel, formed by the progressive extension across the lake basins of "reverse deltas" and their underwater levees, becomes part of the delta network. Ultimately, the typical result is a tortuous channel that "wanders" through small lake remnants without touching them, and is occasionally interrupted by a lake basin not yet completely bridged. Fig. 11 presents examples of such occurences in the Mackenzie Delta. These avulsions appear to be the main mechanism for creation of new channels on the delta plain, and are powered ultimately by the random search for shorter channel paths to base level. A very similar series of events as that described above led to the establishment of the present Atchafalaya Channel (Tuttle and Combe, 1981) in the Mississippi Delta.

To the geomorphologist these occurrences are interesting in that they provide repeated and observable examples of the creation of

Fig.11 Avulsions on the Mackenzie Delta Plain, near 68°25'N and 134°5'W .Notice the new channel in the lower-left quarter of the photograph: it completes an alternative link between Middle and Oniak Channels.

Fed.Dpt.of E.M.R. photo A25776-133 (1981)

self-formed channels. As well, processes leading to the extension of major channels at the delta front are not unrelated to those at work in the more sheltered environments of inner-delta basins. Because delta channels were ultimately formed through such processes, their study is basic to the understanding of channel morphology. In this perspective, broad areas for further study will be discussed in the next paragraphs.

The great irregularity in planform of most of the smaller delta meanders that was described earlier (cf. fig. 1) may be traceable to circumstances accompanying their formation, and to the subdued character of migration thereon. In particular, many currently forming channels appear to be randomly deviated by islands and shores within the lakes they are crossing (cf. fig. 11). More importantly, the very mechanisms of reverse delta progradation within these infilling lakes appear to lead to irregularly spaced abrupt bends in the extending channel. Airphotos show such bends to occur where important "middle ground" shoals (Wright, 1977), formed at the mouth of the reverse deltas, lead to incipient bifurcation, often with abandonment of a minor arm. Very detailed monitoring of reverse deltas may clarify what triggers these periodic bifurcations. In any event, such meander inception processes may be sufficiently different from those in alternate bar contexts to explain differences in meander styles.

Some other morphological characteristics of Delta channels may be better understood if the probable conditions under which these were

formed are considered. For example, consider the apparent weak slope of the curve linking channel depths to widths in the Mackenzie Delta, which was discussed earlier and illustrated in figs. 2a and 2b. This and other aspects of the Regime character of delta channels may be strongly controlled by the constraints on water surface slopes across the delta plain. In Nature, larger channels generally have smaller slopes, and increasing depths maintain boundary shear stresses capable of transporting the sediment load. In contrast, it was argued previously that, in the Delta, slopes cannot vary much between two channels of vastly different size running roughly parallel to each other. This may partly explain why the depth of the larger channel is not much greater than that of the narrower one. Although there is no concensus yet on the rational basis for Hydraulic Geometry, and key components of the problem are very difficult to study in the field, it is possible that bank stability partly limits average boundary shear stresses, and hence depths, in the Delta. As a first approach to this complex problem, it would be interesting to obtain high-flow bank shear stress values over a range of channel sizes.

The irregular "hole and mound" bathymetry detected in many channel reaches (cf. section 2.3) may also reflect formative conditions. Bed material sampling in these areas occasionally brings up small fragments of relatively stiff muds, among the more numerous samples of "fluid mud". It is conceivable that these areas of chaotic bathymetry are localised erosional zones on the channel beds, i.e.: zones where incision has occurred into older, more highly compacted and hence less

easily erodible delta sediments (Thorn and Parsons, 1980), and which have not become completely mantled with transported sediments. While relatively loose fresh alluvium may form the boundary of shallow channels running through old lakes, deeper and wider channels probably have had to be excavated below lake bottom in better consolidated muds. Hollingshead and Rundquist (1977) also present evidence from Shallow Bay that freeze-thaw cycles may have locally produced an overconsolidated crust in silty channel boundary sediments.

A pitted and irregularly channeled topography is common on erosional surfaces in coherent materials such as rock or clay. In particular cases, extended "inner channels" have also been observed to form and these have generally been ascribed to shear stresses concentrated by the action of secondary currents (Shepherd and Schumm, 1974; Partheniades, 1965). This is but one of many possible mechanisms which may explain the existence of such inner channels within Mackenzie Delta channels. Alternative mechanisms include lateral widening near water level due to wave or tidal effects, or incision of the low-flow channel while under ice-cover. In coming field seasons, the extent of inner channeling will be better determined. In particular, it will be verified whether these are also encountered in channels newly formed in the inner delta, far from tidal or storm surge effects. A possible relationship between bank migration rates and the dimensions of cut bank ledges (cf. section 2.3) will also be investigated.

4.4 Channel Abandonment

A final area of enquiry concerns the conditions under which channels become silted-up and abandoned in the Mackenzie Delta. Examples of this phenomenon abound on the delta plain, with small channels making up the extreme majority of cases. Nonetheless, even moderate-sized channels may not be absolutely immune to the process. It is noteworthy in this respect that most of the flow that runs by Inuvik on East Channel ultimately comes from the narrow mouth sections off Middle Channel, some 70km away. End of summer observations indicate that these sections are already remarkably shoal; further shoaling near Middle Channel could gradually reduce flows downstream on East Channel, and in the long run lead to major siltation problems. The author does not imply that this will necessarily happen, but merely wishes to emphasize the relatively delicate balance controlling channel abandonment in delta networks.

The study of airphotos suggests that distributary abandonment may be to a great extent controlled by changes in sediment inputs at the mouth of the distributary, due to parent-channel migration. Junctions to active distributaries are usually located near bend apex on the parent-channel (Mackay, 1963), as the helical flow structure in the latter channel usually maintains low sediment concentrations in this area. With parent-channel migration, the distributary mouth may find itself along an accreting bank: in such cases sediments will deposit in large quantity and completely obstruct distributary flow. Rapid shifting at Horseshoe Bend in Middle Channel has already deposited a large shoal in

front of the mouth of Raymond Channel, and this may be a first step in the abandonment process. In contrast, the flow structure and sedimentation patterns appear to be more complex at the mouth of East Channel.

The control that parent-channel alignment exerts on distributary abandonment will be investigated firstly through a detailed examination of delta air photos. As well, a program of measurements of velocities, helix strength and suspended sediment concentrations along channel bend cross-sections is planned for 1984, in order to verify the role that the helical circulation plays in bend sedimentation in the Delta. Finally, cross-sections at the entrance to East Channel will be surveyed and monumented as a first step in the monitoring of local shoaling tendencies over the next years.

5.0 Summary of Preliminary Findings

Numerous unequally substantiated ideas have been put forth in this progress report, based on a review of existing literature and on the reconnaissance surveys conducted by the author. A major objective of the report has been to review some fluvial geomorphic problems that appear worthy of study, and to suggest some approaches that may be helpful. Nonetheless, both existing and original data point to a number of preliminary conclusions, most of which will be tested further in coming field seasons.

1. Available cross-sectional data suggests that one characteristic of Delta channels may be a particularly slow rate of increase of channel depths as wider channels are considered.

2. Channel migration patterns are dominated by the contrast between rapid shifting along Middle Channel and the very subdued activity of most other Delta channels.

3. Migration patterns appear to be controlled, in large part, by the strength of flow stresses in the different segments of the channel network. Neither hydrothermal nor ice-run erosion appear to have a major effect on the scale or the distribution of channel shifting in the Mackenzie Delta.

4. Data on bed sediments in the channel network suggest that sands may be supplied only briefly during spring high flows to the upstream reaches of many distributaries. Subsequently, summer low flows would gradually evacuate them downstream.

6.0 References

Anderson, R.J. and MacKay, D.K., 1973. Preliminary Study of the Distribution of Flow in The Mackenzie Delta, N.W.T. In Hydrologic Aspects of Northern Pipeline Development. Glaciology Division, Water Resources Branch, Department of the Environment, Ottawa, Ontario. Report 73-3: 71-109.

Apmann, R.P., 1972. Flow processes in open channel bends. J. Hydr Div. A.S.C.E., 98: 795-809

Carson, M.A. and Lapointe, M.F., 1983. The inherent asymmetry of river meander planform. J. of Geol; 91: 41-55.

Church, M. 1981. Proposed Liard River Hydroelectric Development, Review of Environment Studies: Sedimentation. Unpublished Report to B.C. Hydro and Power Authority.

Cooper, R.H. and Hollingshead, A.B. 1973. River bank erosion in regions of Permafrost. In Fluvial processes and sedimentation: Proc. Hydnd Symp. No. 9, Univ. of Alberta, Edmonton: 272-283.

Cunningham, R., 1981. Atchafalaya Delta: Subaerial development. Environmental Implications and Resource Potential. In Proceed. National Symp. on Freshwater Inflow to Esturaries, Cross, R.D. and Williams, D.L. (eds.). Coastal Ecosystems Project, Fish and Wildlife Service, U.S. Department of the Interior, Washington, D.C. Vol. 1: 349-365.

Czudek, T. and Demek, J., 1972. Thermokarst in Siberia and its influence on the development of lowland relief. Quaternary Res. 1: 103-120.

Gill, D., 1971. Vegetation and environment in the Mackenzie River Delta: a study in subarctic ecology. Unpubl. Ph.D. Thesis, Univ. B.C. 694p.

Gill, D., 1972a. The point bar environment in the Mackenzie River Delta. Can. J. Earth Sci. 9: 1382-93.

Gill, D., 1972b. Modification of levee morphology by erosion in The Mackenzie River Delta, N.W.T. In R.J. Price and D.E. Sugden (eds.). Polar Geomorphology. I.B.G. Spec Publ. No. 4: 123-138.

Grissinger, E.H., Little, W.C. and Murphey, J.B., 1981. Erodibility of streambank materials of low cohesion. Transactions of the ASAE, Soil and Water Div.

Hickin, E.J. 1978. Mean flow structure in meanders of the Squamish River, B.C. Can. J. of Earth Sci. 15:. 1833-49.

Hollingshead, G.W. and Rundquist, L.A., 1977. Morphology of Mackenzie Delta channels. In Third Nat. Hydrotechnical Conf. Quebec, C.S.C.E.: 309-326.

Ippen, A.T. and Drinker, P.A., 1962. Boundary shear stresses in curved trapezoidal channels. J. Hyd. Div. A.S.C.E. 88: 143-79.

Jackson, R.G., 1975. Velocity, bed form, texture patterns of meander bends in the Lower Wabash river of Illinois and Indiana. Geol. Soc. Am. Bull. 86: 1511-22.

Johnston, G.H. and Brown, J.E., 1965. Stratigraphy of the Mackenzie River Delta, N.W.T. Geol. Soc. Am. Bull. 76: 103-112.

Leopold, L.B., Wolman, M.G., Miller, J.P., 1964. Fluvial processes in geomophology. San Francisco: Freeman 522 pp.

Mackay, J.R., 1963. The Mackenzie Delta area, N.W.T. Geogr. Branch, Can. Dept. Mines and Techn. Surveys. Mem. 8. 202 p.

Mollard, J.D., 1973. Airphoto interpretation of fluvial features. In Fluvial processes and sedimentation. Proceed. of 9th N.R.C. Hydrology Symposium, Edmonton: 341-380.

Outhet, D.N. 1974. Bank erosion in the Southern Mackenzie Delta, N.W.T. Unpub. MSc. Thesis, U. of Alberta.

Partheniades, E., 1965. Erosion and deposition of cohesive soils. J. of Hydro. Div. A.S.C.E. 91: 105-139.

Richards, K.S., 1977. Channel and flow geometry: a geomorphological perspective. Progress in Phys. Georgr., 1: 65-102.

Ritchie, W. and Walker, H.J., 1974. Riverbank forms of the Colville River Delta, N.W.T. In Reed, J.C. and Sater, J.E. (eds.): The coast and shelf of Beaufort Sea: Arctic Inst. of N. America. :545-62

Rust, B.R.. 1978. A classification of alluvial channel systems. In Miall, A.D. (ed.) Fluvial Sedimentology. Can. Soc. Pet. Geol. Mem. 5: 187-198.

Schumm, S.A., 1968. River adjustment to altered hydrologic regimen: Murrumbidgee River and paleochannels, Australia. U.S. Geol. Surv. Prof. Pap. 598. 65pp.

Scott, K.M., 1978. Effects of permafrost on stream channel behaviour in Arctic Alaska. U.S. Geol. Surv. Prof. Pap. 1068, 19pp.

Shepherd, R. and Schumm, S.A., 1974. Experimental Study of river incision. Bull. Geol. Soc. of America. 85: 257-268.

Thorne, M.F.C. and Parsons, J.G., 1980. Erosion of cohesive sediments in esturaries: an engineering guide. In Third International Symp. on Dredging Technology, BHRA fluid Engineering, Bedford, U.K. Paper F1: 349-358.

Tuttle, J.R. and Combe, A.J., 1981. Flow regime and sediment load affected by alterations of the Mississippi River. In Proceed The National Symp. on Freshwater Inflow to Esturaries. Cross, R.D. and Williams, D.L. (eds) Coastal Ecosystems Project, Fish and Wildlife Service, U.S. Dept. of the Interior. Washington, D.C. Vol. 1: 334-348.

Vanoni, V.A. (ed.), 1975. Sedimentation Engineering. Task Comm. for the preparation of the Manual on Sedimentation. Hydrol. Div. A.S.C.E. New York. 745pp.

Walker, H.J., 1978. Lake Tapping in the Colville River Delta, Alaska. In Proceed of 3rd Intern. Conf. on Permafrost; Edmonton: 233-238.

Walker, H.J. and Arnborg, L., 1966. Permafrost and ice-wedge effects on river bank erosion. In Permafrost: Intern. Conf. Lafayette, Ind., Proc. N.R.C. Pub. No. 1287: 164-171.

Williams, J.R., 1952. Effect of Wind-generated waves on migration of the Yukon River in the Yukon Flats, Alaska. Science, 115: 519-20.

Williams, P.J., 1968. Ice distribution in permafrost profiles. Can. J. Earth Sci. 5: 1381-86.

Wright, L.D., 1977. Sediment Transport and Deposition at river mouths: A Synthesis. Geol. Soc. of Amer. Bull. 88: 857-68.

Yen, C.L., 1970. Bed topography effect on flow in a meander J.Hyd. Div. A.S.C.E. 96: 57-73.

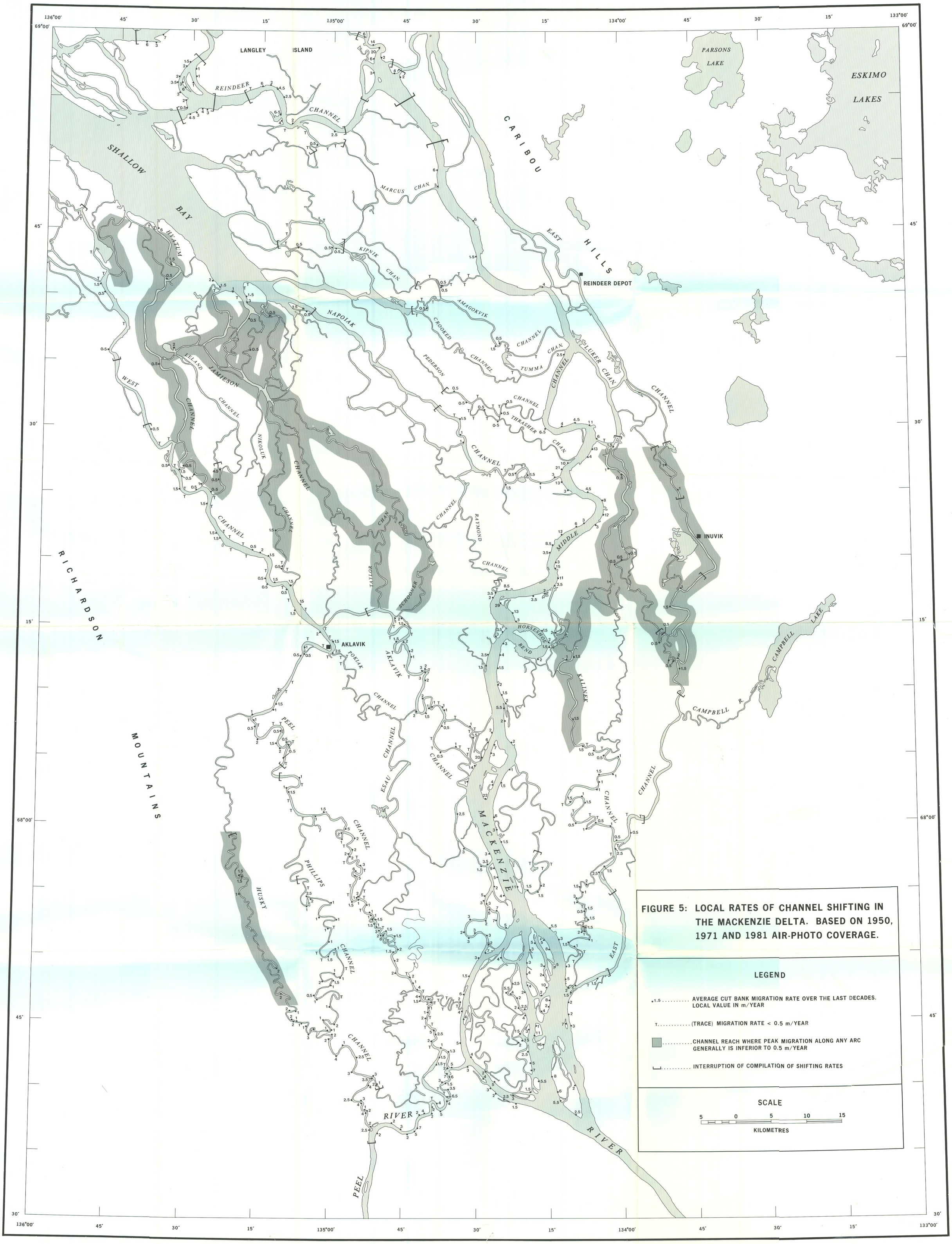


FIGURE 5: LOCAL RATES OF CHANNEL SHIFTING IN THE MACKENZIE DELTA. BASED ON 1950, 1971 AND 1981 AIR-PHOTO COVERAGE.

LEGEND

- •1.5 ..... AVERAGE CUT BANK MIGRATION RATE OVER THE LAST DECADES. LOCAL VALUE IN m/YEAR
- T..... (TRACE) MIGRATION RATE < 0.5 m/YEAR
- ..... CHANNEL REACH WHERE PEAK MIGRATION ALONG ANY ARC GENERALLY IS INFERIOR TO 0.5 m/YEAR
- ..... INTERRUPTION OF COMPILATION OF SHIFTING RATES

SCALE

5 0 5 10 15

KILOMETRES