FINAL REPORT: PART A

YUKON DELTA COASTAL PROCESSES STUDY

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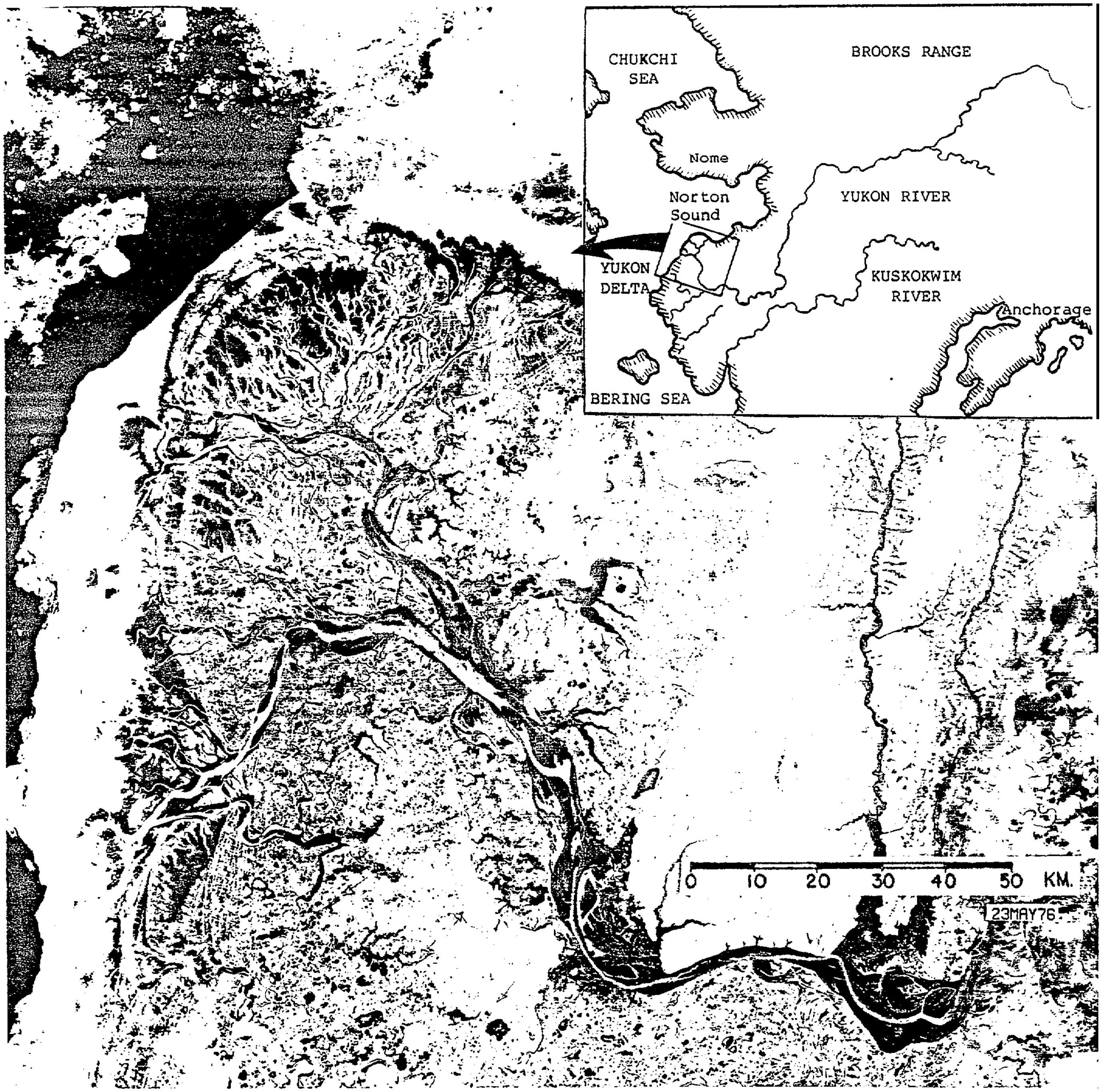
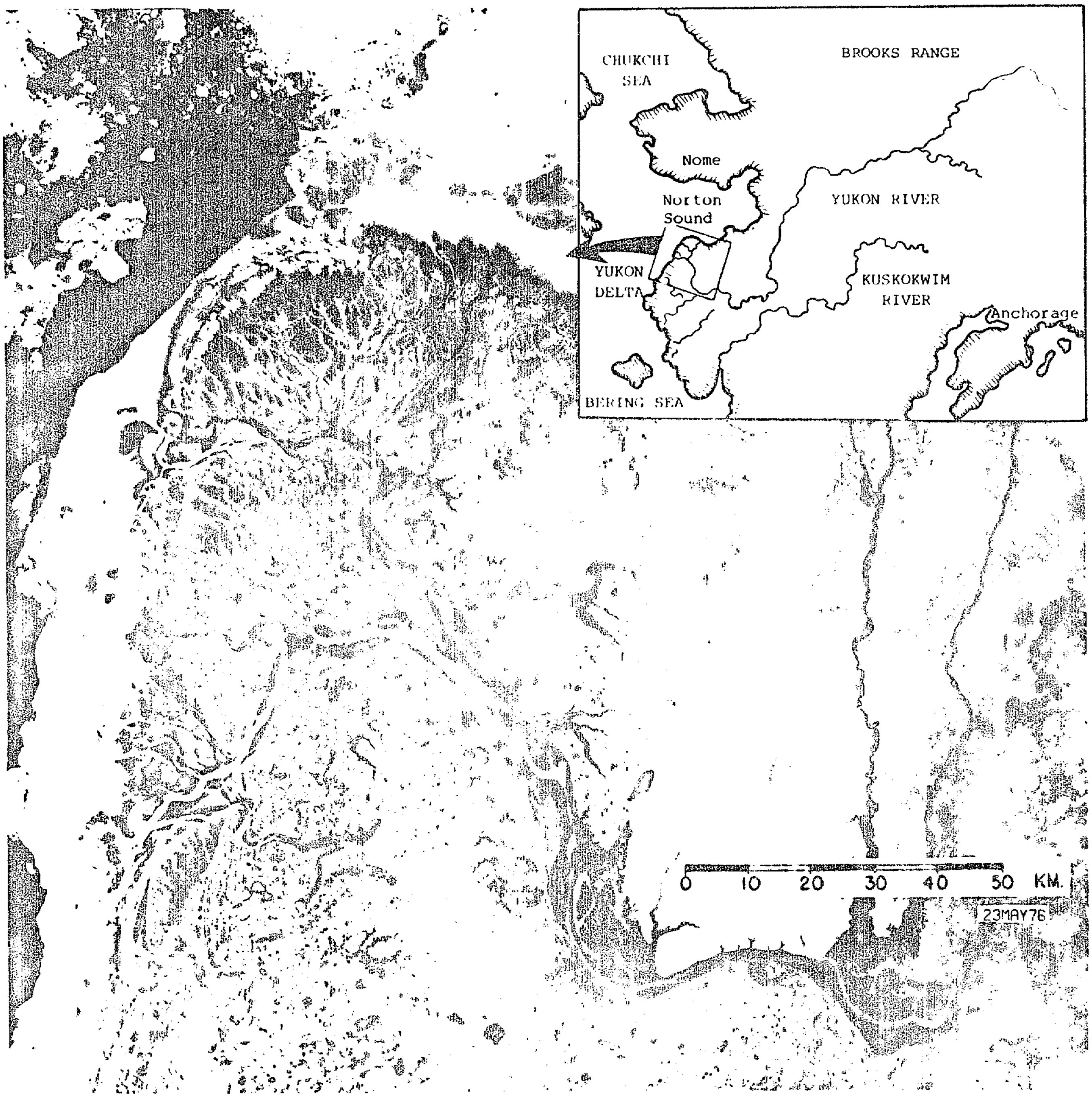


FRONTISPIECE:

LANDSAT Image of the Modern Lobe of the Yukon Delta taken during Spring Breakup.



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I. SUMMARY

Objectives:

The overall objective of this study is to provide information on the depositional environments and associated geologic processes which characterize the Yukon-Kuskokwim delta complex (Fig. 1). These data, in turn, can aid in evaluating the potential environmental impacts of the proposed exploration for hydrocarbons in the Norton Sound region.

Specific objectives of this study fall into two categories: a) those directly related to the initial phase of selecting offshore leases, and b) those related to the possible subsequent selection of shoreline sites and transportation facilities. Because of the need for timely information concerning the selection of offshore tracts, only those objectives and associated data products related to the first category will be considered in this part of the Final Report. They include:

1) Provide information on the age of faulting and volcanism in the region to aid in determining the potential seismic risk.
2) Provide information on the distribution of permafrost in the region to aid in determining the probability of offshore permafrost.
3) Map the depositional environments of the modern Yukon delta, including offshore facies, with an evaluation of the potential geologic hazards (e.g. liquefaction susceptibility, erosion and sedimentation potential) which characterize each depositional environment.
4) Study the seasonality of coastal processes in the Norton Sound region, emphasizing the patterns and rates of ice movement during the winter months as determined from satellite imagery.

Data products related to the latter stages of exploration and development will be provided in the second part of the Final Report to be submitted Summer, 1980.

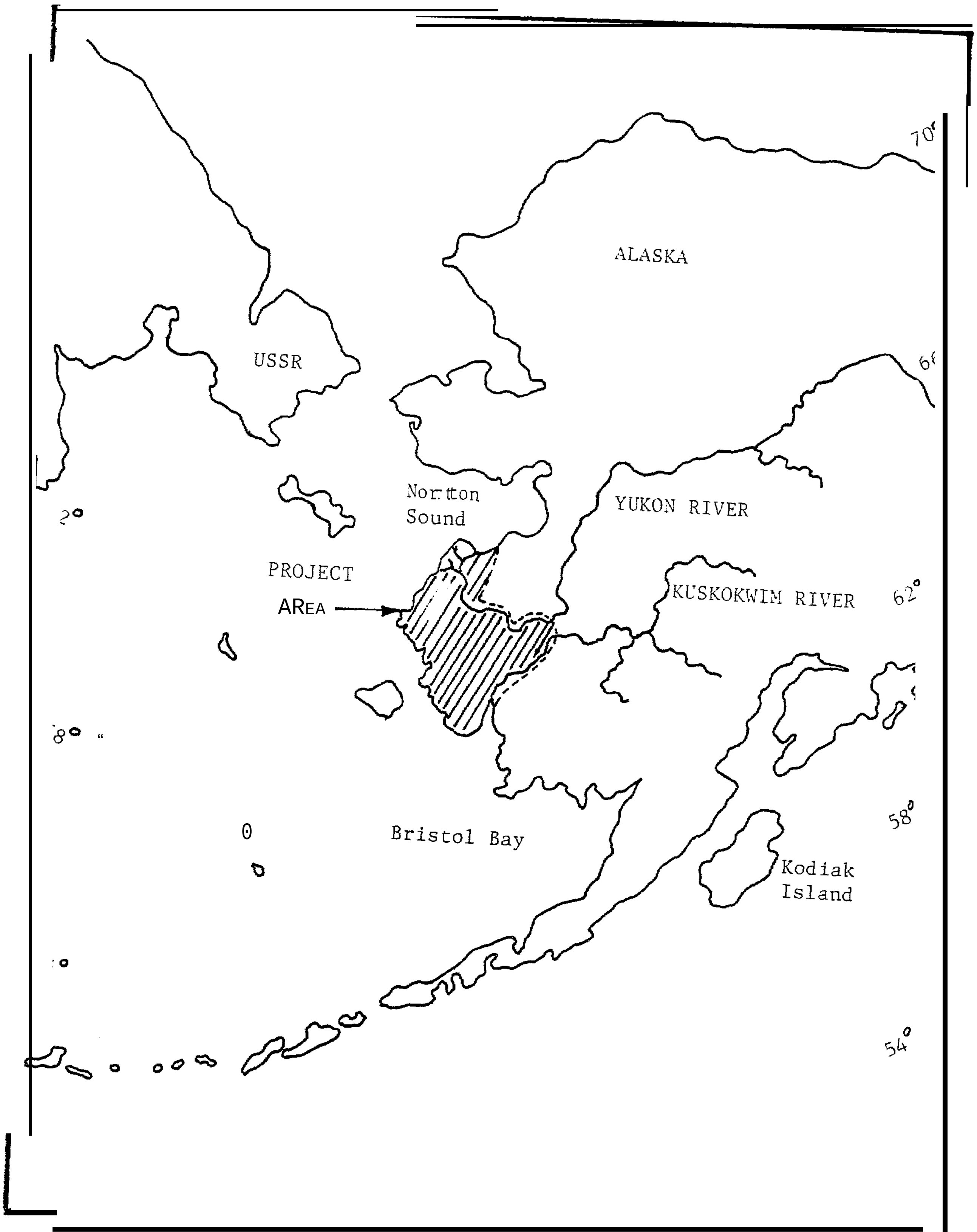

Figure 1: Location of project area - Yukon Delta Coastal Processes Study (R.U. 208).

Conclusions :

a) The Yukon Kuskokwim delta region is characterized by widespread evidence of Quaternary tectonism. Evidence of Holocene faulting, coupled with the relatively high susceptibility for liquefaction of most of the fluvial and deltaic sediments, constitute potentially serious geologic constraints to the selection of offshore sites and the design of offshore structures. The risk from explosive volcanic activity, however, appears minimal.

b) Pleistocene sediments beneath most of Norton Sound contained thick, ice-bound permafrost which was actively forming as recently as 10,000 years ago; some may remain offshore as relict permafrost. Offshore permafrost in modern sediments is less likely, and if present, will be thin, discontinuous, and restricted to water depths <1 meter.

c) The depositional environments of the Yukon delta differ from most previously described deltas, mainly by the presence of a broad, shallow sub-ice platform and associated sub-ice channels. The potential for rapid erosion by these actively meandering subaqueous channels is especially serious, as is the relatively high susceptibility for liquefaction of much of the offshore sediments.

d) The shallowness of Norton Sound, combined with the marked seasonality of marine and fluvial processes, has resulted in a complex pattern of sediment resuspension and reworking. This makes the predicted paths of sediment (and pollutants) transport more complex than might be expected in deeper basins in more temperate climates.

e) Satellite imagery, used in combination with available weather data, has documented relatively systematic patterns of ice movement controlled largely by local winds and offshore bathymetry. This has allowed the sub-division of the Norton Sound region into zones, each characterized by a particular type of ice and ice movement.

Implications

The selection of offshore sites and the design of offshore structures must take into account the potentially high seismic risk based on the evidence of nearby Holocene faulting. In addition, the possibility for seismically induced and wave-induced liquefaction is relatively high for much of the Norton Sound region underlain by well sorted deltaic sediments. Other potential gee-hazards include rapid erosion and sedimentation associated with sub-ice channels, the mobility and deformation of seasonal pack. ice, the extent and variability of shorefast ice, and the possibility of offshore permafrost beneath part of Norton Sound. Lastly, the predicting the paths of sediment and/or pollutants is complicated by the seasonal variability of coastal processes and the shallowness of the depositional basin which cause extensive reworking and redistribution of sediment.

11. INTRODUCTION

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111. CURRENT STATE OF KNOWLEDGE

The suspended sediment load of the Yukon River is the 18th largest in the world (Inman and Nordstrom, 1971), providing over 90% of the sediment presently entering the northern Bering Sea (Lisitsyn, 1966). The Yukon and Kuskokwim Rivers have combined to form the 7th largest delta plain in the world (Inman and Nordstrom, 1971), yet despite its size, relatively little is known of its Quaternary history or the processes by which the Yukon-Kuskokwim complex was formed.

There has been a significant amount of work done on the Cenozoic tectonic history of the region (e.g. Patton, 1973; Nelson and others, 1974; Marlow and others, 1976). Similarly, there have been numerous studies of Quaternary sediments on the northern Bering Sea shelf (e.g. Moore, 1964; McManus and others, 1974; 1977; Nelson and Creager, 1977; Drake and others, 1979) as well as the Holocene sediments at the mouth of the Yukon River (Matthews, 1973). In addition, Thor and Nelson (1979) recently provided a synthesis of the geologic processes and geologic hazards in the Norton Sound region.

With the exception of the work of Matthews, however, none of these studies sampled anything but the most distal portions of the Yukon delta. In addition, the geologic mapping of the subaerial delta complex has been largely restricted to regional reconnaissance mapping (e.g. Hoare, 1961; Hoare and Coonrad, 1959a, 1959b; Hoare and Condon, 1966, 1968, 1971a, 1971b). Thus this is the first study to deal in detail with the depositional environments and processes of both the delta plain and associated offshore facies.

IV. STUDY AREA

The combined Yukon-Kuskokwim delta complex (Figure 2) is an area of unique natural resources covering over 54,000 square kilometers. It has a large native population living in large part on a subsistence economy. It provides access to most of the spawning areas for salmon in the region. It is, in addition, one of the most significant breeding grounds for migratory birds in North America.

The delta region is largely a flat, featureless plain consisting of wet and dry tundra, interrupted by innumerable lakes, many of which are oriented. Many of these lakes have coalesced laterally to form very large bodies of water (e.g., Baird Inlet) connected to the sea by a series of ancient river channels. The flatness of the delta complex is interrupted by numerous small Quarternary shield volcanoes, the major uplifted massifs of the Askinuk and Kuzilvak Mountains, and the Quarternary volcanic complex which forms Nelson Island.

The coastline is extremely varied, in part because of the complex geology along the coast, and in part because of the lateral variability of sediment sources and tidal range. For example, broad tidal flats, locally bordered by short barrier islands, flank the macro-tidal Kuskukwim delta, whereas the micro-tidal Yukon delta is fringed by distributary mouth bars and interdistributary tidal flats. Sandy beaches are present near Hooper Bay, where Wisconsinan(?) sediments provide the source of sediments, whereas steep gravel beaches and rocky headlands form along the cliffed " shorelines at Cape Romanzof, Point Ramanof, and Nelson Island where Cretaceus bedrock crops out. Most of the remaining coastline consists of low, eroding bluffs cut into poorly consolidated Pleistocene deposits.'

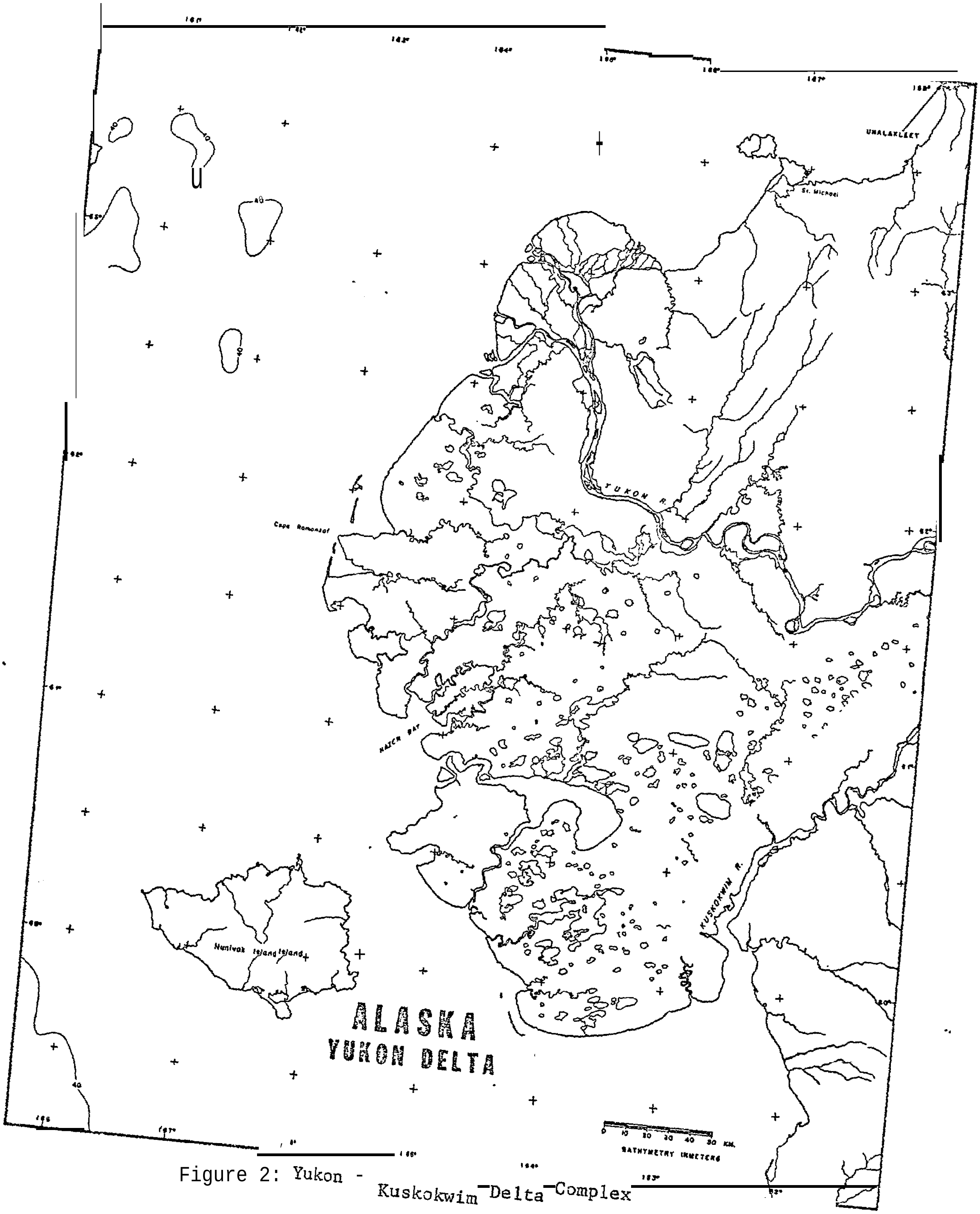

Figure 2: Yukon - Kuskokwim Delta Complex

V. SOURCES, METHODS, AND RATIONALE OF DATA COLLECTION

Geologic mapping in the delta complex (including the delineation of potentially active faults) consisted of the compilation of existing geologic maps, interpretation of aerial photography and sattelite (Landsat) imagery, and field work. Regional reconnaissance mapping by Dr. Joe Hoare and associates at the U.S. Geologic Survey was available for most of the delta region at a scale of 1:250,000. In addition, photo coverage of the entire delta region taken in 1952-1954 is available, as is recent coverage (1973, 1976) for much of the coastline. Landsat imagery was also very useful for regional geologic mapping.

Field work during the summers of 1975-1978 included the description of vegetation assemblages and collection of numerous grab samples and short cores to describe the various depositional environments, the establishment and re-occupation of coastal benchmarks to measure the short-term rates of shoreline change, and the collection of organic-rich material for radiocarbon dating. The radiocarbon dating (Univ. Texas Radiocarbon Lab, Austin) aided in establishing the probable age of most recent faulting in the delta region. Part of the field work also involved obtaining several cores from two volcanic lakes in the delta region using a modified Livingston piston corer from a floating platform. These cores are presently being analysed by Dr. Tom Ager (U.S.G.S., Reston, Vs.) to determine the frequency of explosive volcanism in the region (via ash content), the sources and rates of sedimentation, and evidence of climatic change (via pollen analysis).

The delineation of offshore depositional enviornments was done mainly by interpretation of satellite imagery, bathymetric maps, and offshore cores-provided by the U.S.G.S. (Menlo Park California). The Landsat imagery was particularly useful in delineating the sub-ice channels during periods of freezeup and breakup. Existing bathymetric data (mainly vintage 1899), was compared with traverses obtained by R/V KARLUK (USGS cruise, 1978) to estimate long-term rates of erosion and sedimentation of the delta front. In addition, the locations of the sub-ice channels from 1899 to 1978 were compared by the use of the Landsat imagery, allowing an estimation of the rates of lateral migration (and associated erosion and sedimentation).

The KARLUK also collected 22 vibracores off the front of the modern Yukon delta. These cores, in combination with numerous box cores taken farther offshore by C. Hans Nelson (U.S.G.S. Menlo Park, California) and sediments described by McManus and others (1977) allow a better understanding of the patterns of sedimentation in the region.

Sequential Landsat imagery (1973-1977) was used to study the patterns of ice formation from freezeup to breakup in the Norton Sound region. Sidelap of images taken on successive days allowed the calculation of daily rates and directions of ice floe movement. The resultant patterns of ice movement were compared with synoptic weather data obtained from daily surface synoptic weather charts, as well as available bathymetric data and information of ice gouging (Thor and Nelson; 1979).

VI. RESULTS

Those data products related to geologic problems on the subaerial portions of the delta plain (e.g. geologic and tectonic maps, maps of coastal morphology and shoreline stability) will be included in the second part of the Final report to be submitted Summer, 1980. The results with direct implications to the earlier phases of site selection are discussed in this report. They include the following:

1) Recognition of widespread geomorphic evidence of Quaternary faulting, some of which cut Holocene fluvial deposits. Some of these faults are continuations of major fault systems, hence the magnitude of the potential seismic event may be large, even though the historical seismicity is rather low.
2) There is no evidence of explosive volcanic activity in the delta region having occured during the Holocene, and some suggestion that it may not have occured within the last 24,000 years, thus it seems likely that the risk from volcanism is minimal.
3) Pleistocene sediments beneath most of Norton Sound contained thick, ice-bound permafrost which was actively forming as recently as 10,000 years ago; some may remain offshore as relict permafrost. Offshore permafrost in modern sediments is less likely, and if present, will be thin, discontinuous, and restricted to water depths <1 meter.
4) A map of the depositional environments of the modern Yukon delta (Fig. 3) illustrates the differences between this delta and those previously described. Each depositional environment is characterized as to dominant process and potential geologic hazards. A more detailed discussion of the modern depositional environments is provided by Dupré and Thompson, 1979 (Appendix I).
5) A preliminary map of offshore sediment characteristics (Fig. 5) provides some information as to the degree of sediment reworking and the possible paths of sediment (and pollutant) transport.
6) A preliminary zonation of ice hazards in Norton Sound (Fig. 6) illustrates the relatively systematic variations in patterns and rates of ice movement during the winter. A more detailed study of ice movement in the Norton Sound region is provided by Ray and Dupré, in review (Appendix II).

VII. DISCUSSION

Tectonic Framework:

The Yukon-Kuskokwim delta complex is located within the Koyukuk volcanogenic province which has been characterized by recurrent faulting and syntectonic volcanic activity throughout Mesozoic and Cenozoic time (Patton, 1973). Most of the major faults in the region (e.g., the Kaltag fault) formed and were most active during late Cretaceus and early Tertiary time (Hoare, 1961), however, many of these structures have remained active, albeit at reduced levels of activity, to the present (e.g., Hoare, 1961; Patton and Hoare, 1968; Grim and McManus, 1970).

Most of the newly recognized faults, photo-linears, and measured joint sets within the Quaternary deposits are parallel to or are extension of previously mapped faults. There is no evidence of the Kaltag fault passing through the modern lobe of the Yukon delta, as previously suggested by Hoare and Condon (1971), however this may simply be the result of masking by the relatively young (<2500 yrs) delta. Alternatively the Kaltag may splay into a series of southwest-trending faults which transect the Andreski Mountains and continue across the delta plain.

The age of the most recent faulting remains uncertain, however at least some of the faults appear to cut Holocene deltaic and fluvial deposits. The recentness of fault movement, as based on geologic criteria, is consistent with the recent work on microseismicity in the region by Biswar and Gedney (OCSEAP R.U. 483), as well as the abundance of fault scarps detected by Johnson and Holmes (in Nelson, 1978). Thus it seems clear that the selection of potential transportation corridors must take into account the possibility of significant ground movement along at least some of the fault zones in the area. In addition, all site investigations must evaluate the potential for ground shaking and liquefaction due to such an event, even though the historical seismicity is relatively low . This is particularly important as almost all of the Holocene fluvial and deltaic sediments are characterized by grain size distributions which suggest they are highly susceptible to liquefaction.

The Quarternary volcanism probably occurred over a wide period of time, as evidenced by the various degrees of weathering and slope modification; however paleomagnetic data indicate that almost all of the basalts are normally polarized, hence are younger than 700,000 years old (Hoare and Condon, 1971b). A core taken from a volcanic lake in the middle of the delta complex contains an ash deposit which is approximately 3500 years old. However, the composition of the ash suggests it was derived from a distant source (e.g. Alaska Peninsula). There is no other evidence of volcanism preserved in the core, which probably records an interval of approximately 24,000 years, suggesting either that the most recent volcanism in the region was far removed from the lake or that it predates the core. The latter seems most likely, as cores taken from a volcanic lake near St. Michaels, east of the delta, also show a lack of locally derived pyroclastic material (Dr. Tom Ager, U.S.G.S. , written communication). Thus it seems likely that the risk due to volcanic activity should be considered minimal.

Permaf rest:

The presence of permafrost in the Yukon-Kuskokwim delta region is well established by an abundance of geomorphic criteria, including polygonal ground, palsas, thermokarst lakes, solifluction lobes, and string bogs. The type and extent of permafrost is further documented by field studies, unpublished drillers reports, and a study by the U. S. Geological Survey (Williams, 1970). Previous Annual Reports have described the extent and variability of permafrost in some detail, and will not be repeated here. Rather the concern at present is to discuss the possibility of offshore permafrost in the region.

The modern lobe of the Yukon delta and associated chenier plain are relatively young geologic features, having formed approximately 2500 years ago. There is evidence of permafrost forming in much of the interior parts of the modern delta plain, however it appears to be discontinuous and relatively thin (2-3 m thick ?). There is little evidence of permafrost presently forming along the prograding margin of the delta plain. If permafrost is actively forming in modern deltaic sediments offshore, it is certain to be thin, discontinuous, and restricted to sediments in water depths of less than one meter, coincident with the distribution of bottomfast ice.

The possibility of relict permafrost existing offshore is more difficult to predict. Norton Sound was emergent until as recently as 10,000 years ago when it was flooded during the last glacio-eustatic rise in sea level (C. Hans Nelson, U.S.G.S., unpublished data). Thus until recently Pleistocene sediments similar to those which presently cover much of the delta region were exposed offshore. The Pleistocene sediments onland are characterized by extensive permafrost (including large ice wedges and massive ice) locally Up to 200 m thick. The permafrost began to degrade following the submergence of Norton Sound, however some may remain offshore as relict permafrost depending on 1) the original thickness of permafrost, 2) the nature of the Pleistocene sediments, 3) the thermal properties of the overlying water mass, and 4) the possible presence of Holocene river channels (cf. Hopkins, 1978).

More detailed seismic studies and exploratory drilling are necessary before a more definitive statement can be made as to the presence of offshore permafrost in the Norton Sound region. Nevertheless, it is clear that most of Norton Sound was underlain by thick, ice-bound permafrost which was actively forming as recently as 10,000 years ago. Thus a very real possibility exists for the presence of relict ice-bound permafrost underlying parts of Norton Sound. This possibility seems especially high east of the modern delta, between Apoon pass and St. Michaels, where the shoreline is rapidly eroding Pleistocene sediments at rates of approximately 17 m/yr.. It seems likely that in this area the thick permafrost exposed along the shoreline extends for some distance offshore.

Depositional Environments of the Modern Yukon Delta:

The modern Yukon delta has several depositional environments lacking in deltas formed in more temperate climates. These depositional environments are but one indication of the extreme seasonality of coastal processes which probably characterize many high-latitude continental shelves. Table 1 is a preliminary attempt to assess the relative importance of these processes within each environment. The ability to predict the types of processes as well as the sediment characteristics and geotechnical properties which characterize each environment, should greatly aid in minimizing both the costs and environmental impacts of siting both offshore and onshore structures. This report will emphasize only those environments and processes which might directly affect the early stages of site selection. A more detailed description on the onland environments will be included in the second part of the Final Report.

The subaerial morphology of the Yukon delta is similar to lobate, high-constructional deltas described by Fisher and others (1969) as typical of bedload-dominated rivers emptying into shallow depositional basins. An examination of the subaqueous morphology of the delta, however, suggests such a classification fails to recognize some of the unique aspects of the Yukon delta.

The delta plain is fringed by prograding tidal flats and distributary mouth bars, similar to many previously described deltas. The Yukon is unusual, however, in that the delta front and prodelta are offset from the prograding shoreline by a broad platform (here referred to as the sub-ice platform), typically 1-3 meters deep and locally up to 30 km wide. The resultant subaqueous profile (Fig. A-5)* is quite unlike those of wave and river-dominated deltas described by Wright and Coleman (1973). In addition, the platform is crossed by a series of subaqueous (sub-ice)

*in Appendix A

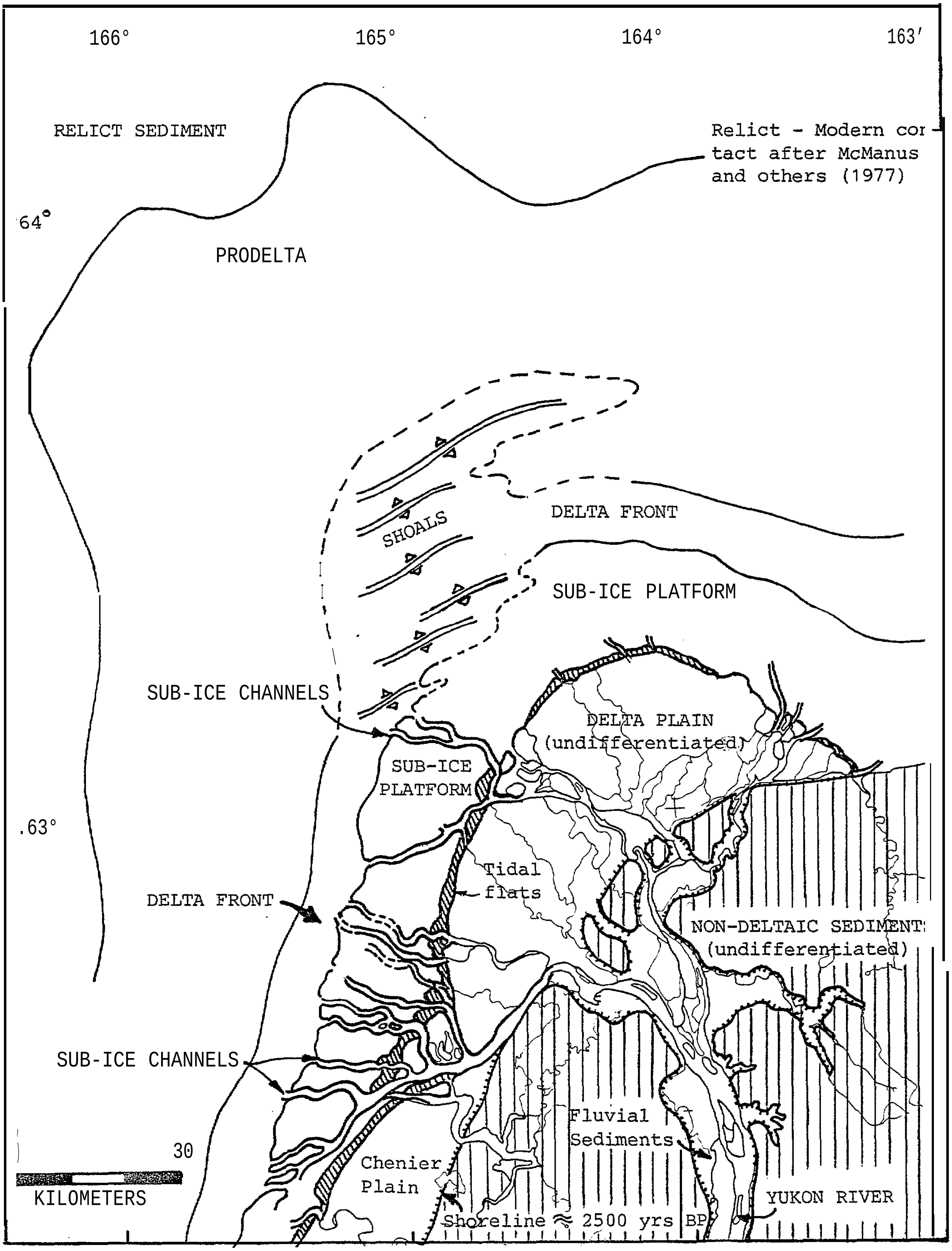

Figure 3: Depositional Environments of the Yukon delta.

	DEPOSITIONAL ENVIRONMENTS	FLOODING	ICE SCOUR	SEDIMENTATION	EROSION	PERMAFROST	LIQUEFACTION
DELTA PLAIN	Active Distributary	High	Moderate	High	High	None	High
	Abandoned Distributary	Moderate	Low	Moderate	High	Low-Mod	Mod-High
	Interdistributary Marsh	Moderate	Low	Low-Mod	Low	Low-Mod	Mod - Low
	Coastal Marsh	High	Moderate	High	Variable	Low	Low
DELTA MARGIN	Distributary Mouth Bar	High	Moderate	High	Low-Mod	Low	Mod-High
	Tidal Flats	High	Mod-High	High	Low	Low	Variable
	Sub-ice platform	N/A	Mod-Low	Variable	Variable	None	Variable
	Sub-ice Channels	N/A	Low	High	High	None	High
DELTA FROST		N/A	High	Variable	Variable	None	Mod-High
PRODELTA		N/A	Mod-Low	Moderate	Mod-Low	None	Low-Mod

Table 1: A preliminary summary of non-tectonic geological hazards of the modern Yukon Delta

channels which extend up to 20 km beyond the mouths of the major distribuaries. ,

The sub-ice platform and associated sub-ice channels appear to be related to the presence of shorefast ice which fringes the delta for almost half of the year. Several workers (e.g. Reimnitz and Bruder, 1972; Reimnitz and Barnes, 1974; Walker, 1974) have noted that patterns of nearshore sedimentation along the north slope of Alaska are strongly influenced by the presence of shorefast ice. Naidu and Mowatt (1975) suggested that this is unique to deltas formed by polar rivers in the Arctic. I believe that these smaller arctic deltas, as well as larger deltas such as the Yukon, Mackenzie, and Lena, actually represent a separate type of ice-dominated delta, morphologically distinct from the wave-,river-, and tide-dominated deltas previously described in the literature (e.g. Galloway, 1975). The Yukon delta may provide a model for such an ice-dominated delta (Dupré and Thompson, 1979; Appendix A).

Delta Plain: The delta plain consists of a complex assemblage of active and abandoned distributary channels and channel bars, natural levees, interdistributary marshes, and lakes (Fig. 4), however for the purpose of this report, it will remain undifferentiated. Much of the older, more inland parts of the delta plain show clear evidence of permaforst, however it appears to be discontinuous and relatively thin (2-3 meters?). Flooding is a major hazard on much of the delta plain, as is erosion and sedimentation associated with the meandering active distributary channels. In addition, much of tine sediment deposited in the channels and channel bars consists of relatively well-sorted sands and silts with a high susceptibility for liquefaction.

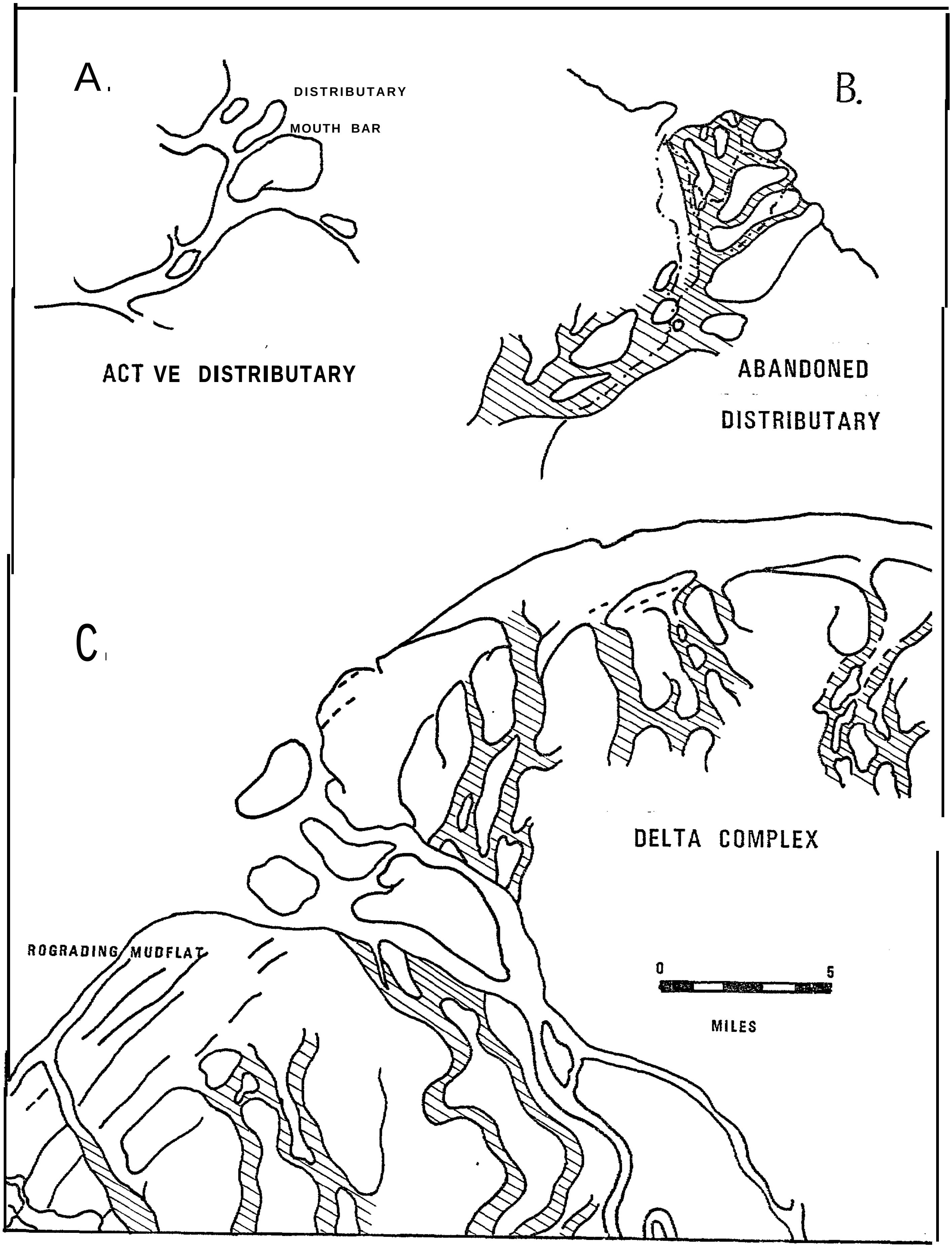

Figure 4: Depositional Environment within the Delta Plain of the Modern Yukon delta.

Delta Margin: The delta margin is a term used here informally to include the programing tidal flats and distributary mouth bars as well as the sub-ice platform and associated sub-ice channels.

The tidal flats are typically 100-1000 m wide where they occur along the prograding margin of the modern delta. They consist of poorly-sorted sandy silts with a low liquefaction susceptibility in areas of relatively low wave energy (on the northern side of the delta), and moderately sorted silty sands with a moderate susceptibility for liquefaction in area of higher wave energy (on the western side of the delta). Rates of net erosion and deposition are relatively small, however rates of shoreline progradation may be locally up to 50 m/yr. In addition, some of the tidal flat areas are eroding at rates of up to 5 m/yr.

The distributary mouth bars are typically middle-ground bars which form at the mouths of the major distributaries. They generally consist of moderately to well-sorted sand and silty sand with a relatively high susceptibility for liquefaction. They are dominately prograding features, however some erosion may occur during storms or where adjacent to laterally meandering sub-ice channels.

The sub-ice channels are the offshore extensions of the major distributary channels, and are most common on the western margin of the" delta. These subaqueous channels are typically 1/2 to 1 km wide, 5-15 m deep, and extend up to 20 km beyond the shoreline. The channels are presently actively transporting sediment {at least during parts of the year) as evidenced by the seaward-migrating sand waves up to 1m high in the channels (D. Thor, U.S.G.S. , personal communication). The presence of the well-sorted channels sands, combined with the relatively steep channel margins, results in a high potential for liquefaction. This is further substantiated by the abundance of liquefaction-induced deformation features observed in cores obtained from channels deposits by the R/V KARLUK (U.S.G.S. cruise, 1978). The channels appear to be actively changing their course by a combination of lateral meandering and avulsion. Lateral rates of channel migration have been measured up to 50 m/yr. on the basis of bathymetric maps and Landsat imagery. Thus the potential exists for erosion of adjacent platform deposits to depths of 5-15 m (equal to the depth of the channels), perhaps during a single flood event. Similarly, rapid sedimentation may be expected on the subaqueous point bar deposits.

The sub-ice platform has an extremely gentle slope (typically 1:1000 or less) and shallow water depths (l-3 m) extending up to 30 km beyond the shoreline. The sub-ice platform on the western margin of the delta is dominated by the proximity of numerous sub-ice channels, hence sub-aqueous levee deposits are common. In contrast, the platform on the northern side of the delta appears to be characterized by more reworking of sediment, with undulatory ridges and troughs especially common near the outer edge of the platform.

Unlike most deltas, there is an offshore increase in the precent of sand on the sub-ice platform (Fig, A-7)* due to the increased reworking of sediment on the outer edge of the platform. The liquefaction potential of these sands may not be as high as first expected, however, because much of the sand is relatively densely packed due to the higher wave energy on the outer platform. In contrast, the sandy levee deposits probably have a high potential for liquefaction. There is little net erosion or deposition on the platform, as it is largely an area of

*in Appendix A

sediment erosion and bypass. The main exception is near sub-ice channels, where erosion can be both substantial and unpredicted.

The delta front is a term used here to describe the relatively steep (typically greater than 1:500) zone which fringes the delta in water depths of approximately 3-14 m. It is an area of relatively rapid deposition in the western portions of the delta due to the proximity of the major sub-ice channels which empty much of their sediment load on the delta front. Up to 6 m of sediment appears to have accumulated in this area during the last 80 years. Most of that deposition was as a series of storm-induced (?) sand layers typically 5-20 cm thick, thus the amount of deposition during any given event is probably relatively small. The northwestern margin of the delta front consists of a series of large (2-5 m high) shoals, locally up to 50 km long. These shoals appear to be migrating laterally into Norton Sound resulting in a complex pattern of long-term erosion and sedimentation. The delta front along the northern margin of the delta appears to be eroding, with up to 4 m of sediment having been removed during the past 80 years. The amount of sediment removed during a single storm event remains uncertain.

Most of the delta front along the western margin of the delta is in the zone of wave buildup and appears to consist of relatively well-sorted, fine grained sand with a relatively high susceptibility for liquefaction. Similarly, the linear shoals consist of moderately well sorted sand with a relatively high susceptibility for liquefaction. The sediment characteristics of the delta front along the northern margin of the delta are less well known, hence their susceptibility for liquefaction remains uncertain.

The prodelta is characterized by extremely gentle slopes (typically

1:2000) marking the distal edge of the deltaic sediments which extend up to 100 km offshore. Sediment is initially deposited from suspension in this environment, however water depths are still relatively shallow (10-20 m) hence much of the sediment is subsequently reworked. Evidence of such reworking is clearly demonstrated by the unusual pattern of textural parameters (Fig. 5). The southwestern margin of the prodelta sediments (adjacent to the largest distributaries) consist of well-sorted silty sand, grading northward to moderately sorted silty sand and eastward to poorly sorted sandy silt and silt.

The potential hazards due to sedimentation and/or erosion appear to be minimal in these deposits, as it seems unlikely that the resuspension of sediment occurs to any great depth. The liquefaction susceptability of these sediments may be relatively ‘nigh, particularly in the silty sands and sands of the western part of the prodelta. These sands are relatively thin, however (typically less than 2 m; Nelson and Creager, 1977), thus they would probably have little effect on deep-seated structures. The silts in the northern part of the prodelta are thicker (up to 8 m), however they may be too poorly sorted to liquefy.

Sediment Dispersion Patterns:

Most of the sediment introduced into Norton Sound is transported by the Yukon River during the summer, much during the relatively short interval of breakup. Some of the sediment is deposited in programing tidal flats and distributary mouth bars along the coast, however most is transported offshore as bedload with the sub-ice channels and as suspended sediment within the sediment plume of the Yukon. Some of the sediment is deposited on the subaqueous levees adjacent to the channels, however much of the bedload appears to be deposited up to 20 km beyond the shoreline at the delta front. In addition, the suspended sediment plume may extend up to 75 km offshore. Once the sediment is initially deposited it may be extensively reworked by a variety of processes. The result (Figure 5) is quite unlike the more typical graded shelf pattern where sediments become progressively finer grained and more poorly sorted offshore.

The sediment on the western portion of the sub-ice platform is typically coarser grained and better sorted than sediment to the northeast; this is due to the proximity of the main distributary channels and the longer fetch and greater wave energy on the western margin of the delta. The sediment on the outer edge of the sub-ice platform is better sorted than closer to the shore because of the reworking by waves and perhaps accelerated sub-ice currents as well. The delta front is generally within the zone of wave buildup, hence consists largely of relatively well sorted sands reworked by wave-induced currents. Similarly the linear shoals of the delta front consist of relatively well sorted sands which appear to be migrating to the northeast, perhaps due to storm-induced currents or a bifurcation of the Alaska Coastal Water. Sediment

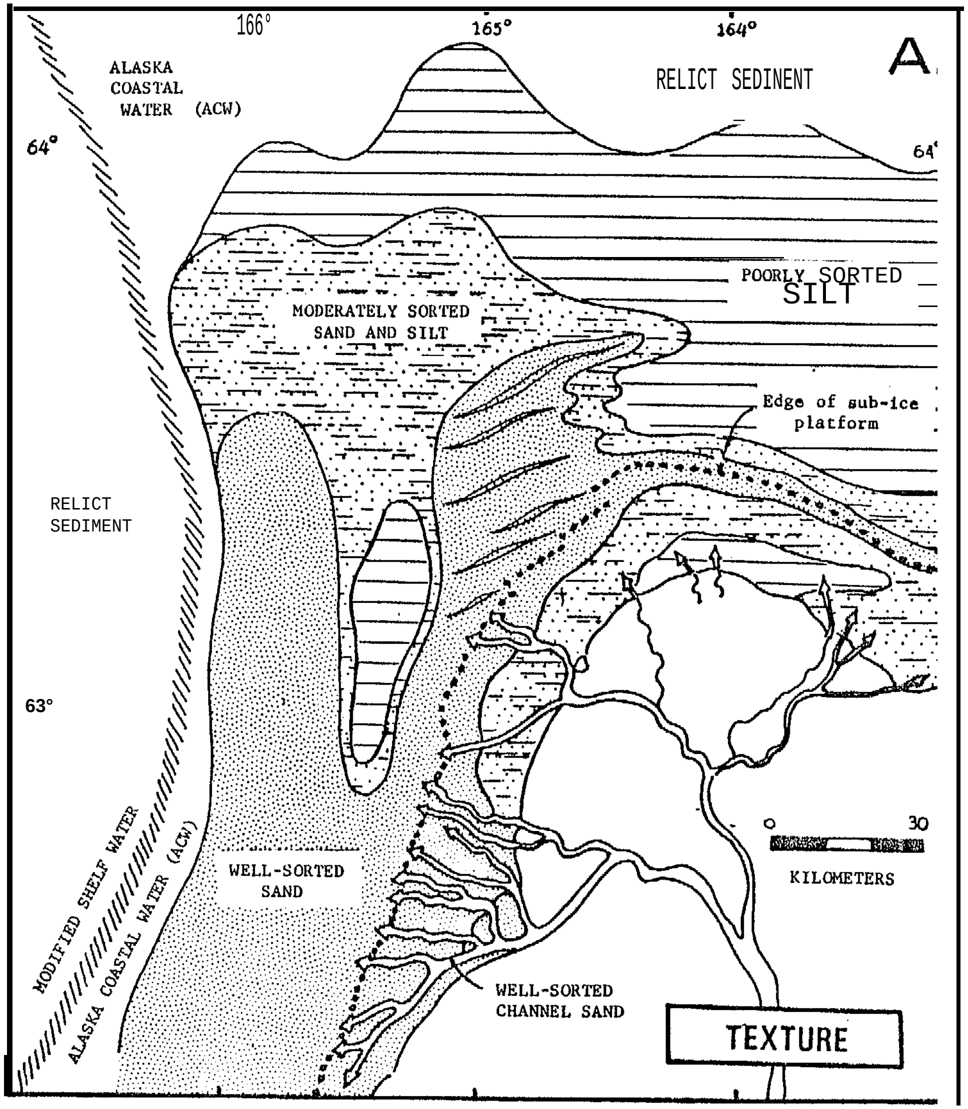

Figure 5A: Schematic representation of sediment charac - teristics based in part on published data (McManus and others, 1977), unpublished data (C. Hans Nelson, U.S. Geological Survey), and extrapolation on the basis of offshore morphology.

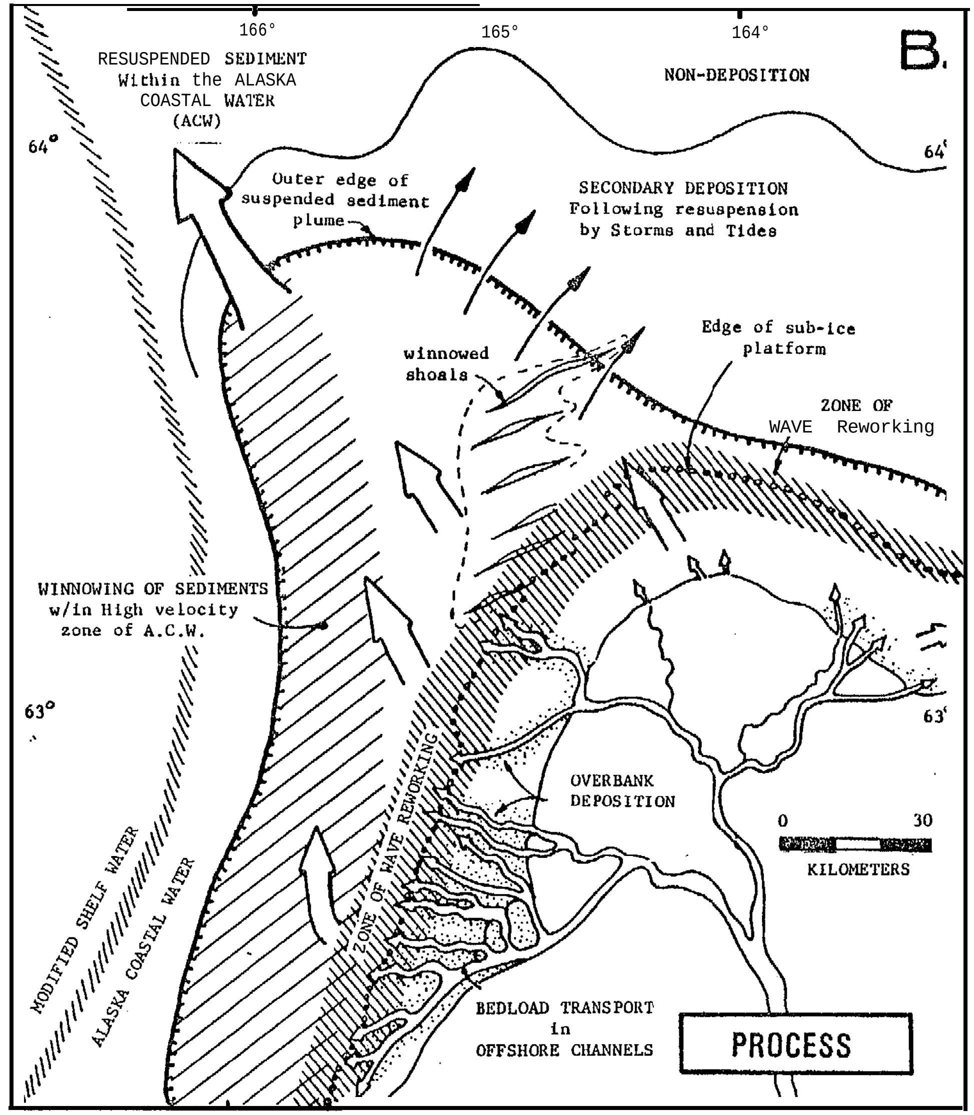

Figure 5B: Hypothetical diagram of dominant process, other than those related to ice, based in part on grain size data, LANDSAT imagery, and offshore bathymetry. Large arrows indicate direction of suspended sediment transport within the initial suspended sediment plume; smaller arrows indicate direction of resuspended sediment into Norton Sound.

initially deposited from suspension on the western margin of the pro-delta is periodically resuspended by a variety of processes (e.g. tides and storms) and reworked. Much of the sediment may remain within the Alaska Coastal Water to be ultimately deposited in the Chukchi Sea, up to 1000 km to the northwest (McManus and others, 1977, Nelson and Creager, 1977). In other cases, the resuspended sediment appears to be transported to the northeast, perhaps in response to storm-induced currents, to be deposited in the central part of Norton Sound.

The sediment supply into Norton Sound is virtually cut off during the winter due to the reduced flow of the Yukon River. Nevertheless, Drake and others (1979) have documented significant amounts of suspended sediment beneath the ice canopy. This implies that sediment is being resuspended during winter as well, although the exact processes and directions of sediment transport remain unclear.

In summary, the patterns of sediment dispersion in the Yukon delta region of Norton Sound are complicated by the shallowness of the depositional basin, the extensive reworking of sediment, and the extreme seasonality of marine processes. This increases the necessity of obtaining much more information before it will be possible to make accurate predictive models of pollutant paths.

Ice Hazards in the Norton Sound-Yukon Delta Region:

The patterns of ice formation, movement, and deformation in the Norton Sound region were studied with the use of Landsat and NOAA satellite imagery for the years 1973-1977. The results document not only the marked seasonality of marine processes throughout the year, but also the significant role of bathymetric and meteorologic conditions in controlling the patterns and rates of ice movement in the region. The results have been summarized in a map of generalized ice hazards Figure 6) , similar in many ways to the maps done for the entire Bering Sea by Stringer (1978). The following is a brief summary of the types of ice-related hazards which characterize each of the zones. The reader is referred to Appendix B for a more detailed discussion of the ice-dominated regime of Norton Sound (Ray and Dupré, in review) .

Zone Ia is a zone of shorefast ice which extends to the outer edge of the sub-ice platform of the Yukon delta, approximately coincident with the 2-3 meters water depth. Over-ice flow (aufeis) occurs throughout the winter in areas of bottomfast ice near the major distributaries (shown in hatchered pattern). Sub-ice currents beneath the floating fast ice may result in some resuspension of sediments in the sub-ice channels and on the outer edge of the sub-ice platform. This is a relatively stable zone throughout the winter, however large sheets of ice may break off during Spring breakup. Zone Ib is a slightly less stable area characterized by floating fast ice during most of the winter, however ice can be completely lacking and replaced by a large area of open water under some conditions (e.g. March 13-15, 1976) . Zone Ic is the zone of shorefast ice which fringes most of Norton

Sound . It is largely floating fast ice, and is more variable in extent and less stable, as large sheets of ice may break off repeatedly throughout the winter. .

Zone IIa is a broad, seaward accreting stamukhi zone formed by the convergence and deformation of ice formed mainly in Norton Sound. The configuration of the outer margin of this zone appears to be controlled by Stuart Island to the east and a series of offshore shoals to the west; it is approximately coincident with the 14m isobath. It is characterized by extensive ice shearing and a relatively high intensity of" ice gouging of the sea floor (as delineated by Thor and Nelson, 1979). Zone IIb is located west of the delta in water depths from 3 to 14 m. It is a relatively unstable area characterized by ice deformation and accretion to the shorefast ice (Zone Ia) during periods of onshore (westerly) winds and an offshore movement of ice and the development of a large, open water area (polyna) during periods of offshore (easterly) winds. It is characterized by a moderately high intensity of ice gouging.

Zone III is an area of seasonal pack ice formed mainly *in situ*, within Norton Sound. The ice typically moves south and west in response to the dominate northeasterly winds throughout the winter, however it may drift slowly in response to oceanic currents during periods of low winds. The southern portion of this zone is characterized by widespread shearing of ice, and is approximately coincident with the area of very high density of ice gouging delineated by Thor and Nelson (1979). The western boundary is approximately coincident with the 20m isobath, separating pack ice formed in Norton Sound from the thicker pack ice formed farther to the north. Bering and Chukchi .pack ice enter the sound only rarely when especially strong northwesterly winds blow.

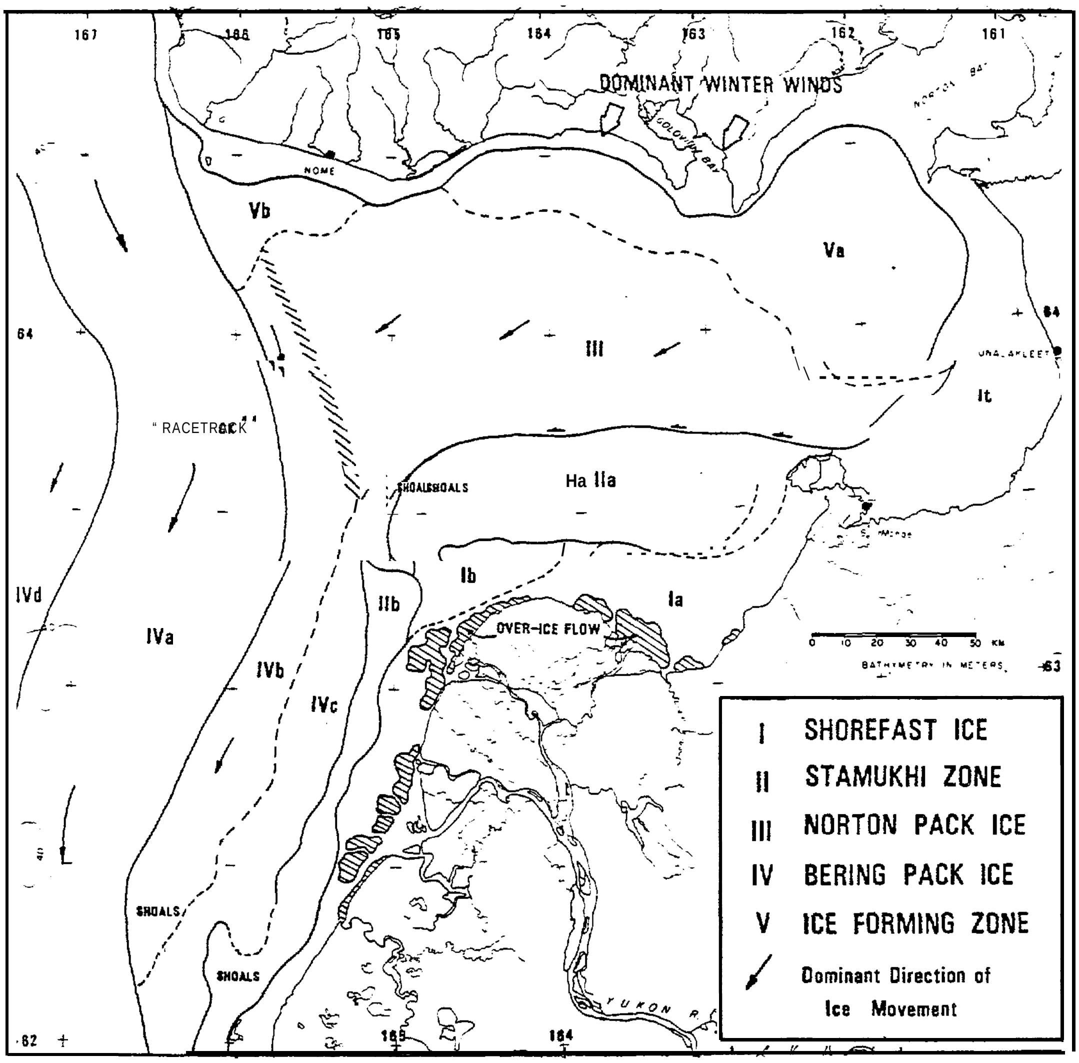

Figure 6: Zonation of ice hazards in the Yukon Delta - Norton Sound Region based mainly on LANDSAT and NOAA satellite imagery, supplemented by information on ice gouging by Thor and Nelson (1979)

Zone IV consists of seasonal pack ice formed in the northern Bering and Chuckchi Seas. It typically moves to the south in response to northerly winds for most of the winter, however short-lived periods of northerly ice movement can occur during the passage of low pressure systems. The ice typically begins to consistently move to the north in late April or early May. Zone IVa is the "racetrack", characterized by intervals of extremely rapid, southerly movement of pack ice (up to 45 km/day) following major ice deformation events north of the Bering Straits (described by Shapiro and Burns, 1975). This zone is characterized by highly fractured nilas ice during periods of relative quiescence. The eastern margin of this zone is approximately coincident with the 22 m isobath. The western margin is more variable, as it appears to be controlled by the geometry of ice piling up on the northern side of St. Lawrence Island. The rapid movement is evidence of the lack of grounded ice, as well as the lack of ice gouging (as delineated by Thor and Nelson, 1979). Zone IVb is in water depths of 22 to 20 m, and is characterized by less rapid ice movement than in the "racetrack". Some grounded ice may occur in this zone, particularly in the area of shoals southwest of the delta. Zone IVC is in water depths of 20 to 14m, and is characterized by open water during periods of easterly winds, and by onshore moving pack ice during periods of westerly winds. It differs from zone IIb mainly by its mobility, i.e. it rarely forms a stamukhi zone accreted to the shorefast ice. Nonetheless, some grounded ice and ice gouging will occur in this zone as well. Zone IVd is similar to zone IVb, and was not studied in detail.

Zones Va and Vb are zones of ice divergence formed by persistent offshore winds (cf. Muench and Ahlas, 1976). "These are typically areas of open water where ice is actively forming for most of the winter.

VIII CONCLUSIONS

1. The Yukon Kuskokwim delta region is characterized by widespread evidence of Quaternary tectonism. Evidence of Holocene faulting, coupled with the relatively high susceptibility for liquefaction of most of the fluvial and deltaic sediments, constitute potentially serious geologic constraints to the selection of offshore sites and the design of offshore structures. The risk from explosive volcanic activity, however, appears minimal.

2. Pleistocene sediments beneath most of Norton Sound contained thick, ice-bound permafrost which was actively forming as recently as 10,000 years ago; some may remain offshore as relict permafrost. Offshore permafrost in modern sediments is less likely, and if present, will be thin, discontinuous, and restricted to water depths <1 meter.

3. The depositional environments of the Yukon delta differ from most previously described deltas, mainly by the presence of a broad, shallow sub-ice platform and associated sub-ice channels. The potential for rapid erosion by these actively meandering subaqueous channels is especially serious, as is the relatively high susceptibility for liquefaction of much of the offshore sediments,

4. The shallowness of Norton Sound, combined with the marked seasonality of marine and fluvial processes, has resulted in a complex pattern of sediment resuspension and reworking. This makes the predicted paths of sediment (and pollutants) transport more complex than might be expected in deeper basins in more temperate climates.

5. Satellite imagery, used in combination with available weather data, has documented relatively systematic patterns of ice movement controlled largely by local winds and offshore bathymetry. This has allowed the sub-division of the Norton Sound region into zones, each characterized by a particular type of ice and ice movement.

IX RECOMMENDATIONS FOR FUTURE WORK

There are a variety of potential geologic hazards which must be considered in the course of developing Norton Basin. Many of these relate to the Quaternary deposits and the processes by which they formed (including those active today). Some of the problems require substantial additional study. They include the following:

1) LIQUEFACTION

Most of the sediments on the delta margin and delta front consist of well-sorted sands and silts which may have a high potential for liquefaction. These sediments commonly occur in the sub-ice channels, the outer edge of the sub-ice platform, and on the delta front in the western part of the delta. This is based not only on the grain size analyses, but also on the abundance of liquefaction-induced deformation features noted in cores from the Karluk, particularly where sub-ice channel facies were cored.

Recommendation : Look at the relationship between the potential for liquefaction as a function of depositional environment, emphasizing the correlation between grain size, liquefaction-induced features, and environment. If the 'correlation exists '(and I believe strongly that it does) , spend more effort in obtaining more 'information on the geotechnical properties of sediments in the various environments and a more detailed map on the distribution of the depositional environments (NB the distribution of the sub-ice channel and delta front " facies as well as the thickness of the Holocene sediments).

2) SUB-ICE CHANNELS

These channels appear restricted to ice-dominated deltas, hence they may present some unexpected problems. They are presently actively meandering with erosion on the cut banks and deposition on the subaqueous point bars. The channels are up to 1/2 km wide and up to 10 m deep, and appear to be areas of active sediment transport as well, with sand waves up to 1 m high locally. There is, therefore, potential for scour and fill in these channels, especially during spring breakup.

Recommendation: Compile existing Landsat and bathymetric data on the geometry and distribution of these channels, including any evidence on the rates of channel migration comparing the old maps with the newer data. Consider *in situ* monitoring before, during, and after breakup to determine the amount of scour and fill that might occur (alternatively, obtain vibracores in the channels to determine the thickness of the channel fill deposits, which should approximate the depth of scour during flooding). Also consider *in situ* monitoring of currents in the channels during storms and under the ice, as they may serve as conduits for return flows resulting in flushing of sediments.

3) DELTA FRONT

The delta front is a relatively steeply dipping area from 3 to 15m water depth which appears to be an area of relatively active deposition in the western part of the delta, near the mouths of the major distributaries. It appears to be an area of erosion, however, on the northern parts of the delta based on preliminary comparisons of 1899 bathymetry with data collected from the R/V KARLUK (USGS cruise, 1978). In addition, the northwestern part of the delta front appears to consist of a series of migrating linear shoals with a resulting complicated patterns of erosion and deposition. This is also an area where liquefaction-induced slope failures are likely to occur.

Recommendation: Make a detailed comparison of the pre-1978 bathymetry with that collected by the R/V KARLUK to determine the direction and rates of movement. If the rates are such as to represent potential hazards, more detailed bathymetric data should be collected (this is probably necessary in any case, as the existing data is quite insufficient). Also obtain side scan data on the delta front looking for evidence of liquefaction-induced slump features, and vibracores to determine the geotechnical properties of the sediments.

4) OFFSHORE PERMAFROST

There is abundant evidence that much (most?) of Norton Sound was underlain by thick, ice-bound permafrost which was actively forming as recently as 10,000 years ago. Thus a very real possibility exists for the presence of relict ice-bound permafrost underlying parts of Norton Sound today.

Recommendation: Delineate the distribution of Holocene and Pleistocene deposits beneath Norton Sound, perhaps with the use of high-resolution seismic profiling, coupled with test drilling to determine the geotechnical properties of the sediments, including the presence, if any, of relict, ice-bound permafrost.

5) SEASONAL VARIABILITY OF MARINE PROCESSES

It has become increasingly apparent that the processes of sediment transport and deposition (and resuspension) are far more complex than previously thought. The extreme seasonality of processes, including those associated with river influx, wind and waves, oceanic and tidal currents, and ice must be studied in more detail if predictive models of sediment (and pollutant) transport are to be properly developed.

Recommendation: Fund a series of coordinated, interdisciplinary studies of in situ monitoring of processes during several periods of the year. -Such a program could be patterned as follows:

a) Winter-dominated period: this would include both lab studies of weather patterns and ice movement as detectable on satellite imagery, as well as field studies to measure ice thickness and patterns of ice movement and deformation, as well as sub-ice processes such as oceanic currents and tides in a variety of environments such as sub-ice channels, the delta front, and prodelta.

b) Breakup: This period is of extreme importance in establishing and maintaining many of the environment which appear unique to ice-dominated coastal zones. In situ monitoring of currents and sediment transport on top of the fast ice and below the ice canopy, both in sub-ice channels and in the sub-ice platform.

c) River-dominated period: This is a period dominated by the high sediment discharge of the Yukon. Studies emphasizing the pattern of sedimentation during this time would be extremely useful. Offshore wave and current meters would be installed at this time.

d) Storm-dominated period: Late summer and early fall is a period dominated by the combined effects of decreasing sediment input and increasing storm frequency (hence sediment reworking). In situ monitoring of offshore processes is particularly important at this time.

e) Freezeup: It also would be useful to study the processes by which the shorefast ice forms and expands over the sub-ice platform and associated channels. This also would require *in situ* monitoring during late October to early November.

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APPENDICES

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APPENDIX A: The Yukon Delta: A Model for Deltaic Sedimentation in an Ice-Dominated Environment; OTC Paper 3434, Proceedings of the 11th Annual Offshore Technology Conference, Houston, Texas.

APPENDIX B: The Ice-Dominated Regimen of the Norton Sound Region Northern Bering Sea, Alaska; in Hood, D.W. (cd.), The Eastern Bering Sea Shelf: Its Oceanography and Resources.

APPENDIX A:

OTC 3434

THE YUKON DELTA : A MODEL FOR DELTAIC SEDIMENTATION IN AN ICE-DOMINATED ENVIRONMENT

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ABSTRACT

Field mapping in the Yukon delta region of western Alaska, combined with laboratory analysis of sediment and Landsat imagery, has provided insights into the role of climate and tectonics on deltaic processes on high-latitude continental shelves. The climatic and tectonic influences on sediment type, in combination with the role of river and sea ice in controlling patterns of sediment transport and deposition, suggest that the Yukon delta may provide a model for deltaic sedimentation in an ice-dominated environment.

The combination of an arctic and sub-arctic climate and extensive Cenozoic tectonism has resulted in the production of a mineralogically immature suite of silts and sands (typically feldspathic litharenites) with a relative paucity of clays. The textural and mineralogical composition of these sediments will, in turn, influence their geotechnical properties as well as post-depositional compaction and diagenetic effects.

The processes of sediment transport and deposition in the Yukon delta vary systematically throughout the year. There exists an ice-dominated, river-dominated, and storm-dominated regimen, each consisting of a characteristic set of processes. These processes can constitute geologic hazards which vary with season and depositional environment, thereby significantly affecting the siting of offshore facilities.

The geometry of the delta and its various depositional environments are strongly influenced by the effects of sea ice. A comparison of the subaqueous profile of the Yukon delta with those of previously described wave- and river-dominated deltas reveals a broad 'sub-ice platform' typically less than 2 m deep and up to 30 km wide separating the intertidal deposits from the prograding delta front. This platform, as well as associated 'sub-ice channels' which extend tens of kilometers offshore from the major distributaries, constitute major differences with previously described deltas. Thus, the Yukon may represent a distinct class of ice-dominated delta, similar in many respects to deltas presently forming in the Arctic. Failure to recognize the unique characteristics of ice-dominated deltas can result in serious errors in the estimation of the reservoir *potential of* deltaic sediments deposited under similar climatic conditions.

References and illustrations at end of paper.

INTRODUCTION

The prospect of oil and gas exploration in Norton Sound (Fig. 1) has focused increased attention on the Yukon delta, both as an area that might be significantly affected by such development, and as a possible analogue for older, Yukon-derived deltaic sediment which might serve as possible reservoir rocks in Norton Basin. Preliminary studies demonstrate that the depositional environments and related processes associated with the Yukon delta differ markedly from those of most previously described deltas. The purpose of this paper is to describe these environments and processes, as they may provide a possible model for a newly defined class of ice-dominated deltas. Parts of the model are speculative, however it may provide a basis for future discussion on the role of ice in deltaic sedimentation on high-latitude continental shelves.

METHODS

Field work during the summers of 1975 through 1978, and interpretation of bathymetric and topographic maps, aerial photographs, and Landsat imagery, have provided an overview of the major depositional environments of the Yukon delta as well as the processes which characterize each environment. Sediment from most of the depositional environments was analyzed using the Rice University Automated Sediment Analyzer (RoASA). This system uses a large settling tube to analyze the sand, a smaller settling tube to analyze the coarse silt, and a hydrophotometer to analyze the fine silt and clay. Additional grain size information was also available for a limited number of samples from the delta front and prodelta environments (McManus and others, 1977) and from a large, sub-ice channel (Matthews, 1973). X-ray photographs of numerous cores were examined to provide additional information on sedimentary structures and bioturbation, particularly in intertidal deposits. In addition, point counts were made of grain mounts of sand collected from a variety of environments to determine the effects of provenance and climate on the composition of the sediment.

GEOLOGIC SETTING

The Yukon River drains an area of approximately 855,000 km^2, providing a water discharge of approximately 6220 m^3/sec and a sediment load of approximately 88 million tons/year, representing about 90% of the total sediment presently entering the Bering Sea (Lisitsyn, 1972). The source area is a region of continuous to discontinuous permafrost dominated by mechanical weathering (including the effects of glaciation). The result of such weathering processes should be a sediment high in silt and with a relative paucity of clays [e.g. Taber, 1943; Hill and Tedrow, 1961), and this is confirmed by size analysis of Yukon sediments (Fig. 2). The source area has a complex history of Cenozoic tectonism, which, in combination with the relative lack of chemical weathering, has resulted in the production of a compositionally immature suite of sands (typically feldspathic litharenites). Thus both the texture and composition of the sediments strongly reflect the climatic and tectonic setting of the drainage basin.

The modern delta of the Yukon River is a relatively young geologic feature, having formed since approximately 2500 years ago, when the river course shifted to where it presently enters Norton Sound (Dupre, 1978). Norton Sound is a broad re-entrant of the northern Bering Sea, characterized by low rates of tectonic subsidence and extremely shallow water depths (generally less than 20 m). The shallowness of the depositional basin has allowed extensive reworking of the deltaic sediments by a variety of processes, including waves, wind- and tidally-induced currents, and oceanic currents, as well as processes associated with ice movement. The relative importance of these processes varies systematically throughout the year, showing the definition of an ice-dominated, river-dominated, and storm-dominated regimen (Fig. 3).

SEASONALITY OF COASTAL PROCESSES

The ice-dominated regimen begins with freeze-up along the coast in late October or November. Shorefast ice extends from 10 to 30 km offshore, where it is terminated by a series of pressure ridges and shear ridges (Stamukhi zone of Reimnitz and others, 1977) formed by the interaction of the shorefast ice with the highly mobile, seasonal pack ice (Fig. 4A). This typically occurs in water depths of 5 to 10 m, and is an area of intense ice gouging. Gouging may result in the resuspension of sediment which is then available for reworking and re-distribution by relatively weak, sub-ice currents, some of which may be induced by vertical movement of the floating fast ice (Barnes and Reimnitz, 1973).

River breakup typically occurs in late May, marking the beginning of the river-dominated regimen. During breakup, much of the sediment bypasses the nearshore zone by a combination of over-ice flow (cf Colville delta) and sub-ice flow through a series of channels which extend up to 30 km offshore (Fig. 4B). Once the shorefast ice melts or drifts offshore, sedimentation is dominated by normal deltaic processes under the influence of the high discharge of the Yukon river. The dominant northeasterly winds are usually weak and blow over a relatively limited fetch, hence the wave energy along the coast is generally low during this time of year.

Increasingly frequent southwesterly winds and waves associated with major storms during the late summer mark the beginning of the storm-dominated regimen. The relatively long fetch and high winds result in high wave energy particularly on the western side of the delta. High wave energy and rapidly decreasing sediment discharge from the Yukon result in significant coastal erosion and reworking of deltaic deposits in the late summer. This continues until freeze-up when ice-related processes regain their dominance.

The northwesterly-flowing Alaska Coastal Water (ACW) impinges on the western side of the delta throughout the year, although there are large seasonal variations in its lateral extent (Coachman and others, 1975). High flow velocities in the ACW appear responsible for a large amount of fine-grained sediment bypassing Norton Sound for final deposition in the Chukchi Sea, 500-1000 km to the northwest (Nelson and Creager, 1977). Similarly, tides with a range of 1-1 1/2 m and tidally-induced currents are active throughout the year, but their significance remains unclear. It seems likely that both the flow within the ACW and the tidally-induced currents are most important in transporting sediment re-suspended by other processes (e.g. storm waves, ice gouging).

DEPOSITIONAL ENVIRONMENTS

The subaerial morphology of the Yukon delta is similar to lobate, high-constructional deltas described by Fisher and others (1969) as typical of bedload-dominated rivers emptying into shallow depositional basins. This is consistent with the geologic setting of the Yukon, however a more careful examination of the subaqueous morphology suggests that such a classification fails to recognize some of the unique aspects of the Yukon delta.

The delta plain is fringed by prograding tidal flats and distributary mouth bars, similar to many previously described deltas. The Yukon delta is unusual, however, in that the delta front and prodelta are offset from the prograding shoreline by a broad platform (herein referred to as a sub-ice platform), locally up to 30 km wide. The result is a subaqueous profile (Fig. 5) quite unlike those of wave- and river-dominated deltas described by Wright and Coleman (1973).

The broad platform (and associated subaqueous channels) appear related to the presence of shorefast ice which fringes the delta for almost half the year. Several workers (e.g. Reimnitz and Bruder, 1972; Reimnitz and Barnes, 1974; Walker, 1974) note that patterns of nearshore sedimentation along the north slope of Alaska are strongly influenced by the presence of shorefast ice. Naidu and Mowatt (1975) suggest that this is unique to deltas formed by polar rivers in the Arctic. We believe that these smaller arctic deltas, as well as larger deltas such as the Yukon, Mackenzie, and Lena, actually represent a separate type of ice-dominated delta, morphologically distinct from the wave-, river-, and tide-dominated deltas previously described in the literature (e.g. Galloway, 1975). The Yukon delta may provide a type example for such an ice-dominated delta (Fig. 6).

The delta plain contains a complex assemblage of active and abandoned distributaries, levees, interdistributary marshes, ● nd lakes. The ● ctive distributaries have a radially bifurcating pattern; individual channels have low to moderate sinuosity. The river hse two main distributaries (1-1 1/2 km wide and 10-15 m deep) ● nd numerous smaller distributaries (sea as small as 20 m wide and 2-5 m deep) typically spaced every 1-2 km along the coa st. Point bars and mid-channel bars are common, particularly along the larger distributaries. Channel and bar deposits ● re typically composed of moderately to well sorted sand and silt y sand, grading upwards and laterally trite organic-rich, poorly sorted silt ● nd mud deposited on natural levees snd in meander swales.

The distributaries frequentl y shift the ir course via channel ● vulsion, often precipitated by ice jams resulting in the deposition of ● n abandoned channel fill typically consisting of organic-rich sandy silt and silt. Abandoned channels are highly prone to flooding ● nd ● re freqently re-occupi ed by distributaries, resulting in a complex delta stratigraphy.

Interdistributary areas in ths older, inactive parts of the delta ace largely marshes characterized by poorly-sorted peaty silt ● nd mud. Freshwater peats may be up to 1 ❑ thick in the oldest parts of the delta . Bane ● hallow lakes occur between natural levee 6, however ❑ ost are in the process of being filled with vegetation. Incipient permafrost development hss resulted in the formation of peat mounds (palsen) in many former lake beds . Interdistributary ● reas ● long the coast ● r e characterized by marshes of ● alt-tolerant grasses and sedges, typially forming over ● ctively prograding tidal deposits. Low washover ridges record short intervals of shorel ine erosion, probably during ma jar storms .

The delta marcin is a term used informally here to include rapidly prograding tidal flats and distributary mouth bars as well as the sub-ice platform and ● ssociated offshore channels. Tidal flats ● re typically 100-1000 m wide where they occur along the prograding margin of the delta. The flats consist of pearly-sorted sandy silt in areas of relatively low wave energy (on the northern side of the delta) to moderately and pvrly-sorted sil ty sand in areas of higher wave energy (on the western side of the delta) . The tidal flat deposits commonly form a f ining-upwards sequence [● pproximately 1 m thick) of mixed bedded, ripple and parallel-laminated silty sand and silt. Primary sedimentary structures are often Obscured, however, b y ● xtenstve bioturbation, e specially in areas of high silt content. Detrital peat is local ly abundant, particularly in the upper parts of the prograding s equences. The tidal flats show abundant ● violence of ice scour and ice plucking similar to that described by Dionne (1969) , however the preservation potential of such features may be small .

Middle-grouhd bars commonly occur ● t the mouths of the larger distributaries. These are characterized by moderately to well-sorted sand in ● reaa of high wave energy ● nd by poorly-sorted silty sand in areas of low wave energy. In addition, individual bars are typically coarser grained and better sorted in the mere proximal parts, getting finer grained on their mere distal ● dge. Sedimentary structures ● re mostly ripple and parallel laminations, with little detrital peat or ● vtdsnce of bioturbation.

Unlike most deltas, the major distributaries continue of fshore ● fter bifurcation at the shoreline. These offshore extensions of the distributaries (here referred to as sub-ice channels), ● re 1/2 to 1 km wide and 5 to 1 S m deep; they extend up to 30 km across the sub-ice platform. The channels have a low to moderate sinuosity with most showing clear evidence of lateral migration and the deposition of subaqueous point bar deposits. These deposits ● re probably characterized by ● f ining-upwards sequence (up to 1 5 m thick) consisting of an erosional channel base overlain by moderately sorted, fine to very fine sand grading upwards to moderately sorted sand and silty sand deposited on subaqueous levees. Landsat imagery shows evidence of these channels being areas of active bedload transport throughout moat of the summer; they may also serve ascondui ts far ● ub-ica currents during the winter months ● s well.

The sub-ice platform (or 2-meter bench of Toimil, 19771 has an extremely gentle slope (typically 1:1000 or less) extending 10-30 km offshore. The average depth over most of the platform Is 1-2 m, however there commonly is an erosional(?) trough up to 5 m deep near the outer edgs of tba platf orm, particularly along the northern ● dqs of the delta. Unlike the nearshore sediment of most deltas, t h e platform appears to be characterized by an offshore increase in the percent of sand (Fig. 7) , ranging from puocly-sorted sandy silt nearshore to poorly and moderately sorted sand and silty sand near the outer edge of the platform. This is similar to trends reported off the north slope of Alaska by Barnes and Re imnitz {1973).

The sub-ice platform appears to & an area of sediment bypassing and reworking throughout much of the year. Sediment bypa sses the inner part of the platform during river breakup initally by over-ice flow (similar to that described by Reimnitz and Bruder, 1972 and Walker, 1974], as well as by sub-ice flow in the of fshore channels crossing the platform. Sediment is deposited from suspension during the summer months, however ❑ uch of that sediment is reworked during storms and perhaps during the winte r months as well . The entire platform is suf ficiently shallow to be reworked by waves, however most of the larger waves break at the outer margin. This suggests that the outer ❑ argin of the platform is an area of relatively high wave energy, providing one mechanism to ● xplatn the offshore increase in sand. In addition, the reduced cross-sectional araa of the water column overlying the sediment may ● ct to ● ccelerate ● uk-ice currants of various origins. The inner part of ths platform is frozen to tha bottom with bottomfast ice, however the outer portion is overlain by floating fast ice where the accentuated sub-tee currents could provide an additional mechanism for winnowing of fine-gra ined sediment f rein the outer margin of the sub-ice platform (cf Barnes and Reimnitz, 1973).

The delta front is a term used here to describe the relatively steep (typically greater than 1:500) margin of ths delta characterized by apparently rapid deposition of sediment in water depths of 2-10 m. Maximum rates of progradat ion probably occur adj scent to the ❑ ajor distributaries (and associated sub-ice channels), presumably during the summer months. The morphology of the delta front is roofs complex along the northwestern part of the delta (Fig. 6B), where it includes a series of large (3-S m high) shoals which a ppear to be migrating laterally into Norton Sound. This northeasterly movement is perpendicular to the dominant direction of ● - x sediment transport, perhaps **representing** ● ither ● **secondary bifurcation** of **the Alaska Coastal Water** or **the** ● ffect **of superimposed storm- or** tidally-induced **currents.** The outs r **margin of the delta front (in** 5-10 ❑ **water** depths) **is** ● n ● rea **of intense ice** gouging **during the winter months** (Thor and *others,* 1977] , **which may result** in **significant resuspension** and **reworking of** the **sediment.**

The sediment characteristics of the delta **front are** poorly known, but the western margin probably **consists of parallel laminated poorly-sorted silty sand** and candy **silt, presumably fining** *offshore.* ***The*** **shoals on the northwestern side** of the **delta** probably **consist of better sorted, sandy sediment.**

The **prodelta is characterized** by **extremely gentle** ● lopea (**typically** 1:2000) marking tha distal ● dge *of* **the deltaic sediments which** ● xtend up **to** 100 **km** offshore . **Sediment** is **initially** deposited **from** suspension **in** this environment, **however water** deptha are still relatively **shallow** (10-20 m) hence much of **the sediment is** ● ubrsqwnely **reworked. Evidence of** such **reworking is** clearly demonstrated by **the** unusual pattern of textural **paramete rs described** by **McManus** and **others** (1977). Tire **southwe stern margin** ***of*** **the prodelta sediments (ad jacent to** the largest **distributaries)** consist of **well-sorted** silty sand, grading **northward to moderately** sorted silty **sand** and eastward to poorly sorted sandy silt and silt. **The** presence **of** sandy **sediments in** the **western part** of the **prodelta** appears to **be in** part the **result of** resuspension of **fine-grained** sediments **and their subsequent** removal **from Norton Sound** by the **relatively high** flow velocities within the **Alaska Coastal Water (McManus** and **others, 1977; Nelson** and **Creager,** 1977).

IMPLICATIONS

The **modern** Yukon delta **has several depositional environments** lacking **in** deltas formed in ❑ ore **temperate** climates. These **depositional environments** are but one indication **of** tha extreme **seasonality** of coastal **processes** which probably characterize many high-latitude continental shelves. **Table** 1 **is a** preliminary attempt **to assess the** relative **importance of** these **processes** within each **environment. The ability to** predict the **types of processes** aa vail as the **sediment** characteristics and **geotechnical** props sties **which** *characterize* each **environment, should** greatly **aid** in **min imizing** both **the** cases and **environmental impacts of siting both offshore and** onshore Structures.

The delta also provides a modern **analogue** for elder **delta ic sediments** formed under, **similar tectonic** and **climatic settings. In** particular, tba **rates of progradation** are **much greater** than the **rates** of tectonic **subsidence,** hence **the thickness of individual progradational sequences** ie **limited** by **the** water depths of **the depositional basin (Fig. 6B)** . This **results** in **the** formation **of** ● **blanket-like deposit, a few tens of meters thick and** thousands **of** km^2 **in aerial extent.** The **distr** ibut ion **of** ehs sand-rich **depos its also** dif **fe** rs **from most** previously **described delta models.** Wuch of ths **delta** plain **consists** ***of*** **a complex pattern** of radially *bifurcating* distributary **sands, however** many **of these well-sorted sands** extend **tens of kilometers** offshore, **having been deposited** in sub-its channels. **These depos** ies **represent off shore extensions of potential reservoir** rocks. In ● ddition, acme of **the coarsest,** best **sorted sands** have baan **deposited** not ● t **the** "shoreline, but **rather** in water depths **of 2-3** m **at** distances of up **to** 30 **km** of **fshore along the** *outer* **margin of** ths **sub-ice** platform. **These sands** ● hould form **a** blanket-like **deposit which may provide** ● noehar **potential reservoir. The** textural **and** mineralogical **composition of the sediment** significant affects **the post -depositional** history *of* the **sediment.** The lack **of** primary clays, particularly **in** the **prodelta deposits,** results in **relatively little soft-red iment compact** ion **and** deformation, **however** the abundant volcanic **roc** k **fragemnts may** undergo **diagenetic** alteration to form an **extensive matrix** of secondary clays , the reby significantly reduc ing **intially high porosities and permeabilities. In summary,** the **failure to recognize the unique geometry and sediment characterisitics** Of **deltaic deposits** formed **in** ● **ice-dom inated environment** could result in **serious** errors **in** ● atimattng **the reservoir potential of older** rocks.

ACKNOWLEGMENTS

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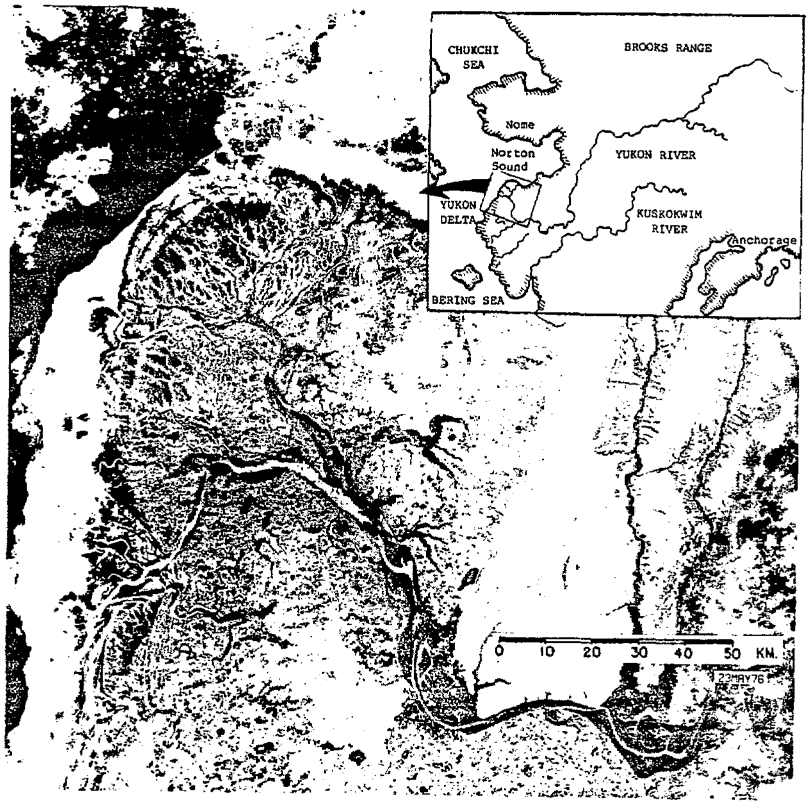
Table 1 -

A preliminary summary of *non-tectonic geological* hazards of the modern *Yukon* Delta

	DEPOSITIONAL ENVIRONMENTS	FLOODING	ICE SCOUR	SEDIMENTATION	EROSION	PERMAFROST
DELTA PLAIN	Active Distributary	High	Moderate	High	High	None
	Abandoned Distributary	Moderate	Low	Moderate	High	Low-Mod
	Interdistributary Marsh	Moderate	Low	Low-Mod	Low	Low-Mod
	Coastal Harsh	High	Moderate	High	Variable	Low
DELTA MARGIN	Distributary Mouth Bar	High	Moderate	High	Low-Mod	Low
	Tidal Flats	sigh	Mod-High	High	Low	Low
	Sub-ice Platform	N/A	Mod-Low	Variable	Variable	None
	Sub-ice Channels	N/A	Low	High	High	None
DELTA FRONT		N/A	High	High	Low?	None
PRODELTA		N/A	Mod-Low	Moderate	Mod-Low	None



FIG, " 1 - LOCATION MAP AND LANDSAT IMAGE OF THE MODERN LOBE OF THE YUKON DELTA TAKEN DURING BREAKUP,

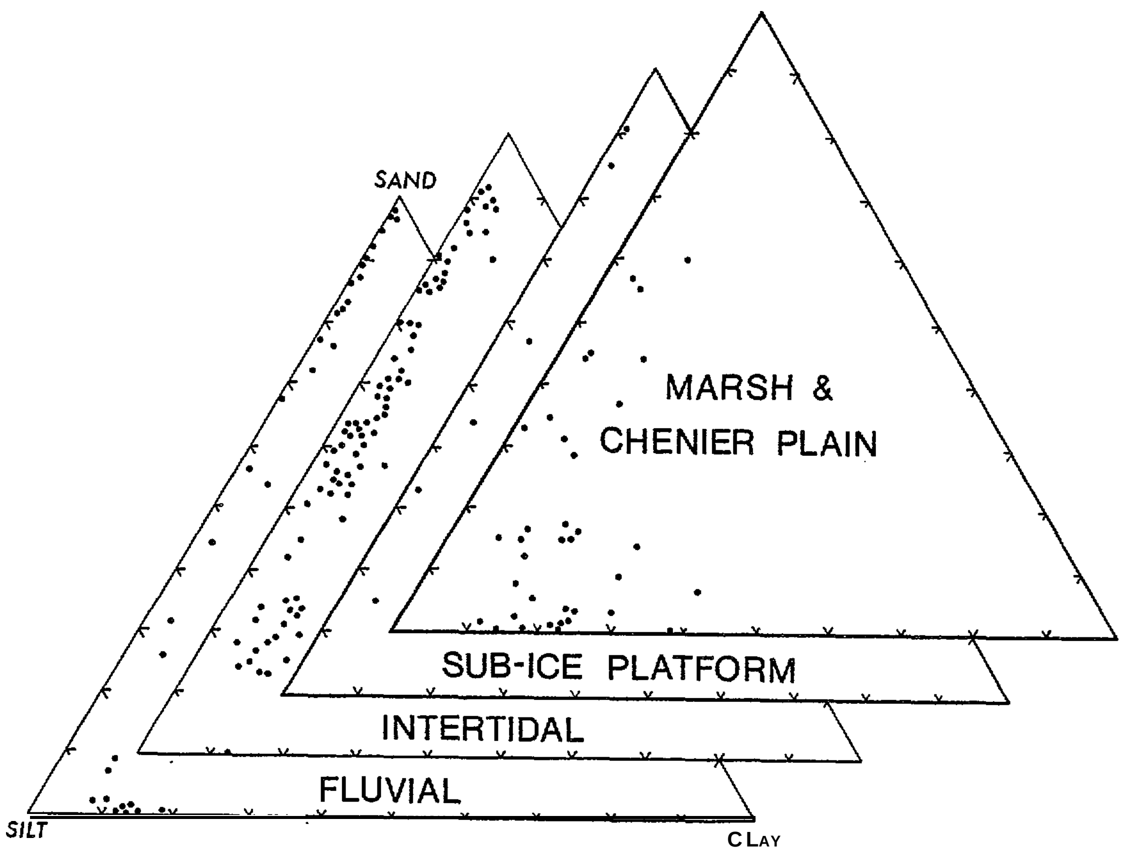
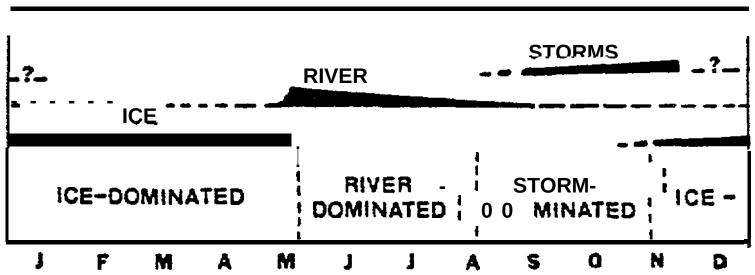
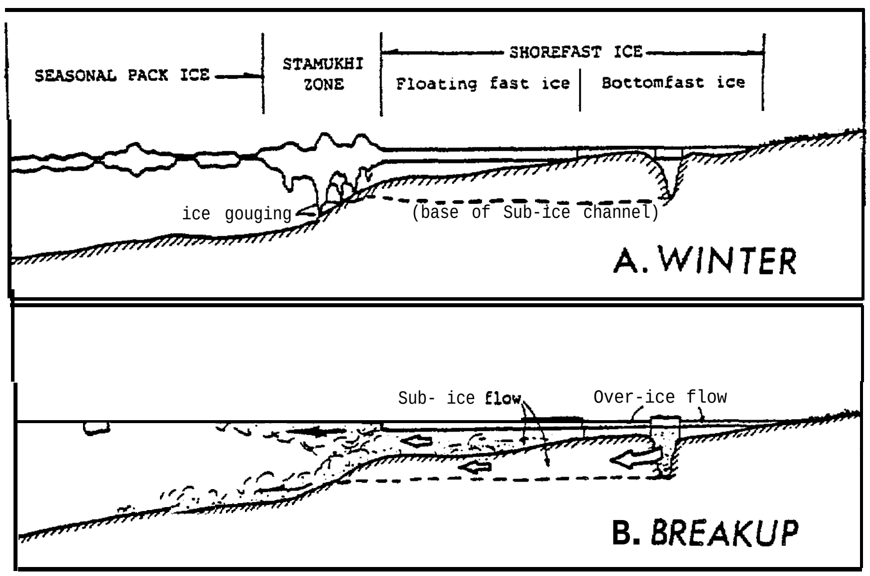


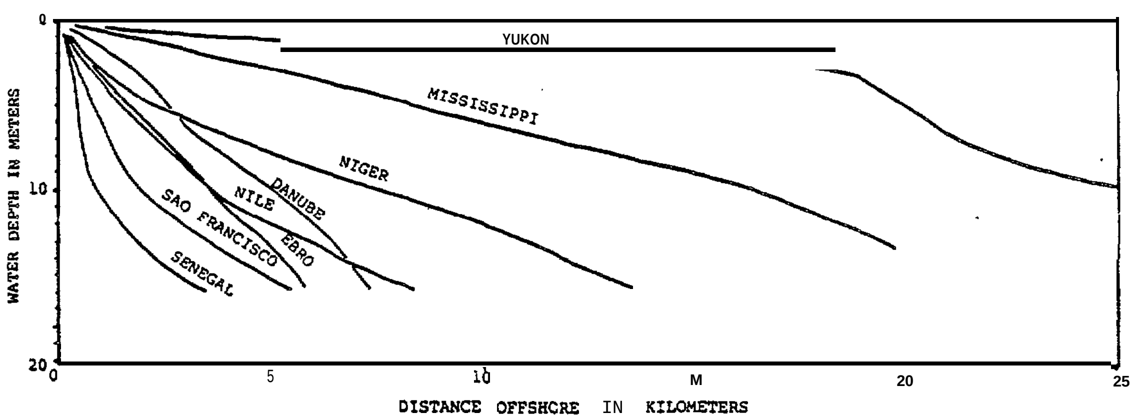
FIG. 2 GRAIN SIZE CHARACTERISTICS OF SEDIMENTS FROM THE DELTA PLAIN AND DELTA MARGIN OF THE YUKON DELTA.



A-3 - Seasonal variability of coastal processes in the Yukon Delta region of Norton Sound.



A-4 - Ice zonation in the winter (A) and its effect on sediment dispersion during breakup (B).



A-5 - Comparison of the subaqueous profiles of wave and river-dominated deltas (after Wright and Coleman, 1973), with that of the Yukon Delta.

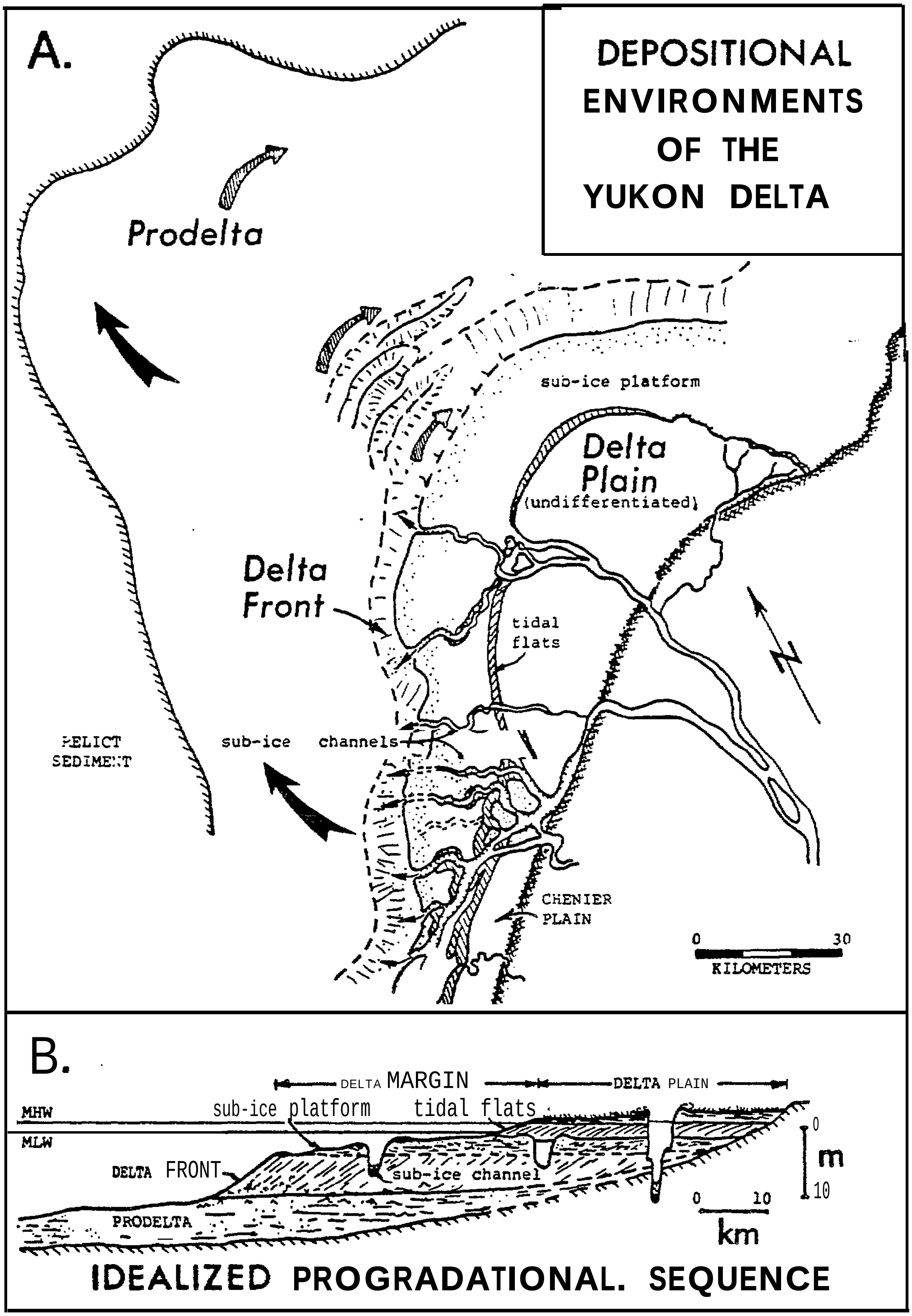

A.
DEPOSITIONAL ENVIRONMENTS OF THE YUKON DELTA
Prodelta
sub-ice platform
Delta Plain (undifferentiated)
Delta Front
tidal flats
RELICT SEDIMENT
sub-ice channels
CHENIER PLAIN
0 30 KILOMETERS
B.
DELTA MARGIN
DELTA PLAIN
MHW
MLW
sub-ice platform
tidal flats
DELTA FRONT
sub-ice channel
PRODELTA
0 10 km
0 m 10
IDEALIZED PROGRADATIONAL. SEQUENCE

Figure A-6

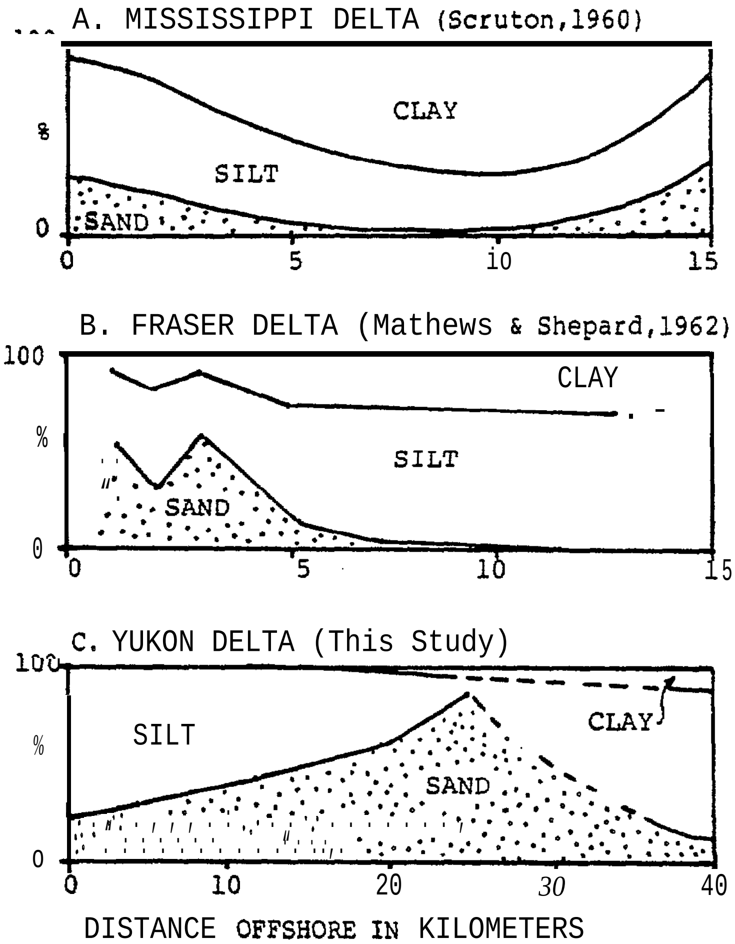


Figure A-7: Comparison of offshore trends of sediment textures off the Mississippi, Fraser, and Yukon Deltas. Note the decreased amounts of clay in areas where mechanical weathering predominates.

Appendix B

THE ICE-DOMINATED REGIMEN OF THE NORTON SOUND REGION OF ALASKA

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ABSTRACT

The patterns of ice formation, movement, and deformation in the Norton Sound region of the Bering Sea were studied with the use of Landsat and NOAA satellite imagery for the years 1973-1977. The results demonstrate not only the marked seasonality of marine processes, but also the significant role of bathymetry and meteorologic conditions in controlling ice movement in the region.

The ice-dominated regimen of the Norton Sound begins with ice freezeup in October and lasts through the winter to spring breakup, sometime in May. Freezeup begins as temperatures drop in early fall, and ice starts to accumulate around the Yukon Delta, during which time water and sediment discharge from the Yukon River and its distributaries becomes insignificant. Oceanographic currents are relatively ineffective in transporting ice during the winter months, as strong northerly winds generally control ice movement in the winter phase. Consequently, ice divergence from the northern coast of Norton Sound, and ice convergence along the, northern margin of the Yukon delta front is common throughout the phase. Ice ridging" and associated gouging result from the compaction of shorefast ice along the northern prodelta. Shearing and gouging also occurs along the western margin of the delta, where pack ice pushed southward by the winds, shears past the fast ice boundary. Periods of rapid advection of pack ice from the Chukchi Sea through the Bering Strait are also indigenous to the winter phase. Such events generate ice floe movement of up to 45 km per day which tends to occur along a relatively narrow band (i.e., the "racetrack") west of Norton Sound. May marks a time of warming temperatures which melt ice from the river channels, as well as a shift to predominantly offshore winds. The higher temperatures and increased discharge from the river triggers ice breakup along the coast. Northward flowing water currents (aided by offshore winds) carry ice away from the delta, and by June the high sediment input of the Yukon River dominates the coastal processes in the delta region.

INTRODUCTION

The prospect of oil and gas exploration in Norton Sound (Fig. 1) has focused increased attention on the sedimentary processes which characterize the region. It has become increasingly apparent, however, that these processes vary systematically throughout the year allowing the recognition of an ice-dominated, river-dominated, and storm-dominated regimen (Fig. 2), each consisting of a characteristic suite of geologic processes and associated geologic hazards (Dupré and Thompson, 1979).

It is the purpose of this paper to discuss the ice-dominated regimen of Norton Sound from its inception at freezeup typically in late October or early November to its end at breakup in May (Fig. 3). Of particular interest is the extent and variability of shorefast ice, the patterns and rates of movement of seasonal pack ice, and the weather conditions under which such movement occurs. Most of this work has been based on the interpretation of satellite imagery; however hopefully it can provide the background for more detailed studies based on ground monitoring and *in situ* measurements.

Previous Work

Most of the work on ice dynamics and its effect on offshore petroleum development has been concentrated in Arctic regions such as the Beafort Sea. In contrast, relatively little work has been published to date on ice movement and morphology in subarctic regions such as the Bering

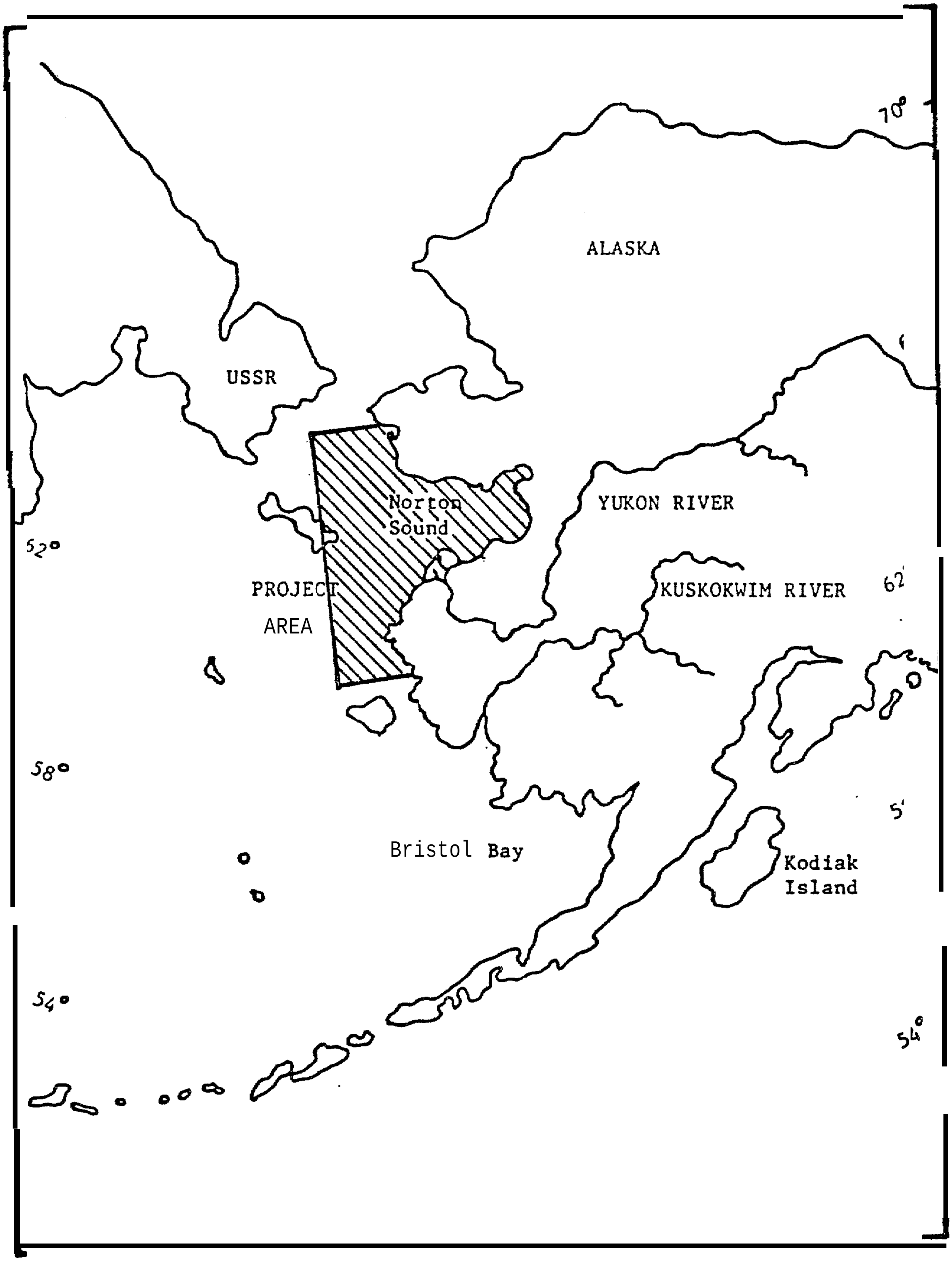

Figure B1: Location of project area

Sea and Norton Sound. Muench and Ahlas (1974) were the first to use satellite imagery to study regional patterns of ice movement in the Northern Bering Sea, however the relatively low resolution of their imagery (NOAA weather satellite data) and the relatively short period of record (March to June, 1974) limited the utility of their work. Shapiro and Burns (1975) used higher resolution Landsat imagery to document a short-lived ice deformation event just to the north of the Bering Straits. Stringer (1977, 1978) mapped a variety of ice-related features in the Beaufort, Chuckchi, and Bering Seas with the use of Landsat imagery. Similarly, Dupré (1978) used Landsat imagery to study the complex interrelationships between ice and patterns of deltaic sedimentation associated with the Yukon delta. This present study is designed to expand on these previous studies, emphasizing the patterns and rates of ice movement in Norton Sound. In doing so, it also provides information to aid in the explanation and extrapolation of patterns of ice gouging in Norton Sound as described by Thor and others (1978).

Methods of study

The data used in this study were compiled from the photographic products of imagery acquired by the Multispectral Scanner system of the Landsat and NOAA-2, 3, 4 satellites. Meteorologic data also were taken from daily surface synoptic charts from the National Climatic Center in North Carolina. The extent of shorefast ice and ice floes was mapped from Landsat images (1:1,000,000) on acetate overlays which were superimposed on standard bathymetric base maps of the

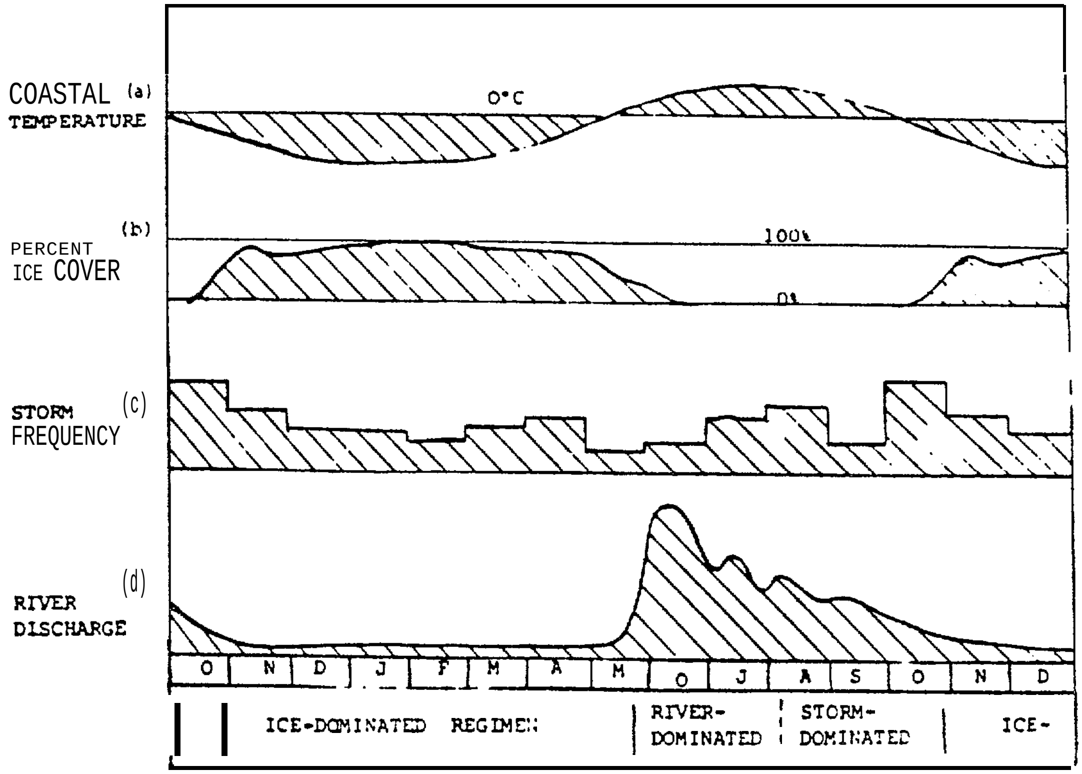

Figure B-2: Diagram illustrating the seasonality of processes in the Yukon Delta - Norton Sound region of the Bering Sea. Sources of data include: (a) Summary of average monthly temperatures at Unalakleet, 1941-1970, (NOAA); (b) Summary of ice observations for Yukon Delta region from Brower et al. (1977); (c) Frequency of major low pressure centers in the northern Bering Sea region, from Brewer et al. (1977); and (d) Discharge of the Yukon River at Kaltag, 1962 (U.S.G.S. Water Resources Data).

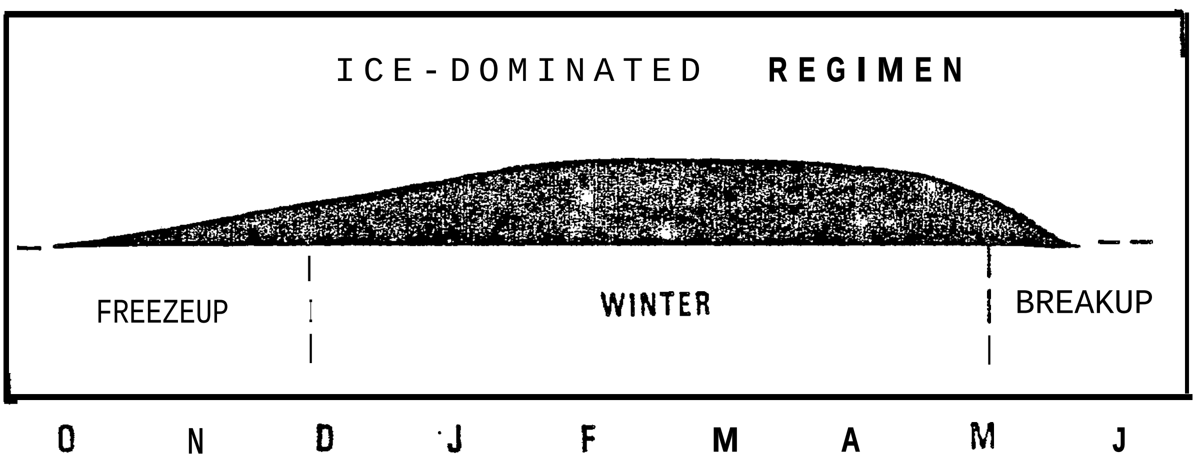

Figure B3: Three phases of the ice-dominated regimen.

northern Bering Sea. Overlays for successive days could be superimposed to chart the movement of particular ice floes over an approximate 24-hour period. Images were registered with respect to landforms in order to map the positions of the ice floes on successive days. In general, sea ice movement cannot be accurately monitored by referencing the scenes to coordinates, as coordinates provided on the margin of Landsat images allow for only approximate registration (Colvocoresses and McEwen, 1973). According to Colvocoresses and McEwen (1973), the systematic, root mean square error of position for points on the satellite images ranges from 200-450 meters, with no detectable additional error associated with image duplication. The sea ice is moving on the order of kilometers per day, hence this error should be considered as insignificant for the purposes of this paper.

The Landsat images were band 5 and 7, 9x9-inch positive prints. The images and the base map appeared to be perfect overlays. The band-5 images proved to be most useful in defining nilas ice, whereas band 7 was more useful for defining the sea-ice boundary and delineating pack-ice floes and areas of shorefast ice. There is no distinction made between newly formed ice and open water on most maps in this paper, because of the difficulty in distinguishing the two.

The NOAA 10x10-inch satellite photoprints (infrared) furnished only general meteorological information. They did provide a good overview of ice movement, however they were not used for detailed measurements. Wind patterns and weather systems could be observed from NOAA imagery, but wind velocity and directional information was obtained from daily surface synoptic charts. Some weather station readings are influenced by local orographic conditions, but in general, most of the information is believed to be useful for the purposes of this study.

ICE-DOMINATED REGIMEN

The pattern of ice formation, movement, and deformation in the Norton Sound region are significantly affected by the nearshore morphology of the Yukon delta. The Yukon River has formed an ice-dominated delta characterized by a broad, shallow sub-ice platform and associated sub-ice channels which extend up to 25 km beyond the major distributaries (Fig. 4). The platform is an area characterized by relatively stable shorefast ice for much of the year, whereas the sub-ice channels are areas of more dynamic ice (and sediment) movement, particularly during breakup. The more steeply dipping delta front is an area of relatively intense deformation and related gouging, whereas the more distal portions of the delta are areas of relatively complex movement of seasonal pack ice. Because of the complexity of ice movement, both in space and time, it seems best to discuss the intervals of freezeup, winter, and breakup separately (Fig. 3).

Freezeup

Ice crystals typically begin to form and accumulate as new ice along the shore of Norton Sound in late October, as coastal temperatures drop below 0°C (Fig. 2). Bottomfast ice forms along the shallow margins of the delta (e.g. on intertidal mudflats and subaqueous levees); some of the smaller sub-ice channels begin to be covered by floating fast ice as well. The larger sub-ice channels which extend beyond the main distributaries are relatively deep and continue to maintain a channelized flow of freshwater offshore, hence are the last of the nearshore areas to freeze.

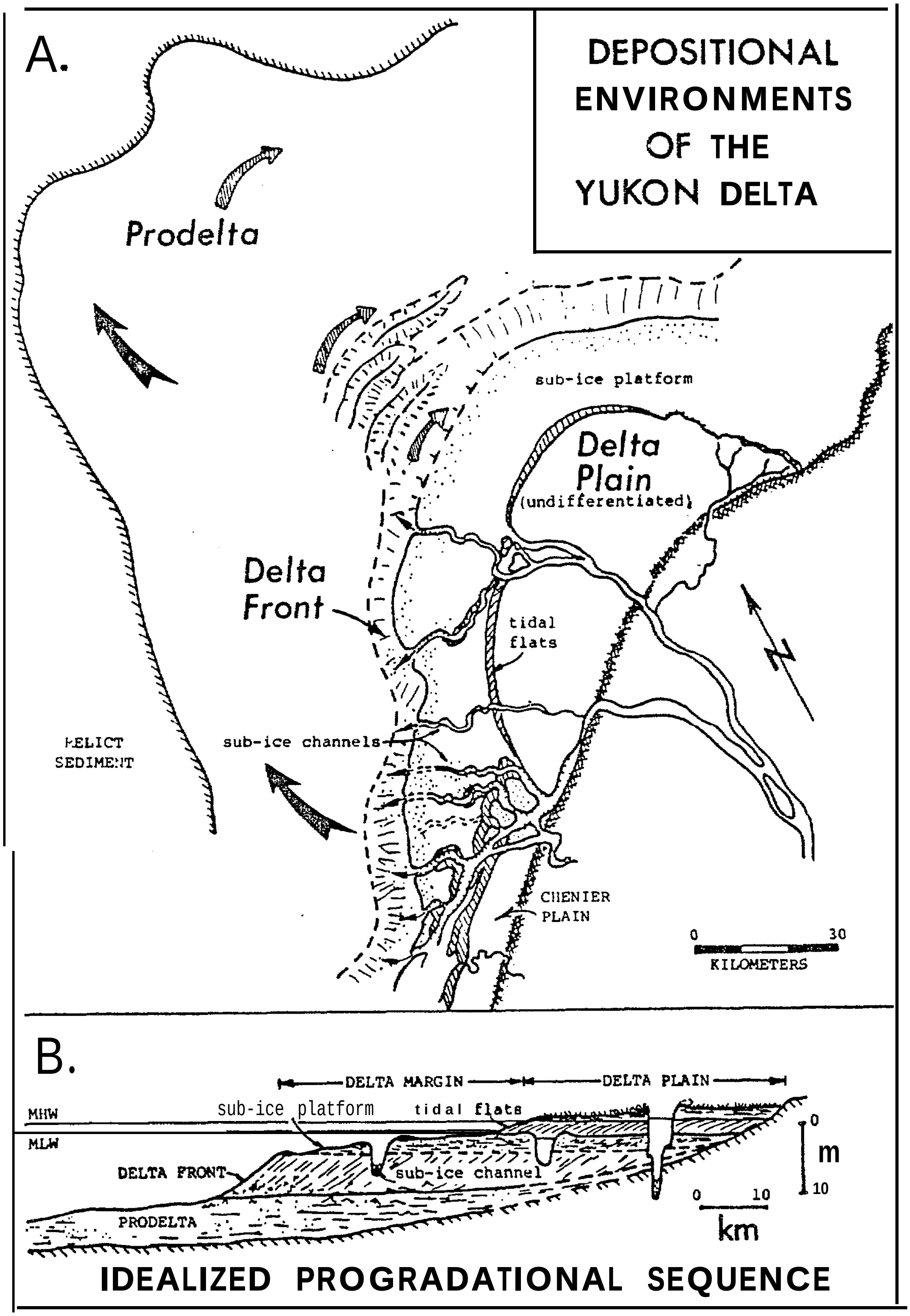

Figure B4: Depositional environments of the modern lobe of the Yukon delta (from Dupré and Thompson, 1979).

The shorefast ice continues to expand farther offshore in November, until it reaches its maximum width of from 15 to 30 km, approximately coincident with the sub-ice platform. Most of the shorefast ice is floating fast ice (Fig, 4), separated from the bottom fast ice by active tidal cracks which coincide approximately with the 1 m isobath. The inner zone of bottomfast ice is often covered with aufeis (Fig. 5) formed by over-ice flow associated with the rise and fall of floating fast ice due to tides, storms, or both. The seaward expansion of the shorefast ice continues until it encounters mobile, seasonal pack-ice, at which time pressure ridges develop and become grounded and a seaward-accreting Stamukhi zone develops, approximately coincident with the delta front in water depths of 5 - 15 m. This generally has occurred by the beginning of December, and for the purpose of this report, marks the beginning of the winter period.

Winter

The winter phase of the ice-dominated regimen is characterized by the establishment of a relatively stable band of shorefast ice fringed by a complex zone of ice deformation features which form the Stamukhi zone (as defined by Reimnitz and others, 1977). The patterns of ice movement beyond the Stamukhi zone are rather complex, reflecting both local and regional meteorologic

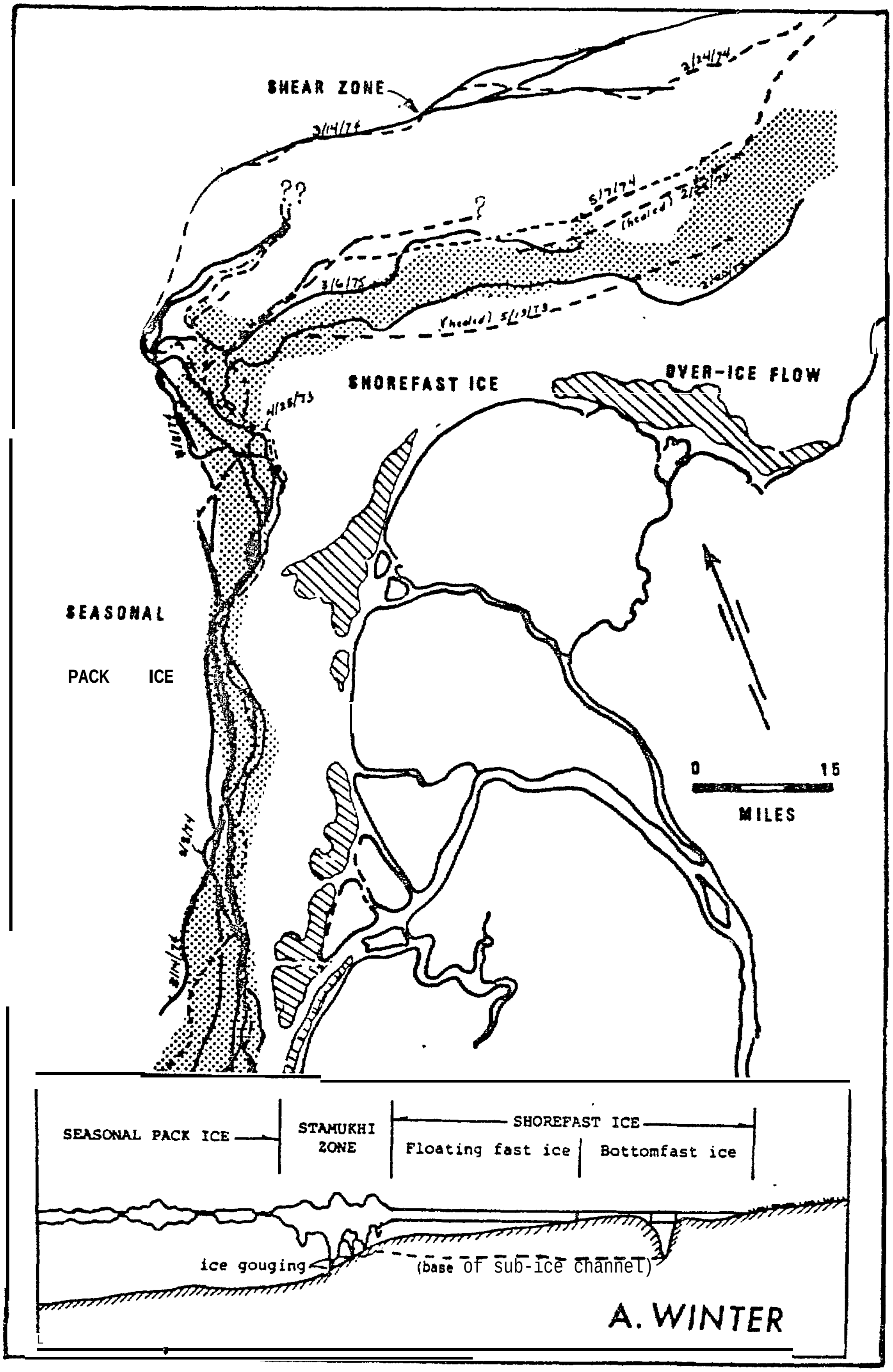

Figure B5: Location of shear zones as determined from LANDSAT imagery, 3/13/73 - 3/6/75. Hatching delineates aufeis formed by over-ice flow; approximately coincident with bottomfast ice. Dots delineate the 5-10 m bathymetric interval.

events as well as the effect of bathemetry in deflecting and grounding ice flows .

Ice movement in Norton Sound is generally controlled by the predominantly northeasterly winds which form in response to a relatively stable high pressure system which develops during the winter months. The northeastern side of Norton Sound is a zone of ice divergence, hence is an area of ice formation throughout the winter. This results in the formation of a very dense winter water mass which can be detected in the eastern part of Norton Sound during the summer months as well (Schumacher and others, 1978), Southwesterly flowing ice formed in the ice divergence zone in the northern part of the sound tends to deform in the ice convergence zone in the southern part of the sound. This results in the formation of a Stamuki zone which accretes seaward until such time as ice can readily move parallel to the shorefast ice and exit the Sound, there to join the stream of rapidly moving Bering Sea pack ice (Fig. 6). The extensive and almost continuous ice deformation on the northern side of the Yukon delta as seen on Landsat imagery is also evidenced by the high density of ice gouging in the area as described by Thor and others (1978) using side-scan sonar.

In general, the seasonal pack ice in Norton Sound is largely derived in situ, and tends to flow to the west and southwest in response to the prevailing winds (Fig. 6) or flow sluggishly in response to relatively weak oceanic currents during periods of relatively weak winds (Fig. 7). Only rarely does Bering Sea pack ice enter Norton Sound in response to prolonged periods of strong westerly winds

The pattern of ice movement to the west of Norton Sound is relatively complex, however it too flows mainly to the south in response to the prevailing northerly winds. Significant reversals in the path of the flow can occur, however,

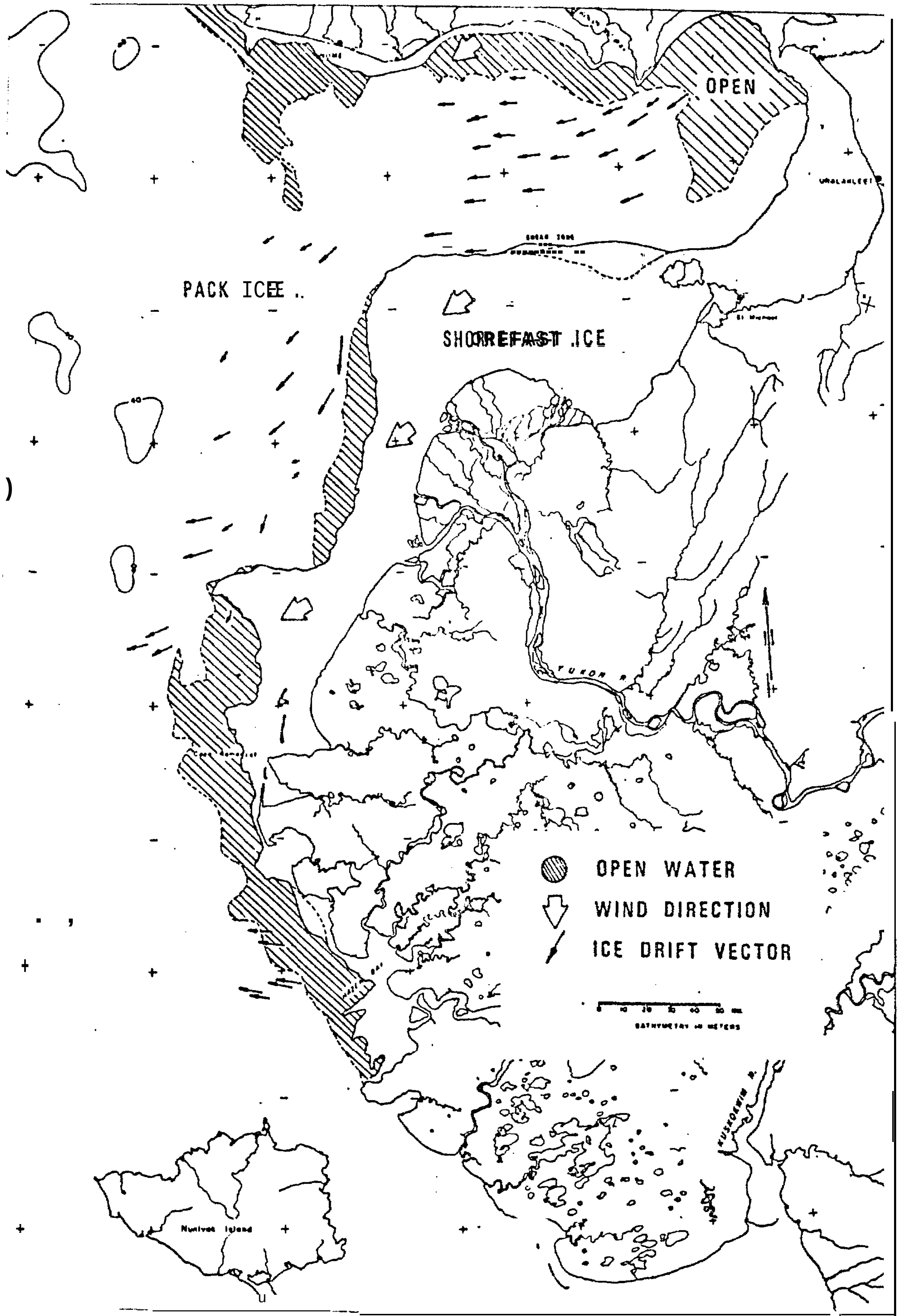

Figure B6: Patterns of ice movement from March 14-15, 1974. Length of ice drift vectors measures distance moved in one day. Dashed lines to north of delta are inactive shear zones.

as illustrated on the Landsat and weather data for Feb. 23-27, 1976 (Fig. 7). During this period winds began to blow up to 25 knots from the south, and as a result the southerly flow of ice ceased, and northerly flows of ice up to 15 km/day were charted (Fig. 7). The rapid reversal was the result of the passage of two large low pressure systems (Fig. 8A-B) and illustrates the extent to which ice movement is responsive to meteorologic events.

Shapiro and Burns (1975) noted that unusually strong northerly winds can result in a major ice deformation event where masses of ice are deformed and funneled out of the Chukchi Sea and through the Bering Straits. Similar deformation features were noted on NOAA (VHRR)imagery for 13-15 March, 1976. During this time, ice floes west of the Yukon delta were moving up to 45 Ian/day (Fig. 9), presumably in response to a major ice deformation event similar to that described by Shapiro and Burns.

It is important to note that the zone of very rapid ice movement is restricted to a relatively narrow band approximately 70 km wide, which is here referred to as the "racetrack". This zone is often recognized as a band of highly fractured nilas ice (Fig. 7) which presumably forms as the source of the pack ice (the Chukchi Sea) becomes temporarily plugged at the Bering Straits. The racetrack can be seen on Landsat imagery throughout much of the winter months, and is a recurring feature from year to year. Its eastern boundary is approximately coincident with the 20 m isobath, suggesting that it may reflect the grounding of ice flows at the entrance to Norton Sound and the resultant deflecting of the ice to the south, parallel to the isobaths.

There is often a zone of open water between the Bering Sea pack ice and the edge of the shorefast ice west of the Yukon delta. This typically forms

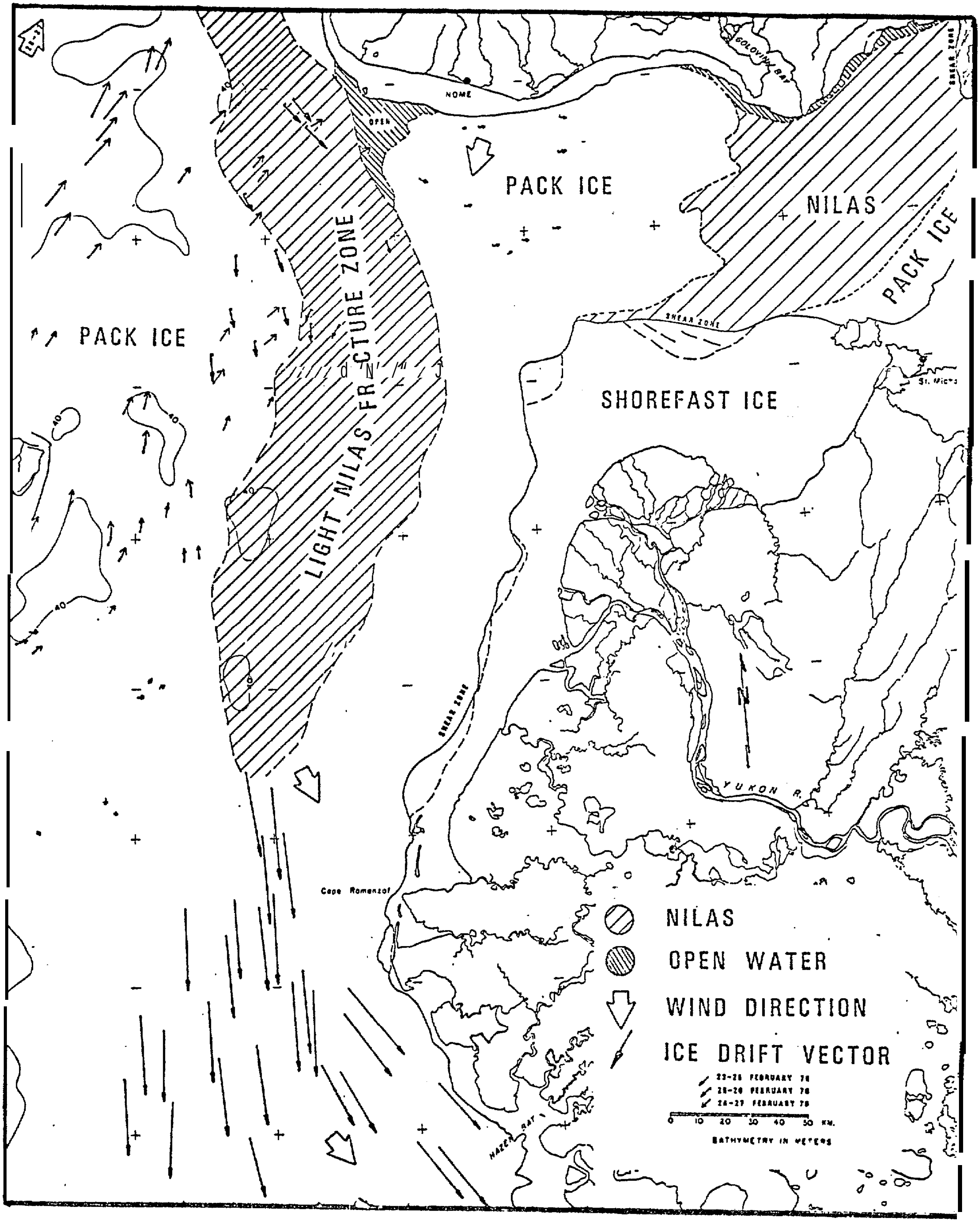

Figure B7: Patterns of ice movement from" 23-27 February 1976. Length of ice drift vectors measures distance ice moved in one day. Dashed lines within the shorefast ice zone to the west of the delta are inactive shear zones. The configuration of shear lines *to* the north of the delta indicates stamukhi.

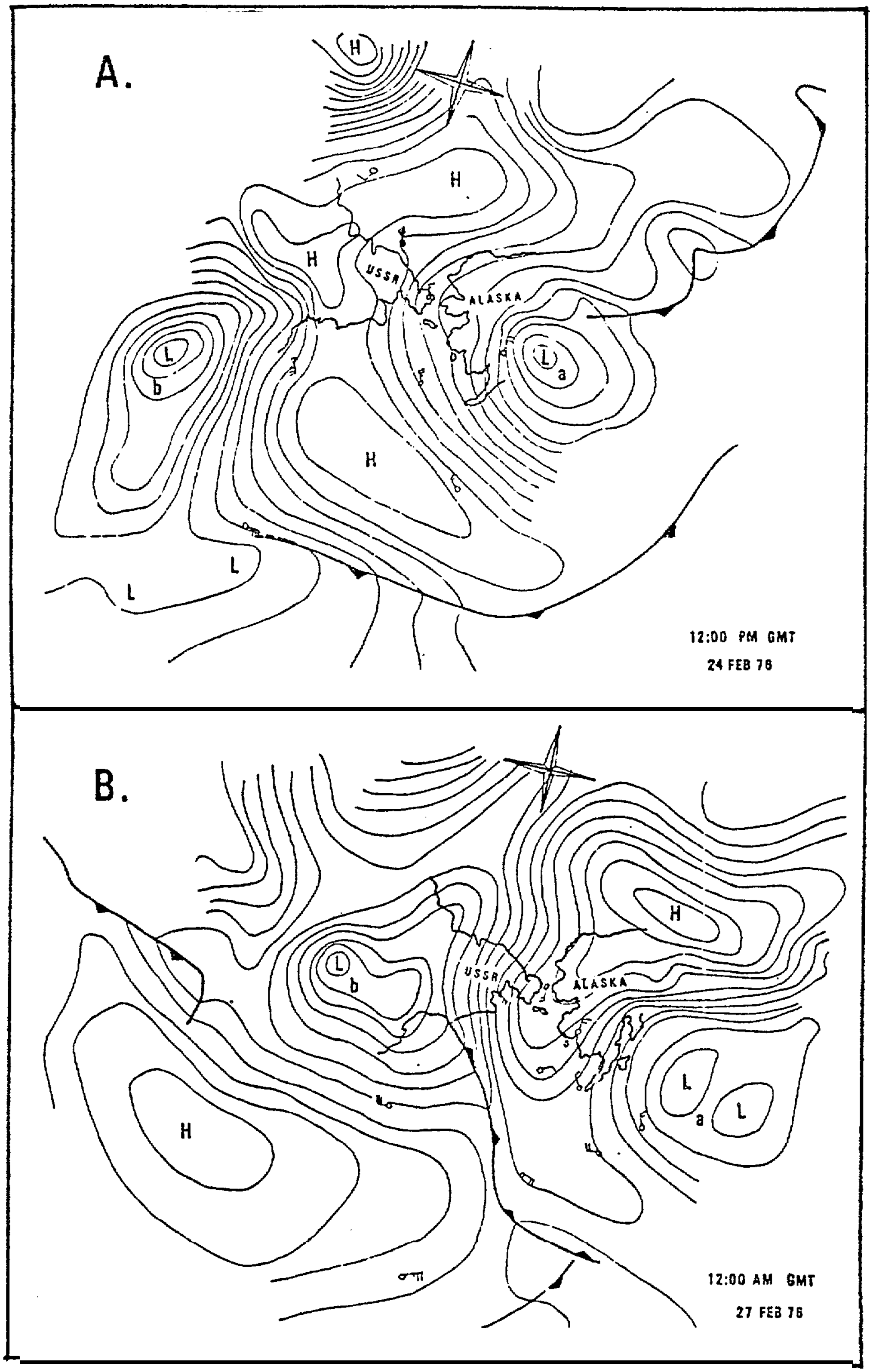

Figure B8: Weather conditions for the period 24 Feb. to 27 Feb., 1976 (from NOAA Surface . Synoptic weather charts). Note the reversal of winds in the Bering Straits area due to the westward migration of low pressure system a and b.

during periods of offshore (i.e., easterly) winds, and may be completely closed during periods of onshore winds. Some of the open water may, however, result from the grounding of relatively deeper ice keels in water depths of 15 - 18 m, thereby acting as an offshore ice barrier to some onshore movement of ice, This zone of open ice west of the delta is of particular interest to the Eskimos in the area, as it greatly facilitates winter hunting.

Little, if any, sediment enters Norton Sound during the winter months, yet the suspended sediment concentration measured beneath the ice in the west-central part of Norton Sound is essentially as high as during much of the summer (personal communication, Dave Drake, U.S.G.S.). This suggests that a significant amount of sediment initially deposited during the summer months is resuspended during the winter, hence is available to be redistributed by sub-ice currents. The unusual offshore increase in sand off the Yukon delta (Dupré and Thompson, 1979) may be the result of such a process, however the exact mechanism(s) for such resuspension are unclear.

Breakup

· Breakup along the coast is a relatively brief event which marks the transition between the ice-dominated and river-dominated regimens, however ‘its significance far outweighs its brevity. River breakup along the Yukon (as with most of the coastal rivers in northern Alaska) is marked by a tremendous increase in sediment and water discharge, resulting in ice jams, extensive inland flooding, and river bank erosion.

As river discharge begins to increase, floating fast ice begins to lift, both in the river and along the coast. The thalweg of the sub-ice channels are especially well delineated by the floating fast ice at this time.

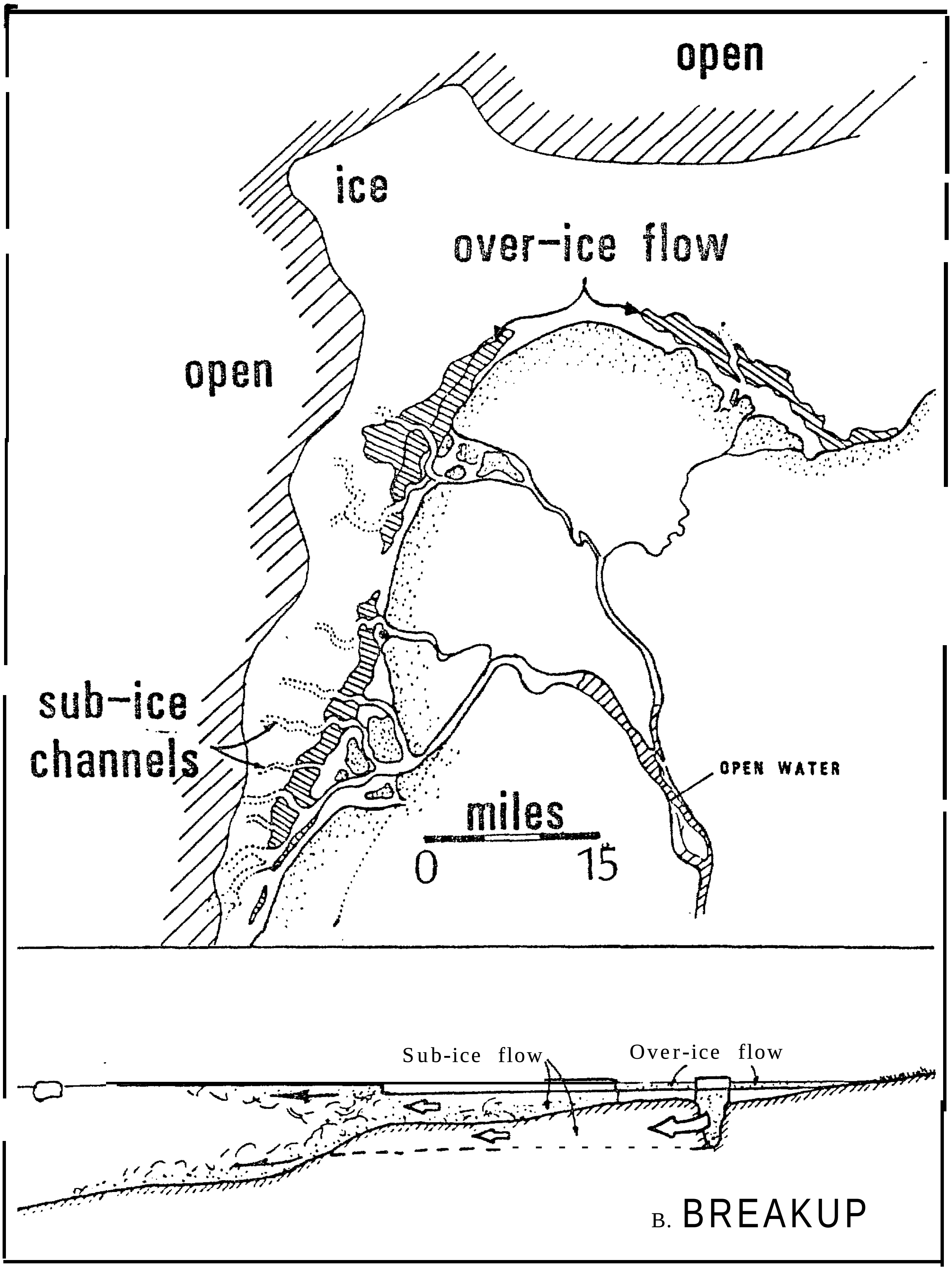

Figure B10: Diagram of over-ice flow and sub-ice channels, which provide two mechanisms for sediments to by-pass the sub-ice platform.

The bottomfast ice begins to be flooded by an over-ice flow (Fig. 9) which has been described on the North Slope by Reimnitz and Bruder, 1972 and Walker, 1974.

Some sediment is carried onto the ice, thereby effectively bypassing much of the inner sub-ice platform. Much of the sediment appears to remain in the sub-ice channels, which cross the sub-ice platform. Some of the sediment is probably deposited from suspension on subaqueous levees farther offshore, however much of it probably bypasses the sub-ice platform completely, to be deposited on the delta front or prodelta. The role of sub-ice sediment transport during breakup is particularly intriguing, yet it remains almost. unknown. The floating ice that marks the sub-ice channels soon breaks up and is removed to sea. Much of the over-ice flow may drain through strudel holes (Reimnitz and Bruder, 1972) or cause the bottomfast ice to melt in place. Large pieces of floating fast ice break off to be transported farther offshore. Grounded ice may remain in some shallow areas to the northwest of the delta; floating pack ice may remain trapped in the middle of Norton Sound because of the sluggish currents.

Figure 10 illustrates conditions, which are typical during breakup, Floe movement' is to the north as is common during late April and May when northerly winds die down and northward flowing currents become more effective in transporting ice (cf. Muench and Ahlnas, 1974). The floes were moving up to 20 km/day on 7 May, 1974 (Fig. 10), however a low pressure system moved into the area on the 8th, bringing a temporary restoration of "winter-phase" northerlies. Temporary reversals of ice movement towards the south were also noted in late May, 1974 by Muench and Ahlnas(1974). These short-lived events are typically associated with the passage of a low pressure system crossing the Bering Sea,

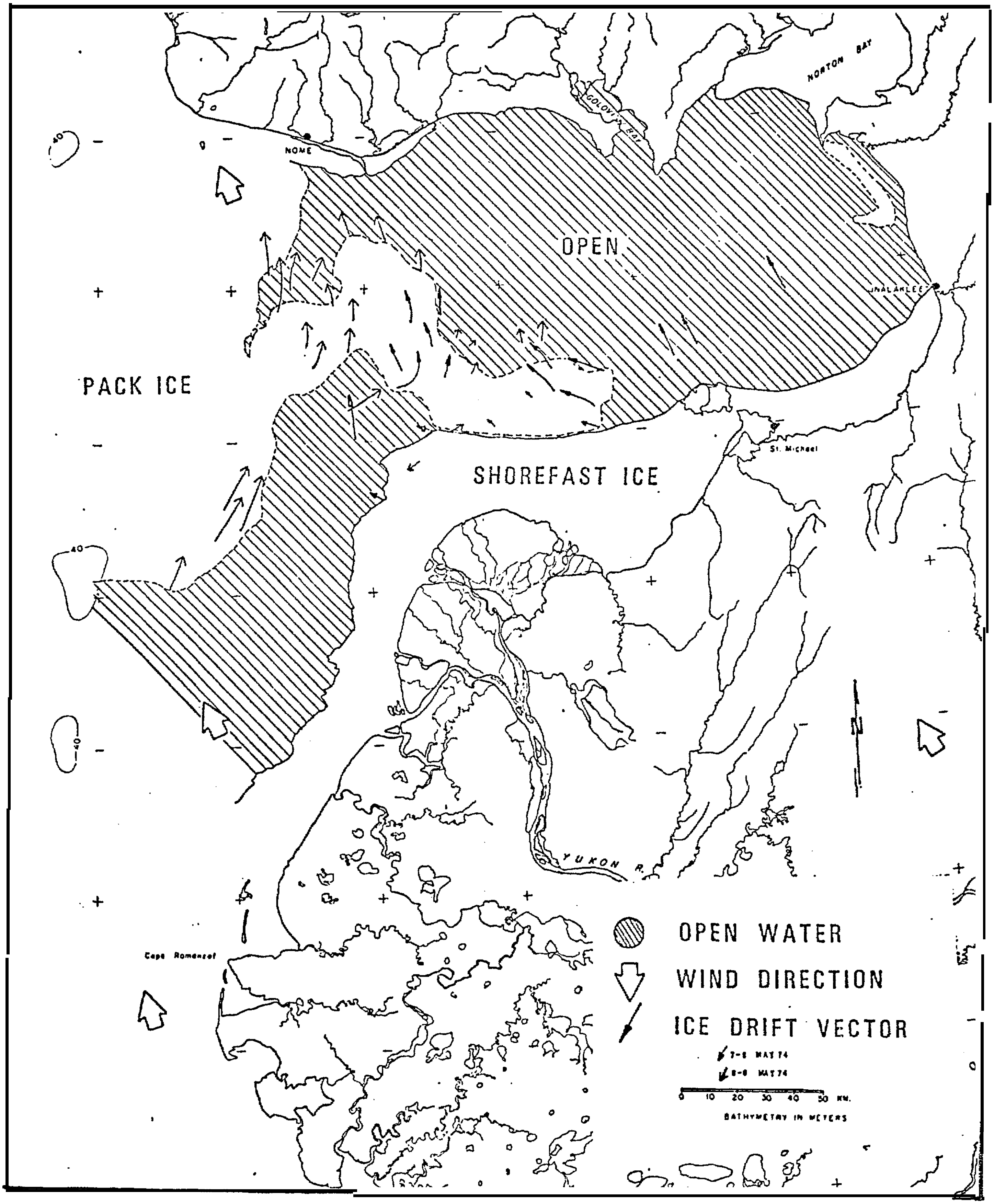

Figure B11: Patterns of ice movement from 7-9 May 1974. Length of ice drift vectors measures distance moved in one day. Pack ice is less consolidated than earlier in the year.

however southerly winds typically follow, facilitating the breakup and removal of the shorefast ice. By early June the shorefast ice is usually no longer present, although some areas of unconsolidated pack-ice floes may be present, particularly in the center of Norton Sound. At this time the distributary channels have been cleared of ice and are introducing an apron of sediment-laden water over much of the prodelta region, marking the beginning of the river-dominated regimen.

Discussion of Ice Gouging

Throughout the winter phase of the ice-dominated regimen, shorefast ice stretches to the 5 - 10 m isobath, and follows it around Norton Sound and down the western edge of the Yukon prodelta front. In situ ice approximately 0.7 - 1.2 m thick (Brewer and others, 1977) diverges from the Norton Bay area, and compacts to form stamukhi and pressure ridge zones against the shorefast ice fringing the Yukon delta. These zones become incorporated into the shorefast ice zone, stabilizing the fast-ice edge (Reimnitz and others, 1977). The impact and subsequent deformation of ice convergence can cause pressure ridge raking, producing numerous parallel furrows as the keels plow through the bottom sediments (Reimnitz and Barnes, 1974). Solitary, or single-keel ice gouge is also ubiquitous in Norton Sound (Thor and others, 1978).

Seasonal pack ice shears past the grounded, or fast ice along the 7 - 12 m isobath, which trends nearly north-south from Shpanberg Strait to Etolon Strait. Thick Bering Sea ice, or advected Chukchi Sea ice up to 12 m and 20 'm thickness respectively (Thor and others, 1978) becomes caught up in this shear zone, as floes are propelled southward by Arctic northerlies, during the ice-dominated regimen. In the dynamic zone where moving sea ice collides with stationary fast ice, high energy is expended on the sea floor. The result is an area of intense gouge between the 7 m and 20 m isobaths. Thor and others (1978) observed this phenomena in the Norton Basin. A corresponding area of intense gouging between the 10 m and 20 m water depths was studied earlier by Reimnitz and others (1977) on the Beaufort Sea continental shelf.

The Yukon prodelta is the site of 85% of all ice gouges measured by Thor and others (1978), with 78% of the ice gouging in water 10 - 20 m deep. For the most part, the major gouge trends parallel isobaths, as would be expected based on the bathymetric contour of the stamukhi zone marking the interface between stationary and moving ice along this contour. None of the data collected by Thor and others (1978) were in water depths of less than 10 m, hence the potential for ice gouging in more shallow depths is uncertain. Nonetheless, the inner part of the stamukhi zones typically begin at 5 - 7 m water depths, hence some gouging would also be expected (Fig. 4) in this zone as well.

SUMMARY

The patterns of ice formation, movement, and deformation in the Norton Sound region were studied with the use of Landsat and NOAA satellite imagery for the years 1973-1977. The results document not only the marked seasonality of marine processes throughout the year, but also the significant role of bathymetric and meterologic conditions in controlling the patterns and rates of ice movement in the region. The results have been summarized in a map of generalized ice hazards Figure 6), similar in many ways to the maps done for the entire . Bering Sea by stringer (1978). The following is a brief summary of the types of ice-related hazards which characterize each of the zones.

Zone Ia is a zone of shorefast ice which extends to the outer edge of the sub-ice platform of the Yukon delta, approximately coincident with the 2-3 meters water depth. Over-ice flow (aufeis) occurs throughout the winter in areas of bottomfast ice near the major distributaries (shown in hatchered pattern). Sub-ice currents beneath the floating fast ice may result in some resuspension of sediments in the sub-ice channels and on the outer edge of the sub-ice platform. This is a relatively stable zone throughout the winter, however large sheets of ice may break off during Spring breakup. Zone Ib is a slightly less stable area characterize by floating fast ice during most of the winter, however ice can be completely lacking and replaced by a large area of open water under some conditions (e.g. March 13-15, 1976). Zone Ic is the zone of shorefast ice which fringes most of Norton

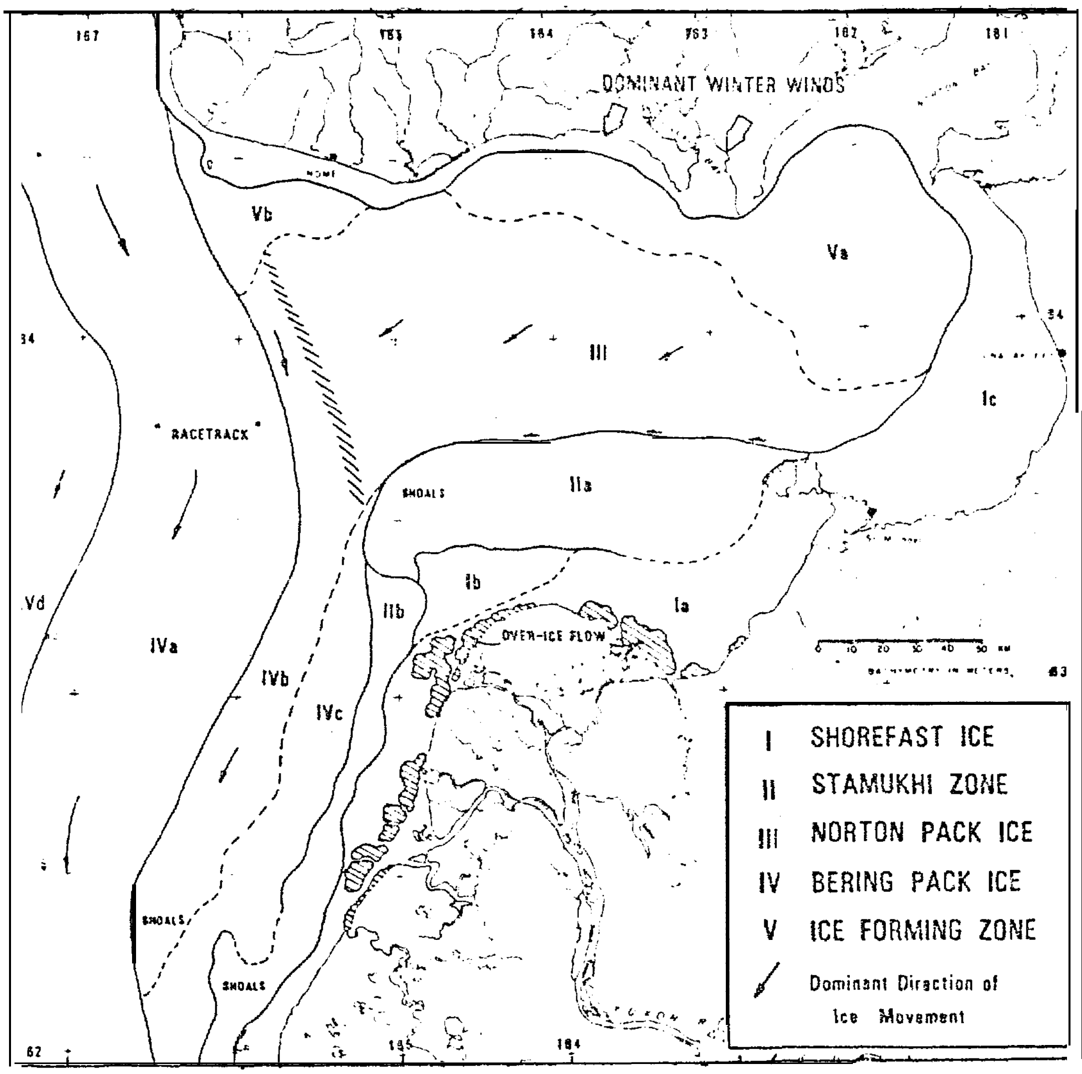

Figure 12B: Zonation of ice hazards in the Yukon Delta - Nor Con Sound Region based mainly on LANDSAT and NOAA satellite imagery, supplemented by information on ice gouging by Thor and Nelson (1979)

Sound . It is largely floating fast ice, and is more variable in extent and less stable, as large sheets of ice may break off repeatedly throughout the winter. .

Zone IIa is a broad, seaward accreting stamukhi zone formed by the convergence and deformation of ice formed mainly in Norton Sound. The configuration of the outer margin of this zone appears to be controlled by Stuart Island to the east and a series of offshore shoals to the west; it is approximately coincident with the 14m isobath. It is characterized by extensive ice shearing and a relatively high intensity of ice gouging of the sea floor (as delineated by Thor and Nelson, 1979) . Zone IIb is located west of the delta in water depths from 3 to 14 m. It is a relatively unstable area Characterized by ice deformation and accretion to the shorefast ice (Zone Ia) during periods of onshore (westerly) winds and an offshore movement of ice and the development of a large, open water area (polyna) during periods of offshore (easterly) winds. It is characterized by a moderately high intensity of ice gouging.

Zone III is an area of seasonal packice formed mainly in situ, within Norton Sound. The ice typically moves south and west in response to the dominate northeasterly winds throughout the winter, however it may drift slowly in response to oceanic currents during periods of low winds. The southern portion of this zone is characterized by widespread shearing of ice, and is approximately coincident with the area of very high density of ice gouging delineated by Thor and Nelson (1979). The western boundary is approximately coincident with the 20m isobath, separating pack ice formed in Norton Sound from the thicker pack ice formed farther to the north. Bering and Chukchi pack ice enter the sound only rarely when especially strong northwesterly winds blow.

Zone IV consists of seasonal pack ice formed in the northern Bering and Chuckchi Seas. It typically moves to the south in response to northerly winds for most of the winter, however short-lived periods of northerly ice movement can occur during the passage of low pressure systems. The ice typically begins to consistantly move to the north in late April or early May. Zone IVa is the "racetrack", characterized by intervals of extremely rapid, southerly movement of pack ice (up to 45 km/day) following major ice deformation events north of the Bering Straits (described by Shapiro and Burns, 1975). This zone is characterized by highly fractured nilas ice during periods of relative quiescence. The eastern margin of this zone is approximately coincidant with the 22 m isobath. The western margin is more variable, as it appears to be controlled by the geometry of ice piling up on the northernside of St. Lawrence Island. The rapid movement is evidence of the lack of grounded ice, as well as the lack of ice gouging (as delineated by Thor and Nelson, 1979). Zone IVb is in water depths of 22 to20m,and is characterized by less rapid ice movement than in the "racetrack". Some grounded ice may occur in this zone, particularly in the area of shoals southwest of the delta. Zone IVc is in water depths of 20 to 14m, and is characterized by open water during periods of easterly winds, and by onshore moving pack ice during periods of westerly winds. It differs from zone IIb mainly by its mobility, i.e. it rarely forms a stamukhi zone accreted to the shorefast ice. Nonetheless, some grounded ice and ice gouging will occur in this zone as well. Zone IVd is similar to zone IVb, and was not studied in detail.

Zones Va and Vb are zones of ice divergence formed by persistent offshore winds (cf. Muench and Ahlas, 1976). These are typically areas of open waterwhere ice is actively forming for most of the winter.

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