YUKON DELTA COASTAL PROCESSES STUDY

by

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INTRODUCTION

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

The specific objectives of this study are directly related to the initial phase of selecting offshore leases. 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.

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 seventh 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 it was formed.

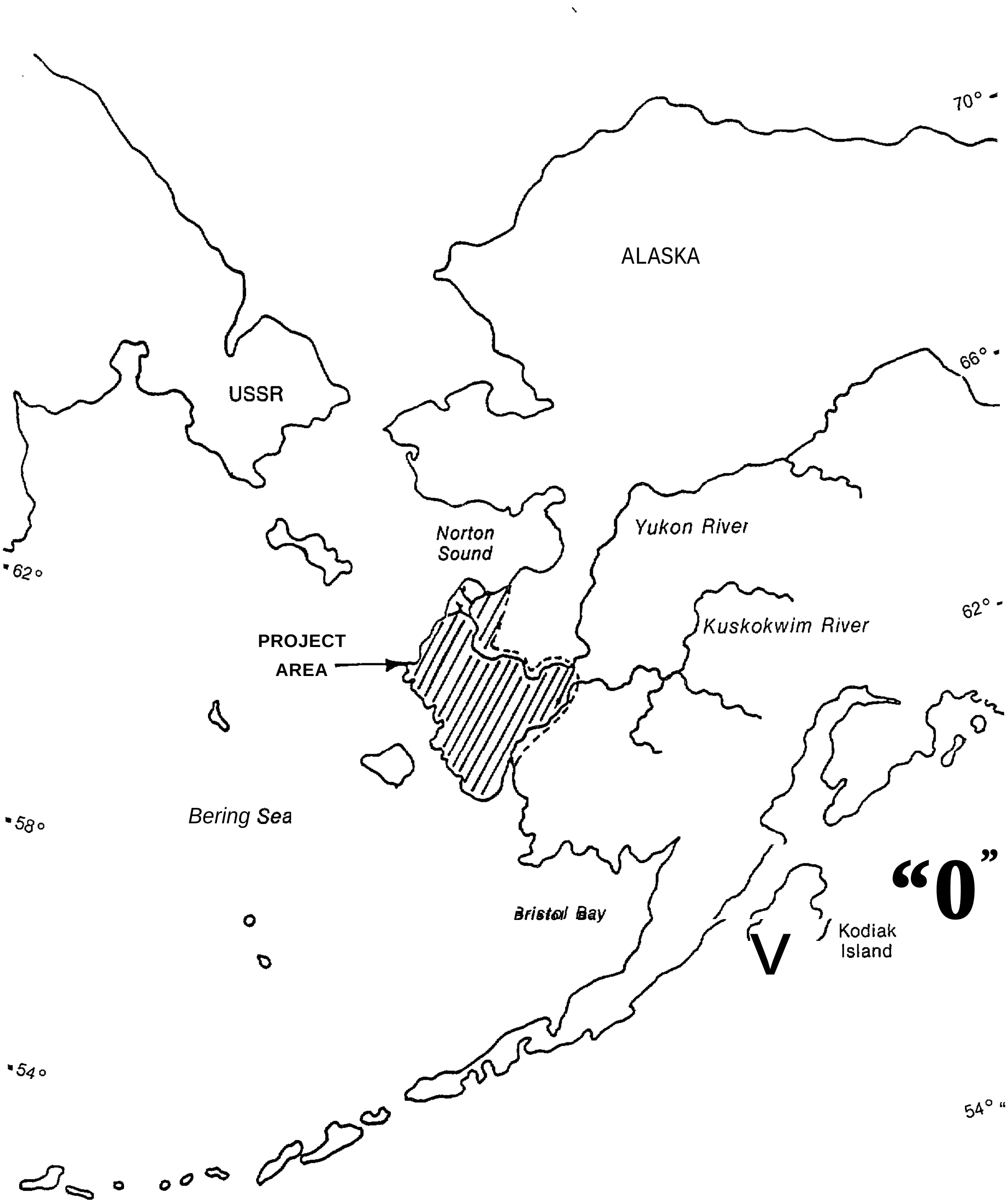

Figure 1.--Location of project area, Yukon Delta Coastal Processes Study (OCSEAP Research Unit 208).

A significant amount of work has been done on the Cenozoic tectonic history of the region (e.g., Patton 1973; Nelson *et al.* 1974; Marlow et al. 1976). There have also been numerous studies of Quaternary sediments on the northern Bering Sea shelf (e.g., Moore 1964; McManus et al. 1974, 1977; Nelson and Creager 1977; Drake et al. 1979), as well as the Holocene sediments at the mouth of the Yukon River (Matthews 1973). In addition, Thor and Nelson (1979) provided a synthesis of the geologic processes and 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). This is the first study to deal in detail with the depositional environments and processes of both the delta plain and the associated offshore facies.

STUDY AREA

The combined Yukon-Kuskokwim Delta complex (Fig. 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. The delta 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 the 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 Quaternary shield volcanoes, the major uplifted massifs of the Askinuk and Kuzilvak mountains, and the Quaternary volcanic complex that 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 macrotidal Kuskokwim Delta, whereas the microtidal 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 Romanof, and Nelson Island where Cretaceus bedrock crops out. Most of the remaining coastline consists of low, eroding bluffs cut into poorly consolidated Pleistocene deposits.

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 satellite (Landsat) imagery, and field work. Regional reconnaissance mapping by Dr. Joe Hoare and associates at the U.S. Geological Survey was available for most of the delta region at a scale of 1:250,000. In addition, photographic coverage of the entire delta region taken in 1952-54 is available, as is more 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 1975-78 included the description of vegetation assemblages and collection of numerous grab samples and short cores to describe the various depositional environments, the establishment and reoccupation 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 (University of Texas Radiocarbon Laboratory, 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 being analyzed by Dr. Tom Ager (USGS, Reston, Virginia) 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).

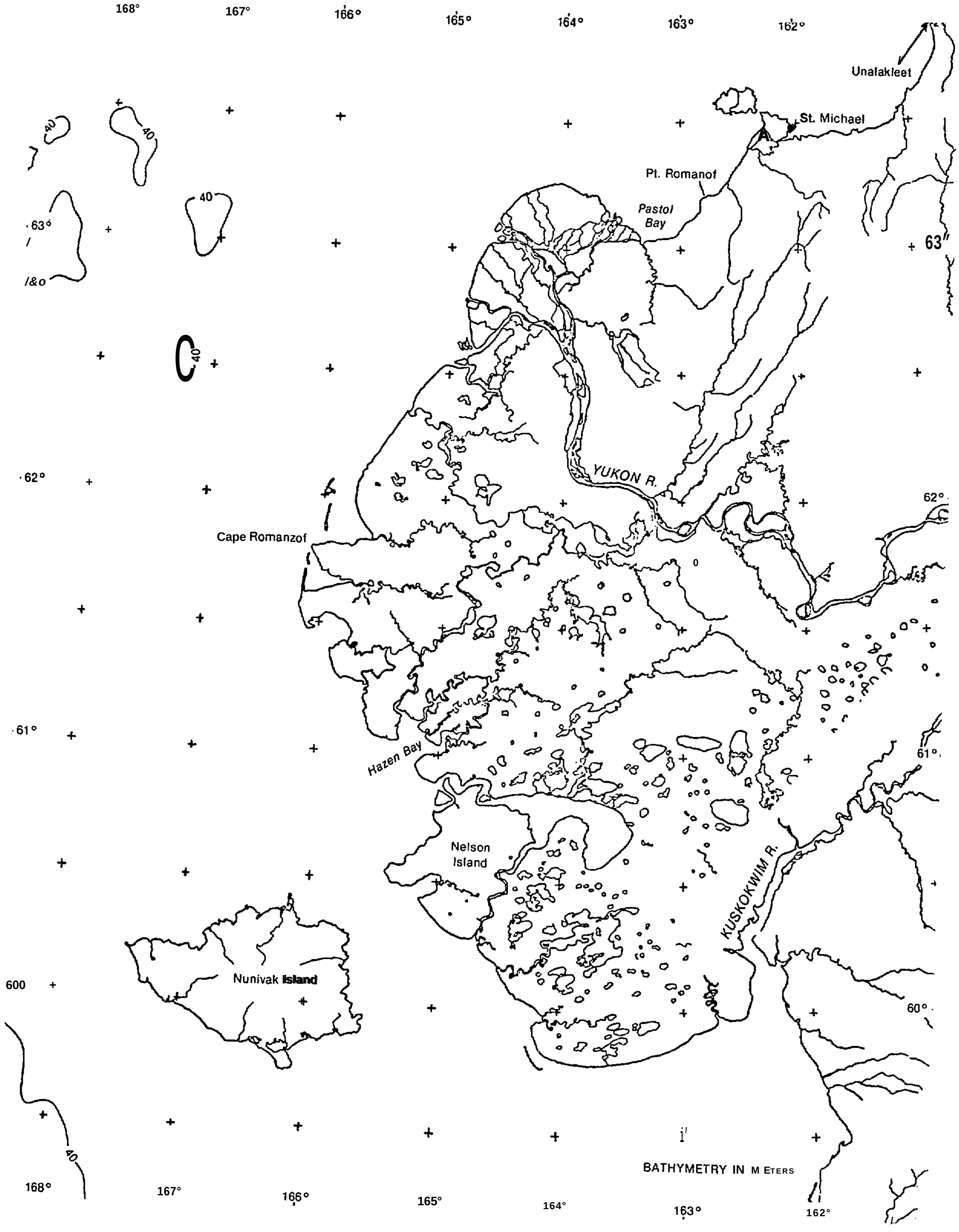

Figure 2.--Yukon-Kuskokwim Delta complex.

The delineation of offshore depositional environments was done mainly by interpretation of satellite imagery, bathymetric maps, and offshore cores provided by the USGS (Menlo Park, California). The Landsat imagery was particularly useful in delineating the sub-ice channels during periods of freeze-up and breakup. Existing bathymetric data (mainly vintage 1899), were compared with traverses obtained by RV 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 (USGS, Menlo Park, California) and sediments described by McManus et *al.* (1977) allow a better understanding of the patterns of sedimentation in the region.

Sequential Landsat imagery (1973-77) was used to study the patterns of ice formation from freeze-up 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 on ice gouging (Thor and Nelson 1979).

RESULTS

The results with direct implications to the earlier phases of site selection are:

1) There is widespread geomorphic evidence of Quaternary faulting, with some faults cutting 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 occurred during the Holocene, and some suggestion that it may not have occurred within the last 24,000 years. It seems likely, therefore, that the risk from volcanism is minimal.

3) Pleistocene sediments beneath most of Norton Sound contained thick, ice-bound permafrost that 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 less than 1 m.

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 (provided in the Appendix).

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 (1981).

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 the Mesozoic and Cenozoic (Patton 1973), Most of the major faults in the region (e.g., the Kaltag fault) formed and were most active during the late Cretaceus and early

Tertiary (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 extensions 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 (<2,500 years old) 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; 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 work on microseismicity in the region by Biswar and Gedney (OCSEAP Rsearch Unit 483), as well as the abundance of fault scarps detected by Johnson and Holmes (cited in Nelson 1978). Therefore, 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 because almost all of the Holocene fluvial and deltaic sediments are characterized by grain size distributions that suggest they are highly susceptible to liquefaction.

The Quaternary 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 less 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 3,500 years old. However, the composition of the ash suggests it was derived from a distant source (e.g., Alaska Peninsula). No other evidence of volcanism is 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. Michael, east of the delta, also show a lack of locally derived pyroclastic material (Dr. Tom Ager, USGS, pers. commun.). Thus it seems likely that the risk due to volcanic activity should be considered minimal.

Permafrost

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 are further documented by field studies, unpublished drillers reports, and a study by the U.S. Geological Survey (Williams 1970). Previous annual reports from RU 208 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 2,500 years ago. There is evidence of permafrost forming in much of the interior parts of the modern delta plain, yet it appears to be discontinuous and relatively thin (2-3 m?). There is little evidence of permafrost presently forming along the programing 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 1 m, 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, USGS, unpubl. data). Thus, until recently, Pleistocene sediments similar to those which presently cover much of the delta region were exposed offshore. The Pleistocene sediments on land 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, but some may remain offshore as relict permafrost, depending on 1) the original thickness of the 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. Michael, where the shoreline is rapidly eroding Pleistocene sediments at rates of approximately 17 m/year. 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 that are 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.

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

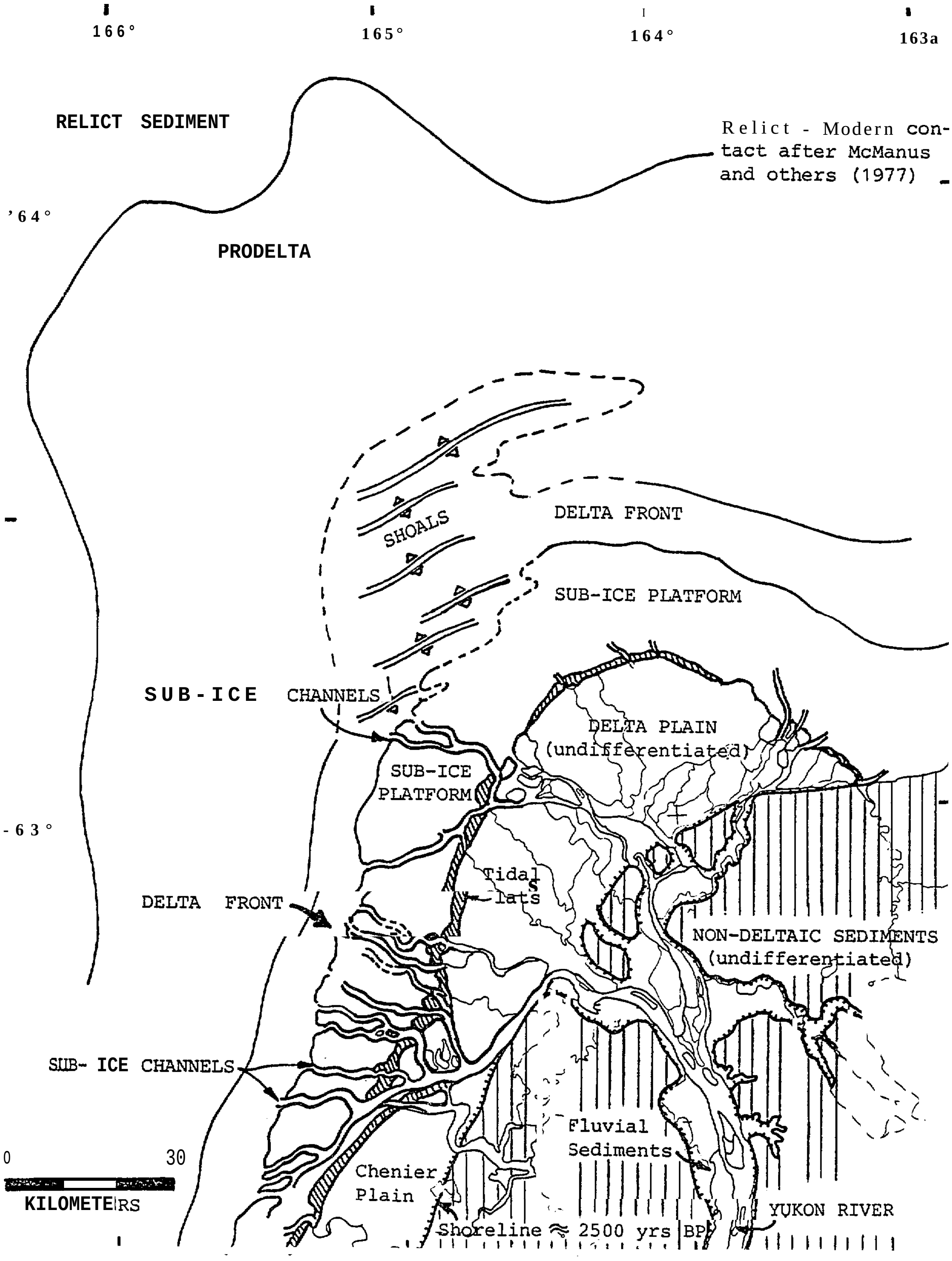

Figure 3.--Depositional environments of the Yukon Delta.

Table 1.--Preliminary summary of nontectonic geological hazards of the modern 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 front	N/A	High	Variable	Variable	None	Mod-High
Prodelta	N/A	Mod-Low	Moderate	Mod-Low	None	Low-Mod

The delta plain is fringed by programing 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 m deep and locally up to 30 km wide. The resultant subaqueous profile (see Appendix Fig. 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) channels which extend up to 20 km beyond the mouths of the major distributaries.

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 Arctic coast 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; see Appendix).

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 permafrost, but it appears to be discontinuous and relatively thin (2-3 m?). Flooding is a major hazard on much of the delta plain, as are erosion and sedimentation associated with the meandering active distributary channels. In addition, much of the sediment deposited in the channels and channel bars consists of relatively well-sorted sands and silts with a high susceptibility for liquefaction.

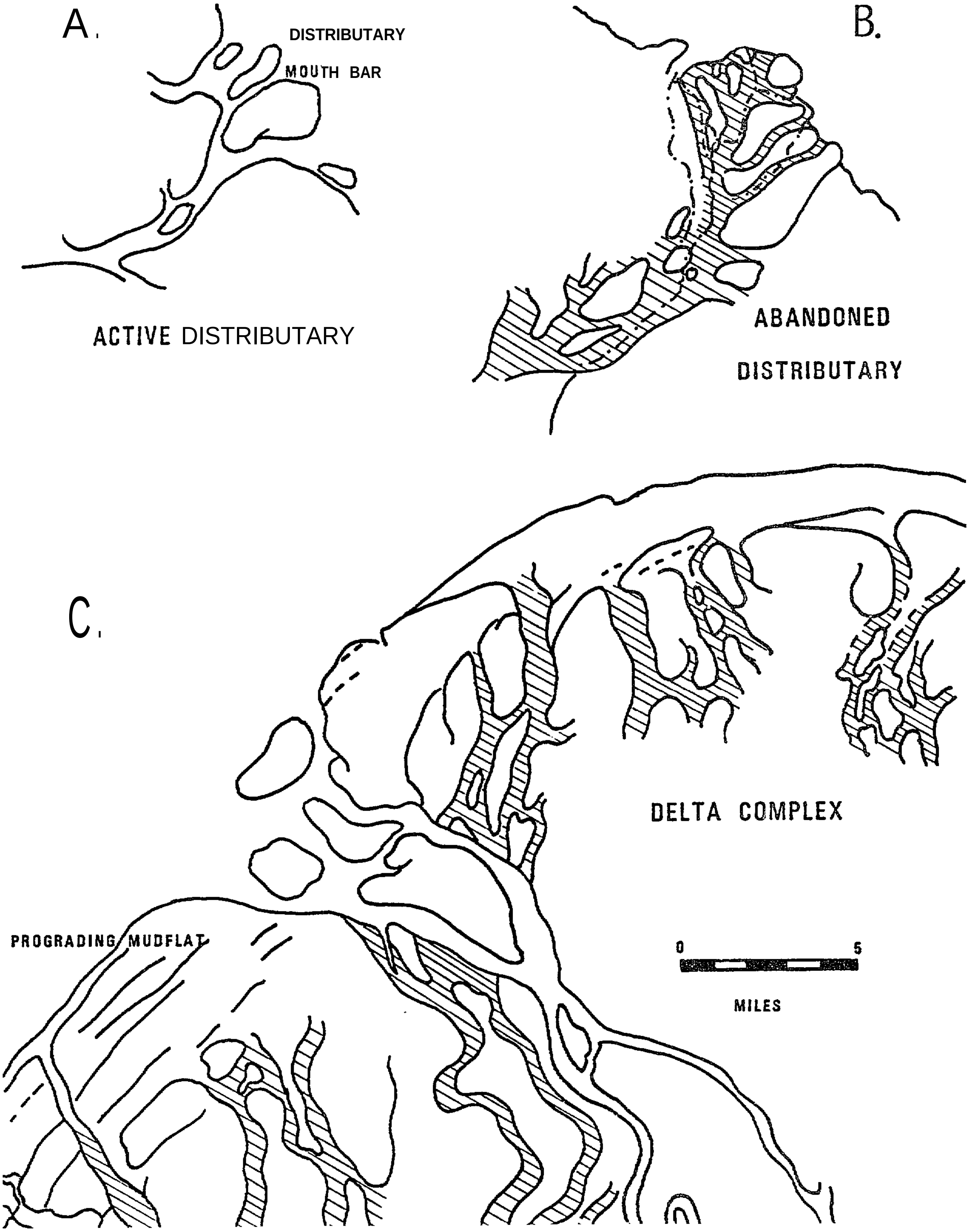

Figure 4.--Depositional environment within the delta plain of the modern Yukon Delta.

Delta Margin

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

The tidal flats are typically 100-1,000 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 areas of higher wave energy (on the western side of the delta). Rates of net erosion and deposition are relatively small; locally, however, rates of shoreline progradation may be up to 50 m/year. In addition, some of the tidal flat areas are eroding at rates of up to 5 m/year.

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 dominantly prograding features, but 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 0.5 to 1 km wide and 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 1 m high in the channels (D. Thor, USGS, pers. commun.). The presence of the well-sorted channel 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 channel deposits by the RV Karluk (USGS cruise, 1978) . The channels appear to be actively changing their course by a combination of lateral meandering and avulsion. Lateral rates of channel migration up to 50 m/year have been measured from 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. Similarly, rapid sedimentation may be expected on the subaqueous point bar deposits.

The sub-ice platform has an extremely gentle slope (typically 1:1,000 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 subaqueous 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 percentage of sand on the sub-ice platform (Appendix Fig. 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 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 that 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 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 1:2,000) 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) consists 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 susceptibility of these sediments may be relatively high, particularly in the silty sands and sands of the western part of the prodelta. Because these sands are relatively thin (typically less than 2 m; Nelson and Creager 1977), however, 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), but 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 prograding tidal flats and distributary mouth bars along the coast, but 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

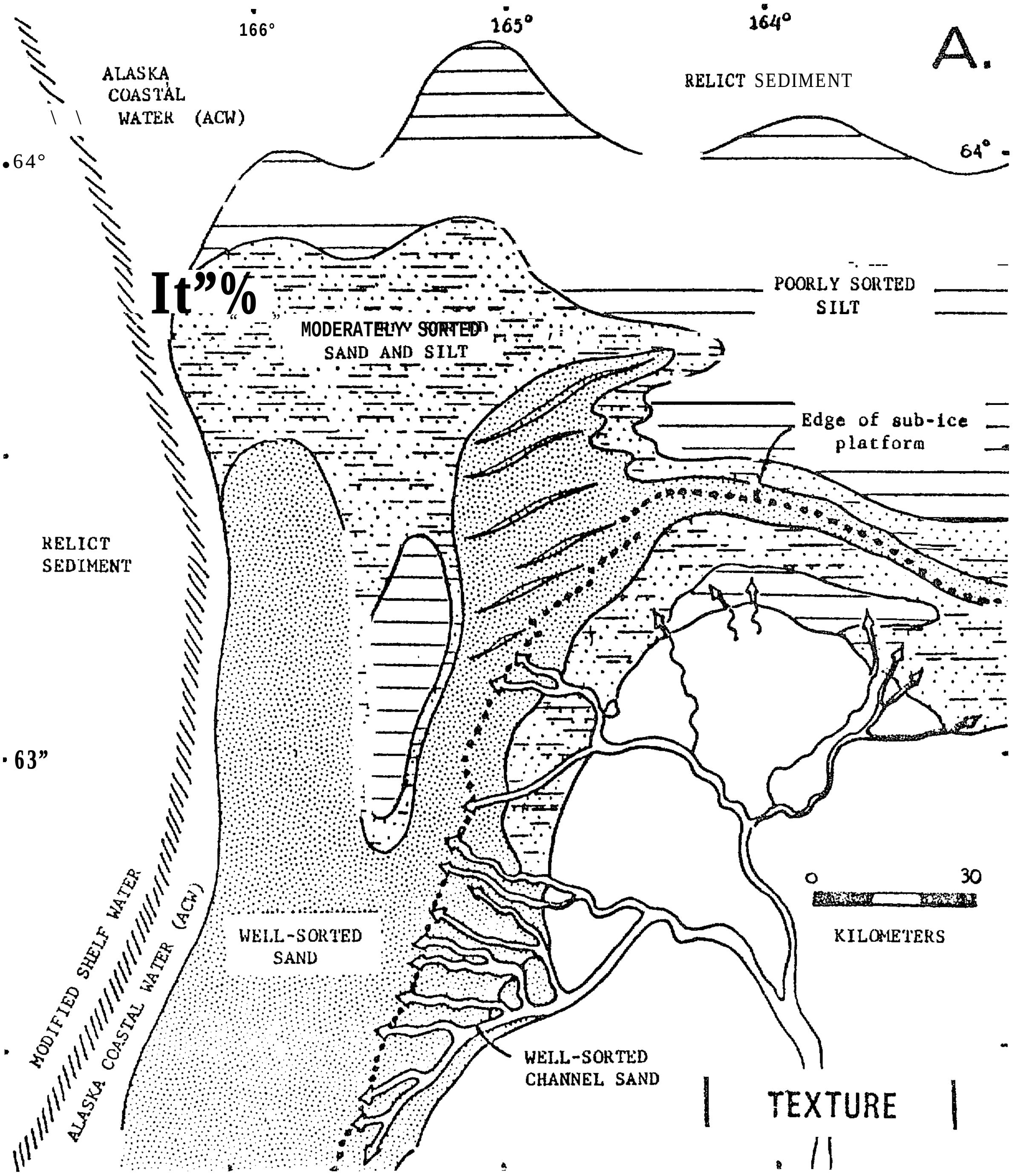

Figure 5A.--Schematic representation of sediment characteristics based on published data (McManus et al. 1977), unpublished data (C. Hans Nelson, U.S. Geological Survey), and extrapolation on the basis of offshore morphology.

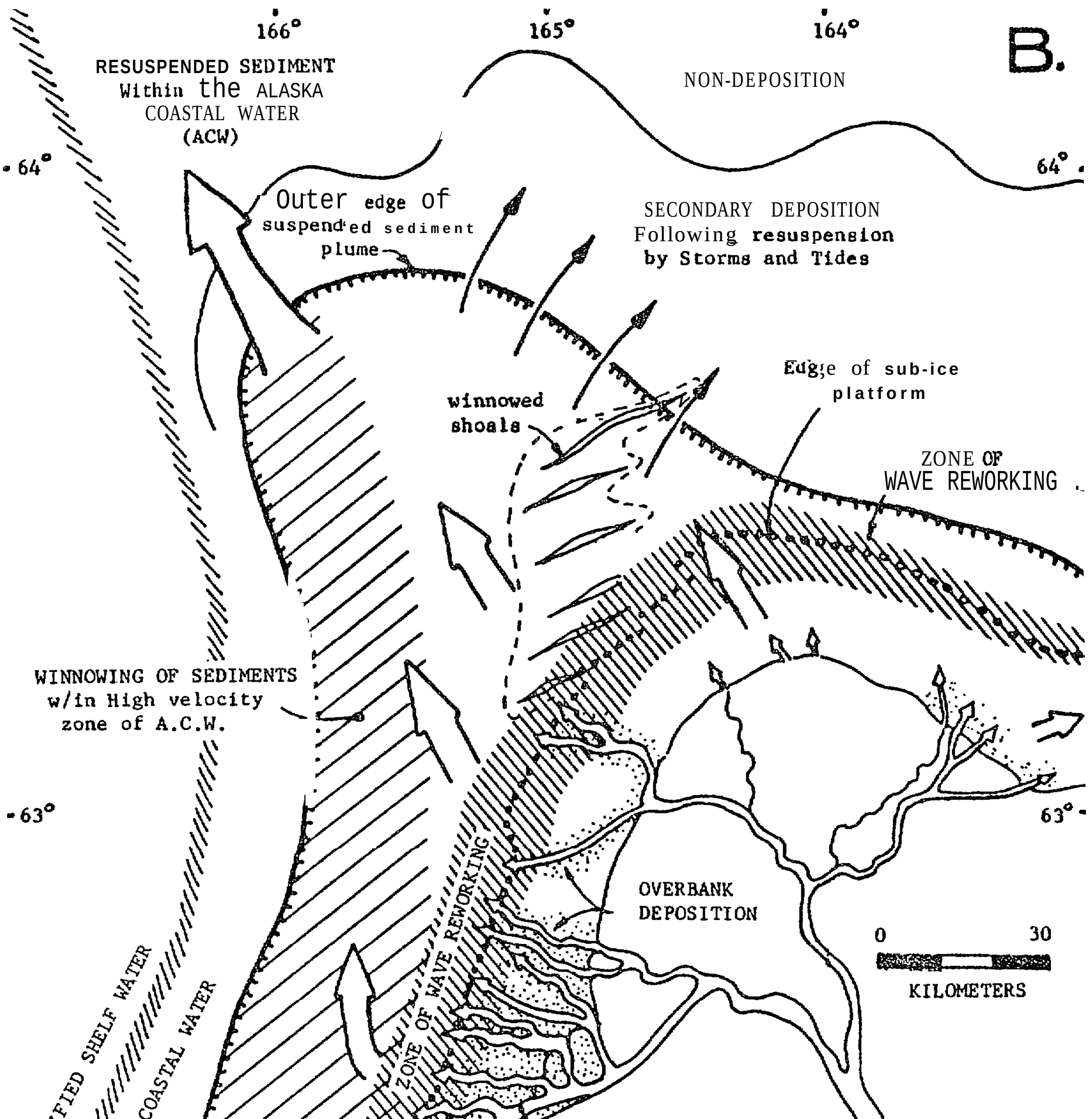

Figure 5B.--Hypothetical diagram of dominant processes, other than those related to ice, based on grain size data, Landsat imagery, and offshore bathymetry. Large arrows indicate direction of suspended sediment transport within the initial suspended sediment plume; smaller arrows indicate direction of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

subaqueous levees adjacent to the channels, but 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 (Fig. 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 initially deposited from suspension on the western margin of the prodelta 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 1,000 km to the northwest (McManus et al. 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 et al. (1979) 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 1973-77. 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 (Fig. 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 that characterize each of the zones. The reader is referred to Ray and Dupré (1981) for a more detailed discussion of the ice-dominated regime of Norton Sound.

Zone Ia is a zone of shorefast ice that extends to the outer edge of the sub-ice platform of the Yukon Delta, approximately coincident with water depths of 2-3 m. Over-ice flow (aufeis) occurs throughout the winter in areas of bottomfast ice near the major distributaries (see hatching in Fig. 6). 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, but 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, but ice can be completely lacking and replaced by a large area of open water under some conditions (e.g., 13-15 March 1976). Zone Ic is the zone of shorefast ice that 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 14-m 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 predominant northeasterly winds throughout the winter, but 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 20-m isobath, separating pack ice formed in Norton Sound from the thicker pack ice formed farther to the north. Pack ice from the Bering and Chukchi seas enters the sound only rarely, when especially strong northwesterly winds blow.

Zone IV consists of seasonal pack ice formed in the northern Bering and Chukchi 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 Bering Strait (described by Shapiro and Burns 1975) . This zone is characterized by highly fractured nilas ice during periods of relative quiescence. The eastern margin 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

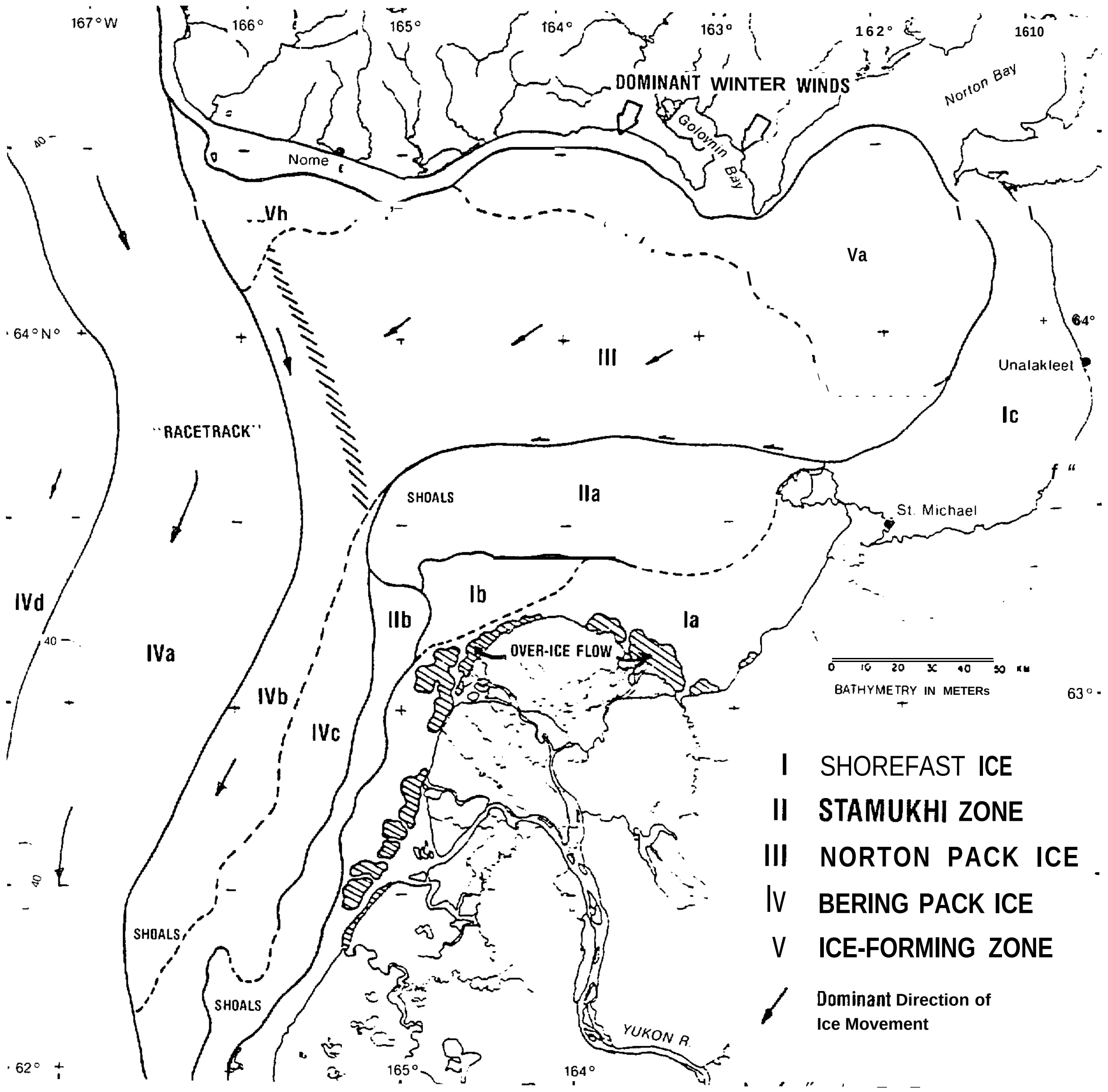

Figure ii.--Zonation of ice hazards in the Yukon Delta-Norton Sound region based mainly on Landsat and NOAA satellite imagery, supplemented by information on ice gouging by Thor and Nelson (1979).

Nelson 1979). Zone IVb is in water depths of 20 to 22 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 14 to 20 m, 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 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 Ahlnas 1976). These are typically areas of open water where ice is actively forming for most of the winter.

CONCLUSIONS

1. The Yukon-Kuskokwim Delta region is characterized by widespread evidence of Quaternary tectonism. Evidence of Holocene faulting, and the relatively high susceptibility for liquefaction of most of the fluvial and deltaic sediments, impose potentially serious geologic constraints on the selection of offshore sites and 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 that 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 less than 1 m.

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 pollutant) 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 subdivision of the Norton Sound region into zones, each characterized by a particular type of ice and ice movement.

IMPLICATIONS AND RECOMMENDATIONS FOR FUTURE STUDY

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 geohazards 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, 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.

Recommendations for Future Study

Many of the potential geologic hazards which must be considered in the course of developing Norton Basin relate to the Quarternary 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 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 of the distribution of the depositional environments (noting well 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 to be restricted to ice-dominated deltas, hence they may present some unexpected problems. They are actively meandering, with erosion on the cut banks and deposition on the sub-aqueous point bars. The channels are up to 0.5 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 by 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 water depths of 3 to 15 m, 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, judging from preliminary comparisons of 1899 bathymetry with data collected from the RV Karluk (USGS cruise, 1978). In addition, the northwestern part of the delta front appears to consist of a series of migrating linear shoals, with 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 RV 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 are quite insufficient) . In addition, 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 that 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 laboratory studies of weather patterns and ice movement as detectable on satellite imagery, and 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 environments 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, would be necessary.

c) River-dominated period: This period is 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.

d) Storm-dominated period: Late summer-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 during this period.

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

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APPENDIX

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

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

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This paper was presented at the 11th Annual Offshore Technology Conference in Houston, Texas, 30 April-3 May 1979 (OTC Paper 3434).

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 subarctic 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 is 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.

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 processes which characterize each environment. Sediment from most of the depositional environments was analyzed using the Rice University Automated Sediment Analyzer. 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 et al. 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 855,00 km^2, providing a water discharge of approximately 6,220 m^3/sec and a sediment load of approximately 88 million tons/year, representing almost 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.

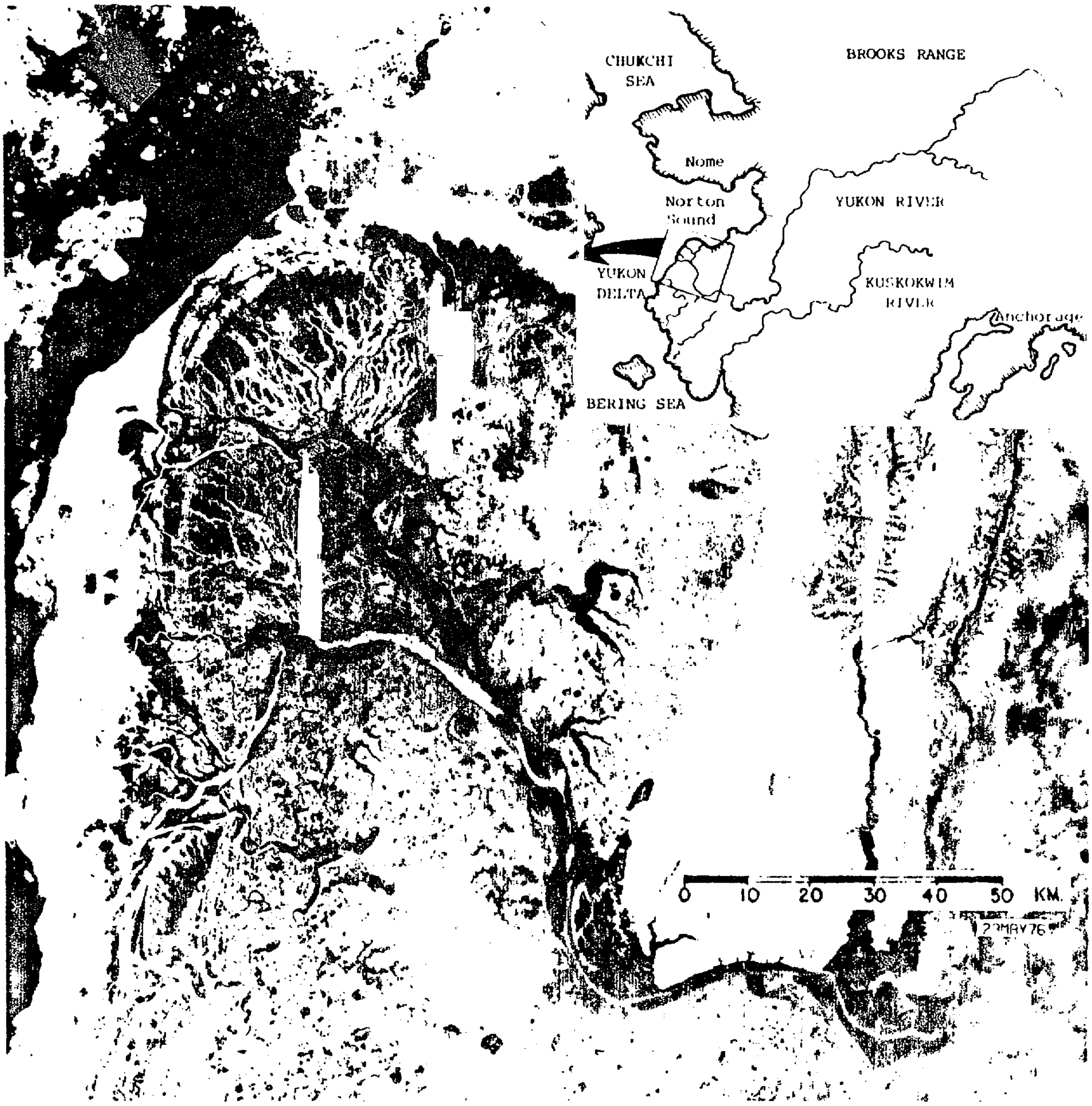

Figure 1.--Location map and Landsat image of the modern lobe of the Yukon Delta taken during breakup.

The modern delta of the Yukon River is' a relatively young geologic feature, having formed since approximately 2,500 years ago, when the river course shifted to where it presently enters Norton Sound (Dupré 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 tide-induced currents, and oceanic currents, as well as processes associated with ice movement. The relative importance of these processes varies systematically throughout the year, allowing the definition of ice-dominated, river-dominated, and storm-dominated regimens (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 et al. 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 redistribution 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 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 impinges on the western side of the delta throughout the year, although there are large seasonal variations in its lateral extent (Coachman et al. 1975). High flow velocities in the Alaska Coastal Water appear responsible for a large amount of fine-grained sediment bypassing Norton Sound for final deposition in the Chukchi Sea, 500-1,000 km to the northwest (Nelson and Creager 1977). Similarly, tides with a range of 1-1.5 m and tidally induced currents are

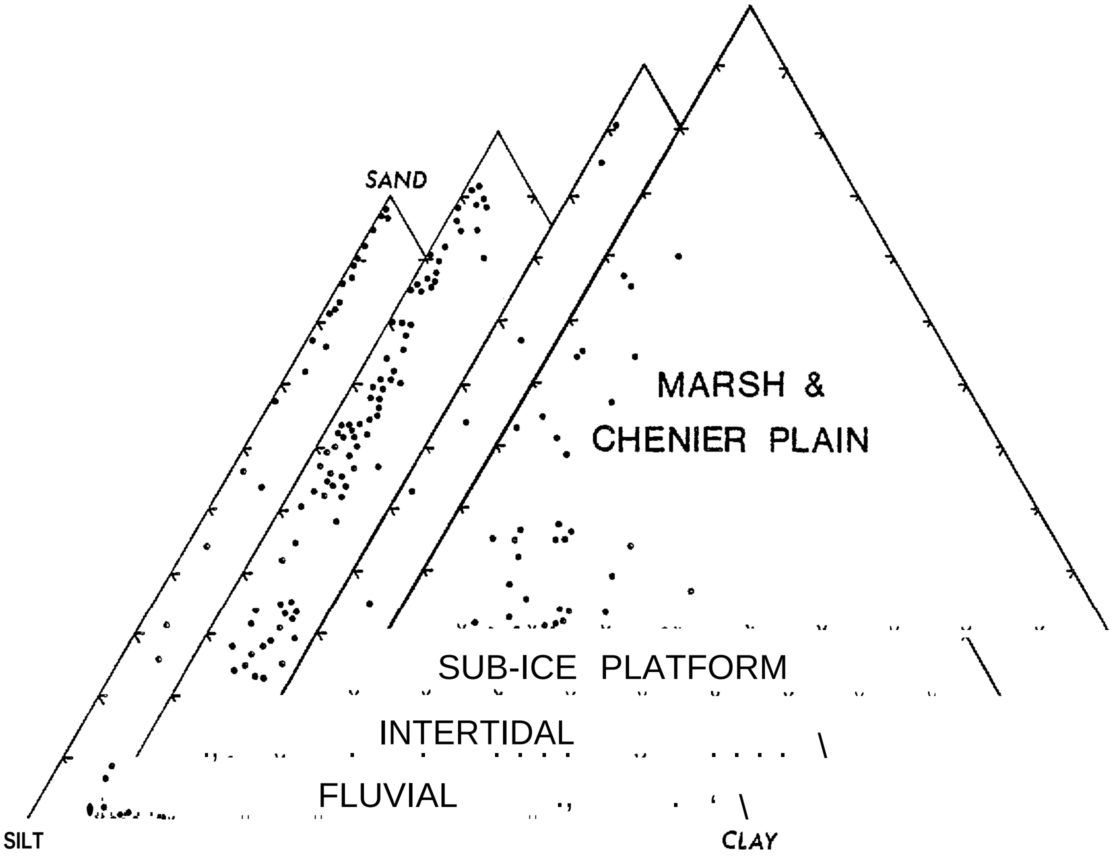

Figure 2. Grain size characteristics of sediments from the deltaplain and delta margin of the Yukon Delta.

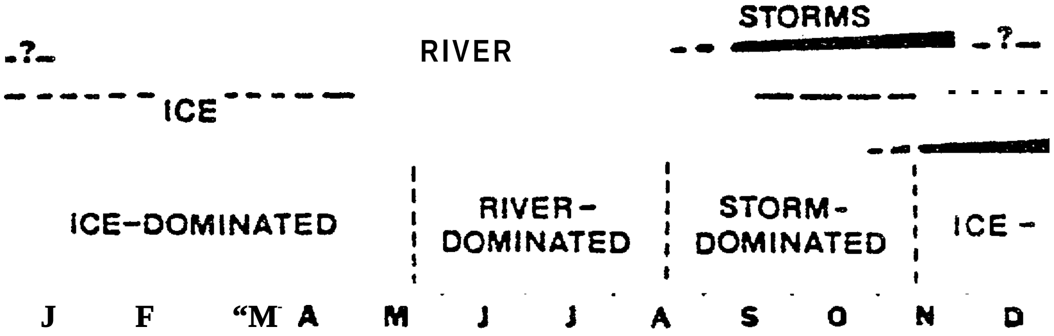

Figure 3.--Seasonal variability of coastal processes in the Yukon Delta region of Norton Sound.

active throughout the year, but their significance remains unclear. It seems likely that both the flow within the Alaska Coastal Water and the tidally induced currents are most important in transporting sediment resuspended 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 Delta. 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 (here 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) appears 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 and 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 model for such an ice-dominated delta (Fig. 6).

The delta plain contains a complex assemblage of active and abandoned distributaries, levees, interdistributary marshes, and lakes. The active distributaries have low to moderate sinuosity. The river has two main distributaries (1.5 km wide and 10-15 m deep), and numerous smaller distributaries (some as small as 20 m wide and 2-5 m deep) typically spaced every 1-2 km along the coast. Point bars and midchannel bars are common, particularly along the larger distributaries. Channel and bar deposits are typically composed of moderately to well sorted sand and silty sand, grading upwards and laterally into organic-rich, poorly sorted silt and mud deposited on natural levees and in meander swales.

The distributaries frequently shift their course via channel avulsion, often precipitated by ice jams resulting in the deposition of an abandoned channel fill typically consisting of organic-rich sandy silt and silt. Abandoned channels are highly prone to flooding and are frequently reoccupied by distributaries, resulting in a complex delta stratigraphy.

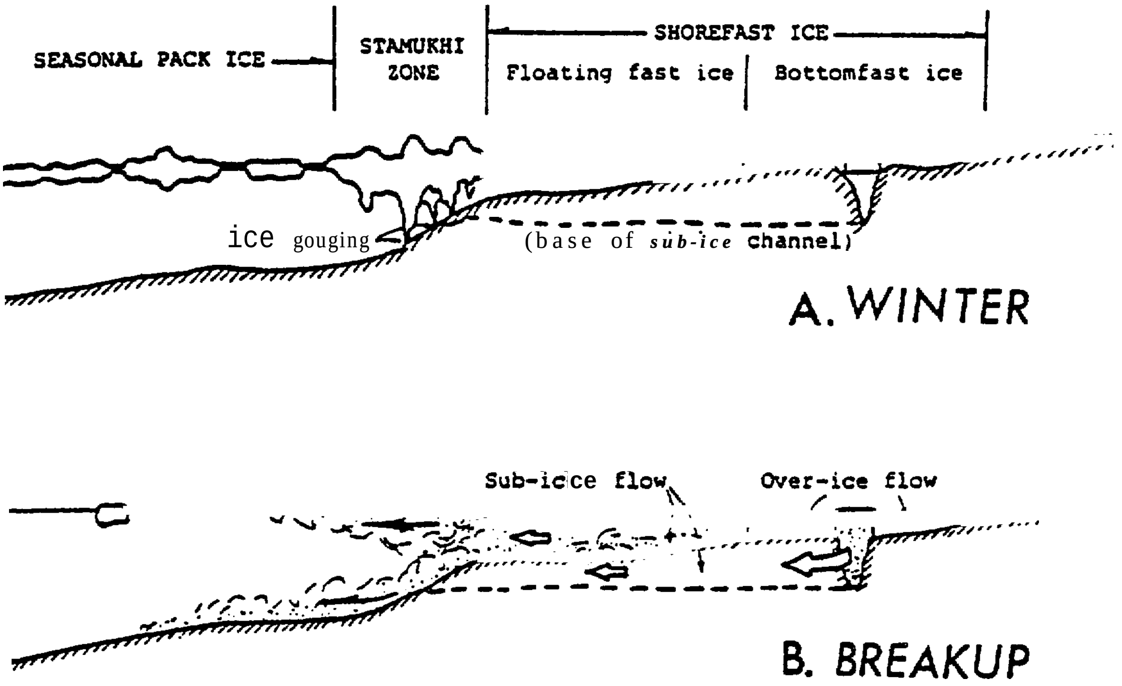

Figure 4.--Ice zonation in the winter (A) and its effect on sediment dispersion during breakup (B).

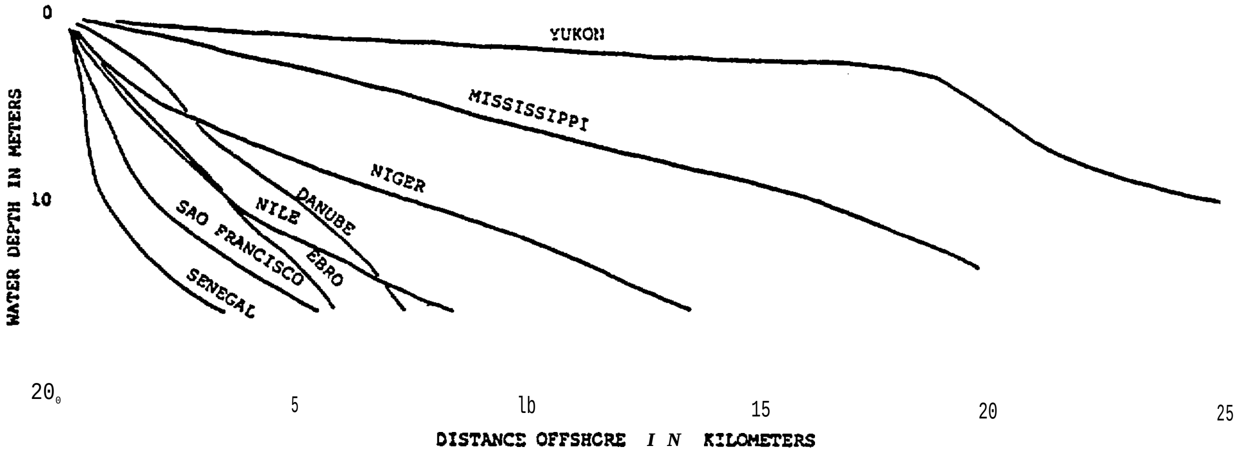

Figure 5.--Comparison of the subaqueous profiles of wave- and river-dominated deltas (Wright and Coleman 1973) with that of the Yukon Delta.

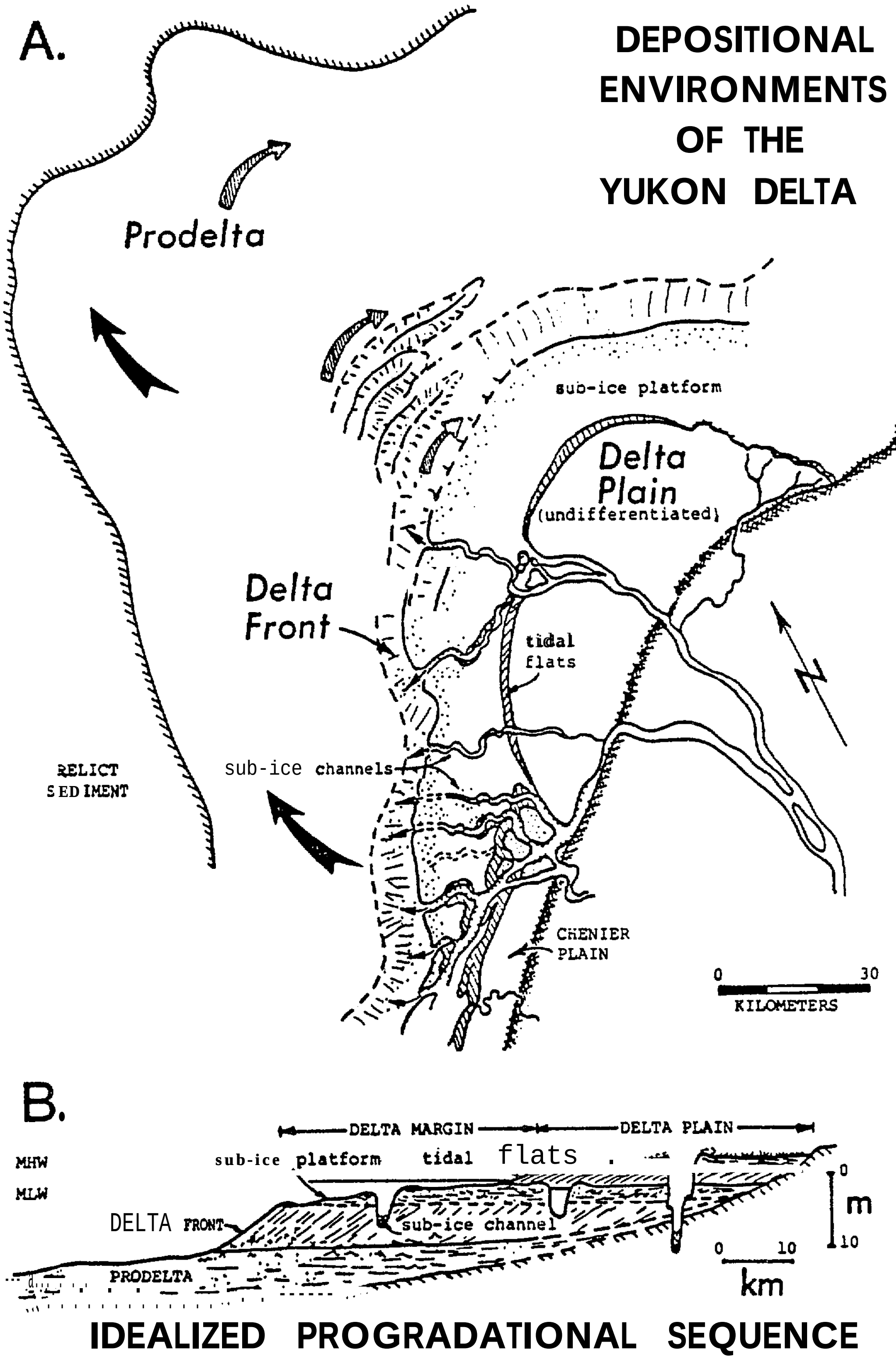

Figure 6.--Depositional environments of the Yukon Delta and idealized progradational sequence.

Interdistributary areas in the older, inactive parts of the delta are largely marshes characterized by poorly sorted silt and mud. Freshwater peats may be up to 1 m thick in the oldest parts of the delta. Some shallow lakes occur between natural levees, but most are in the process of being filled with vegetation. Incipient permafrost development has resulted in the formation of peat mounds (palsen) in many former lake beds. Interdistributary areas along the coast are characterized by marshes of salt-tolerant grasses and sedges, typically forming over actively prograding tidal deposits. Low washover ridges record short intervals of shoreline erosion, probably during major storms.

The delta margin is a term used informally here to include rapidly prograding tidal flats and distributary mouth bars as well as the sub-ice platform and associated offshore channels. Tidal flats are typically 100-1,000 m wide where they occur along the prograding margin of the delta. The flats consist of poorly sorted sandy silt in areas of relatively low wave energy (on the northern side of the delta) to moderately and poorly sorted silty sand in areas of higher wave energy (on the western side of the delta). The tidal flat deposits commonly form a fining-upwards sequence (approximately 1 m thick) of mixed bedded, ripple and parallel-laminated silty sand and silt. Primary sedimentary structures are often obscured, however, by extensive bioturbation, especially in areas of high silt content. Detrital peat is locally abundant, particularly in the upper parts of the prograding sequences. The tidal flats show abundant evidence of ice scour and ice plucking similar to that described by Dionne (1969); however, the preservation potential of such features may be small.

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

Unlike most deltas, the major distributaries continue offshore after bifurcation at the shoreline. These offshore extensions of the distributaries (here referred to as sub-ice channels), are 0.5 to 1 km wide and 5 to 15 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 are probably characterized by a fining-upwards sequence (up to 15 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 most of the summer; they may also serve as conduits for sub-ice currents during the winter months as well.

The sub-ice platform (or 2-meter bench of Toimil 1977) has an extremely gentle slope (typically 1:1,000 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 edge of the platform, particularly along the northern edge of the delta. Unlike the nearshore sediment of most deltas, the platform appears to be characterized by an offshore increase in the percentage of sand (Fig. 7), ranging from poorly 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 Reimnitz (1973).

The sub-ice platform appears to be an area of sediment bypassing and reworking throughout much of the year. Sediment bypasses the inner part of the platform during river breakup initially 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 offshore channels crossing the platform. Sediment is deposited from suspension during the summer months; however, much of that sediment is reworked during storms and perhaps during the winter months as well. The entire platform is sufficiently shallow to be reworked by waves, but most of the larger waves break at the outer margin. This suggests that the outer margin of the platform is an area of relatively high wave energy, providing one mechanism to explain the offshore increase in sand. In addition, the reduced cross-sectional area of the water column overlying the sediment may act to accelerate sub-ice currents of various origins. The inner part of the platform is frozen to the bottom with bottomfast ice; however, the outer portion is overlain by floating fast ice where the accentuated sub-ice currents could provide an additional mechanism for winnowing of fine-grained sediment from the outer margin of the sub-ice platform (of Barnes and Reimnitz 1973).

The delta front is a term used here to describe the relatively steep (typically greater than 1:500) margin of the delta characterized by apparently rapid deposition of sediment in water depths of 2-10 m. Maximum rates of progradation probably occur adjacent to the major distributaries (and associated sub-ice channels), presumably during the summer months. The morphology of the delta front is more complex along the northwestern part of the delta (Fig. 6B), where it includes a series of large (3-5 m high) shoals which appear to be migrating laterally into Norton Sound. This northeasterly movement is perpendicular to the dominant direction of summer sediment transport, perhaps representing either a secondary bifurcation of the Alaska Coastal Water or the effect of superimposed storm- or tide-induced currents. The outer margin of the delta front (in 5-10 m water depths) is an area of intense ice gouging during the winter months (Thor et al. 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 sandy 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 slopes (typically 1:2,000) 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

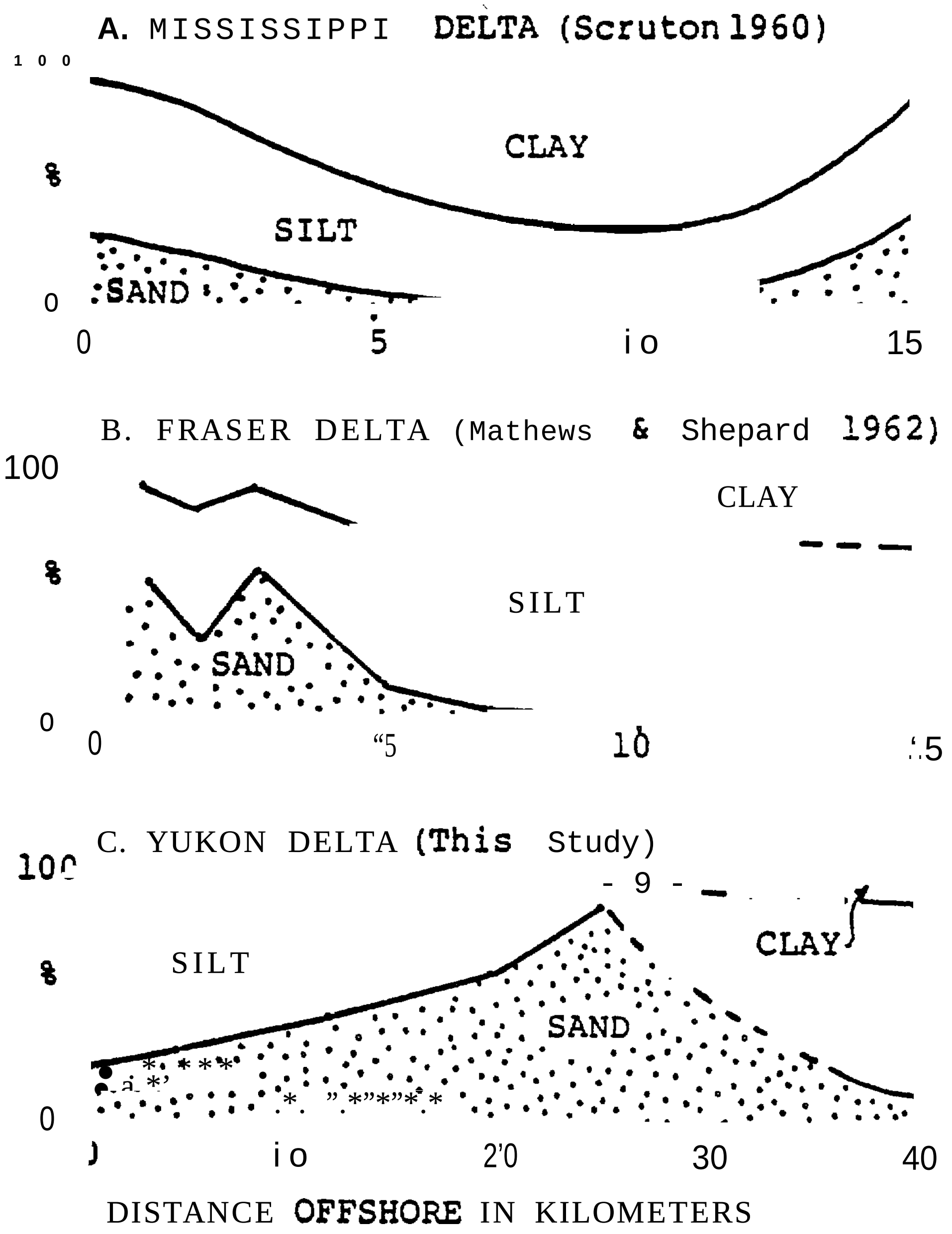

Figure 7.--Comparison of offshore trends of sediment textures off the Mississippi, Fraser, and Yukon deltas. Note the decreased amounts of clay in areas where mechanical weathering predominates.

reworking is clearly demonstrated by the unusual pattern of textural parameters described by McManus et al. (1977). 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 presence of sandy sediments in the western part of the prodelta appears to be in part the result of resuspension removal from Norton Sound by the relatively high flow velocities within the Alaska Coastal Water (McManus et al. 1977; Nelson and Creager 1977).

IMPLICATIONS

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.

The delta also provides a modern analogue for older deltaic sediments formed under similar tectonic and climatic settings. In particular, the rates of progradation are much greater than the rates of tectonic subsistence, hence the thickness of individual progradational sequences is

Table 1.--Preliminary summary of nontectonic geological hazards of the modern 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
Interdiatributary 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 front	N/A	High	Variable	Variable	None	Mod-High
Prodelta	N/A	Mod-Low	Moderate	Mod-Low	None	Low-Mod

limited by the water depths of the depositional basin (Fig. 6B). This results in the formation of a blanket-like deposit, a few tens of meters thick and thousands of square kilometers in aerial extent. The distribution of the sand-rich deposits also differs from most previously described delta models. Much of the delta plain consists of a complex pattern of radially bifurcating distributary sand; however, many of these well-sorted sands extend tens of kilometers offshore, having been deposited in sub-ice channels. These deposits represent offshore extensions of potential reservoir rocks. In addition, some of the coarsest, best sorted sands have been deposited not at the shoreline, but rather in water depths of 2-3 m at distances of up to 30 km offshore along the outer margin of the sub-ice platform. These sands should form a blanket-like deposit which may provide another potential reservoir. The textural and mineralogical composition of the sediment significantly affects the post-depositional history of the sediment. The lack of primary clays, particularly in the prodelta deposits, results in relatively little soft-sediment compaction and deformation; however, the abundant volcanic rock fragments may undergo diagenetic alteration to form an extensive matrix of secondary clays, thereby significantly reducing initially high porosities and permeabilities. In summary, the failure to recognize the unique geometry and sediment characteristics of deltaic deposits formed in the ice-dominated environment could result in serious errors in estimating the reservoir potential of older rocks.

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