DEPOSITIONAL ENVIRONMENTS OF THE YUKON DELTA, NORTHEASTERN BERING SEA[1]

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ABSTRACT

Dupré, W. R. 1982 Depositional environments of the Yukon Delta, northeastern Bering Sea. In: C. H. Nelson & S. D. Nio (eds): The northeastern Bering shelf: new perspectives of epicontinental shelf processes and depositional products – Geol. Mijnbouw 61: 063-070.

The Yukon River provides approximately 90% of the sediment presently entering the northeastern Bering Sea. Most of that sediment is initially deposited in Norton Sound, a broad, microtidal embayment typically less than 20 m deep. The shallowness of the depositional basin has allowed extensive reworking of the deltaic sediments by a variety of processes. These include waves, tidally and wind-induced currents, and oceanic currents, as well as processes associated with the movement and deformation of sea ice. The relative importance of these processes varies systematically throughout the year. The seasonal variability is best described by the definition of an ice-dominated, river-dominated, and storm-dominated regimen, each consisting of a characteristic suite of geologic processes.

The morphology of the Yukon Delta also reflects the climatic extremes of this high-latitude, epicontinental sea. The subaqueous profile of the delta differs from most previously described deltas in that the shoreline is separated from the prograding margin of the delta by a 'sub-ice platform' which is typically 2-3 m deep and extends up to 25 km offshore. The platform is crossed by a series of 'sub-ice channels' which extend up to 25 km beyond the mouths of the major distributaries. The platform and associated subaqueous channels are related to the presence of shorefast ice which fringes the delta for half of the year, and appear to be characteristic of ice-dominated deltas formed in high-latitudes.

INTRODUCTION

The northeastern Bering Sea, and particularly the Norton Sound region (Fig. 1), has been an area of relatively intense study over the past 15 years, in part due to the increasing interest in the hydrocarbon potential of the region. Much of Norton Sound is covered with modern deltaic deposits derived from the Yukon River, hence an understanding of the deltaic processes in this modern epicontinental sea is essential to the understanding of the shelf sediment dynamics.

It is the purpose of this paper to provide an overview of the depositional processes and environments which characterize the Yukon Delta. At least some of those processes and environments appear to be unique to high-latitude, epicontinental shelves. As such, the Yukon Delta may serve as a model for an ice-dominated delta (DUPRÉ & THOMPSON, 1979). In addition, this paper can serve as a framework for other papers in this volume which deal in more detail with specific aspects of the offshore deltaic sediments; e.g. sedimentary and biogenic structures (HOWARD & NELSON, 1982, this volume), depositional and erosional features (HUNTER ET AL, 1982, this volume), geotechnical properties (OLSEN ET AL, 1982), and microfauna (MCDOUGALL, 1982).

METHODS

Field work during the summers of 1975 through 1978, combined with the interpretation of bathymetric charts and topographic maps (circa 1873-1978), aerial photographs (circa 1952-1977), and Lansat imagery (circa 1973-1978), have provided an overview of the major depositional environments of the Yukon Delta, as well as the processes which characterize each environment. Approximately 300 sediment samples from most of the depositional environments were analyzed using the Rice University Automated Sediment Analyzer (RUASA) which uses settling tubes to analyze sand and coarse silt, and a hydrophotometer to analyze fine silt and clay. Published grain size data were also available for a limited

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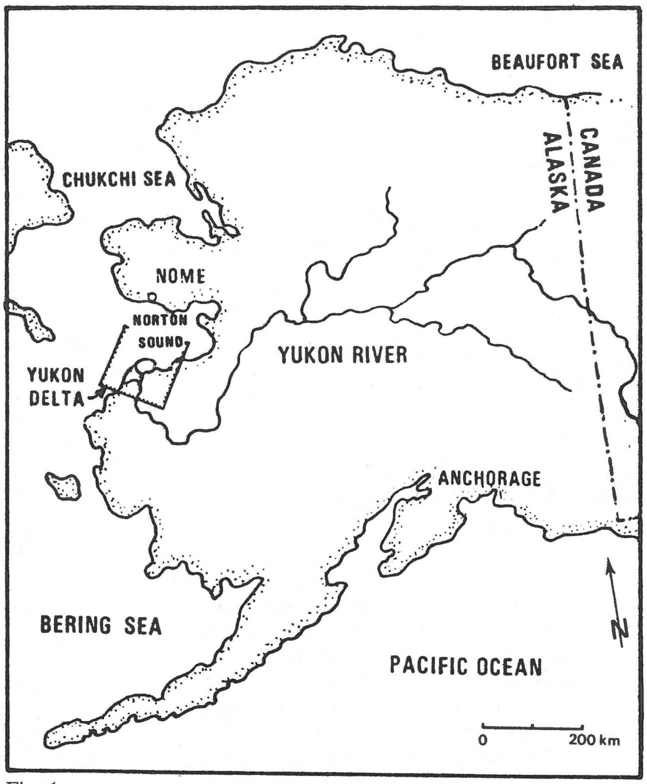

Fig. 1.
Index map of study area. Box delineates area mapped in figure 5A.

number of samples from the prodelta environment (MCMANUS ET AL, 1977) and from a large sub-ice channel (MATTHEWS, 1973). Additional samples from some of the offshore environments were kindly provided by Hans Nelson (U.S. Geological Survey, Menlo Park, CA.). X-ray photographs of numerous cores were examined to provide additional information on sedimentary structures and bioturbation in both nearshore and onshore sediments (collected in this study), and in offshore sediments (collected by J. Howard and H. Nelson). Lastly, the composition of the sands was determined by point counting grain mounts of fluvial and deltaic sediments; these sands were classified according to the classification of FOLK (1980).

GEOLOGIC SETTING

The Yukon River drains an area of approximately 855,000 km^2, providing an average water discharge of approximately 6220 m^3/sec, and a suspended sediment discharge of from 30-90 million tons/yr (see DRAKE ET AL, 1980 for a more complete discussion of the sediment load of the Yukon River). This represents approximately 90% of the sediment presently entering the northeastern Bering Sea (LISITSYN, 1966). The source area is a region of continuous to discontinuous permafrost, dominated by the effects of mechanical weathering (including glaciation). The results of such weathering processes should be a sediment high in silt and with a relative paucity of clays (TABER, 1943; HILL & TEDROW, 1961), and this is confirmed by size analysis of Yukon sediments (DUPRÉ & THOMPSON, 1979). The lack of extensive chemical weathering has also resulted in a relatively high percentage of feldspars being preserved in the sands. In addition, the source area has a complex history of Mesozoic and Cenozoic tectonism which has provided an abundant suite of lithic fragments as well. The result has been the production of a compositionally immature suite of sands (typically feldspathic litharenites), reflecting both the climatic and tectonic setting of the drainage basin.

The modern delta of the Yukon River is a relatively young geologic feature, having begun to form not earlier than 2500 years ago when the river shifted its course to where it presently enters Norton Sound (DUPRÉ, 1978). Norton Sound is a broad, microtidal 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, allowing the definition of an ice-dominated, river-dominated, and storm-dominated regimen (Fig. 2), described in more detail by RAY & DUPRÉ (1981).

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. 3A). This typically occurs in water depths of 7 to 14 m, and results in extensive ice gouging (as delineated by THOR & NELSON, 1979). It provides one mechanism for the resuspension of sediment beneath the ice, 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 & REIMNITZ, 1973). Tidal currents are probably more important, however, in resuspending sediment beneath the ice, as documented by DRAKE ET AL. (1979).

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, Alaska) and sub-ice flow through a series of channels which extend up to 25 km offshore (Fig. 3B). Once the shorefast ice melts or drifts offshore, sedimentation is dominated by normal deltaic processes associated with the high sediment discharge of the

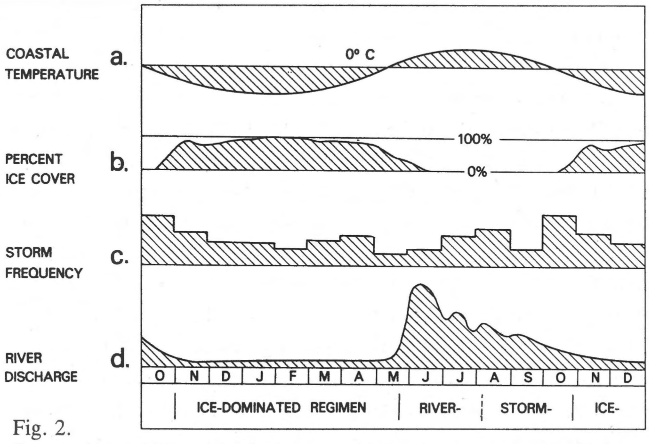

Fig. 2.
Seasonal variability and relative magnitude of processes in the Yukon Delta-Norton Sound region of the Bering Sea. Sources of data include: (a) summary of average monthly temperatures at Unalakleet, 1941-1970, (NOAA); (b) summary of ice observations for Yukon Delta region from Brower et al. (1977); (c) frequency of major low pressure centers in the northern Bering Sea region, from Brower et al. (1977); and (d) discharge of the Yukon River at Kaltag, 1962 (U.S.G.S. Water Resources Data).

Yukon River. The dominant northeasterly winds are usually weak and blow over a relatively limited fetch, hence the waves are usually small during this time of the year. Frictional attenuation across the shallow margin of the delta further decreases the nearshore wave energy by several orders of magnitude. The low wave energy, combined with the high sediment input, results in relatively rapid progradation of the delta during this period.

Increasing frequent southwesterly winds and waves associated with major storms during the late summer and early fall characterize the storm-dominated regimen. The relatively long fetch and high winds result in high wave energy, especially along the western margin of the delta. High wave energy and rapidly decreasing sediment discharge from the Yukon River result in significant coastal erosion and reworking of deltaic sediments. Resuspension of offshore sediment during storm events is common during this period (DRAKE ET AL., 1980). 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 ET AL., 1975). High flow velocities within the ACW appear responsible for a large amount of suspended sediment ultimately bypassing Norton Sound, to be deposited in the Chukchi Sea, 500 to 1000 km to the northwest (NELSON & CREAGER, 1977). Similarly, tides with a range of 1 to 1.5 m and tidally induced currents are active throughout the year, although their significance remains unclear. It seems likely that currents within the ACW (and perhaps storm-induced currents as well) are most important in transporting sediment resuspended by other processes (e.g., spring tides, storm waves, ice gouging).

DEPOSITIONAL ENVIRONMENTS

The subaerial morphology of the Yukon Delta is similar to lobate, high-constructional deltas described by FISHER ET AL., (1969) as typical of bedload-dominated rivers emptying into shallow depositional basins. This is consistent with the geologic setting of the Yukon River. 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 prograding outer margin of the delta is offset from the shoreline by a broad platform (here referred to as a sub-ice platform), locally up to 25 km wide. The result is a subaqueous profile (Fig. 4) quite unlike those of wave- and river-dominated deltas described by WRIGHT & COLEMAN (1973). It is, however, similar to the offshore profiles of the Colville Delta (Alaska) and the Mackenzie Delta (Canada). In addition, the platform is crossed by a series of subaqueous (sub-ice) channels which extend up to 25 km beyond the mouths of the major distributaries. Similar offshore channels have been recognized off the Colville Delta (WALKER, 1974) and off some of the Arctic deltas of Russia (IVANOV & NALIMOV, 1978).

The sub-ice platform and associated 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 & BRUDER, 1972; REIMNITZ & 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 & MOWATT (1975) have 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, distinquished from previously described wave-, river-, and tide-dominated deltas

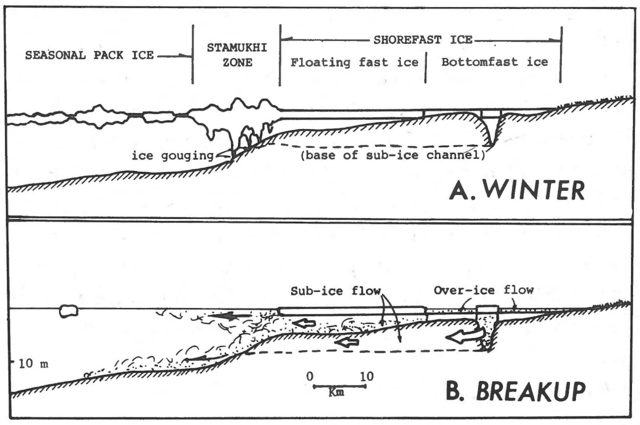

Fig. 3.
Ice zonation about the Yukon Delta during the winter (A) and its effect on sediment dispersion during Spring Breakup.

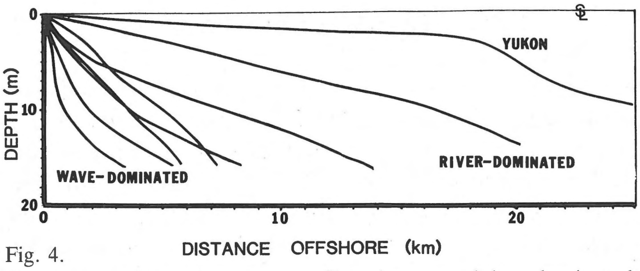

Fig. 4.
Comparison of the subaqueous profiles of wave- and river-dominated deltas (after Wright & Coleman, 1973) with that of the Yukon Delta.

(e.g. GALLOWAY, 1975) by the presence of a sub-ice platform and associated sub-ice channels. The Yukon Delta may provide a model for such an ice-dominated delta (Fig. 5).

Delta plain

The delta plain contains a complex assemblage of active and abandoned distributary channels and channel bars, natural levees, interdistributary marshes, and lakes. The active distributaries have a radially bifurcating pattern; individual channels have low to moderate sinuousity. The river has two main distributaries (1-1,5 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 mid-channel 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. This results in the deposition of an abandoned channel fill typically consisting of organic-rich sandy silt and silt. Abandoned channels are highly prone to flooding, however, and are frequently reoccupied by distributaries, resulting in a complex stratigraphic record.

Interdistributary areas in the older, inland parts of the delta are largely marshes characterized by poorly sorted peaty silt and mud. Freshwater peats up to 1 m thick cap much of the older parts of the delta (KLEIN & DUPRÉ , 1980). Some shallow lakes occur between natural levees, however, 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 capping prograding intertidal deposits. Low washover ridges rich in peat detritus record short intervals of shoreline erosion, probably during storms.

Delta front platform

The delta front platform is an informal term used 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 100-1000 m wide where they occur along the prograding shorelines. The tidal flats range from 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). These deposits commonly form a fining-upwards sequence (approximately 1 m thick) of mixed stratified, 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 distributary mouth 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 towards their 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 25 km across the sub-ice platform. Landsat imagery shows evidence that these channels are actively transporting sediment throughout the summer, however they may also serve as conduits for sub-ice current during the winter as well. Active sediment transport is also indicated by the seaward-migrating sand waves up to 1 m high within the bottoms of the channels, (HUNTER ET AL,. 1982, this volume). These channels appear to be changing their course by a combination of lateral migration and channel avulsion. Lateral migration up to 50 m/yr. has resulted in the deposition of a fining-upwards sequence of subaqueous point bar deposits up to 15 m thick. This sequence probably consists of an erosional base overlain by cross stratified, moderately sorted, fine grained sand grading upwards into moderately poorly sorted silty sand and silt deposited on subaqueous levees.

The sub-ice platform has an extremely gentle slope (typically 1:1000 or less) and shallow water depths (1-3 m) extending up to 25 km beyond the shoreline. The platform in 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

(HUNTER ET AL., 1982, this volume). Unlike most deltas, there is an offshore increase in the percentage of sand on the sub-ice platform (Fig. 6) similar to that described off the North Slope of Alaska by BARNES & REIMNITZ (1973). This presumably is due to the increased reworking of sediment on the outer edge of the platform.

The sub-ice platform appears to be largely an area of sediment bypass 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 & BRUDER, 1972 and WALKER, 1974), and 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 subsequently reworked during storms and perhaps during the winter months as well. The entire platform is sufficiently shallow to be reworked by waves, however, most of the larger waves break at the outer margin. Thus the outer edge of the platform is an area of relatively high wave energy, providing one mechanism to explain the offshore increase in sand. Tidal currents may also play a role in resuspending sediment on the outer platform. The inner part of the platform is frozen to the bottom

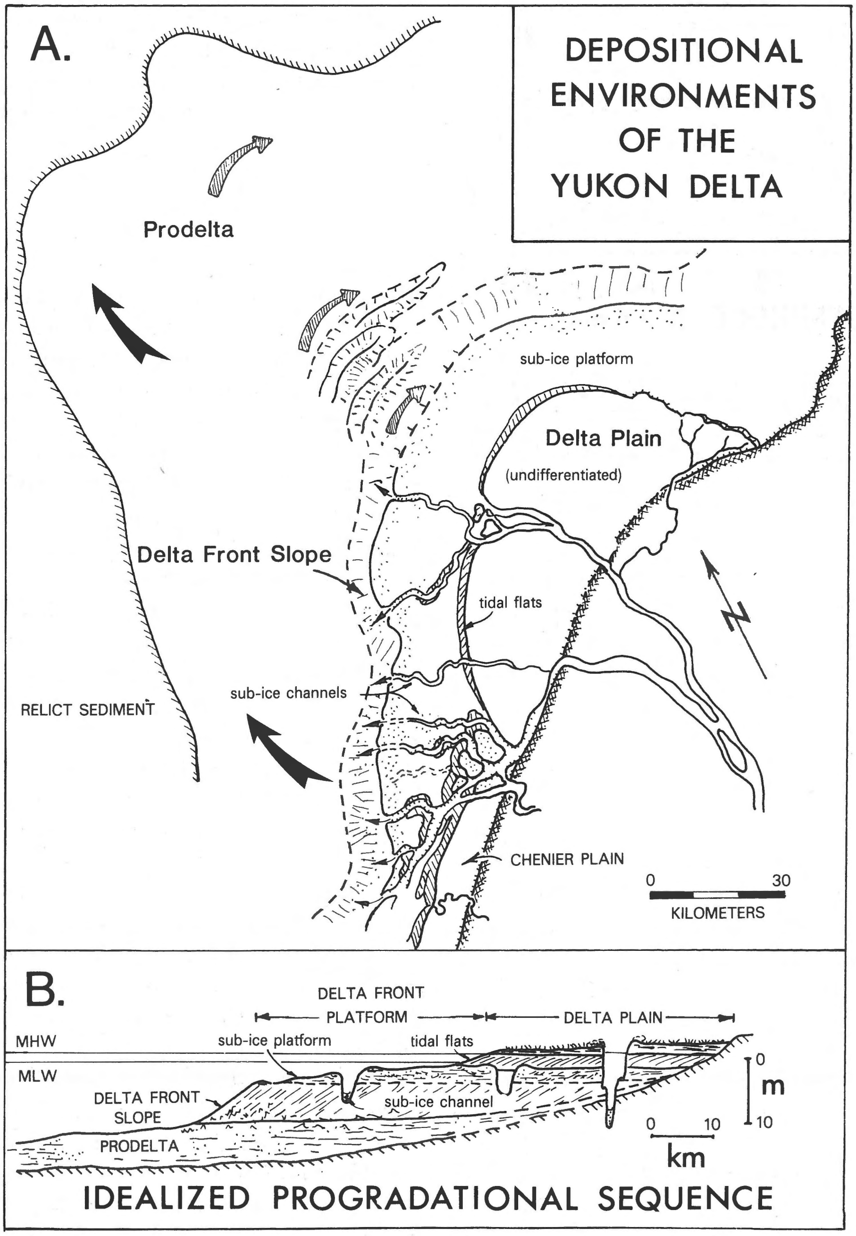

Fig. 5.
Depositional environments (A) and idealized progradational sequence (B) of the Yukon delta (modified from Dupré & Thompson, 1979). Distributions of relict sediments after McManus et al., 1977. See insert in Fig. 1 for location of map area.

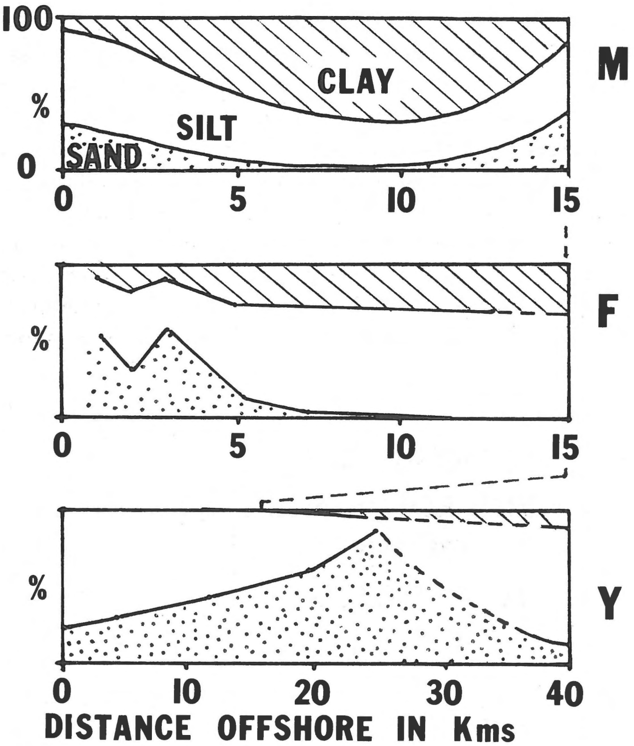

Fig. 6.
Comparison of offshore sediment trends of the Yukon delta (**Y**) with those of the Mississippi (**M**, after Scruton, 1960) and Fraser (**F**, after Mathews & Shepard, 1962) deltas. Note the decreasing clay content, coincident with the increasing dominance of mechanical weathering.

with bottomfast ice during the winter, however, the outer portion is overlain by floating fast ice where sub-ice currents could provide an additional mechanism for winnowing of fine-grained sediment from the outer margin of the sub-ice platform (cf. BARNES & REIMNITZ, 1973).

Delta front slope

The delta front slope is a term used here to describe the relatively steep (typically greater than 1:500) zone of sandy sediments 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 during the summer months. In contrast, the delta front slope appears to be eroding along the northern margin of the delta. Long-term patterns of erosion and sedimentation are more complex on the north-western delta front where a series of large (2-3 m high) shoals, locally up to 50 km long, appear to be migrating into Norton Sound. This northeastward movement is perpendicular to the dominant direction of suspended sediment transport during the summer, hence it presumably represents secondary sediment transport either by a bifurcation of the Alaska Coastal Water or by superimposed storm- or tidally induced currents. Patterns of sediment transport are further complicated by the extensive ice gouging which occurs during the winter on the outer edge of the delta front (THOR & NELSON, 1979) in water depths of 7 to 14 m.

The sediment characteristics of the delta front are relatively poorly known. Nevertheless, most of the delta front on the western margin of the delta is in the zone of wave buildup, hence probably consists of relatively well-sorted sand grading offshore into more poorly sorted silty sand and sandy silt. This is supported by data from a limited number of box cores from this zone (HOWARD & NELSON, 1982, this volume). The linear shoals also consist of relatively well sorted sand, as described by NELSON ET AL., (1982, this volume). The sediments on the northern portion of the delta region are probably finer grained and more poorly sorted than their western counterparts, because of the lower wave energy to the north of the delta.

Prodelta

The prodelta is characterized by extremely gentle slopes (typically 1:2000) marking the distal edge of the deltaic sediments extending up to 100 km offshore. These sediments grade seaward into shelf sediments relatively unaffected by deltaic processes. Landward they grade into the relatively more coarse delta front slope sands. The sediments within the prodelta environment are initially deposited from suspension, however, the relatively shallow water depths (10-20 m) allow significant reworking of the sediments. The degree of reworking is clearly demonstrated by the unusual textural patterns within the prodelta sediments as described by MCMANUS ET AL., (1977).

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 presence of relatively coarse sediments in the western part of the prodelta appears to be in part the result of resuspension of fine-grained sediment and their subsequent removal by the relatively high flow velocities within the Alaska Coastal Water (MCMANUS ET AL., 1977; NELSON & 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 an area of poorly sorted silt in the central part of Norton Sound.

The sediment supply into Norton Sound is virtually cut off during the winter months due to the reduced flow of the Yukon River. Nevertheless, DRAKE ET AL., (1979) report that the amounts of suspended sediment beneath the ice canopy in the outer prodelta region is as high as during non-storm periods during the summer. This implies that sediment is being resuspended during the winter months as well, presumably by tidal currents. At least some of the resuspension may, however, be related to the formation of scour depression associated with ice gouging (LARSEN ET AL., 1979).

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 marine processes which probably characterize most high-latitude epicontinental shelves, both past and present. The Yukon Delta may also serve as a model of older deltaic sediments deposited in such a setting. Rates of sedimentation are much greater than rates of tectonic subsidence, hence the thickness of individual progradational sequences is limited by the shallow water depths of the depositional basin (Fig. 5B). The result is a blanket-like deposit a few tens of meters thick and thousands of km^2 in aerial extent. The distribution of the sand-rich lithofacies also differs from previously described deltas. Much of the delta plain consists of a complex pattern of radially bifurcating distributary channel sands, capped by thin peats formed in a tundra environment. Many of these well-sorted channel sands extend tens of kilometers offshore, however, having been deposited in sub-ice channels. Some of the best sorted sands were not deposited at the shoreline, but rather on the outer edge of the sub-ice platform, in water depths of 2-4 m and up to 25 km offshore. Well-sorted sands also form in a series of linear shoals which extend up to 50 km offshore. Lastly, sediments within the prodelta range from sand to silt, reflecting the complex patterns of sediment resuspension and reworking throughout the year.

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