Linear Sand Bodies in the Bering Sea Epicontinental Shelf

by

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ABSTRACT

The epicontinental shelf of the Bering Sea is characterized by variations in river and glacial sediment supply, wave energy, tidal range (microtidal to mesotidal), and tidal, geostrophic, and storm-induced currents. These factors, combined with the effects of the Holocene rise in sea level, have resulted in the formation of a complex assemblage of linear sand bodies of similar morphology and lithology, but different origins. The sand bodies are large features <10 km long found from the present shoreline to tens of kilometers offshore in water depths up to 50 m. They include modern sand bodies formed by present-day processes; relict sand bodies formed during lower stands of sea level; and palimpsest sand bodies formed under past conditions but modified by modern day processes. Together they reflect the wide variety of offshore sand bodies that may be found in epicontinental settings like the modern North Sea or some ancient shelves.

The different types of sand bodies (linear tidal sand ridges, shore parallel shoals, delta front channels, leeside shoals, ancient shoreline shoals and morainal features) may be identified by variations from the norm: linear morphology, orientation parallel to the strand line, enclosure by shelf sand or mud, fine sand texture, and horizontal lamination. Linear tidal sand ridges (5-35 by 1-3 km) which form at the present time in the macrotidal, funnel-shaped Kuskokwim Bay, are oriented perpendicular to the shoreline, enclosed by tidal flat and shelf mud, and sometimes sigmoidal in shape. The modern shore parallel shoals (including barrier islands) (5-10 by .5-1 km) form in mesotidal environments, are the smallest of the shelf sand bodies, and typically are bounded by tidal flat mud inshore and shelf mud offshore. Delta front channels {20 -30 by 2-4 km) extend seaward from the modern river distributaries and form sand bodies perpendicular to the shoreline; they are enclosed by graded overbank sand beds and mud, and are characterized by large- to small-scale trough cross lamination. Leeside shoals, (25-100 by 5 to 25 km) which form now and in the past behind obstructions to unidirectional shelf currents, are the longest, possess the finest grain size, and exhibit the most consistent rhythmic flat lamination of any sand bodies encountered on the Bering shelf. Ancient shoreline shoals (15-30 by 3-7 km) are remnant shoreline features paralleling strand lines of lower sea levels; they contain cycles of ripple and trough cross lamination alternating with high angle foreset beds formed by modern sand waves that cover crests of these sand bodies. Relict sand and gravel bodies deposited in moraines are distinguished by their coarse grain size and irregular size and shape.

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INTRODUCTION

The epicontinental shelf of the eastern Bering Sea is characterized by large variations in fluvial input at different locations and in the energy of systems that distribute and deposit the load. Sediment is distributed not only by wave and tidal currents but also by strong geostrophic and storm-induced currents. The wide variety of processes, combined with the effects of the Holocene rise in sea level, has resulted in the deposition of sand bodies with similar linear morphology but different depositional settings, orientations, and origins that this paper describes. Examples include: linear tidal sand ridges, and shore-parallel shoals (including barrier islands) like those in the North Sea, as well as delta-front (sub-ice) channels, leeside shoals, ancient shoreline shoals, and morainal features that may be more specific to the Bering shelf.

The Bering epicontinental shelf contains a combination of (1) modern sand bodies formed by present-day processes, (2) relict sand bodies formed under past conditions, and (3) palimpsest sand bodies formed under past conditions but modified by modern-day processes. The variety of modern sand bodies on Bering shelf may be similar to that found on ancient shelves. The recognition of these differences is crucial to reconstruction of ancient epicontinental shelf facies and the task of hydrocarbon exploration.

Methods

The morphology, geometry, and lithology of the sand bodies on the Bering shelf have been studied over the past decade using a combination of high-resolution bathymetry, seismic profiling, side-scan sonar, vibracores of 2-6 m, box cores, and grab samples. Sediment samples have been analyzed for grain size and X-rayed to determine internal sedimentary structures. Grain-size distributions have been mapped vertically and horizontally using standard grain-size techniques, although the degree of detail varies in different locations. In sane areas of extremely shallow water of Kuskokwim Bay and off the Yukon Delta, shipboard surveys and sampling have not been possible. There, sediments have been sampled by helicopter and sand bodies have been mapped using satellite imagery.

Geologic and oceanographic settings

Tidal range and wave climate vary greatly in different locations of the eastern Bering shelf. Waves with 10-12-second periods and with heights of 10-20 m are possible in the southern shelf, but maximum wave heights are only 7 m on the northern Bering shelf (Arctic Environmental Information, 1977). Similarly, maximum spring tidal heights range from up to 5 m in the upper Kuskokwim Bay to less than 0.5 m in the northeastern Bering shelf. Where the Alaskan Coastal Water flows northward and is constricted by the eastern Seward Peninsula side of Bering Strait, bottom current speeds of over 200 cm/s occur (see Fig. 1 of Nelson, this volume). In the constrictions of Anadyr and. Shpanberg Straits, maximum current speeds are 100-150 cm/s. In Norton Sound even small-scale storm tide events have been observed to increase current speeds of the northward geostrophic flow from less than 30 to 70 cm/s (Cacchione and Drake, 1979).

Quaternary glaciation and sea-level fluctuations on the northern Bering shelf have been crucial to the development of morainal and ancient shoreline sand bodies. Continental and valley glaciers near the eastern side of Anadyr Strait and off Nome, respectively, have left moraines that have been reworked by the Pleistocene-Holocene transgression of the past 20,000 years (see Fig. 4 in Nelson, this volume). Sea-level stillstands accompanying the late Pleistocene-Holocene transgression remain as coast-parallel offshore bars (Nelson and Hopkins, 1972; Tagg and Greene, 1973). The stillstands are most apparent at depths of 10 to 12 m, 20 to 24 m, 30 m, and 38 m (see Nelson, this volume).

Both the Yukon and Kuskokwim Rivers contribute large amounts of sediment to the northeastern Bering Sea and this input is a significant factor in the development of presently forming sand bodies. The Yukon provides $60\text{-}90 \times 10^6$ t, or 90% of the modern fluvial sediment introduced into the entire Bering Sea; the second largest source is the Kuskowkim River which yields nearly 4×10^6 t of sediment annually (Drake et al., 1980).

TIDAL SAND RIDGES

Linear tidal sand ridges form in structurally subsiding macrotidal (>4 m) embayments (Hayes, 1975) such as Kuskokwim Bay (Fig. 1). Tidal sand ridges are best developed in the bay at the mouth and offshore from the Kuskokwim River but also occur in other nearby macrotidal embayments (e.g., Bristol Bay). The tidal sand ridges in Kuskokwim Bay typically are 0.5 to 4 km wide, 4 to 50 km long, and range in relief from 4 to 10 m near the mouth of the river to 32 m offshore (Fig. 2). Some of the Kuskokwim tidal sand ridges, like those in the North Sea, are asymmetric in cross section and slightly sigmoidal in plan view, a configuration that reflects opposing tidal currents (Caston, 1972).

The grain size on the emergent surface of the tidal ridges consists of fine, well-sorted sand (Fig. 2). The tidal mud flats that flank the ridges consist of very poorly sorted silt (Fig. 3). Bedforms on ridge surfaces consist of sand waves of about 50 m wavelength that contain superimposed current ripples. The only internal structures observed in shallow trenches cut into the emergent ridges were horizontal parallel laminations. Apparently, like the predominance of parallel lamination observed on the ebb-daninated side of the tidal sand ridges of the Oosterscheld Estuary in the

Netherlands (Nio and others, 1979), preservation of internal structures of large-scale bedforms is limited in Kuskokwim Bay tidal ridges.

Orientation of the tidal sand ridges is roughly parallel to the rectilinear tidal currents (Fig. 2). The currents range from slightly over 50 cm/s in the outer part of the bay to nearly 150 cm/s knots at the mouth of the Kuskokwim River (U.S. Department of Commerce, NOAA, 1977). The landward increase in tidal current velocity is also paralleled by a landward increase in tidal range, the maximum of which is 5 m at the river's mouth. Current attenuation within the river channel results in an upstream decrease in tidal amplitude to slightly less than 1.5 m approximately 100 km inland and also causes an asymmetry in the tidal currents to flood-dominated in the lower part of the river, similar to that described in the Ord River, Australia by Coleman and Wright (1978).

Most sand ridges in Kuskokwim Bay appear to be formed by present-day tidal reworking of sand by the river. Sane of the sand bodies farthest offshore may have formed during intervals of lowered sea level and thus may be palimpsest or relict features like the "moribund" sand ridges described by Kenyon and others (1979). The sand ridges in the nearshore regions of the bay are slightly offset to the east of the main trend, smaller in scale and size, and more closely spaced than are the ridges farther offshore (Fig. 2). The sand ridges that trend more northwesterly are more sigmoidal in shape, possibly because of the increased tidal amplification and flood-dominated tidal asymmetry toward the river's mouth. The longest and straightest ridges are found in the southeastern part of the region, where it is possible that ebb and flood currents are more equal (Fig. 2).

SHORE-PARALLEL SAND SHOALS AND ASSOCIATED BARRIER ISLANDS

The linear tidal ridges of the macrotidal upper Kuskokwim Bay region grade westward into mesotidal (2-4 m) areas where wide tidal flats, large tidal channels, and an outer fringe of submergent to emergent shoals occur (Fig. 3). The shoals nearest the mouth of the Kuskokwim River are approximately 30 km offshore and are emergent only during lowest spring tides, They grade westward into low-lying barrier islands approximately 10 km offshore. Similar barrier islands present in mesotidal areas along the western margin of the Yukon-Kuskokwim delta complex off Cape Romanzof were not studied.

The shore-parallel shoals (including barrier islands) in Kuskokwim Bay are 5 to 10 km long, 0.5 to 1 km wide; and may have as much as 15 m of relief above the adjacent seafloor. They, like the tidal shoals, are characterized by well-sorted fine sand (Fig. 2) and are enclosed by silty sand that grades inshore to the silty mud of the tidal flats (Figs. 2 and 3). The barrier islands rise approximately 2 m above sea level, but unlike those formed in drier temperate climates, they lack eolian dunes. When the easternmost shoals are emergent, however, sand waves are seen that sometimes intersect each other at right angles (Fig. 4-1). The sand waves, although planed to small amplitudes, are covered by sets of divergently oriented ripples formed by diversely oriented nearshore waves and tidal currents. The only observed internal sedimentary structures of these ephemeral ripples and sand waves are parallel laminations.

The shore-parallel sand bodies and barrier islands form in equilibrium with the mesotidal setting on the west. Emergent barrier islands grade eastward to submergent shoals where there is an increase in tidal range. Barrier islands decrease in length and tidal channels become more numerous.

Tidal flats increase in width to more than 10 km. Farther to the east the shore-parallel shoals grade into the shore-perpendicular linear tidal ridges in a macrotidal setting.

The barrier island, shore-parallel shoals and tidal sand ridges forming in equilibrium with tidal and wave energy today in Kuskokwim Bay are similar to those in the Rhine River estuary of the North Sea (Hayes, 1975; Nummendal, 1979)9 The size and setting of the Kuskokwim system make it essentially a replica of the Rhine River-North Sea system if Kuskokwim Bay were inverted from north to south. Sand bodies in both systems are representative of epicontinental shelf macrotidal, funnel-shaped estuary systems with a significant sediment input (Coleman and Wright, 1978).

DELTA FRONT (OR SUB-ICE) CHANNELS

The Yukon River mouth, in contrast to the funnel-shaped estuary of the nearby Kuskokwim River, has a constructional, lobate delta (Fig. 1). The delta shoreline is an area of relatively low wave energy and tides (typically 1 m or less) (Arctic Environmental Information, 1977). Deltaic sedimentation also is strongly affected by the presence of shorefast ice that fringes the delta for almost seven months of the year (Duprè, this volume) . The shorefast ice forms over the sub-ice platform that is typically 2-3 m deep and extends as far as 30 km offshore. The platform is crossed by a series of subaqueous channels that extend offshore fran major distributaries of the delta (see Fig. 5 in Duprè, this volume) . These channels are typically 5 to 10 m deep, and 0.5 to 1 km wide; lateral migration of the channels produces sand bodies approximately 10 m thick and 1 to 4 km wide that extend up to 25 km beyond the shoreline.

The grain size of the channel fill varies widely from well-sorted medium to fine sand in thalwegs of the inshore active channel (Fig. 4-F) to graded sand beds interbedded with silty mud that flank and may in part fill abandoned channels (Fig. 4-G). Individual graded units up to 30 cm thick vary from well-sorted fine sand at the base to poorly sorted silt at the top. Off the eastern delta, where current channel fill is low, fine sand occurs and the sand beds in the upper sequence of channel fill are only a few centimeters thick.

Large-scale megaripples on the floor of active subaqueous channels appear to be represented by large-scale, moderately dipping crossbedding (Fig. 4-F). Subaqueous point-bar sequences presently form in meandering sub-ice channels and consist of trough cross-laminated sand fining upward into interbedded silt and peat. A complete vertical sequence of sedimentary structures in ascending order is flat-laminated, trough cross-laminated and flat-laminated sand (Fig. 4-G). Farther offshore the basal flat-laminated beds may be replaced by mainly trough cross-laminated or ripple-laminated units with thin, flat-laminated upper parts.

The presence of the sub-ice platform and associated subaqueous channels appears to be restricted to the ice-dominated deltas (see Fig. 5 in Dupré, this vol.) that are common in arctic and sub-arctic shelves today. The effect of the shorefast ice is to extend the well-sorted distributary sand far beyond the shoreline, resulting in elongate sand bodies enclosed in thinner sand and mud overbank deposits.

LEESIDE SHOALS

Leeside shoals are large accumulations of sand deposited in the current lee behind land barriers that interrupt continuous, strong geostrophic current flows in the northern Bering Sea (see Fig. 1 in Nelson, this volume). These shoals are most typically found on the east sides of straits where land projects westward into the strongest current flow. Examples are north of Cape

Romanzof, the Yukon delta, and northwest of Cape Prince of Wales (Fig. 1) . Leeside shoals also form in the north lee of King and St. Lawrence Islands which obstruct the strong northerly water circulation (Fig. 1) .

Leeside shoals vary in size and shape from long and narrow behind King Island (2o by 5 km) and Cape Prince of Wales (100 by 14 km) (Fig. 1) to broad and diffuse sand bodies (45 by 25 Ion) north of the modern Yukon delta. The ir relief ranges from 10 to 20 m, and their orientation generally parallels the current flow direction rather than the shape of the coastline, fran which they are typically detached.

The grain size of the leeside shoal in all settings is very fine sand (Fig. 1), and consequently, asymmetric current ripples are the typical surface bedform. Sedimentary structures of the shoal north of Cape Prince of Wales, where geostrophic current shear is maximum and most continuous, are very even parallel flat laminations and intermittent ripple laminations (Fig. 4-D). The leeside shoal north of the Yukon delta (Fig. 1) exhibits well-developed alternating layers of crossbedded and horizontally laminated sand (see Fig. 2 in Howard and Nelson, this volume). Large-scale tabular foresets also develop as the sand body apparently grows offshore from the edge of the the Yukon delta-front platform (Fig. 4-E).

Because deposition results from flow separation on the lee side of obstructions (Middleton and Southard, 1977), the sediment source for leeside shoals is entrainment of sediment that has been stripped from adjacent coastlines, river mouth discharge, or upcurrent shelf sand. One sand source of the Cape Prince of Wales leeside shoal is believed to be very fine sand eroded fran the southern Seward Peninsula beaches between Cape Prince of Wales and Port Clarence. These beaches lack very fine sand (<5% at 8 stations) whereas the leeside shoal and beach on the north side of Cape Prince of Wales are composed of dominantly very fine sand (>97% at 6 stations). The very fine sand fraction normally eroded from beaches and deposited in offshore bars during storm events apparently is entrained and carried northward through the Bering Strait by the geostrophic current. Because of flow separation on the lee side north of Cape Prince of Wales, the entrained very fine sand is deposited on the beaches and leeside shoal.

The leeside shoal north of the modern Yukon delta contains very fine sand derived fran the southwest distributary that is the main discharge point of the Yukon River (Dupré, this volume). This distributary is located in the maximum current-shear region of eastern Shpanberg Strait (see Fig. 1 of Nelson, this volume), where strong geostrophic currents are located. These currents entrain the deltaic sediment and deposit the sand in the leeside shoal located 30-130 km north and east of the main river discharge point (see Fig. 5 in Dupré, this volume). In the delta-front area, geostrophic water circulation is not vigorous and is reinforced by intermittent storm tides (Nelson and Creager, 1977; Nelson, this volume). Apparently, in this more complex delta setting, the leeside shoal develops a diffuse fan shape and contains a wider variety of internal sedimentary structures (Fig. 4-E and Fig. 2 in Howard, this volume).

ANCIENT SHORELINE SHOALS

Many areas of the Bering shelf are marked by well-developed fields of linear sand bodies formed by ancient shorelines (Fig. 1). The largest of these is a series of long, linear shoals that lie offshore from Port Clarence at water depths of 10-12, 20-24, 30, and 38 meters (Fig. 5). A well-defined linear field of ridges at similar water depths exists off Nome (Nelson and Hopkins, 1972; Hopkins, 1973; Tagg and Greene, 1973). West of St. Lawrence Island is a long, linear ridge at a depth of 30 m that also appears to be an ancient shoreline (Fig. 1). All of the shoals described above occur in the Chirikov Basin, an area where detailed studies of ancient beaches have been made because strong currents have prevented burial by post-Holocene deposition (Nelson and Hopkins, 1972; McManus and others, 1974; see Nelson, this volume).

The sand bodies formed by ancient shoreline shoals are 15 to 30 km long, 3 to 7 km wide, and 10 to 15 m high. Seismic reflection and sampling reveals that the sand ridges off Port Clarence are at least 6 m thick and are composed of well-sorted fine to medium sand (Figs. 1 and 5). Troughs between the sand ridges contain very fine sand to silt (Fig. 5). Near Nome and northwest of St. Lawrence Island, the ancestral shoreline features have been incised into pebbly, sandy glacial till (Nelson and Hopkins, 1972; see Fig. 4 in Nelson, this volume) and consequently contain fine to coarse sand and gravel.

Near Port Clarence, bottom currents rework the crests of the ancient shoreline shoals into a series of mobile bedforms (Fig. 5). The largest features are sand waves with wavelengths up to 200 m and heights of 2 m (Nelson and others, 1978). Superimposed on them are smaller, slightly oblique sand waves that have wavelengths up to 10 m and heights of up to0.5 m. Linguoid ripple fields with wavelengths of 10-30 cm and wave heights of a few centimeters occur on the stoss side of sand waves (Fig. 4-H). All of the bedforms have crests aligned transverse to the linear ridge crest and are asymmetric, steep side to the north, transverse to the flow direction of the strong geostrophic currents. Significant modification of ice gouges by these mobile bedforms shows that the bedform fields are presently active. Near Port Clarence, when strong north winds create large storm waves, the small-scale bedforms may be modified by ephemeral oscillation ripples until the normal northward current regime resumes. Near Nome, there is an even greater degree of mixing between asymmetric ripples developed by tidal current flow and oscillation ripples developed inshore by storm waves (Hunter and Thor, this volume) . The region of the large, linear ridge west of St. Lawrence Island also has mobile bedforms (Nelson and others, 1978).

In the largest area of ancient shoreline shoals near Port Clarence, reworking of the ancient shoreline shoals by modern currents results in well-developed sedimentary structures, especially on the shoals closer to shore. Ripple lamination is ubiquitous and bioturbation is dominant, particularly on offshore shoals and at several meters depth in all shoals. Ripple lamination commonly present near the surface, caps an underlying sequence of foreset beds. This cycle sometimes is repeated at about 50-cm intervals and may represent alternating episodes of linguoid ripple and small-scale (50 cm wave height) sand-wave migration along shoal crests (Fig. 5-C and 5-H). Thin mud-drapes and storm pebble lag horizons also are typical in the nearsurface sediment of ancient shoreline shoals (Fig. 5A) .

The ancient shoreline shoals typically are flanked by older, limnic, peaty mud with radiocarbon dates ranging from 12,000 to more than 40,000 years B.P. (see Fig. 5 in Nelson, this volume). The presence of thin, modern mud (<50 cm) over peaty mud with radiocarbon dates exceeding 40,000 yrs B.P. indicates lack of modern deposition or scour between the shoals. Consequently, the intervening sand shoals on bedrock highs (Fig. 5) appear to represent ancient constructional ridges undergoing present-day modification on their crest by migration of surface bedforms; the main ridges, however, do not change significantly in size or shape.

The shape of the submerged shoals west of Port Clarence is similar to that of the modern, subaerial Port Clarence spit (Fig. 5F-F'); in addition their grain size is coarser (fine to medium sand) relative to that of enclosing inner shelf deposits (fine to very fine sand) , or of leeside shoals (very fine sand) in Chirikov Basin (Fig. I) (see Figs. 3 and 6 of Nelson, this volume). Both characteristics suggest that the submerged shoals may be Pleistocene shoreline analogs to the Port Clarence Spit and that they formed by littoral drift processes, depositing fine to medium sand at lower stillstands of sea level (Figs. 1 and 5; Nelson, this volume) . submerged shoal crests off Port Clarence and St. Lawrence Island are similar in depth and grain size to ancient shoreline features at Nome and elsewhere in the northern Bering Sea (Figs. 1 and 5) , again lending support to an origin during older sea-level stillstands at water depths of 10-12, 20-24, and 30 m (Nelson and Hopkins, 1972; Hopkins, 1973).

Many areas of the U.S. Atlantic shelf characterized by similar fields of linear sand ridges (Duane and others, 1972) have been interpreted as shoreface ridges stranded by a retreating shoreline (Field, 1980). Present-day reworking by shelf currents is modifying these features into active mobile bedform fields like those on Bering Shelf (Swift and Field, 1980).

GLACIAL MORAINES

A few large bodies of sand and gravel deposited by ancient glacial activity remain exposed and surrounded by Pleistocene transgressive sand on the seafloor in the Chirikov Basin region. A large outwash fan approximately 5 km in diameter is located offshore southeast of Nane (Fig. 1). Two very large coarse sand and gravel ridges about 75 km long and 25 km wide extend southward fran Cape Prince of Wales toward the center of Chirikov Basin and northward from St. Lawrence Island to the same point. The two ridges are traceable as the ends of major moraines of continental glaciers that moved southward into Chirikov Basin from Siberia (see Fig. 4 in Nelson, this volume; Grim and McManus, 1970; Nelson and Hopkins, 1972).

The glacial features in general are coarser grained than the other shoals of the eastern Bering continental shelf (Fig. 1). Because gravel is difficult to sample, we have not been able to observe internal sedimentary structures.

SAND BODY GENESIS

Hydrographic and sedimentary processes vary from south to the north on the eastern Bering epicontinental shelf and consequently genesis and age of shelf sand bodies vary according to geographic location. Toward the southeast, tidal currents and wave energy dominate sedimentation as well as the local transport history, whereas in the northeastern shelf area, the effects of ice and geostrophic bottom currents flowing to the north are more important. The influx of fluvial sediment is particularly important in the southeastern and east-central region of the shelf, whereas glacial deposition and local transgressive history during the Pleistocene are more significant in the northeastern shelf area.

The extensive development of modern sand bodies in the southeastern and east-central Bering shelf relates to high influx of fluvial sediment in that area, which receives 90% of the Bering Sea's sediment load (Lisitsyn, 1966). The sand bodies in the southeastern shelf are modern features derived from sediment deposited by the Kuskokwim River and modified by tidal currents and waves in Kuskokwim Bay. The funnel-shaped estuary of the Kuskokwim River contains linear, coast-perpendicular sand ridges that are characteristic of a tide-dominated river mouth (Coleman and Wright, 1978). Shore-parallel sand bodies in west and northwest Kuskokwim Bay result from a mesotidal regime. In the microtidal (<2 m) environment off the Yukon River, channel sand bodies develop on the delta front platform mainly because of processes associated with shorefast ice and the high sediment discharge of the Yukon River (Dupré, this volume).

By contrast, sand and gravel bodies in the northeastern Bering shelf are the result either of relict or palimpsest deposition. The leeside sand bodies probably accumulated during the present Holocene high sea level and other Pleistocene highstands. Seismic-reflection profiles over the north end of the leeside shoal in east-central Shpanberg Strait and the shoal north of the Yukon delta show significant Holocene deposition (see Fig. 4 in Nelson, this volume) . Profiles over leeside shoals indicate several episodes of deposition, most likely from sedimentation during several past high sea levels. The consistent lithology of very fine sand and horizontal flat laminations indicates that flow separation in the lee of obstructions results in deposition of the suspended sand load as bottom currents pass over the sand body. Ripple laminations and high-angle foreset beds in the Yukon shoal, show the influence of storm events on these typical flat-laminated deposits.

Unlike the leeside sand bodies, which exhibit significant Holocene deposition, the formation of the ancient shoreline sand bodies is related mainly to deposition of fine to medium sand by littoral drift currents on strandlines during lower stands of sea levels. The history of these ridges is complex, as deposits formerly at a lower sea level are now being modified into active ripple and sand wave fields by present-day bottom currents. Mobile bedforms are further disrupted by pebble lags and mud drapes formed during present-day storm events; thus, the resultant internal sedimentary structures do *not* represent the shoreline processes mainly responsible for formation of the main sand ridges. Internal structures, except for rare trough crossbedding, are mainly unknown in those relict sand and gravel bodies deposited by glacial events, but *now are* preserved by strong modern geostrophic currents,

GEOLOGIC SIGNIFICANCE OF SAND-BODY CHARACTERISTICS

The eastern Bering epicontinental shelf contains numerous offshore and nearshore large, linear sand bodies. Nearshore and offshore sand bodies resemble one another in that they are composed of well-sorted fine sand and are essentially linear, except for several of the leeside shoals and glacial features. They differ in that nearshore sand bodies orient with wave and tidal currents, but offshore shelf sand bodies mainly follow trends of geostrophic and storm-related currents.

Other distinctions may help to differentiate sand bodies because of differences in shape, grain size and internal sedimentary structures (Table 1). Shore-parallel shoals appear to be consistently shaped, smaller, and more coincident with shoreline trends than the other types of shoals. Linear tidal ridges and delta-front channels are generally perpendicular to shoreline trends and are quite consistent in gross size and shape, except for sinuosity of meanders in channel-fill bodies and sigmoidal shape in tidal ridges. Leeside shoals are oriented parallel to dominant shelf currents and are long and narrow where current speeds are consistently unidirectional and strong; elsewhere, they may be more fan-shaped. Overall size varies quite markedly depending on the size of the adjacent land barrier, the magnitude of flow, and sediment load. Ancient shoreline sand bodies also vary in size and have different shapes and orientations with respect to the shoreline (Fig. 1).

Grain size varies for different types of shelf sand bodies (Table 1). Deposits of subaerial glaciers dominated by coarse sand and fine gravel are distinctively coarser grained than all other types. In contrast, leeside shoals consisting of very fine sand because of deposition from the suspended sediment load, are typically the finest grained (Fig. 1). Ancient shoreline shoals are consistently coarser grained than deltaic or leeside deposits.

Internal sedimentary structures, although difficult to assess in cores from modern deposits, again help differentiate modern shelf shoals and perhaps provide one of the best criteria for ancient analogs. Leeside sand bodies, where uncomplicated by deltaic and storm sand sedimentation? are characterized by consistent, rhythmic flat lamination (Fig. 4-C). The very fine grain size of sand making up leeside sand bodies inhibits development of large-scale bedforms and thus such deposits generally should lack large- and medium-scale crossbedding, although ripple lamination of storms may interrupt flat lamination. Large-, medium-, and small-scale trough cross-laminations, on the other hand, are persistent in sand bodies and enclosing overbank deposits of delta-front channels. Because large-scale bedforms form in channel thalwegs, large-scale cross-bedding in clean sand should characterize the main-channel sand body, while smaller scale trough cross-lamination should characterize overbank mud that encloses the sand body. Rhythmic graded storm sand with vertical sequences of internal structure, organic debris, and mud caps also should be associated with younger channel-fill and laterally equivalent deposits. High-angle foreset beds in cyclic sequences with ripple and trough cross-lamination help identify shoreline sand bodies stranded by eustatic rises of sea level, but reworked by mobile bedforms while submerged. Modification of these ancient shoreline sand bodies by present-day mobile bedform fields and bioturbation suggests that internal structures of the original beach formation processes may rarely be present in such sand bodies.

In reconstructing ancient shelf environments, researchers must realize that 1) sand-body genesis is highly variable within the same shelf setting, 2) large sand bodies may be detached far from shore and not parallel later strandlines, and 3) features of different history and age may coexist (Table 1).

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AGE	TYPE	ENVIRONMENT OF DEPOSITION	LENGTH (KM)	WIDTH (KM)	RELIEF (M)	LITHOLOGY	SEDIMENTARY STRUCTURES	DISTINGUISHING FEATURES
Holocene - Modern	Linear tidal sand ridges	Macrotidal funnel-shaped bay and estuary.	5-35	1-3	4-32	Fine sand	parallel lamination, surface ripple fields, sand waves observed	Enclosed by tidal flat and shelf mud, shore-perpendicular, varying in size and shape--sometimes sigmoidal.
	Shore-parallel shoals (+ barrier islands)	Outer edge of sub-tidal flats in mesotidal regions.	5-1o	0.5-1	15	do.	Same as above	Enclosed by tidal flat and shelf mud, shore parallel, consistent limited size and shape.
	Delta front (sub-ice) channels	Offshore extensions of major distributaries.	20-30	2-4	5-15	Fine to very fine sand in thalweg, graded sand beds in overbank mud	Trough crossbedding graded sand beds with flat lamination, cross lamination in vertical sequence	Enclosed by graded overbank sand beds in mud, shore perpendicular, large-scale trough crossbeds in thalweg sand beds.
Pleistocene-Holocene Palimpsest	Leeside shoals	Lee of islands or peninsulas interrupting strong geostrophic bottom currents.	25-100	5-25	10-20	Very fine sand	Rhythmic flat laminations alternating with occasional thin ripple laminations	Enclosed by shelf sand and mud, orientation parallel to shelf currents not shoreline, widely varying shape and sise, very fine sand size with rythmic flat lamination interrupted by ripples.
	Ancient shoreline shoals	Shoreline deposits formed during still-stands of sea level.	15-30	3-7	10-15	Fine to medium sand inter-interrupted near surface by pebble lags and mud drapes	Alternating ripple and trough cross-lamination with high-angle foreset beds, bioturbation common	Enclosed by shelf sand and mud, parallel to ancient strandlines, high angle foresets interrupted by ripple and trough crosslamination, storm pebble and shell lags, bioturbation in lower and offshore sequences.
Pleistocene Relict	Morainal features	Glacial deposition during lowstands of sea level.	5-75	5-25	10-15	Medium-coarse sand and gravel	Rare trough cross-lamination and shell laminations	Enclosed by shelf sand and mud, size and shape variable, not shore parallel or perpendicular, coarse and variable grain size.

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Figure Captions

Figure 1. Location of sand bodies on the eastern Bering epicont inental shelf.

Figure 2. Physiographic, hydrographic, and textural characteristics of Kuskokwim Bay sand bodies.

Figure 3. General geology of Kuskokwim Bay sand bodies.

Figure 4. Seafloor bedforms and internal sedimentary structures of sand body deposits on Bering Shelf. See Fig. 1 for photo locations.

A. Boxcore slab from crest of Ukivok ancient shoreline shoal west of Port Clarence showing storm shell lags and clay drapes (31 m water depth).

B. Boxcore slab containing thick well-sorted transgressive lag gravel from shoreline stillstand at depth of 30 m off NW cape of St. Lawrence Island. Note faint crossbedding in center of cast.

C. Vibracore radiograph fran crest of 'Tin City shoal west of Port Clarence showing ripple lamination, foreset bedding and trough cross-lamination in a typical sequence (18 m water depth) .

D. Vibracore radiograph from leeside shoal north of Cape Prince of Wales (6 m water depth) showing rhythmic horizontal laminations and occasional ripple laminations.

E. BoxCore radiograph from Yukon leeside shoal northwest of Yukon Delta showing ripple lamination and foreset bedding (10 m water depth).

F. Vibracore radiograph from delta-front channel thalweg showing trough crossbedding off Yukon Delta (1 m water depth).

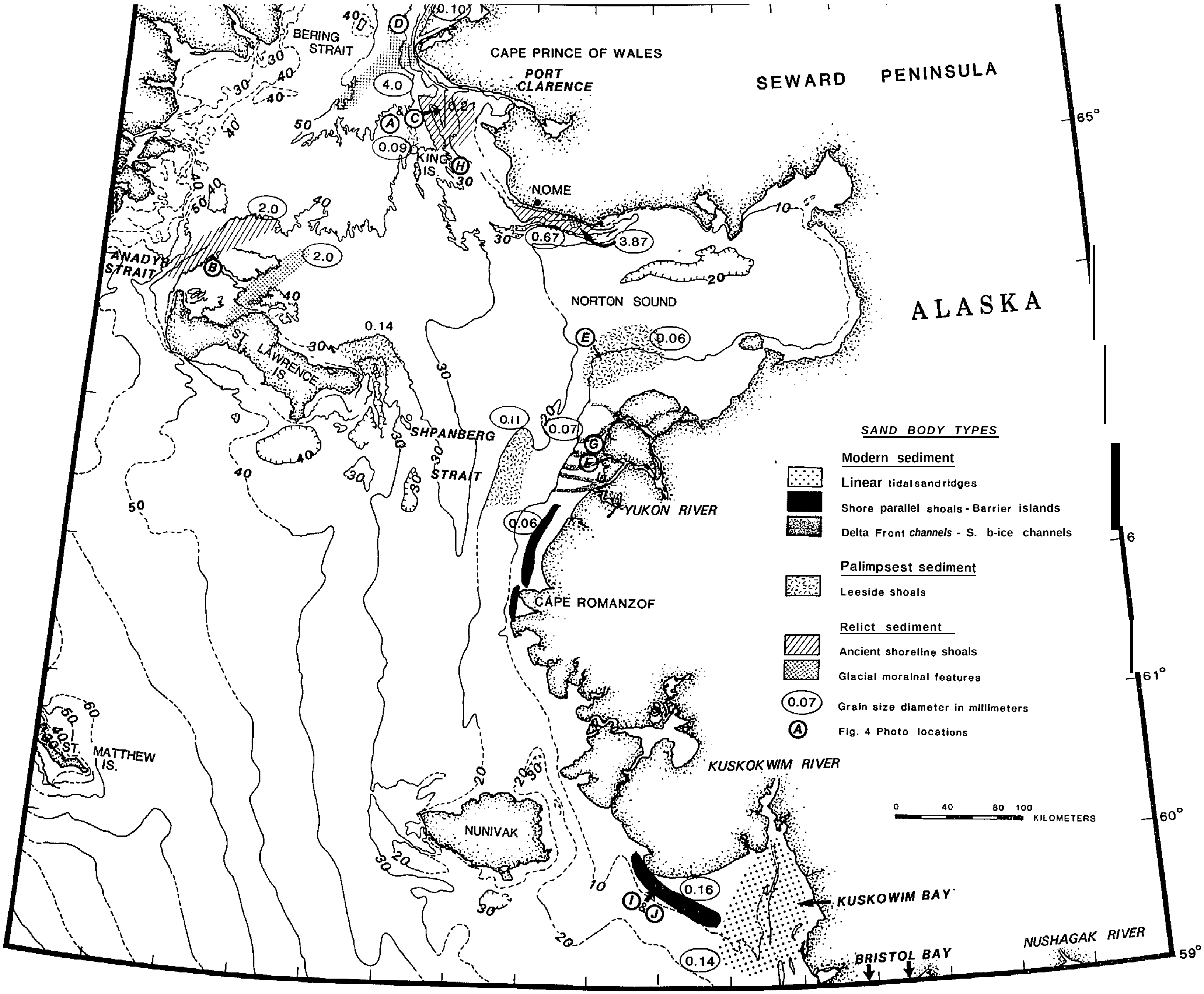
G. Photograph of vibracore epoxy peel from margin of delta front channel west of Yukon Delta showing a graded storm sand layer with a typical vertical sequence of flat, cross, and flat lamination from base to top of layer (1.5 m water depth).

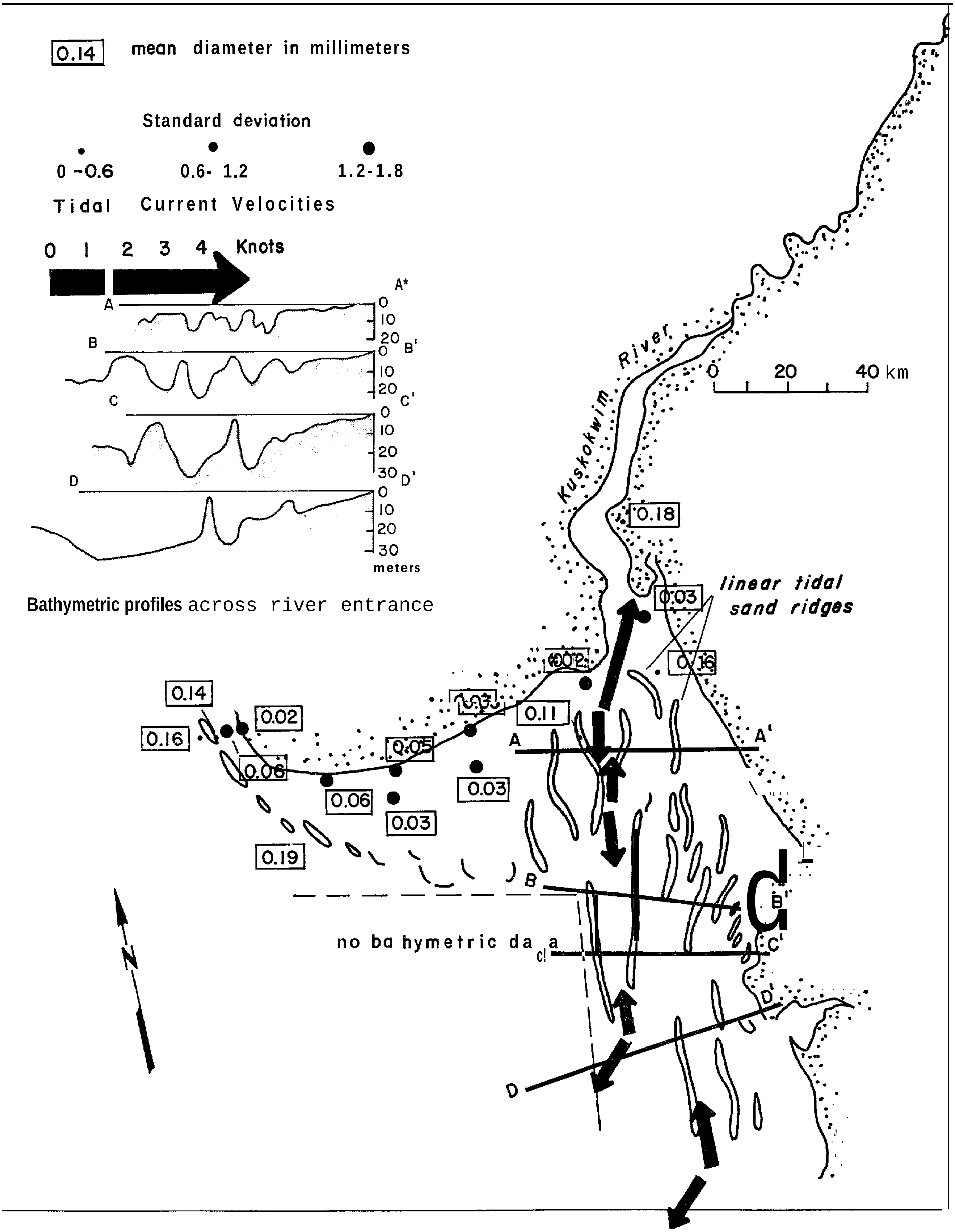
H. 70-mm bottom photograph of a small sand wave (0.5 m wave height and 10 m wavelength) with superimposed linguoid ripples on the crest of York shoal west of Port Clarence (17 m water depth).

I. Oblique aerial photograph of a shore-parallel shoal in northeast Kuskokwim Bay.. Note subdued cross sets of sand waves.

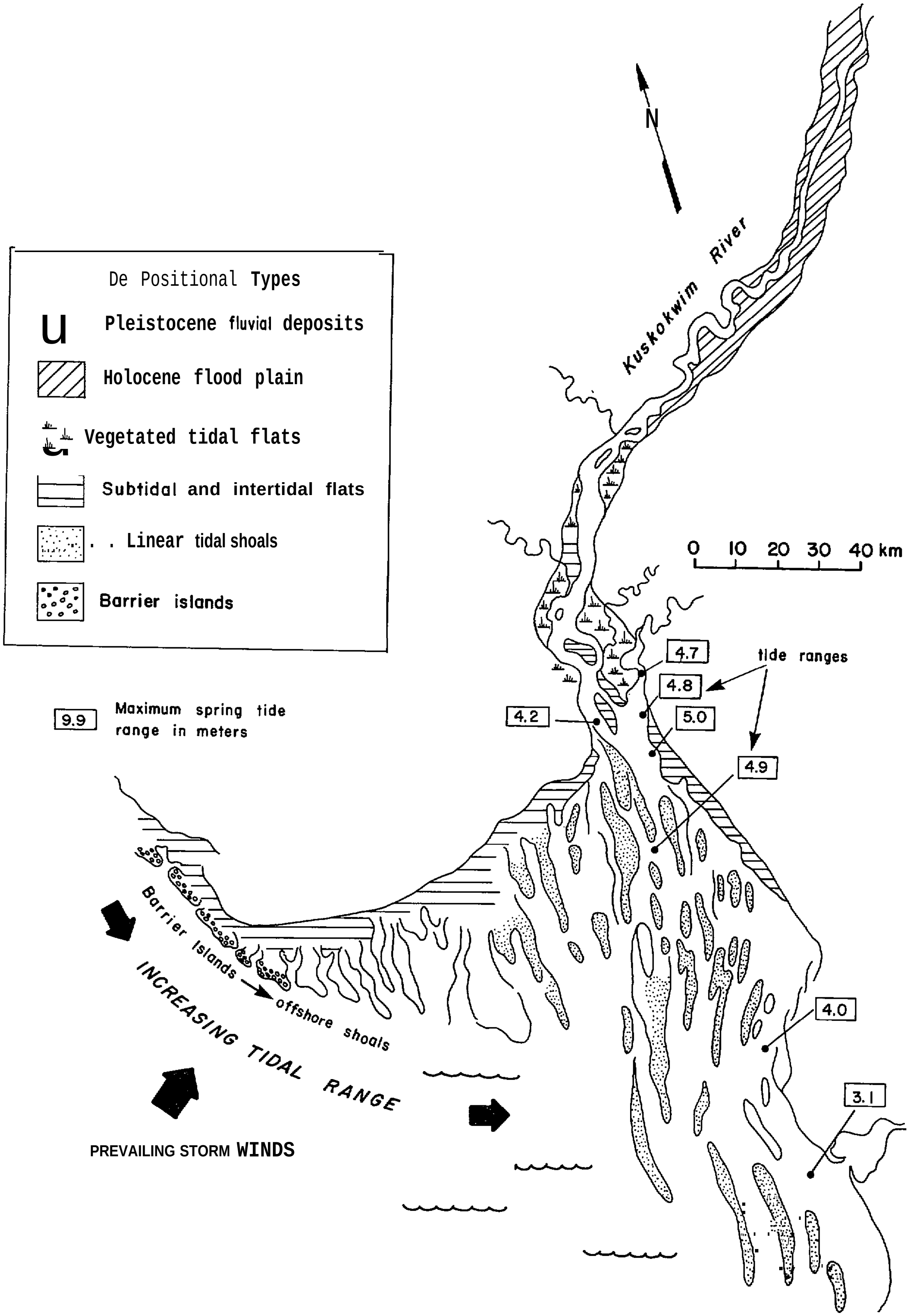
J. Ground-based photograph of ripples on a shore-parallel shoal in northwest Kuskokwim Bay.

Figure 5. Morphology texture, and bedforms of sand ridges near Bering Strait.

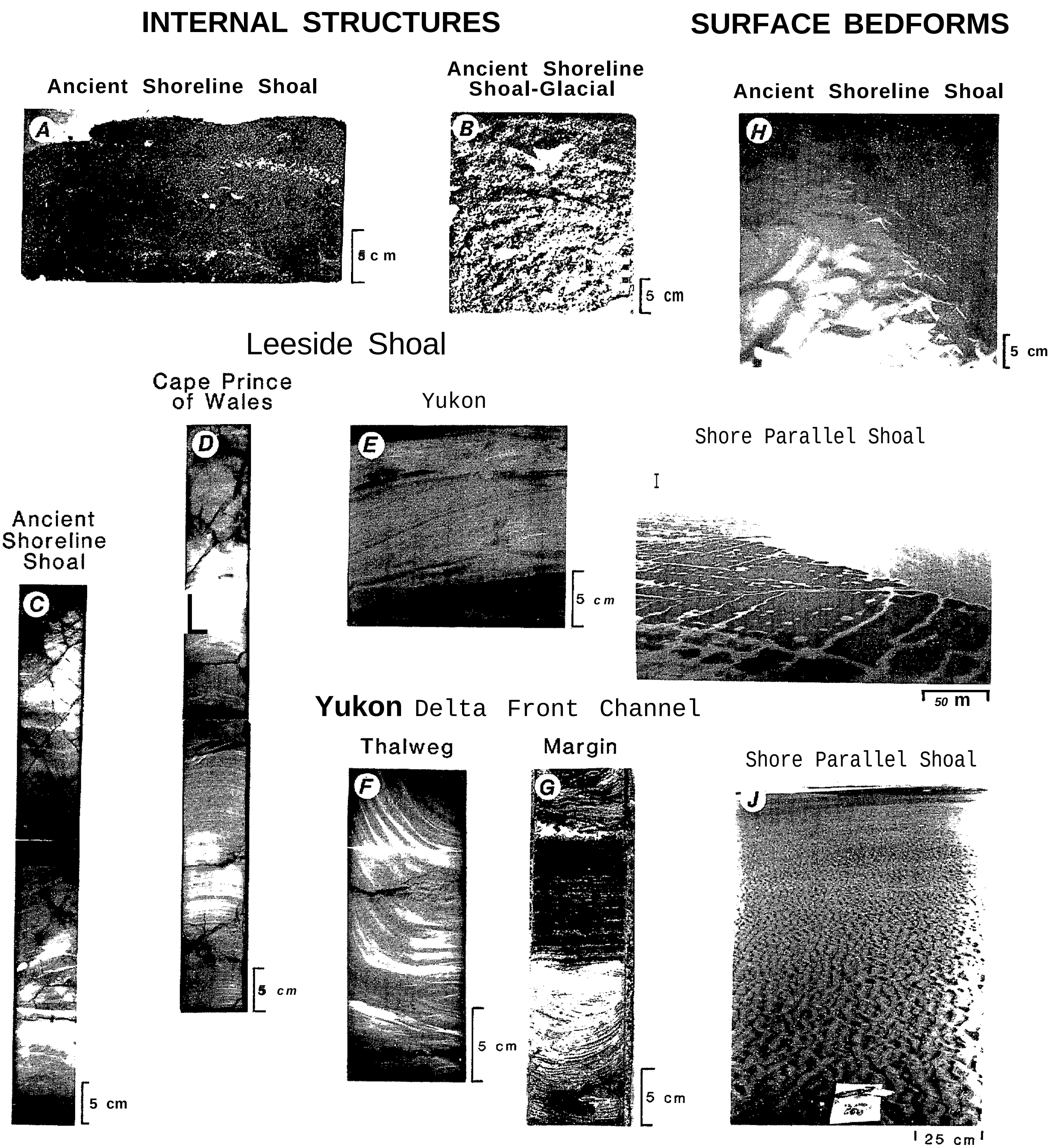

BERING STRAIT
CAPE PRINCE OF WALES
PORT CLARENCE
SEWARD PENINSULA
KING IS.
NOME
ANADYR STRAIT
NORTON SOUND
ALASKA
ST. LAWRENCE IS.
SHPANBERG STRAIT
YUKON RIVER
CAPE ROMANZOF
ST. MATTHEW IS.
NUNIVAK
KUSKOKWIM RIVER
KUSKOWIM BAY
BRISTOL BAY
NUSHAGAK RIVER
65°
61°
60°
59°
SAND BODY TYPES
Modern sediment
Linear tidal sand ridges
Shore parallel shoals - Barrier islands
Delta Front channels - S. b-ice channels
Palimpsest sediment
Leeside shoals
Relict sediment
Ancient shoreline shoals
Glacial morainal features
0.07 Grain size diameter in millimeters
A Fig. 4 Photo locations
0 40 80 100 KILOMETERS



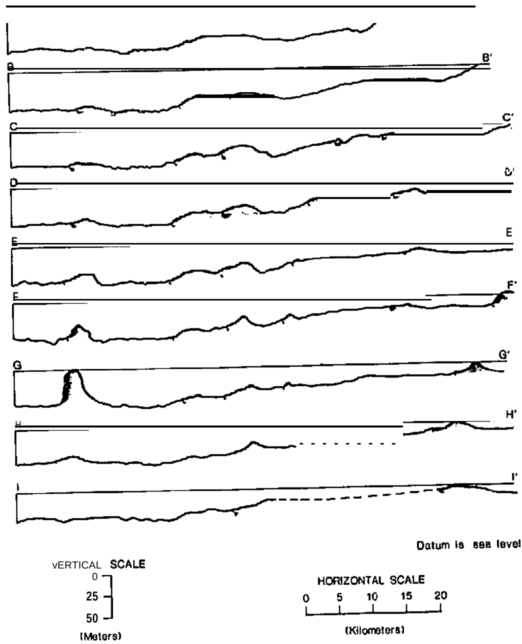
0.14 mean diameter in millimeters
Standard deviation
0 -0.6
0.6- 1.2
1.2-1.8
Tidal Current Velocities
0 1 2 3 4 Knots
Bathymetric profiles across river entrance
meters
Kuskokwim River
0 20 40 km
linear tidal sand ridges
no ba hymetric da a
N
0.18
0.03
0.02
0.16
0.11
0.14
0.16
0.02
0.06
0.05
0.06
0.03
0.03
0.19

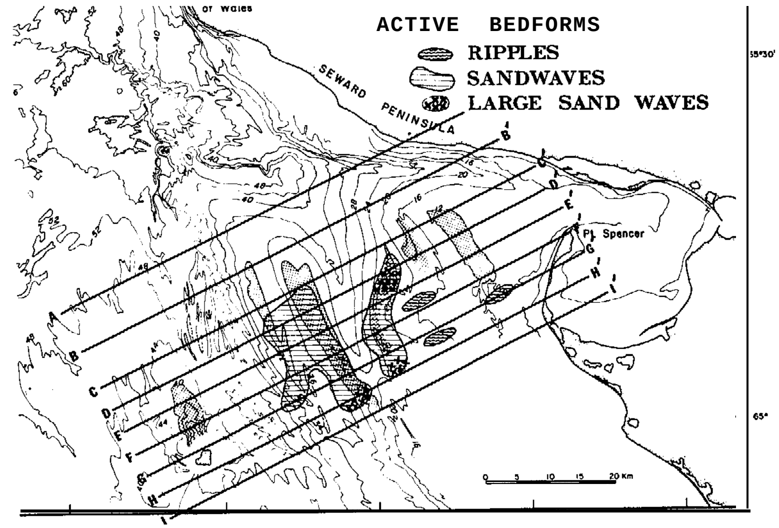


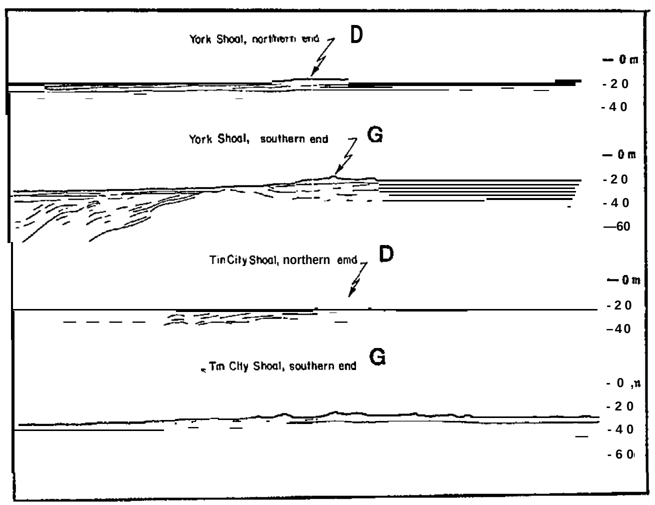
De Positional Types
U Pleistocene fluvial deposits
Holocene flood plain
Vegetated tidal flats
Subtidal and intertidal flats
. . Linear tidal shoals
Barrier islands
9.9 Maximum spring tide range in meters
N
Kuskokwim River
0 10 20 30 40 km
tide ranges
4.7
4.8
4.2
5.0
4.9
4.0
3.1
Barrier Islands
offshore shoals
INCREASING TIDAL RANGE
PREVAILING STORM WINDS



INTERNAL STRUCTURES
SURFACE BEDFORMS
Ancient Shoreline Shoal
A
5 cm
Ancient Shoreline Shoal-Glacial
B
5 cm
Ancient Shoreline Shoal
H
5 cm
Leeside Shoal
Cape Prince of Wales
D
5 cm
Yukon
E
5 cm
Ancient Shoreline Shoal
C
5 cm
Shore Parallel Shoal
I
50 m
Yukon Delta Front Channel
Thalweg
F
5 cm
Margin
G
5 cm
Shore Parallel Shoal
J
25 cm







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