

VARIATION IN SAND BODY TYPES ON THE EASTERN BERING SEA EPICONTINENTAL SHELF¹

C. HANS NELSON², WILLIAM DUPRÉ³, MICHAEL FIELD² & JAMES D. HOWARD⁴

ABSTRACT

Nelson, C. H., W. Dupré, M. Field & J. D. Howard 1982 Variation in sand body types on the eastern Bering Sea epicontinental shelf. In: C.H. Nelson & S. D. Nio (eds): The northeastern Bering shelf: new perspectives of epicontinental shelf processes and depositional products –Geol. Mijnbouw 61: 037-048.

The eastern 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 effect of the Holocene rise in sea level, have resulted in the formation of a complex assemblage of generally 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.

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 0.5-1 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 sandbeds and muds and are characterized by large to small-scale trough-cross lamination.

Lee side shoals, (25-100 by 5-25 km) form 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 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 modified from moraines are distinguished by their coarse grain size and irregular size and shape.

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 effect 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, lee side shoals, ancient shoreline shoals, and morainal features that may be more specific to the Bering Shelf.

The eastern Bering epicontinental shelf contains a combination of (1) modern sand bodies formed by present-day processes, (2) relict sand bodies formed under past condi-

¹ Nabyscript received: 1981-10-23

Revised manuscript received and accepted: 1982-01-08

² U.S. Geological Survey, Menlo Park, California 94025, U.S.A.

³ Dept. of Geology, University of Houston, Houston, Texas 77004, U.S.A.

⁴ Skidaway Inst. of Oceanography, Savannah, Georgia, U.S.A.

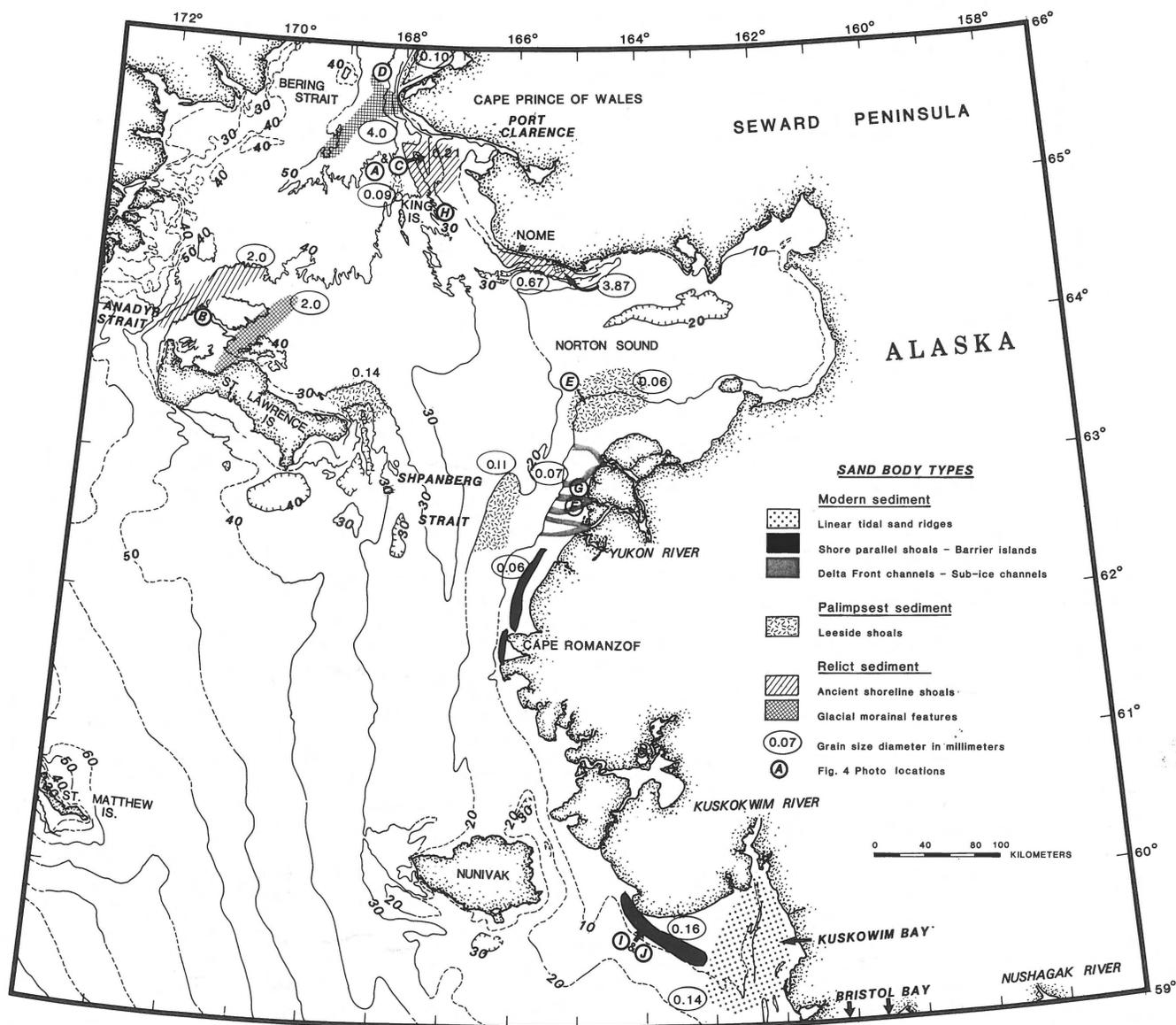


Fig. 1
Location of sand bodies on the eastern Bering epicontinental shelf.

tions, 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 to hydrocarbon exploration.

Methods

The morphology, geometry, and lithology of the sand bodies on the eastern 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. Grainsize distributions have been mapped vertically and horizontally using standard grain-size techniques, although the degree of detail varies in different locations. In some 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 from the south to the southwest 10-12 second periods and with heights of 10-

20 m are possible in the southern Bering Shelf, but maximum wave heights are only 7 m on the northern Bering Shelf (BROWER ET AL., 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 Seward Peninsula side of Bering Strait, bottom current speeds of over 200 cm/s occur (see figure 1 in NELSON 1982, this volume). In the constrictions of Anadyr and Shpanberg Straits, maximum current speeds are 100-150 cm/s. In Norton Sound even moderate storms have been observed to increase current speeds of the northward geostrophic flow from less than 30 to 70 cm/s (CACCHIONE & DRAKE, 1979).

Quaternary glaciations and sea level fluctuations on the northeastern 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 figure 4A in NELSON, 1982, this volume). Sea level stillstands accompanying the late Pleistocene-Holocene transgression remain as coast-parallel offshore bars (NELSON & HOPKINS, 1972; TAGG & GREENE, 1973). The stillstands are most apparent at depths of minus 10 to 12 m, 20 to 24 m, 30 m, and 38 m (see NELSON 1982, this volume). A complete transgressive history in northeastern Bering Sea is given in NELSON, 1982 (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 River provides $60-90 \times 10^6$ t, or 90% of the modern fluvial sediment introduced into the entire Bering Sea; the second largest source is the Kuskokwim River which yields nearly 4×10^6 t of sediment annually (DRAKE ET AL., 1980; LISITSYN, 1966).

TIDAL SAND RIDGES

Linear tidal sand ridges generally form in structurally subsiding macrotidal (> 4 m) embayments (HAYES, 1975) which is the setting for Kuskokwim Bay (Fig. 1). Tidal sand ridges are best developed in the bay at the mouth and offshore from the Kuskokwim River but they 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 30 m, offshore (Fig. 2). Some of the Kuskokwim tidal sand ridges, 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 flank the inshore side of ridges and consist of very poorly

sorted silt (Fig. 3). Limited observations of bedforms on ridge surfaces reveal sand waves of about 50 m wavelength with superimposed current ripples. The only internal structures observed in shallow trenches cut into the emergent ridges were horizontal parallel laminations.

Preservation of internal structures of large-scale bedforms in Kuskokwim Bay tidal ridges is limited to parallel lamination. This is similar to observations on the ebb dominated side of the tidal sand ridges of the Oosterschelde Estuary in the Netherlands (NIO ET AL, 1979).

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 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 an increase in tidal range, the maximum being 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. It 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 & WRIGHT (1978).

Most sand ridges in Kuskokwim Bay appear to be formed by present-day tidal reworking of bay sand introduced now or at past low sea levels by the Kuskokwim River. Some of the sand bodies farthest offshore may have formed during intervals of lowered sea level and thus may be palimpsests or relict features like the 'moribund' sand ridges described by KENYON ET AL (1979). The sand ridges in the nearshore regions of the bay are less parallel to the main N-S trend, smaller in size, and more closely spaced than 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 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.

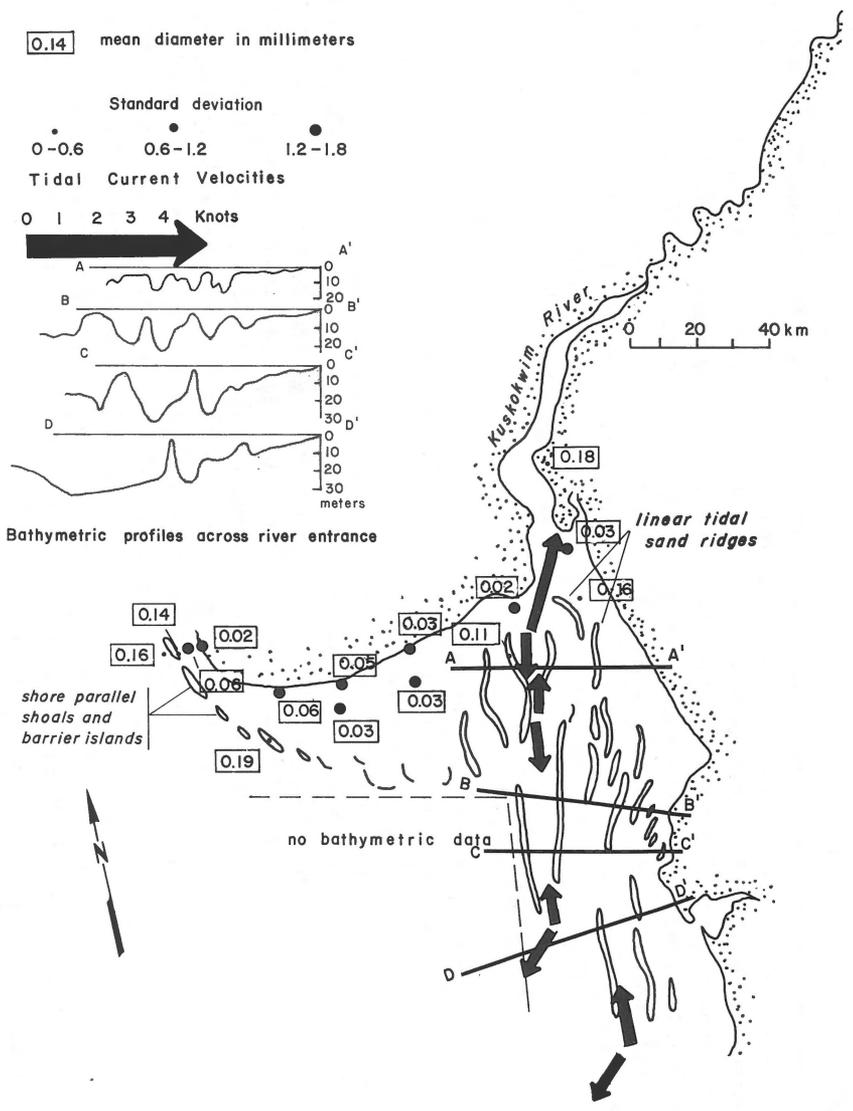


Fig. 2
 Physiographic, hydrographic, and textural characteristics of Kuskokwim Bay sand bodies.

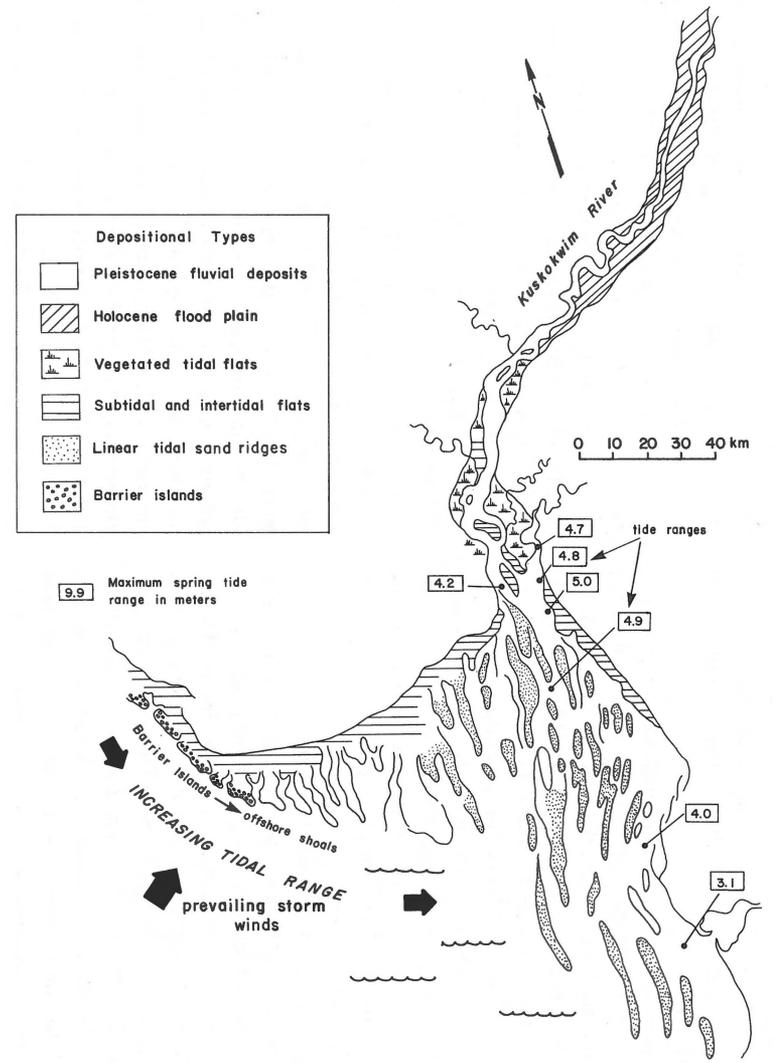


Fig. 3
 General geology of Kuskokwim Bay sand bodies.

The shore-parallel shoals (including barrier islands) in Kuskokwim Bay are 5 to 10 km long, 0.5 to 1 km wide, and the bathymetry suggests as much as 15 m of relief above the adjacent seafloor. Like the tidal ridges, the shore-parallel shoals are characterized by well-sorted fine sand (Fig. 2) and they pass laterally into 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-I).

The sand waves, although planed to small amplitudes, are covered by sets of divergently oriented ripples that were formed by diversely oriented nearshore waves and tidal currents. The only internal sedimentary structures of these ephemeral ripples and sand waves observed are parallel laminations.

The shore-parallel sand bodies and barrier islands form in equilibrium with the dominant south-southwest wave energy and the mesotidal setting in the western Kuskokwim Bay (BROWER ET AL., 1977). Emergent barrier islands grade eastward to submergent shoals where there is an increase in tidal range, barrier islands decrease in length, tidal channels become more numerous and 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; NUMMEDAL, 1979). 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 & WRIGHT, 1978)

DELTA FRONT (OR SUB-ICE) CHANNELS

The Yukon river at its mouth, in contrast to the funnel shaped estuary of the nearby Kuskokwim River, has a constructional, lobate delta with low wave energy and tidal range (Fig 1) (BROWER ET AL. 1977). Subaqueous channels that extend 30 km offshore from major distributaries of the delta (see figure 5 in DUPRÉ, 1982, this volume) 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. Actively filling channels are not found off the northern and eastern margins of the modern Yukon subdelta. These graded sand beds in the upper sequence of channel fill are only a few centimeters thick.

Large-scale megaripples as observed by sidescan sonar on the floor of active subaqueous channels appear to be represented by large-scale, moderately dipping crossbedding (20°) seen in unoriented vibracores of 2 m penetration (Fig. 4-F). Subaqueous point bar sequences presently form in meandering sub-ice channels. They consist of trough cross-laminated sand and they fine upward into interbedded graded silt beds in mud. In the graded sand and silt beds of upper channel fill and levees, 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 in the individual graded beds, the basal flat-laminated portion may be replaced by mainly trough cross-laminated or ripple-laminated units with thin, flat-laminated upper parts. The well-sorted sand of subaqueous distributary channels is thus enclosed in thinner sand and mud overbank deposits.

Sand progradation into the channels may take place as a part of river flood stage deposition and/or storm surge processes (DUPRÉ, 1982, this volume; NELSON, in press). The associated overbank and upper channel fill of graded sand beds appears to be the product of storm surge progradation of sand caused by rapidly waning strong ebb flow currents coupled with cyclic wave loading and sediment liquefaction (NELSON, in press).

LEE SIDE SHOALS

Lee side shoals are large accumulations of sand, not always linear, that are deposited in the current lee behind land barriers that interrupt continuous, strong geostrophic current flows in the northern Bering Sea (see figure 1 in NELSON, 1982, 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 Romazof, the Yukon Delta, and northwest of Cape Prince of Wales (Fig. 1). Lee side shoals also form in the north lee of King and St. Lawrence islands which obstruct the strong northerly water circulation (Fig. 1).

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

The grain size of the lee side shoal in all settings is very fine sand that does not exhibit large scale bedforms (MIDDLETON & SOUTHARD, 1977; LARSEN ET AL, 1979) (Fig. 1); 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 mainly flat laminations interrupted occasionally by ripple laminations (Fig. 4-D). The lee side shoal north of the Yukon Delta (Fig. 1) exhibits well-developed alternating layers of crossbedded and flat laminated sand (see figure 2 in HOWARD & NELSON, 1982, this volume). Large-scale tabular foresets also are found on the northern edge of this sand body (Fig. 4-B).

Sediment deposition apparently results from flow separation on the lee side of obstructions where strong upstream currents suddenly slack and drop their entrained sediment load (MIDDLETON & SOUTHARD, 1977). Each setting for lee side sand body development has a commonality of constricted strong upstream current flow. The consistent disruption of the unidirectional flow results in upbuilding of major sand bodies in the downstream lee of the obstruction.

The sediment source for lee side 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 lee side shoal is believed to be the southern Seward Peninsula beaches between Cape Prince of Wales and Port Clarence. The lack of very fine sand (< 5% at 8 stations) there, but presence in the lee side shoal (Fig. 1) and the beach on the north side of Cape Prince of Wales (97% at 6 stations) suggest the following hypothesis.

The very fine sand fraction normally found in beaches of this region, which elsewhere is moved into offshore bars during storm events, apparently is entrained and carried northward through the Bering Strait by the geostrophic current. Large plumes of fine sand have been photographed bypassing Cape Prince of Wales during storms. Because of flow separation on the lee side north of Cape Prince of Wales,

the very fine sand entrained from beaches and the shelf to the south is deposited north of the Cape in the large lee side shoal.

The lee side shoal north of the modern Yukon Delta contains very fine sand derived from the southwest distributary that is the main discharge point of the Yukon River (DUPRÉ, 1982, this volume). This southwest distributary is located in the maximum current shear region of eastern Shpanberg Strait (see figure 1 of NELSON, 1982, this volume), where strong geostrophic currents are located. These currents entrain the deltaic sediment and deposit the sand in the lee side shoal located 30-130 km north and east of the main river discharge point (see figure 5 in DUPRÉ, 1982, this volume). Apparently, in this more complex delta setting, the lee side shoal develops a non-linear fan shape and contains a wider variety of internal sedimentary structures (Fig. 4-E and figure 2 in HOWARD & NELSON, 1982, this volume).

ANCIENT SHORELINE SHOALS

Many areas of the Bering shelf are marked by well-developed fields of linear sand bodies formed at 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 minus 10-12, 20-24, 30, and 38 m (Fig. 5). A well-defined linear field of ridges at similar water depths exists off Nome (NELSON & HOPKINS, 1972; HOPKINS, 1973; TAGG & 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 mentioned above occur in Chirikov Basin, an area where detailed studies of ancient beaches have been possible because strong currents have prevented their burial by post-Holocene deposition (NELSON & HOPKINS, 1972; MCMANUS ET AL, 1974; NELSON, 1982, this volume).

The sand bodies formed by ancient shoreline shoals are 15

Fig. 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 from crest of Tin City Shoal west of Port Clarence showing ripple lamination, foreset bedding and through cross-lamination in a typical sequence (18 m water depth).
- D. Vibracore radiograph from lee side shoal north of Cape Prince of Wales (6 m water depth) showing rhythmic horizontal laminations and occasional ripple laminations.
- E. Boxcore radiograph from Yukon lee side 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 northwest Kuskokwim Bay.

to 30 km long, 3 to 7 km wide, and 10 to 15m in relief. Vibracoring has sampled the sand ridges off Port Clarence to a depth of 6m and they are composed of well-sorted fine to medium sand (Figs. 1 and 5). Troughs between the sand ridges are made up of very fine sand and silt (Fig. 5). Near Nome and northwest of St. Lawrence Island, the ancient shoreline features have been incised into pebbly, sandy glacial till (NELSON & HOPKINS, 1972; see figure 4 in NELSON, 1982, 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 ET AL., 1978; FIELD ET AL., 1981) Superimposed on these are smaller slightly oblique sand waves that have wavelengths up to 10 m and heights of up

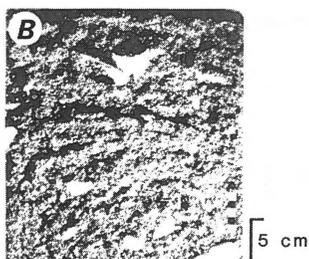
INTERNAL STRUCTURES

SURFACE BEDFORMS

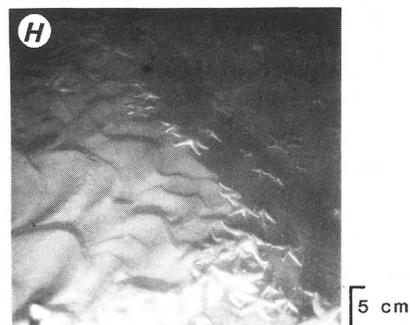
Ancient Shoreline Shoal



Ancient Shoreline Shoal-Glacial

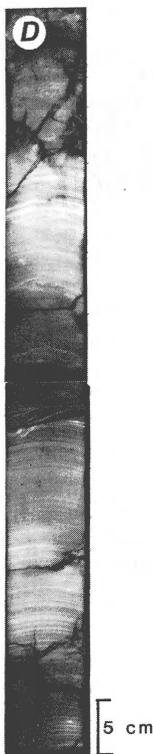


Ancient Shoreline Shoal

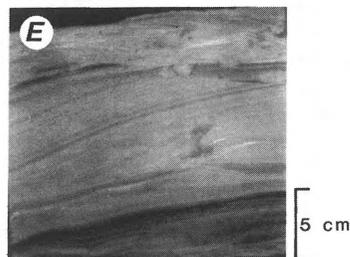


Leeside Shoal

Cape Prince of Wales



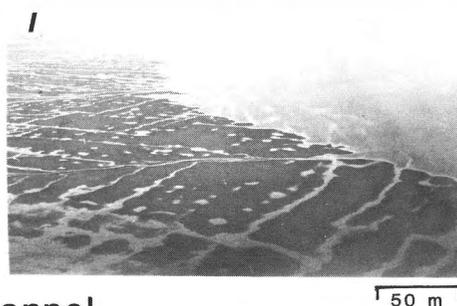
Yukon



Ancient Shoreline Shoal

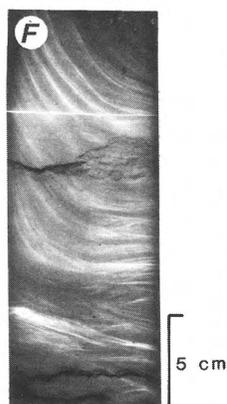


Shore Parallel Shoal

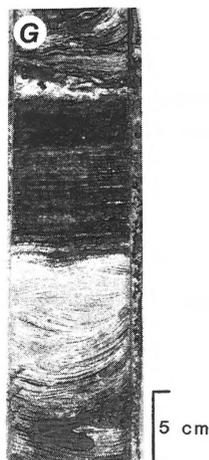


Yukon Delta Front Channel

Thalweg



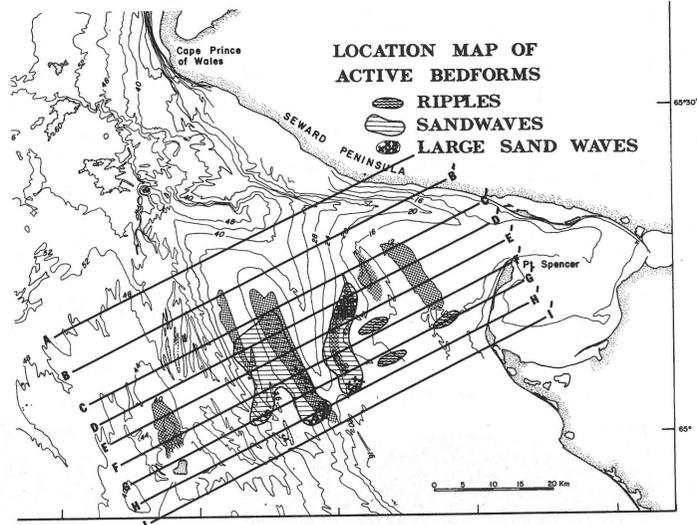
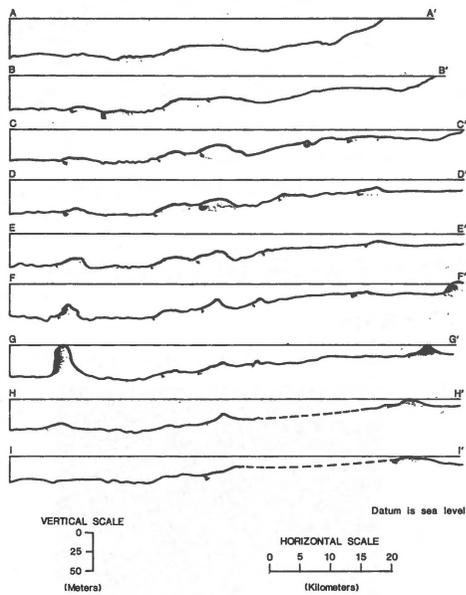
Margin



Shore Parallel Shoal



BATHYMETRIC PROFILES



SEDIMENT DISTRIBUTION

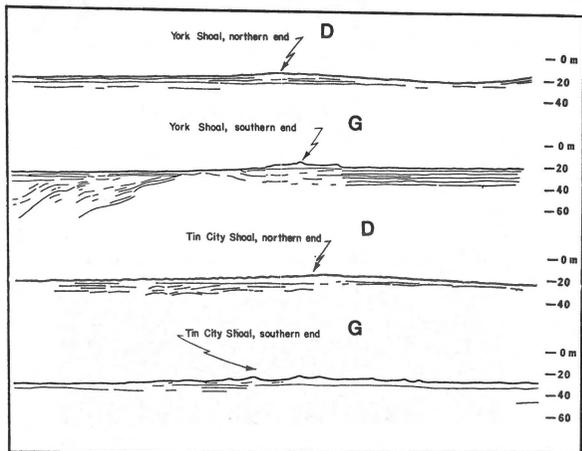
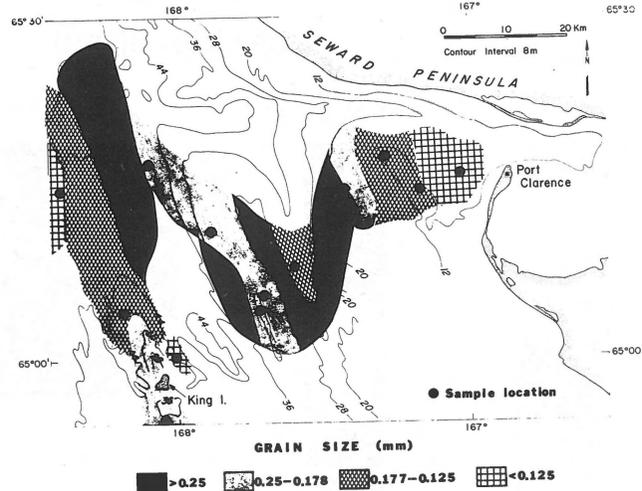


Fig. 5 Morphology, texture, and bedforms of sand ridges near Bering Strait. Seismic profiles in southwest quadrant on profile lines D and G show reflection of Tertiary bedrock overlain by constructional lenses of ancient shoreline shoals.

to 0.5 m. Linguoid ripples with wavelengths of 10-30 cm and 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. (FIELD ET AL.; 1981). 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 ET AL., 1982, this volume). The region of the large, linear ridge west of St. Lawrence Island also has mobile bedforms (NELSON ET AL., 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 tabular 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 figure 5 in NELSON, 1982, 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 deposited 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. 5 F-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 lee side shoals (very fine sand) in Chirikov Basin (Fig. 1) (see figures 3 and 6 of NELSON, 1982, 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, 1982, 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 & HOPKINS, 1972; HOPKINS, 1973).

Many areas of the U.S. Atlantic shelf characterized by similar fields of linear sand ridges (DUANE ET AL, 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 & FIELD, 1981).

GLACIAL MORAINES

A few large bodies of sand and gravel deposited by ancient glacial activity remain uncovered 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 Nome (Fig. 1) (NELSON & HOPKINS, 1972). Coarse sand and gravel ridges, 75 km long and 25 km wide, extend southward from Cape Prince of Wales toward the center of Chirikov Basin and northward from St. Lawrence Island towards the same point. The two ridges are traceable as the ends of major moraines of continental glaciers that moved southward into Chirikov Basin Siberia (see figure

4 in NELSON, 1982, this volume; GRIM & MCMANUS, 1970; NELSON & HOPKINS, 1972).

The glacial features in general are coarser grained than the other shoals of the eastern Bering continental shelf (Fig. 1). Because it is difficult to sample, we have not been able to observe internal sedimentary structures, except for rare cross lamination noted in near surface gravels that apparently have been reworked by storm-related currents (NELSON ET AL., 1981).

The origin of glacial features is deduced from seismic profiling, drilling, and correlative land mapping (GRIM & MCMANUS, 1972; NELSON & HOPKINS, 1972; TAGG & GREEN, 1973). Preservation of these features on the sea floor is attributed to their location in areas of strong bottom currents that have prevented burial by Holocene transgressive deposition (NELSON, 1982, this volume).

SAND BODY GENESIS

Hydrographic and sedimentary processes and Holocene history vary from south to the north on the eastern Bering epicontinental shelf and consequently the genesis and the age of shelf sand bodies vary according to geographic location. Toward the southeast, tidal currents and wave energy dominate sedimentation, whereas in the northeastern shelf area, the glacial effects 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. The sand bodies in the southeastern shelf are modern features derived from sediment supplied 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 & 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, 1982, this volume).

In contrast with the Yukon Kuskokwim Delta area, sand and gravel bodies in the northeastern Bering shelf are the result either of relict or palimpsest deposition. The lee side sand bodies, however, probably accumulated both during the present Holocene high sea level and other Pleistocene highstands. Seismic reflection profiles over the north end of the lee side shoal in east-central Shpanberg Strait and the shoal north of the Yukon Delta show significant Holocene

Table I.
Characteristics of Bering Shelf Sand Bodies

AGE	TYPE	ENVIRONMENT OF DEPOSITION	LENGTH (KM)	WIDTH (KM)	RELIEF (M)	LITHOLOGY	SEDIMENTARY STRUCTURES	DISTINGUISHING FEATURES
	Linear tidal sand ridges	Macrotidal funnelshaped 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 subtidal flats in mesotidal regions	5-10	0.5-1	15	Fine sand	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 cross-bedding 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
	Lee side 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 size, very fine sand size with rhythmic flat lamination interrupted by ripples.
	Ancient shoreline shoals	Shoreline deposits formed during stillstands of sea level.	15-30	3-7	10-15	Fine to medium sand 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.
	Morainial features	Glacial deposition during lowstands of sea level.	5-75	5-25	10-15	Medium coarse sand and gravel	Rare trough crosslamination and shell laminations	Enclosed by shelf sand and mud, size and shape variable, not shore parallel or perpendicular, coarse and variable grain size.

deposition (see figure 4 in NELSON, 1982, this volume). Profiles over other lee side shoals indicate several episodes of deposition. These sedimentation episodes most likely occurred during several past high sea level stages that are necessary for lee side shoal depositional mechanisms. The consistent lithology of very fine sand and rhythmic flat laminations indicates that flow separation in the lee of obstructions results in deposition of the suspended sand load from currents passing over the sand body. Ripple laminations and high-angle foreset beds in the lee side shoal north of the Yukon Delta perhaps show the influence of storm events and

progradation of this more complex sand body off the Yukon Delta front platform (NELSON, in press).

Unlike the lee side 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 strand lines during lower stands of sea level. The history of these ridges is complex; deposits formerly at a lower sea level are now being modified into active ripple and sand wave fields by present-day bottom currents (NELSON ET AL., 1978; FIELD ET AL; 1981). Mobile bedforms are further disrupted by pebble lags and mud drapes

formed during present-day storm events; thus, the resultant internal sedimentary structures in the near surface 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 other relict sand and gravel bodies deposited by glacial events.

GEOLOGIC SIGNIFICANCE OF SAND-BODY CHARACTERISTICS

The eastern Bering epicontinental shelf contains a wide variety of offshore and nearshore large (tens of kilometers), sand bodies. Nearshore and offshore sand bodies resemble one another in that they are composed of well-sorted fine sand and are typically linear, except for some of the lee side shoals and glacial features. They differ in that nearshore sand bodies orient with wave and tidal currents, but offshore sand bodies mainly follow trends of geostrophic currents or are relict.

Differences in shape, grain size, and internal sedimentary structures of this variety of sand bodies in the same area provide other distinctions that may help to differentiate similar ancient sand bodies (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; their local orientation may vary due to sinuosity of meanders in channel-fill bodies and sigmoidal shape in tidal ridges.

Lee side shoals are oriented parallel to shelf currents and are long and narrow where the current is dominantly unidirectional and strong, elsewhere, they may be more fan-shaped. Overall size varies quite markedly depending on the size of the adjacent land barrier, on flow magnitudes, and on the 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 other types. In contrast, lee side shoals consisting of very fine sand-because of deposition from the suspended sediment load of bottom currents-typically are the finest grained (Fig. 1). Ancient shoreline shoals are consistently coarser grained than deltaic or lee side deposits because of transport and deposition by littoral drift.

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. Lee side sand bodies, where uncomplicated by local deltaic and storm sand sedimentation, are characterized by consistent, rhythmic flat lamination (Fig. 4-C). The very fine grain size of sand making up lee side sand bodies inhibits development of large-scale crossbedding,

although storm induced ripple lamination 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 rhythmic thin bedded sands in overbank mud that encloses the sand body. These graded storm sand layers with characteristic vertical sequences of internal structure also may be associated as part of the fining upward channel-fill. High-angle foreset beds in cyclic sequences with ripple and trough cross-lamination help identify sand bodies stranded by eustatic rises of sea level, but reworked by mobile bedforms while submerged; similar sequences have been observed in ancient sand bodies in the same setting. (KITELEY & FIELD, 1980). Modification of ancient shoreline sand bodies, present-day mobile bedform fields, and bioturbation suggests that internal structures of the original beach formation processes may be modified in such sand bodies.

In reconstructing ancient broad, epicontinental shelf environments, researchers must realize that 1) sand-body types and genesis are 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).

ACKNOWLEDGMENTS

Devin Thor, along with the scientific staff and crews of the R/V SEA SOUNDER, assisted in field data collection. Matthew and Bradley Larsen provided figure compilations, radiography, and grain size analyses. Louise M. Kiteley and Hugh McLean gave constructive review comments.

The cruises were supported jointly by the U.S. Geological Survey and by the Bureau of Land Management through interagency agreement with the National Oceanic and Atmospheric Administration, under which a multi-year program responding to needs of petroleum development of the Alaska continental shelf is managed by the outer Continental Shelf Environmental Assessment Program (OCSEAP) Office.

REFERENCES

- Brower, W.A., Jr., H. W. Searly, J. L. Wise, H. F. Diaz & A. S. Prechtel. 1977 Climatic atlas of the outer continental shelf waters and coastal regions of Alaska 2-Bering Sea, Arctic Environmental Information and Data Centre, University of Alaska, National Climatic Centre, Environmental Information and Data Center, (Asheville, N.C.) and NOAA: 443 pp.
- Cacchione, D. A. & D. E. Drake 1979 Sediment transport in Norton Sound, Alaska: Regional patterns and GEOPROBE system measurements-U.S. Geol. Surv. Open-File Rep. 79-1555: 88 pp.

- Caston, V. N. D. 1972 Linear sand banks in the southern North Sea-Sedimentology 18: 63-78.
- Coleman, J.M. & L.D. Wright 1978 Sedimentation in an arid macrotidal alluvial river system: Ord River, Western Australia: - J. Geol. 86: 621-642.
- Drake, D. E., D. A. Cacchione, C. H. Nelson & R. D. Muench 1980 Sediment transport in Norton Sound, Alaska-Mar. Geol. 36: 97-126.
- Duane, D. B., M. E. Field, E. P. Meisburger & others 1972 Linear shoals on the Atlantic inner continental shelf, Long Island to Florida. In: D. J. P. Swift, and others(eds): Shelf sediment transport: Process and pattern Dowden, Hutchison and Ross (Stroudsburg, PA): 447-498.
- 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.
- Field, M. E. 1980 Sand bodies on coastal plain shelves: Holocene record of the U.S. Atlantic inner shelf off Maryland. J. Sed. Pet. 50: 505-528.
- Field, M. E., C. H. Nelson, D.A. Cacchione & D. E. Drake 1981 Sand waves on an epicontinental shelf: northern Bering Sea. In: C. A. Nittrouer (ed.): Sedimentary dynamics of continental shelves-Dowden & Hutchinson (Strasbourg, P. A): 48 pp.
- Grim, M. S. & D. A. McManus 1970 A Shallow-water seismic profiling survey of the northern Bering Sea Mar. Geol. 8: 293-320.
- Hayes, M. O. 1975 Morphology of sand accumulation in estuaries. In: L. E. Cronin, Estuarine Research, Geology and Engineering-Academic Press (New York) 2: 3-22.
- Hopkins, D. M. 1973 Sea level history in Beringia during the past 250,000 years-Quat. Res. 3: 520-540.
- Howard, J. D. & C. H. Nelson 1982 Sedimentary structures on a delta-influenced shallow shelf, Norton Sound, Alaska. In: C. H. Nelson & S. D. Nio (eds): The northeastern Bering shelf: new perspectives of epicontinental shelf processes and depositional products - Geol. Mijnbouw 61: 029-036.
- Hunter, R., D. R. Thor & M. L. Swisher 1982 Depositional and erosional features of the inner shelf, 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: 049-062.
- Kenyon, H., R. H. Belderson, A. H. Stride & M. A. Johnson 1979 Longitudinal tidal sand banks of north European Seas. In: Internat. Assoc. Sedimentol., Internat. Mtg on Holocene marine sedimentation in the North Sea Basin, 49 (Abstr):
- Kitely, L. W. & M. E. Field 1980 Patterns of shallow marine deposition, Upper Cretaceous of northern Colorado - Am Assoc. Pet. Geol. Bull. 64-733.
- Larsen, M.C., C. H. Nelson & D. R. Thor 1979 Geologic implications and potential hazards of scour depressions on Bering shelf, Alaska-Environ. Geol., 3: 39-47.
- Lisitsyn, A. P. 1966 Recent sedimentation in the Bering Sea - U.S.S.R. Academy of Science, Institute of Oceanology (English transl.: Israel Program for Scientific Translations 1969: 614 pp.
- McManus, D. A., K. Venkatarathnam, D. M. Hopkins & C. H. Nelson 1974 Yukon River sediment on the northernmost Bering Sea shelf - J. Sed. Pet. 44: 1052-1060.
- Middleton, G. V. & J. B. Southard 1977 Mechanics of sediment movement. Lecture notes for short course no. 3, Soc. Econ. Paleontol. Mineral. Eastern Section - (Binghamton, N. Y.) Soc. Econ. Paleontol. Mineral: 192 pp.
- Nelson, C. H. 1982 Late Pleistocene-Holocene transgressive sedimentation in deltaic and non-deltaic areas of the northeastern Bering epicontinental shelf. In: C. H. Nelson & S. D. Nio (eds): The northeastern Bering shelf: new perspectives of epicontinental shelf processes and depositional products - Geol. Mijnbouw 61: 005-018.
- Nelson, C. H. (in press) Modern shallow-water graded sand layers from storm surge processes on Bering Shelf: A mimic of Bouma sequences and turbidite systems- J. Sed. Pet. 52:
- Nelson, C. H., D. A. Cacchione, D. E. Drake & M.E. Field, 1978 Areas of active large-scale sand wave and ripple fields with scour potential on the Norton Basin seafloor. In: Environmental assessment of the Alaskan Continental Shelf, Annual reports of the principal investigators- U. S. Dept. of Commerce, NOAA, OCSEAP (Boulder, CO) 12: 291-307.
- Nelson, C.H., R.W. Rowland, S.W. Stoker & B. R. Larsen 1981 Interplay of Physical and biological sedimentary structures. In: D. W. Hood (ed.): The Eastern Bering Shelf: Its Oceanography and Resources - US. Dept. of Commerce NOAA: 625 pp.
- Nelson, C. H. & D. M. Hopkins 1972 Sedimentary processes and distribution of particulate gold in northern Bering Sea - U.S. Geol. Surv. Prof. Pap. 689: 27 pp.
- Nio, S. D., J. H. Van den Berg & C. Siegenthaler 1979 Excursion guide to the Oosterschelde Basin, southwest Netherlands; an example of Holocene tidal sedimentation. In: Internat. Assoc. Sedimentol., Intern. Mtg on Holocene marine sedimentation in the North Sea Basin: Guidebook for excursions: 9-35.
- Nummedal, D. 1979 Tidal inlet sediment dispersal along the German North Sea coast. Internat. Assoc. Sedimentol., Internat. Mtg on Holocene marine sedimentation in the North Sea Basin (Abstr): 2.
- Swift, D. J. P. & M. E. Field (1981) Evolution of a classic sand ridge field: Maryland sector North American inner shelf-Sedimentology 28: 461 - 482.
- Tagg, A. R. & H. G. Greene 1973 High-resolution seismic survey of a nearshore area, Nome, Alaska-U.S. Geol. Surv. Prof. Pap. 759-A: 23 pp.
- U.S. Dept. of Commerce, National Oceanic and Atmospheric Administration 1977 Tide Tables, 1977, west coast of North and South America. National Ocean Survey.