Graded Storm Sand Layers Offshore from the Yukon Delta, Alaska

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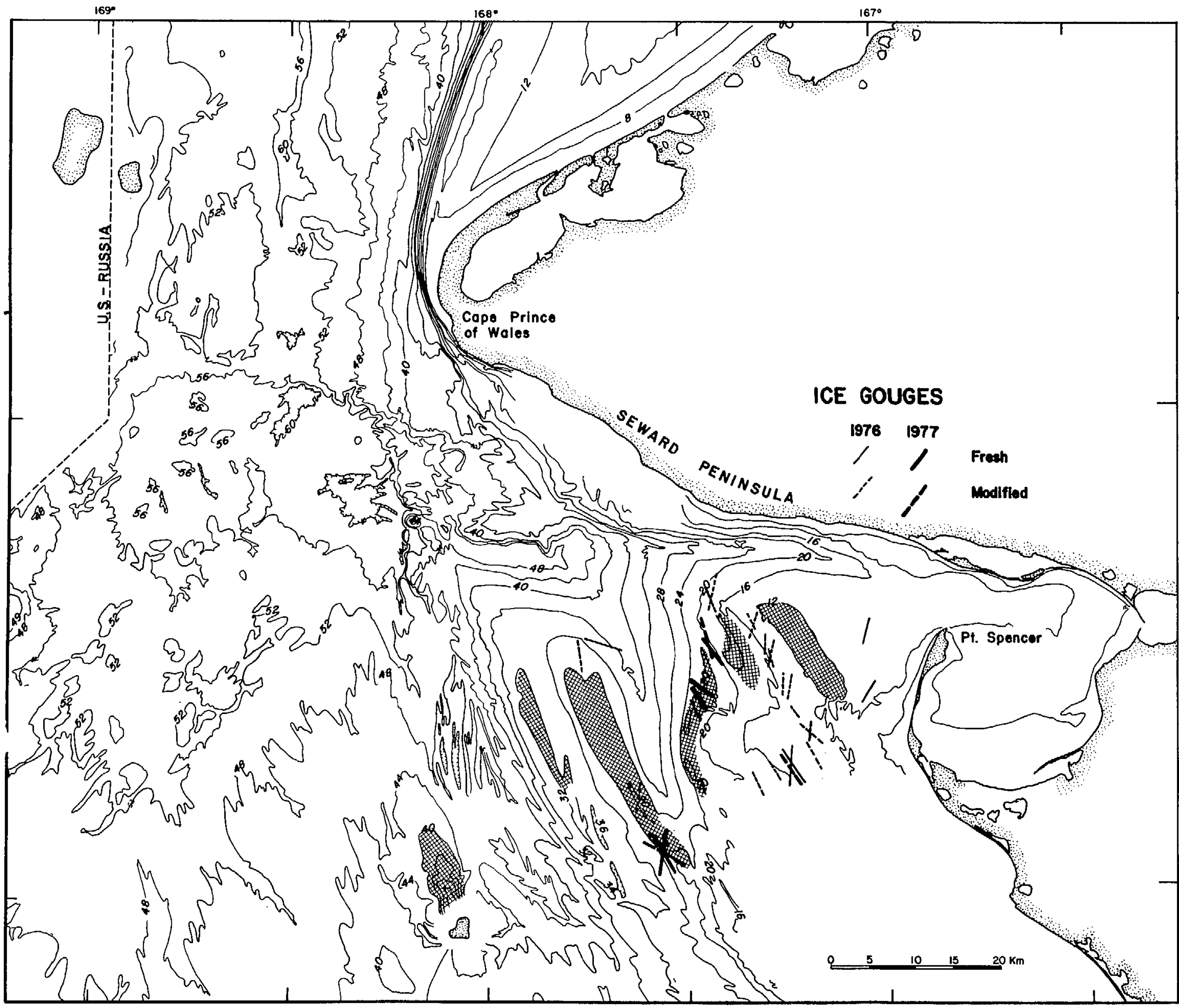
Introduction

The northern Bering Sea has a history of severe storm surges. The most recent, and perhaps the worst in historical times, occurred in November, 1974 (Fathauer, 1975). Evidence of storm surge events is exhibited in sea-floor stratigraphy as well as shoreline flooding and indicates that significant widespread changes in sea-floor sedimentation take place (Nelson and Creager, 1977). These changes have implications for installations on the sea floor and for mass transport of pollutants.

This paper describes the interbedded sand layers found in southern Norton Sound off the modern Yukon Delta that are deposited by the storm surge events. Such deposits are evident in both modern and ancient deposits of epicontinental shelves (Hays, 1967; Howard and Reineck, in press; Anderton, 1976). These graded sand layers in very shallow water mimic many of the features of thin-bedded turbidite sands, although the shallow water deposits are thought to have a very different mechanism of deposition related to storm surge processes.

Two factors in the oceanographic setting of northern Bering Sea magnify the effects of storm surge. The sea floor is very shallow (less than 20 m deep over wide areas) particularly in Norton Sound. Consequently there is intensive wave reworking which causes extensive sea-floor erosion, mass movement, displacement, and offshore progradation of significant amounts of sediment during storm surges.' The second factor 1S a system of strong dynamic bottom currents that can move large amounts of sediment northward to Chukchi Sea during normal weather. Much more sediment is moved when the current is reinforced by relaxing of the sea surface set-up caused by storm surge


ICE GOUGES
1976
1977
Fresh
Modified
SEWARD PENINSULA
Cape Prince of Wales
Pt. Spencer
U.S. - RUSSIA
169°
168°
167°
65°30'
65°
0 5 10 15 20 Km

(Fig. 1) (Fleming and Heggarty, 1966; Coachman et al., 1976; Cacchione and Drake, 1979; Schumacher and Tripp, 1979).

Another important influence on the sedimentation in southern Norton Sound is the effect of seasonal processes on the Yukon River delta. During the winter months from November to May the Yukon River averages 40,000 cfs when the ice-covered river is fed mainly by base flow (Dupré, 1976). Within less than a week of river breakup, peak discharges may reach 1,000,000 cfs or more and then decline throughout the summer.

Characteristics of Graded Sand Storm layers

Over 10,000 km^2 of southern Norton Sound display graded sand layers interbedded with silty mud. This paper focuses on the prominent interbedded very fine sand and coarse silt layers that show definite vertical size gradation of grain size and sedimentary structures. In addition to the vertical gradation within individual beds, there are lateral gradations in grain size, thickness of layers, and sedimentary structures for the complete system of beds from onshore to offshore. Vertical grading and areal gradations are found in a common surface sand layer throughout southern Norton Sound. Graded sand layers in the subsurface at each location are like the surface layer (Fig. 2) (Larsen et al. 1980). Patterns of grain size and layer thickness also vary areally from west to east across the front of the Yukon delta.

Onshore to offshore, the graded sand beds become finer grained and thinner, contain a smaller percentage of graded sand layers, and show less complete sequences of vertical sedimentary structures (Figs. 3 and 4). Inshore the graded sand layers make up 50-100 percent of the total sedimentary section (Fig. 3); they range from 10-20 cm thick and the basal part of the layer is made up of fine-grained sand (Fig. 5). Approximately 60-75 km from the Yukon Delta shoreline, the graded sands are generally I-2 cm thick, less than 35 percent of the total section, and the base of the layers is composed of very fine sand or coarse silt (Figs. 2-5).

The graded layers typically contain a vertical sequence of sedimentary structures (S_b-S_e, see Fig. 5). The base of a layer may or may not contain flat-laminated medium to fine sand (S_b). In the center section of a sand layer, cross lamination and convolute lamination are dominant (S_c). In the upper part of the layer, in the very fine sand or coarse silt, flat lamination again predominates and often laminated beds of epiclastic plant fragments become very prominent (S_d). The upper flat-laminated sequence of the individual sand beds grades into normal, continuous mud deposition (S_e) in most instances, although this mud cap may be lacking.

Going from nearshore to offshore, there is a less complete sequence of vertical structures in graded sand layers (Figs. 3 and 5). In the nearshore graded layers lower (S_b) flat lamination is often present whereas in distal layers, flat lamination at the base is not encountered (Figs 3 and 5). In addition, in the most distal layers, occasionally both the lower flat lamination and cross lamination are missing leaving only flat laminated sands. Trough cross lamination characterizes the nearshore graded sand beds whereas ripple lamination or starved ripple drift prevails in the distal graded sand beds (Fig. 5).

A surface sand layer is present in many of the cores and could potentially be a correlative layer from the 1974 storm surge (Fathauer, 1975) (Fig. 2). Such a continuous layer was not encountered at the surface and sand content was 30% less over wide regions of Norton Sound in field seasons prior to 1974 (Fig. 6) (Nelson et al., in Press)* Oxidized grain coatings also were noted in surface sands, giving the thicker sands a yellowish color rather than the usual olive drab 'hue. Such coatings suggest a subareal source and that progradation of sand layers offshore may correlate with extensive shoreline erosion. Such shoreline erosion extended up to several hundred meters inland in the 1974 storm (Sallenger et al., 1978). Offshore movement of extensive sand masses from delta source areas from the 1974 storms is also indicated by the grading of thicker to thinner layers offshore (Fig. 2). It is not possible to confirm the dating of this upper sand layer, but it does exhibit a consistent pattern of trends in thickness, grain size and vertical sequence of sedimentary structures that is the same as the average of these characteristics throughout theentire core sequences. Thus, the surface layer appears to be a verification of the areal patterns of gradation in these vertical sequences of graded sand beds.

In addition, extensive change in surface texture of the sediment since 1974 can be shown in certain areas of the sea floor (Fig. 6). Change is most prominent nearshore off the modern Yukon subdelta where storm sand layers are thicker than they are far offshore. Coarser texture is found in most inshore areas where pre and post 1974 data is available. A 30-50 percent increase in sand content is noted in these regions. In the furthest offshore region of the central sound, no change is apparent, as would be expected in ths distal region where storm sands are poorly developed at best and are subject to more intense bioturbation (Nelson et al., in press).

Characteristics of graded sand beds also vary from the western side of the delta to the eastern nearshore area of the delta. In the western delta the individual sand layers are approximately 18 cm thick whereas in the eastern area most sand layers are 8-9 cm thick with occasional layers of up to 20 cm in thickness (Fig. 5). Similarly, in the distal areas off the western delta, sand layers average 5-10 cm thick whereas off the eastern area sand layers average 1-2 cm thick (Fig. 2).

Thickness of graded sand layers varies areally, depending on local morphology vertically in different stratigraphic horizons. Some cores change from thicker to thinner layers from base to top (Fig. 5) and others change from thinner to thicker layers from base to top. The cores taken in channels consist almost entirely of sand and may or may not contain thick graded sands, whereas cores taken on the flanks of the channels and on the delta front platform have well-developed graded beds; these become thinner at greater distances from the channels.

Depositional Processes of the Graded Sand Layers

The vertical and areal trends of graded sand layers permits speculation concerning the method of deposition. The well-developed vertical sequence of sedimentary structures and vertical gradation of grain size in the individual beds suggests that a rapidly waning current deposits these beds. It is apparent that this rapidly waning current is stronger inshore and gradually relaxes offshore, as shown by the pronounced change to thinner beds, fewer beds, and finer-grained beds offshore. In addition, it is apparent that sources vary and that pathways of the rapidly waning current are influenced by the sub-ice channel system (Dupré, 1979). It seems that the western delta, where 90 percent of the sediment is introduced, has a much more vigorous transport of the prograded sand beds from onshore to offshore. In contrast, the eastern delta is a region with much less effective sand transport from onshore to offshore.

Two possible mechanisms may be suggested for deposition of prograding graded sand beds in southern Norton Sound. One possible cause, particularly associated with inshore sub-ice channel locations, may be the sudden high river discharge at the time of spring breakup. The graded sand sheets may be deposited annually during the high discharge. The lack of evidence of an even cyclic event in the stratigraphy and the extent of deposition over 100 km from shore, suggest that such a deposit is unlikely from a freshwater flood plume entering salt water.

The second and favored hypothsis is that the prograding sand beds are deposited by storm surge runoff currents that develop from the relaxation of sea level set-up after passage of the strong south to southwesterly winds that usually accompany the major low-pressure storms in this region (Fathauer, 1975) (Fig. 7). In small storms, sea surface set up of a meter and current speed increases of over 100% have been measured in central Norton Sound (Cacchione and Drake, 1979; Schumacher and Tripp, 1979). Measurement of offshore set-up nearly equal to shoreline set-up and known occurrences of up to 5 m of shoreline set-up (Sallenger et al., 1978) indicate storm surge runoff currents several orders of magnitude greater than normal current speeds are possible.

The progradation of sand from onshore to offshore is potentially enhanced by cyclic wave loading on the delta front that can interact with the favorable grain size that is present. The possibility of cyclic wave loading and liquefaction potential appears to be verified by theoretical calculations based on wave pressures measured at the GEOPROBE site (Cacchione and Drake, 1979; Clukey et al., 1980). Consequently, a synergistic effect of sea level set-up, wave cyclic loading and liquefaction, and strong bottom return flow onshore toward offshore, is reinforced by the relaxing of the sea surface set-up. The pathway of the bottom return flow is apparently affected by the onshore channel systems whereas offshore, beyond the 30 km reach of the channel, sheet flow apparently gives a uniform distribution of thin sands (Fig. 7).

Another possible gradational process may be due to the greater effect of waves inshore. There, trough cross lamination predominates, whereas offshore current ripple lamination and starved ripple drift are apparent as the sand progradation process may be dominated mainly be bottom current flow with lesser influence of waves and a waning source of sand in the distal regions.

Isopach thicknesses of Holocene sediment in Norton Sound (Nelson and Creager, 1977) and comparison of these thicknesses with total sedment input from the Yukon River during the Holocene, indicate that significant amounts of sediment have been removed from the sea floor by sediment resuspension (Nelson and Creager, 1977). Detailed stratigraphy and lithology suggest the same conclusion. The section of Yukon Holocene muds is exceptionally thin in many places adjacent to the delta source region and this indicates sediment removal. Numerous lag layers of pebbles and shells and thin sands are apparent in the distal areas of Yukon muds of central and northern Norton Sound (Fig. 5). These form when storm waves resuspend the bottom mud but leave behind coarse ice-rafted pebbles, shell fragments, and coarse fraction in the bottom muds.

Additional new evidence of resuspension appears in the form of a thick storm sand layer now observed on the surface of southern Norton Sound; a layer of this thickness is not apparent in the past thousands of years of stratigraphy. This suggests that originally thick sand layers of major storms are eroded away due to resuspension by smaller storm events subsequent to the major event, so that the stratigraphic record may preserve storm sand layers that are thinner than those originally deposited. A generally thicker surface sand, compared to the other sand layers in each individual core, verifies the model of sediment resuspension.

Resuspension of bottom sediment by waves is also suggested by side-scan sonar and underwater television videotapes which show large scour depressions and formation of oscillation ripples by storm waves (Larsen et al., 1979).

Ice gouges covered by sediment in regions of intense ice scouring again suggest significant sediment resuspension and movement in southern Norton Sound (Thor and Nelson, 1980).

Potential Hazards and Storm-surge Deposition and Erosion

All evidence indicates that unusually large amounts of sediment are resuspended and then transported from Bering Sea to Chukchi Sea (Nelson and Creager, 1977) consequently any structure impeding this movement requires careful design. Data on suspended sediment verifies that about 10 percent of the Yukon River input to Norton Sound may be carried as part of the normal suspended sediment load that is bypassing through the Bering Strait. Because as much as 40 percent of the late Holocene discharge of the Yukon River appears to be missing from Norton Sound (Nelson and Creager, 1977), then, Up to 20 million metric tons of sediment per year, on the average, may be suspended and carried to Chukchi Sea by the strong northward flowing currents. The several hundred percent increase of suspended sediment transport, observed during a small storm in 1977, by Cacchione and Drake (1979), suggests that most of the 40 percent displacement of the suspended sediment occurs during storm events.

In summary, there are extremely large amounts of suspended sediment moving rapidly in the coastal waters along Alaska, often in intermittent large concentrations generated by storms and the early summer seasonal runoff. The fall storm season consequently could cause extremely wide dispersal of any oil spill material residing on the sea floor. Recent data by Drake (in press) suggest sediment resuspension, may also be vigorous, even during the season of ice cover because of greater constriction of currents in the delta region where the most rapid deposition occurs. Thus, any pollutants residing on the sea floor face extremely wide dispersal from northern Bering Sea to distances as far as a thousand kilometers to the north into the Arctic Ocean.

Storm surges generally dominate the mass movements of suspended sediment and also can be seen to move large amounts of rapidly programing sand in bedload transport for distances of up to 60 km offshore. This intensive transport and deposition could affect offshore facilities, especially pipelines. Storm sand layers deposited by such events could be impeded in their transport by any structures that protrude on the sea floor. These protruding structures could act as a dam, holding back the sediment transport and of course, would be put under severe stress if the sediment piled up rapidly against any feature such as a pipeline on the sea floor.

Conclusions and Suggestions for Future Work

A complex and vigorous setofsedimentarY processes are apparent in the shallow Yukon Delta front platform and prodelta regions. A major depositional sequence of graded sands may prograde offshore in storm surges. These graded sand beds with a vertical sequence of structures that mimic those of turbidites (Bouma, 1962) provide an example of shallow water deposition from rapidly waning storm surge currents that is very much like that of turbidity currents.

Storm surges and their concomitant wave and current activity have important effects on this basin that must be considered in planning for offshore development, Extensive erosion of the sea floor, resuspension of sediment, and transport of materials and any attached pollutants is one aspect. The second potential effect is movement of extensive sand sheets from shoreline and nearshore sources to offshore areas. Rapid deposition of ?5 cm or more of sand can smother biota immediately and alter texture of the substrate over extensive areas for a number of years. Thus, a sea-floor baseline measured at-one time, alters markedly in post-storm conditions. Future studies should monitor conditions with an instrument such as the

GEOPROBE which can help to determine the severity of sea-floor erosion in different locations during a storm. A number of deep vibracores are needed to determine recurrence intervals of such events and characteristics before and after such a catastrophic episode.

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Figures

Figure 1. Bottom water currents and bathymetry of the northern Bering Sea.

Figure 2. Thickness and distribution of a surface sand layer in samples taken after the 1974 storm surge.

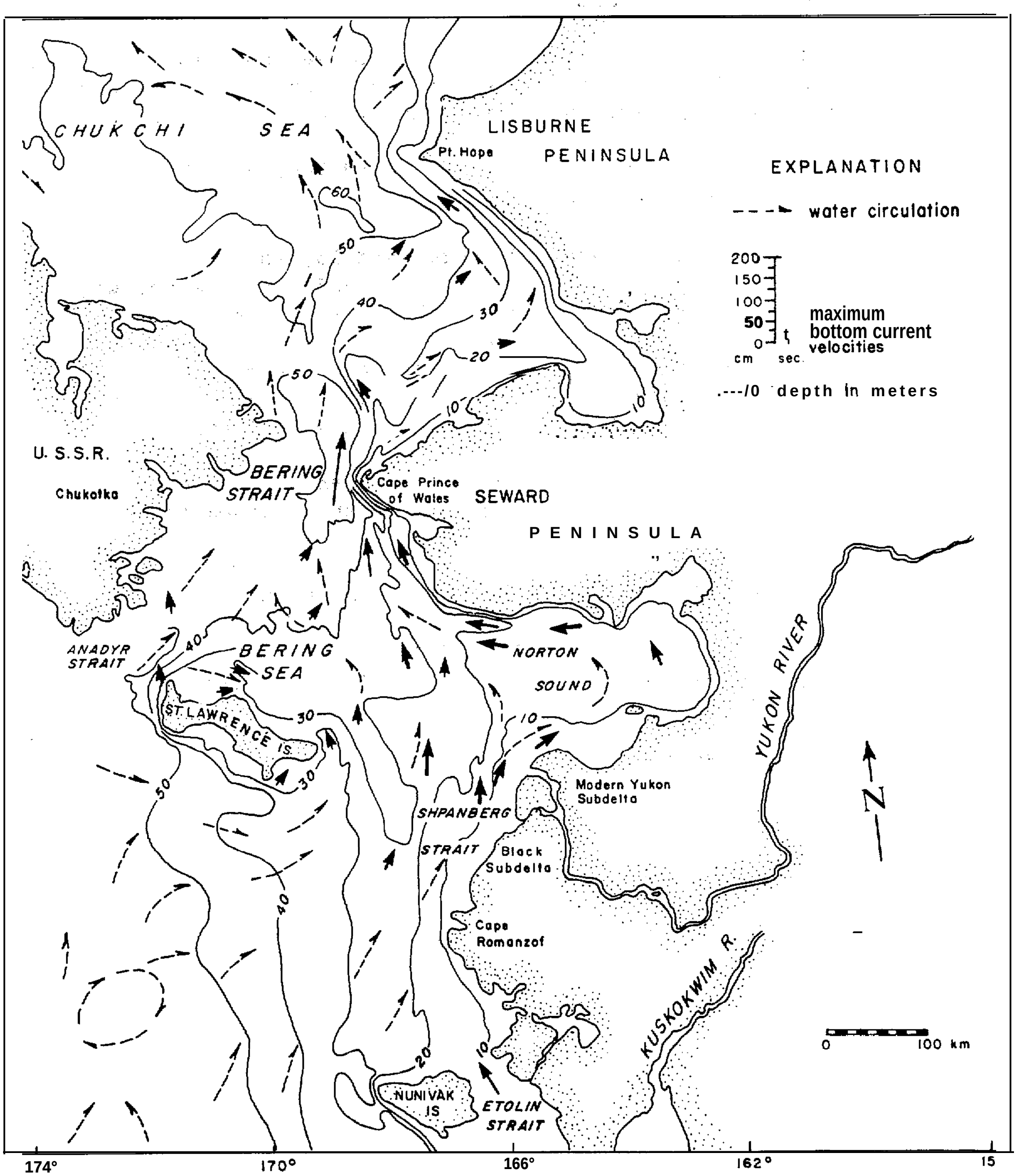
Figure 3. Distribution of vertical sequences of sedimentary structures in storm sand layers in southern Norton Sound and thickness of graded sand beds expressed as a prercent of total core length.

Figure 4. Mean Grain size change in graded sand layers with distance from the Yukon Delta shoreline.

Figure 5. Sedimentary structures of storm sand layers
A. Homogeneous trough cross-bedded sand from the thalweg of the sub-ice channel extending off the southwest distributary of the Yukn River, 3 km from shoreline.
B. Inshore (5 km from shoreline) graded sand layer from interchannel area of sub-ice channel off the southwest distributary showing lower flat lamination S_b, cross lamination S_c, upper flat lamination and Se mud cap.
C. Offshore graded sand showing Se-e and $S_{d\,e}$ sequences from a 2 m vibracore, 22 km from shoreline off the northeastern part of the delta.
D. Radiograph of distal graded sands and pebble and shell lags from a box core 115 km from Yukon Delta shoreline.

Figure 6. Model depicting sedimentary processes of a storm surge runoff current that may deposit graded storm sand layers off the Yukon Delta in Norton Sound.

Figure 7. Change in surface texture, pre- and post-1974 storm surge in Norton Sound.



CHUKCHI SEA
LISBURNE PENINSULA
Pt. Hope
EXPLANATION
water circulation
200
150
100
50
0
cm sec.
maximum bottom current velocities
----10 depth in meters
58°
66°
64°
62°
60°
U. S. S. R.
Chukotka
BERING STRAIT
Cape Prince of Wales
SEWARD PENINSULA
ANADYR STRAIT
BERING SEA
NORTON SOUND
ST. LAWRENCE IS.
YUKON RIVER
Modern Yukon Subdelta
SHPANBERG STRAIT
Black Subdelta
Cape Romanzof
KUSKOKWIM R.
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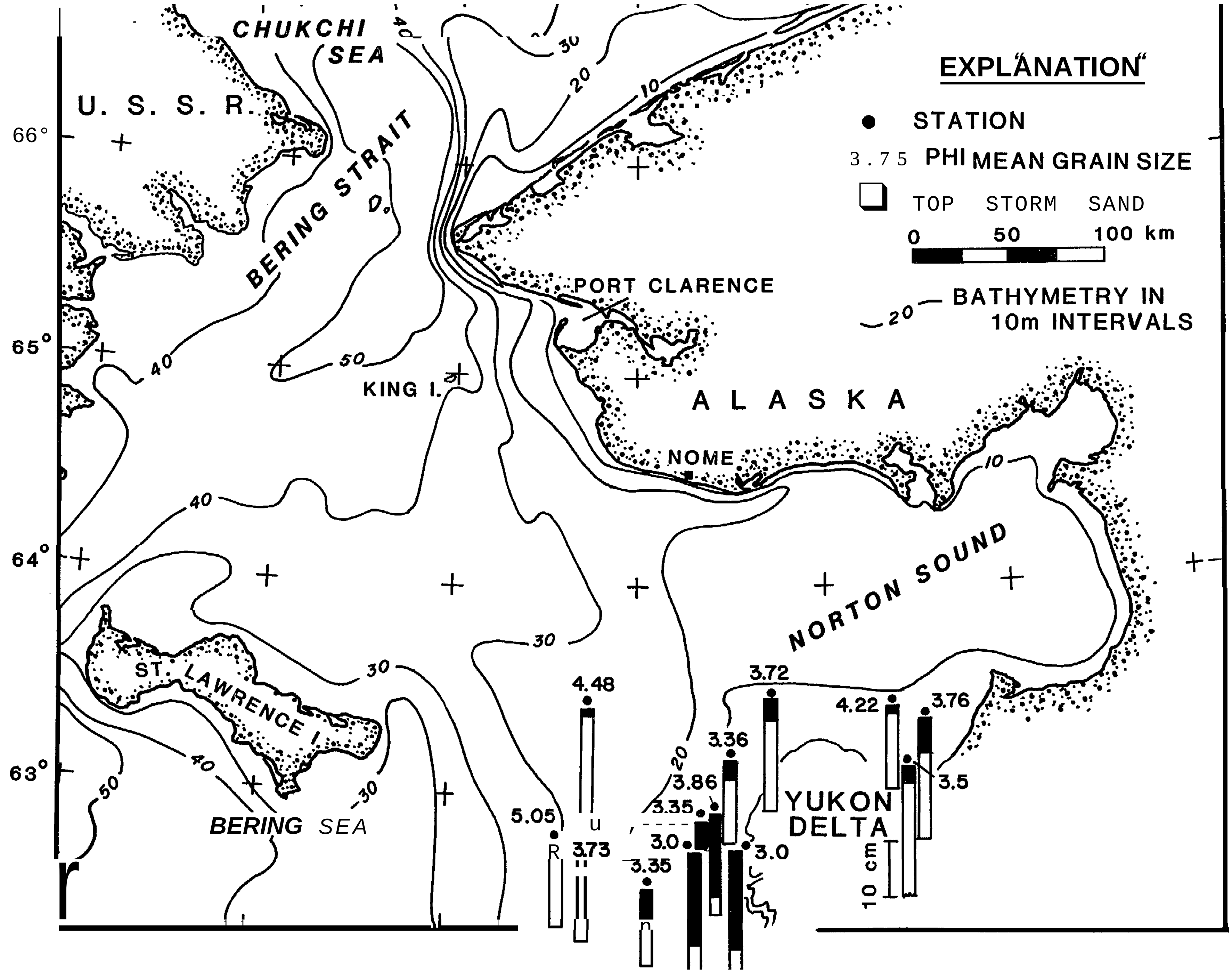
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U. S. S. R.
BERING STRAIT
PORT CLARENCE
KING I.
ALASKA
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NORTON SOUND
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BERING SEA
YUKON DELTA
66°
65°
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EXPLANATION
STATION
3.75 PHI MEAN GRAIN SIZE
TOP STORM SAND
0 50 100 km
BATHYMETRY IN 10m INTERVALS
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5.05
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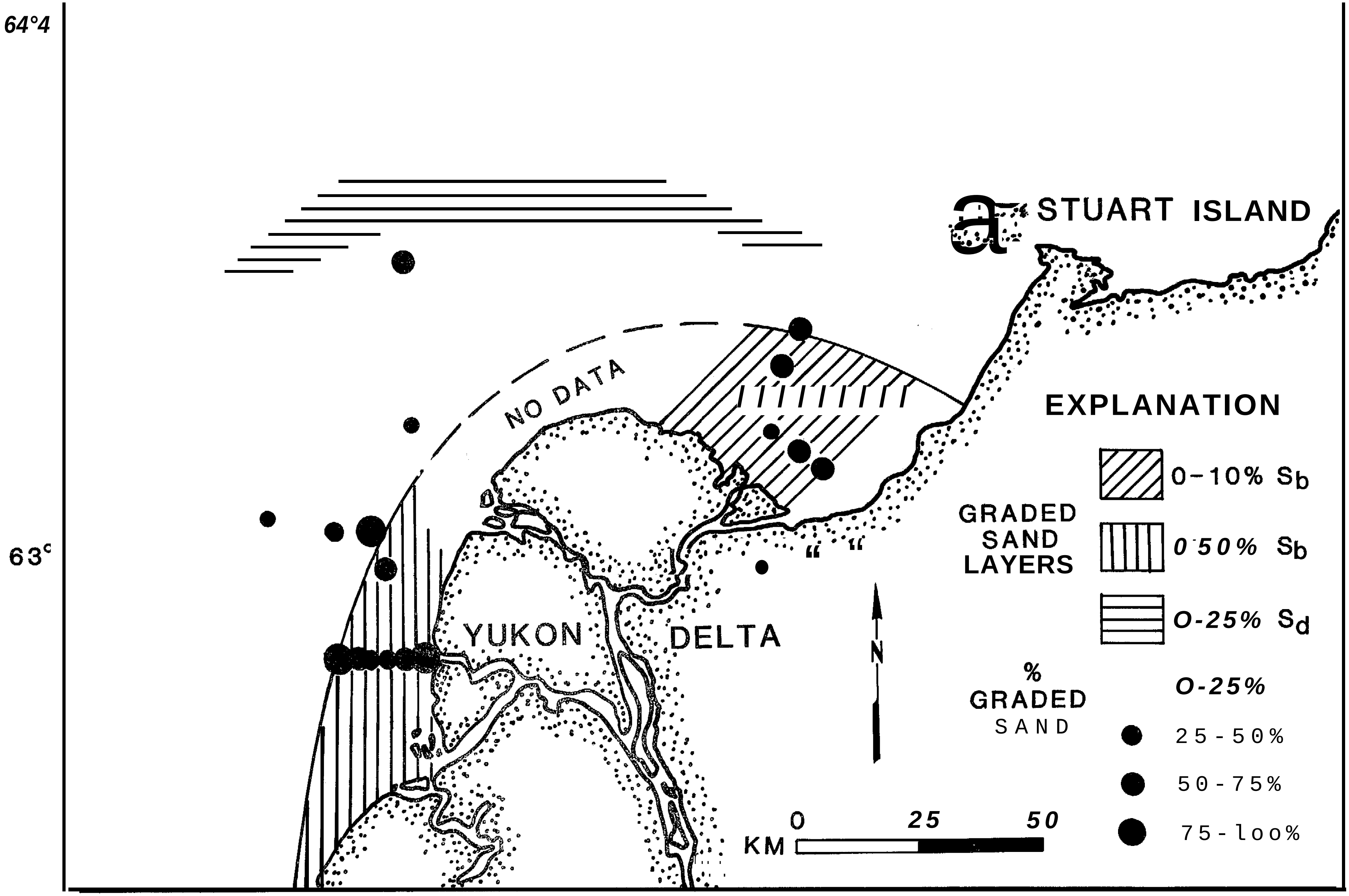

64°4
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STUART ISLAND
NO DATA
YUKON
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N
EXPLANATION
GRADED SAND LAYERS
0-10% Sb
0-50% Sb
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% GRADED SAND
O-25%
25-50%
50-75%
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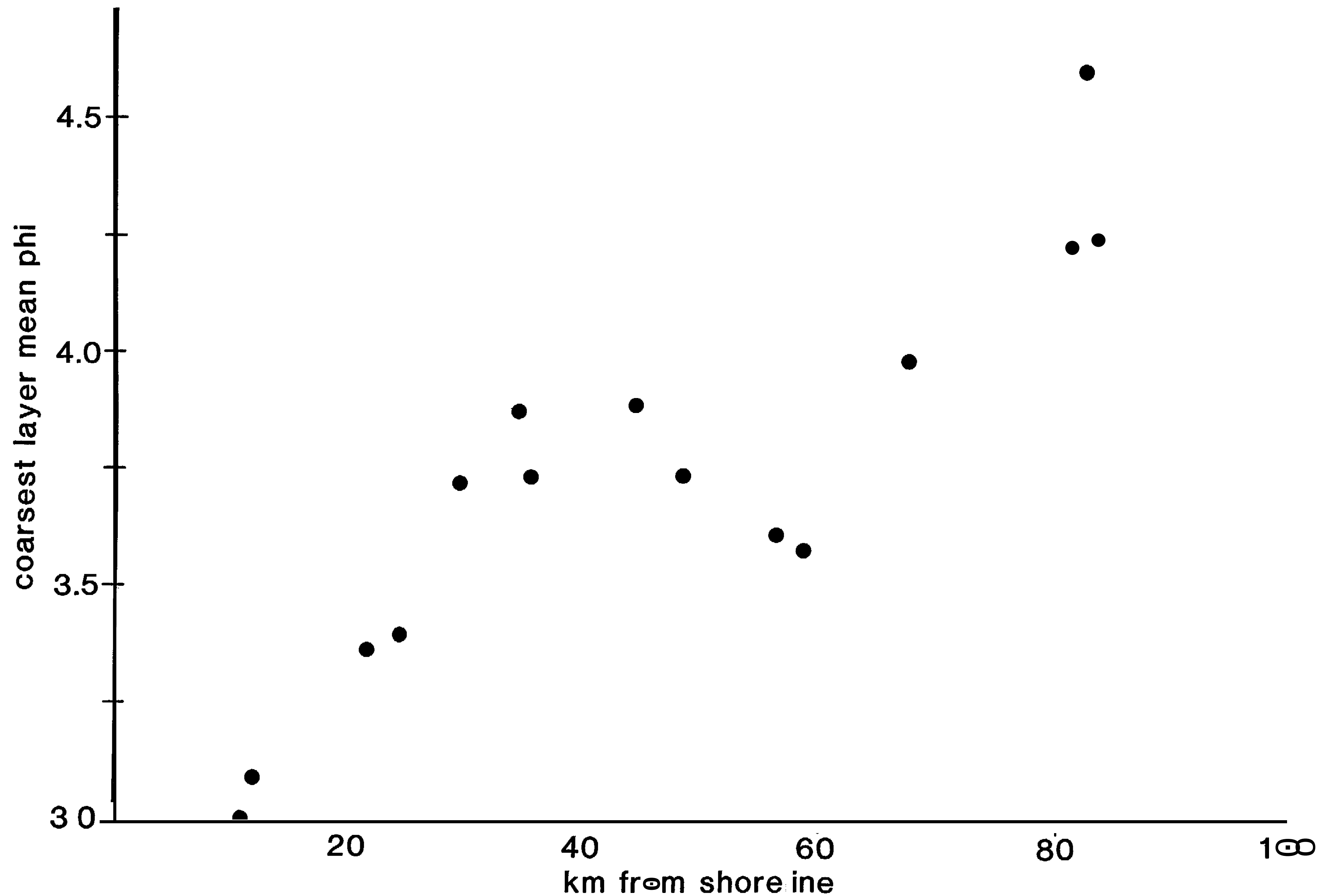
KM 0 25 50


coarsest layer mean phi
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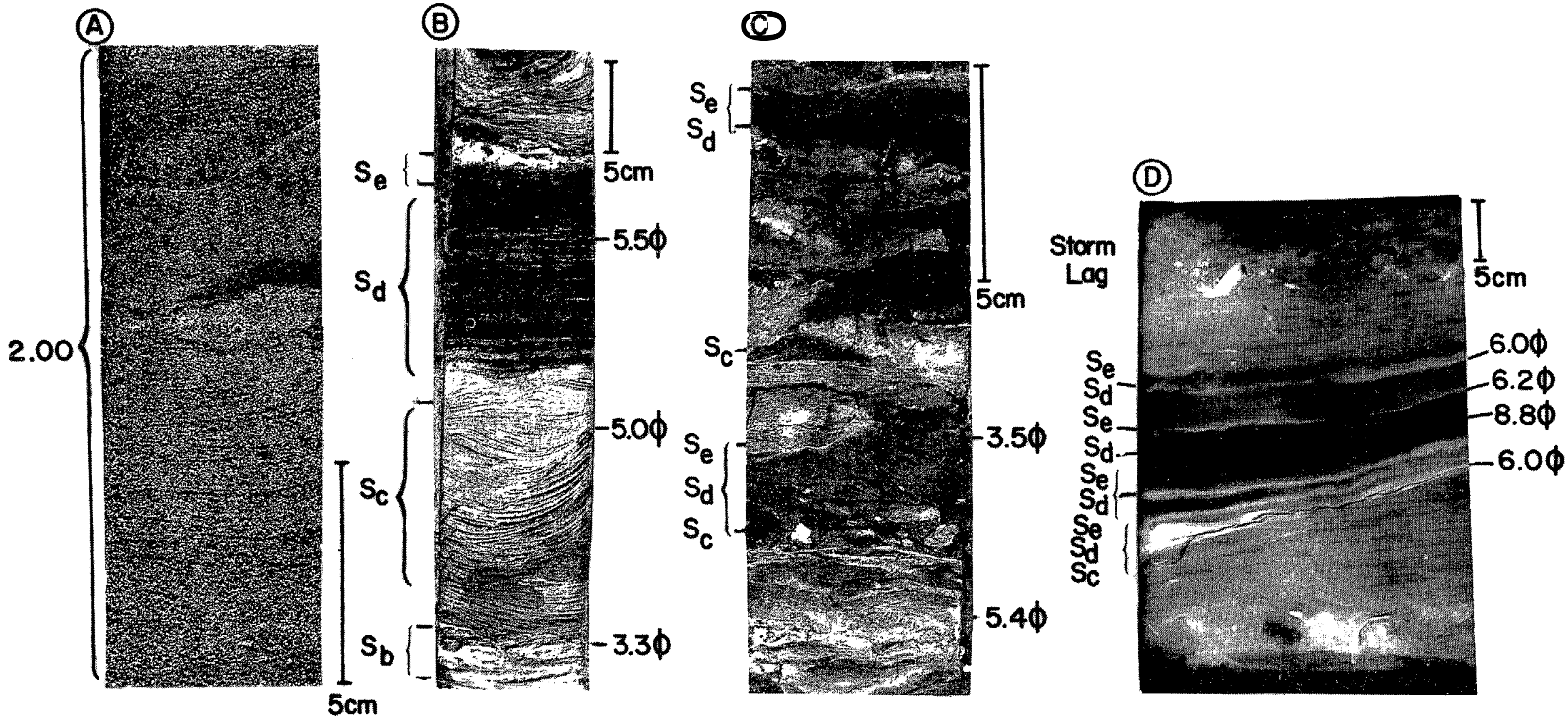
km from shoreline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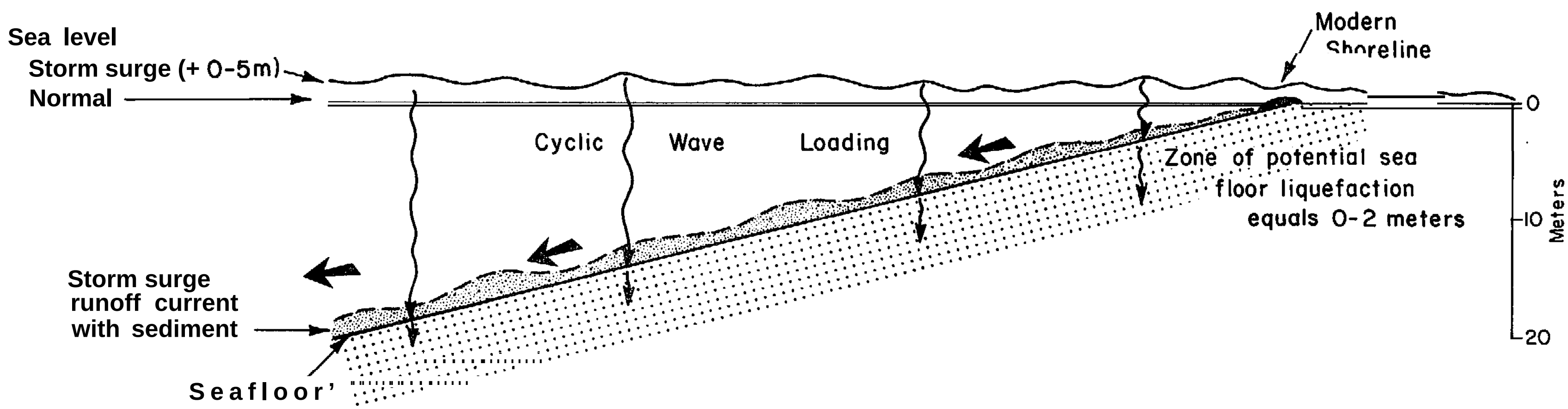
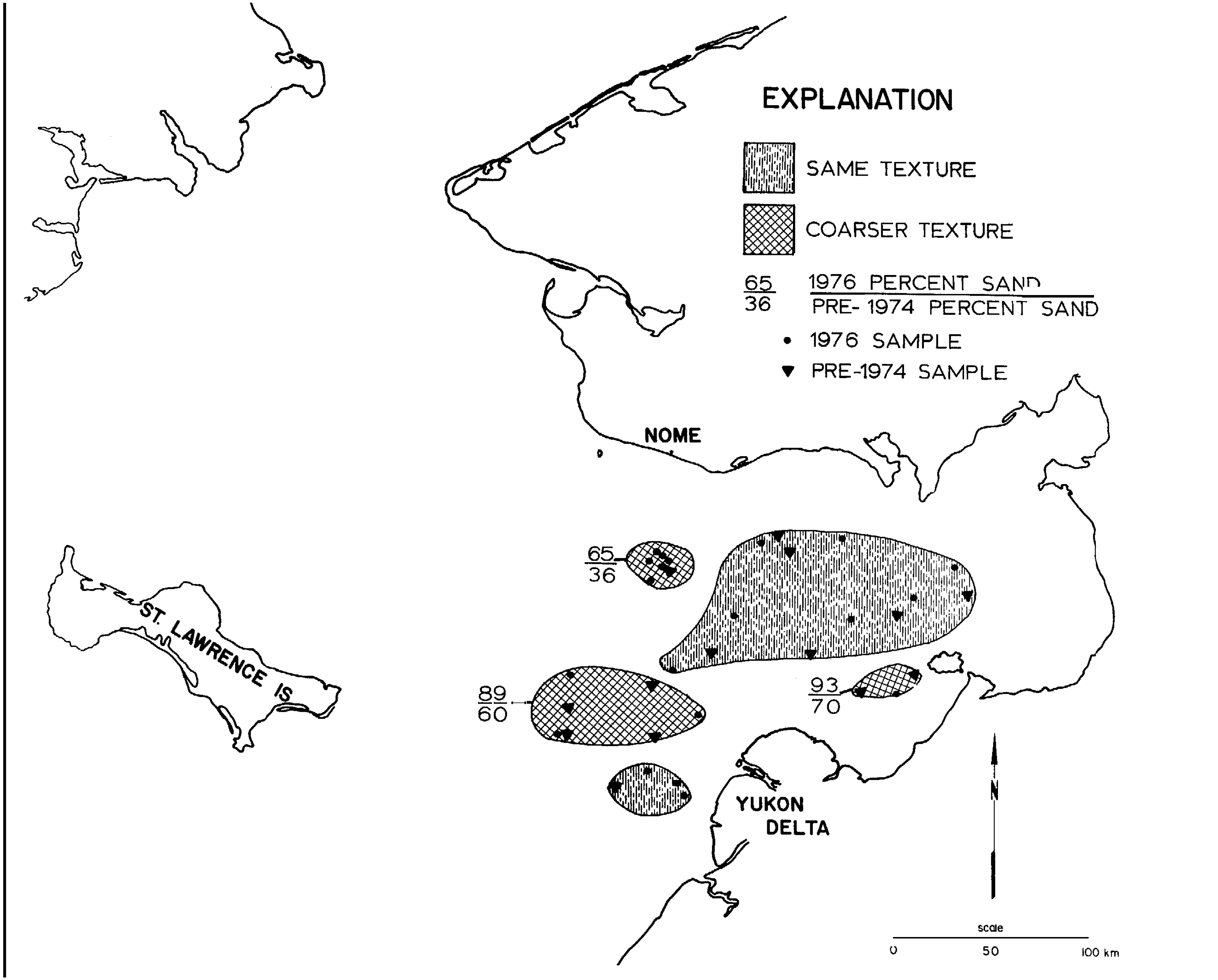
STORM SURGE PROCESSES




EXPLANATION
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ST. LAWRENCE IS.
YUKON DELTA
N
scale
0
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