

DEPOSITIONAL AND EROSIONAL FEATURES OF THE INNER SHELF, NORTHEASTERN BERING SEA¹

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ABSTRACT

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Sonographs and bathymetric profiles from water depths less than 15 m in the Nome-Solomon, Port Clarence, and Yukon Delta areas of the Alaskan Bering Sea coast show features generated by waves, currents, and drifting ice. The surficial sediments in the Nome-Solomon and Port Clarence areas range in grain size from sand to boulder gravel and have many surface features visible on sonographs, whereas the sediments off the Yukon Delta are fine sands and silts that have few such features.

Materials in the Nome-Solomon and Port Clarence areas have been segregated by grain size into ribbons and irregular, elongate, and lobate patches. The sand patches commonly have convex-up profiles and probably rest on gravel lag deposits that are exposed in adjacent gravel patches. Coarse sand and fine gravel patches and ribbons are characterized by symmetrical ripples, spaced 0.5 to 2 m apart, that could only have been generated by storm waves. Gravelly sand waves in the Nome-Solomon area were formed by westward shore-parallel currents. Boulder gravel ridges in this area are of unknown origin.

Sand and gravel ribbons are common near the entrance to Port Clarence. Unlike ribbons elsewhere, which have been attributed to tidal or other currents, the ribbons in the Port Clarence area show features suggesting generation by storm waves. These ribbons are oriented approximately normal to the associated large wave ripples, and both the ripples and ribbons vary in orientation in ways that can be explained as effects of wave refraction over a shoaling bottom. Ribbonlike features of unknown origin occur locally on the Yukon delta front.

Ice-gouged furrows, though less common than in areas farther offshore, occur in all the nearshore areas studied. The gouges are 5 to 15 m wide, as much as hundreds of meters long, and usually less than 0.25 m deep.

INTRODUCTION

Strong currents are known to occur on parts of the northern Bering Sea continental shelf, particularly in the approaches to Bering Strait. These currents include a semipermanent northward drift toward Bering Strait and fluctuating tidal and wind-driven currents (COACHMAN ET AL., 1975). The importance of these currents for transporting sediment in areas more than a few kilometers from shore has been shown by NELSON & HOPKINS (1972), MOORE & WELKIE (1976), FIELD ET

AL. (1977), NELSON ET AL. (1982, this volume), CACCHIONE ET AL. (1982, this volume), and DRAKE ET AL. (1980). Studies by HUNTER ET AL. (1979), in contrast, have shown that waves and wave-induced currents are the dominant agents of sediment transport on the beaches during the ice-free season. The shoreface, from the shoreline to a depth of 15 m, seemed likely to include the zone of transition from wave dominance to current dominance and was the target of the present study.

We selected for detailed study three areas that offer a wide variety of sediment grain sizes and exposures to waves and currents: Port Clarence and vicinity, the stretch of coast from Nome to Solomon, and the Yukon delta complex (Fig. 1).

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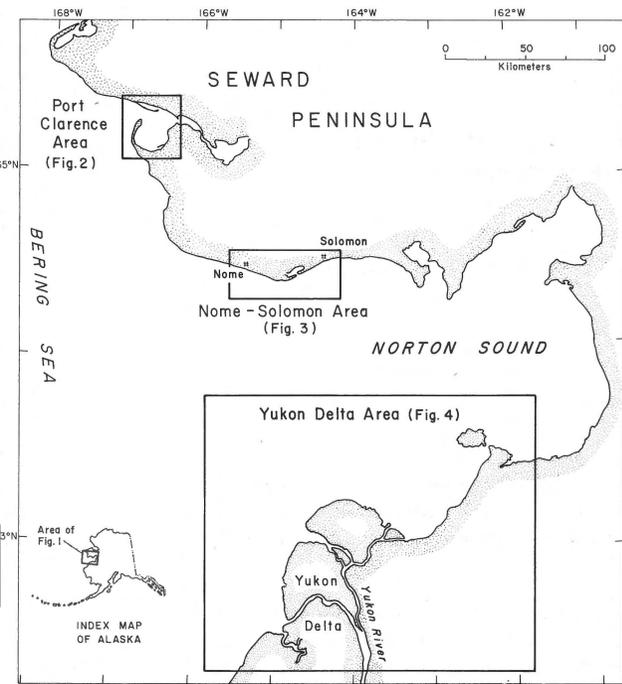


Fig. 1
Index map showing area studied in the northeastern the Bering Sea.

METHODS

Data were gathered aboard the R/V KARLUK, a shallow-draft (1 m) vessel, during June and July, 1978. Data collected while underway include side-scan sonar, 7 kHz, and 200 kHz records. Underwater television tapes obtained while drifting over limited areas proved very useful in identifying features seen on the sonographs. Observations were made at a few stations by diving with scuba, and a few sediment samples were collected to supplement those gathered during previous studies by NELSON & HOPKINS (1972), MOORE & WELKIE (1976), and MCMANUS ET AL. (1977). Navigation was by Loran-C in the Yukon Delta area and by radar in the areas off the southern Seward Peninsula.

SETTING AND SEDIMENT CHARACTER

Port Clarence

Port Clarence is an embayment 25 to 30 km across (Fig. 2), protected from the Bering Sea by a Holocene gravel spit (BLACK, 1958). To the north, a Holocene gravel barrier separates Port Clarence from Breving Lagoon. The entrance connecting Port Clarence to the Bering Sea is 7.3 km wide and has a maximum depth of 16 m. The relatively flat axial region of the entrance is floored by mud (MOORE & WELKIE, 1976; MCMANUS ET AL., 1977), but the sloping margins, where most of the features visible on sonographs are located, are floored

by sand and gravel. The surficial sediments are presumably Holocene, but the thickness of Holocene deposits is not known.

The mean tidal range in Port Clarence is 0.4 m. Currents through the entrance have not been studied, but the small tidal range and large cross-sectional area of the entrance ensure that the tidal currents are not extremely strong. Storm surges, known to be as high as 3.25 m (SALLENGER & DINGLER, 1978), undoubtedly create stronger currents through the entrance. The northward drift of the Alaskan Coastal Water toward Bering Strait (COACHMAN ET AL., 1974) may not affect the embayed coast near Port Clarence very strongly. The only long fetch for waves is to the southwest.

Nome-Solomon Area

The coast in the Nome area has been shaped by erosion of Pleistocene glacial and associated deposits (HOPKINS ET AL., 1960; NELSON & HOPKINS, 1972; TAGG & GREENE, 1973). Holocene barriers of sand and gravel have formed in the area from Safety Sound to Solomon (Fig. 3). The shoreface in the Nome-Solomon area slopes steeply to a depth of 12 m. Beyond the shoreface, the seafloor slopes more gently. The deposits of Nome are gravel lag deposits of the Holocene transgression and thin sand patches of Holocene age. Similar sand and gravel occur off the Safety Sound-Solomon area, but the thickness of Holocene and late Pleistocene transgressive deposits is not known.

The mean range of the largely diurnal tide at Nome is 0.3 m.

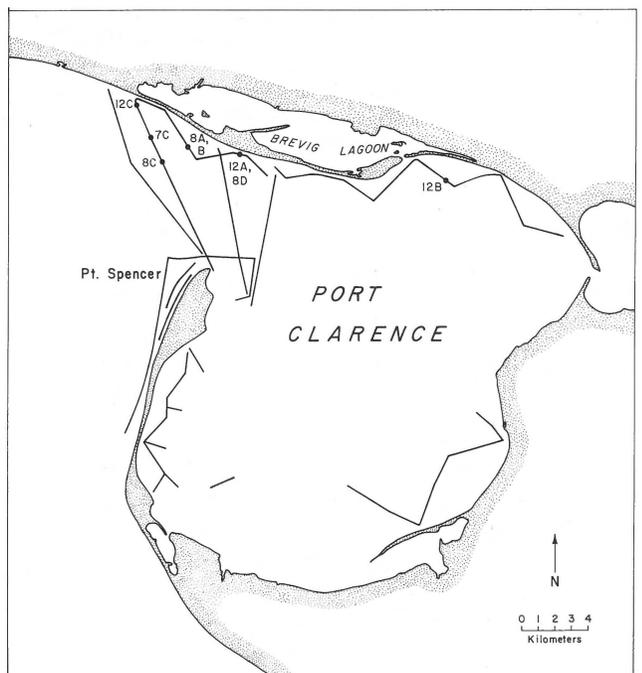


Fig. 2
Map Showing tracklines and locations of illustrated features in the Port Clarence area.

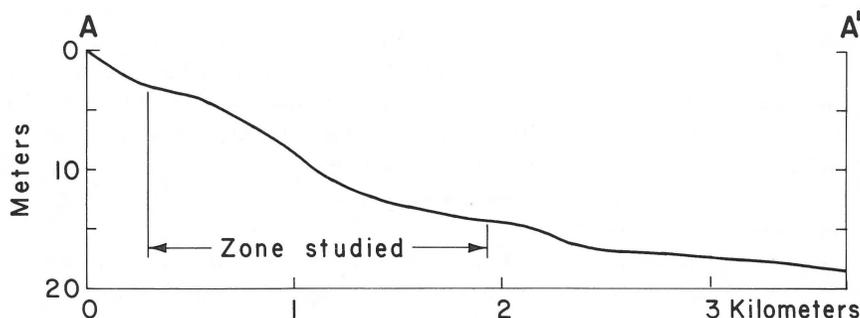
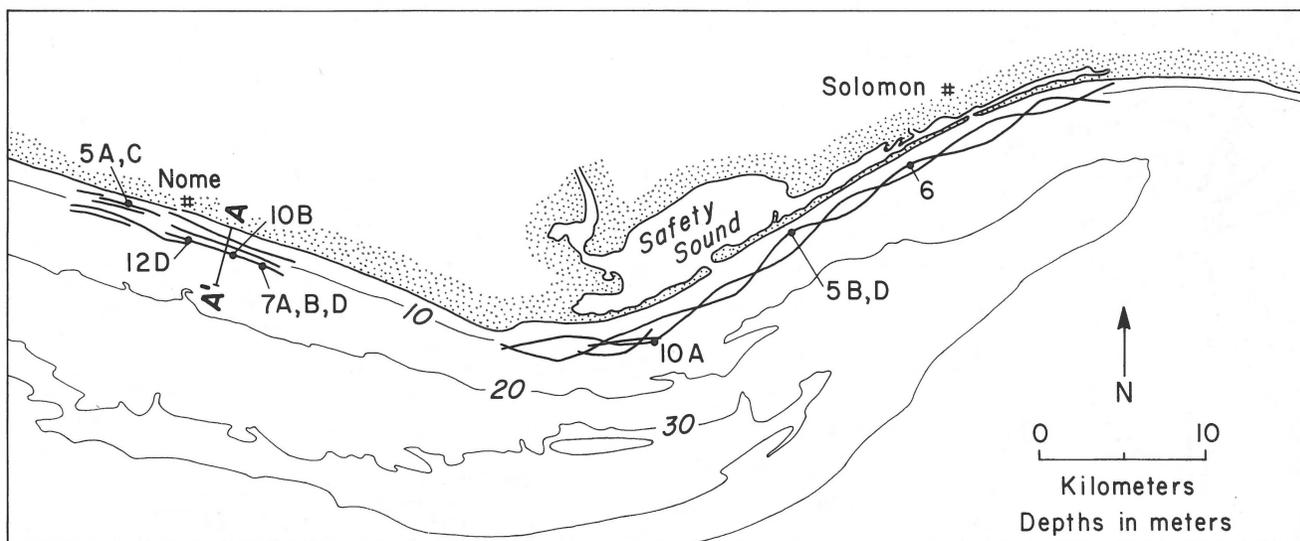


Fig. 3
Map showing tracklines and locations of illustrated features in the Nome-Solomon area.

Tidal currents off Nome are directed along shore to the east and west. These currents are strong despite the low tidal range; PEARSON ET AL., (1981) reported an amplitude of 27.7 cm/s for the major axis of the K_1 tidal-current component and 14.5 cm/s for the O_1 component off Nome. A few short-term measurements in nearshore areas indicate that strong net westward currents occur off Nome in northern Norton Sound (NELSON & HOPKINS, 1972; COACHMAN ET AL., 1975; MUENCH ET AL., 1981). Currents associated with storm surges, which are as high as 4.75 m at the eastern end of Norton Sound (SALLENGER & DINGLER, 1978), may be much stronger than any currents that have been measured. Wave fetches are fairly long to the south and southeast and longest to the southwest.

Yukon Delta

The Yukon River debouches into the northern Bering Sea and forms a large arcuate delta complex in southwestern Norton Sound. The offshore part of this complex comprises three major components (Fig. 4); (1) a sub-ice platform, (2) a delta front, and (3) a prodelta (DUPRÉ, 1982, this volume). The sub-ice platform extends 10 to 30 km offshore as a nearly

featureless plain at water depths of 1 to 3 m. Dissecting the platform are several subaqueous distributary channels. The delta front, which is relatively steep and locally irregular, extends from the break in slope at the outer edge of the sub-ice platform to a water depth of 10 m. The prodelta slopes gently seaward from the toe of the delta front across a large part of Norton Sound. Sediment of the delta complex is silt to fine sand.

Wave and currents patterns in southwestern Norton Sound are poorly known. The major wave trains move northward across the Bering shelf and refract clockwise around the protruding Yukon shoals (SALLENGER & DINGLER, 1978). Fetches are shorter to the north and northeast. The mean tidal range varies from 0.5 to 1.2 m around the delta margin.

Marine Climate

The coastal waters of the northeastern Bering Sea are usually free of ice from middle or late May to late October or early November. During the icefree season the wind and wave regimens are variable; no distinctly dominant wind or wave direction is evident in data from the northeastern Bering Sea (BROWER ET AL., 1977). The largest storms usually occur

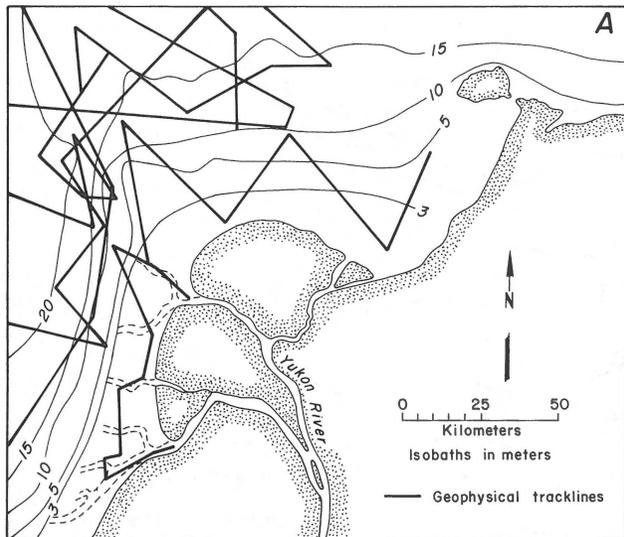


Fig. 4
A. Map of tracklines in Yukon Delta area.

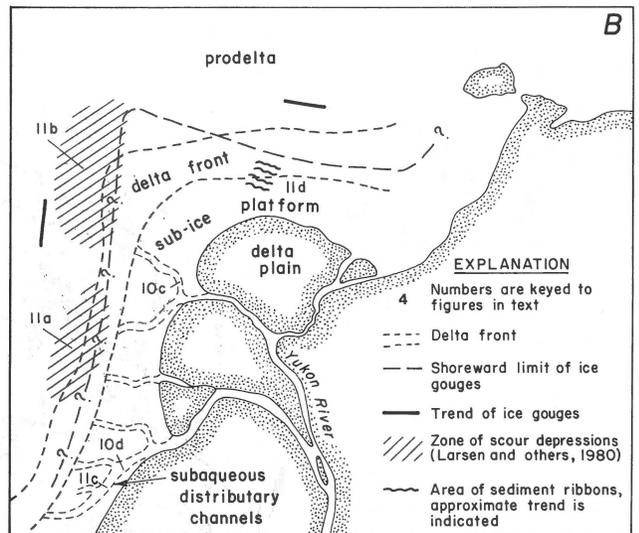
around the time of freeze-up in the fall, and the winds and waves during these storms are mostly from the east, northeast, or north. However, some of the greatest storms, such as that of November 1974, have winds from the south or southwest (SALLENGER & DINGLER, 1978). Storms may or may not affect the coastal waters, depending on the fetch in the direction of the storm winds and the timing of the storm with respect to freeze-up. In general, the direction of the dominant waves along a given stretch of shore is closely related to the direction of greatest fetch.

FEATURES PRODUCED BY WAVES AND CURRENTS

Port Clarence and Nome-Solomon Areas

Features in the Port Clarence and Nome-Solomon inner shelf are similar, largely because of the similarly coarse sediments in the two areas. Wave- and current-produced features in these areas include sand and gravel patches and ribbons, wave ripples, and large current-produced transverse bedforms.

Patches – Irregular segregations or patches of sand and gravel are ubiquitous in the Nome-Solomon area (Fig. 5). On sonographs, the sand patches are light toned and the gravel patches dark toned. The patches are extremely variable in diameter, ranging from 10 to 500 m. In the shallowest water depths studied, 4 to 8 m, the sand patches are sharply separated from gravel, which consists of cobbles and boulders. These shallow-water patches range in shape from very irregular (Fig. 5a) to roughly elongate at high angles to shore (Fig. 5b). Locally the sand patches are smoothly curved seaward-convex lobes spaced an average of 450 m apart (Fig. 6). Some sand patches can be distinguished from gravel



B. Map of morphologic features shown on sonographs in Yukon Delta area.

patches by differences in acoustic signature on bathymetric profiles (Fig. 5c, d). The sand patches have smooth convex-up surfaces that typically rise above the intervening gravel, and with little doubt the sand forms lenses resting on a gravel substrate. Where the gravel surface is irregular in profile, ridges or mounds of gravel commonly rise above the sand lenses (Fig. 5).

In water deeper than 10 m, the patches become less distinct because patches of pebbly sand and pebble gravel commonly occur between the coarser gravel and the sand. Much of the pebbly sand and pebble gravel is visibly rippled on sonographs (Fig. 7). Many patches differing in grain size from adjacent patches are recognizable more by differences in ripple size and trend than by tonal differences on the sonographs (Fig. 7b).

The patches tend to be elongate at high angles to shore and to have straighter boundaries at high angles to shore than at low angles. This elongation represents a tendency toward ribbonlike forms, but no well-developed ribbons are found in the Nome-Solomon area. The possible significance of the ribbonlike forms will be discussed in connection with the well-developed ribbons in the Port Clarence area. The lobate form and regular spacing of some of the nearshore sand patches suggest that they were formed by stationary rip currents or edge waves; similar features have been seen off Rhode Island by MORANG & MCMASTER (1980).

Wave Ripples – Ripples with spacings of 0.5 to 2.0 m are commonly visible on sonographs in both the Nome-Solomon and Port Clarence areas (Fig. 7). These large ripples were identified as wave generated by their symmetry as seen on the sonographs, by underwater television, and by diving. They occur in moderately to well sorted, coarse to very coarse sand and pebble gravel. Similar large wave ripples in similarly coarse sediment are known from many areas (TRASK, 1955;

VAUSE, 1959; NEWTON & WERNER, 1972; CHANNON & HAMILTON, 1976). All of the large wave ripples were inactive when seen by television camera or by diving and must have formed during storms. In addition to the large inactive ripples, active ripples too small to be visible on sonographs were present in medium-grained sand.

All of the large, inactive wave ripples in the Port Clarence entrance trend NW-SE and can be explained as products of storm waves propagating northeastward from offshore parts of the Bering Sea. In the Nome area, at least three sets of large, inactive wave ripples can be seen at a depth of 12 m (Fig. 7d). The largest ripples have a spacing of 1.3 to 2.0 m, trend NW-SE, and occur in the coarsest sediment (median diameter of 2 to 8 mm); the middle-sized ripples have a spacing of 0.7 m, trend E-W, and occur in sediment of intermediate grain size; and the smallest ripples visible on the sonographs have a spacing of 0.4 m, trend WNW-ESE, and

occur in relatively fine sediment (median diameter of 0.5 to 2 mm). All three sets of large, inactive wave ripples were probably formed by shoreward-propagating storm waves. The largest ripples in the coarsest rippled sediment must have formed first during a major storm. This large storm presumably formed ripples in finer sediment as well, but only the ripples in the coarsest sediment remained inactive and unmodified until the time of observation. After the largest ripples, successively smaller ripples were formed in successively finer material by what must have been successively smaller waves at successively later times, either during later phases of a single storm or during later storms.

In more detailed hydrodynamic terms, the wave ripples may be classified as vortex ripples because of their steepness (DINGLER & INMAN, 1977). At least the larger ripples are probably of orbital type, having a spacing similar to the orbital diameter of the waves (figures 11-13 in CLIFTON, 1976).

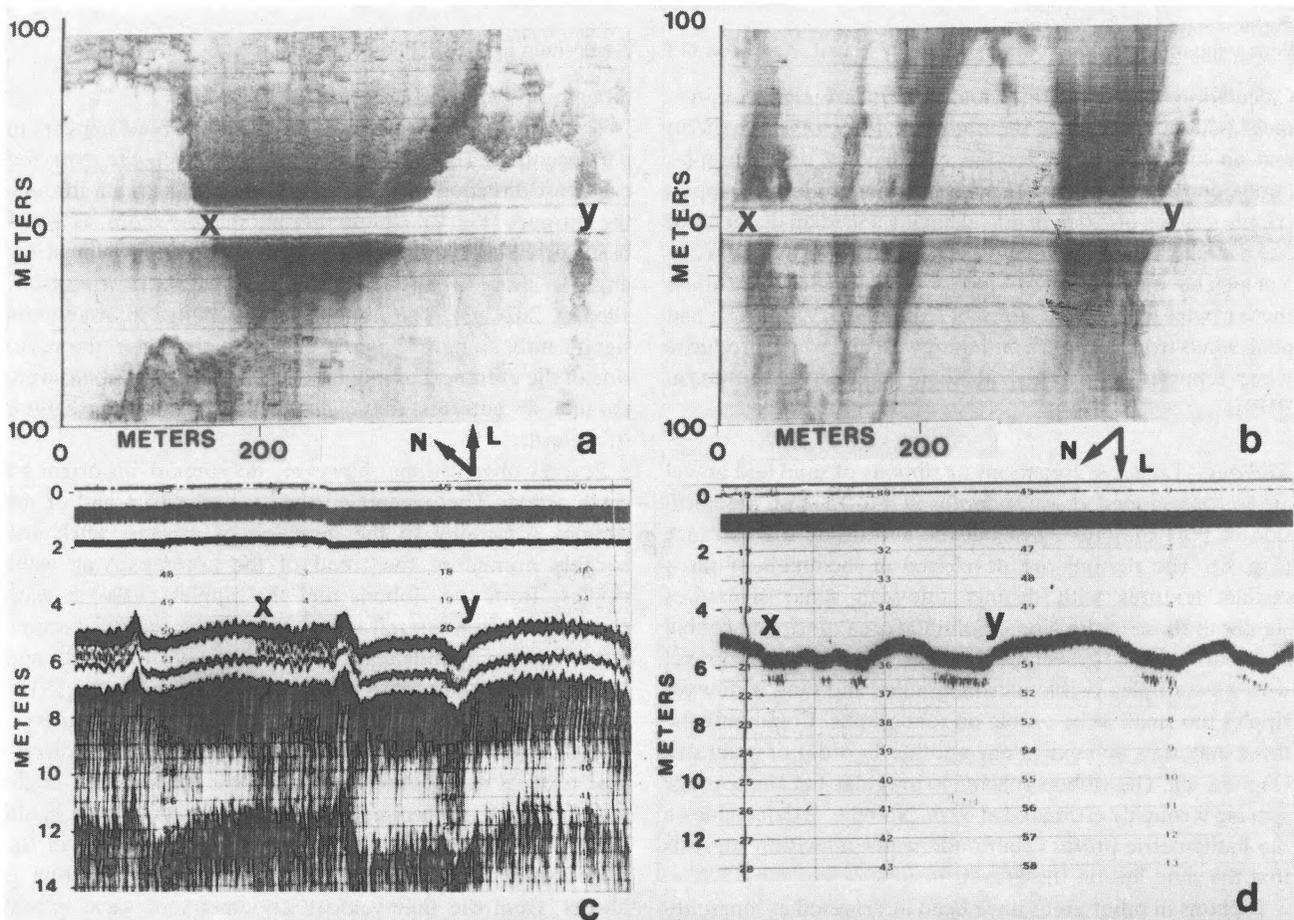


Fig. 5
Irregular to elongate sand and gravel patches in the Nome-Solomon area. Distinctive points allowing comparison of a sonograph and its accompanying bathymetric profile are labelled x and y. North and landward directions indicated by arrows labelled N and L. Sand is light, gravel dark on the sonographs. (Positions of profiles in Fig. 3).

- Sonograph of irregular patches.
- Sonograph of elongate patches.
- Bathymetric profile of area shown in a.
- Bathymetric profile of area shown in b.

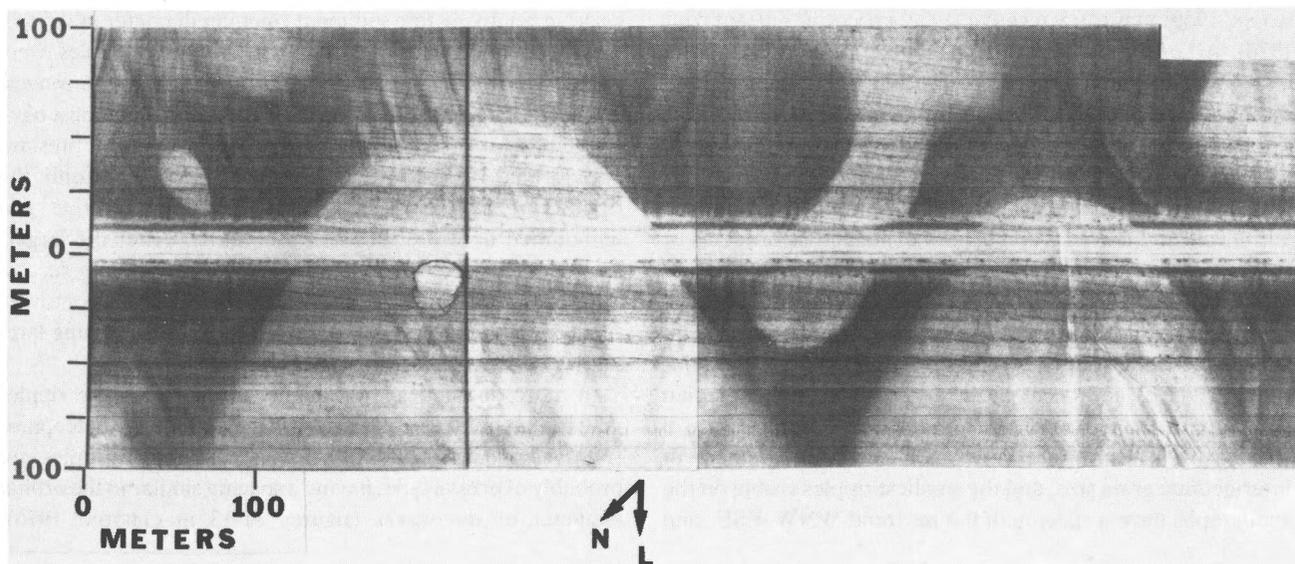


Fig. 6
Sonograph of lobate sand patches off Safety Sound. Arrows as in Fig. 5. (Position of sonograph in Fig. 3).

Calculations based on threshold velocities for grain movement (RANCE & WARREN, 1969; KOMAR, 1976; DINGLER, 1979) and on the upper limit for the existence of orbital ripples (MOGRIDGE & KAMPHUIS, 1972) suggest that the largest ripples (ripple spacing of 2.0 m in gravel having a median diameter of 2 to 8 mm at a water depth of 12 m) were formed by waves 2 to 5 m high having a period of 6 to 11 s. It is tempting to attribute these ripples to the great storm of November 1974, which had peak winds from the south and southwest and which produced waves reportedly 3-4 m high at Nome (SALLENGER & DINGLER, 1978).

Ribbons – Linear segregations or ribbons of sand and gravel are well developed at water depths of 4 to 15 m on the north side of Port Clarence, just outside and inside the entrance (Fig. 8). The ribbons are developed in sediments of three distinct textures with distinct side-scan sonar signatures similar to those in the Nome-Solomon area: unrippled cobble and coarse-pebble gravel, pebbly sand and fine-pebble gravel with wave ripples visible on sonographs, and sand with wave ripples too small to be visible on sonographs. Commonly the three materials lie next to one another in order of grain size (Fig. 8a, c). The ribbon spacing is irregular but the average spacing is roughly estimated at 60 m. No relief is detectable on the bathymetric profiles, but underwater television suggests that the sand lies on the gravel.

Ribbons in other areas have been interpreted as longitudinal bedforms produced by currents (KENYON, 1970). The currents that produce most ribbons are tidal, though wind-driven currents have apparently produced some ribbons or similar textural bands (STRIDE & CHESTERMAN, 1973; MCKINNEY ET AL., 1974). For the Port Clarence area, however, a strong though not conclusive argument can be made that the ribbons are produced by wave action and are oriented parallel to the

direction of wave propagation.

The evidence for a wave origin of the ribbons appears in part negative. The ribbons are not parallel to the expected east-west direction of tidal or storm-surge currents through the entrance (Fig. 9). Nor do they parallel the shore, as would be expected for Ekman currents driven by winds at almost any angle to shore in very shallow water (NEUMANN & PIERSON, 1966, p. 202-203). The ribbons do not change in orientation significantly along irregularly curving isobaths on the north side of the entrance, as might be expected if the ribbons were parallel to currents that were deflected around seafloor irregularities.

Several observations, however, do support an origin by wave action. The general northeast-southwest trend of the ribbons is parallel to the direction of greatest fetch and roughly normal to the trend of the accompanying wave ripples. Both the ribbons and the ripples curve in ways consistent with wave refraction; that is, the ribbons become more nearly perpendicular to shore as the bottom shoals and the ripples become more nearly parallel to shore (Fig. 9).

Exactly how waves might produce ribbons is not known, though several mechanisms are conceivable. Originally irregular textural segregations produced by other causes might streak out by subsequent sediment transport. This could result from either wave-induced net water motion in the direction of wave propagation or, if net water motion is absent, from the time-velocity asymmetry of wave orbital motion (short but strong pulses in the direction of wave propagation and longer but weaker pulses in the opposite direction). Langmuir circulation induced by waves or by wave-current interaction (FALLER & CAPONI, 1978), might be capable of forming linear textural segregations where no segregations had existed previously.

The hypothesis of ribbon generation by wave action is

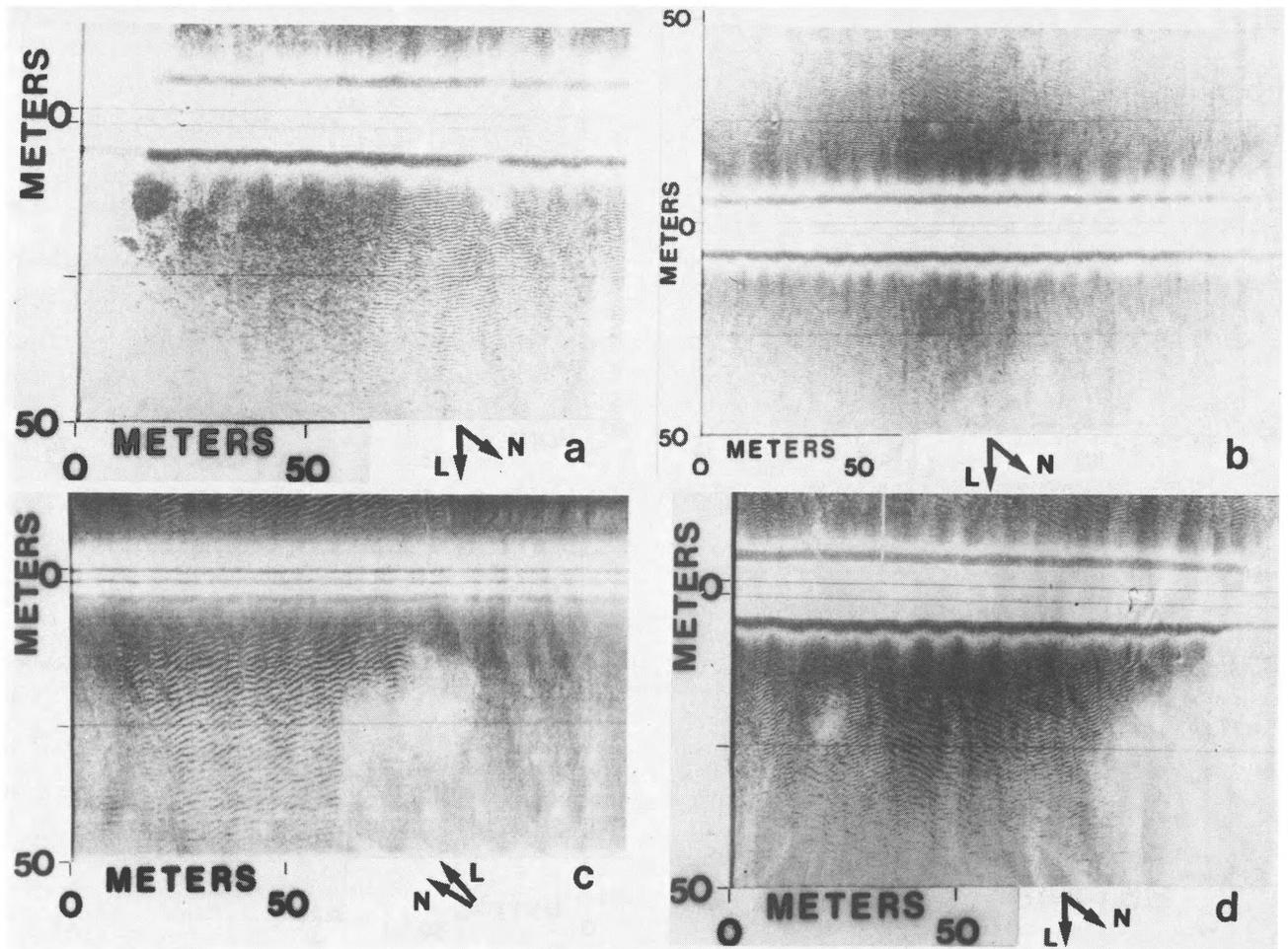


Fig. 7
 Sonographs of wave ripples and associated features. Arrows as in Fig. 5. (Positions of sonographs in Figs. 2 & 3).
 a. Sand, gravel, and rippled fine gravel patches off Nome.
 b. Patches off Nome distinguished by differences in ripple-size and trend.
 c. Sand, gravel, and rippled fine gravel patches in Port Clarence area.
 d. Sand and rippled fine gravel patches off Nome. Note the three areas distinguished by differences in ripple-size and trend.

complicated by the fact that some of the ribbons in very shallow water are parallel to, and possibly bounded by, ice gouges (Fig. 8d). Those ribbons may have been produced by gouging. The occurrence of straight parallel ribbons through a depth range of 4 to 15 m, however, is difficult to reconcile with an origin by gouging, given the probability of ice grounding somewhere in that depth range.

An origin by wave action may explain the ribbonlike tendencies of the elongate textural segregations in the Nome-Solomon area. The poorer development of ribbonlike forms in there as opposed to the Port Clarence area could be explained by a greater variability in wave directions, as suggested by the greater variability in orientation of wave ripples.

Ribbons or elongate textural patches oriented at high angles to shore or normal to wave ripples have been observed elsewhere. MCKINNEY ET AL. (1974) observed textural bands oriented normal to large wave ripples on the Atlantic shelf of

the southeastern United States. NEWTON ET AL. (1973) observed bands oriented at high angles to shore at relatively shallow depths (30-40 m) on the Atlantic shelf of northwest Africa. SWIFT ET AL. (1976) and SWIFT & FREELAND (1978) observed textural bands oriented at high angles to shore off the northeastern United States but were not certain whether the bands were parallel to or transverse to the currents. REIMNITZ ET AL. (1976) interpreted shore-normal rippled and unrippled bands off the west coast of Mexico as products of rip currents. Such an interpretation is not feasible for the Port Clarence ribbons, which extend to water depths of 15 m, more than 3 km from shore. Textural bands tentatively interpreted as a product of Langmuir circulations generated by a combination of wind and waves have been observed on the San Pedro shelf off southern California (KARL, 1980).

Current-Produced Transverse Bedforms – Bedforms that can definitely be interpreted as produced by currents are not

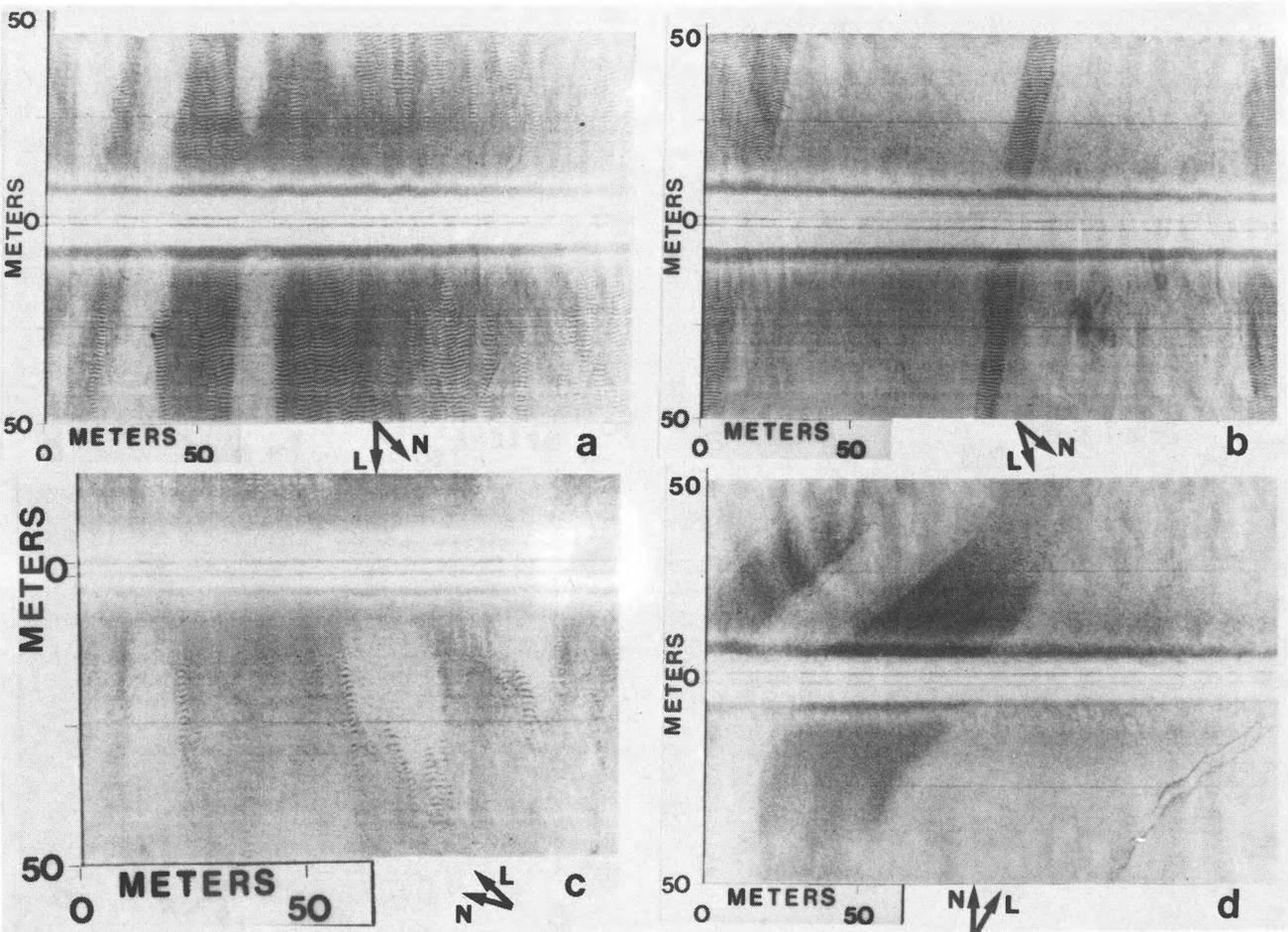


Fig. 8 Sonographs of ribbons in the Port Clarence area. Arrows as in Fig. 5. (Positions of sonographs in Fig. 2).

- a. Sand, gravel, and rippled fine gravel ribbons.
- b. Sand and rippled fine gravel ribbons.
- c. Elongate patches of sand surrounded by gravel, with narrow transitional zones of rippled fine gravel.
- d. Sand and gravel ribbons oriented parallel to ice gouge (lower right); note gougelike features at boundaries between sand and gravel.

common in the Port Clarence and Nome-Solomon areas. Asymmetric sand waves having spacings of 2 to 4 m occur near the bases of the marginal slopes of the entrance to Port Clarence (Fig. 9). Asymmetric transverse bedforms composed at least partly of pebble gravel occur in water depths of 12 to 15 m off Safety Sound (Fig. 10a). These gravelly sand waves are as much as 2.5 m in height, average 200 m in spacing, trend at a high angle to shore (N 12°E), and face westward.

Boulder ridges in water depths of 12 to 15 m off Nome trend at high angles to shore (trend N 33-60°E) and have relatively steep west-facing slopes (Fig. 10b). Underwater television showed that the west-facing slopes are composed of boulders and the more gentle east-facing slopes are composed of sand and relatively fine gravel.

The direction of asymmetry of the bedforms off Safety Sound is in accord with the dominance of westward currents in northern Norton Sound (NELSON & HOPKINS, 1972; COACHMAN ET AL., 1975). These bedforms were probably produced by

westward tidal currents reinforced by the semipermanent net westward drift, by storm-surge relaxation currents, or by a combination of these currents. The boulder ridges off Nome cannot certainly be attributed to current action. If they were produced by modern currents, only storm-surge relaxation currents could possibly be of adequate strength. An alternative explanation is that the boulder ridges were produced during the Holocene transgression at water depths shallower than present. Even assuming an origin in shallower water, it remains unknown whether the ridgelike form of the boulder masses was produced by wave and current action or resulted from the original distribution of boulders in the glacial or glaciofluvial material eroded during the Holocene transgression.

Areas Off Yukon Delta

Rolling and hummocky topography – Irregular rolling and hummocky topography characterizes the seaward edge of the

sub-ice platform and the upper part of the delta front (Fig. 4b). On the northern side of the delta, the rolling topography consists of east-west-trending sediment shoals that form a transition zone between the sub-ice platform and the delta front. Water depths over the shoal crests are 1 to 2 m and over the intervening troughs are 4 to 6 m. The shoal crests are 3 to 6 km apart. Seaward of the shoals, on the upper part of the delta front, smaller undulatory features occur. Relief is as much as 1 m, and the crests are 100 to 300 m apart. Below a water depth of about 5 m, the undulations disappear and the delta front slopes smoothly down to the nearly flat prodelta.

The morphology of the offshore part of the delta changes from the northern to the western side. The sub-ice platform on the western side is narrower than the platform on the northern side, and the slope of the delta front and prodelta on the western side is twice as steep as the slope on the northern side. The western delta front is irregular and hummocky but does not have the shoals or rolling topography characteristic of the northern delta front. Locally, the western delta front has seaward-facing steps, which may be slump scarps, with as much as 0.5 m relief. Possible slump features are shown in Figure 11a. Current-scour depressions eroded into underlying competent beds are also seen on the lower part of the western delta front or upper prodelta (Fig. 11b). Two major and numerous minor subaqueous distributary channels cut through the sub-ice platform and delta front (Fig. 4b). In

contrast, the northern parts of the sub-ice platform and delta front have no channels. Scour features in the channels (Fig. 11c) are proof that the channels are modern and active.

The differences in topographic features between the northern and western sides of the offshore delta complex suggest differences in type or intensity of the processes at work. Unlike the northern side, which faces Norton Sound, the western side faces the open Bering Sea and is strongly affected by the north-flowing Alaskan Coastal Water Current. The northern delta front and sub-ice platform are in a destructive or erosive phase characterized by wave and current reworking of sediment infor features such as shoals, ripples, and rolling topography. The western delta front and sub-ice platform are in a constructive phase characterized by rapid sedimentation and associated processes such as channeling, current scour, and slumping.

Sand waves and ripples – Sand waves and ripples are found on the upper parts of the delta front and on the flanks and bottoms of the major subaqueous distributary channels on the western side of the delta (Fig. 4b). Wavy bedforms visible on depth profiles on the upper part of the delta front have heights of 10 to 50 cm and wavelengths of 10 to 200 m. These bedforms progressively increase in height toward the tops of the transition-zone shoals. The bedform crests trend generally east-west, subparalleling the trend of the shoals.

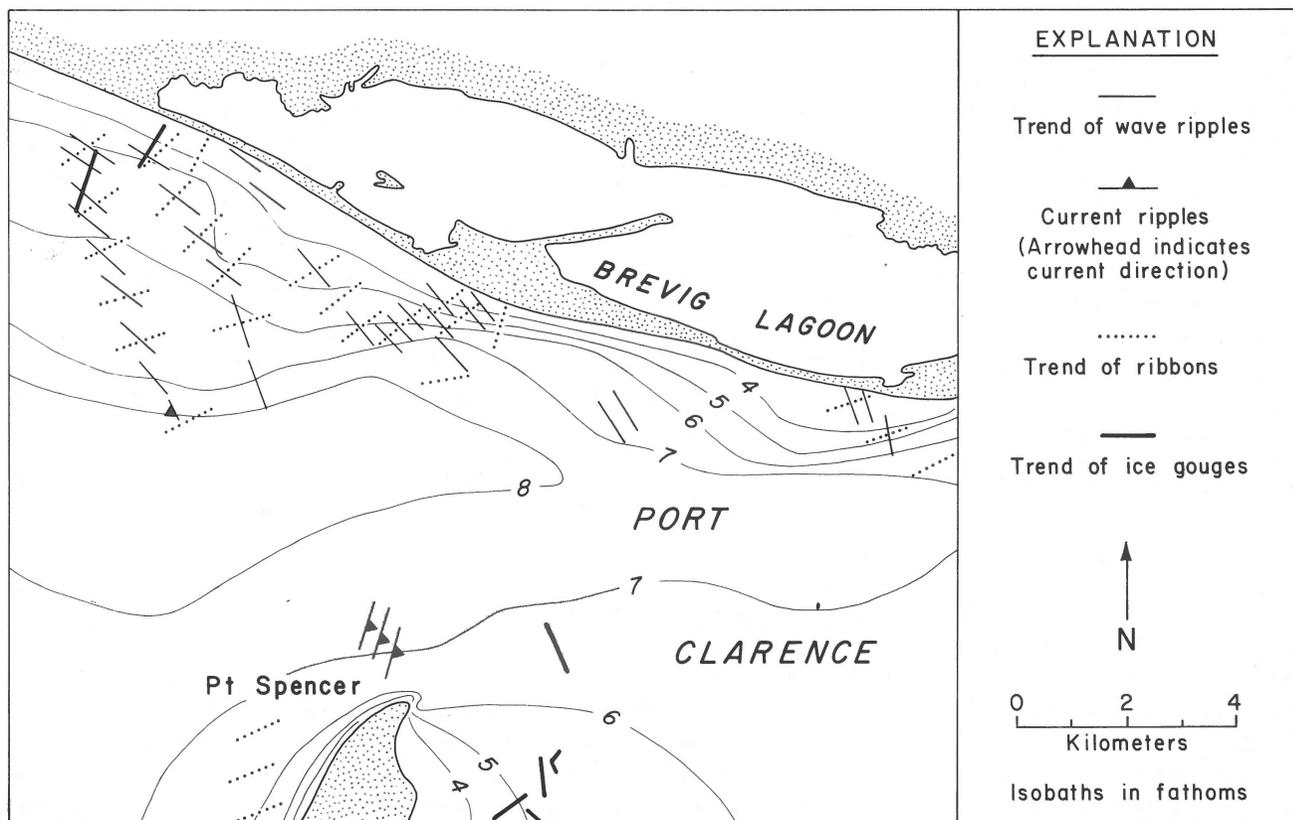


Fig. 9
Map of features shown on sonographs in vicinity of Port Clarence entrance.

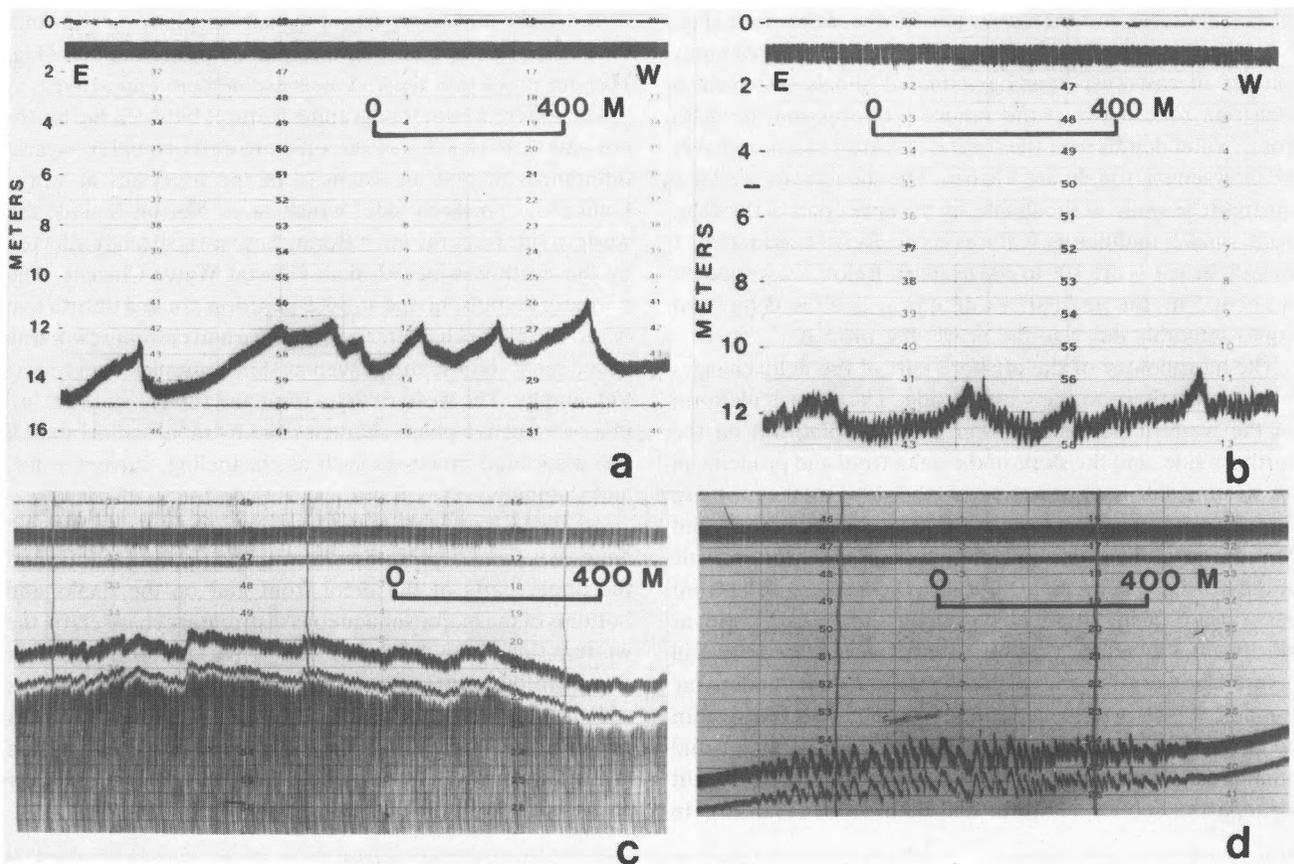


Fig. 10
Bathymetric profiles of sand waves and similar features. (Position of profiles in Figs. 3 & 4B).

- Large transverse bedforms composed partly of gravel, off Safety Sound.
- Somewhat asymmetric ridges whose steep west faces are of boulder gravel, off Nome.
- Large sand waves in a channel that crosses the sub-ice platform, Yukon Delta.
- Small sand waves in a channel that crosses the sub-ice platform, Yukon Delta.

Asymmetric ripples on the flanks of subaqueous distributary channels have wavelengths of 3 to 5 m. Sand waves in the channels are strongly asymmetrical seaward-facing bedforms with wavelengths ranging from 25 to 200 m and heights of 0.5 to 1 m (Fig. 10c, d).

The sand waves and ripples are interpreted to be in equilibrium with the present wave and current regimes. Bedforms on the delta front are caused by waves and/or currents over the shoals of the delta front. Ripples on the flanks of subaqueous distributary channels are possible caused by overbank flow during times of high river discharge. Sand waves on channel bottoms are caused by high flow velocities during times of high river discharge.

Ribbons – Light and dark bands interpreted as sediment ribbons (Fig. 11d) are visible on sonographs from the upper part of the northern delta front (Fig. 4b). The ribbons occur on the crests, flanks, and throughs of the broadly rolling ridges characteristic of the upper part of the delta front. The ribbons trend N 60-90°W, generally parallel to the trend of the rolling topography. Spacing between ribbons varies from 10 to 150 m. The wider spaced ribbons occur more commonly in

the trough areas. Associated with the ribbons are wavy bedforms, visible on depth profiles, that have wavelengths similar to the ribbon spacing, but no one-to-one correspondence between these two features could be identified. This lack of correspondence between relief features and ribbons eliminates the possibility that the ribbon features are simply bedform shadows and suggests that grain-size variations may be responsible for making the ribbons visible on sonographs. Unfortunately, no closely spaced samples are available to test this possibility. The ribbons are possibly longitudinal features produced by currents.

FEATURES PRODUCED BY ICE

Furrows produced by gouging of the seafloor are found in parts of the study area (Fig. 12). Three types of gouges occur: two are formed naturally by ice plowing the bottom sediment and one is formed artificially by anchors, anchor chains, or cables dragging the bottom. Single ice gouges are produced by a single ice keel plowing the bottom sediment. These gouges range in width from 5 to 20 m and are as much as one meter

deep, although most are less than one-half meter deep (Fig. 12a, b). Multiple gouges are produced by multikeel ice plowing or 'raking' the bottom sediment, creating numerous parallel furrows (Fig. 12c). Zones of raking are as much as 100 m wide. Artificial gouges are straighter and narrower (2 m or less) than most ice gouges (Fig. 12d).

Both single and multiple gouges are related to ice dynamics in Norton Sound. Landsat imagery has been used to study ice movement in the northeastern Bering Sea (DUPRÉ, 1978). Pack ice usually moves in a southwestward or westward direction, pushed by the prevailing northeasterly winds. When this pack ice collides with other floes or with stationary shorefast ice, ice keels are forced deeper into the water. These keels keep moving with the ice pack but extend down far

enough to plow the bottom. Gouges in Norton Sound generally trend subparallel to the shore (Fig. 4b), in agreement with ice movement directions as determined by satellite imagery. Ice-gouge trends in and around Port Clarence are more randomly oriented (Fig. 9), suggesting more complex ice movement in this embayed area.

Ice gouges are not common in the Nome-Safety Sound area because of ice movement patterns and because of current and wave action. The generally southwestward direction of ice movement in Norton Sound makes this northern part of the sound an area of ice divergence, not conducive to intense or dense gouging. Southwestern Norton Sound (Yukon prodelta area), in contrast, is an area of ice convergence and consequently of high gouge density (THOR ET AL., 1981) Gouges are

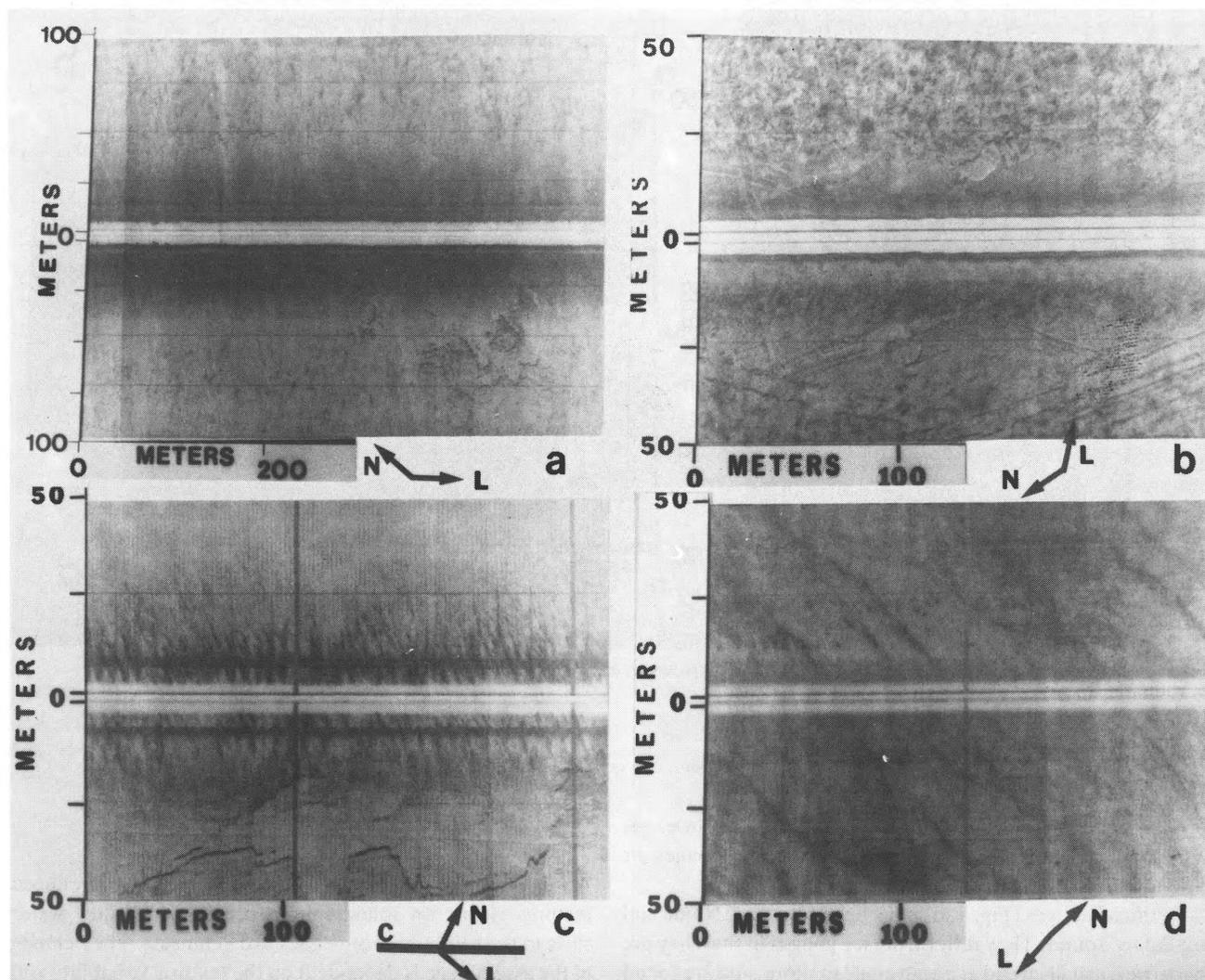


Fig. 11
Features shown on sonographs in the Yukon Delta area. Arrows as in Fig. 5: channel indicated by line labelled C. (Positions of sonographs in Fig 4B).

- a. Probable slump features.
- b. Current-scour depressions and ice gouges.
- c. Scour features in a channel that crosses the sub-ice platform.
- d. Ribbonlike features.

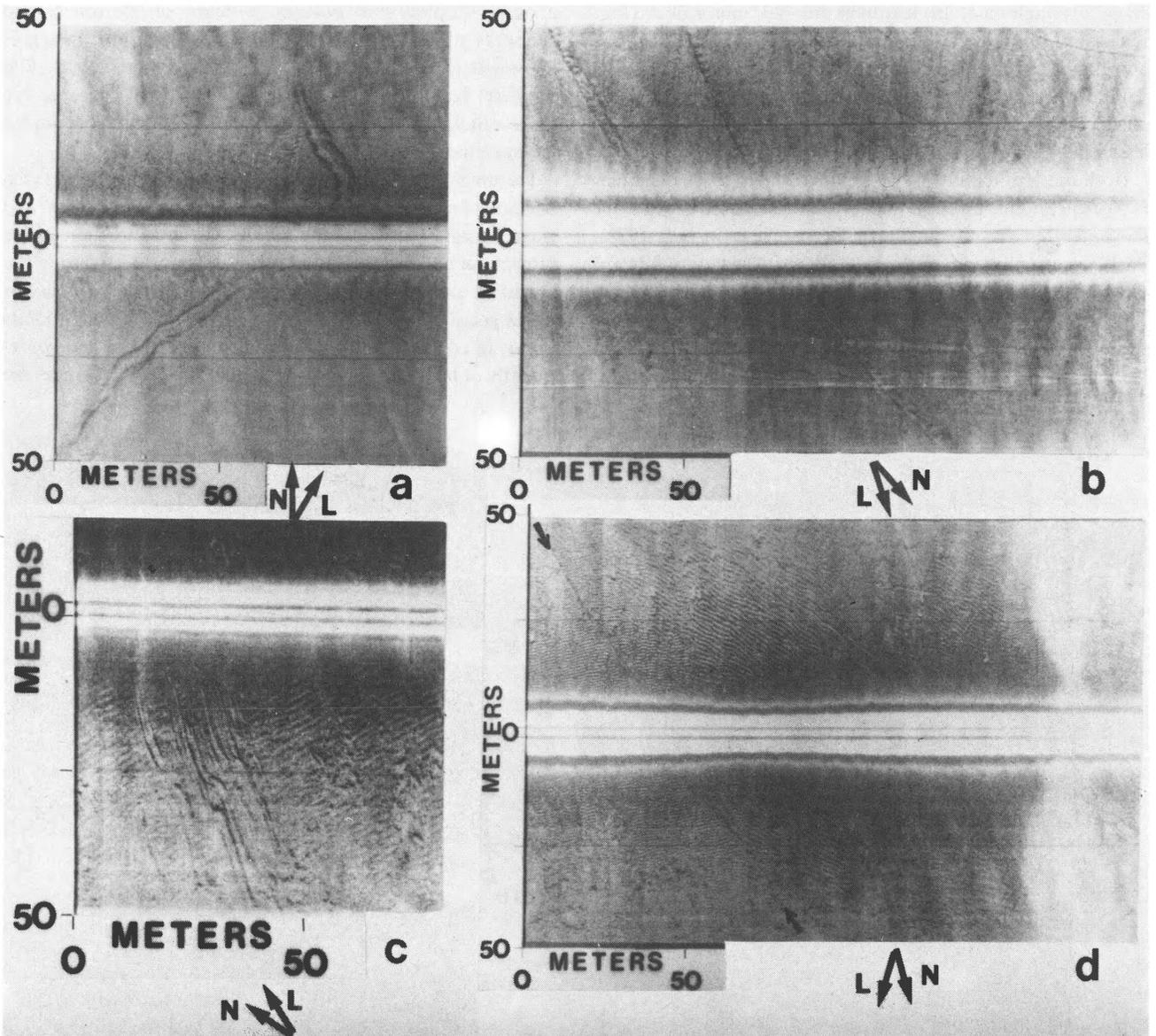


Fig. 12 Sonographs of ice gouges and similar features. Arrows as in Fig. 5. (Positions of sonographs in Figs. 2 & 3).
 a. Solitary gouge in the Port Clarence area.
 b. Solitary gouges in the Port Clarence area.
 c. Pressure-ridge raking in the Port Clarence area.
 d. Artificial gouges off Nome produced by cables or anchors; one is marked by arrows.

probably ephemeral features in this area because storm waves and tidal currents are capable of eroding the gouges or burying them by sediment.

Artificial gouges (Fig. 12d) have been found off Nome and off Safety Sound. They differ from ice gouges in that they are narrower, usually trend at a high angle to shore, and are found only in areas that have high barge traffic. Potential gouging tools are: (1) anchors and anchor chains that drag the bottom during deployment or recovery, (2) long tow cables between barges and tugboat, which tend to drag bottom even while underway, and (3) stabilization cables that trail from barge sterns.

CONCLUSIONS

A relatively rich assemblage of wave- and current-produced features visible on sonographs is present in shallow water close to the southern shore of Seward Peninsula. The richness of the assemblage is dependent on the textural variability and general coarseness of the sediment. Few features were seen on sonographs from the fine sand and silt areas off the Yukon Delta except in channels subject to river discharge.

In this area, close to the southern shore of Seward Peninsula, features inferred to be produced by waves are more common than features inferred to be produced by

currents. Where current-formed features do occur, they tend to be restricted to deeper parts of the shallow depth zone investigated here. Although the current-formed features are not common, some of them imply considerable sediment transport by strong currents. In the Nome-Solomon area, the current-formed features indicate westward sediment transport opposite from the wave-induced net sediment transport along the beaches. Current-formed features attributable to fluvial discharge occur in the Yukon Delta area.

The more problematical features described here clearly need to be investigated further. Among such features are the lobate sand patches off Safety Sound, the ribbons interpreted to be produced by wave action in the Port Clarence area, the boulder ridges off Nome and Safety Sound, and the ribbons on the Yukon Delta.

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