DEPOSIT IONAL AND EROSIONAL FEATURES **OF** THE
INNER SHELF, NORTHEASTERN BERING SEA

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ABsTRACT

Monographs 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 monographs, whereas the sediments of 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 wer 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. Some gouges off Nome and Safety Sound are caused by tugboat cables, barge cables, or anchors dragging on the bottom.

INTRODUCTION

Strong currents are known to occur in parts of the northern Bering Sea, 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 geologic importance of these currents in areas more than a few kilometers from shore has been shown in studies by Nelson and Hopkins (1972), Moore and Welkie (1976), Field et al. (1977), Nelson et al (1977), Cacchione et al. (this volume), and Drake et al. (in press). Studies by Hunter et al. (1979), in contrast, have shown that waves and wave-induced currents are the daninant geologic agents 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 daninance, and this previously little studied depth zone 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 (Fig. 1).

Data on these areas were gathered aboard the R/V KARLUK during June and July 1978. Data collected while underway include side-scan sonar, 7 kHz, and 200 kHz records; data collected at stations include underwater television tapes, observations made while diving with scuba, and a few sediment samples to supplement those gathered during previous studies by Nelson and Hopkins (1972), Moore and Welkie (1976), and McManus et al. (?977).

SETTING

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). On the north, a Holocene gravel barrier separates Port Clarence from Brevig Lagoon. The inlet to Port Clarence is 7.3 km wide, has a maximum depth of 16 m, and is floored by mud (Moore and Welkie, 1976; McManus et al., 1977). The margins of the inlet, where most of the features visible on monographs 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 inlet have not been studied, but the small tidal range and large cross-sectional area of the inlet ensure that the tidal currents are not extremely strong. Storm surges, known to be as high as 3.25 m (Sallenger et al., 1978), undoubtedly create stronger currents. The northward drift of the Alaskan Coastal Water toward Bering Strait (Coachman et al., 1975) 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 Nane area has developed by erosion of Pleistocene glacial and associated deposits (Hopkins et al., 1960; Nelson and Hopkins, 1972; Tagg and Greene, 1973). In the area from Safety Sound to Solomon, Holocene barriers of sand and gravel have formed in front of the mainland (Fig. 3). The shore face in the Nome-Solomon area slopes steeply to a depth of 12 m. Beyond the shore face, the seafloor slopes more gently. The only Holocene deposits off Nome are gravel lag deposits and thin sand patches. Sand and gravel of presumed Holocene age occur off the Safety Sound-Solomon area, but the thickness of Holocene deposits is not known.

The mean tidal range at Nome is 0.3 m. Strong westward currents, tidal in part but reinforced by a net drift, are known to occur in northern Norton Sound (Nelson and Hopkins, 1972; Coachman et al. , 1975). Currents associated with storm surges, which are as high as 4.75 m at the east end of Norton Sound (Sallenger et al., 1978), may be very strong. Fetches for waves 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: (1) a sub-ice platform, (2) a delta front, and (3) a prodelta (Dupré, this volume) (Fig. 4). The sub-ice platform extends 10 to 30 km offshore as a bearkt featureless plain at water depths of lto3 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. Sediment of the delta complex is silt to fine sand.

Wave and current patterns in southwestern Norton Sound are poorly known. The major wave trains move northward fran the southern Bering Sea and refract clockwise around the protruding Yukon shoals (Sallenger et al., 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 fran middle or late May to late October or early November. During the ice-free season the wind and wave regimens are variable; no distinctly dominant wind or wave direction is evident in data from the northeastern Bering Sea (Brewer et al., 1977). The largest storms usually occur 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. These 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

Areas off Southern Seward Peninsula

Features in the Port Clarence and Nome-Solomon inner shelf areas off the southern Seward Peninsula are similar, largely because of the similarly coarse sediment 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 of sand and gravel are ubiquitous in the Nome-Solomon area (Fig. 5). On monographs, the sand patches are light toned and the gravel patches dark toned. The patches are extremely variable in width, 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). On some of the bathymetric profiles, sand patches can be distinguished fran gravel patches by differences in acoustic signature (Fig. SC, 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, gravel ridges or mounds 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 monographs (Fig. 7). Many textural segregations are recognizable more by differences in ripple size and trend than by tonal differences on the monographs (Fig. 7b).

The tendency for the patches to be elongate at high angles to shore and to have straighter boundaries at high angles to shore than at low angles represents a tendency toward ribbonlike forms. No well-developed ribbons are found in the Nome-Solomon area, however. 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 an origin by stationary rip currents or edge waves.

Wave Ripples

Ripples with spacings of 0.5 to 2.0 m are commonly visible on monographs in both the Nome-Solomon and Port Clarence areas (Fig. 7). These ripples were identified as wave generated by their symmetry as seen on the monographs, by underwater television, and by diving. They occur wherever the sediment is moderately to well sorted and of a suitable grain size, in the very coarse sand to pebble gravel grades. Wave ripples of similar size in similarly coarse sediment are known from many areas (Trask, 1955; Vause, 1959; Newton and Werner, 1972; Channon and 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 monographs were present in medium-grained sand.

All wave ripples in the Port Clarence inlet area trend northwest-southeast and can be explained as products of storm waves propagating northeastward out of the Bering Sea. In the Nome area, at least three sets of wave ripples can be seen at a depth of 12 m (Fig. 7d). The largest ripples (spacing 1.3 m) were formed by waves from the southwest, the middle-sized ripples (spacing 0.7 m) were formed by waves from the south, and the smallest ripples visible on the monographs (spacing 0.4 m) were formed by waves from the south-southwest. Ripples of successively smaller size occur in successively finer sediment. Waves generated during a major storm must have formed the largest ripples in the coarsest rippled sediment. 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 were formed, successively smaller ripples were formed in successively finer material by what must have been successively smaller waves at successively later times.

In more detailed hydrodynamic terms, the wave ripples may be classified as vortex ripples because of their steepness (Dingier and Inman, 1977). At least the larger ripples are probably of orbital type, having a spacing similar to the orbital diameter of the waves (Clifton, 1976, Figs. 11-13). Calculations based on threshold velocities for grain movement (Rance and Warren, 1969; Komar, 1976; Dingier, 1979) and on the upper limit for the existence of orbital ripples (Mogridge and 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 of6 toll s.

Ribbons

Linear segregations or ribbons of sand and gravel are well developed at water depths of 4 to 8 m on the north side of Port Clarence, just outside and inside the inlet (Fig. 8). The ribbons are developed in three sizes of material 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 monographs, and sand with wave ripples too small to be visible on monographs. Commonly the three materials lie next to one another in order of grain size (Fig. 8a, c). The ribbons show little regularity of spacing or width, 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 current-produced bedforms (Kenyon, 1970). The currents that produce most ribbons are tidal, though wind-driven currents have apparently produced some ribbons or similar textural bands (Stride and Chesterman, 1973; McKinney et al., ?974) . 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 is in part negative. The ribbons are not parallel to the expected east-west direction of tidal or storm-surge currents through the inlet (Fig. 9). Nor are the ribbons approximately parallel to shore, as would be expected for Ekman currents driven by winds at almost any angle to shore in very shallow water (Neumann and Pierson, 1966, p. 202-203). The ribbons do not change in orientation significantly along irregularly curving isobaths on the north side of the inlet, as might be expected if the ribbons were parallel to currents that were deflected around seafloor irregularities.

Several positive kinds of evidence suggest 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.

Exactly how waves might produce ribbons is not known, though several mechanisms are conceivable. Originally irregular textural segregations produced by other causes might become streaked out by sediment transport caused either by wave-induced net water motion in the direction of wave propagation or, if net water motion is absent, by 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 (Failer and 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 complicated by the fact that some of the ribbons in very shallow water are parallel to, and possibly bounded by, ice gouges (Fig. 8d). These ribbons may have somehow 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 sanewhere 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 that area than in the Port Clarence area could be explained by a greater variability of 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 and Pilkey (1969) 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 and 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 common in the Port Clarence and Nome-Solomon areas. Asymmetric sand waves having spacings of 2 to 4 m occur in the deeper parts of the inlet 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 bedforms 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 Nane 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 and 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 origin of the boulder ridges off Nane is not known. If they were produced by modern currents, only storm-surge relaxation currents could possibly be of adequate strength, and even these currents may not be capable of moving boulders. An alternative explanation is that the boulder ridges were produced during the Holocene transgression at water depths shallower than pre sent. If so, they may be similar in origin to the boulder ridges at water depths of 4 to 8 m off Nane (Fig. 5c) except that sand and finer gravel have been banked up against their east sides. 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). North of the delta, the topography consists of east-west-trending sediment shoals that form a transition zone between the sub-ice platform and the delta f rent. 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, the surface is undulatory or rolling. 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 morphologic character 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 and erosion 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. In contrast, the northern parts of the sub-ice platform and delta front have no channels. Scour in the channels (Fig. 11c) is 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 different processes or differences in degree and 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 into 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 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.

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 Impacting the shoals of the delta front. Ripples on the flanks of subaqueous distributary channels are possibly 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

Features interpreted as sediment ribbons (Fig. 11d) are visible on sonographs from an area north of the Yukon delta, on the upper part of the delta front (Fig. 4b). The ribbons occur on the crests, flanks, and troughs 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 tend to occur more commonly in the trough areas. Associated with the ribbons are wavy bed-relief features, visible on depth profiles, that have wavelengths similar to ribbon spacing, but the lack of a one-to-one correspondence in location or spacing between these two features obscures their relations. As ribbon and interribbon areas were not sampled, the grain size of these features is not known. The character of the ribbons on the sonographs, however, requires some acoustic difference (probably grain size) between ribbon and interribbon areas. The lack of correspondence between relief features and ribbons eliminates the possibility that the ribbon features are simply bedform shadows.

The ribbons occur in shallow water on the south side of the entrance to Norton Sound. This area is highly susceptible to southern Bering Sea storm waves, storm-surge run-off, the Alaskan Coastal Water Current, and tidal currents that would pass through the area either in a westward or an eastward direction. The ribbons here are subparallel to known or probable current directions and are possibly longitudinal features produced by one or more of these 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 gouging 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 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.

Gouge furrows are not a common feature in the Nome/Safety Sound area because of ice movement patterns and because of current and wave action. Ice generally moves in a southwestward direction, making northern Norton Sound an area of ice divergence, not conducive to intense or dense gouging. Southwestern Norton Sound (Yukon prodelta area) is an area of ice convergence and consequently of high gouge density. Gouges are 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 fran barge sterns.

CONCLUSIONS

A rich assemblage of wave- and current-produced features visible on monographs 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 monographs fran the fine sand and silt areas of the Yukon delta except in channels subject to river discharge.

In general, features hewn or thought to be produced by waves are more common than current-formed features. 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, sane 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.

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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REFERENCES

Black, R. F. (1958) Permafrost, water-supply, and engineering geology of Point Spencer Spit, Seward Peninsula, Alaska. Arctic, 11, 102-116.

Brewer, W. A., Jr., Diaz, H. F., Prechtel, A. S., Searby, H. W. & Wise, J. L. (1977) Climatic atlas of the outer continental shelf waters and coastal regions of Alaska. Vol. II, Bering Sea. Arctic Environ. Inf. and Data Center, Anchorage, Alaska, and Natl. Climatic Center, Asheville, N. C.

Cacchione, D. A., Drake, D. E. & Wiberg, Patricia (this volume) Bottom shear stress generated by waves and currents in the northern Bering Sea. Spec. Pub. Internat. Assoc. Sedimentologists.

Channon, R. D. & Hamilton, D. (1976) Wave and tidal current sorting of shelf sediments southwest of England. Sedimentology, 23, 17-42.

Clifton, H. E. (1976) Wave-formed sedimentary structures - a conceptual mode 1. In (Ed. by R. A. Davis, Jr. & R. L. Ethington) Beach and nearshore sedimentation. Spec. Pap. Sot. econ. Paleont. Miner. 24, 126-148.

Coachman, L. K., Aagaard, Knut & Tripp, R. B. (1975) Bering Strait: the regional physical oceanography. Univ. Washington Press, Seattle.

Dingier, J. R. (1979) The threshold of grain motion under oscillatory flow in a laboratory wave channel. J. sedim. Petrol. 49, 287-294.

Dingier, J. R. & Inman, D. L. (1977) Wave-formed ripples in nearshore sands. Conf. Coastal Engring., 15th, Proc. 2109-2125.

Drake, D. E., Cacchione, D. A., Muench, R. D. & Nelson, C. H. (in press) Sediment transport in Norton Sound, Alaska. Mar. Geol.

Dupré, W. R. (1978) Yukon delta coastal processes study, in Environmental assessment of the Alaskan continental shelf, Annual reports of principal investigators for the year ending March 1978. Vol. XI, Hazards. Natl. Oceanic and Atmospheric Admin. and Bur. Land Management, 384-446.

Dupré, W. R. (this volume) Seasonal variations in deltaic sedimentation on a high-latitude epicontinental shelf. Spec. Pub. Internat. Assoc. Sedimentologists.

Failer, A. J. & Caponi, E. A. (1978) Laboratory studies of wind-driven Langmuir circulations. Jour. Geophys. Res. 83, 3617-3633.

Field, M. E., Nelson, Hans, Cacchione, D. A. & Drake, D. E. (1977) Dynamics of bedforms of an epicontinental shelf: northern Bering Sea (abs.). Am. geophys. Union Trans. (EOS), 58, 1162.

Hopkins, D. M., McNeil, F. S. & Leopold, E. B. (1960) The coastal plain of Nome, Alaska. Internat. geol.Cong., XXI Ssss., 4, 46-57.

Hunter, R. E., Sallenger, A. H. & Dupré, W. R. (1979) Maps showing directions of longshore sediment transport along the Alaskan Bering Sea coast. Misc. Field Studies Map U. S. geol. Surv. MF-1049.

Karl, H. A. (1980) Speculations on processes responsible for mesoscale current lineations on the continental shelf, Southern California. Mar. Geol. 34, M9-M18.

Kenyon, N. H. (1970) Sand ribbons of European tidal seas. Mar. Geol. 9, 25-39.

Komar, P. D. (1976) Beach precesses and sedimentation, Prentice-Hall, Englewood Cliffs, N. J.

Larsen, M. C., Nelson, Hans & Thor, D. R. (1980) Geologic implications and potential hazards of scour depressions on Bering shelf, Alaska. Environmental Geol. 3, 39-47.

Mac Intyre, I. G. & Pilkey, O. H. (1969) Preliminary comments on linear sand-surface features, Onslow Bay, North Carolina continental shelf: problems in making detailed sea-floor observations. Maritime sediments, 5, 26-29.

McKinney, T. F., Stubblefield, W. L. & Swift, D. J. P. (1974) Large-scale current lineations on the central New Jersey shelf: investigations by side-scan sonar. Mar. Geol. 17, 79-102.

McManus, D. A., Rolls, Venkatarathnam, Hopkins, D. M. & Nelson, C. H. (1977) Distribution of bottom sediments on the continental shelf, northern Bering Sea. Prof. Pap. U. S. geol. Surv. 759-C.

Mogridge, G. R. & Kamphuis, J. W. (1972) Experiments on bed form generation by wave action. Conf. Coastal Engring., 13th, ProC., 2, 1123-1142.

Moore, J. R. & Welkie, C. J. (1976) Metal-bearing sediments of economic interest, coastal Bering Sea. Alaska geol. Sot. Symposium on recent and ancient sedimentary environments of Alaska, Proc. ICI-X17.

Nelson, C. H., Cacchione, D. A., Field, M. A., Drake, D. E. & Nilsen, T. H. (1977) Complex ridge and trough topography on a shallow current-dominated shelf, northwest Alaska (abs.). Bull. Am. Assoc. Petrol. Geol. 61, 817.

Nelson, C. H. & Hopkins, D. M. (1972) Sedimentary processes and distribution of particulate gold in the northern Bering Sea. Prof. Pap. U. S. geol. Surv. 689.

Neumann, Gerhard & Pierson, W. T., Jr. (1966) Principles of physical oceanography. Prentice-Hall, Englewood Cliffs, N. J.

Newton, R. S., Seibold, E. & Werner, F. (1973) Facies distribution patterns on the Spanish Sahara continental shelf mapped with side-scan sonar. "Meteor" Forsch-Ergebnisse, Reihe C., 15, 55-77.

Newton, R. S. & Werner, Friedrich (1972) Transitional-size ripple marks in Kiel Bay (Baltic Sea). Meyniana, 22, 89-94.

Rance, P. J. & Warren, N. F. (1969) The threshold of movement of coarse material in oscillatory flow. Conf. Coastal Engring., 11th, Proc. 1, 487-491.

Reimnitz, Erk, Toimil, L. J., Shepard, F. P. & Gutierrez-Estrada, Mario (1976) Possible rip-current origin for bottom ripple zones to 30 m depth. Geology, 4, 345-400.

Sallenger, A. H., Jr., Dingier, J. R. & Hunter, R. E. (1978) Coastal processes and morphology of the Bering Sea coast of Alaska, in Environmental assessment of the Alaskan continental shelf, Annual reports of principal investigators for the year ending March 1978. Vol. XII. Hazards. Natl. Oceanic and Atmospheric Admin. and Bur. Land Management, 451-502.

Stride, A. H. & Chesterman, W. D. (1973) Sedimentation by non-tidal currents around northern Denmark. Mar. Geol., 15, M53-M58.

Swift, D.J.P., Freeland, G. L., Gadd, P. E., Han, G., Lavelle, J. W. & Stubblefield, W. L. (1976) Morphologic evolution and coastal sand transport, New York-New Jersey shelf. In Middle Atlantic Continental Shelf and the New York Bight (Ed. by M. G. Gross). Am. Soc. Limnol. Oceanog. Special Symposia, 2, 69-89.

Swift, D. J. P. & Freeland, G. L. (1978) Current lineations and sand waves on the inner shelf, Middle Atlantic Bight of North America. J. sedim. Petrol. 48, 1257-1266,

Tagg, A. R. & Greene, H. G. (1973) High-resolution seismic survey of an offshore area near Nome, Alaska. Prof. Pap. U. S. Geol. Survey 759-A.

Trask, P. D. (1955) Movement of sand around southern California promontories. U. S. Corps Engrs. Beach Erosion Board Tech. Memo. 76.

Vause, J. E. (1959) Underwater geology and analysis of recent sediments off the northwest Florida coast. J. sedim. Petrol. 29, 555-563.

FIG. 1 -- Index map showing areas studied in the northeastern Bering Sea.

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.

FIG. 4 -- a. Map of tracklines in Yukon delta area.

b. Map of morphologic features, and of features shown on monographs in Yukon delta area.

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.

a. Sonograph of irregular patches.

b. Sonograph of elongate patches.

c. Bathymetric profile of area shown in a.

d. Bathymetric profile of area shown in b.

FIG. 6 -- Sonograph of cuspate sand and gravel patches off Safety Sound.

FIG. 7 -- -Monographs of wave ripples and associated features.

a. Sand (light-toned), gravel (dark-toned), 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.

FIG. 8 -- Sonographs ox ribbons in the Port Clarence area.

a. Sand (light-toned], gravel (dark-toned), 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 gauge (lower right); note gauge-like features at boundaries between sand and gravel.

FIG. 9 -- Map of features shown on monographs in vicinity of Port Clarence entrance.

Fig. 10 -- Bathymetric profiles of sound waves and similar features.

a. Large transverse bedforms compared partly of gravel, off Safety Sound.

b. Somewhat asymmetric ridges whose steep west faces are of boulder gravel, off Nome.

c. Large sand waves in a channel that crosses the sub-ice platform, Yukon delta.

d. Small sand waves in a channel that crosses the sub-ice platform, Yukon delta.

FIG. 11 -- Features shown on monographs in Yukon delta area.

a. Probable slump features.

b. Current-scour depressions and ice gouges.

c. Scour features in a channel that crosses the sub-ice platform.

d, Ribbon-1ike features.

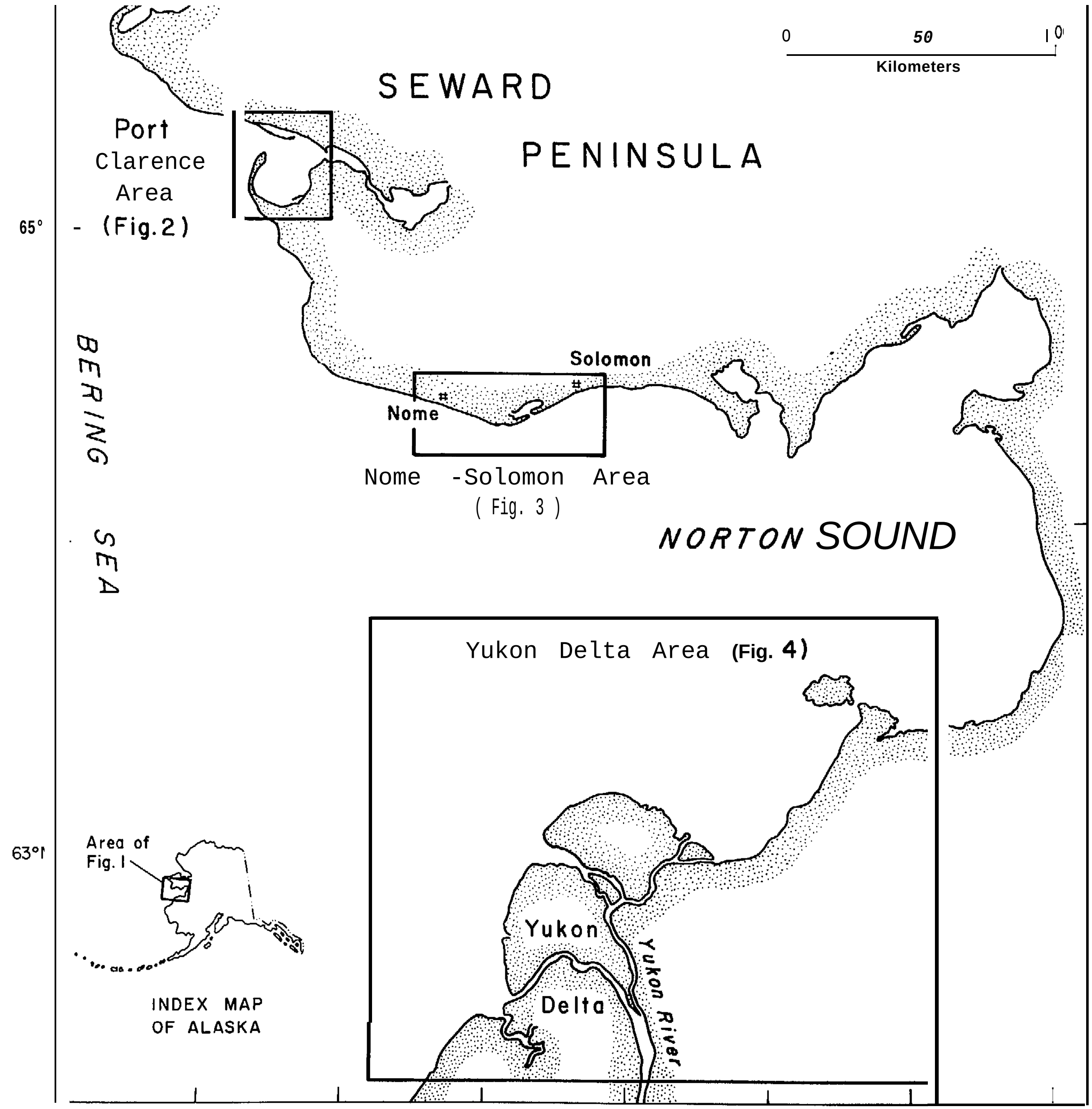
FIG. 12 -- -Monographs of ice gouges and similar features.

a. Solitary gouge in the Port Clarence area.

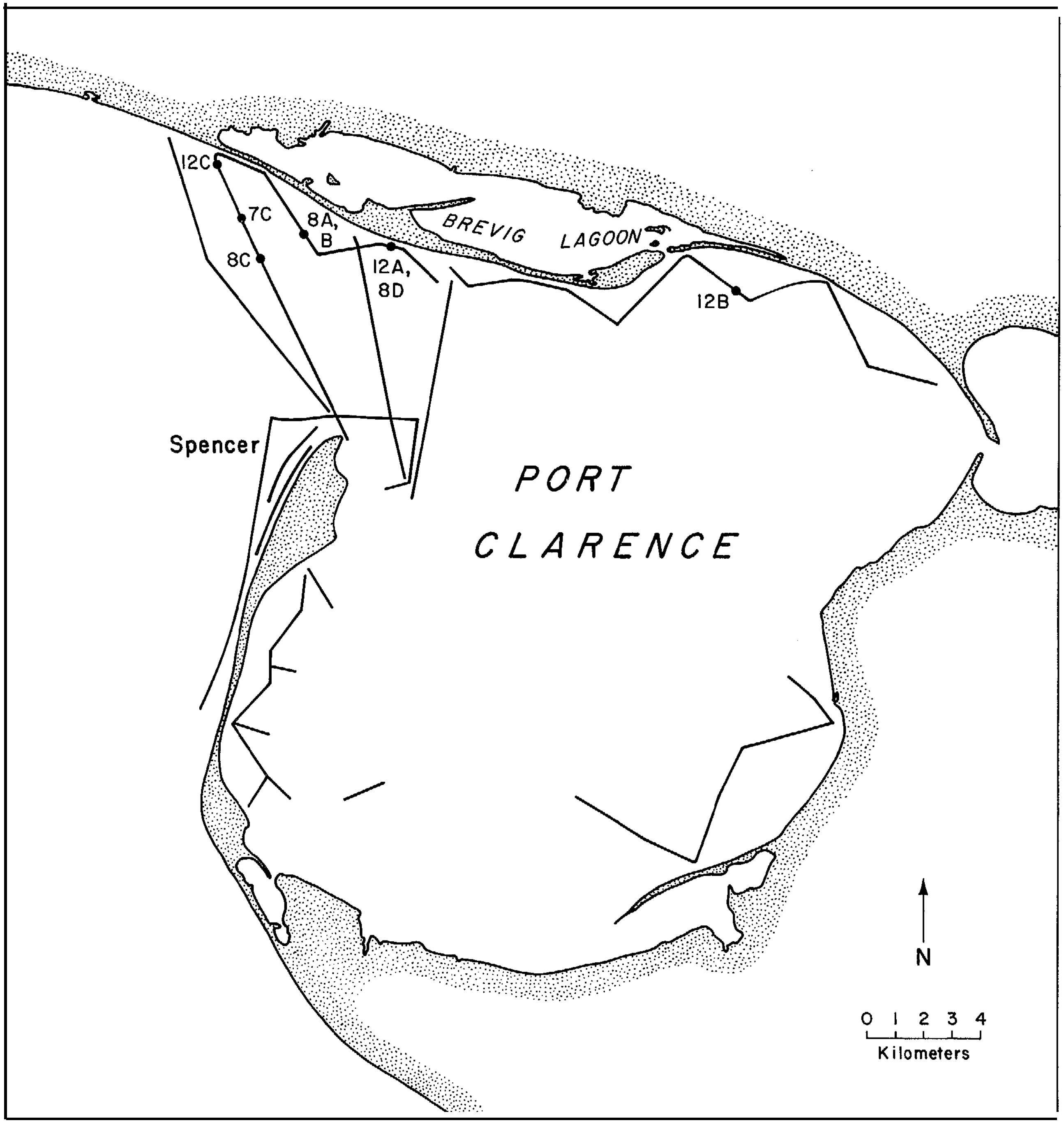
b. Solitary gouges in the Port Clarence area.

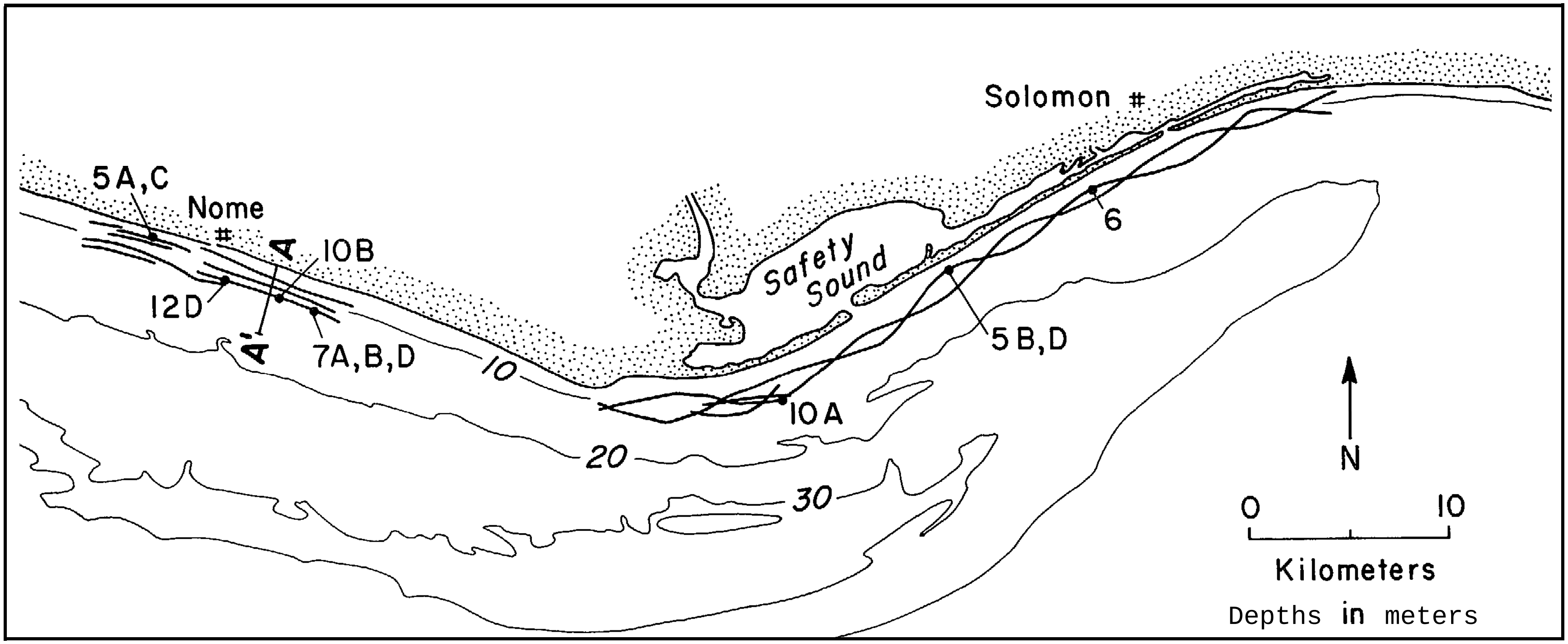
c* Pressure-ridge raking off Safety Sound,

d. Artificial gouges off Nome; one is marked by arrows.

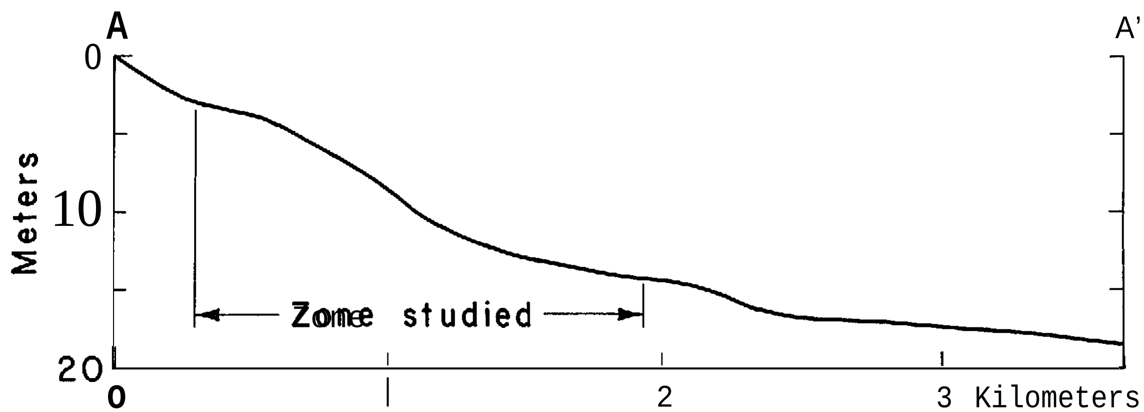


0 50 100
Kilometers
SEWARD
PENINSULA
Port
Clarence
Area
(Fig.2)
65°
BERING
SEA
Solomon
Nome
Nome -Solomon Area
(Fig. 3)
NORTON SOUND
Yukon Delta Area (Fig. 4)
63°
Area of
Fig. 1
INDEX MAP
OF ALASKA
Yukon
Delta
Yukon River

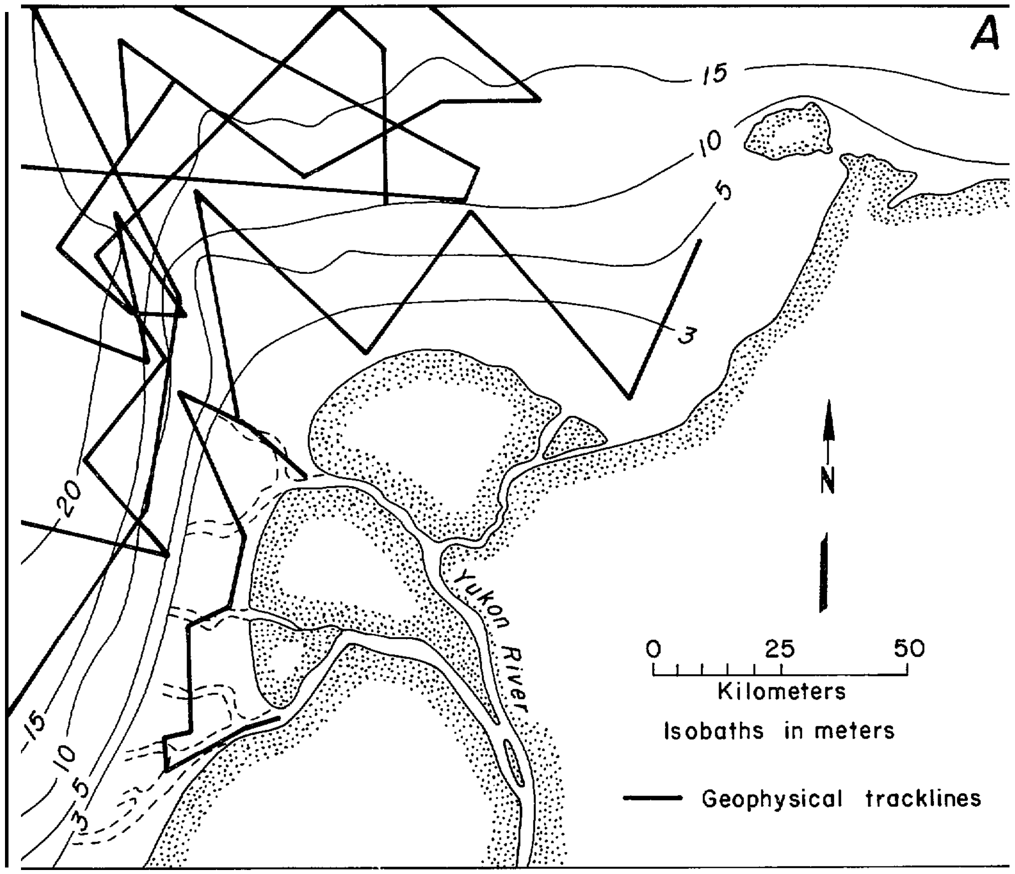

BREVIG LAGOON
PORT CLARENCE
12C
7C
8C
8A, B
12A, 8D
12B
Spencer
N
0 1 2 3 4
Kilometers

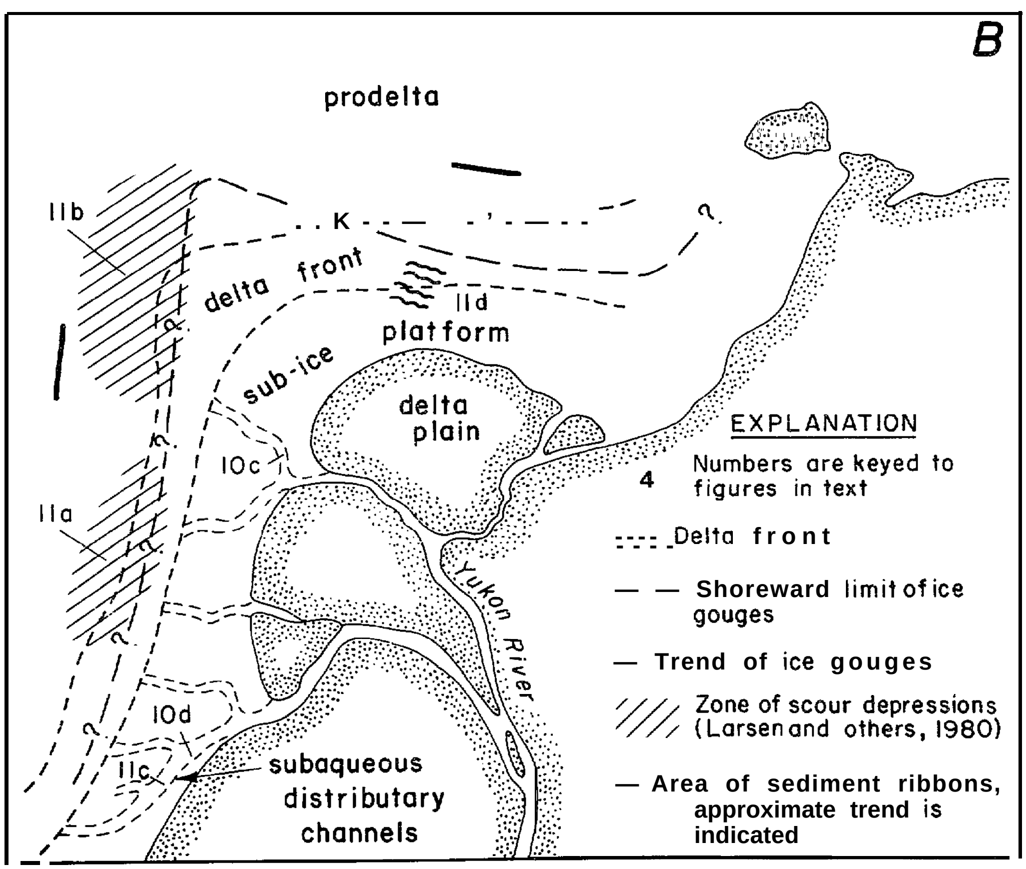


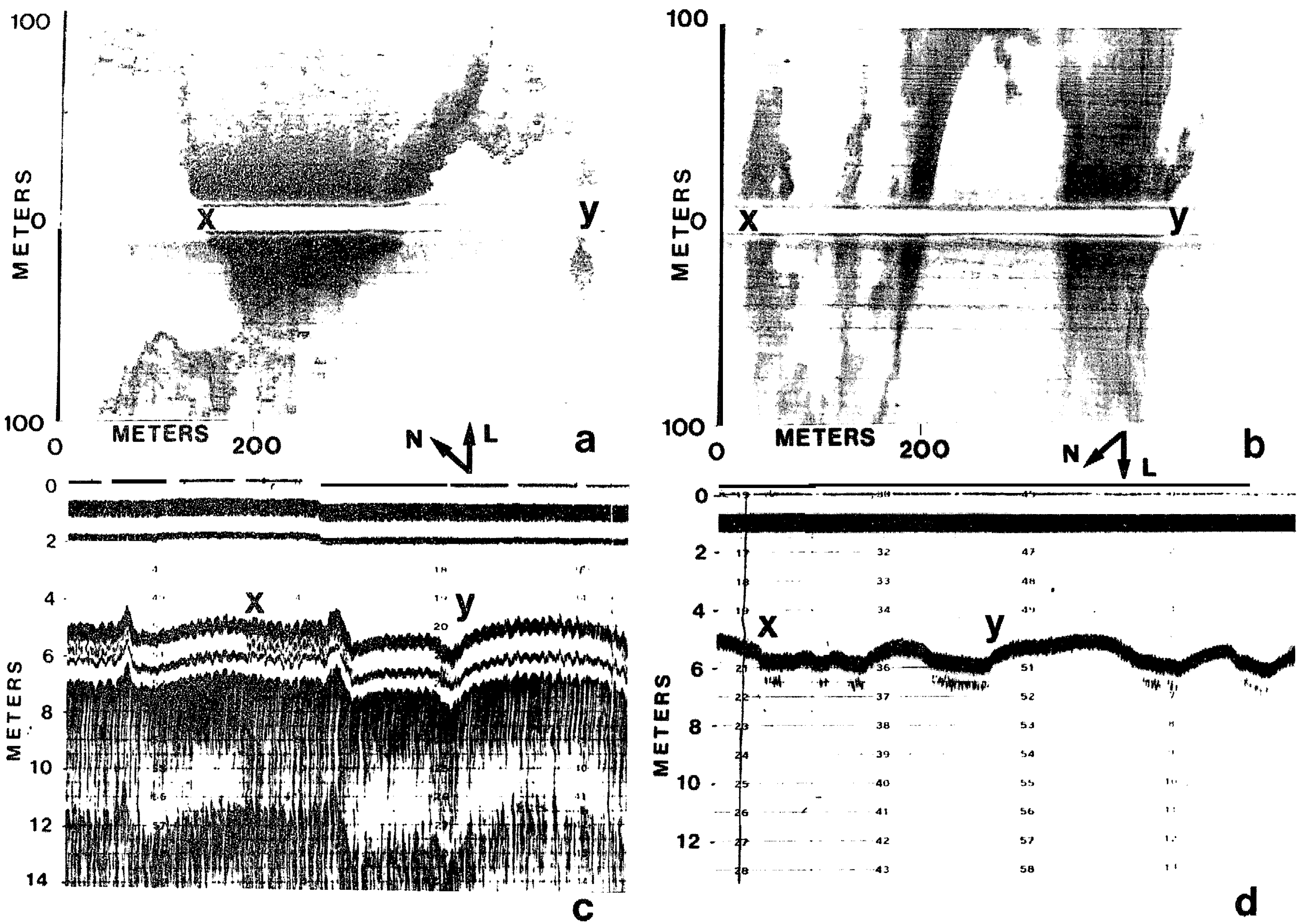
Solomon
5A,C
Nome
A
A'
10B
12D
7A,B,D
10
Safety Sound
6
5B,D
10A
20
30
N
0
10
Kilometers
Depths in meters



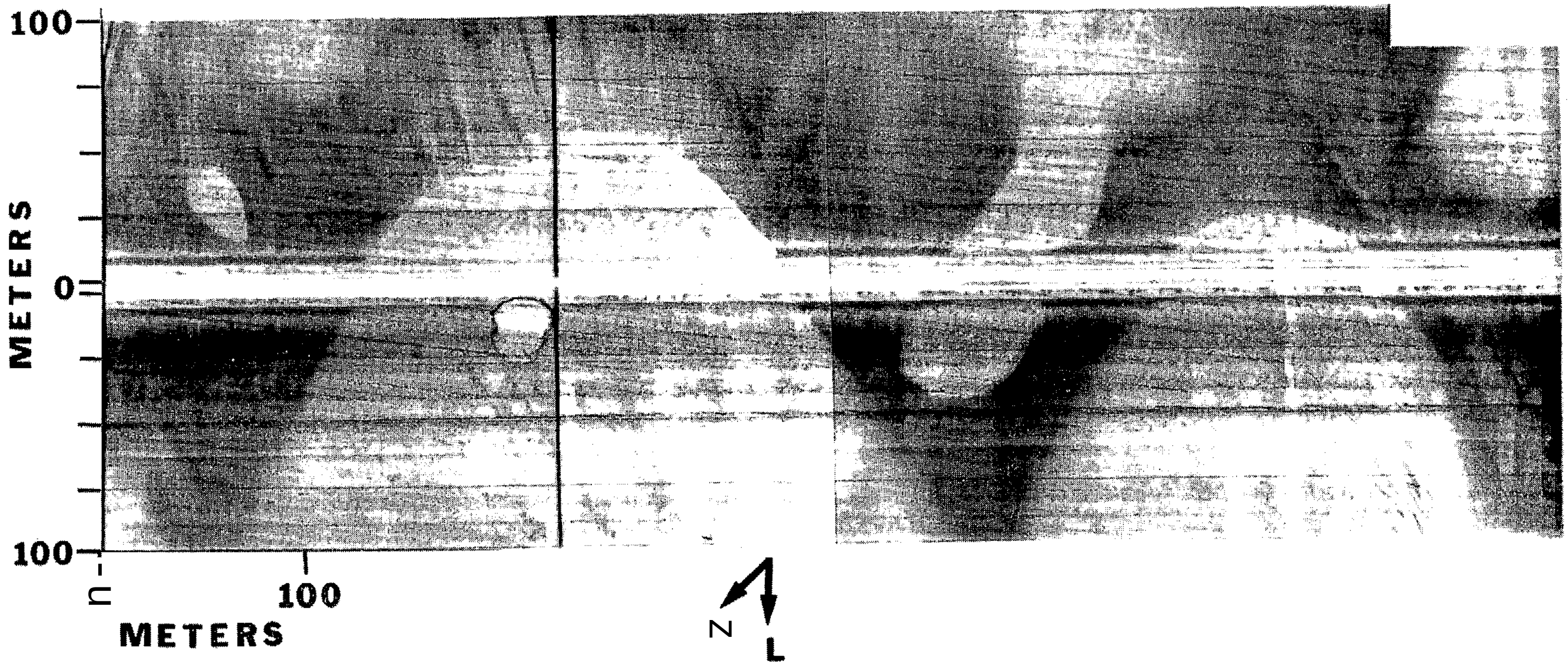
A
A'
0
10
20
Meters
Zone studied
0
2
3 Kilometers

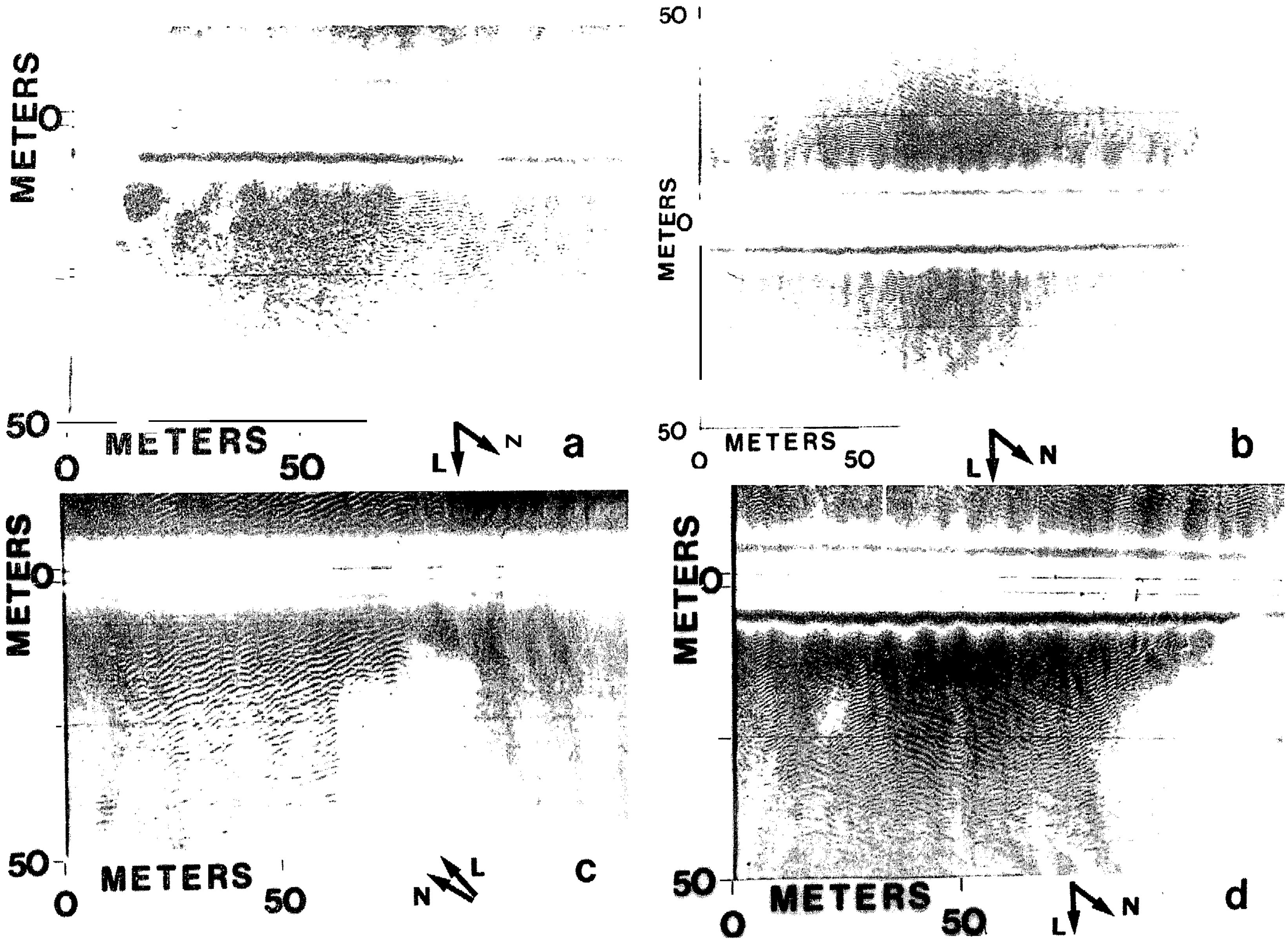

A
15
10
5
3
20
15
10
5
3
Yukon River
N
0 25 50
Kilometers
Isobaths in meters
Geophysical tracklines

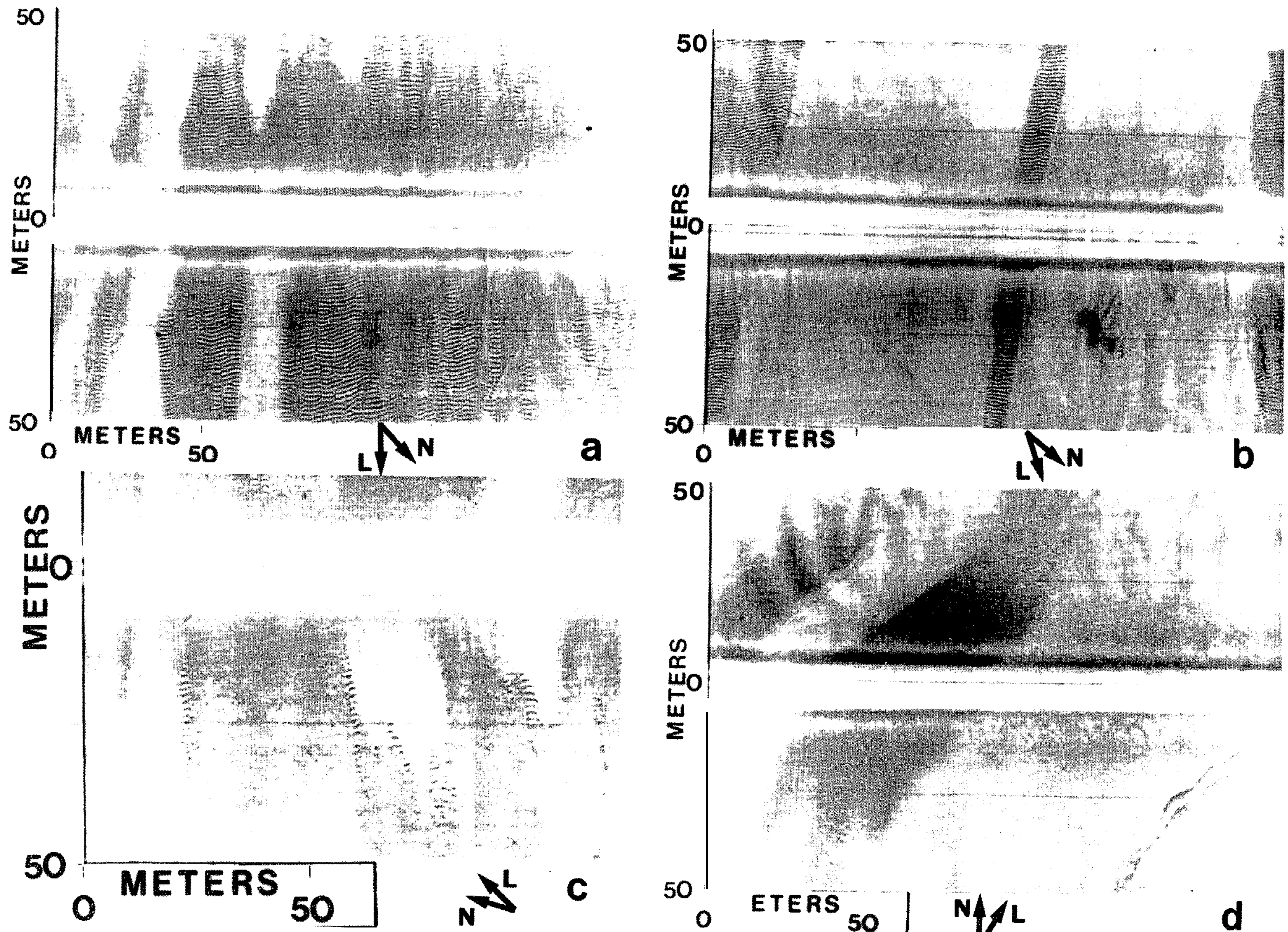

B
prodelta
K
11b
delta front
11d
platform
sub-ice
delta plain
10c
11a
10d
11c
subaqueous distributary channels
Yukon River
EXPLANATION
4 Numbers are keyed to figures in text
Delta front
Shoreward limit of ice gouges
Trend of ice gouges
Zone of scour depressions (Larsen and others, 1980)
Area of sediment ribbons, approximate trend is indicated



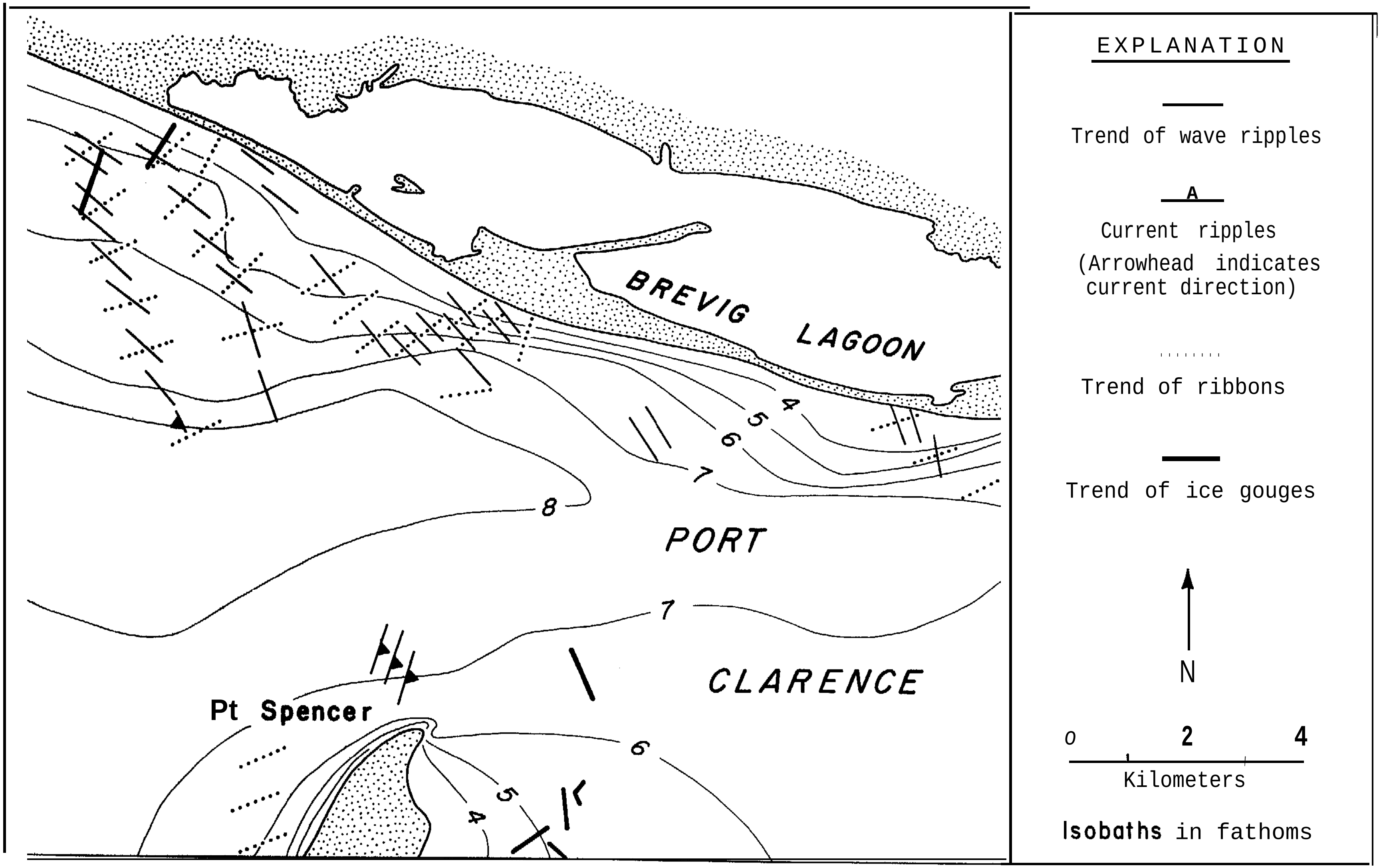
100
METERS
0
100
0
METERS
200
x
y
N
L
a
b
c
d
2
4
6
8
10
12
14

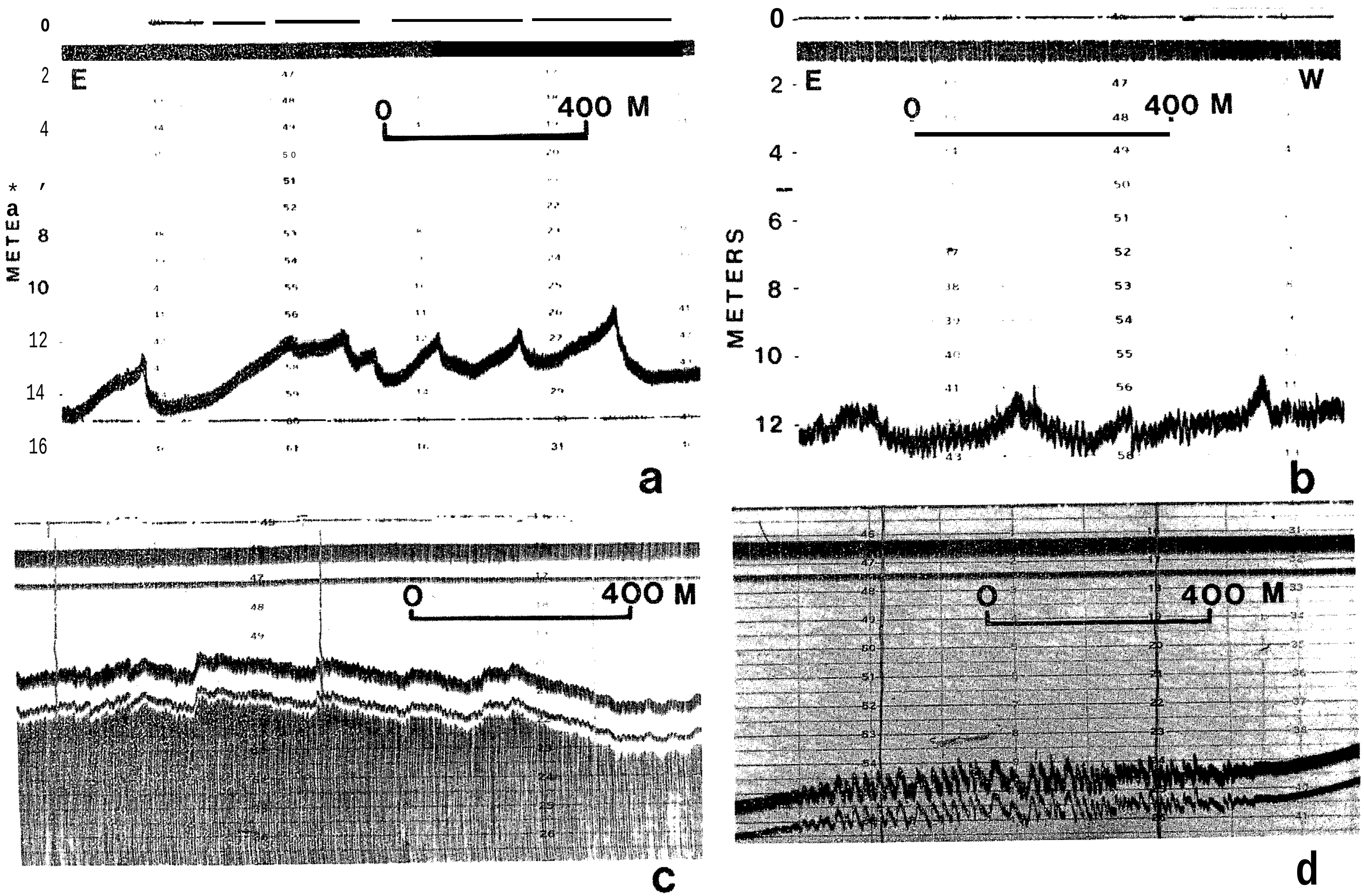

100
0
100
METERS
0
100
METERS
N
L


METERS
0
50
METERS
0
50
L
N
a
50
METERS
0
50
METERS
0
50
L
N
b
METERS
0
50
METERS
0
50
N
L
c
METERS
0
50
METERS
0
50
L
N
d

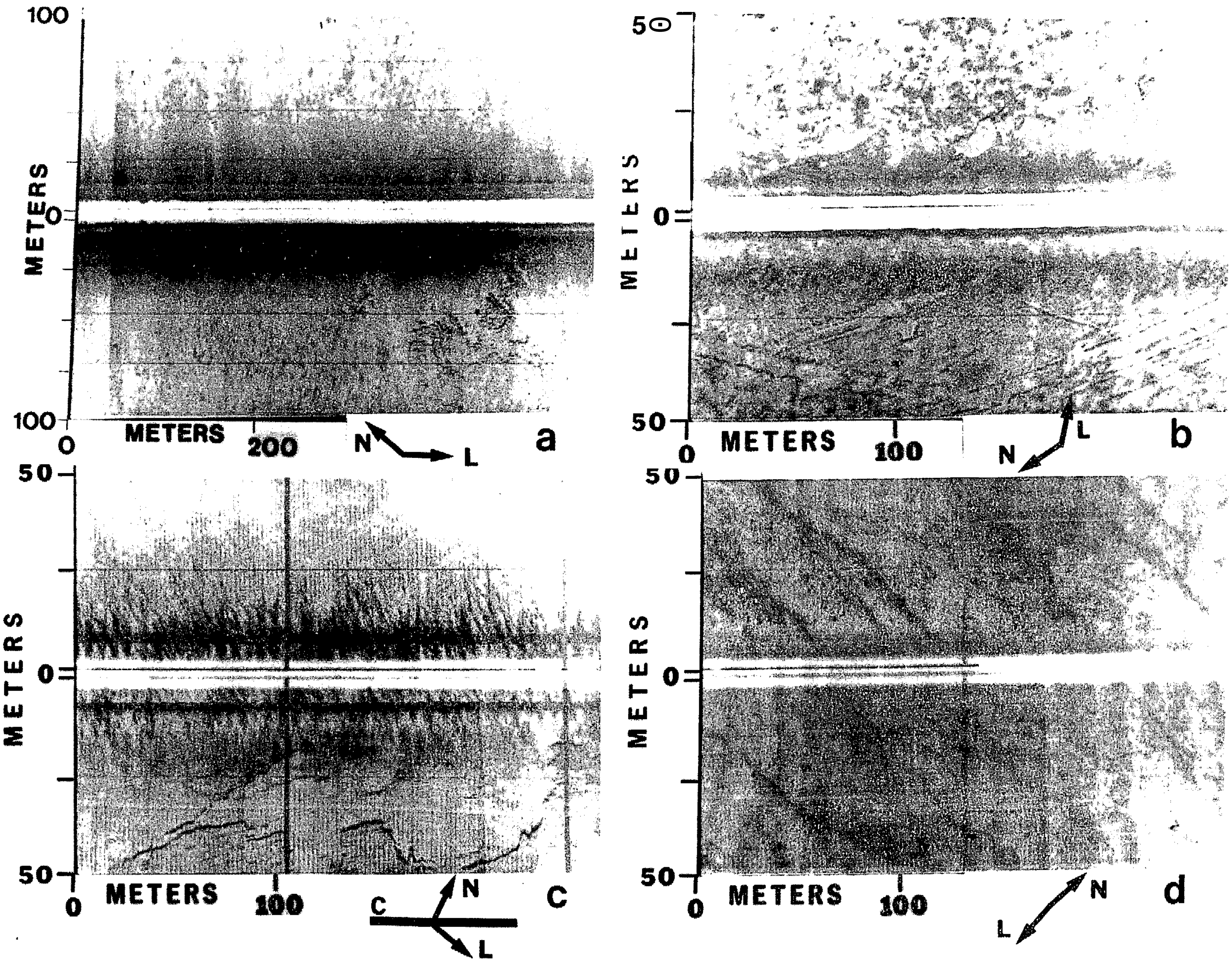


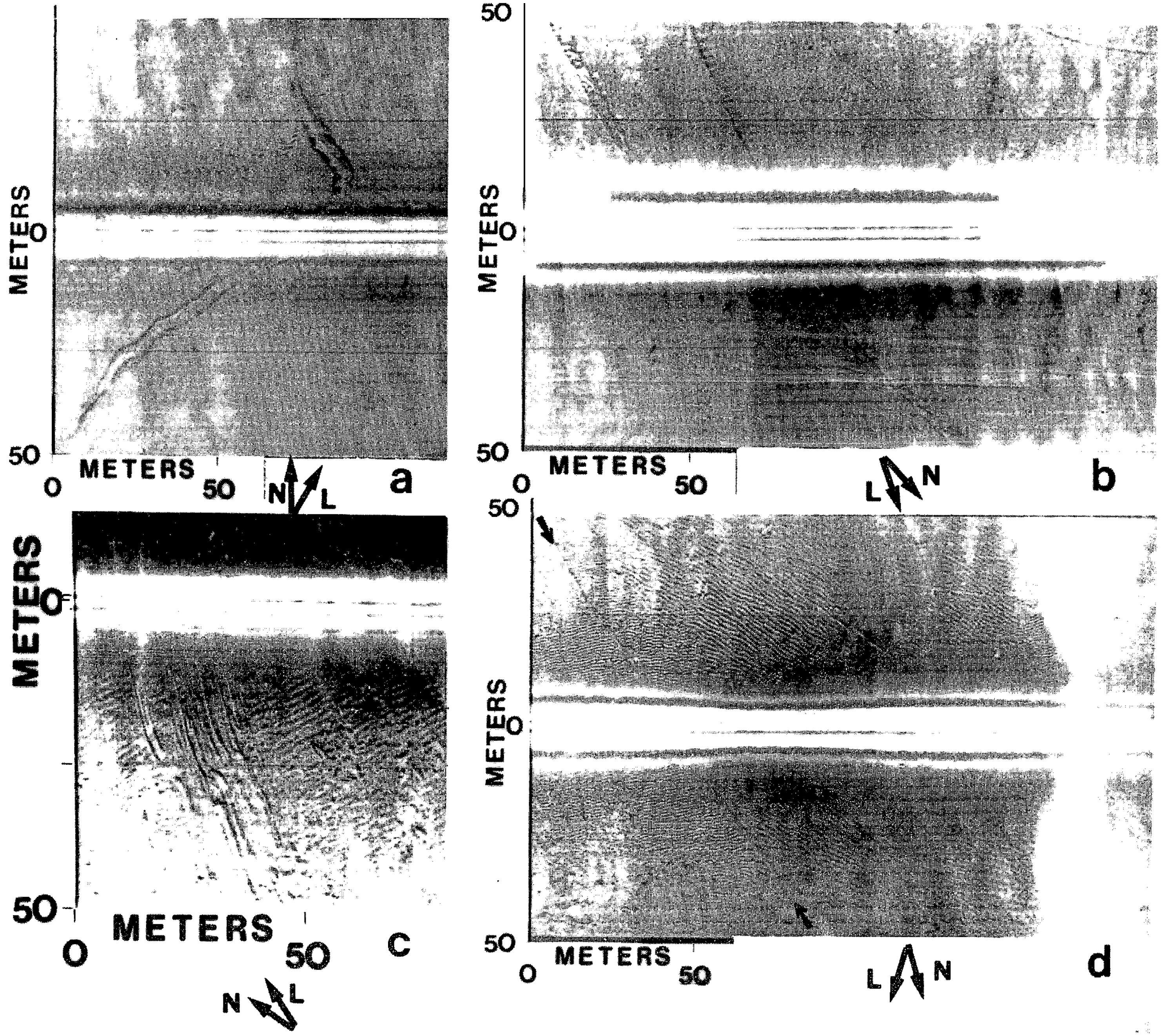
50
METERS
0
50
0
METERS
50
L
N
a
50
METERS
0
50
0
METERS
L
N
b
METERS
0
50
0
METERS
50
N
L
c
50
METERS
0
50
0
ETERS
50
N
L
d


BREVIG LAGOON
PORT CLARENCE
Pt Spencer
4
5
6
7
8
7
6
5
4
EXPLANATION
Trend of wave ripples
A
Current ripples
(Arrowhead indicates current direction)
Trend of ribbons
Trend of ice gouges
N
0
2
4
Kilometers
Isobaths in fathoms



0
2
4
8
10
12
14
16
E
0
400 M
a
METERS
0
2
4
6
8
10
12
E
W
0
400 M
b
0
400 M
c
0
400 M
d


100
0
100
METERS
0
METERS
200
N
L
a
50
0
50
METERS
0
METERS
100
N
L
b
50
0
50
METERS
0
METERS
100
C
N
L
c
50
0
50
METERS
0
METERS
100
N
L
d



METERS
0
50
METERS
0
50
N
L
a
METERS
0
50
50
METERS
0
50
L
N
b
METERS
0
50
METERS
0
50
c
N
L
METERS
0
50
50
METERS
0
50
L
N
d