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TIDAL FLAT SEDIMENTS - TEXTURE, WILLAPA BAY, WASHINGTON

by

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This report is preliminary and has not been reviewed for conformity with U. S. Geological Survey editorial standards and stratigraphic nomenclature

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ABSTRACT

The purpose of this study was to texturally characterize the sediments of the mid-estuary tidal flats between Goose Point and Pickernell Creek in Willapa Bay, Washington and to compare these flats with other flats in the estuary.

The mean grain size of sediments on tidal flats in the mid-estuary are fine sand (2-3 Ø). Sand shoals at the Bay entrance and erosion of cliffs between Goose Point and Pickernell Creek are the source of the sand. The subordinate mud fraction is supplied by rivers and creeks; little mud is deposited on the tidal flats except for those flats immediately adjacent to the rivers. Gravel is a minor component and is concentrated in sediments near the base of the cliffs high on the tidal flats.

Variability in texture within the study area is most pronounced near the Palix River and Pickernell Creek. The average characteristics of mid-estuary tidal flat sediments are best described as poorly sorted, fine-grained sand with strongly-fine skewed leptokurtic distributions.

Distribution patterns of textural parameters show consistent trends of hydraulic energy. Locally, textural patterns reflect (1) the coarsing effects of a flood current gyre between Goose Point and Sandy Point, and (2) relatively narrow flats (i.e., greater slopes) have coarser sediments proportionately higher upslope than wider flats.

The following comparisons can be made between tide flats in Willapa Bay. Mean grain size varies systematiclly up-estuary permitting the estuary to be artifically divided into 3 parts: outer estuary = 2-3 Ø; mid-estuary = 3-4 Ø; and inner estuary = greater than 4 Ø. Outer estuarine tide flats extend deep into the estuary, particularly to the south. The transition from

outer to inner estuarine tide flats based on textural differences is a rapid change (i.e., occurs over a short distance).

INTRODUCTION

Textural analysis is one of the most fundamental operations performed by geologists in the interpretation of depositional environments. Often, granulometric analysis provides the framework into which many other observations are placed. The purpose of this paper is to texturally characterize the sediments of mid-estuary tidal flats in Willapa Bay, Washington. This study is part of a larger investigation into (1) developing an understanding of deposititonal processes, and (2) facies characteristics of modern estuarine deposits.

Until recently, there have been relatively few sedimentological studies of Willapa Bay. The first significant, published study of the modern sediments in the Bay was by Andrews (1965). From the mid 1970's to the present, a number of investigations by geologists from the U. S. Geological Survey (Menlo Park, California) have contributed to the understanding of depositional processes operative in Willapa Bay (e.g, Clifton and others, 1976; Anima, 1979; Hill and Chin,1979; Luepke and Clifton, 1979; Phillips, 1979; Clifton and Phillips, 1980).

Terminology: In this report, general geographic subdivisions of Willapa Bay are refered to as outer, mid-, or inner estuary. Outer estuary refers to the area near the Bay mouth, while areas nearest the rivers is termed inner estuary. Between the two is the mid-estuary. Relative to tidal flats within the Bay, "upper" refers to an area of a flat nearest the shoreline; the "lower" flat is adjacent to the main tidal channels. Between the upper and lower flat is the mid-flat area. In describing trends, "upslope" refers to changes in parameters going from the lower flat to the upper flat; "up-estuary refers to parametal changes going toward a freshwater source (i.e., rivers and creeks).

STUDY AREA

The following description of the study area is mainly a synthesis of information contained in Garrett and others (1962), Andrews (1965), Clifton and Phillips (1978), and Anima (1979).

Geographic Location

Willapa Bay, a coastal plains estuary, is located on the southwestern Washington coast (Fig. 1). The Bay entrance is some 31 km south of Grays Harbor and approximately 47 km north of the Columbia River mouth.

Geomorphology

Willapa Bay forms a water area of about 375 km^2 at high tide. The Bay is a complex estuary that is composed of three large and several small estuaries. The single bay resulted from the formation of North Beach Peninsula, a 32 km long sand spit extending northward from the mainland.

Surrounding the Bay on three sides, Willapa Hills reach elevations of 3 to 5 km. These hills are a northwest-trending major anticline and are the southern extension of the Olympic Mountains. The hills are composed of dark gray, coarse-to-fine grained basalt flows and breccia. Included locally are sedimentary beds, altered palagonite beds, and pillow basalts; all these beds are Eocene in age.

Tertiary sedimentary rocks (Eocene to Miocene) flank the Willapa Hills in the central and southern Bay area. The sedimentary beds are consolidated sandstone, shale, lenses of conglomerate, and local submarine basalt flows. Origin of these sediments are both continental and marine.

Quaternary terrace deposits are immediately adjacent to Willapa Bay. The deposits consists of consolidated silt, sand, and gravel-all are indurated to the extent that vertical cliffs are produced by wave action. The upper surface of the terraces around the Bay vary from a few to several tens of meters above sea level.

North Beach Peninsula stands more than 7.5 meters above sea level. According to drilling logs, the bar is a sand deposit as much as a few hundred meters thick. The sediment composing the sand bar is from the Columbia River. Except for the beach areas and northernmost tip, the peninsula is covered with vegetation.

The Bay entrance is about 8 km across and generally obstructed by large sand shoals. The main channel runs adjacent to Cape Shoalwater. Over the past hundred years, this channel has migrated causing extensive erosion to the north.

Willapa Bay has two main channels (Fig. 2). The south channel (Nahcotta), about 29 km long, is protected from open water by the North Beach Peninsula. The other channel runs east from the Bay mouth for approximately 19 km. The east channel is the mouth of the Willapa River, the largest tributary flowing into the bay. Water depths in the main channels vary from about 6 to 25 meters; widths range approximately from 90 to 2200 meters. Both channels show a somewhat sinuous configuration which is influenced by the tides.

Extensive intertidal flats rim the Bay. The sediments of the flats range from well sorted sand near the main channels to mud toward the inner estuary. In the southern part of the Bay, tidal flats are muddier due to decreases in water circulation and well developed salt marshes. Sections of the north Bay also have dense vegetation on the flats.

Climate

The main climate controls over the North Pacific are the semipermanent high and low pressure regions, terrain, and ocean.

During the summer, when a semipermanent high pressure cell predominates, air flow is nothwesterly, cool, and relatively dry. In the winter, the Aleutian low pressure replaces the high. Air flow becomes southwesterly and brings moist air onshore. Willapa Bay experiences gale force winds during winter storms.

Mean annual precipitation is about 220 cm. Monthly precipitation is least in July/August (4cm) and greatest in December (38cm). However, only a few precipitation records are available for the basin with only rare records from higher elevations.

The mean annual air temperature varies from approximately 11°C (July) to 4.5°C (January). Extreme temperatures are infrequent and short in duration; overall, the moderating influence of the ocean is noticed in the air temperatures of the area.

Relatively high humidities (70-85% in winter, 25-70% in summer) result in low water losses to evaporation. The annual evaporation loss is about 51-63 cm.

Tides, Currents, and Wave Climate

Characteristic of mixed tides on the Pacific coast, tides in the Bay show diurnal inequality. Between mean high high water and mean lower low water, the diurnal variance is 2.5 m at the Bay mouth to 3.1 m at Nahcotta. Willapa Bay at mean high tide has a water-covered area of about 375 km^2; at low tide and 178 km^2 is covered with water The result is approximately 197 km^2 of broad tidal flats.

The average current velocity during ebb and flood tides is about 2.5 knots. The greatest currents (4.6 knots) occur on the ebb tide at the Bay mouth. Even greater velocities may occur during periods of strong south winds due to the northward flow of the ebbing tide coupled with the wind effects.

Waves generated offshore have little effect on the southern Bay because of the protection afforded by North Beach Peninsula. An exception is at the Bay entrance where bottom sediment is in tensively reworked by waves. Local winds are the most significant agent generating waves in the inner Bay.

Water Properties

Water characteristics in Willapa Bay may change rapidly. On an outgoing tide, about 65% of the water leaves the Bay. If this water is caught up in a littoral drift, it is swept away and replaced with ocean water on the incoming tide.

The fall season is a period of relatively high salinity (30 parts per thousand). This results when the Columbia River plume shifts to the south and water offshore of the Bay mouth is replaced with more saline ocean water. During the winter, salinity can drop as low as five parts per thousand due to (1) increased runoff from winter precipitation and (2) the Columbia River plume swinging to the north. With decreases in the amount of runoff during the spring, the salinity begins to increase (approximately 20 parts per thousand). Summer salinities (about 25 parts per thousand) result from much reduced rainfall and the influx of more ocean water. The salt water wedge is sharpest in the summer and fall.

Water Temperatures fluctuate seasonally. On the average, the temperatures range from 7-9 °C in the winter to 14-20 °C in the summer.

Compared to other west coast estuaries, the Bay is relatively unpolluted. The population of the basin is small (under 25,000) and industrial discharges are small. The major industry, lumber mills, burn their saw dust and dump little of their waste wood products into the Bay or tributaries.

Runoff

Willapa Bay receives runoff from about 2400 km^2 of land area (principally the west flank of the Willapa Hills). Runnoff is variable due to seasonal variation in precipitation and lack of snow or other surface storage to maintain summer flow. Runoff during July to September accounts for less than two percent of the average annual runoff. Overall, the runoff figures are generally higher than would be anticipated from the available precipitation records.

Sediments

Sediments in Willapa Bay (Fig. 3) are supplied by the Pacific Ocean, terrace deposits, rivers, and aeolian sand deposits.

The Pacific Ocean supplies most of the sand deposited in the Bay. A combination of littoral drift and tides causes extensive erosion along Cape Shoalwater. The eroded sediment is carried into the Bay where it is deposited along Toke Spit and Ellen Sands.

By erosional processes, large amounts of mud and sand are derived from the Quaternary terraces around the Bay. During high tides (especially in the winter and/or associated with storms), wave action undercuts the vertical cliffs and stacks causing slumping or slides of the deposits.

Nine rivers supply sediment to Willapa Bay. The majority of clay and silt (minor amounts of gravel and sands) deposited in the Bay come from these rivers.

Sand flats along North Beach Peninsula are composed mainly of sediment derived from aeolian deposits on the barrier spit. Cooper (1958) observed blowouts at the end of the tree line to Leadbetter Point which allowed sand deposited along the open coast to be carried into the Bay by the onshore winds. Some sediment is also provided by subtidal channels eroding into beach and nearshore sands.

Flora and Fauna

Flora

Differences in taxonomic composition, distribution, and density of Bay flora occur between salt marshes, tidal flats, and channels. Vegetation associated with salt marshes is diverse and generally dense; *Spartina*, *Triglochin*, and *Salicornia* are characteristic species. On the tidal flats, the flora changes somewhat systematically upslope. Near the channel, algal mats or mounds are common; shoreward, more robust species such as *Zostera marina* and *Zostera noltii* occur. Vegetation in the channels is low in diversity and density, consisting primarily of algal "clumps."

Fauna

Reports on fauna in Willapa Bay are rare and deal almost exclusively with the oyster industry. Description of the faunal community can be at best only very general. For example, the Bay contains enough commercially important fish species (e. g., salmon and sturgeon) to support a small industry; oysters and crabs are also commercially harvested; substantial varieties of invertebrates (e.g.,molluscs, crustaceans, and polychaetes) are common. Of importance, however, is a report by Sayce (1976) on exotic species introduced into the Bay. These introductions centered around the efforts of the oyster industry to reestablish itself after being wiped out by a red tide between 1917 and 1919.

Specific Study Area

The specific study area is located on the intertidal flats between approximately Goose Point and Pickernel Creek on the east side of Willapa Bay. (Fig. 4). Geographically, this area occupies a mid-estuary position.

The width of the flat varies from a few hundred meters up to a kilometer. A large intertidal runoff channel just south of Goose Point, cuts across the flat from near this shoreline to Nahcotta channel. Other large surface features include runoff ridges and sand wave fields. Terrace deposits up to 10 m high occur along the active shoreline adjacent to the flats.

Salt marsh development is common near the Palix River and Pickernell Creek. During the summer, locally extensive grass beds occasionally develop on the sand flats.

Unconsolidated sediments cover most of the flats; bedrock (consolidated mudstone) occurs locally.

METHODS

Field Methods

Surface samples for textural analysis were taken at 36 sample locations (Fig. 4) using a 3.5 X 15.5 cm butyrate tube. Pre-labelled tubes were (1) pushed into the sediment as far as possible, (2) excavated, and (3) capped. Where full penetration was not possible due to induration of substrate, dense vegetation, etc.,- a "representative" grab sample of the surface sediment was taken. Textural samples were immediately refrigerated to retard bacterial growth; refrigeration continued until the samples were opened for analysis.

Laboratory Methods

All sediment size analyses (using whole samples) were conducted at the U. S. Geological Survey Marine Sedimentation Laboratory (MSL) in Menlo Park, California, according to methods outlines in Folk's (1974) Petrology of Sedimentary Rocks. Sand fractions (-1.0 Ø to 4.0 Ø) were analyzed using the MSL Rapid Sediment Analyzer (2m settling tube, Griffo amplifier, Omni Scribe recorder). Silt/clay fractions (4.0 Ø to 14.0 Ø) were analyzed on an EIS Model 6805A hydrophotometer.

RSA cumulative curve charts were reduced at 0.5 Ø intervals using an overlay calibrated to the MSL RSA. Hydophotometer data were recorded as direct transmission values at 0.5 Ø intervals. RSA and hydrophotometer data were computer processed using a MSL program for sediment size analysis (SDSZAN). This program converts sediment data to graphical and moment statistics, ratios, cumulative and straight percent, histograms, and cumulative curves.

To better illustrate the geomorphic effects (e.g., change in slope) on trends in textural parameters in the study area, a unique method for the construction of isopleth maps is employed. The shoreline between the Bay Center Harbor and Pickernell Creek was divided into 36 naturally occurring straightline segments. These segments were then plotted end to end to form a single straight-line shoreline (= artificial shoreline). A line drawn parallel to the artificial shoreline at an arbitary distance represents the mean lower low water line (= artificial MLLW line). The area between the two parallel lines represents the intertidal flat. A line perpendicular to shoreline and extending across the entire tide flat was drawn through each sample station. The position of the station along the line relative to shoreline was determined by the distance ratio:

$$\frac{\text{distance from shoreline to station}}{\text{distance from shoreline to MLLW line}}$$

The position of the intercept of the perpendicular line through the station along the shoreline was determined by the ratio:

$$\frac{\text{distance along straight shorelines from Bay Center harbor to intercept}}{\text{distance along straight shorelines from Bay Center harbor to Pickernell Creek}}$$

These coordinates were used to plot each station on the artificial tide flat used to make isopleth maps. Reference points (e.g., Goose Point) are also plotted on the isopleth maps using the same technique.

DISCUSSION OF RESULTS

Textural characteristics and variability in the study area are discussed in terms of individual components, two-component ratios, total-component composite, and statistical grain-size parameters.

Single-Component Vaiability

Gravel

The areal distribution of gravel size detritus (greater than 2.00 mm) is shown in figures 5 and 6A, and the percentages of gravel at each station are tabulated in Table 1. Most of the gravel is biogenic detritus, predominantly bivalve (Mollusc) shells. The shells are generally fragmented. Inorganic gravel-sized material (e.g., mud clasts, pebbles) was quantitatively insignificant. Overall, gravel was absent in most samples (78%) and comprised less than one percent of the bottom sediment in the others (22%). One sample (S711-1) was 9.4% gravel. The distribution pattern appears generally random with some increase in frequency and concentration on the upper flats along the base of the cliffs, particularly at Goose Point. Lithic clasts are more common in those samples near the cliffs - the apparent souce of the clasts.

Sand

The areal distribution of sand-size (0.063-2.00 mm) detritus in the sediments is shown in figure 7 and the percentages of sand at each station are tabulated in Table 1. The sand-size fractions are composed of both terrigenous and biogenic (e.g., forams and molluscs) components. Individual grains are very angular and elongate. Sand content of the sediment samples ranges from 33.0 to 99.3 percent. Most stations (53%) have greater than 90 percent sand content while only two stations (6%) had less than 70 percent sand.

The sand isopleth map (Fig. 6B) shows two trends in distribution: (1) a decrease in the sand-size fraction upslope (i.e., across the tide flat); and (2) a decrease in sand content in a up-estuary direction. The areas of relatively high sand concentrations (greater than 95 percent) are mainly along the channel margins and between Goose Point and Sandy Point. Areas relatively deficient in sand (less than 90 percent) are localized near the Palix River and Pickernell Creek and along the upper tide flat to the south.

The sand distribution pattern probably represents the composite response to current energy flux, source areas, and topography. Decreasing sand up-estuary reflects both a decrease in energy and increase in distance away from the major source area (sand shoals at the Bay mouth and barrier spit). Upslope decreases in sand also reflect a decrease in tidal energy away from the channels. Significant local variations in the distribution pattern tend to confuse the general trends. These local variations result from small local sources, changes in the width of the tide flat, and unique current patterns. An increase in sand content along the upper flat is due to erosion of the cliffs producing sand-size detritus. Between Ramsey Point and Pickernell Creek, sand encroaches to a mid-flat position. Here, the tide flat is narrow and the slope steeper. As a result, higher energy gradients extend proportionately further onto the flat. The sand concentration between Goose Point and Sandy Point extends across the entire flat. This pattern probably results from a flood current gyre flowing counter-clockwise on the flat (Fig. 8). This area of the flat is also a slight topographic low which would tend to focus tidal currents resulting in a longer duration of tidal flow. All these factors promote removal of finer sediment fractions.

Silt

The areal variability in the amount of silt-size (3.9 - 63 us) detritus is shown in Figure 9 and by the silt percentage isopleth map (Fig. 6C). Silt percentages at individual sample stations range from 0.5 to 65.0 percent (Table 1). Twenty-seven samples (75%) contained less than 10 percent silt; only two samples (6%) had greater than 50 percent silt. The tide flat areas adjacent to the Palix River and Pickernell Creek have the greatest silt content. The distribution of silt is largely the inverse of sand distribution patterns. Silt content of the bottom sediments increase upslope and up-estuary . Areas relatively deficient in silt (less than one percent) are localized along the channel margin and in the area of the current gyre between Goose Point and Sandy Point. Near the rivers, relatively high percentages of silt extend across the entire width of the tide flat. Silt content is greatest near their source (rivers and creeks) and on the upper flat where current energy is lower.

Clay

The areal distribution of clay size (less than 3.9 um) detritus is shown by figures 6D and 10. Clay percentages in bottom sediments at individual stations range from 0.3% to a maximum of 7.1% (Table 1). The distribution of clay is similar to the distribution of silt and is inversely related to sand distribution. Clay content increases upslope and up-estuary. The major areas of clay concentration (greater than 3 percent) are adjacent to the Palix River and Pickernell Creek. The sediments in the area between Goose Point and Sandy Point have the least amount of clay. The distribution of clay reflects changes in energy and distance from source. The rivers are the source of the clay; therefore, with increasing distance from the source the clay content decreases. Higher energy areas near the channel margins and in the area of the current gyre have little clay.

Component-Ratio Variability

Tide flat sediment variability can also be defined in terms of component-ratio variability. All two component ratios were calculated and are presented in Table 2. Ratios can be more effective in demonstrating the interrelation of two lithologic components than single-component percentages. In this study, sand/mud and silt/clay ratios had the most significant distribution patterns.

Sand/Mud Ratios

Sand and mud (silt & clay fractions) comprise the two basic textural components in the study area, and their interrelationships are shown in figure 12 and by the ratio isopleth map (fig. 11A). Sand/mud ratios for individual stations are given in Table 2. The sand/mud ratios vary from 0.5 to 141.3. Only rarely (2 samples) is mud the dominant component. Sand/mud ratios decrease up-estuary but no trend upslope is evident. Most of the study area is characterized by sand/mud ratios less than 25. The highest ratios are located between Goose Point and Sandy Point where the sand content is greater than 95% (Fig. 6B). The relatively closely spaced isopleths in this area indicates a rapid transition of one sediment type to another - probably a result of winnowing out the fine material by the flood current gyre and ebb current runoff. In contrast, the more widely spaced isopleths to the south indicate a more gradual transition between sediment types - a condition reflecting gradual decrease in hydraulic energy up-estuary.

Silt/Clay Ratios

The silt/clay ratios are shown in figure 13 and by the ratio isopleth map (Fig. 11B). Ratio values range from 1.2 to 33.5 (Table 2). Only four samples (11%) have ratios greater than five. Silt/clay ratios increase both in an up-estuary and upslope direction. Two prominant salients of relatively high ratios (greater than 2.5) extend across the flats near areas adjacent to rivers. The only area approaching equal proportions of silt and clay (ratios less than 1.5) is between Goose Point and Sandy Point in the area of very high sand content (greater than 95 percent). The increasing proportion of silt near the rivers and on the upper tide flat indicates slightly higher energy which maintains progressively larger proportions of clay in suspension. Increased hydraulic energy is attributed to greater currents or discharge associated with rivers and increasing wave surge on the upper flat. The pattern also reflects the greater energy associated with the flood current gyre.

It is interesting to note that much of the local variation observed in distribution patterns of individual component percentages "disappears" using the component ratios. The result is a clearer picture of larger geographic trends but the loss of information as to the subtle effects of such factors as tide flat width (i.e., changes in slope) is significant.

Total Component Variability

The total composite variability of sediments collected from the tide flat is evaluated by combining sand, silt, and clay components. The sediment types have been determined by plotting the relative proportions of the three detrital components on ternary diagrams after Shepard's (1954) classification system.

Sediment composition within the study area is shown by figure 14. The majority of the samples (89%) are in the sand category. Only four samples plotted in other categories: two in silty sand and two in sandy silt. Overall, the sediments show little gross diversity. The general absence of well-defined zonation of sediment composition relative to water depth (i.e., upslope) and geographic location (i.e., up-estuary) characterizes the study area (Fig. 15).

A general synthesis of all the textural variability previously described is shown by the sediment distribution map (Fig. 16) which indicates that the sediments over most of the study area is sand. Mud is dominant only on flats immediately adjacent to the Palix River where the sediment is classified as sandy silt. These gross textural characteristics can be attributed to relatively high energy conditions due to current and wave surge associated with mid-estuary tidal flats which present significant amounts of much deposition.

Granulometric Analysis

The sediments were also evaluated texturally in terms of their statistical grain-size parameters. These measures are very sensitive to the hydraulic regime. Parameters studied include mean (central tendency measure), standard deviation, skewness, and kurtosis. In order to compare these results with earlier studies in Willapa Bay by Andrews (1965), graphic measures of Folk and Ward (1957) were used; moment measures for each station were calculated and are tabulated in Table 3. Size terminology follows the Udden-Wentworth grade scale and is expressed in terms of Krumbein's (1934) phi unit (Ø) transformation.

Mean Diameters

The average grain-size variability in terms of mean diameter is shown in figures 17 and 18. The mean diameter distribution map (Fig. 17) shows the actual distribution of average grain size; the isopleth map (Fig. 18A) shows grain-size gradients.

The mean diameter ranged from coarse silt (4.67 Ø) to fine sand (2.21 Ø) (Table 3). The two sediment types represent the extreme ends of the size spectrum; however, coarse silt occurs only in isolated localities adjacent to the Palix River. Most of the study area is covered by a combination of fine to very fine sand. The coarser sediments are generally on the outer flats.

Trends in distribution are depicted by the isopleth map (Fig. 18) which shows grain-size gradients. Overall, the map shows a grain-size pattern similar to some of the other patterns, (e.g. fig. 17) but with a greater degree of hydraulic sensitivity. The pattern reflects a composite response indicating size gradients both across and along the tide flat. Grain size decreases shoreward (i.e., upslope), largely reflecting a decrease in current and wave energy. Sediments also become finer up-estuary (i.e., toward the Palix River and Pickernell Creek) which reflects the increasing amount of fine material supplied to the flats by the rivers. The two coarser salients extending onto the mid- to upper flat result for two different reasons. The flat between Goose Point and Sandy Point is closer to (1) the major sand source (e.g. Ellen Sands) and (2) higher wave energy and focused tidal energy. Also the local current gyre defined by Anima (1979) winnows out mud. The southern coarse salient between Ramsey Point and Pickernell Creek is probably the result of a change in topography. Here, the tide flat is much narrower compared to the flats near Goose Point and consequently has a steeper slope. The result is that greater hydraulic energy extends proportionately further across the flat carrying coarser grained material closer to the beach and/or winnows out mud on the lower flat.

Standard Deviations

The standard deviation was used as a measure of sediment sorting and is shown by figures 18B and 19, and tabulated by station in Table 3. Among individual samples, standard deviation values range from a minimum of 0.62 Ø to a maximum of 2.72 Ø. The sediments in the study area can be classified as well sorted (0-1.0 Ø), poorly sorted (1.0-2.0 Ø), or very poorly sorted (2.0-4.0 Ø) using Folk's (1974) verbal scale. The majority of the study area contains poorly sorted sediments. Very-poorly sorted sediments are adjacent to the Palix River and Pickernell Creek. The area between Goose Point and Sandy Point is characterized by well sorted sediments.

A comparison of the standard deviation trends with the mean grain-size trends indicates a relationship between the two parameters. Although differences in local variability occur, the general trends are similar (Fig. 18A-B): a general increase in standard deviation up-estuary; increases in standard deviations upslope are not as obvious. Overall, however, sorting characteristics are generally correlated with mean grain size. The sorting becomes poorer as the grain-size decreases. Fine material is winnowed out in higher energy areas such as between Goose Point and Sandy Point which improves the sorting characteristics.

Skewness

Skewness values for the sediments on the flats are shown in figures 18C and 20, and tabulated in Table 3. Values at individual sample stations range from +1.00 to -.17. Approximately 3% of the samples were coarse-skewed (-0.1 to -0.3), 14% near symmetrical (-0.1 to +0.1), 14% fine-skewed (+0.1 to + 0.3), and 69% strongly fine-skewed (+0.3 to +1.0) using Folk's (1974) verbal classification scale. The majority of the study area is composed of strongly fine-skewed sediments. Negatively skewed sediments and nearly symmetrical sediments had relatively coarse mean grain sizes (Table 3).

The general distribution trend is an increase in strongly fine-skewed sediments upslope and up-estuary. The pattern exhibits a good correlation with mean grain size (Fig. 18A). The trend appears to reflect transport of finer material toward the beach or erosion of the fine material from cliffs. Duane (1964) related skewness to environmental energy in Pamlico Sound sediments. He found that sediments deposited in relatively high-energy areas where intensive winnowing occurred, truncation of the fine fraction occurred; sediments characterized by fine-skewness were found in low-energy environments. The variability of skewness especially near the Palix River is probably due to the polymodal nature of the sediments (Table 3). Several investigations (e.g., Friedman, 1967; Cronan, 1972) noted that polymodal sediments can exhibit variable skewness values, depending on the specific proportions of component sub-populations. As a measure of the asymmetry of a sediments size frequency distribution relative to a normal Gaussian distibution, skewness values in the study area reflect overall particle excesses within the fine tail portions of size distribution. The tendency toward fine skewness may be due to rivers such as the Palix discharging large volumes of muddy water. This results in deposition of finer fractions. However, the fine skewed sediments near the cliffs may reflect erosion of fines from these terrace deposits.

Kurtosis

Kurtosis values are tabulated in Table 3 and the distribution shown in figure 21 and in a isopleth map (fig. 18D). In using this statistical measurement, negative values indicate platykurtosis, a value near zero is mesokurtic distribution and positive values indicate leptokurtosis. Values in the study area ranged from +0.42 to +15.51. Most of the area consists of leptokurtic sediments of varying degree; the more strongly leptokurtic sediments are concentrated on the lower flat and in the southern half of the study area. Mesokurtic sediments are common near the Palix River and Pickernell Creek and in the northern half of the study area.

The genetic significance of kurtosis is poorly understood. However, in conjunction with skewness, it can be an indicator of sediment population mixing. Folk (1966) noted that (1) platykurtic (excessively flat) distributions may reflect the mixing of log-normal populations in nearly equal proportions, (2) leptokurtic (excessively peaked) distributions may reflect the mixing of a highly dominant population with a highly subordinate population, and (3) mesokurtic (Gaussian) distributions reflect a single log-normal population. The kurtosis distibution pattern indicates that the relatively mesokurtic sediments near the Palix River and Pickernell Creek result from the mixing of a sand population with a finer mud population transported by the rivers and deposited from suspension. Between Goose Point and Sandy Point, mesokurtic sediments are concentrated around an area of near-symmetrical skewed, sand-dominated sediments. The leptokurtic sediments in the southern half of the study area may reflect the mixing of a dominant sand population transported up the estuary or eroded from the cliffs with a highly subordinate mud population transported down the estuary.

Comparison With Other Willapa Bay Tide Flats

Geographically, the study area occupies a mid-estuary position. Texturally, how does the study area compare with outer and inner tide flats in the Bay? To answer these questions, the data from this study is compared to data from 29 tide flat stations of Andrews (1965); the stations were scattered throughout the Bay system including one station (#50) in our study area (Fig. 22). Textural parameters of the 29 stations were extracted from Andrews (1965) and are summarized in Table 4.

When mean grain size data of this study is plotted with similar data from Andrews, a distinct distribution pattern within Willapa Bay is evident (Fig. 23). The tidal flat sediments become progressively finer going up-estuary. Three aspects of this pattern are noteworthy: (1) relatiely coarse sediments extend many kilometers into the estuary particularly to the south, (2) the transition from dominantly fine sand sediments to muddy sediments occurs over a short distance (i.e., rapid transition, and (3) outer and mid-estuary tidal flat sediments are texturally very similar (both are approximately 94% sand, 4% silt, 2% clay, 2.54 mean grain size; Table 5).

The pattern of sediment distribution on intertidal flats observed in Willapa Bay is the result of (1) decreasing current and wave energy up-estuary, (2) increasing distance from the major sand source at the Bay entrance, and (3) increasing fluvial influence in the inner estuary.

CONCLUSIONS

Texturally, the mid-estuary tidal flat is composed predominantly of sand; quantitatively, the dominant component is fine sand (2-3 Ø). The source of the sand are the sand shoals near the Bay mouth and erosion of vertical cliffs along the tide flat beach. The subordinate mud fraction is more common on flats adjacent to rivers and creeks reflecting an open dispersal system with substantial fine material moving to other environments. Gravel detritus is quantitatively minor, and is concentrated along the base of vertical cliffs high on the tide flat. The majority of the study area is classified as a sand province.

Textural variability is most pronounced near the Palix River and Pickernell Creek and on the upper tide flat. Genetically, the textural variability indicates a composite fabric of marine sands supplies from offshore and transported along large channels and finer material transported in suspension by the rivers and settling out due to flocculation. The average characteristics of mid-estuary tidal flat sediment is best described as poorly sorted, fine-grained sand with strongly-fine skewed leptokurtic distributions.

Textural parameters exhibit generally consistent trends of sediments fining upslope and up-estuary. The trends reflect a response to decreasing hydraulic energy. Locally, textural distribution patterns show the width of the tide flat affects the distribution of sediment subpopulations - narrow flats with steep slopes have coarser material proportionately higher on the flat than relatively wide flats.

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TABLES

Table 1. Single component percentages of surficial sediments in study area.

Sta. #	Gravel (%)	Sand (%)	Silt (%)	Clay (%)	Mud (%)	Shepard's Class
S706-1	0	98.95	0.56	0.48	1.04	1
S706-2	0	92.90	4.78	2.31	7.09	1
S710-2	0	38.69	54.72	6.58	61.30	3
S711-1	9.39	81.27	6.96	2.36	9.33	1
S711-2	0	76.80	19.50	3.69	23.20	1
S711-3	0	98.40	0.94	0.64	1.59	1
S712-1	0	83.92	15.01	1.05	16.07	1
S712-2	0	77.69	16.01	6.28	22.30	1
S714-1	0.61	97.20	1.71	0.46	2.17	1
S717-1	0	89.58	6.63	3.77	10.41	1
S718-2	0.13	98.32	0.87	0.66	1.53	1
S718-3	0	99.19	0.50	0.29	0.80	1
S719-5	0	87.94	8.30	3.74	12.05	1
S719-6	0	99.16	0.47	0.36	0.83	1
S720-3	0	89.68	6.66	3.65	10.31	1
S720-4	0	96.33	2.40	1.26	3.66	1
S721-4	0	96.03	2.79	1.17	3.96	1
S723-1	0.41	91.91	6.02	1.64	7.67	1
S723-2	0	89.37	8.54	2.08	10.62	1
S723-3	0	98.32	1.21	0.46	1.67	1
S801-1	0	89.69	7.84	2.46	10.30	1
S801-2	0	88.49	9.31	2.19	11.50	1
S801-3	0	94.15	3.97	1.87	5.84	1
S804-1	0	96.33	2.36	1.30	3.66	1
S804-2	0.26	87.88	8.09	3.75	11.84	1
S804-3	0	96.48	2.36	1.14	3.51	1
S805-2	0	70.37	22.65	6.97	29.62	2
S805-3	0	84.21	11.75	4.02	15.78	1
S806-1	0	72.55	20.37	7.07	27.44	2
S808-2	0.17	96.00	2.46	1.35	3.82	1
S809-1	0	82.51	12.53	4.95	17.49	1
S810-1	0.07	97.47	2.00	0.45	2.45	1
S810-2	0	98.44	0.87	0.67	1.55	1
S810-3	0	99.29	0.38	0.31	0.70	1

Table 2. Two component ratios for tidal flat sediments in the study area.

Sta.#	Gravel / Sand	Sand / Silt	Silt / Clay	Sand / Clay	Sand / Mud	Gravel / Mud
S706-1	0	174.77	1.17	205.80	94.51	0
S706-2	0	19.41	2.07	40.19	13.09	0
S710-1	0	0.50	33.47	17.01	0.49	0
S710-2	0	0.70	8.31	5.87	0.63	0
S711-1	0.116	11.66	2.94	34.32	8.70	1.006
S711-2	0	3.93	5.27	20.76	3.31	0
S711-3	0	103.98	1.46	152.57	61.84	0
S712-1	0	5.58	14.17	79.24	5.22	0
S712-2	0	4.85	2.54	12.35	3.48	0
S714-1	0.006	56.57	3.73	211.21	44.62	0.284
S717-1	0	13.49	1.76	23.75	8.60	0
S718-2	0.001	111.83	1.33	148.96	63.87	0.088
S718-3	0	195.97	1.71	336.49	123.84	0
S718-4	0.001	122.50	1.67	205.49	76.75	0.073
S719-5	0	10.59	2.21	23.45	7.29	0
S719-6	0	209.30	1.30	273.16	118.50	0
S720-3	0	13.45	1.82	24.57	8.69	0
S720-4	0	40.09	1.90	76.39	26.29	0
S721-4	0	34.33	2.38	81.95	24.19	0
S723-1	0.004	15.25	3.66	55.82	11.97	0.053
S723-2	0	10.45	4.10	42.90	8.40	0
S723-3	0	81.06	2.62	212.50	58.68	0
S801-1	0	11.44	3.18	36.39	8.70	0
S801-2	0	9.50	4.24	40.31	7.69	0
S801-3	0	23.69	2.11	50.19	16.09	0
S804-1	0	40.73	1.81	73.96	26.26	0
S804-2	0.003	10.85	2.15	23.43	7.41	0.023
S804-3	0	40.79	2.05	83.93	27.45	0
S805-2	0	3.10	3.24	10.09	2.37	0
S805-3	0	7.16	2.92	20.92	5.33	0
S806-1	0	3.56	2.88	10.26	2.64	0
S808-2	0.002	38.91	1.82	70.96	25.13	0.046
S809-1	0	6.58	2.53	16.65	4.71	0
S810-1	0.001	48.74	4.36	212.82	39.66	0.029
S810-2	0	112.28	1.29	145.78	63.43	0
S810-3	0	258.03	1.21	312.48	141.33	0

Table 3. Statistical grain-size parameters.

Sta #	Mean	Skewness	Kurtosis	Standard Deviation	No. of Modes
S706-1	2.5454	0.4788	0.4174	0.7261	2
S706-2	2.4207	0.3125	5.9770	1.5468	4
S710-1	4.3622	0.1849	1.0677	1.3432	2
S710-2	4.6655	0.3680	1.1582	1.9704	2
S711-1	2.4568	-0.0257	5.3672	1.9963	1
S711-2	3.3767	0.6528	1.6462	1.8828	3
S711-3	2.4475	-0.0235	0.4934	0.8177	3
S712-1	3.0452	0.5054	1.1497	1.2482	1
S712-2	3.5382	0.7854	2.2050	2.3180	3
S714-1	2.3880	0.1751	1.0726	0.8548	2
S717-1	2.5642	0.5167	12.3045	1.8774	3
S718-2	2.4289	-0.0392	1.0347	0.8570	2
S718-3	2.2977	-0.0287	1.3414	0.6415	3
S718-4	2.2649	0.3549	1.6918	0.7853	2
S719-5	2.4931	0.7064	4.8437	1.9672	5
S719-6	2.4732	0.3447	0.8441	0.6738	2
S720-3	2.5160	0.6519	15.5141	1.8788	2
S720-4	2.3575	0.1191	1.9404	1.1827	3
S721-4	2.4579	0.0103	2.0308	1.1127	3
S723-1	2.7364	0.4569	2.3790	1.3950	3
S723-2	2.7079	0.4390	4.8674	1.5494	2
S723-3	2.5567	0.6217	0.8507	0.8001	3
S801-1	2.8486	0.4851	2.2704	1.5980	3
S801-2	2.7174	0.5330	2.8512	1.6137	2
S801-3	2.4407	0.5990	6.2290	1.4069	2
S804-1	2.4776	0.5283	3.9060	1.1782	3
S804-2	2.4995	0.6883	6.7909	1.9597	3
S804-3	2.2115	-0.1691	3.2413	1.1350	2
S805-2	3.6500	0.7551	1.0050	2.5692	3
S805-3	2.7978	0.7093	3.5008	2.0588	4
S806-1	3.4303	0.3773	1.1681	2.7176	4
S808-2	2.3982	0.4507	4.3580	1.2005	3
S809-1	3.0851	0.7760	7.9452	2.1722	3
S810-1	2.5152	0.2015	1.2565	0.7725	2
S810-2	2.5062	1.0000	0.9463	0.8270	4
S810-3	2.5327	0.2456	0.8948	0.6287	3

Table 4. Textural parameters of intertidal samples from Andrews (1965).

Sta. #	Gravel (%)	Sand (%)	Silt (%)	Clay (%)	Shepard's Class	Mean (Ø)	Standard Deviation	Skewness
1	0	52.62	41.18	6.20	2	4.12	1.710.47	
2	0	51.98	39.26	8.76	2	4.07	1.96	0.40
4	0.003	78.40	14.29	7.28	1	3.20	1.86	0.70
6	0	68.83	23.78	7.39	2	3.59	1.63	0.84
10	0	95.51	3.36	1.12	1	2.62	0.32	0.10
12	0	73.49	20.85	5.56	2	3.44	1.39	0.75
14	0	79.99	15.14	4.87	1	3.22	1.43	0.74
15	0	78.90	15.46	5.64	1	3.21	1.47	0.74
17	0	95.53	3.35	1.12	1	2.51	0.35	0.26
18	0	97.88	1.74	0.39	1	2.58	0.32	0.26
19	0.5	98.64	0.82	0.00	1	2.32	0.31	0.00
30	0	98.83	1.17	0.00	1	2.37	0.25	-0.25
43	0.21	94.24	3.85	1.71	1	2.56	0.50	0.31
47	0	5.02	65.15	29.83	7	6.92	2.33	0.37
49	0.57	21.47	67.33	10.63	3	5.18	2.38	0.28
50	0	64.50	32.64	2.86	2	3.51	0.86	0.14
51	0	83.28	11.15	5.57	1	2.84	1.52	0.71
52	0	95.11	3.91	0.98	1	2.56	0.42	0.27
53	0	100.00	0.00	0.00	1	2.44	0.32	-0.16
54	0	99.72	0.28	0.00	1	2.43	0.41	-0.24
55	0	97.15	2.85	0.00	1	2.62	0.40	0.13
56	0	47.89	41.28	10.83	2	4.56	2.13	0.46
63	0	90.68	6.02	3.30	1	2.56	0.71	0.33
64	0	98.88	1.12	0.00	1	2.40	0.27	-0.07
66	0	66.42	24.71	8.87	2	3.73	1.93	0.83
68	0	29.95	56.00	14.05	3	4.93	2.49	0.52
71	0	74.02	21.85	4.12	2	3.13	1.41	0.69
76	0	32.98	52.69	14.33	3	4.85	2.47	0.46
77	0	20.59	61.46	17.95	3	5.48	2.41	0.54

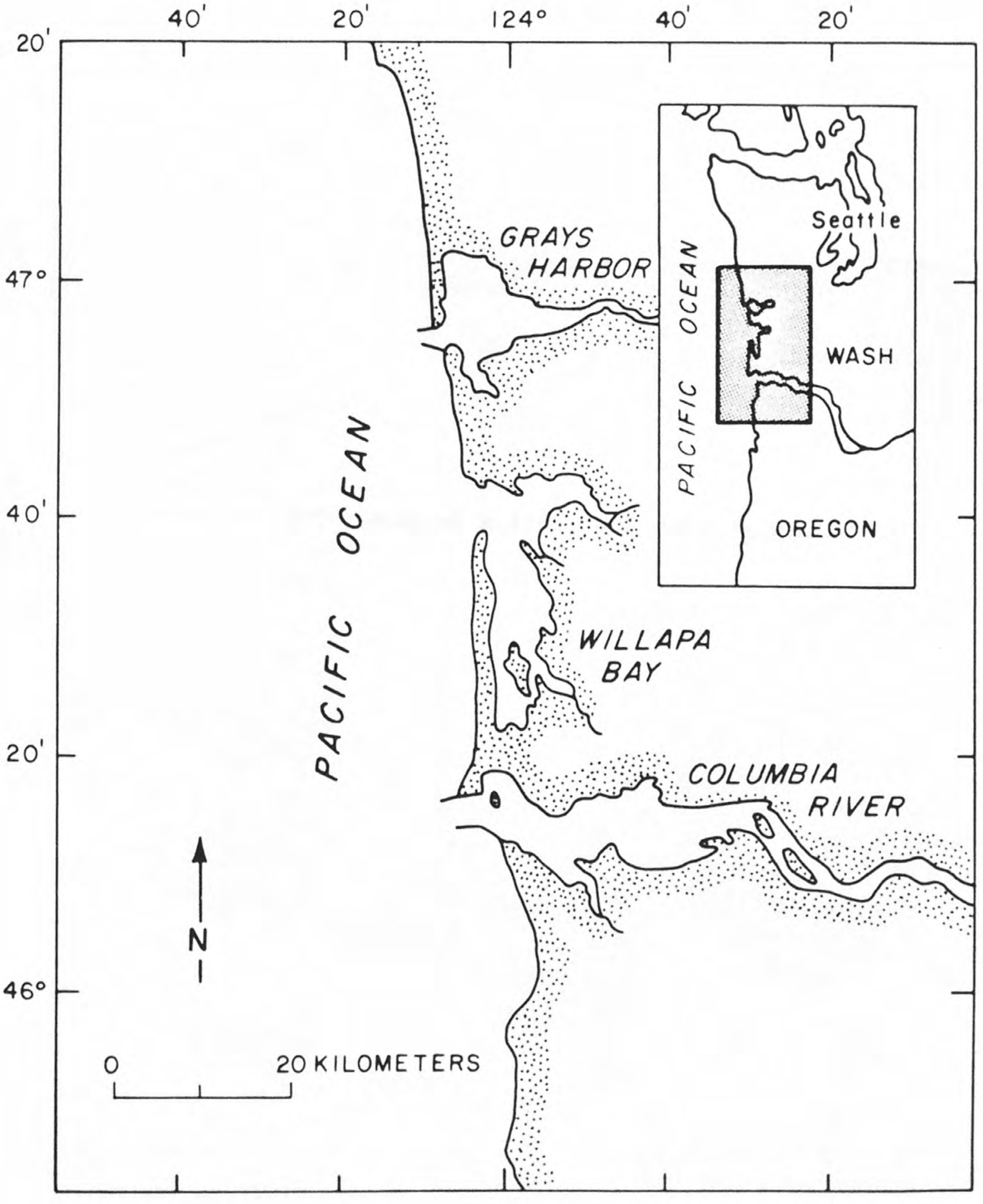
Table 5. Average textural parameters of tidal flat sediments from the outer and mid-estuary.

Parameter	A[1]	B[2]
% Sand	93.59	93.64
% Silt	4.28	4.86
% Clay	2.13	1.44
Mean Grain Size	2.52	2.59

[1] A = Mid-estuary; data from this study
[2] B = Outer estuary; data of Andrews (1965)

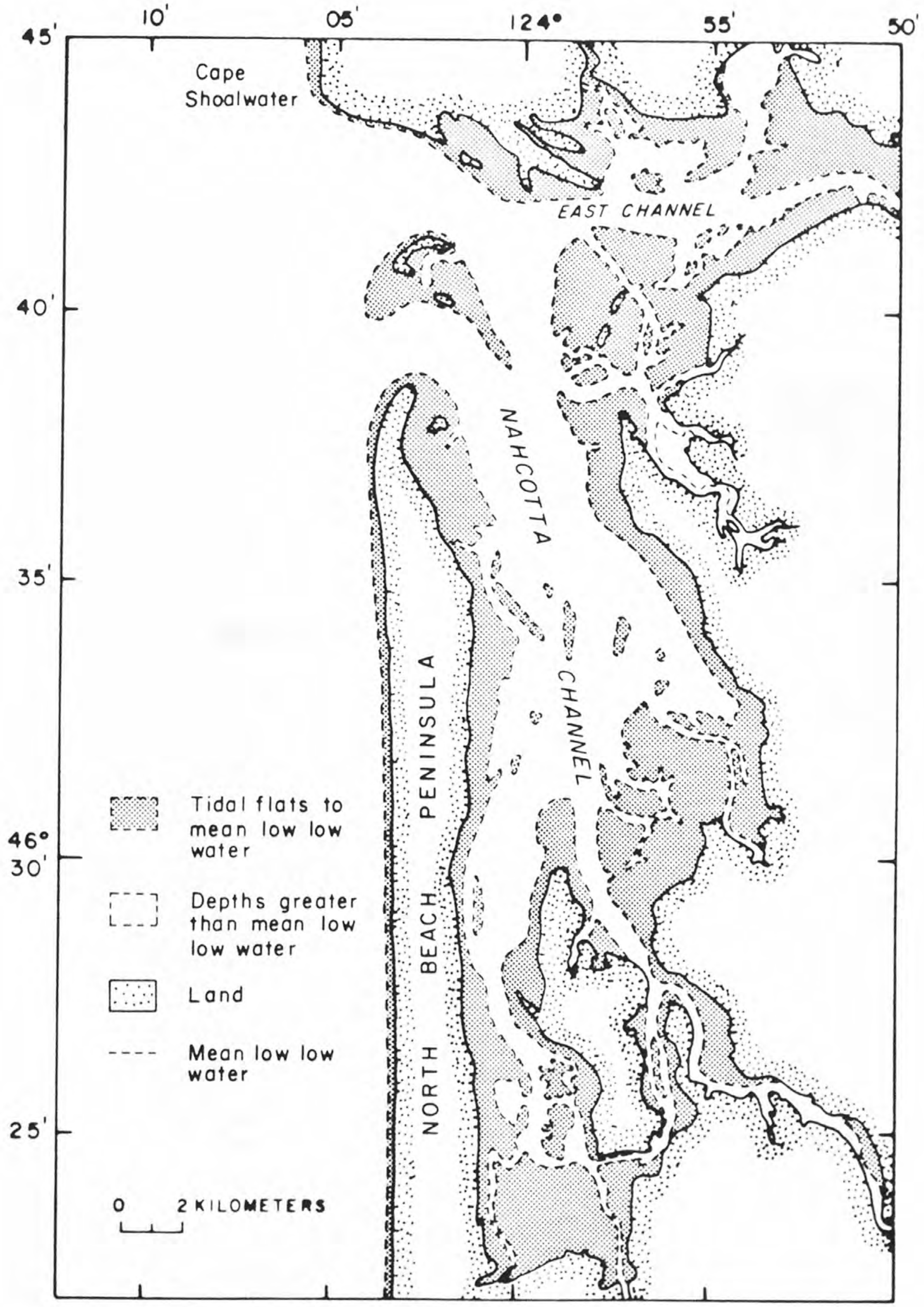
FIGURES

Fig. 1. Index map showing location of Willapa Bay, Washington.



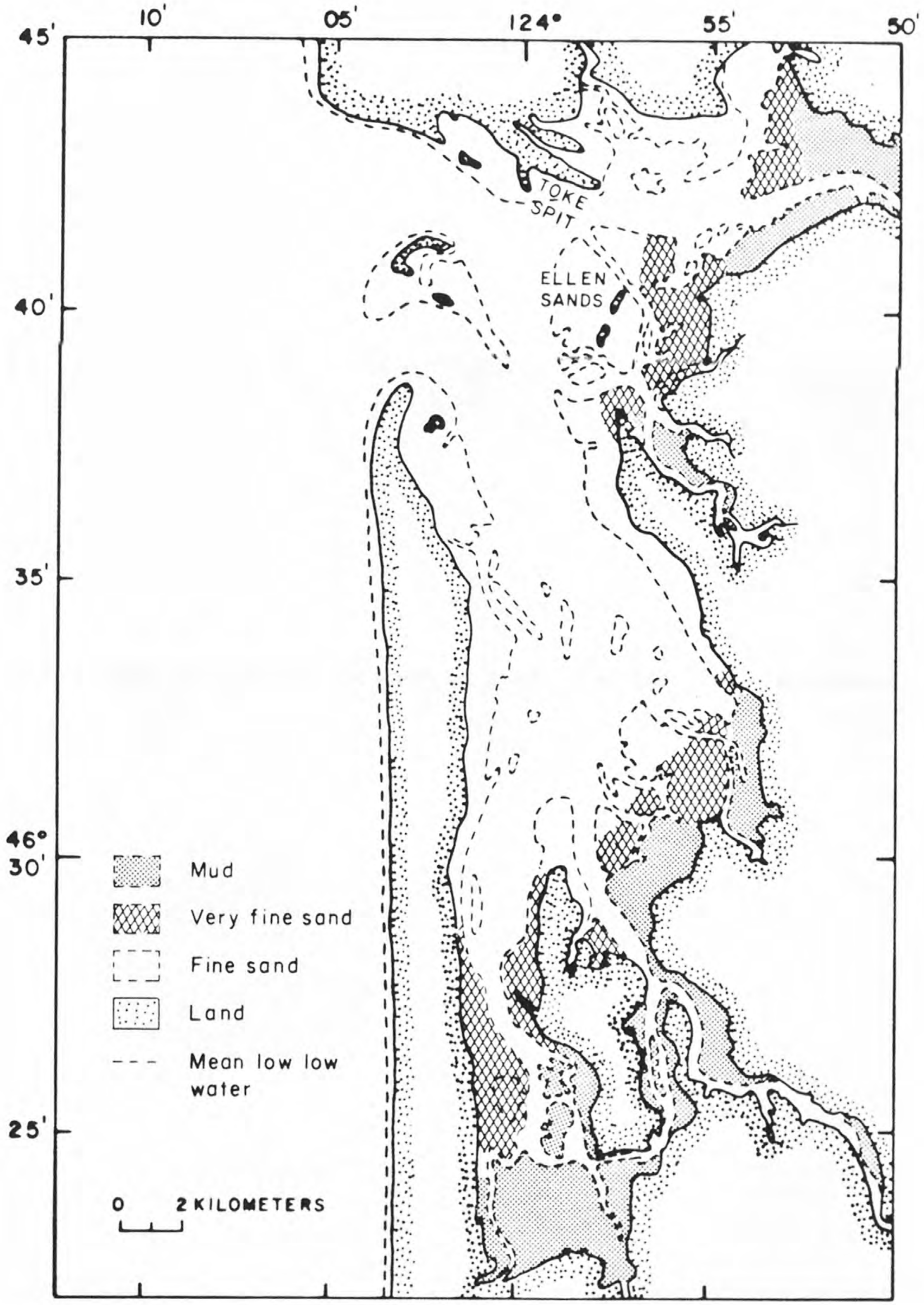
40'
20'
124°
40'
20'
20'
47°
40'
20'
46°
GRAYS HARBOR
PACIFIC OCEAN
WILLAPA BAY
COLUMBIA RIVER
N
0
20 KILOMETERS
Seattle
WASH
OREGON
PACIFIC OCEAN

Fig. 2. Bathymetry of Willapa Bay, Washington.



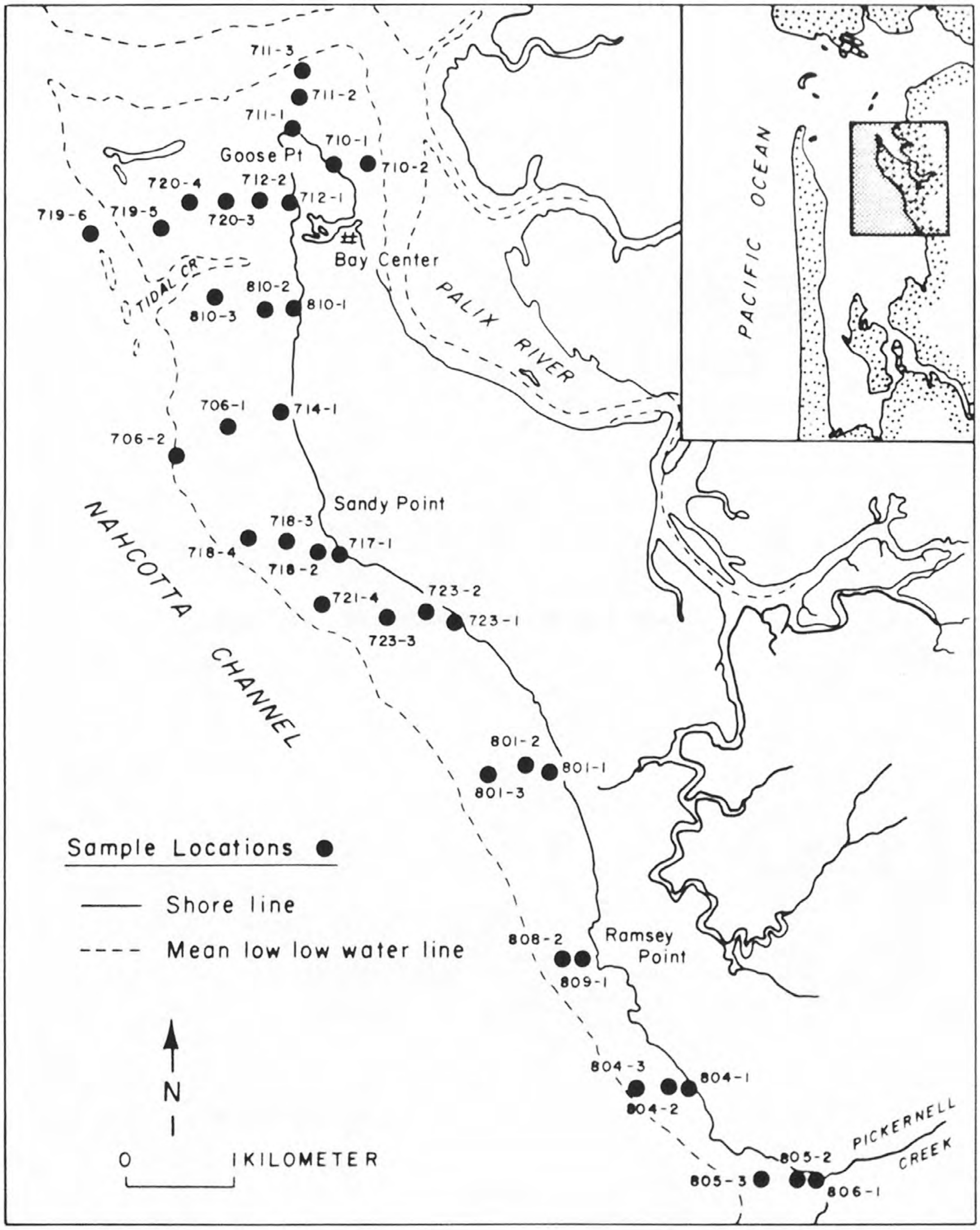
10'
05'
124°
55'
50'
45'
40'
35'
46° 30'
25'
Cape Shoalwater
EAST CHANNEL
NAHCOTTA
CHANNEL
NORTH BEACH PENINSULA
Tidal flats to mean low low water
Depths greater than mean low low water
Land
Mean low low water
0
2 KILOMETERS

Fig. 3. Sediment texture in Willapa Bay, Washington.



10'
05'
124°
55'
50'
45'
40'
35'
46°
30'
25'
TOKE SPIT
ELLEN SANDS
Mud
Very fine sand
Fine sand
Land
Mean low low water
0 2 KILOMETERS

Fig. 4. Index map showing location of study area and sample stations.



711-3
711-2
711-1
710-1
710-2
Goose Pt
720-4
712-2
712-1
719-6
719-5
720-3
Bay Center
TIDAL CR
810-2
810-1
810-3
PALIX RIVER
PACIFIC OCEAN
706-1
714-1
706-2
NAHCOTTA CHANNEL
Sandy Point
718-3
717-1
718-4
718-2
723-2
721-4
723-1
723-3
801-2
801-1
801-3
Sample Locations
Shore line
Mean low low water line
808-2
Ramsey Point
809-1
N
804-3
804-1
804-2
0
1 KILOMETER
PICKERNELL CREEK
805-2
805-3
806-1

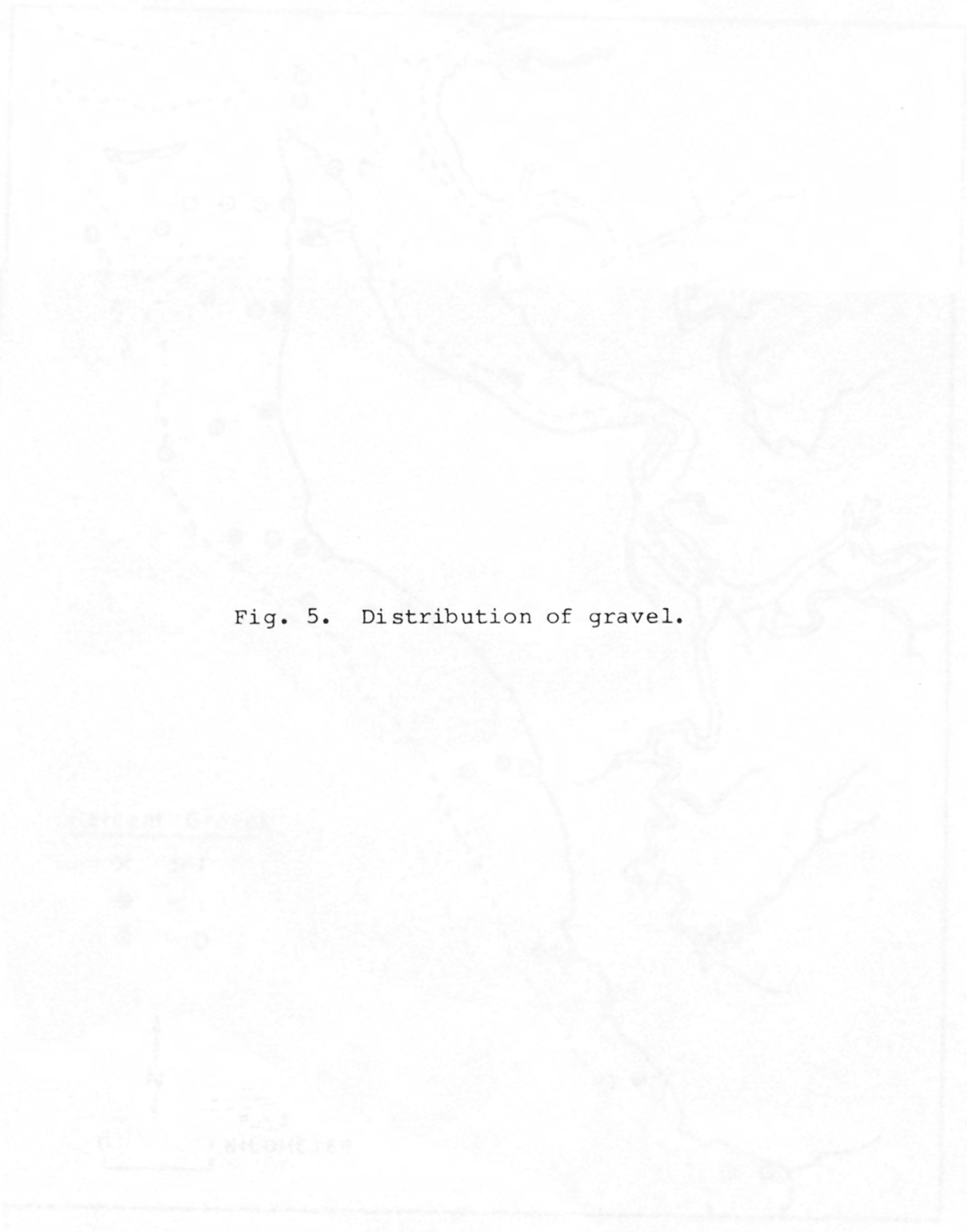


Fig. 5. Distribution of gravel.

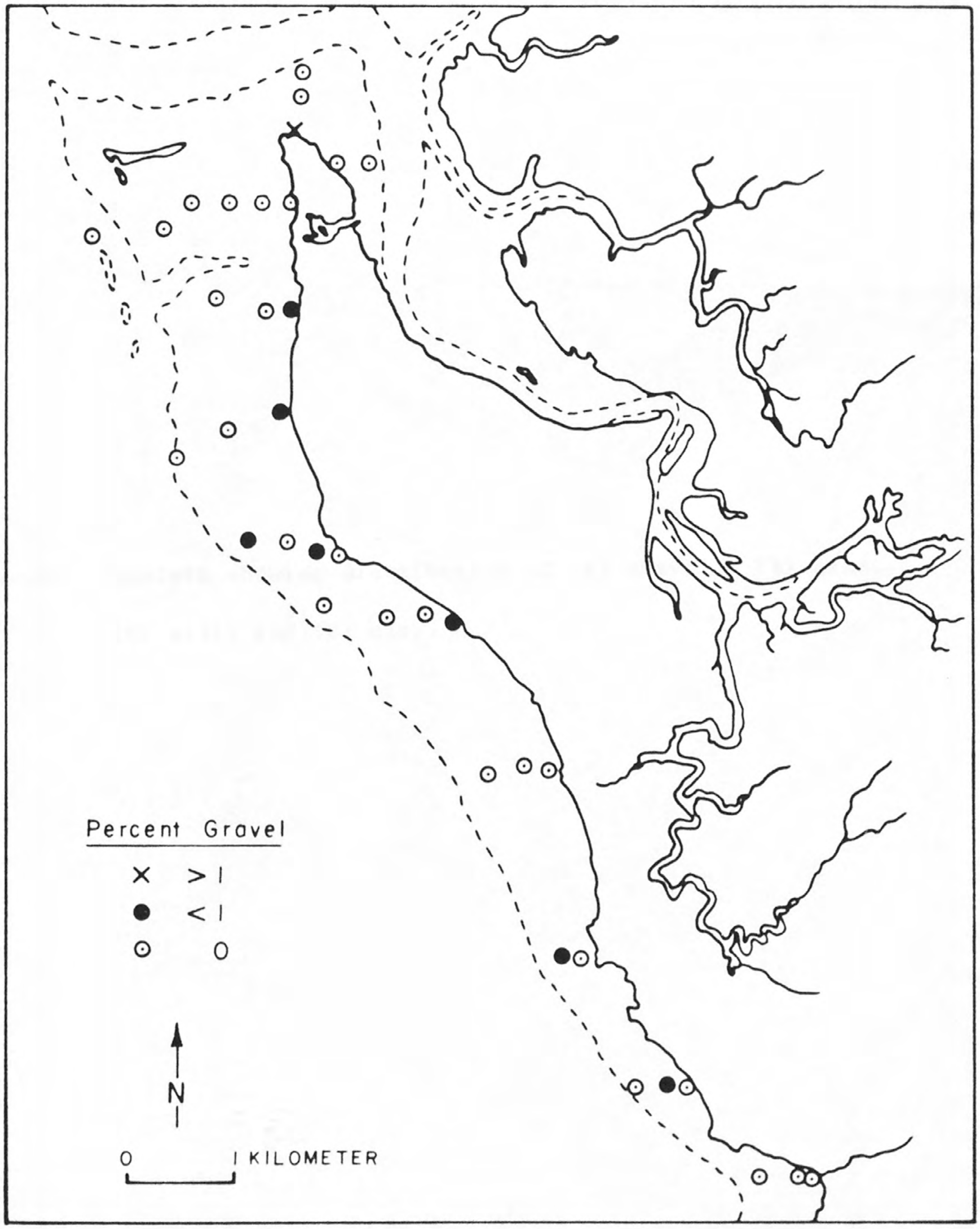
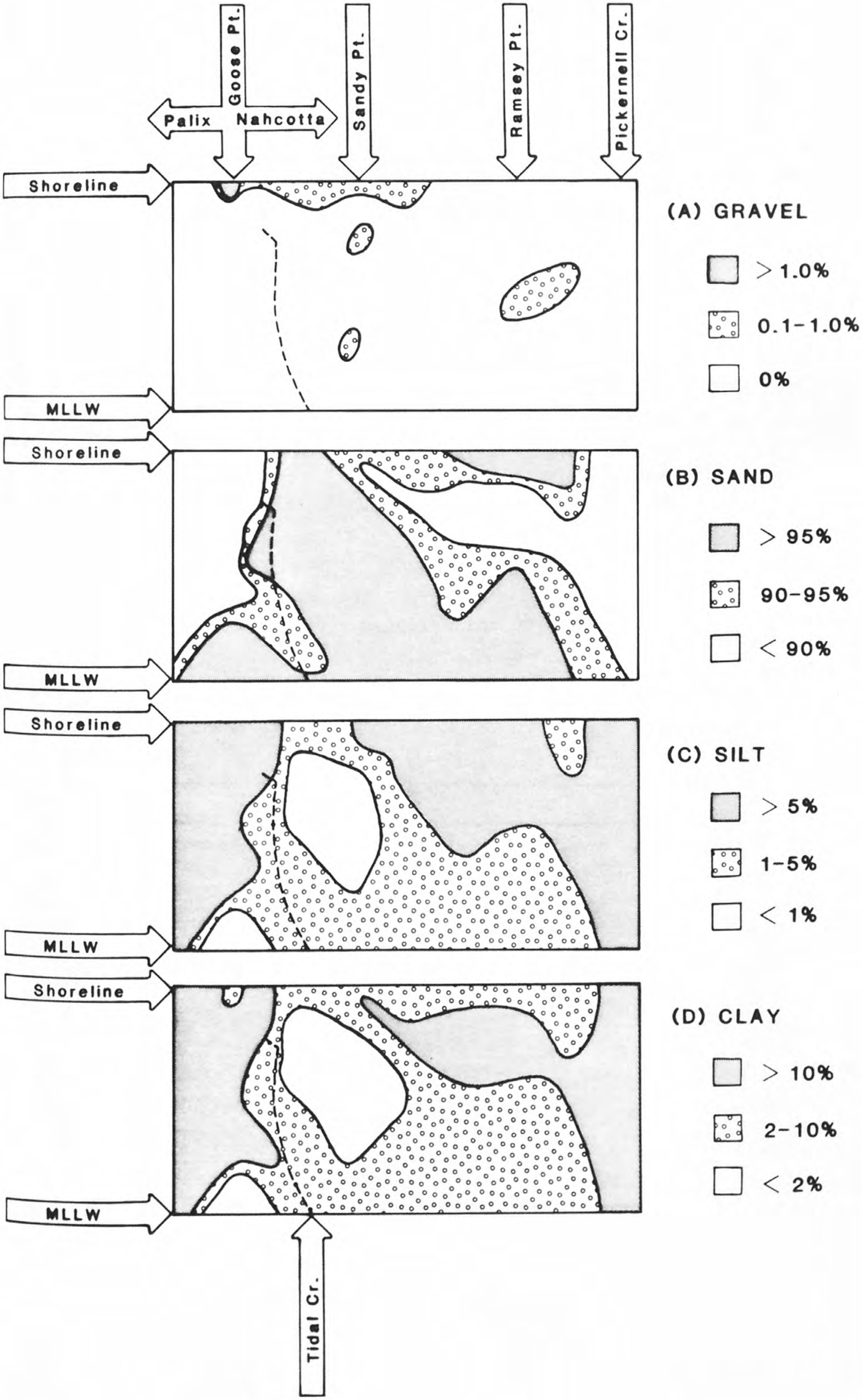

Percent Gravel
× > 1
● < 1
⊙ 0
N
0 1 KILOMETER

Fig. 6. Isopleth showing distribution of (A) gravel, (B) sand, (C) silt, and (D) clay.



Goose Pt.
Palix
Nahcotta
Sandy Pt.
Ramsey Pt.
Pickernell Cr.
Shoreline
MLLW
(A) GRAVEL
> 1.0%
0.1-1.0%
0%
Shoreline
MLLW
(B) SAND
> 95%
90-95%
< 90%
Shoreline
MLLW
(C) SILT
> 5%
1-5%
< 1%
Shoreline
MLLW
(D) CLAY
> 10%
2-10%
< 2%
Tidal Cr.

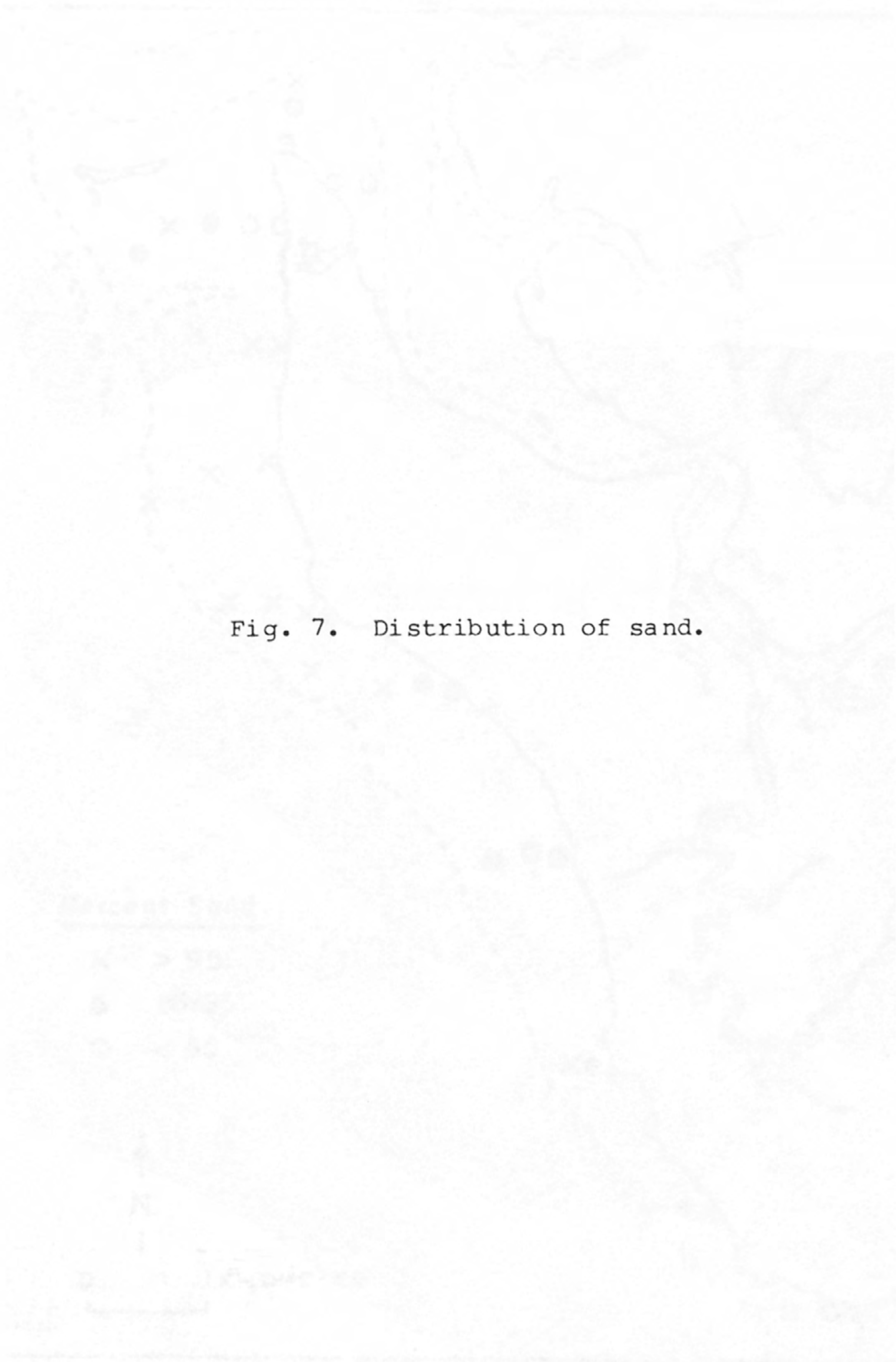
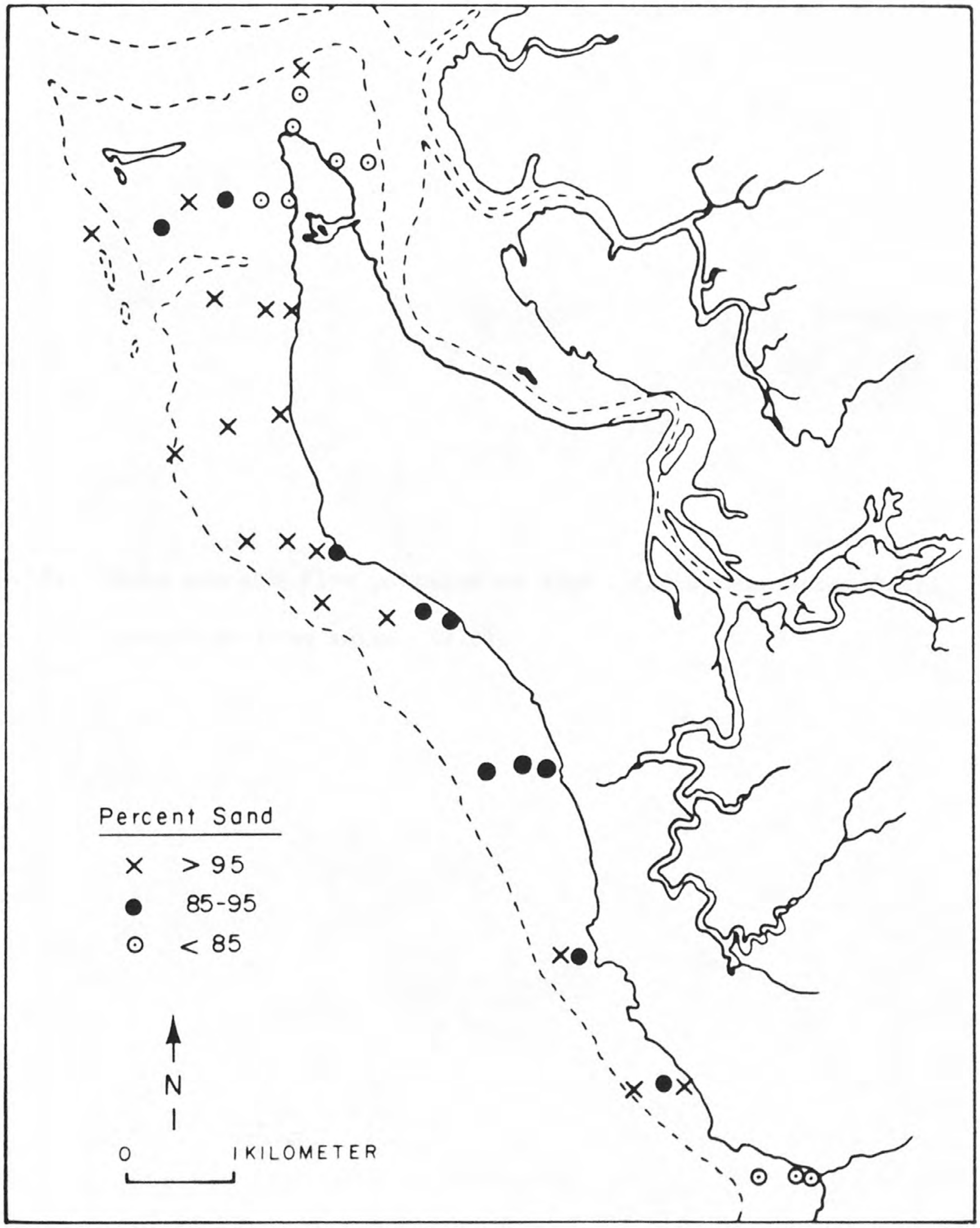
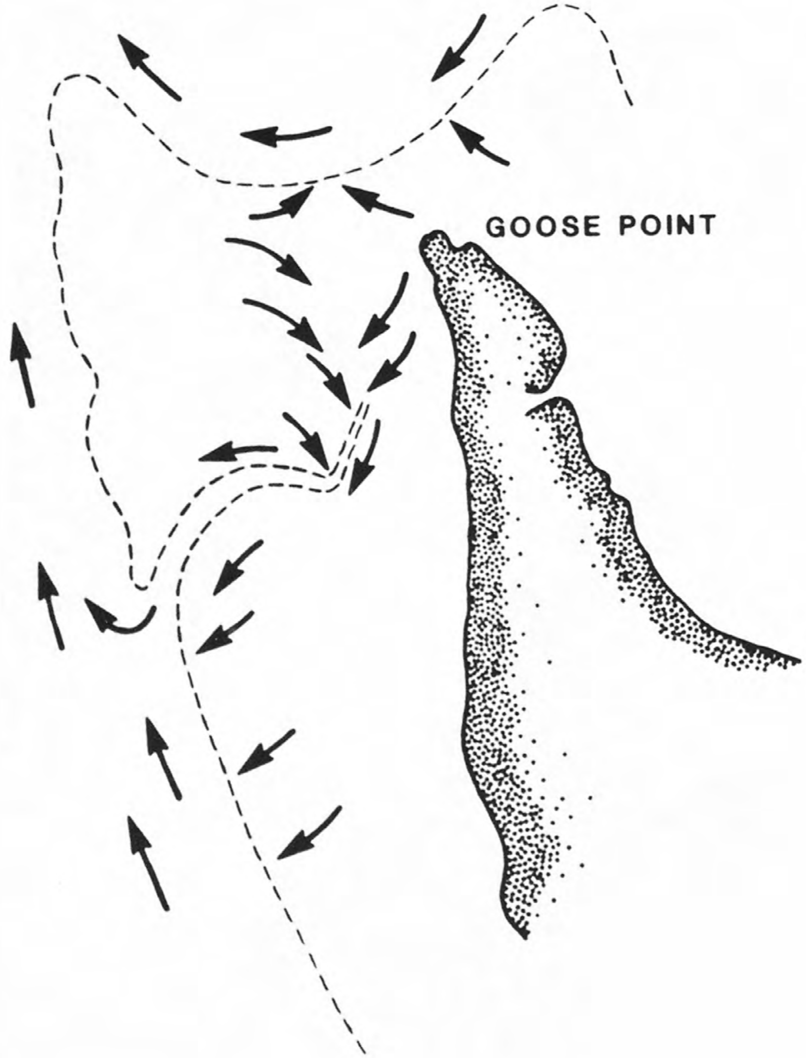


Fig. 7. Distribution of sand.

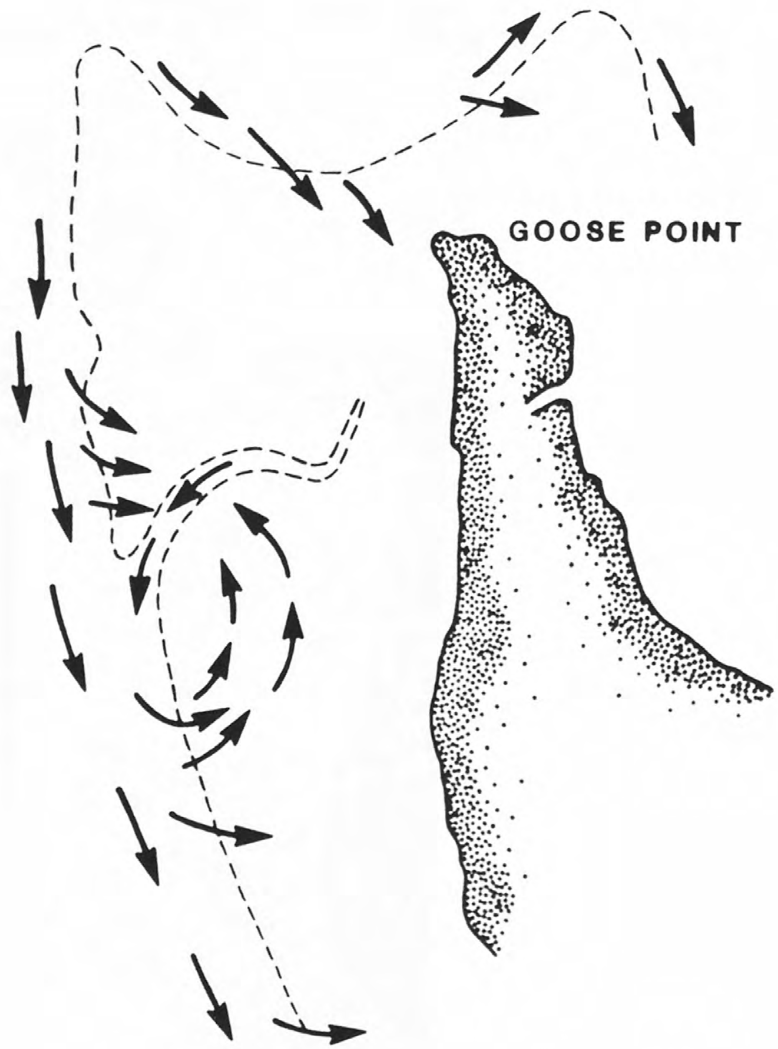


Percent Sand
× > 95
● 85-95
⊙ < 85
N
0
1 KILOMETER

Fig. 8. Flood and ebb flow patterns on tidal flats near Goose Point (modified from Anima, 1979).



EBB CURRENT PATTERN



FLOOD CURRENT PATTERN

Fig. 9. Distribution of silt.

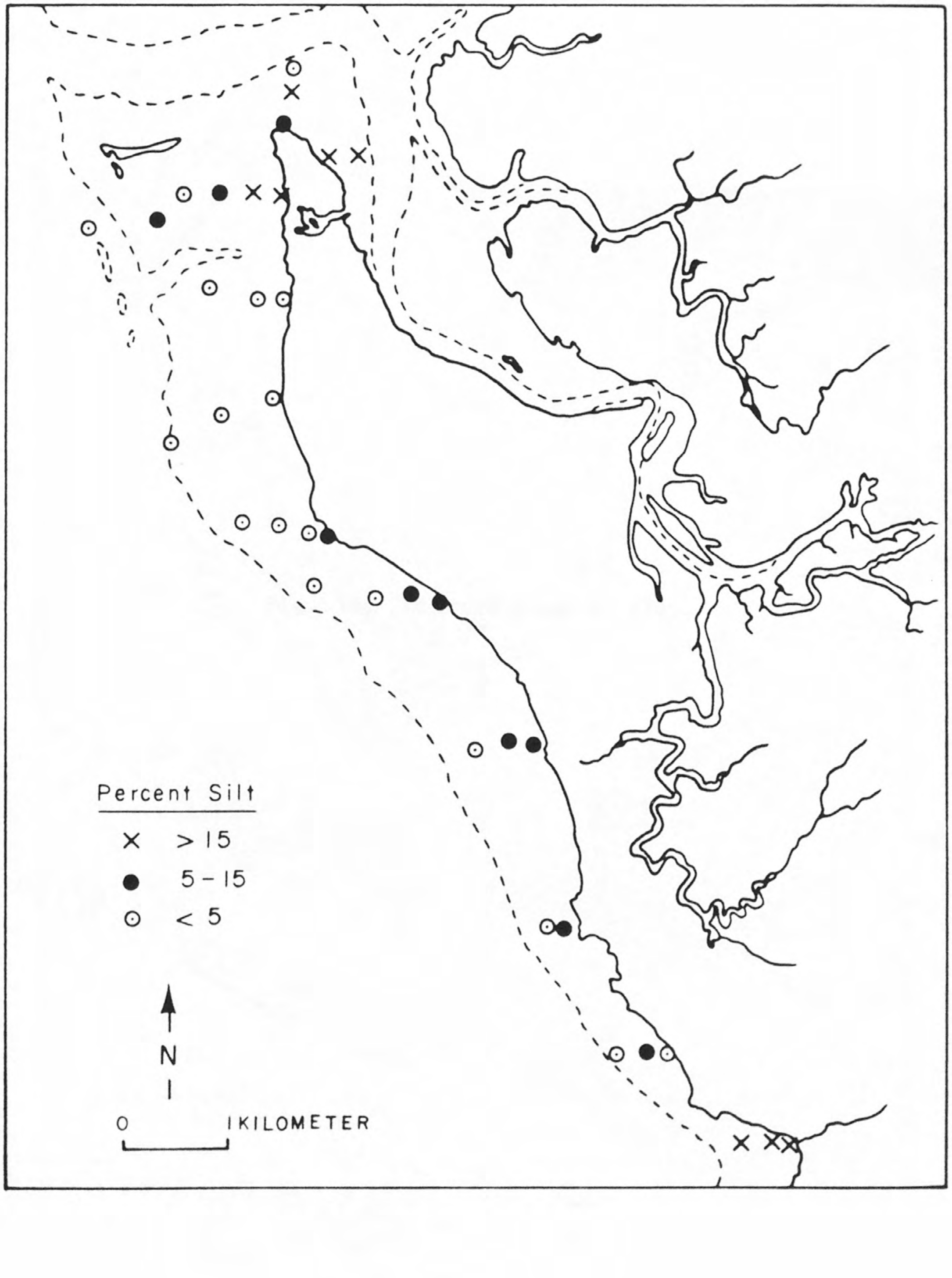

Percent Silt
× >15
● 5-15
⊙ <5
N
0 1KILOMETER

Fig. 10. Distribution of clay.

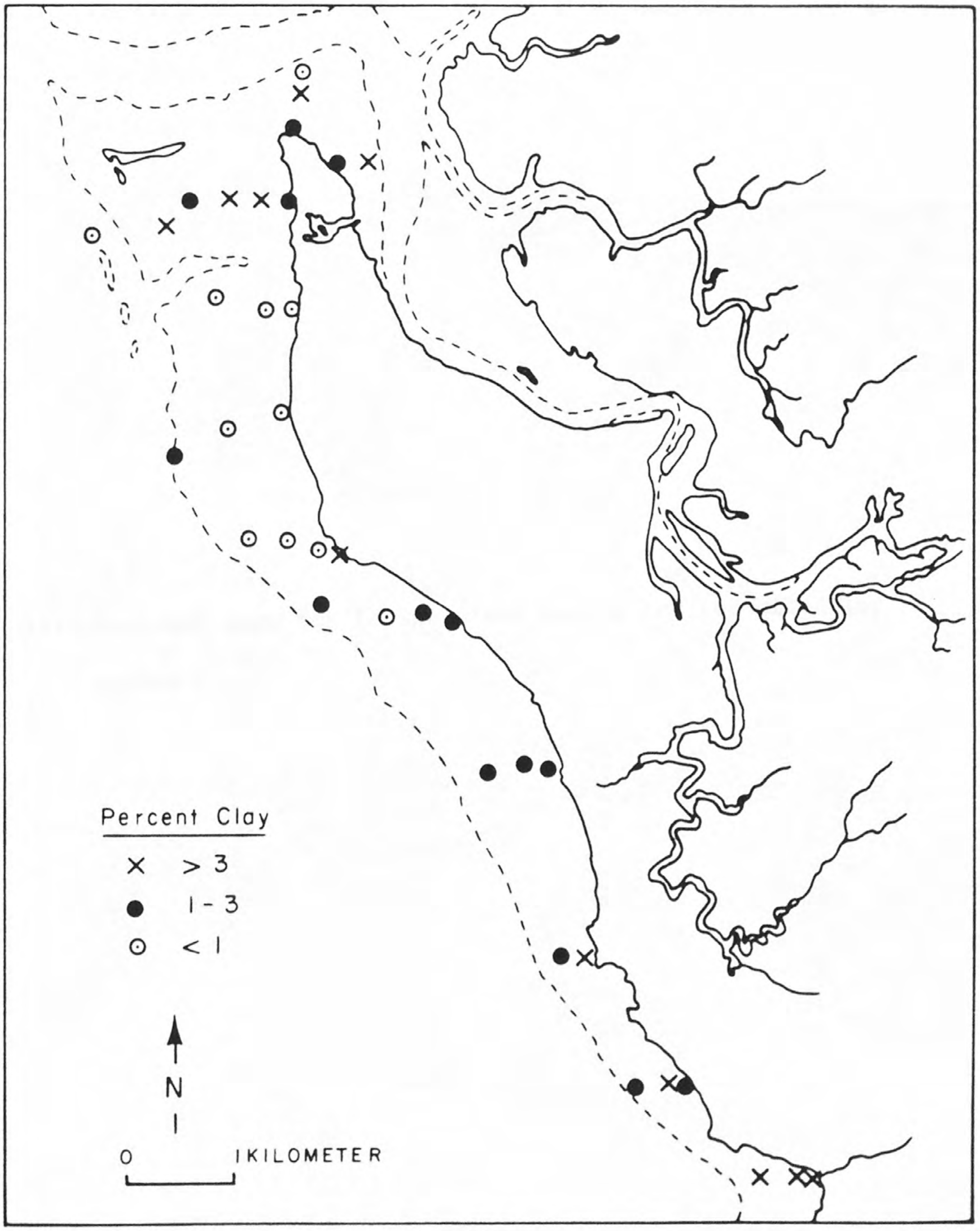

Percent Clay
> 3
1 - 3
< 1
N
0
1 KILOMETER

Fig. 11. Isopleth maps for (A) sand/mud ratios and (B) silt/clay ratios.

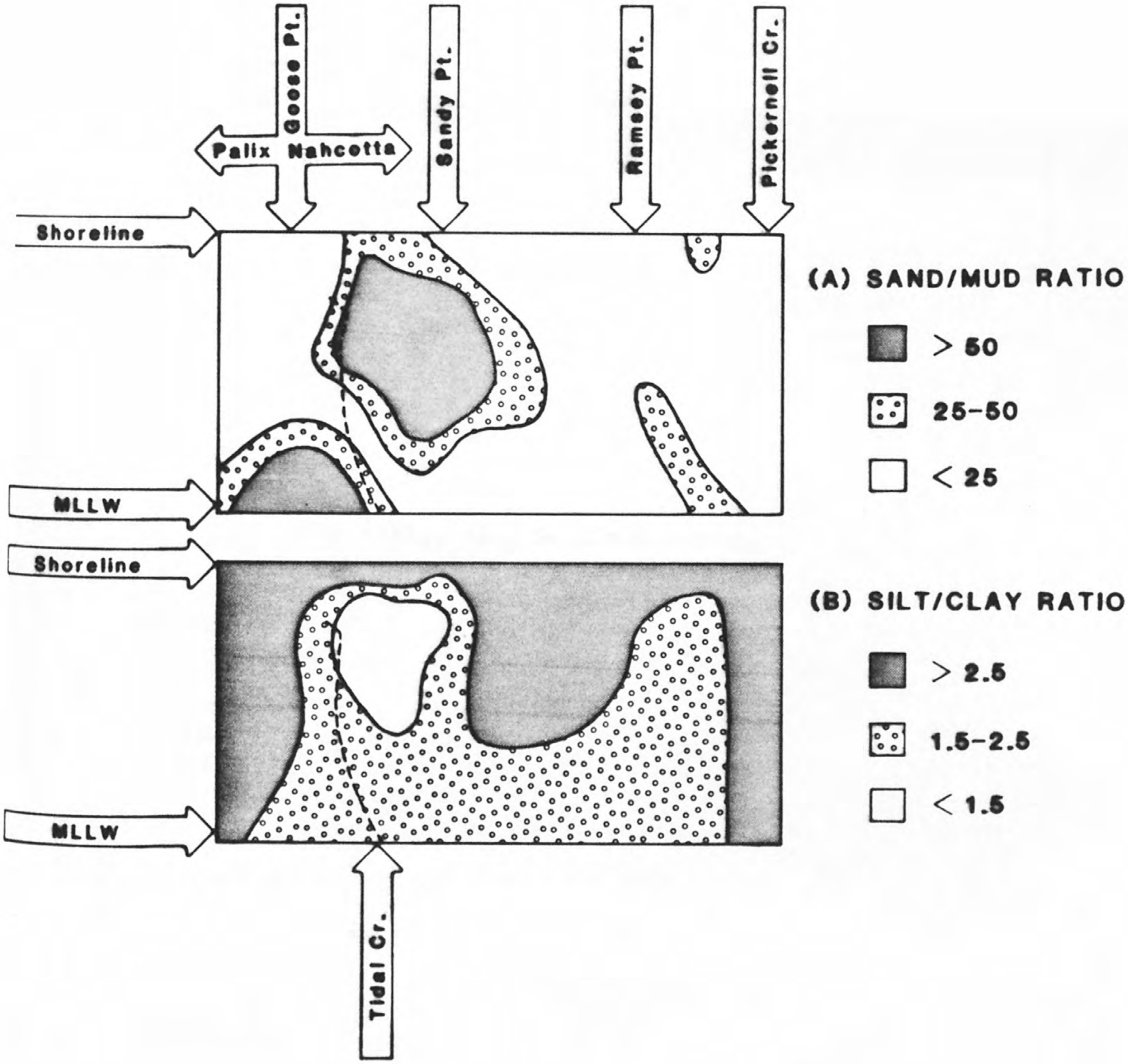
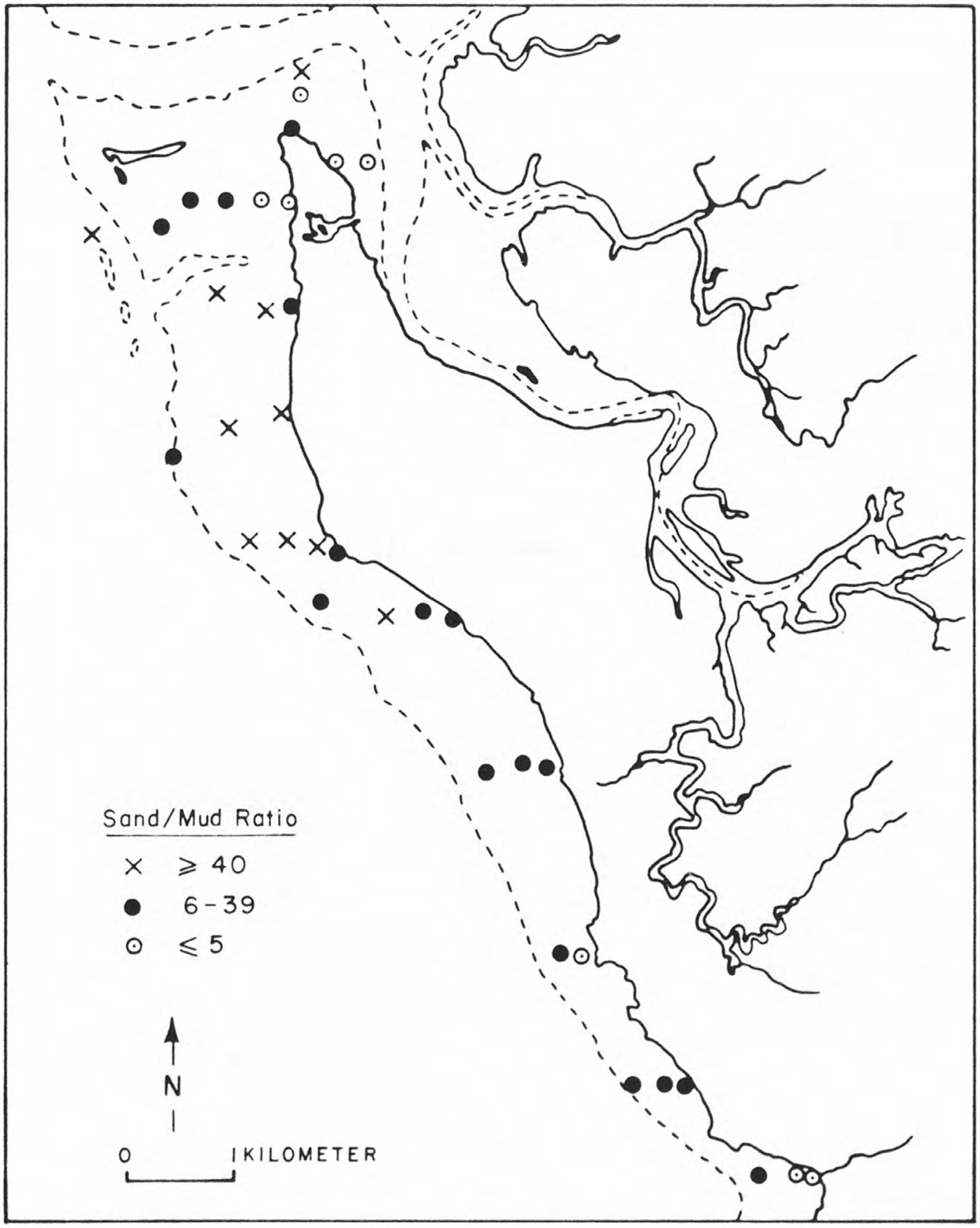
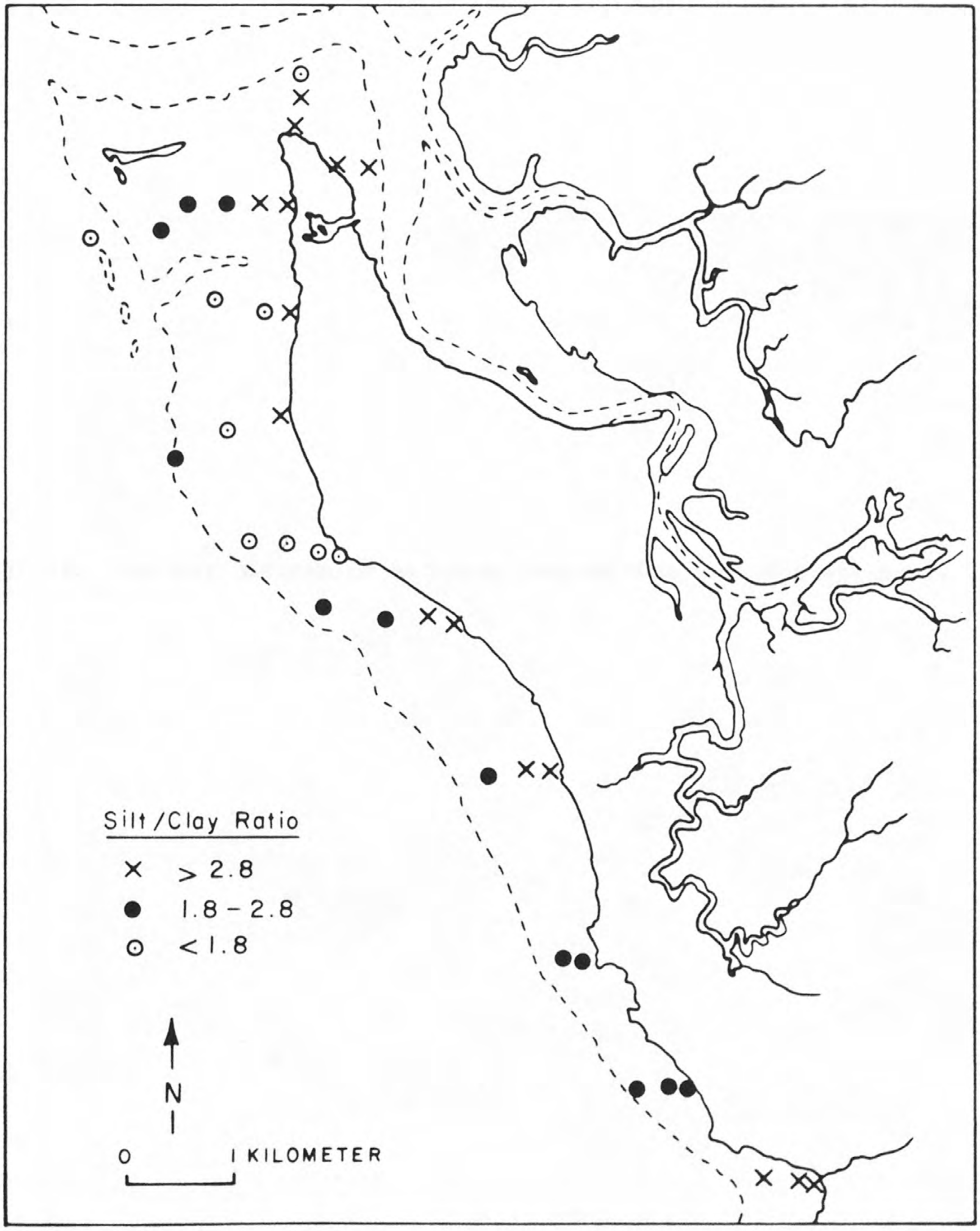

Goose Pt.
Palix
Nahcotta
Sandy Pt.
Ramsey Pt.
Pickernell Cr.
Shoreline
MLLW
(A) SAND/MUD RATIO
> 50
25-50
< 25
Shoreline
MLLW
(B) SILT/CLAY RATIO
> 2.5
1.5-2.5
< 1.5
Tidal Cr.

Fig. 12. Sand/mud ratios.



Sand/Mud Ratio
× ≥ 40
● 6-39
⊙ ≤ 5
N
0 1 KILOMETER

Fig. 13. Silt/clay ratios.


Silt/Clay Ratio
> 2.8
1.8 – 2.8
< 1.8
N
0
1 KILOMETER

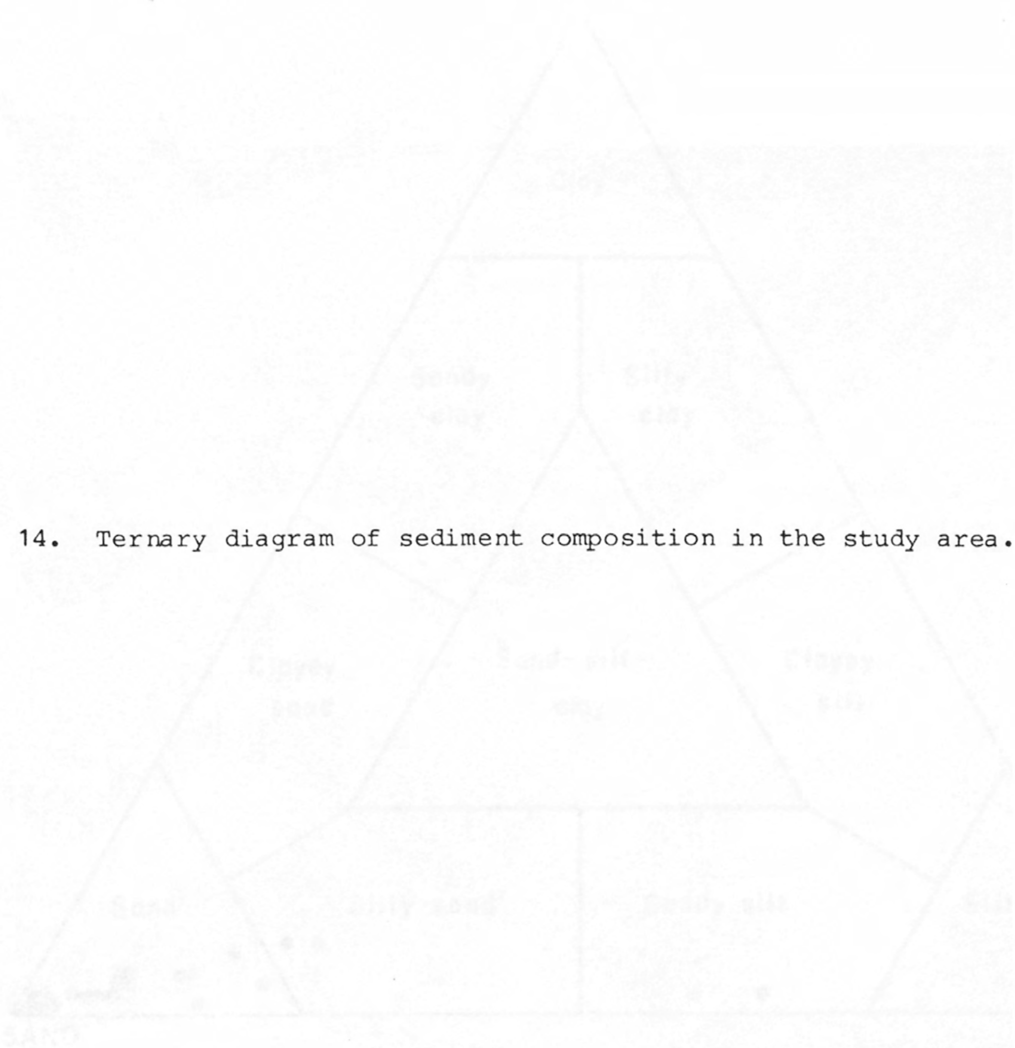


Fig. 14. Ternary diagram of sediment composition in the study area.

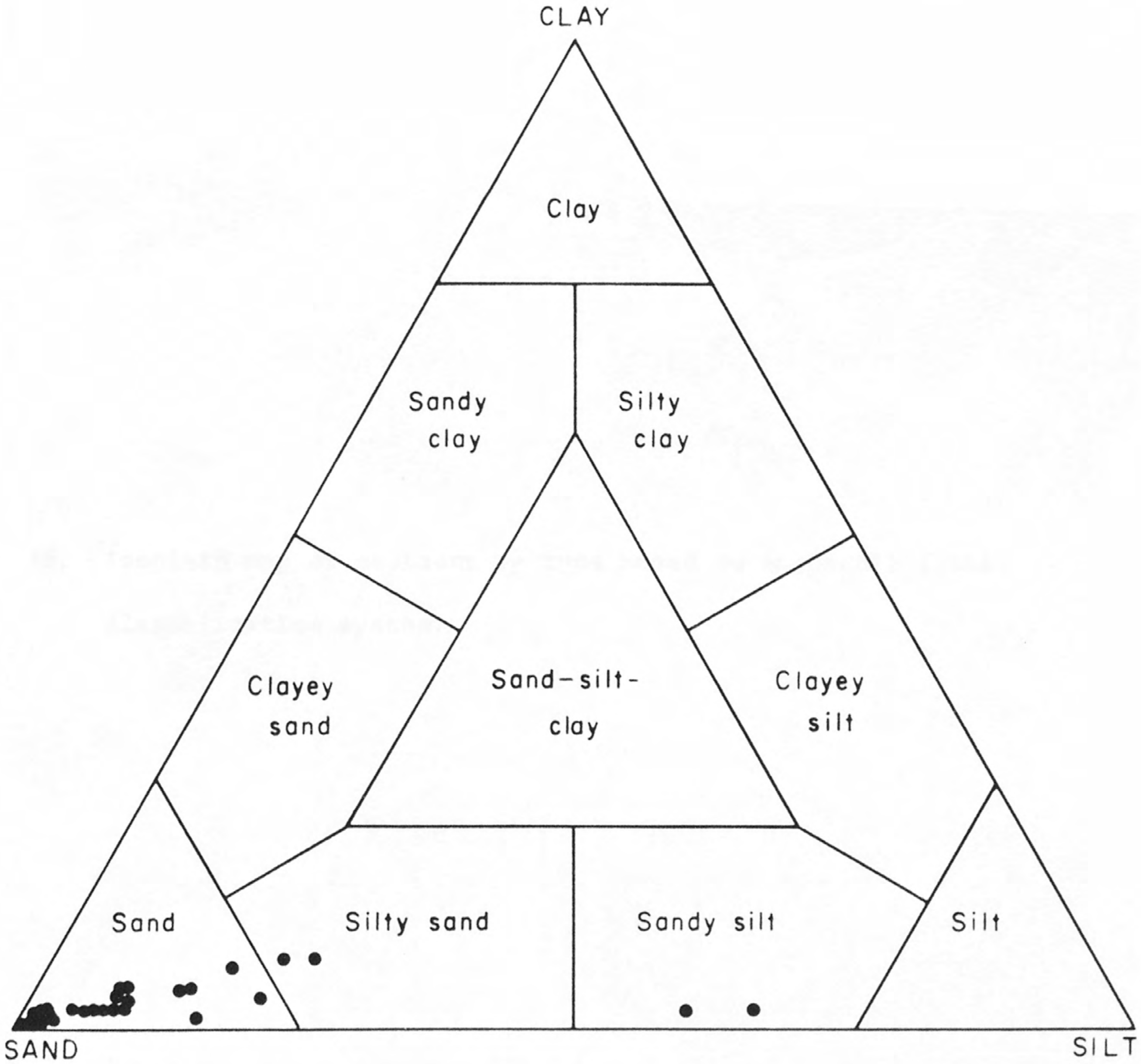

CLAY
Clay
Sandy clay
Silty clay
Clayey sand
Sand-silt-clay
Clayey silt
Sand
Silty sand
Sandy silt
Silt
SAND
SILT

Fig. 15. Isopleth map of sediment by type based on Shepard's (1954) classification system.

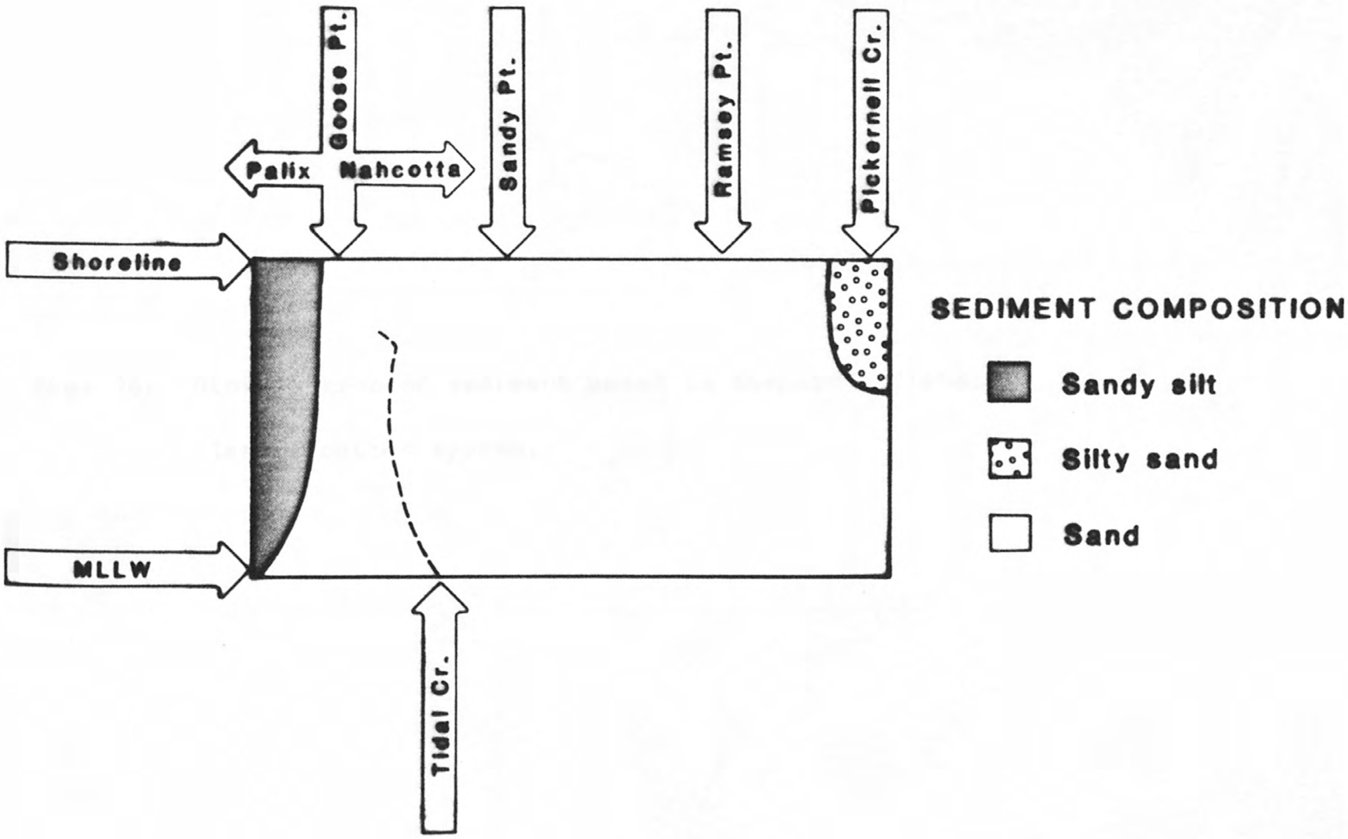
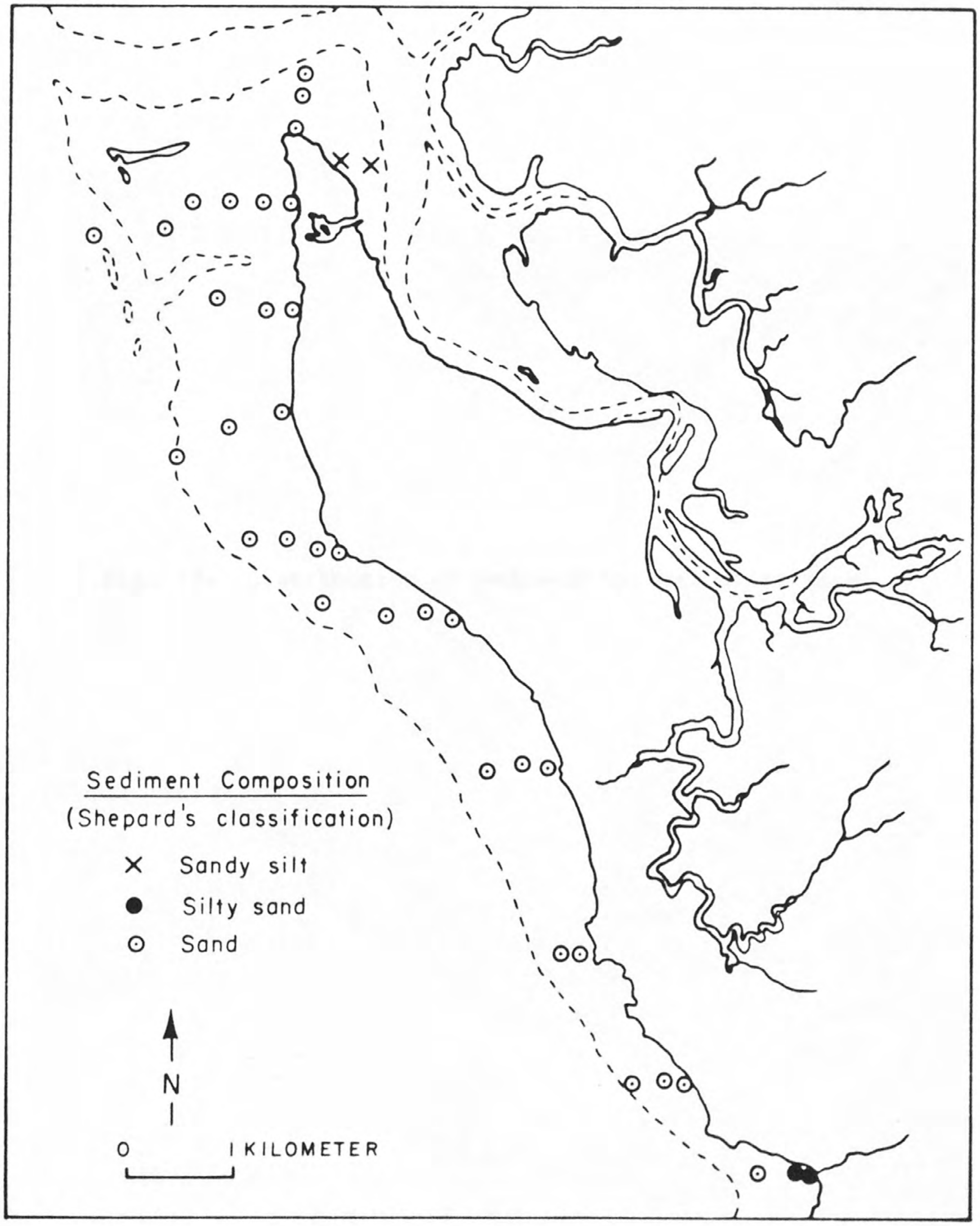

Goose Pt.
Palix
Nahcotta
Sandy Pt.
Ramsey Pt.
Pickernell Cr.
Shoreline
MLLW
Tidal Cr.
SEDIMENT COMPOSITION
Sandy silt
Silty sand
Sand

Fig. 16. Distribution of sediment based on Shepard's (1954) classification system.


Sediment Composition
(Shepard's classification)
Sandy silt
Silty sand
Sand
N
0
1 KILOMETER

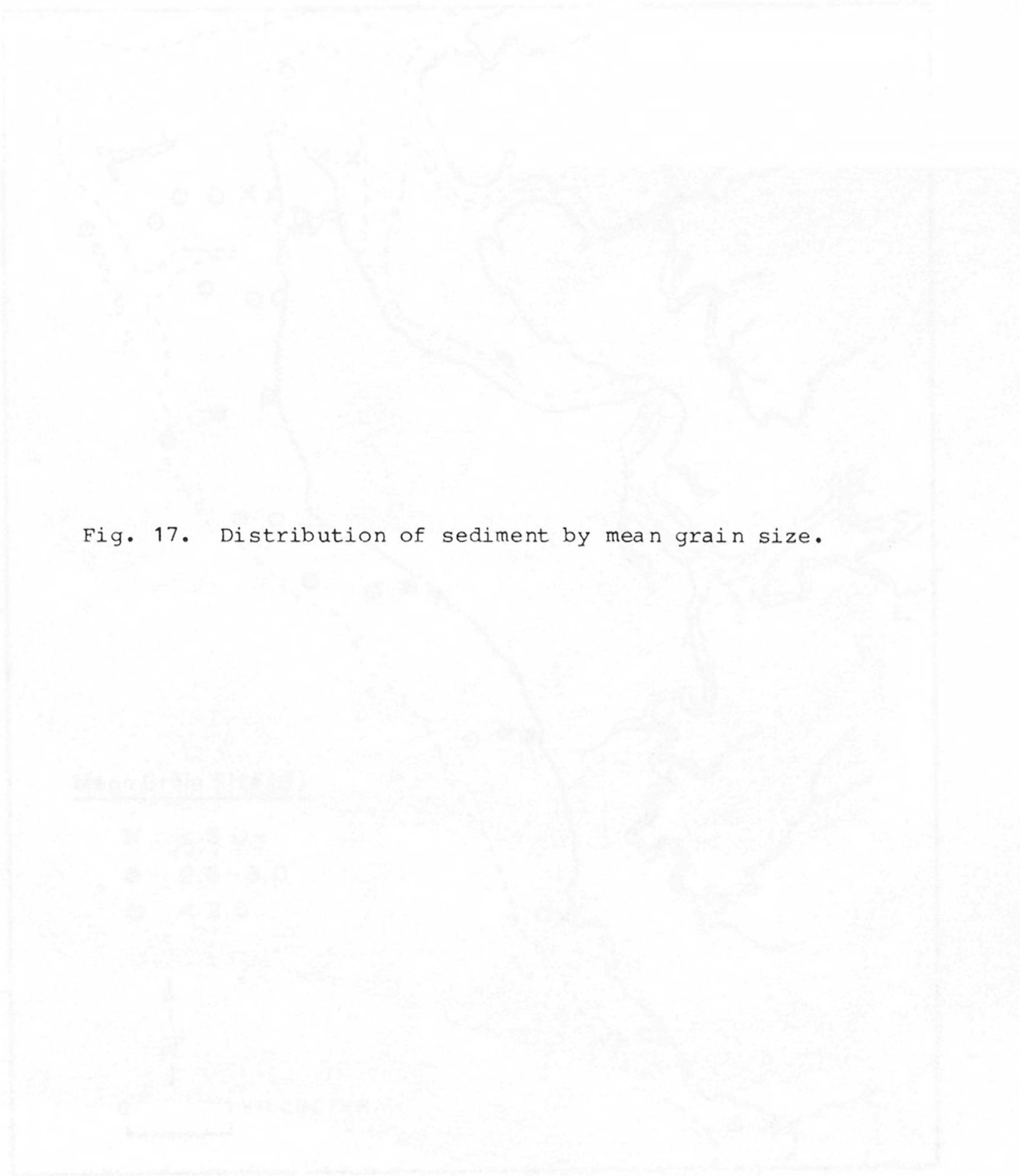
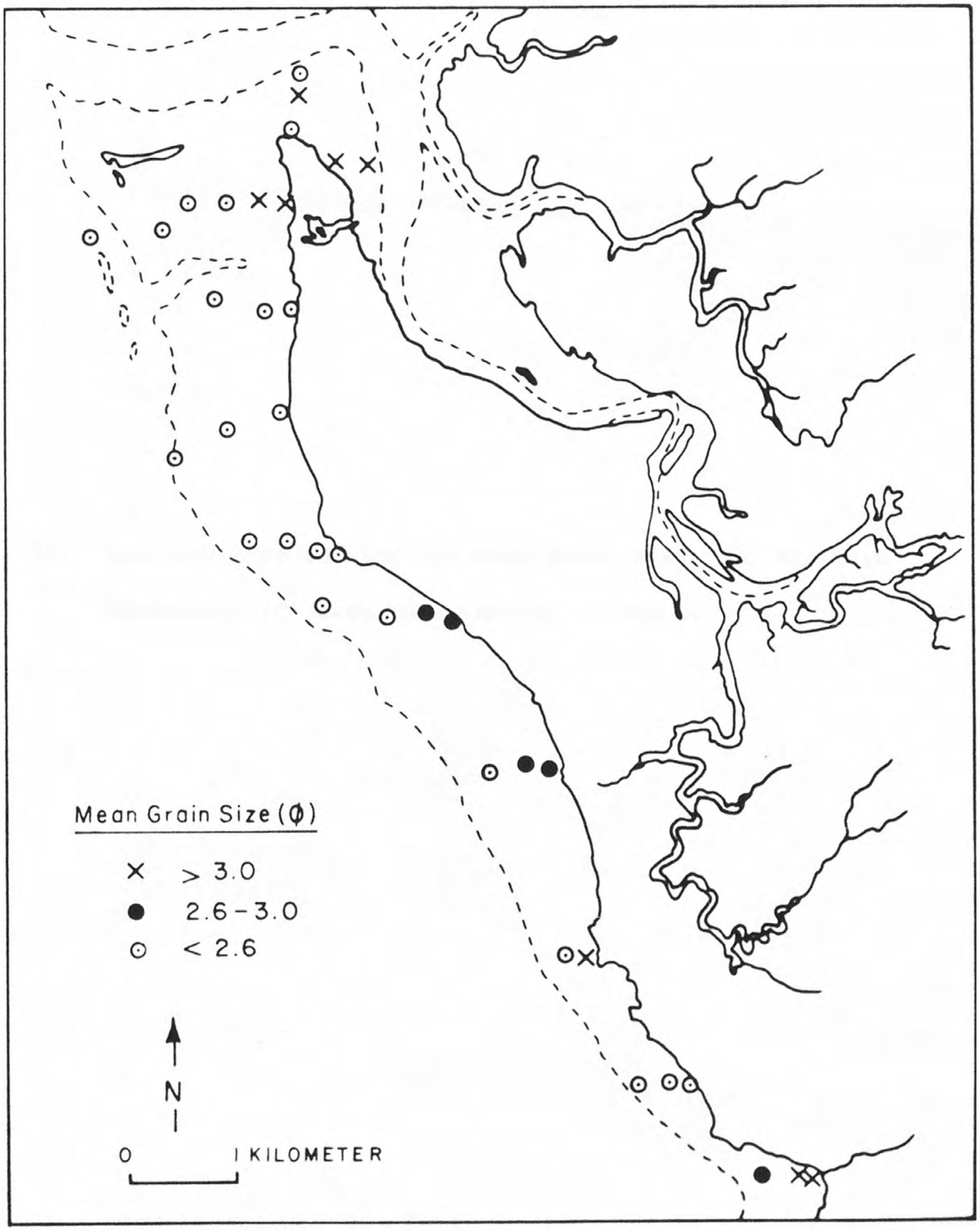
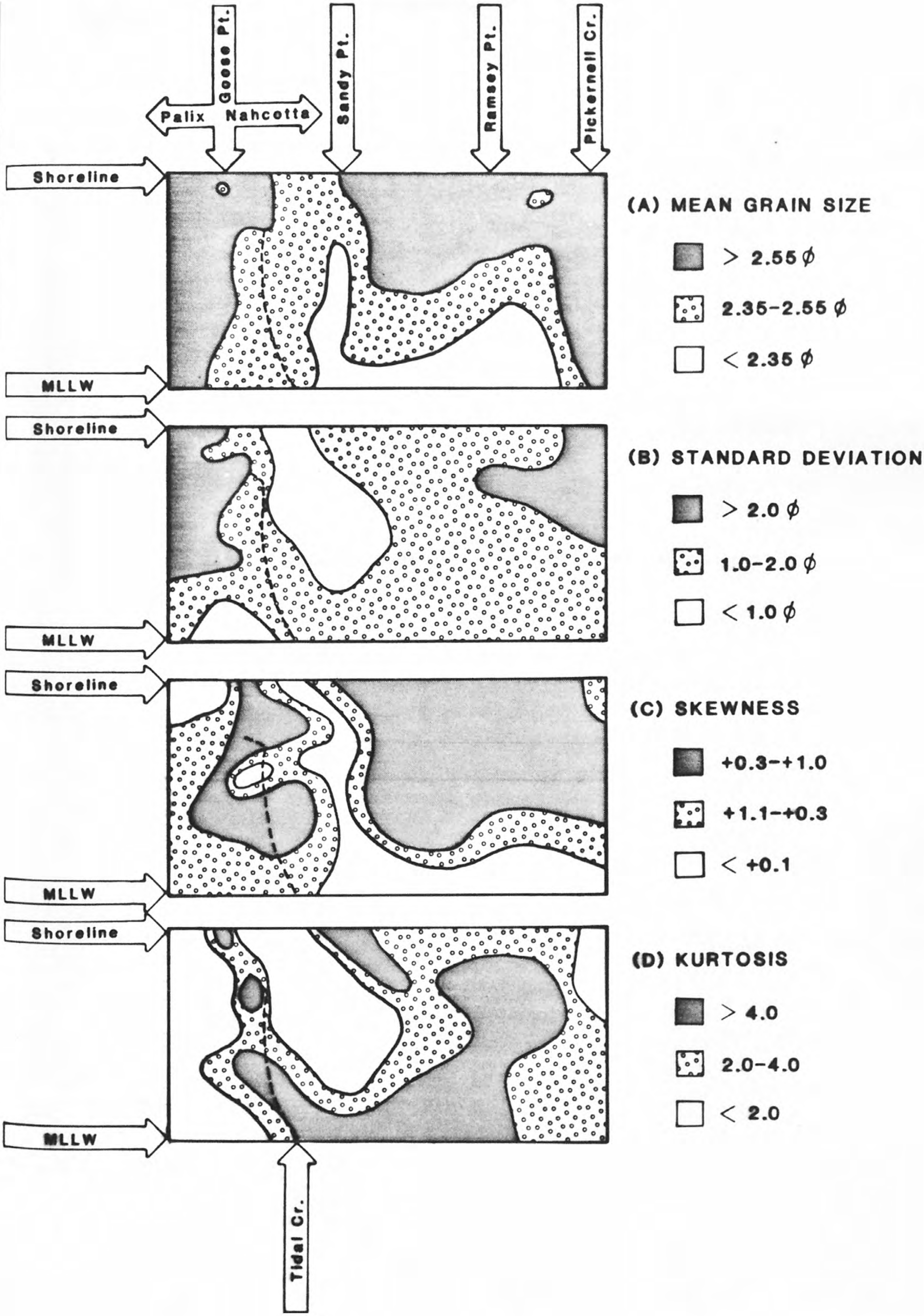


Fig. 17. Distribution of sediment by mean grain size.



Mean Grain Size (Ø)
× > 3.0
● 2.6–3.0
⊙ < 2.6
N
0 1 KILOMETER

Fig. 18. Isopleth maps showing (A) mean grain size, (B) standard deviation, (C) skewness, and (D) kurtosis.



Goose Pt.
Palix
Nahcotta
Sandy Pt.
Ramsey Pt.
Pickernell Cr.
Shoreline
MLLW
(A) MEAN GRAIN SIZE
> 2.55 ϕ
2.35–2.55 ϕ
< 2.35 ϕ
Shoreline
MLLW
(B) STANDARD DEVIATION
> 2.0 ϕ
1.0–2.0 ϕ
< 1.0 ϕ
Shoreline
MLLW
(C) SKEWNESS
+0.3–+1.0
+1.1–+0.3
< +0.1
Shoreline
MLLW
(D) KURTOSIS
> 4.0
2.0–4.0
< 2.0
Tidal Cr.

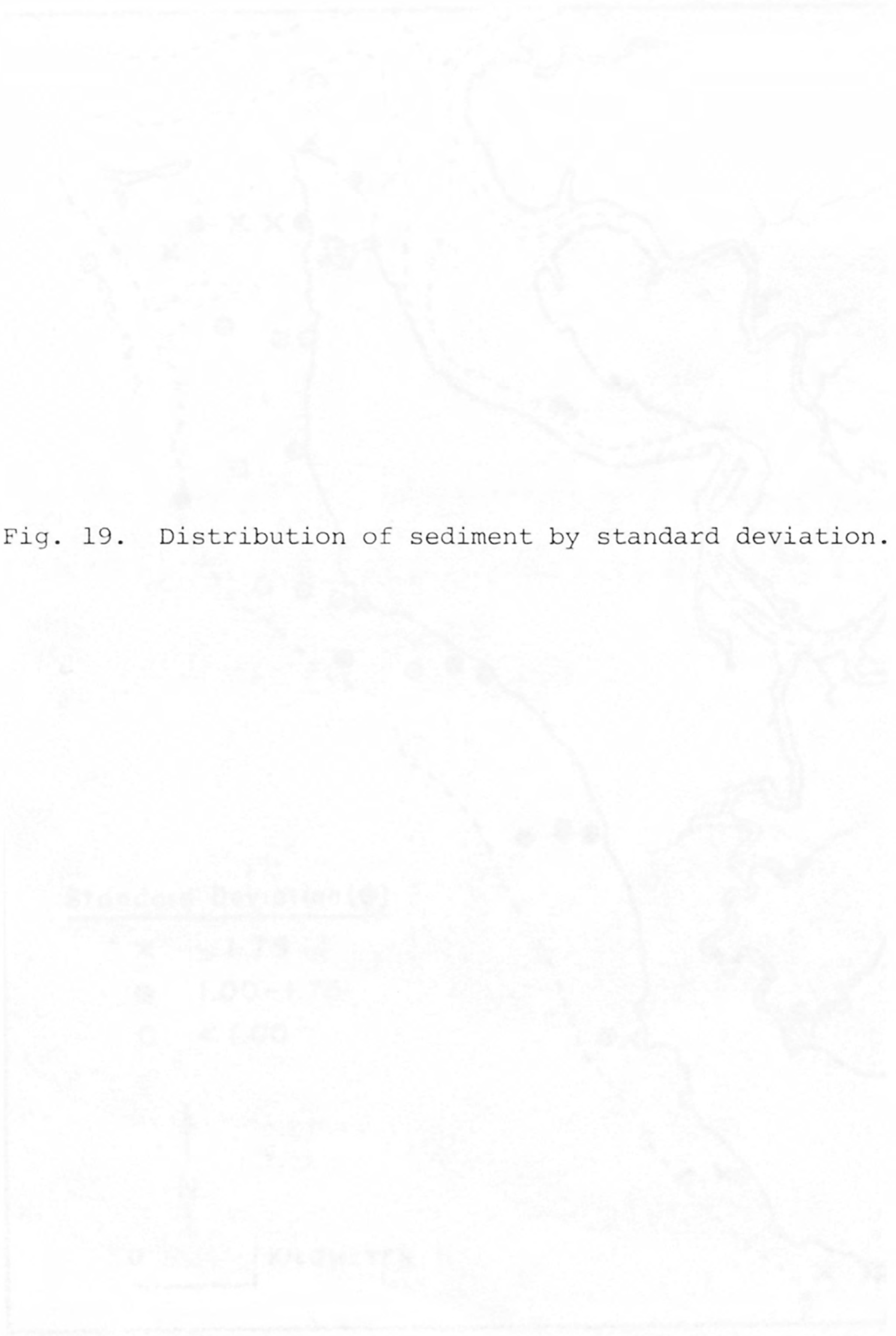


Fig. 19. Distribution of sediment by standard deviation.

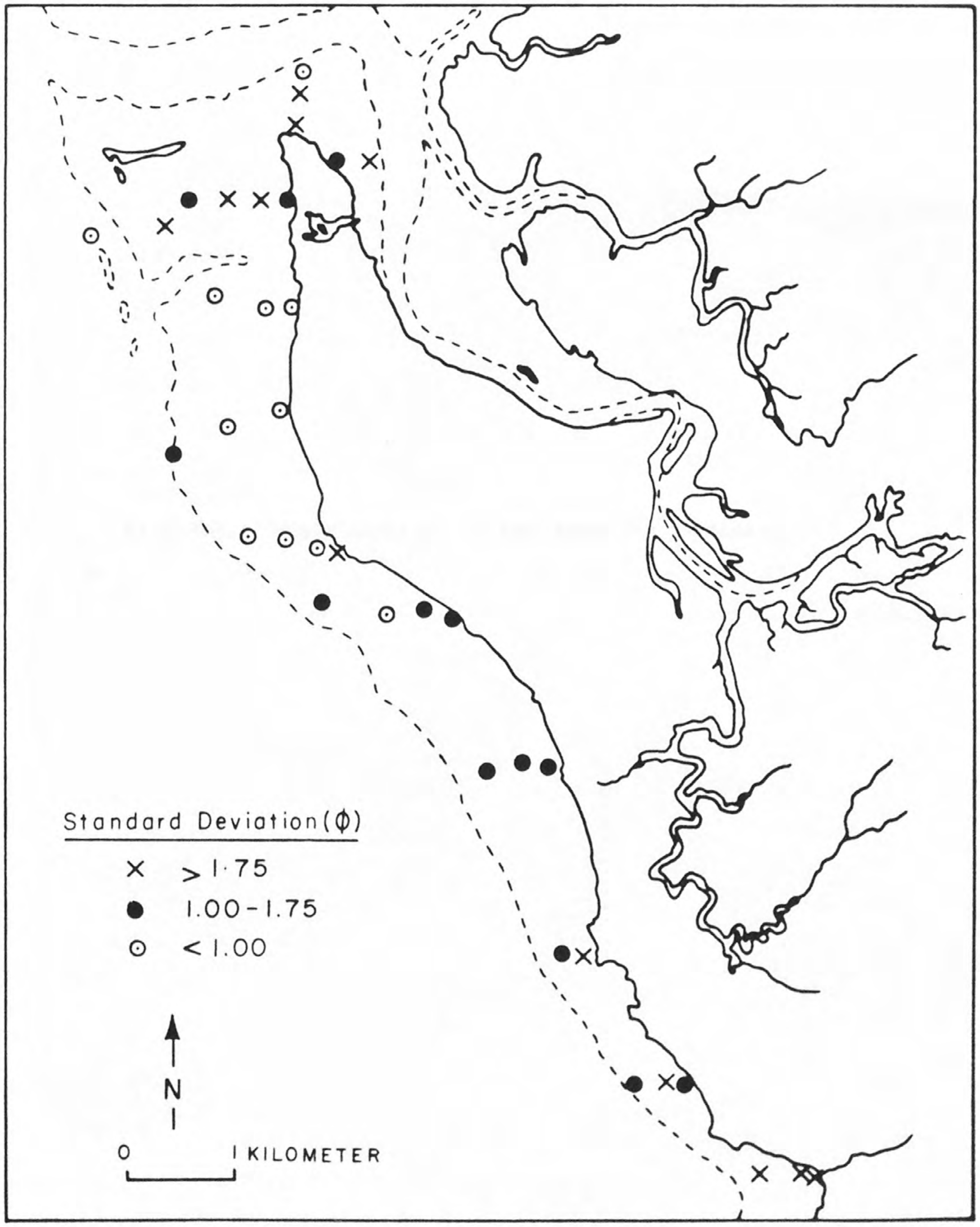

Standard Deviation (ϕ)
× > 1·75
● 1.00 - 1.75
⊙ < 1.00
N
0 1 KILOMETER

Fig. 20. Distribution of sediment by skewness.

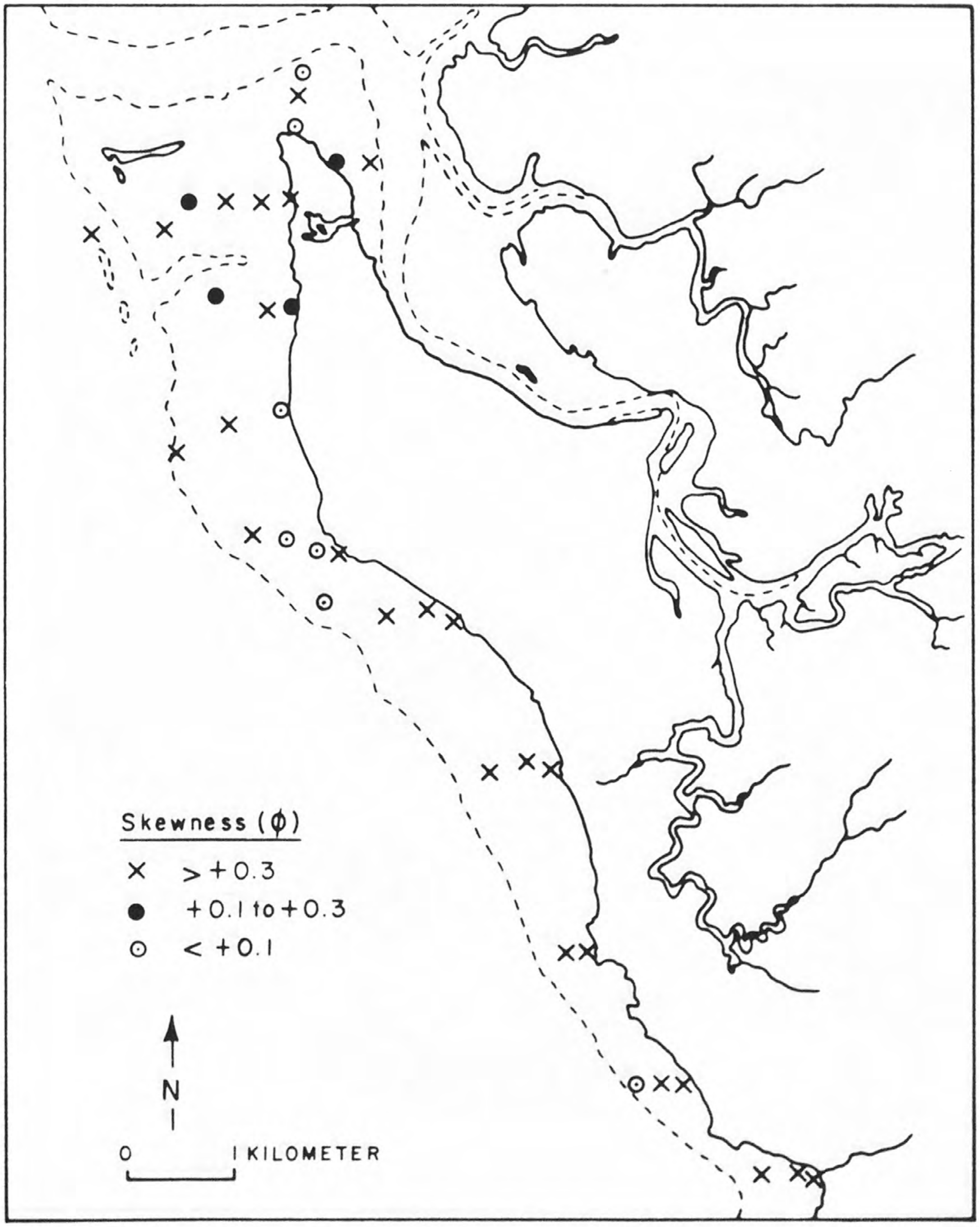

Skewness (φ)
> +0.3
+0.1 to +0.3
< +0.1
N
0
1 KILOMETER

Fig. 21. Distribution of sediment by kurtosis.

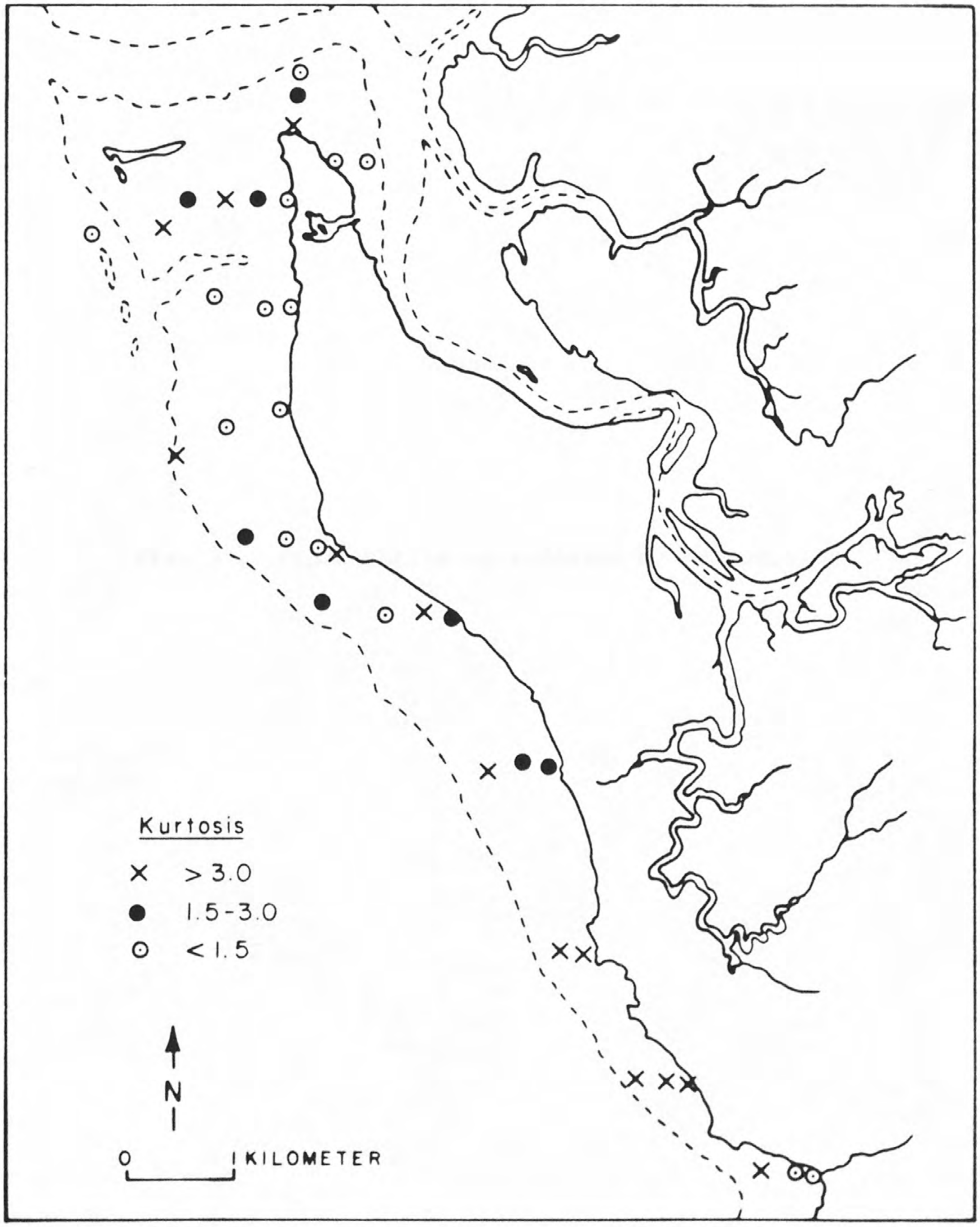

Kurtosis
> 3.0
1.5-3.0
< 1.5
N
0
1 KILOMETER

Fig. 22. Intertidal sample locations of Andrews (1965).

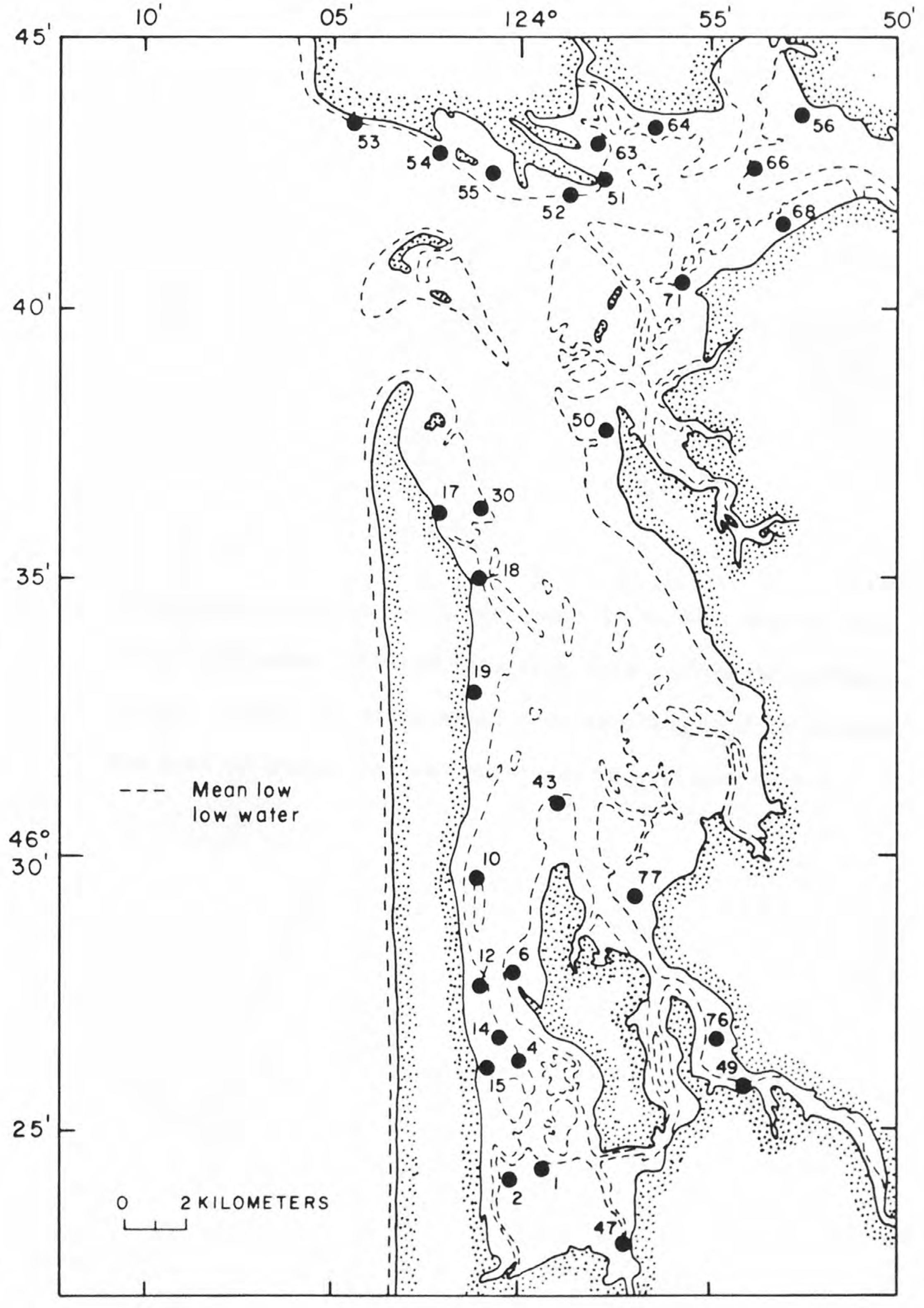
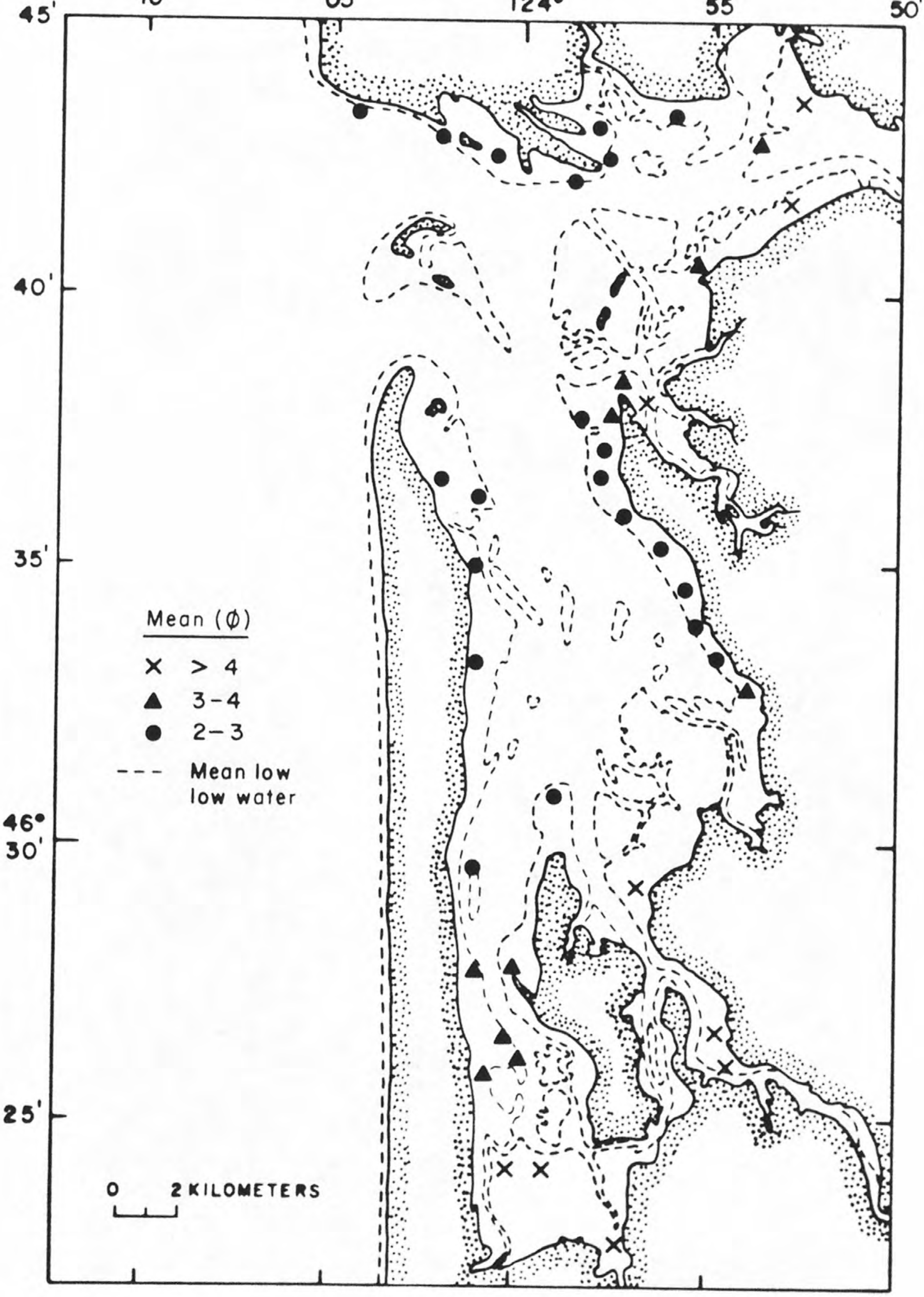

10'
05'
124°
55'
50'
45'
40'
35'
46°
30'
25'
53
54
55
52
51
63
64
56
66
68
71
50
17
30
18
19
43
10
77
12
6
14
4
15
76
49
1
2
47
Mean low
low water
0 2 KILOMETERS

Fig. 23. Distribution of tidal flat sediments in Willapa Bay by mean grain size using combined data from this report and Andrews (1965). Within my study area, each sampling profile across the flat is summarized and presented as a single symbol.



10'
05'
124°
55'
50'
45'
40'
35'
46°
30'
25'
Mean (Ø)
× > 4
▲ 3-4
● 2-3
Mean low low water
0 2 KILOMETERS